PA193 - Secure coding principles and practices

Language level vulnerabilities:
Buffer overflow, type overflow, strings

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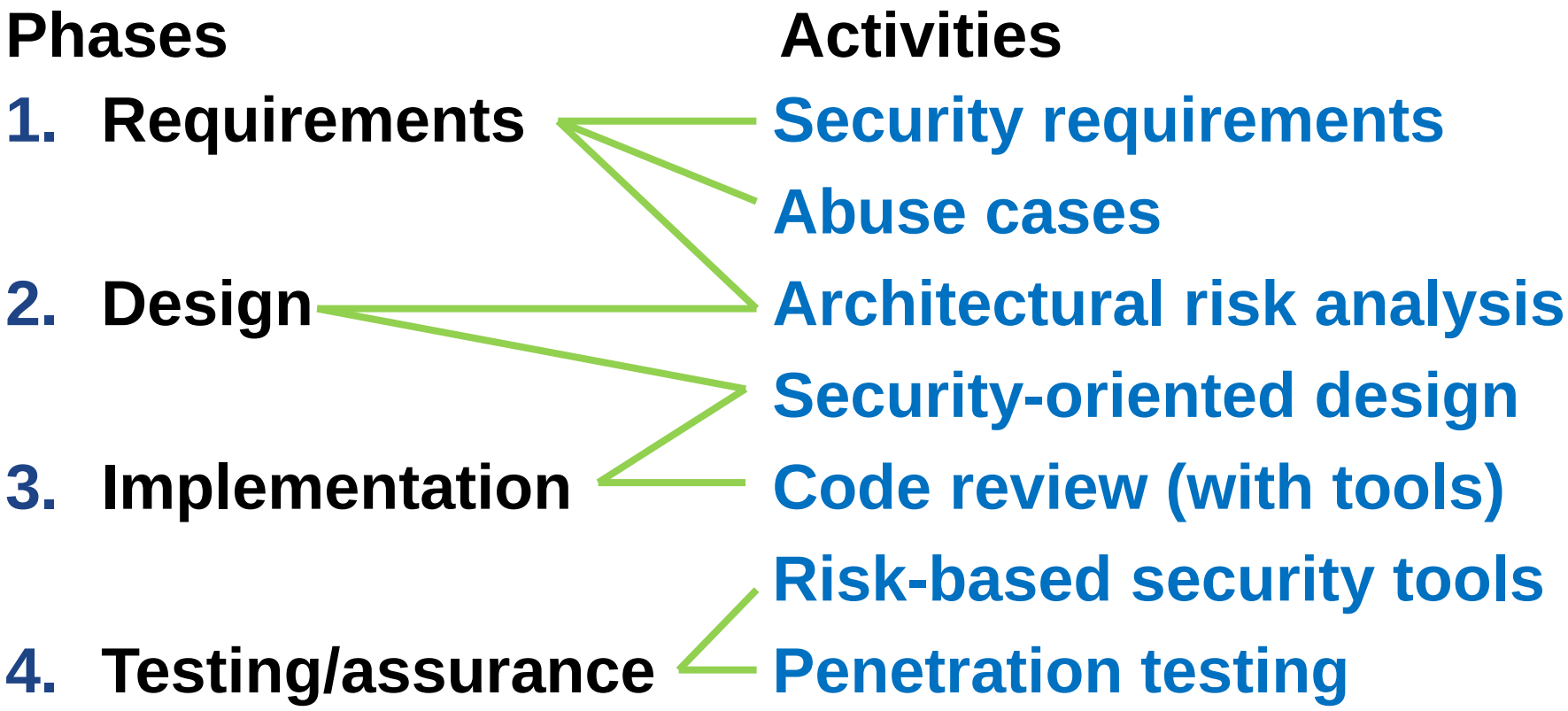
Security engineering – big picture



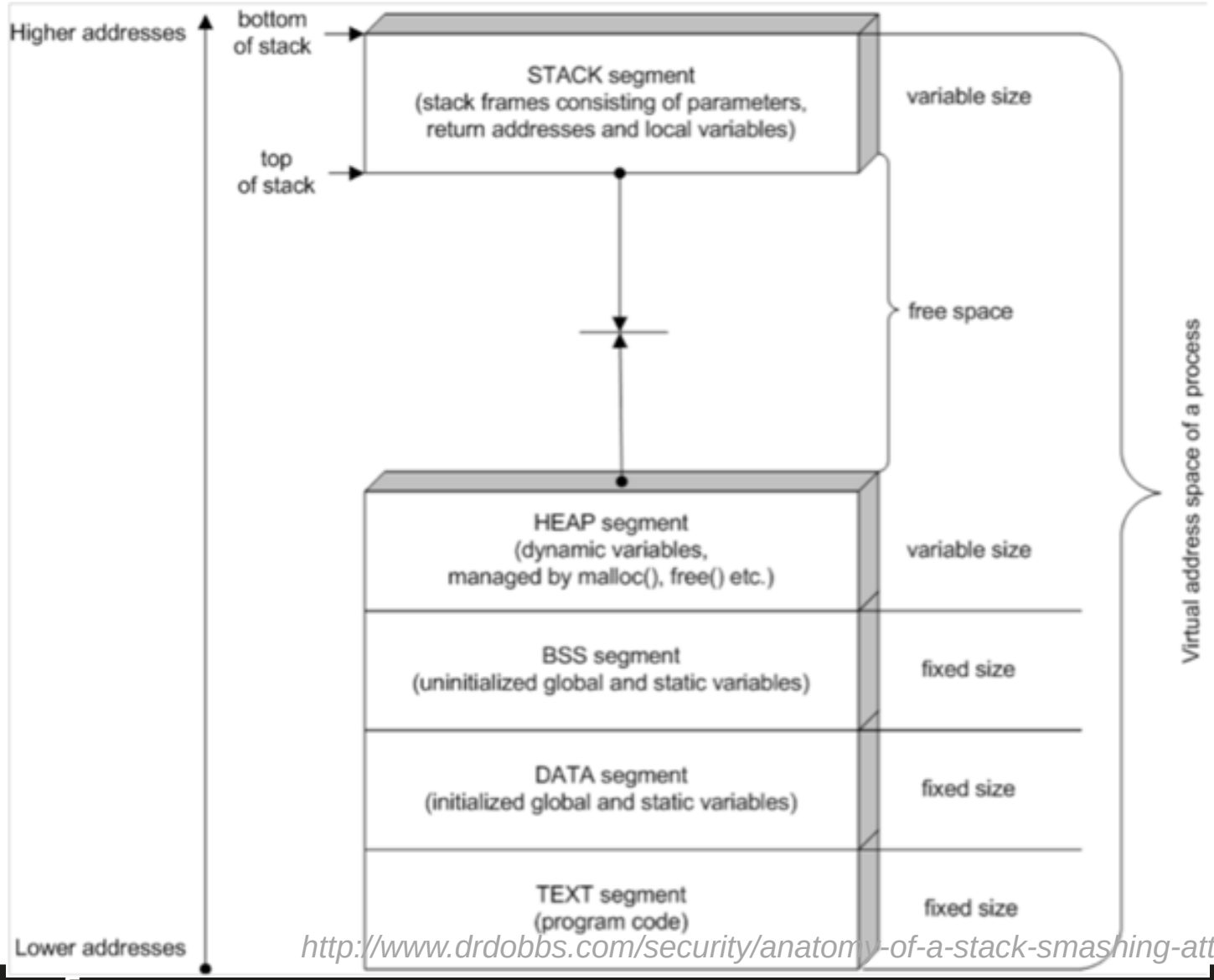
Based on Software security by M. Hicks (Coursera): https://class.coursera.org/softwaresec-002

Overview

- Lecture: problems, prevention
  - buffer overflow (stack/heap/type)
  - string formatting problems
  - compiler protection
  - platform protections (DEP, ASLR)
- Labs
  - compiler flags, buffer overflow exercises

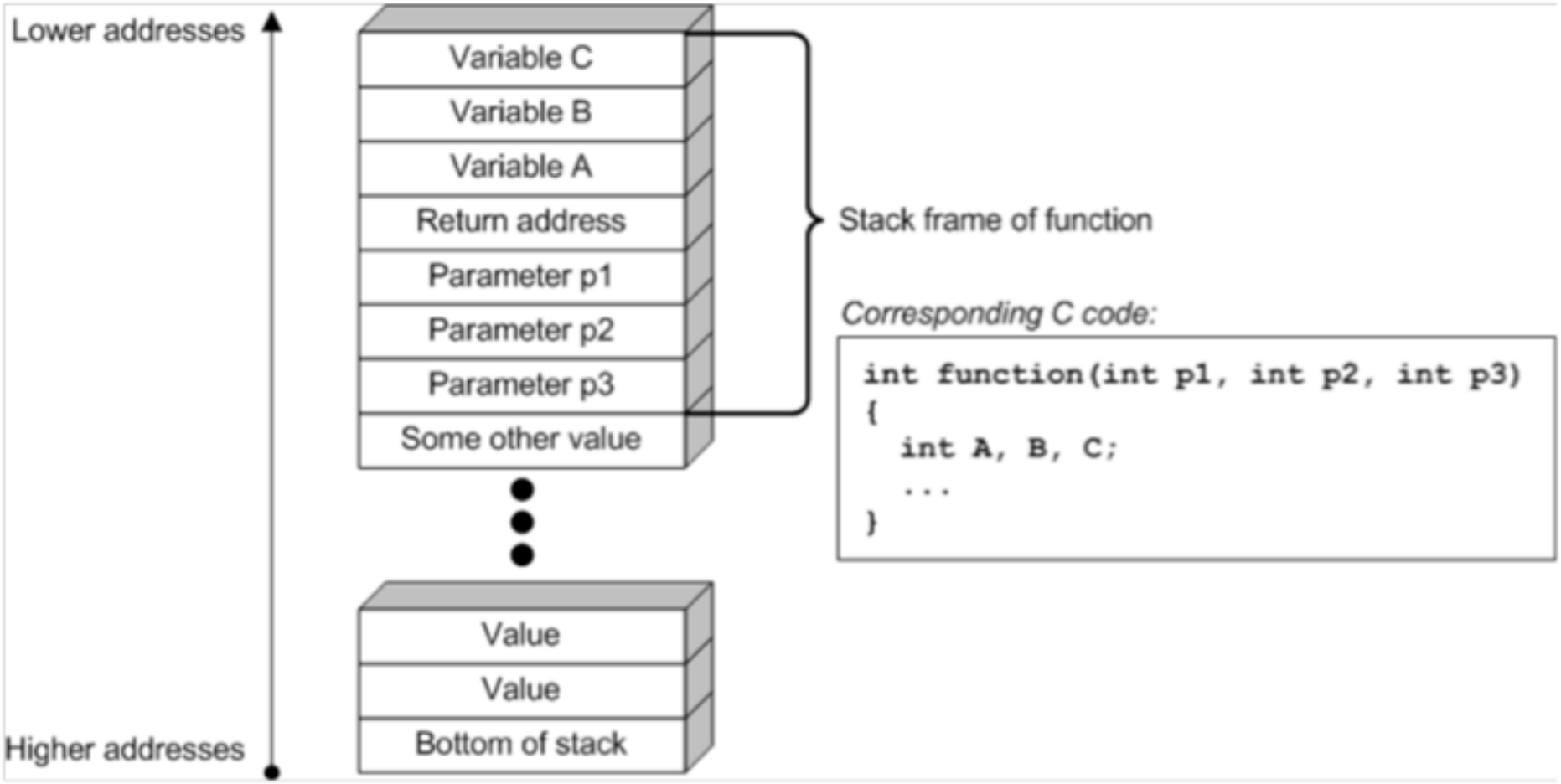
PROBLEM?

Process memory layout



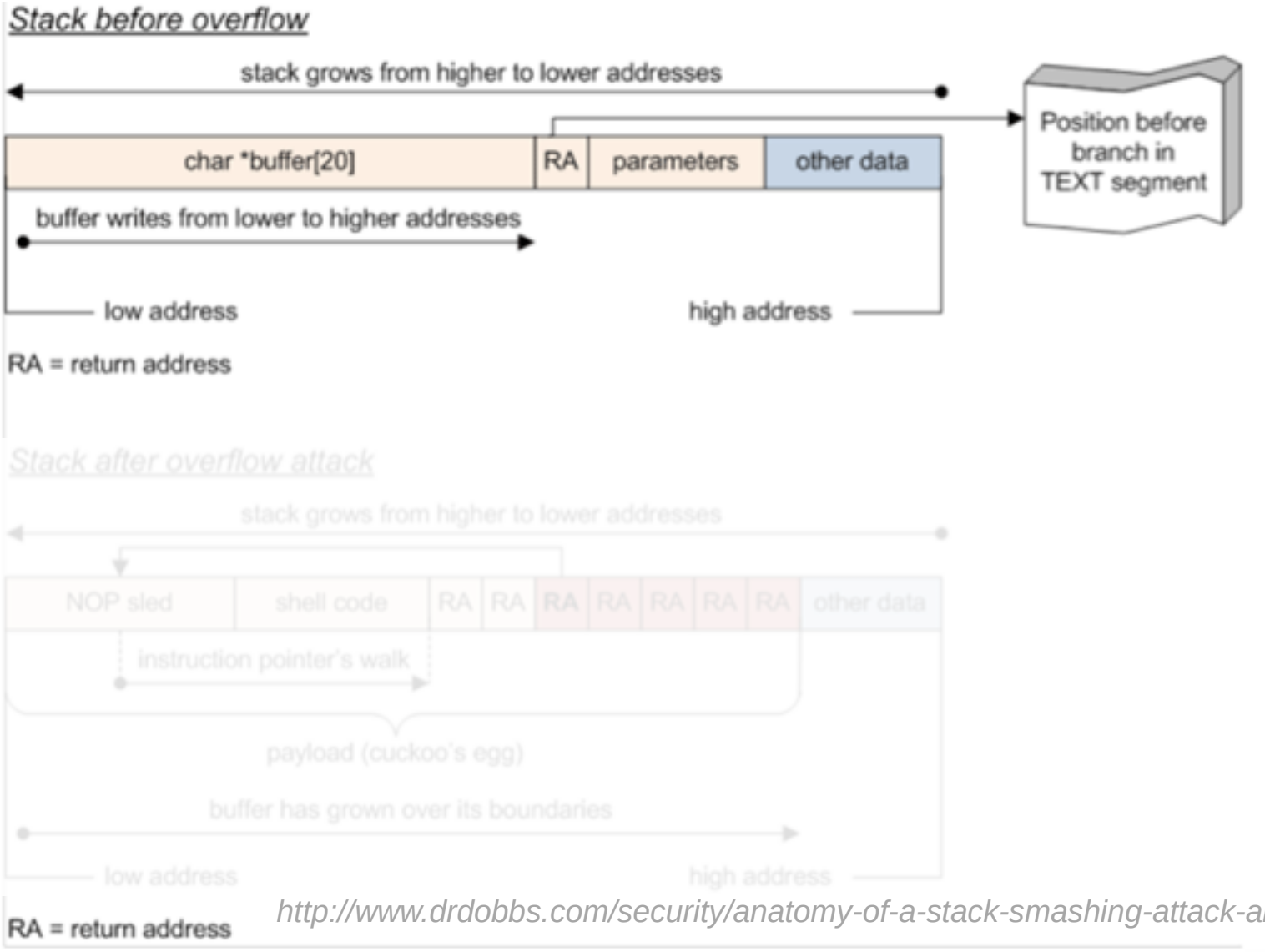
http://www.drdobbs.com/security/anatomy-of-a-stack-smashing-attack-and-h/240001832#

Stack memory layout



http://www.drdobbs.com/security/anatomy-of-a-stack-smashing-attack-and-h/240001832#

Stack overflow



http://www.drdobbs.com/security/anatomy-of-a-stack-smashing-attack-and-h/240001832#

Memory overflow - taxonomy

1. Buffer overflows
2. Stack overflows
3. Format strings
4. Heap overflows
5. .data/.bss segment overflows

Try this at home!

```
// Note: GCC and MSVC uses different memory alignment
// Try "12345678DevilEvecosia" as a password for gcc build
// Try "1234567812345678Devil I am. Ha Ha" as a password for MSVC debug build

void demoBufferOverflowData() {
	int		unused_variable = 30;
#define NORMAL_USER		'n'
#define ADMIN_USER		'a'
	int		userRights = NORMAL_USER;
#define USER_INPUT_MAX_LENGTH  8
	char	userName[USER_INPUT_MAX_LENGTH];
	char	passwd[USER_INPUT_MAX_LENGTH];

	// print some info about variables
	printf("%-20s: %p\n", "userName", userName);
	printf("%-20s: %p\n", "passwd", passwd);
	printf("%-20s: %p\n", "unused_variable", &unused_variable);
	printf("%-20s: %p\n", "userRights", &userRights);
	printf("\n");

	// Get user name
	memset(userName, 1, USER_INPUT_MAX_LENGTH);
	memset(passwd, 2, USER_INPUT_MAX_LENGTH);
	printf("login as: ");
	fflush(stdout);
	gets(userName);

	// Get password
	printf("%s@vulnerable.machine.com: ", userName);
	fflush(stdout);
	gets(passwd);

	// Check user rights (set to NORMAL_USER and not changed in code)
	if (userRights == NORMAL_USER) {
		printf("\nWelcome, normal user '%s', your rights are limited.\n\n", userName);
		fflush(stdout);
	}
	if (userRights == ADMIN_USER) {
		printf("\nWelcome, all mighty admin user '%s'!\n", userName);
		fflush(stdout);
	}

	// How to FIX:
	//memset(userName, 0, USER_INPUT_MAX_LENGTH);
	//fgets(userName, USER_INPUT_MAX_LENGTH - 1, stdin);
	//memset(passwd, 0, USER_INPUT_MAX_LENGTH);
	//fgets(passwd, USER_INPUT_MAX_LENGTH - 1, stdin);
}
```

```
void demoBufferOverflowData() {
      int           unused_variable = 30;
#define NORMAL_USER          'n'
#define ADMIN_USER           'a'
      int           userRights = NORMAL_USER;
#define USER_INPUT_MAX_LENGTH  8
      char          userName[USER_INPUT_MAX_LENGTH];
      char          passwd[USER_INPUT_MAX_LENGTH];

      // print some info about variables
      printf("%-20s: %p\n", "userName", userName);
      printf("%-20s: %p\n", "passwd", passwd);
      printf("%-20s: %p\n", "unused_variable", &unused_variable);
      printf("%-20s: %p\n", "userRights", &userRights);
      printf("\n");

      // Get user name
      printf("login as: ");
      gets(userName);

      // Get password
      printf("%s@vulnerable.machine.com: ", userName);
      gets(passwd);

      // Check user rights (set to NORMAL_USER and not changed in code)
      if (userRights == NORMAL_USER) {
            printf("\nWelcome, normal user '%s', your rights are limited.\n\n", userName);
      }
      if (userRights == ADMIN_USER) {
            printf("\nWelcome, all mighty admin user '%s'!\n", userName);
      }
}
```

Variable containing current access rights

Array with fixed length (will be overwritten)

Help output of address of local variables stored on the stack

Reading username and password (no length checking)

Print information about current user rights

Data in memory

```
void demoBufferOverflowData() {
    int     unused_variable = 30;
#define NORMAL_USER     'n'
#define ADMIN_USER      'a'
    int     userRights = NORMAL_USER;
#define USER_INPUT_MAX_LENGTH   8
    char    userName[USER_INPUT_MAX_LENGTH];
    char    passwd[USER_INPUT_MAX_LENGTH];

    // print some info about variables
    printf("%-20s: %p\n", "userName", userName);
    printf("%-20s: %p\n", "passwd", passwd);
    printf("%-20s: %p\n", "unused_variable", &unu
    printf("%-20s: %p\n", "userRights", &userRigh
    printf("\n");

    // Get user name
    memset(userName, 1, USER_INPUT_MAX_LENGTH);
    memset(passwd, 2, USER_INPUT_MAX_LENGTH);
    printf("login as: ");
    fflush(stdout);
```

100 %

Memory 1

Address: 0x0024FB1B Columns: Auto

```
0x0024FB1B  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc
0x0024FB2C  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc
0x0024FB3D  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc
0x0024FB4E  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc
0x0024FB5F  cc 02 02 02 02 02 02 02 02 cc cc cc cc cc cc cc cc cc
0x0024FB70  01 01 01 01 01 01 01 01 cc cc cc cc cc cc cc cc 6e
0x0024FB81  00 00 00 cc cc cc cc cc cc cc cc 1e 00 00 00 cc cc
0x0024FB92  cc cc 85 20 45 b8 6c fc 24 00 9a 20 dd 00 00 00 00
0x0024FBA3  00 00 00 00 00 00 e0 fd 7f cc cc cc cc cc cc cc cc
0x0024FBB4  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc
0x0024FBC5  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc
0x0024FBD6  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc
0x0024FBE7  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc
0x0024FBF8  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc
0x0024FC09  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc
```

Autos | Locals | Memory 1 | Threads | Modules | Watch 1

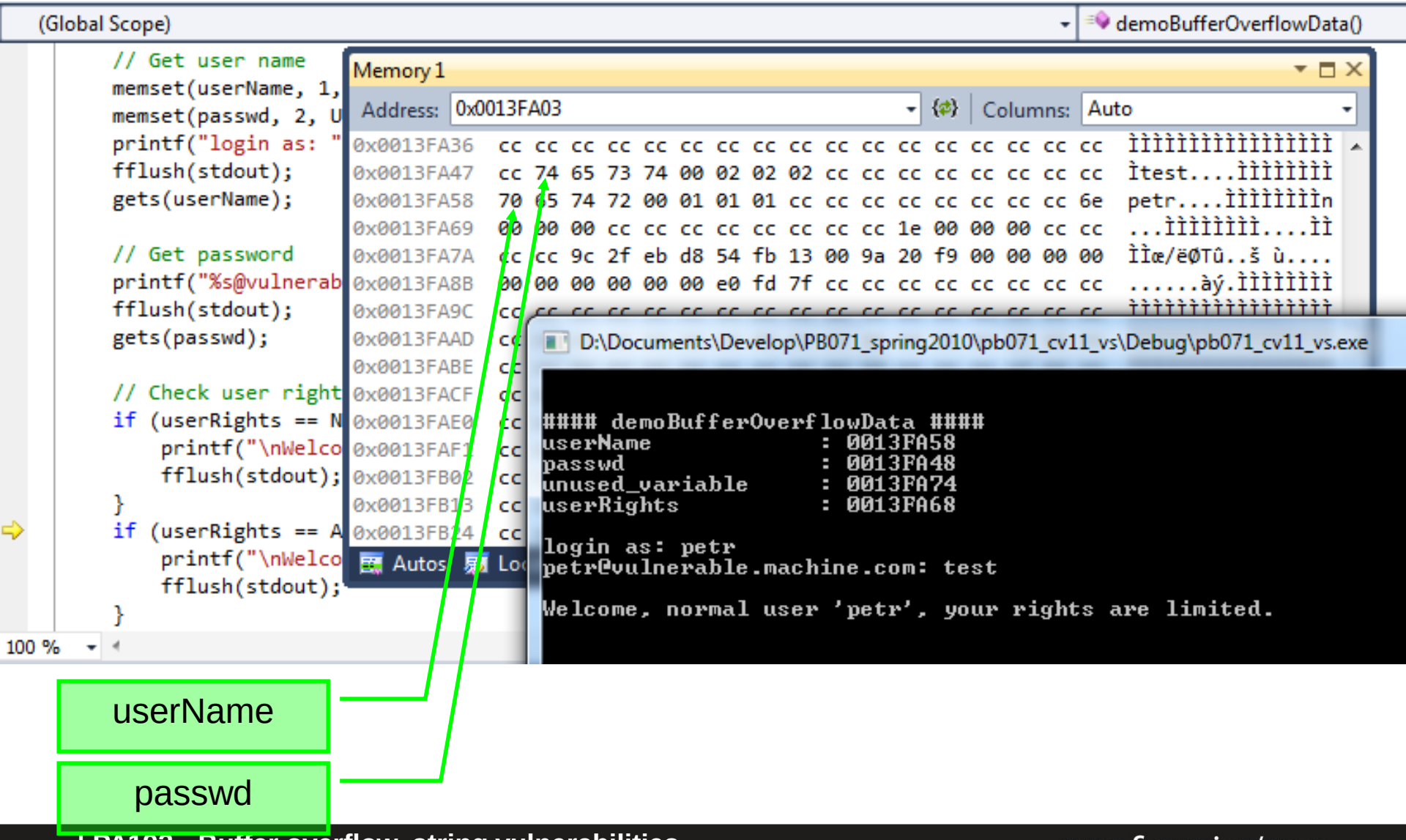
userName

passwd

userRights

unused_variable

Running without malicious input



Running with malicious input – userName

insert ‘evil’ into userName

```
// Get user name
memset(userName, 1, USER_INPUT_MAX_LENGTH);
memset(passwd, 2, USER_INPUT_MAX_LENGTH);
printf("login as: ");
fflush(stdout);
gets(userName);

// Get password
printf("%s@vulnerable.machine.com: ", userNam
fflush(stdout);
gets(passwd);

// Check user rights (set to NORMAL_USER and
if (userRights == NORMAL_USER) {
    printf("\nWelcome, normal user '%s', your
    fflush(stdout);
}
if (userRights == ADMIN_USER) {
    printf("\nWelcome, all mighty admin user
```

100 %

Memory 1

Address: 0x0024FB1B Columns: Auto

```
0x0024FB1B  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc  ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FB2C  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc  ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FB3D  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc  ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FB4E  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc  ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FB5F  cc 02 02 02 02 02 02 02 cc cc cc cc cc cc cc cc  Ì.......ÌÌÌÌÌÌÌÌ
0x0024FB70  65 76 69 6c 00 01 01 01 cc cc cc cc cc cc cc 6e  evil....ÌÌÌÌÌÌÌn
0x0024FB81  00 00 00 cc cc cc cc cc cc cc cc 1e 00 00 00 cc  ...ÌÌÌÌÌÌÌ....ÌÌ
0x0024FB92  cc cc 85 20 45 b8 6c fc 24 00 9a 20 dd 00 00 00  ÌÌ. E¸lü$.š Ý...
0x0024FBA3  00 00 00 00 00 00 e0 fd 7f cc cc cc cc cc cc cc  ......àý.ÌÌÌÌÌÌÌ
0x0024FBB4  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc  ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FBC5  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc  ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FBD6  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc  ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FBE7  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc  ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FBF8  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc  ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FC09  cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc cc  ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
```

Autos | Locals | Memory 1 | Threads | Modules | Watch 1

Running with malicious input - passwd

Insert
‘1234567812345678Devil I am. Ha Ha’
into passwd

```
printf("login as: ");
fflush(stdout);
gets(userName);

// Get password
printf("%s@vulnerable.machine.com: ",
fflush(stdout);
gets(passwd);

// Check user rights (set to NORMAL_U
if (userRights == NORMAL_USER) {
    printf("\nWelcome, normal user '%
    fflush(stdout);
}
if (userRights == ADMIN_USER) {
    printf("\nWelcome, all mighty adm
    fflush(stdout);
}

// How to FIX:
```

Memory 1

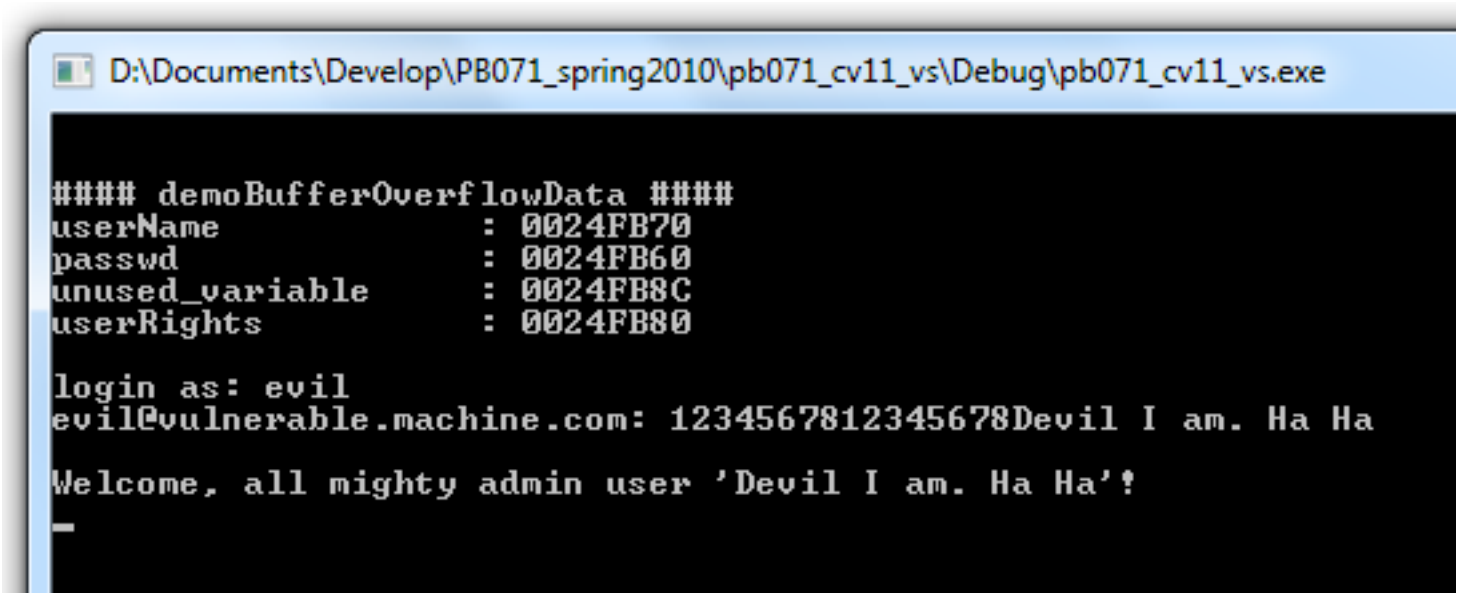
Address: 0x0024FB1B Columns: Auto

0x0024FB1B	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FB2C	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FB3D	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FB4E	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FB5F	cc	31	32	33	34	35	36	37	38	31	32	33	34	35	36	37	Ì1234567812345678
0x0024FB70	44	65	76	69	6c	20	49	20	61	6d	2e	20	48	61	20	48	Devil I am. Ha Ha
0x0024FB81	00	00	00	cc	cc	cc	cc	cc	cc	cc	cc	1e	00	00	00	cc	...ÌÌÌÌÌÌÌÌ....ÌÌ
0x0024FB92	cc	cc	85	20	45	b8	6c	fc	24	00	9a	20	dd	00	00	00	ÌÌ. E¸lü$.š Ý....
0x0024FBA3	00	00	00	00	00	00	e0	fd	7f	cc	cc	cc	cc	cc	cc	cc	......àý.ÌÌÌÌÌÌÌÌ
0x0024FBB4	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FBC5	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FBD6	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FBE7	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FBF8	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ
0x0024FC09	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	cc	ÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌÌ

Autos | Locals | Memory 1 | Threads | Modules | Watch 1

- Too long password overflow **`userName`** and **`userRights`**

Running with attacker input - result



Try this at home!

Other stack overflow demos

1. Stack overflow – auth. privileges change
2. Adjacent memory overflow – reveal password
3. Smash function return address – attacker code exec
4. Type overflow – overflow integer causing BO
5. Buffer overflow - shell execution

- Example with debugging with instruction-wise mode

Try this at home!

```
void demoAdjacentMemoryOverflow(char* userName, char* password) {
      // See more at http://www.awarenetwork.org/etc/alpha/?x=5
    // Once string is not null terminated, lot of functions will behave wrongly:
      // sprintf, fprintf, snprintf, strcpy, strcat, strlen, strstr, strchr, read...
      // memcpy, memmove - if length to copy is computed via strlen(string)

      char message[100];
      char realPassword[] = "very secret password nbu123";
      char buf[8];

      // print some info about variables
      printf("%-20s: %p\n", "message", message);
      printf("%-20s: %p\n", "userName", userName);
      printf("%-20s: %p\n", "password", password);
      printf("%-20s: %p\n", "realPassword", &realPassword);
      printf("%-20s: %p\n", "buf", &buf);
      printf("\n");

      memset(buf, 0, sizeof(buf));
      memset(message, 1, sizeof(message));
      strncpy(buf,userName,sizeof(buf));              // We will copy only characters which fits into buf

      // Now print username to standard output - nothing sensitive, right?
      sprintf(message, "Checking '%s' password\n",buf);
      printf("%s", message);
      if (strcmp(password, realPassword) == 0) {
              printf("Correct password.\n");
      }
      else {
              printf("Wrong password.\n");
      }

      // FIX: Do not allow to have non-terminated string
      // Clear buffer for text with zeroes (terminating zero will be there)
      // strncpy(buf,arg1,sizeof(buf) - 1);
}
```

Try this at home!

```
void vulnerable_function(const char* input) {
    char buf[10];
       memset(buf, 0, sizeof(buf));

       printf("%-20s: %9p\n", "buf", &buf);
    printf("My stack looks like:\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n\n");
    fflush(stdout);
    strcpy(buf, input);

    printf("Now the stack looks like:\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n%9p\n\n");
    fflush(stdout);
}

/**
 * This function contains code that attacker likes to execute.
 * It may be otherwise inaccessible privileged function (e.g., something like "admin_createNewUser()")
 * or code not originally present in the program code, but inserted by an attacker into the memory
 * (with starting address set at the begin of inserted code)
 */
void attackers_code(void) {
    printf("Augh! I've been hacked!\n");
       system("mmc.exe lusrmgr.msc");
       //system("rm -rf");
}

void demoBufferOverunFunction() {
       // Example taken from Howard and LeBlanc, modified to run with gcc compiler
       // This is a bit of cheating to make life easier - we will print the addresses of functions
       // In real scenario, attacker needs to find it by himself (e.g., multiple tests on test machine, dump)
       printf("Address of vulnerable_function() = %p\n", vulnerable_function);
       printf("Address of attackers_code() = %p\n", attackers_code);
       printf("Address of demoBufferOverunFunction = %p\n", demoBufferOverunFunction);
       fflush(stdout);
       vulnerable_function("12345678");                              // No problem
       vulnerable_function("1234567812aaaaaaa");          // Writing behind the array, but still nothing happens
       vulnerable_function("1234567812aaaaaaaa\x14\xff\x22\x01\xde\x16\x40");  // But now its works  - attac
}
```

Type-overflow vulnerabilities - motivation

- Quiz – what is insecure in given program?
- Can you come up with attack?

```
for (unsigned char i = 10; i >= 0; i--) {
    /* ... */
}
```

- And what about following variant?
  - Be aware: char can be both signed (x64) or unsigned (ARM)

```
for (char i =  both 0; i >= 0; i--) {
    /* ... */
}
```

Type overflow – basic problem

- Types are having limited range for the values
  - char: 256 values, int: 2^{32} values
  - add, multiplication can reach lower/upper limit
  - `char value = 250 + 10 ==` ?
- Signed vs. unsigned types
  - `for (unsigned char i = 10; i >= 0; i--) {/* ... */ }`
- Type value will underflow/overflow
  - CPU overflow flag is set
  - but without active checking not detected in program

Try this at home!

Type overflow – example with dynalloc

```
typedef struct _some_structure {
        float   someData[1000];
} some_structure;

void demoDataTypeOverflow(int totalItemsCount, some_structure* pItem,
                          int itemPosition) {
 // See http://blogs.msdn.com/oldnewthing/archive/2004/01/29/64389.aspx
 some_structure* data_copy = NULL;
 int bytesToAllocation = totalItemsCount * sizeof(some_structure);
 printf("Bytes to allocation: %d\n", bytesToAllocation);
 data_copy = (some_structure*) malloc(bytesToAllocation);
 if (itemPosition >= 0 && itemPosition < totalItemsCount) {
    memcpy(&(data_copy[itemPosition]), pItem, sizeof(some_structure));
 }
 else {
    printf("Out of bound assignment");
    return;
 }
 free(data_copy);
}
```

Format string vulnerabilities - motivation

- Quiz – what is insecure in given program?
- Can you come up with attack?

```
int main(int argc, char * argv[]) {
    printf(argv[1]);
    return 0;
}
```

Format string vulnerabilities

- Wide class of functions accepting format string
  - printf(“%s”, X);
  - resulting string is returned to user (= attacker)
  - formatting string can be under attackers control
  - variables formatted into string can be controlled
- Resulting vulnerability
  - memory content from stack is formatted into string
  - possibly any memory if attacker control buffer pointer

Information disclosure vulnerabilities

- Exploitable memory vulnerability leading to read access (not write access)
  - attacker learns some information from the memory
- Direct exploitation
  - secret information (cryptographic key, password...)
- Precursor for next step (very important with DEP&ASRL)
  - module version
  - current memory layout after ASRL (stack/heap pointers)
  - stack protection cookies (/GS)
- http://www.eeye.com/eEyeDigitalSecurity/media/ResearchPapers/eeyeMRV-Oct2006.pdf

Format string vulnerability - example

- Example retrieval of security cookie and return address

```
int main(int argc, char* argv[]) {
  char buf[64] = {};
  sprintf(buf, argv[1]);
  return printf("%s\n", buf);
}
```

argv[1] submitted by an attacker
E.g., %x%x%x….%x
Stack content is printed

strncpy - manual

function

strncpy

<cstring>

```
char * strncpy ( char * destination, const char * source, size_t num );
```

Copy characters from string

Copies the first *num* characters of *source* to *destination*. If the end of the *source* C string (which is signaled by a null-character) is found before *num* characters have been copied, *destination* is padded with zeros until a total of *num* characters have been written to it.

No null-character is implicitly appended at the end of *destination* if *source* is longer than *num*. Thus, in this case, *destination* shall not be considered a null terminated C string (reading it as such would overflow).

destination and *source* shall not overlap (see memmove for a safer alternative when overlapping).

Parameters

`destination`
Pointer to the destination array where the content is to be copied.

`source`
C string to be copied.

`num`
Maximum number of characters to be copied from *source*.
size_t is an unsigned integral type.

http://www.cplusplus.com/reference/cstring/strncpy/?kw=strncpy

Non-terminating functions for strings

- strncpy
- snprintf
- vsnprintf
- mbstowcs
- MultiByteToWideChar
- wcsncpy
- snwprintf
- vsnwprintf
- wcstombs
- WideCharToMultiByte

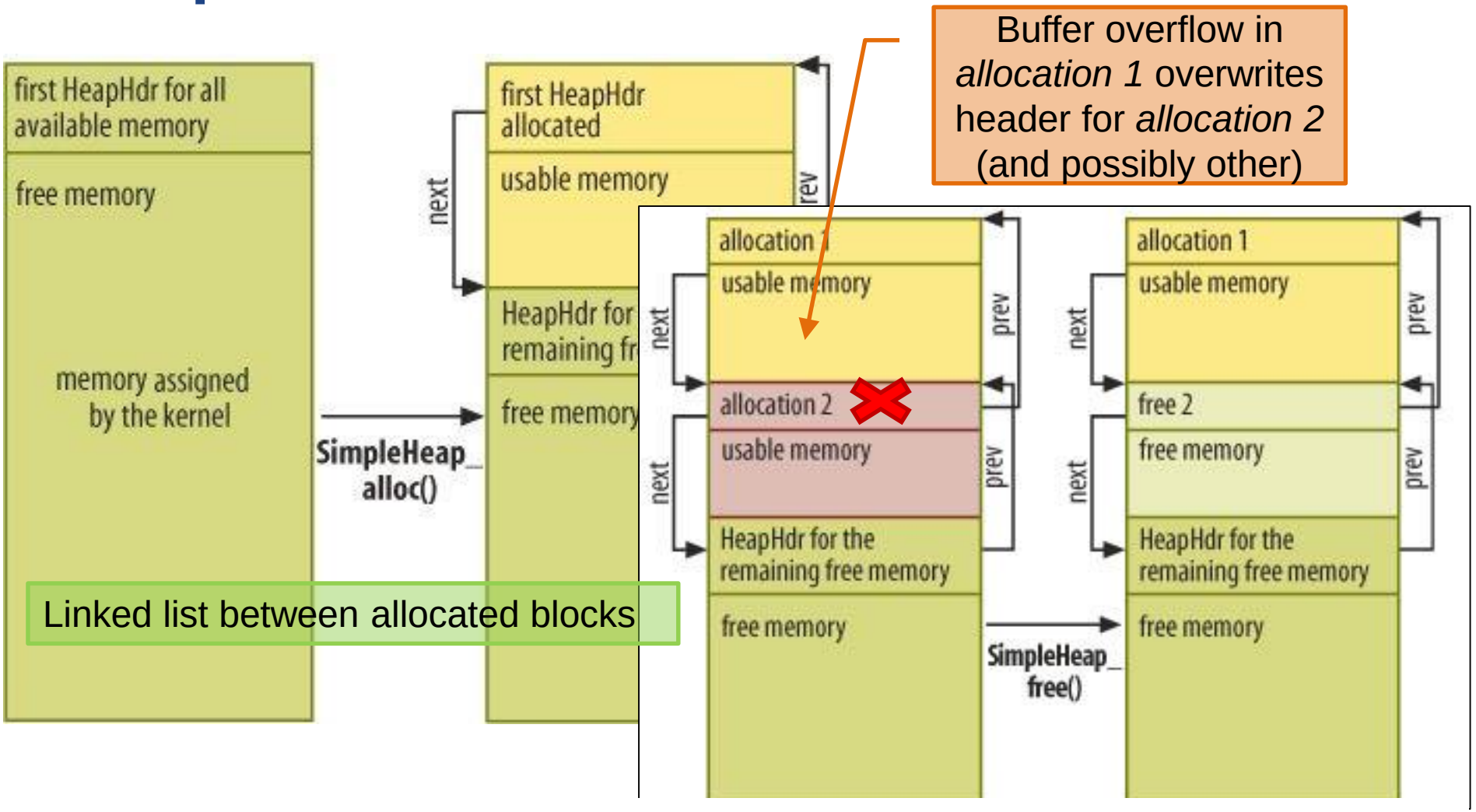
- Non-null terminated Unicode string more dangerous
  - C-string processing stops on first zero
  - any binary zero (ASCII)
  - 16-bit aligned wide zero character (UNICODE)

Non-terminating functions - example

- What is wrong with following code?

```
int main(int argc, char* argv[]) {
    char buf[16];
    strncpy(buf, argv[1], sizeof(buf));
    return printf("%s\n",buf);
}
```

Heap overflow



Felix "FX" Lindner, http://www.h-online.com/security/features/A-Heap-of-Risk-747220.html

Heap overflow – more details

- Assumption: buffer overflow possible for buffer at heap
- Problem:
  - attacker needs to write his pointer to memory later used as jump
  - no return pointer (jump) is stored on heap (as was for stack)
- Different mechanism for misuse
  - overwrite **`malloc`** metadata (few bytes before allocated block)
    - only **`next`**, **`prev`**, **`size`** and **`used`** can be manipulated
    - fake header (**`hdr`**) for fake block is created
  - let **`unlink`** function to be called (merge free blocks)
    - fake block is also merged during merge operation
    - **`hdr->next->next->prev = hdr->next->prev;`**

address in stack that will be interpreted later as jump pointer

address of attacker's code

SOURCE CODE PREVENTION

How to detect and prevent problems?

1. Protection on the source code level
   - languages with/without implicit protection
     - containers/languages with array boundary checking
   - usage of safe alternatives to vulnerable function *(this lecture)*
     - vulnerable and safe functions for string manipulations
   - proper input checking *(3. lecture)*
   - automatic detection by static and dynamic checkers *(4. lecture)*
   - security testing, fuzzing *(5. lecture)*
2. Protection by compiler (+ compiler flags) *(this lecture)*
   - runtime checks introduced by compiler (stack protection)
3. Protection by execution environment *(this lecture)*
   - DEP, ASRL...

How to write code securely (w.r.t. BO) I.

- Be aware of possibilities and principles
- Never trust user's input, always check defensively
- Use safe versions of string/memory functions
- Always provide a format string argument
- Use self-resizing strings (C++ **`std::string`**)
- Use automatic bounds checking if possible
  - C++ **`std::vector.at(i)`** instead of **`vector[i]`**

How to write code securely (w.r.t. BO) II.

- Run application with lowest possible privileges
- Let your code to be reviewed
- Use compiler-added protection
- Use protection offered by platform (privileges, DEP, ASRL, sandboxing...)

Secure C library

- Secure versions of commonly misused functions
  - bounds checking for string handling functions
  - better error handling
- Also added to new C standard ISO/IEC 9899:2011
- Microsoft Security-Enhanced Versions of CRT Functions
  - MSVC compiler issue warning C4996, more functions then in C11
- Secure C Library
  - http://docwiki.embarcadero.com/RADStudio/XE3/en/Secure_C_Library
  - http://msdn.microsoft.com/en-us/library/8ef0s5kh%28v=vs.80%29.aspx
  - http://msdn.microsoft.com/en-us/library/wd3wzwts%28v=vs.80%29.aspx
  - http://www.drdobbs.com/cpp/the-new-c-standard-explored/232901670

Secure C library – selected functions

```
char *gets(
   char *buffer
);

char *gets_s(
   char *buffer,
   size_t sizeInCharacters
);
```

- Formatted input/output functions
  - **gets_s**
  - **scanf_s**, wscanf_s, **fscanf_s**, fwscanf_s, ss
    vfscanf_s, vfwscanf_s, vscanf_s, vwscanf_s,
    vswscanf_s
  - **fprintf_s**, fwprintf_s, **printf_s**, printf_s, snprintf_s, snwprintf_s, **sprintf_s**, swprintf_s, vfprintf_s, vfwprintf_s, vprintf_s, vwprintf_s, vsnprintf_s, vsnwprintf_s, vsprintf_s, vswprintf_s
  - functions take additional argument with buffer length
- File-related functions
  - tmpfile_s, tmpnam_s, fopen_s, freopen_s
    - takes pointer to resulting file handle as parameter
    - return error code

Secure C library – selected functions

- Environment, utilities
  - getenv_s, wgetenv_s
  - bsearch_s, qsort_s
- Memory copy functions
  - memcpy_s, memmove_s, strcpy_s, wcscpy_s, strncpy_s, wcsncpy_s
- Concatenation functions
  - strcat_s, wcscat_s, strncat_s, wcsncat_s
- Search functions
  - strtok_s, wcstok_s
- Time manipulation functions...

CERT C/C++ Coding Standard

- CERT C Coding Standard
  - https://www.securecoding.cert.org/confluence/display/seccode/CERT+C+Coding+Standard
- CERT C++ Coding Standard
  - https://www.securecoding.cert.org/confluence/pages/viewpage.action?pageId=637
- Cern secure coding recommendation for C
  - https://security.web.cern.ch/security/recommendations/en/codetools/c.shtml
- Smashing the stack in 2011
  - https://paulmakowski.wordpress.com/2011/01/25/smashing-the-stack-in-2011/

COMPILER PREVENTIONS

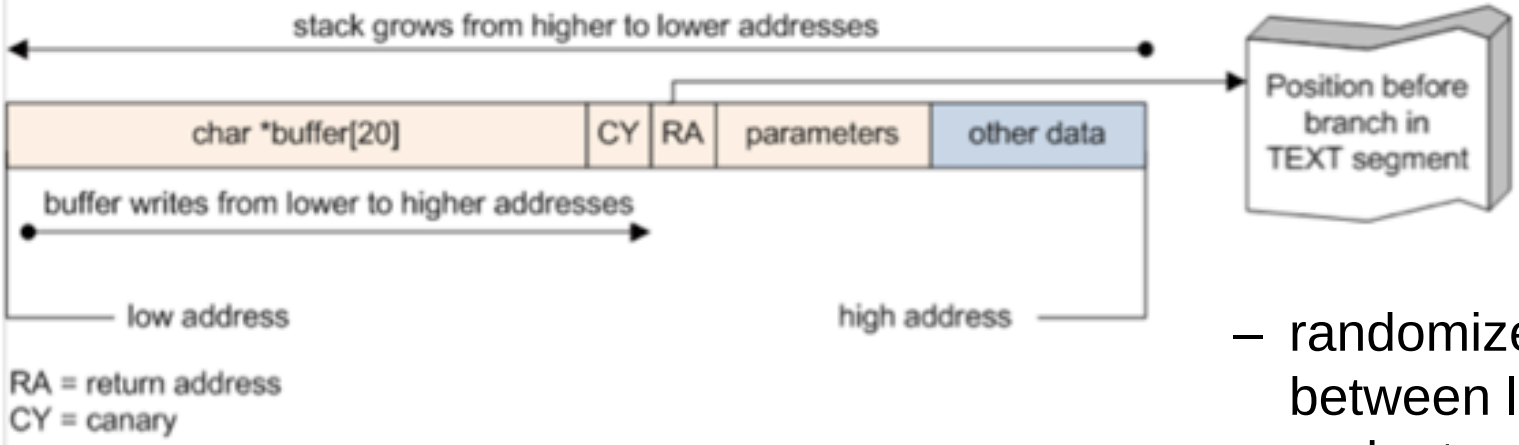
MSVC Compiler security flags - /RTC

- Microsoft's MSVC in Visual Studio
  - http://msdn.microsoft.com/en-us/library/aa290051%28v=vs.71%29.aspx
- Nice overview of available protections
  - http://msdn.microsoft.com/en-us/library/bb430720.aspx
- Visual Studio → Configuration properties → C/C++ → All options
- Run-time checks
  - /RTCu switch
    - uninitialized variables check
  - /RTCs switch
    - stack protection (stack pointer verification)
    - initialization of local variables to a nonzero value
    - detect overruns and underruns of local variables such as arrays
  - /RTC1 == /RTCsu

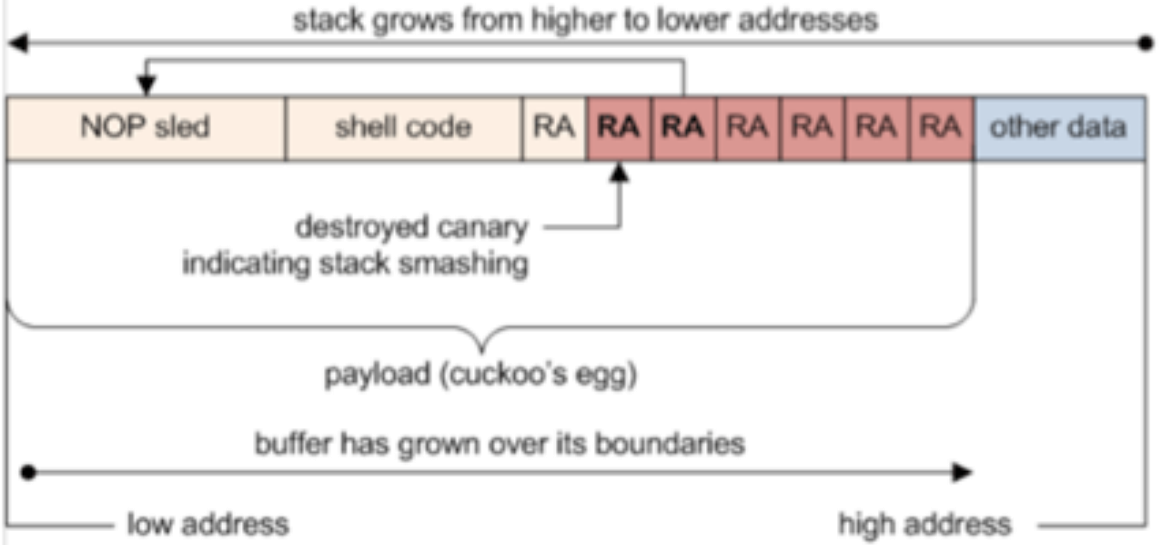
MSVC Compiler security flags - /GS

- /GS switch (added from 2003)
  - http://msdn.microsoft.com/en-us/library/8dbf701c.aspx
  - multiple different protections against buffer overflow
  - mostly focused on stack protection
- /GS protects:
  - return address of function
  - address of exception handler
  - vulnerable function parameters (arguments)
  - some of the local buffers (GS buffers)
- /GS protection is (automatically) added only when needed
  - to limit performance impact, decided by compiler (/GS rules)
  - `#pragma strict_gs_check(on)` - enforce strict rules application

Stack before overflow with canary



Stack after overflow attack with destroyed canary



- randomized cookie between local variables and return address
- function prolog (add security cookie)
- and epilog (check cookie)

http://www.drdobbs.com/security/anatomy-of-a-stack-smashing-attack-and-h/240001832#

/GS Security cookie ('canary') - details

- /GS Security cookie
  - random DWORD number generated at program start
  - master cookie stored in .data section of loaded module
  - xored with function return address (pointer encoding)
  - corruption results in jump to undefined value
- __security_init_cookie
  - http://msdn.microsoft.com/en-us/library/ms235362.aspx

Stack without /GS

Function parameters
Function return address
Frame pointer
Exception Handler frame
Locally declared variables and buffers
Callee save registers

Stack after /GS

Function parameters
Function return address
Frame pointer
Cookie
Exception Handler frame
Locally declared variables and buffers
Callee save registers

/GS buffers

- Buffers with special protection added
  - http://msdn.microsoft.com/en-us/library/8dbf701c.aspx
  - automatically and heuristically selected by compiler
- Applies to:
  - array larger than 4 bytes, more than two elements, element type is not pointer type
  - data structure with size more than 8 bytes with no pointers
  - buffer allocated by using the _alloca function
    - stack-based dynamic allocation
  - any class or structure with GS buffer

/GS – vulnerable parameters

- Protection of function's vulnerable parameters
  - parameters passed into function
  - copy of vulnerable parameters (during fnc's prolog) placed below the storage area for any other buffers
  - variables prone to buffer overflow are put on higher address so their overflow will not overwrite other local variables
- Applies to:
  - pointer
  - C++ reference
  - C-structure containing pointer
  - GS buffer

Is /GS protection bulletproof?

Y
Function parameters
Function return address (of Y == X)
Frame pointer
Cookie
Exception Handler frame
Locally declared variables and buffers
Callee save registers

X
Function parameters
Function return address (of X)
Frame pointer
Cookie
Exception Handler frame
Locally declared variables and buffers
Callee save registers

- What if pointer to buffer allocated in X is passed into function Y?
  - Return address of X can be overwritten in Y

/GS – what is NOT protected

- /GS compiler option does not protect against all buffer overrun security attacks
- Corruption of address in vtable
  - (table of addresses for virtual methods)
- Example: buffer and a vtable in an object, a buffer overrun could corrupt the vtable
- Functions with variable arguments list (...)

/GS – more references

- Compiler Security Checks In Depth (MS)
  - http://msdn.microsoft.com/en-us/library/aa290051%28v=vs.71%29.aspx
- /GS cookie effectiveness (MS)
  - http://blogs.technet.com/b/srd/archive/2009/03/16/gs-cookie-protection-effectiveness-and-limitations.aspx
- Windows ISV Software Security Defenses
  - http://msdn.microsoft.com/en-us/library/bb430720.aspx
- How to bypass /GS cookie
  - https://www.corelan.be/index.php/2009/09/21/exploit-writing-tutorial-part-6-bypassing-stack-cookies-safeseh-hw-dep-and-aslr/

GCC compiler - StackGuard & ProPolice

- StackGuard released in 1997 as extension to GCC
  - but never included as official buffer overflow protection
- GCC Stack-Smashing Protector (ProPolice)
  - patch to GCC 3.x
  - included in GCC 4.1 release
  - **`-fstack-protector`** (string protection only)
  - **`-fstack-protector-all`** (protection of all types)
  - on some systems enabled by default (OpenBSD)
    - **`-fno-stack-protector`** (disable protection)

GCC compiler & ProPolice - example

```
1  #include <string.h>
2
3  void vuln(const char *str)
4  {
5    char buf[20];
6    strcpy(buf, str);
7  }
8
9  int main(int argc, char *argv[])
10 {
11   vuln(argv[1]);
12   return 0;
13 }
```

http://www.drdobbs.com/security/anatomy-of-a-stack-smashing-attack-and-h/240001832#

GCC -fno-stack-protector

```
1  vuln:
2  .LFB0:
3      .cfi_startproc
4      pushq   %rbp                ; current base pointer onto stack
5      .cfi_def_cfa_offset 16
6      movq    %rsp, %rbp          ; stack pointer becomes new base pointer
7      .cfi_offset 6, -16
8      .cfi_def_cfa_register 6
9      subq    $48, %rsp           ; reserve space for
10                                     ; local variables on stack
11
12         ; bring arguments from registers onto stack
13     movq    %rdi, -40(%rbp)     ; 1st argument from rdi to stack
14
15         ; prepare parameters for strcpy()
16     movq    -40(%rbp), %rdx     ; 1st argument to rdx
17     leaq    -32(%rbp), %rax     ; 2nd argument to rax
18
19         ; call strcpy()
20     movq    %rdx, %rsi          ; source address from rdx to
21     movq    %rax, %rdi          ; destination address from ra
22     call    strcpy              ; call strcpy()
23
24     leave                       ; clean-up stack
25     ret                         ; return
26     .cfi_endproc
```

```
1  #include <string.h>
2
3  void vuln(const char *str)
4  {
5    char buf[20];
6    strcpy(buf, str);
7  }
8
9  int main(int argc, char *argv[])
10 {
11   vuln(argv[1]);
12   return 0;
13 }
```

How to bypass stack protection?

- Scenario:
  - long-term running of daemon on server
  - no exchange of cookie between calls

1. Obtain security cookie by one call
2. Use second call to change only the return address
   - cookie is now known and can be incorporated into stack-smashing data
   - or change cookie so return address will change to attacker target (is xored to return address!)

GCC -fstack-protector-all

```
vuln:
.LFB0:
    .cfi_startproc
    pushq   %rbp                ; current base pointer onto stack
    .cfi_def_cfa_offset 16
    movq    %rsp, %rbp          ; stack pointer becomes new base pointer
    .cfi_offset 6, -16
    .cfi_def_cfa_register 6
    subq    $48, %rsp           ; reserve space for
                                   ; local variables on stack

        ; bring arguments from registers onto stack
    movq    %rdi, -40(%rbp)     ; 1st argument from rdi to stack

        ; SSP's prolog: put canary onto stack
    movq    %fs:40, %rax        ; canary from %fs:40 to rax
    movq    %rax, -8(%rbp)      ; canary from rax onto stack
    xorl    %eax, %eax          ; set rax to zero

        ; prepare parameters for strcpy()
    movq    -40(%rbp), %rdx     ; 1st argument to rdx
    leaq    -32(%rbp), %rax     ; 2nd argument to rax

        ; call strcpy()
    movq    %rdx, %rsi          ; source address from rdx to rsi
    movq    %rax, %rdi          ; destination address from rax to rdi
    call    strcpy              ; call strcpy()

        ; SSP's epilog: check canary
    movq    -8(%rbp), %rax      ; canary from stack to rax
    xorq    %fs:40, %rax        ; original canary XOR rax
    je  .L3                 ; if no overflow -> XOR results in zero
                                   ;                => jump to label .L3
                                   ; if overflow    -> XOR results in non-zero
    call    __stack_chk_fail    ;               => call __stack_chk_fail()

.L3:
    leave                       ; clean-up stack
    ret                         ; return
    .cfi_endproc
```

```
#include <string.h>

void vuln(const char *str)
{
  char buf[20];
  strcpy(buf, str);
}

int main(int argc, char *argv[])
{
  vuln(argv[1]);
  return 0;
}
```

Control flow integrity

- Promising technique with low overhead
- Classic CFI (2005), Modular CFI (2014)
  - avg 5% impact, 12% in worst case
  - part of LLVM compiler (but only for C)

1. Analysis of source code to establish control-flow graph (which fnc can call what other fnc)
2. Assign shared labels between valid caller X and callee Y
3. When returning into function X, shared label is checked
4. Return to other function not permitted

- https://class.coursera.org/softwaresec-002/lecture/view?lecture_id=49

PLATFORM PROTECTIONS

Data Execution Prevention (DEP)

- *Motto: When boundary between code and data blurs (buffer overflow, SQL injection…) then exploitation might be possible.*
- Data Execution Prevention (DEP)
  - prevents application to execute code from non-executable memory region
  - available in modern operating systems
    - Linux kernel > 2.6.8, WinXP SP2, Mac OS X, iOS, Android
  - difference between ‘hardware’ and ‘software’ based DEP

Hardware DEP

- Supported from AMD64 and Intel Pentium 4
  - OS must add support of this feature (around 2004)
- CPU marks memory page as non-executable
  - most significant bit (63th) in page table entry (NX bit)
  - 0 == execute, 1 == data-only (non-executable)
- Protection typically against buffer overflows
- Cannot protect against all attacks!
  - e.g., code compiled at runtime (produced by JIT compiler) must have both instructions and data in executable page
  - attacker redirect execution to generated code (JIT spray)
  - used to bypass Adobe PDF and Flash security features

Software DEP

- Unrelated to NX bit (no CPU support required)
- When exception is raised, OS checks if exception handling routine pointer is in executable area
  - Microsoft's Safe Structured Exception Handling
- Software DEP is not preventing general execution in non-executable pages
  - different form of protection than hardware DEP

Return-oriented programming (ROP) I.

- Return-into-library technique (Solar Designer, 1997)
  - http://seclists.org/bugtraq/1997/Aug/63
  - method for bypassing DEP
  - no write of attacker's code to stack (as is marked by DEP)
  - function return address is replaced by pointer of selected standard library function instead
  - library function arguments are also replaced according to attackers needs
  - function return will result in execution of library function with given arguments
- Example: system call wrappers like **`system()`**

Return-oriented programming (ROP) II.

- But 64-bit hardware introduced different calling convention
  - first arguments to function are passed in CPU registers instead of via stack
  - harder to mount return-into-library attack
- Borrowed code chunks
  - attacker tries to find instruction sequences from any function that pop values from the stack into registers
  - necessary arguments are inserted into registers
  - return-into-library attack is then executed as before
- Return-oriented programming extends previous technique
  - multiple borrowed code chunks (gadgets) connected to execute Turing-complete functionality (Shacham, 2007)
  - automated search for gadgets possible by ROPgadget
  - https://www.youtube.com/watch?v=a8_fDdWB2-M
  - partially defended by ASLR (but information leakage)

Blind ROP

- Recent technique (IEEE S&P 2014)
  - Randomization assumed
  - But no re-randomization on restart if server crash

1. Information leak for reading the stack
2. Find gadgets at runtime to affect write()
3. Dump binary to find gadgets (same as before)

Address Space Layout Randomization (ASLR)

- Random reposition of executable base, stack, heap and libraries address in process's address space
  - aim is to prevent exploit to reliably jump to required address
  - performed every time a process is executed
  - random offset added to otherwise fixed address
  - entropy of random offset is important (bruteforce)
- Applies to program and also dynamic libraries
- Introduced by Memco software (1997)
  - fully implemented in Linux PaX patch (2001)
  - MS Windows Vista, enabled by default (2007)
  - MS Windows 8, improved entropy (2012)

ASLR – how much entropy?

- Usually depends on available memory
  - possible attack combination with enforced low-memory situation
- Linux PaX patch (2001)
  - around 24 bits entropy
- MS Windows Vista (2007)
  - heap only around 5-7 bits entropy
  - stack 13-14 bits entropy
  - code 8 bits entropy
  - http://www.blackhat.com/presentations/bh-dc-07/Whitehouse/Presentation/bh-dc-07-Whitehouse.pdf
- MS Windows 8 (2012)
  - additional entropy, Lagged Fibonacci Generator, registry keys, TPM, Time, ACPI, new rdrand CPU instruction
  - http://media.blackhat.com/bh-us-12/Briefings/M_Miller/BH_US_12_Miller_Exploit_Mitigation_Slides.pdf

ASRL entropy in MS Windows 7&8 (2012)

Entropy (in bits) by region	Windows 7		Windows 8		
	32-bit	64-bit	32-bit	64-bit	64-bit (HE)
Bottom-up allocations (opt-in)	0	0	8	8	24
Stacks	14	14	17	17	33
Heaps	5	5	8	8	24
Top-down allocations (opt-in)	0	0	8	17	17
PEBs/TEBs	4	4	8	17	17
EXE images	8	8	8	17*	17*
DLL images	8	8	8	19*	19*
Non-ASLR DLL images (opt-in)	0	0	8	8	24

* 64-bit DLLs based below 4GB receive 14 bits, EXEs

ASLR entropy is the same for both 32-bit and 64-bit processes

64-bit processes receive much more entropy on Windows 8, especially with

Taken from Ken Johnson, Matt Miller (Microsoft Security Engineering Center), BlackHat USA 2012
http://media.blackhat.com/bh-us-12/Briefings/M_Miller/BH_US_12_Miller_Exploit_Mitigation_Slides.pdf

DEP&ASRL – MSVC compilation flags

- /NXCOMPAT (on by default)
  - program is compatible with hardware DEP
- /SAFESEH (on by default, only 32bit programs)
  - software DEP
- /DYNAMICBASE (on by default)
  - basic ASLR
  - Property Pages → Configuration Properties → Linker → Advanced → Randomized Base Address
  - http://msdn.microsoft.com/en-us/library/bb384887.aspx
- /HIGHENTROPYVA (on by default, only 64bit programs)
  - ASRL with higher entropy
  - http://msdn.microsoft.com/en-us/library/dn195771.aspx

ASRL – impact on attacks

- ASLR introduced big shift in attacker mentality
- Attacks are now based on gaps in ASRL
  - legacy programs/libraries/functions without ASRL support
    - ! /DYNAMICBASE
  - address space spraying (heap/JIT)
  - predictable memory regions, insufficient entropy

DEP and ASLR should be combined

- *"For ASLR to be effective, DEP/NX must be enabled by default too."* M. Howard, Microsoft
- /GS combined with /DYNAMICBASE and /NXCOMPAT
  - /DYNAMICBASE randomizes position of master cookie for /GS
  - /NXCOMPAT prevents insertion of new attackers code and forces ROP
  - /DYNAMICBASE randomizes code chunks used later for ROP
  - /GS prevents modification of return pointer used later for ROP
- Visual Studio → Configuration properties →
  - Linker → All options
  - C/C++ → All options

SUMMARY

The state of memory safety exploits

Most systems are not compromised by exploits	• About 6% of MSRT detections were likely caused by exploits [29] • Updates were available for more than a year for most of the exploited issues [29]
Most exploits target third party applications	• 11 of 13 CVEs targeted by popular exploit kits in 2011 were for issues in non-Microsoft applications [27]
Most exploits target older versions of Windows (e.g. XP)	• Only 5% of 184 sampled exploits succeeded on Windows 7 [28] • ASLR and other mitigations in Windows 7 make exploitation costly [30]
Most exploits fail when mitigations are enabled	• 14 of 19 exploits from popular exploit kits fail with DEP enabled [27] • 89% of 184 sampled exploits failed with EMET enabled on XP [28]
Exploits that bypass mitigations & target the latest products do exist	• Zero-day issues were exploited in sophisticated attacks (Stuxnet, Duqu) • Exploits were written for Chrome and IE9 for Pwn2Own 2012

Taken from Ken Johnson, Matt Miller (Microsoft Security Engineering Center), BlackHat USA 2012
http://media.blackhat.com/bh-us-12/Briefings/M_Miller/BH_US_12_Miller_Exploit_Mitigation_Slides.pdf

Final checklist

1. Be aware of possible problems and attacks
   - Don’t make exploitable errors at the first place!
   - Automated protections cannot fully defend everything
2. Use safe versions of vulnerable functions
   - Secure C library (xxx_s functions)
   - Self-resizing strings/containers for C++
3. Compile with all protection flags
   - MSVC: **`/RTC1,/DYNAMICBASE,/GS,/NXCOMPAT`**
   - GCC: **`-fstack-protector-all`**
4. Apply automated tools
   - BinScope Binary Analyzer, static and dynamic analyzers, vulns. scanners
5. Take advantage of protection in the modern OSes
   - and follow news in improvements in DEP, ASRL...

Mandatory reading

- SANS: 2015 State of Application Security
  - https://www.sans.org/reading-room/whitepapers/analyst/2015-state-application-security-closing-gap-35942
  - What are main differences between builders and defenders?
  - Which applications are of main security concern?
  - Which security standards/methodologies are followed?
- SoK: Eternal War in Memory
  - http://www.cs.berkeley.edu/~dawnsong/papers/Oakland13-SoK-CR.pdf
  - http://www.slideshare.net/daniel_bilar/song-2013-so-k-eternal-war-in-memory
  - What are techniques to ensure memory safety?
  - What is performance penalty for memory protection techniques?

Books - optional

- Writing secure code, chap. 5
- Security Development Lifecycle, chap. 11
- Embedded Systems Security, D., M. Kleidermacher

Questions

Additional reading

- Compiler Security Checks In Depth (MS)
  - http://msdn.microsoft.com/en-us/library/aa290051%28v=vs.71%29.aspx
- GS cookie effectiveness (MS)
  - http://blogs.technet.com/b/srd/archive/2009/03/16/gs-cookie-protection-effectiveness-and-limitations.aspx
- Design Your Program for Security
  - http://www.dwheeler.com/secure-programs/Secure-Programs-HOWTO/internals.html
- Smashing The Stack For Fun And Profit
  - http://www-inst.cs.berkeley.edu/~cs161/fa08/papers/stack_smashing.pdf
- Practical return oriented programming
  - http://365.rsaconference.com/servlet/JiveServlet/previewBody/2573-102-1-3232/RR-304.pdf

Tutorials - optional

- Buffer Overflow Exploitation Megaprimer (Linux)
  - http://www.securitytube.net/groups?operation=view&groupId=4
- Tenouk Buffer Overflow tutorial (Linux)
  - http://www.tenouk.com/Bufferoverflowc/bufferoverflowvulexploitdemo.html
- Format string vulnerabilities primer (Linux)
  - http://www.securitytube.net/groups?operation=view&groupId=3
- Buffer overflow in Easy RM to MP3 utility (Windows)
  - https://www.corelan.be/index.php/2009/07/19/exploit-writing-tutorial-part-1-stack-based-overflows/

Heap overflow - references

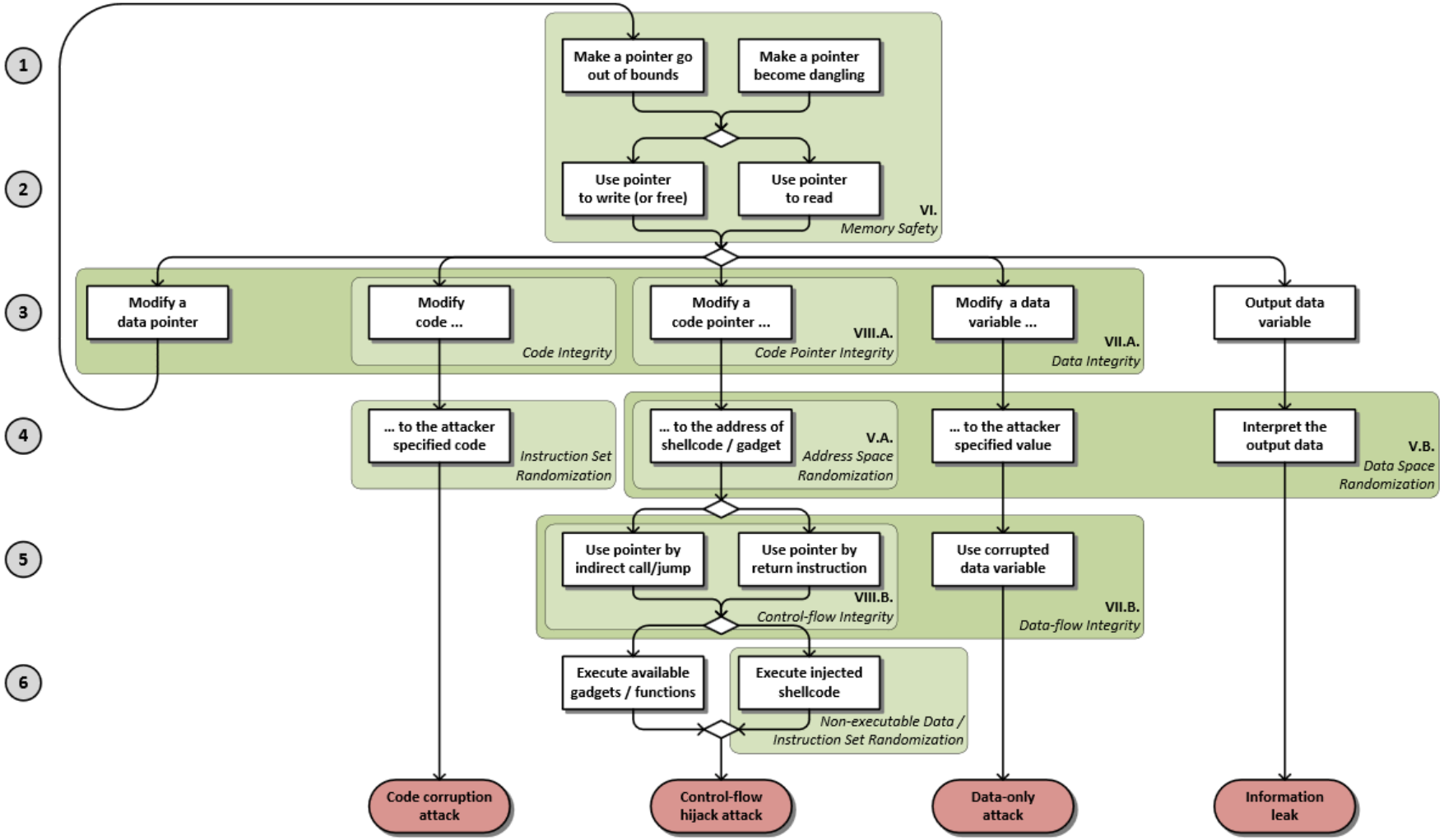
- Detailed explanation (Felix "FX" Lindner, 2006)
  - http://www.h-online.com/security/features/A-Heap-of-Risk-747161.html?view=print
- Explanation in Phrack magazine (blackngel, 2009)
  - http://www.phrack.org/issues.html?issue=66&id=10#article
- Defeating heap protection (Alexander Anisimov)
  - http://www.ptsecurity.com/download/defeating-xpsp2-heap-protection.pdf
- Diehard – drop-in replacement for malloc with memory randomization
  - http://plasma.cs.umass.edu/emery/diehard.html
  - https://github.com/emeryberger/DieHard

ROP - references

- Explanation of ROP
  - https://www.usenix.org/legacy/event/sec11/tech/full_papers/Schwartz.pdf
- Blind ROP
  - Return-oriented programming without source code
  - http://www.scs.stanford.edu/brop/
- Automatic search for ROP gadgets
  - https://github.com/0vercl0k/rp

http://www.cs.berkeley.edu/~dawnsong/papers/Oakland13-SoK-CR.pdf

SoK: Eternal War in Memory



SoK: Eternal War in Memory

	Policy type (main approach)	Technique	Perf. % (avg/max)	Dep.	Compatibility	Primary attack vectors
Generic prot.	Memory Safety	SofBound + CETS	116 / 300	×	Binary	—
		SoftBound	67 / 150	×	Binary	UAF
		Baggy Bounds Checking	60 / 127	×	—	UAF, sub-obj
	Data Integrity	WIT	10 / 25	×	Binary/Modularity	UAF, sub-obj, read corruption
	Data Space Randomization	DSR	15 / 30	×	Binary/Modularity	Information leak
	Data-flow Integrity	DFI	104 / 155	×	Binary/Modularity	Approximation
CF-Hijack prot.	Code Integrity	Page permissions (R)	0 / 0	✓	JIT compilation	Code reuse or code injection
	Non-executable Data	Page permissions (X)	0 / 0	✓	JIT compilation	Code reuse
	Address Space Randomization	ASLR	0 / 0	✓	Relocatable code	Information leak
		ASLR (PIE on 32 bit)	10 / 26	×	Relocatable code	Information leak
	Control-flow Integrity	Stack cookies	0 / 5	✓	—	Direct overwrite
		Shadow stack	5 / 12	×	Exceptions	Corrupt function pointer
		WIT	10 / 25	×	Binary/Modularity	Approximation
		Abadi CFI	16 / 45	×	Binary/Modularity	Weak return policy
		Abadi CFI (w/ shadow stack)	21 / 56	×	Binary/Modularity	Approximation

http://www.cs.berkeley.edu/~dawnsong/papers/Oakland13-SoK-CR.pdf