Computer Science 5271
Fall 2014
Midterm exam (solutions)
October 14th, 2014
Time Limit: 75 minutes, 2:30pm-3:45pm

- This exam contains 12 pages (including this cover page) and 5 questions. Once we tell you to start, please check that no pages are missing.
- Before starting the exam, you can fill out your name and other information of this page, but don't open the exam until you are directed to start. Don't put any of your answers on this page.
- You may use any textbooks, notes, or printouts you wish during the exam, but you may not use any electronic devices: no calculators, smart phones, laptops, etc.
- You may ask clarifying questions of the instructor or TA, but no communication with other students is allowed during the exam.
- Please read all questions carefully before answering them. Remember that we can only grade what you write on the exam, so it's in your interest to show your work and explain your thinking.
- By signing below you certify that you agree to follow the rules of the exam, and that the answers on this exam are your own work only.

The exam will end promptly at 3:45pm. Good luck!

Your name (print): ____________________

Your UMN email/X.500: ____________________`@umn.edu`

Number of rows ahead of you: __________ Number of seats to your left: __________

Sign and date: ____________________

Question	Points	Score
1	20	
2	24	
3	20	
4	20	
5	16	
Total:	100	

1. (20 points) Matching, specific to general. Fill in each blank next to a more specific term or concept with the letter of a more general term or concept it is an instance of. (Don't mix this up with any other relationships, like "used together with" or "sounds like".) Each answer is used at least once, some more than once.

   (a) __**A**__ Unix file permissions

   (b) __**L**__ DEP

   (c) __**K**__ `chown` (**G** is also technically correct and was accepted.)

   (d) __**H**__ Bell-LaPadula

   (e) __**J**__ Linux kernel

   (f) __**B**__ Unix file descriptor

   (g) __**J**__ L4 microkernel

   (h) __**G**__ `printf`

   (i) __**L**__ non-executable stack

   (j) __**D**__ function pointer overwrite

   (k) __**K**__ `execve` (**G** is also technically correct and was accepted.)

   (l) __**G**__ `system`

   (m) __**F**__ precondition

   (n) __**C**__ Facebook Connect

   (o) __**E**__ return to `libc`

   (p) __**I**__ TOCTTOU bug

   (q) __**H**__ Biba

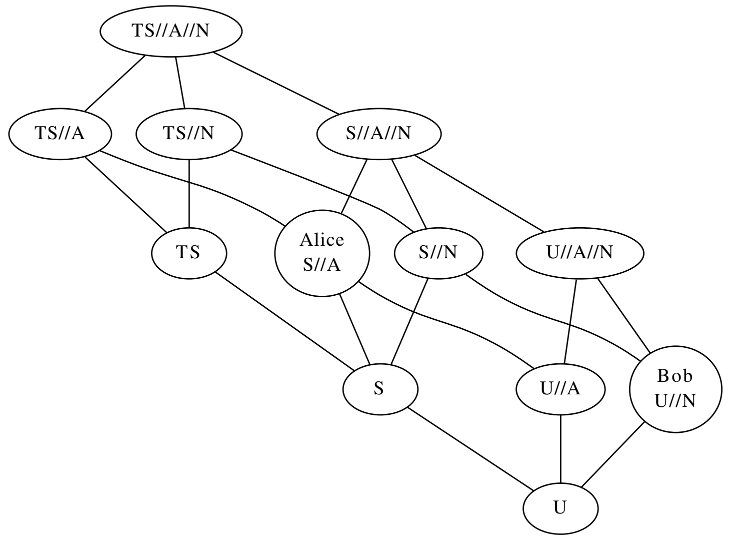
   (r) __**E**__ ROP

   (s) __**D**__ stack smashing

   (t) __**C**__ Microsoft Passport

   A. access control list B. capability C. centralized authentication D. code injection attack E. code reuse attack F. invariant G. `libc` function H. MAC model I. race condition J. reference monitor K. system call L. $W \oplus X$

2. (24 points) Multiple choice. Each question has only one correct answer: circle its letter.



(a) The military systems of a small island nation use a BLP security policy according to the lattice pictured above: there are three levels for unclassified (U), secret (S), and top secret (TS) information, and specialized compartments for secrets specific to the army (A) and navy (N); the country has no air force. Suppose that the email system is configured to allow emails to be delivered only if BLP would allow information flow from the sender to recipient. If Alice is a lieutenant in the army with clearance S//A, and Bob is a private in the navy with clearance U//N, which of these describes how they can communicate?

A. They can send emails in both directions
B. Alice can send email to Bob, but not Bob to Alice
C. Bob can send emails to Alice, but not Alice to Bob
D. Neither Alice nor Bob can send emails to the other

The two lattice elements are incomparable.

(b) Continuing with the lattice from the previous question, suppose that intelligence gathered by both Alice and Bob is put together in a combined report. What is the correct classification of this report?

A. TS//A//N B. S//A **C. S//A//N** D. S//N E. U//A//N

Producing the combined report corresponds to the join operator in the lattice.

(c) This feature of the x86 architecture makes overlapping instructions possible:

A. Instructions have variable length
B. Instruction lengths are not multiples of 8 bits
C. There is no PC-relative addressing
D. There are few general-purpose registers
E. Most byte sequences are legal instructions

C, D, and E are all true, and E helps make ROP more effective, but overlapping instructions would be possible even without them. B is false.

(d) In the classic style of ROP for x86, this register plays a role analogous to the program counter `%eip`:

A. `%esi` B. `%gs` **C.** `%esp` D. `%ebp` E. `%eax`

The gadget pointers on the stack are analogous to instructions, and the stack pointer plays the role of the program counter: it points at the current instruction and is advanced to point to the next instruction.

(e) Which of these intended instructions could **not** supply the end of a gadget in an ROP or JOP attack?

A. `xor %eax, %ebx` (`0x31 0xc3`)

B. `add %dh, %ah` (`0x00 0xf4`)

C. `jmp *%ebx` (`0xff 0xe3`)

D. `add %ax, -0x1d(%edi,%edi,8)` (`0x66 0x01 0x44 0xff 0xe3`)

E. `ret` (`0xc3`)

E and C would be usable directly as the last instructions of a ROP or JOP gadget respectively. A and D contain the byte sequences of E and C respectively, so they could be used to obtain the same effect as E or C from misaligned execution. But B is not usable in either of these ways.

(f) Which of these security mechanisms is **not** deployed in most modern systems?

A. Stack canaries B. W $\oplus$ X **C. CFI** D. Access control lists E. ASLR

A is implemented in most modern compilers (for instance the `-fstack-protector` *option of GCC which is on by default in Ubuntu). B and E are defenses implemented in modern OSes: for instance they're both effectively the default on most Linux systems. D is a standard OS feature: for instance Linux has both classic permissions which are a simple ACL mechanism and POSIX ACLs which are more general. But CFI is currently only in the realm of research: it provides good protection but there are worries about compatibility and overhead.*

(g) In a 32-bit Linux/x86 program, which of these objects would have the lowest address (numerically least when considered as unsigned)?

A. A global array

B. A local array in `main`

C. An environment variable

D. A command-line argument in `argv`

E. A local `int` variable in a function

A is in the data section, probably with an address like `0x0804be20`*. The other ones would all be in the stack area with addresses around* `0xbfff0000`*.*

(h) This function has so few secure uses that it has been removed from the latest version of the C standard:

A. `system` **B.** `gets` C. `setuid` D. `strcat` E. `sprintf`

A, D, and E can all be used securely if you're careful, and are all still in C11. `setuid` *is a Unix system call not a C standard function, but the system call is not very dangerous because it only has any effect if you're already root (note that a setuid binary like BCLPR does not require the* `setuid` *system call).* `gets` *was removed from C11.*

(i) Which of these systems is **not** designed using privilege separation?

A. Android B. `qmail` C. OpenSSH **D. The Linux kernel** E. Google Chrome

Android runs every app as its own user. `qmail` *runs different parts of mail delivery as separate users. OpenSSH makes many parts of the server unprivileged. Google Chrome runs each tab as a separate sandboxed process. But Linux is a monolithic design in which the entire kernel has supervisor privileges.*

(j) Which of these C expressions does **not** evaluate to 0 on a system where ints are 32 bits?

- A. `5 / 10`
- **B.** `(int)(signed char)'\xa2' - (unsigned)(unsigned char)'\xa2'`
- C. `0x80000000u + -(0x80000000u)`
- D. `0x01000000 << 8u`
- E. `10 >> 4`

A is zero because C's integer division truncates. D and E are zero because the bits are shifted off the left or right respectively. In answer C, `0x80000000` *is the strange non-zero value that is its own negation, but when added to itself it still overflows to zero. But in B, the left side is sign-extended while the right hand is zero-extended, so they differ by* -256*.*

(k) This format specifier allows a format string vulnerability to be used to overwrite memory:

A. `%d` B. `%x` C. `%s` D. `%c` **E.** `%n`

A-D all only produce output, they can't be used for an overwrite.

(l) The following set of 8 instruction types is Turing complete, even if self-modifying code is prohibited. Removing which instruction type would leave the set not Turing complete?

- A. Decrement a memory location
- B. Unconditional direct jump
- C. Store register to memory
- D. Set register to constant
- E. Increment a memory location
- F. Load register from memory
- **G. Branch if register is zero**
- H. Exchange register with memory location

Without some kind of conditional branches, you can't implement general computations: for instance a given program without conditionals will either always terminate or never terminate, so the halting problem is decidable for such programs. Another way to approach this question is to notice that if for any of the instructions, you could rewrite your program to replace it with other instructions on the list, removing the instruction doesn't reduce the expressiveness. When you have loops, you can implement increment (E) by repeated decrement (A) and vice-versa. Each of C, F, and H could be implemented using the other two. D could be implemented using F. B could be implemented using D and G.

3. (20 points) Attacks versus defenses. We've discussed a number of defense techniques that try to make C programs less vulnerable to attacks, but not every defense helps against every attack technique. In the following matrix, the rows correspond to techniques an attacker might use, and the columns correspond defense techniques. Fill in each entry of the matrix according to whether that defense helps stop that attack technique. Each entry should be a letter C, P, or N, with the following meanings:

   C = Complete protection: the attack technique is no longer possible

   P = Partial protection: the attack technique blocked in some but not all circumstances, or more difficult but still possible

   N = No protection: the defense does not affect the attack technique

   Answer for each attack technique on its own, not counting other attack techniques it might sometimes be combined with. We've already filled in some of the entries for you.

	ASLR	Non-executable stack	Coarse-grained CFI	Adjacent stack canaries	Shadow stack
Shellcode in environment variable	P	**C**	C	**N**	**N**
Return address overwrite	P	**N**	**N/P**	**P**	**C**
Directory traversal	**N**	N	**N**	**N**	**N**
ROP using `ret`	**P**	**N**	**P**	**N**	**C**
Non-control data overwrite	**N/P**	**N**	**N**	N	**N**

Directory traversal is an OS/interaction logic problem, so none of these defenses affect it. Environment variables are stored on the stack, so making the stack non-executable keeps them from being used for shellcode. A shadow stack constrains returns to only go to the correctly matching call site, so both a one-shot return address overwrite or an ROP attack would be blocked. Adjacent stack canaries block sequential overwrites but not random-access ones. ASLR makes ROP more difficult because the addresses of gadgets change. Coarse-grained CFI makes ROP more difficult by restricting the possible jump targets, but call-preceded ROP is still possible. Similarly coarse-grained CFI might restrict the targets an overwrite might successfully change a return address to, but after any legal call site is also possible; we accepted both N and P. ASLR would have no effect on whether a stack-based non-control data overwrite like the one in BCLPR is possible, but it might make it more difficult to overwrite a location elsewhere, and if you were trying to overwrite a pointer it might also make choosing the overwrite value more difficult, so we accepted both N and P.

4. (20 points) Race conditions. Below are four code samples from C programs interacting with a Unix filesystem. Two of the samples suffer from race condition vulnerabilities. For each vulnerable sample, describe a possible attack in three phases: select a point in the execution of the vulnerable code where an attack action should interleave by checking one of the boxes. Then, specify any preparation action, the interleaved action, and any final action for the attacker to take. If the code is not vulnerable, you can simply write "not vulnerable" in the preparation action line and leave the rest blank. Specify the actions clearly: for instance shell commands or short code snippets might work well.

   Similar to the situation in HA1, you can assume that the listed code is running with root privileges, while the attacker is unprivileged; unqualified paths refer to a directory owned by the attacker. An attack can succeed if it writes to or removes the file `/etc/passwd`, or if it can read a secret file `/root/.ssh/key`; you do not need to include details of what to write to or read from these files. The attacker can also succeed by reading data described in the code as "secret."

   Your attacks are worth 7 points each, while correctly identifying the non-vulnerable code segments is worth 3 points each. If you want to optimize for partial credit, you can fill in either more or less than two attacks if you want.

(a)

```
int fd = open("file", O_WRONLY);
assert(fd != -1);
☐
int res = fstat(fd, &st_buf);
assert(!res);
☐
if ((st_buf.st_mode & 0222) != 0222) {
    /* Not enough write privileges */
    abort();
}
☐
write(fd, data, data_size);
☐
close(fd);
```

Preparation action:

Interleaved action:

Final action:

This code is not vulnerable. There's a time gap between the `open` *and the* `fstat`*, but because* `fstat` *uses the file descriptor from* `open` *it will always refer to the same file. So it isn't possible to change the file and cause an unintended file to be written to.*

(b)

```
int res = stat("/etc/hostname", &st_buf);
assert(!res);
☐
char *buf = malloc(st_buf.st_size);
assert(buf);
☐
int fd = open("/etc/hostname", O_RDONLY);
assert(fd != -1);
☐
read(fd, buf, st_buf.st_size);
☐
write(1, buf, st_buf.st_size);
```

Preparation action:

Interleaved action:

Final action:

This code is not vulnerable. There's a time gap between the `stat` *and the* `open`*, but the* `/etc` *directory is not writable by an unprivileged user, so there's no way to cause* `/etc/hostname` *to point to something else. If the file could change, the size used by the code could be out of date, but this would not be useful for an attacker; in particular the same size is used for all the operations so there could not be a buffer overflow.*

(c)

```
int res = stat("file", &st_buf);
assert(!res);
☒
if ((st_buf.st_mode & 0222) != 0222) {
    /* Not enough write privileges */
    abort();
}
☒
int fd = open("file", O_WRONLY);
assert(fd != -1);
☐
write(fd, data, data_size);
☐
close(fd);
```

Preparation action:
`chmod 666 writable`
`ln -s writable file`

Interleaved action:
`ln -nsf /etc/passwd file`
(Either of the two checked interleaving locations would work)

Final action:
Password file overwritten

(d)

```
int fd = open("file",
  O_CREAT|O_WRONLY|O_TRUNC, 0666);
assert(fd != -1);
☒
int res = fchmod(fd, 0600);
  /* readable only by root */
☐
write(fd, secret, 1024);
☐
close(fd);
```

Preparation action:
None required

Interleaved action:
In the attacker's program:
`fd2 = open("file", O_RDONLY);`

Final action:
Read the secret data using `fd2`*. Because the open occurred before the* `fchmod`*, the file descriptor will still work.*

5. (16 points) Call-preceded ROP. Suppose you want to subvert the execution of a program with a code-reuse attack, but it uses a defense mechanism that constrains return instructions to jump only to locations right after legitimate calls. The task of creating an attack under these constraints is called call-preceded ROP. This also generally implies that the gadgets consist of intended instructions, so you can plan out your attack at the source-code level.

   For this question, your job is to formulate the plan for a call-preceded ROP attack against the program shown on the next page. The function `vulnerable` contains a buffer overflow vulnerability that will let you overwrite the stack with a sequence of return addresses of your choosing, plus you also have control of the inputs to the program. Similar to HA1, you can assume that this program is running as root, so your goal as an attacker is to get it to run a shell such as `/bin/sh`.

   We've marked a number of locations in the program right after function calls with labels running from `A:` though `K:`. This isn't quite legal C syntax, but the way we used the comma operator is intended to remind you that by returning to a different return site like this, you can replace the value that the calling function considers to be the return value of the function. For figuring out what you want to overwrite the stack with, you need to decide what sequences of return addresses you want the program to follow, starting with where you want the `vulnerable` function to return to, if not `K`. Write these down by letter in order, left to right. In the final attack there may need to be some extra space between the return addresses to account for other stack usage in the functions, but you don't need to worry about that.

   You can assume that ASLR is disabled, so code and global data in the program have fixed addresses. In your plan for what to supply as the arguments to the program, you can write a formula for the value used in the attack, using the `&` operator as in C to refer to addresses of code and/or data. The first two arguments to the program are floating point numbers and the third is a string.

   As a hint, we've only included in the program source the parts that you will need for your attack, and we've written the GOT/PLT machinery as if it were source code so it's easier to read. But we've included more return address spaces than you will probably need. The source code is on the next page so you can look at it all at once, but write your answers below.

   Value for program argument 1 (number):

   `((unsigned)&puts_got - 4)/10000000.0`

   Value for program argument 2 (number):

   `&system/10000000.0`

   Value for program argument 3 (string):

   `"/bin/sh"`

   Return addresses (first to execute on the left):

I	**D**	**F**							

```
typedef int (*func_ptr)(const char *);

func_ptr puts_got = puts;
int puts_plt(const char *s) {
  return ((*puts_got)(s), A:);
}

func_ptr system_got = system;
int system_plt(const char *s) {
  return ((*system_got)(s), B:);
}

struct list_node {
  struct list_node *next; /* offset 0 */
  struct list_node *prev; /* offset 4 */
  char *element; /* offset 8 */
};

struct point_info {
  int x; /* offset 0 */
  int y; /* offset 4 */
  char *descr; /* offset 8 */
};

void list_delete(struct list_node *p) {
  p->next->prev = p->prev;
  (free(p), C:);
}

char *process_ent(void) {
  struct list_node *n;
  char *s;
  n = (lookup_node(), D:);
  s = n->element;
  (list_delete(n), E:);
  return s;
}
```

```
void print_message(int msg_num) {
  const char *msg;
  msg = (lookup_msg(msg_num), F:);
  (printf("Message %d is: ", msg_num), G:);
  (puts_plt(msg), H:);
}

struct point_info pt;

int which_point = 0;

struct point_info *select_point(void) {
  which_point++;
  (printf("Selecting point\n"), I:);
  if (which_point == 0) {
    return &pt;
  } else {
    /* ... */
  }
}

void vulnerable(const char *s) {
  char buf[10];
  /* ... */
  (strcpy(buf, s), J:);
}

int main(int argc, char **argv) {
  assert(argc == 4);
  pt.x = 10000000.0*strtod(argv[1], 0);
  pt.y = 10000000.0*strtod(argv[2], 0);
  pt.descr = argv[3];
  (vulnerable(getenv("VAR")), K:);
  return 0;
}
```

In case you've forgotten, here's a reminder about some of the standard functions used in this example. `puts` prints a string to the standard output. `system` uses a string as a shell command. `strcpy` copies a null-terminated string without checking the size of the destination. `strtod` converts a string into a floating point number with type `double`; the first argument is the string and the second argument is not important for this question. If you assign a `double` value to an `int`, it will be rounded to a whole number, if it's within range. `getenv` returns the value of an environment variable, which in a case like this is under the control of an attacker.

Here's how the attack works. In outline, we use type confusion to control pointers using integers, then use the two controlled pointers for a GOT overwrite that makes `puts_plt` *be a synonym for* `system`*. Then all we need to do is call* `puts_plt` *with the shell we want to execute. The code following I will load a pointer to the global variable* `pt`*, whose contents are controlled from the command line, into the return value (i.e.,* `%eax`*). If we then go to D, value will be interpreted as if it were a pointer to a* `list_node`*: in particular the fields of a point that were integers at offsets 0 and 4 will be reinterpreted as pointers. In the* `list_delete` *function, these pointers will supply a location to overwrite and the value to write there: the location to write is the value of the* `next` *field plus 4 bytes, while the value to write is the value of the* `prev` *field. (This is similar to an exploit technique used with doubly-linked lists including heap blocks.) A particularly useful thing to overwrite is the GOT entry for the* `puts` *function, named* `puts_got` *here: in particular we can overwrite it to point to the* `system` *function.* `list_delete` *will return to E but we don't need to supply that because it will be done automatically (it will overwrite about where the D is in our attack stack). Finally returning to F will use the attacker controlled string as the argument to* `puts_plt`*.*