Exam 2 topics

Lectures

- Programming with Memory
- x86 Basics
- x86 Control Flow
- x86 Procedures, Call Stack
- Representing Data Structures
- Buffer Overflows
- Processes Model
- Shells

Labs

- Pointers in C
- x86 Assembly
- x86 Stack
- Data structures in memory
- Buffer overflows
- Processes

Topics

- C programming: pointers, dereferencing, arrays, structs, cursor-style programming, using malloc
- x86: instruction set architecture, machine code, assembly language, reading/writing x86, basic program translation
- Procedures and the call stack, data layout, security implications
- Processes, shell, fork, wait
- Basics of: malloc implementation, caching

Assignments

- Pointers
- x86
- Buffer
- Concurrency
- Malloc checkpoint

Exam 2: ISA
December 10 (during last lab)

Practice problems

For Exam 2: ISA

x86 short answer practice problems

ex

1. Which x86 instructions implicitly change the stack pointer? How do they change it?

2. What are some things defined by the *word size*? What is the word size we have been using for x86 in class?

3. Describe the general idea of a buffer overflow exploit in C code compiled to x86.

4. Describe how a child process's memory is related to the memory of the parent process.

x86 short answer practice problems

ex

1. Which x86 instructions implicitly change the stack pointer? How do they change it?

pushq	popq	call	ret
`%rsp -= 8`	`%rsp += 8`	`%rsp -= 8`	`%rsp += 8`

2. What are some things defined by the *word size*? What is the word size we have been using for x86 in class?

Register size, address size, pointer size

NOT instruction size (variable-width instruction size)

3. Describe the general idea of a buffer overflow exploit in C code compiled to x86.

Buffer overflow occurs when code lacks bounds checking in writing untrusted input to a destination region of memory that is too small. Buffer overflow attacks can overwrite the return addresses on the stack to point to further exploit code.

4. Describe how a child process's memory is related to the memory of the parent process.

The child process starts with a copy of the state of the parent's memory. It is a private copy: the child and the parent do not share memory once the child is created.

2-D array practice problem

ex

```
long a[2][3];
```

1. Draw a picture of how this array is laid out in memory, labeling the indices and byte offset of each element (starting with `a[0][0]` at offset `+0`);

Recall: `index = C*r + c`

scale by element size

```
long get_elem_1_2(long a[2][3]){
  return a[1][2];
}
```

2. Write x86 assembly code to implement this function.

2-D array practice problem: solution

ex

```
long a[2][3];
```

1. Draw a picture of how this array is laid out in memory, labeling the indices and byte offset of each element (starting with `a[0][0]` at offset `+0`);

Recall: `index = C*r + c`

scale by element size

a[0][0]	a[0][1]	a[0][2]	a[1][0]	a[1][1]	a[1][2]
+0	+8	+16	+24	+32	+40

```
long get_elem_1_2(long a[2][3]){
  return a[1][2];
}
```

2. Write x86 assembly code to implement this function.

Since we know the size, we can calculate
C*r+c = 3*1+2 = 5, 5*sizeof(long) = 5*8 = 40

```
movq 40(%rdi),%rax
retq
```

x86 arithmetic practice problem

ex

```
long funmath0(long x, long y) {
  return x + 4*y + 21;
}
```

```
long funmath1(long x, long y) {
  return 2*x + 4*y + 21;
}
```

```
long funmath2(long x, long y) {
  return 6*x + 5*y + 21;
}
```

```
funmath0:
  leaq    21(%rdi,%rsi,4), %rax
  ret

funmath1:
  leaq    (%rdi,%rsi,2), %rax
  leaq    21(%rax,%rax), %rax
  ret
```

Implement the above functions in x86 *without* `addq` or `mulq`.
You can use `leaq` and any other x86 instruction.

Recall: addressing modes can only multiply by 1, 2, 4, or 8.

x86 arithmetic practice problem

ex

```
long funmath0(long x, long y) {
  return x + 4*y + 21;
}
```

```
long funmath1(long x, long y) {
  return 2*x + 4*y + 21;
}
```

```
long funmath2(long x, long y) {
  return 6*x + 5*y + 21;
}
```

3 possible answers:

```
funmath0:
  leaq    21(%rdi,%rsi,4), %rax
  ret

funmath1:
  leaq    (%rdi,%rsi,2), %rax
  leaq    21(%rax,%rax), %rax
  ret

funmath2:
  leaq    (%rdi,%rdi,2), %rdx
  leaq    (%rsi,%rsi,4), %rax
  leaq    21(%rax,%rdx,2), %rax
  ret
```

Implement the above functions in x86 *without* `addq` or `mulq`.

You can use `leaq` and any other x86 instruction.

Recall: addressing modes can only multiply by 1, 2, 4, or 8.

Processes practice problem

ex

```
void f(int s) {
  printf("A\n");
  int pid = fork();
  if (pid != 0) {
    printf("B\n");
    waitpid(pid, &s, 0);
    printf("C\n");
  } else {
    printf("D\n");
  }
}
```

In how many different orders could the print statements print to the terminal? List them.

Processes practice problem

ex

```
void f(int s) {
  printf("A\n");
  int pid = fork();
  if (pid != 0) {
    printf("B\n");
    waitpid(pid, &s, 0);
    printf("C\n");
  } else {
    printf("D\n");
  }
}
```

In how many different orders could the print statements print to the terminal? List them.

Two:

ABDC or ADBC

x86 recursive procedure practice problem

ex

```
       mystery:
401106 mov    $0x0,%eax
40110b test   %edi,%edi
40110d jne    401110 <mystery+0xa>
40110f ret
401110 push   %rbx
401111 mov    %esi,%ebx
401113 sub    $0x1,%edi
401116 call   401106 <mystery>
40111b movslq %ebx,%rsi
40111e add    %rsi,%rax
401121 pop    %rbx
401122 ret
```

1. What register is being saved to the stack? Why?

2. What instruction address gets saved to the stack? Why?

3. What is this function computing?

0x7fdf28	<ret address in main>	main
		mystery(2, 5)

4. Fill in the top of this stack up to when the function returns to main for `mystery(2, 5)`.

What is each value returned, in order?

x86 recursive procedure practice problem

ex

```
       mystery:
401106 mov    $0x0,%eax
40110b test   %edi,%edi
40110d jne    401110 <mystery+0xa>
40110f ret
401110 push   %rbx
401111 mov    %esi,%ebx
401113 sub    $0x1,%edi
401116 call   401106 <mystery>
40111b movslq %ebx,%rsi
40111e add    %rsi,%rax
401121 pop    %rbx
401122 ret
```

1. What register is being saved to the stack? Why?
   `%rbx`, so that it is not overwritten in the recursive call
2. What instruction address gets saved to the stack? Why?
   `0x40111b`, return address after recursive call
3. What is this function computing?

   Multiplies its two arguments

```
int mult(int x, int y) {
    if (x == 0)  return 0;
    return y + mult(x - 1, y);
}
```

`%rax: 0`

0x7fdf28	<ret address in main>	main
0x7fdf20	unknown rbx	mystery(2, 5)
0x7fdf18	0x40111b	%rax: 10
0x7fdf20	5	mystery(1, 5)
0x7fdf18	0x40111b	%rax: 5
		mystery(0, 5)
		%rax: 0

C programming practice problem

Alice attempted to write the following C code to implement the functionality "return a null-terminated string with 3 copies of the given char"

1. What is incorrect about this implementation?

   Hint: consider the stack vs. heap

```
/* Return a string with 3 copies of c */
char* thriceChar(char c) {
  char s[4];
  for (int i = 0; i < 3; i++) {
    s[i] = c;
  }
  s[n] = '\0';
  return s;
}
```

2. Implement a correct version of this function using `malloc`

C programming practice problem

Alice attempted to write the following C code to implement the functionality "return a null-terminated string with 3 copies of the given char"

```
/* Return a string with 3 copies of c */
char* thriceChar(char c) {
  char s[4];
  for (int i = 0; i < 3; i++) {
    s[i] = c;
  }
  s[3] = '\0';
  return s;
}
```

1. What is incorrect about this implementation?

   Hint: consider the stack vs. heap

`s` is allocated in the current stack frame, so we shouldn't return a pointer to it!

2. Implement a correct version of this function using `malloc`

```
char* thriceChar(char c) {
    int n = 3;
    char* s = malloc(n + 1);
    if (!s) { return NULL; }
    for (int i = 0; i < 3; i++) {
        s[i] = c;
    }
    s[3] = '\0';
    return s;
}
```

Memory layout, C programming

```c
typedef struct {
  char *name;
  int number[10];
} Contact;

int main() {
  Contact contact1;
  Contact *contact2 = (Contact *)malloc(sizeof(Contact));
  // TODO: use contacts
  return 0;
}
```

Give examples of which data in this program is laid out in instructions (text), on the stack, in the heap, and in registers

Give example code that fills in data for both contacts. After filling in the data, clean up the memory used as needed.

Memory layout, C programming

Instructions: `main` function definition

Stack: `contact1` entire struct (48 bytes)

Heap: `contact2` entire struct (48 bytes) returned from `malloc`

Registers:

`sizeof(Contact)` value must go in `%rdi`

`0` must go in `%rax`

```c
int main() {
  Contact contact1;
  Contact *contact2 = malloc(sizeof(Contact));
  // The `char *` is a pointer, not itself space for
  // the name. We'll use malloc for heap space here.
  contact1.name = malloc(sizeof(char)*6);
  contact2->name = malloc(sizeof(char)*4);
  // Note: contact1 uses . while contact2 uses ->
  strcpy(contact1.name, "Alice");
  strcpy(contact2->name, "Bob");
  for (int i = 0; i < 10; i++) {
    contact1.number[i] = i;
    contact2->number[i] = i + 1;
  }
  // Imagine using more, then clean up:
  free(contact1.name);
  free(contact2->name);
  free(contact2);
  return 0;
}
```

x86 struct/LinkedList practice problem

ex

```
nodeFunc2:
        pushq   %rbp
        pushq   %rbx
        subq    $8, %rsp
        movl    %esi, %ebx
        movslq  %esi, %rax
        testq   %rdi, %rdi
        je      .L1
        movq    %rdi, %rbp
        movl    8(%rdi), %esi
        cmpl    %esi, %ebx
        jb      .L5
.L3:    movq    0(%rbp), %rdi
        movl    %ebx, %esi
        call    nodeFunc2
.L1:    addq    $8, %rsp
        popq    %rbx
        popq    %rbp
        ret
.L5:    movl    %esi, %ebx
        jmp     .L3
```

```c
typedef struct Node {
  struct Node* next;
  unsigned int value;
} Node;

long nodeFunc2(Node* node, unsigned int x) {
    // ???
}

long nodeFunc1(Node* node) {
  nodeFunc2(node, 0);
}
```

Consider the above function that calculates something useful about a linked list of unsigned integers using a helper function.

1. Identify which pieces of x86 refer to `next` and `value`.
2. Identify the base case of the recursive function `nodeFunc2`. What is returned in this case?
3. Identify the recursive case of `nodeFunc2`. What is the argument passed to the recursive call?
4. What is `nodeFunc1` calculating with helper `nodeFunc2`?

x86 struct/LinkedList practice problem

ex

```
nodeFunc2:
        pushq   %rbp
        pushq   %rbx
        subq    $8, %rsp
        movl    %esi, %ebx
        movslq  %esi, %rax
        testq   %rdi, %rdi
        je      .L1
        movq    %rdi, %rbp
        movl    8(%rdi), %esi
        cmpl    %esi, %ebx
        jb      .L5
.L3:    movq    0(%rbp), %rdi
        movl    %ebx, %esi
        call    nodeFunc2
.L1:    addq    $8, %rsp
        popq    %rbx
        popq    %rbp
        ret
.L5:    movl    %esi, %ebx
        jmp     .L3
```

At call, `%rsp` must be a multiple of 16

```
typedef struct Node {
  struct Node* next;
  unsigned int value;
} Node;
long nodeFunc2(Node* node, unsigned int max) {
  if (node == 0) {
    return max;
  }
  if (node->value > max) {
    max = node->value;
  }
  nodeFunc2(node->next, max);
}
long nodeFunc1(Node* node) {
    nodeFunc2(node, 0);
}
```

2nd argument renamed for clarity

node = `%rdi`

base case

note order of x86 comparison

recursive case

`%rdi` accesses `node`, the pointer itself

`8(%rdi)` accesses `node->value`, `(%rdi)` and `0(%rbp)` accesses `node->next`,

if `(node->value > x)`, jump to `.L5`, sets `%ebx` to `node->value`

`%ebx` calculates the max of `node->value` and `x`

in the base case, returns second arg, `x` (the maximum value found so far)

`nodeFunc1` uses its helper to **find the maximum value** within a linked list.

Struct practice problem

ex

```
struct s {
  long x;
  char y;
  int p[5];
  char z;
  short w;
};
```

1. Draw a picture of how this struct is laid out in memory, labeling the byte offset of each field (starting with `a` at offset `+0`);

2. Modify your picture to show how much space a single element of this struct would take if used as an element of an array (e.g., the total size).

Recall: a short is 2 bytes in C

3. Rearrange the fields of the struct to minimize wasted space. Draw the new offsets and the total size.

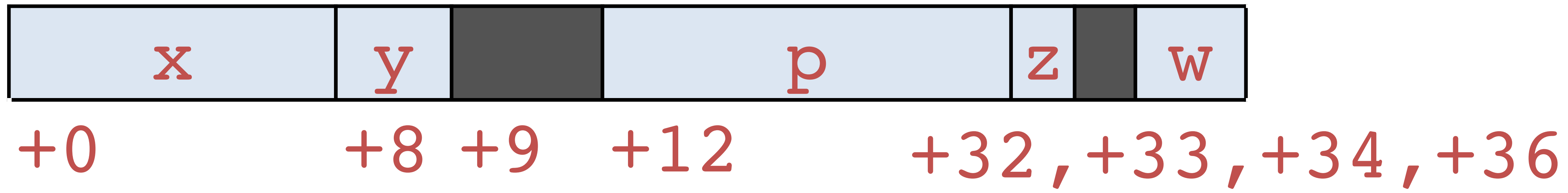
Struct practice problem

ex

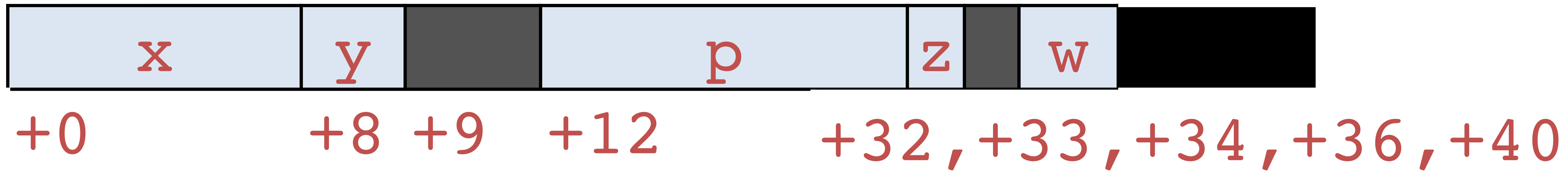
```
struct s {
  long x;
  char y;
  int p[5];
  char z;
  short w;
};
```

Recall: a short is 2 bytes in C

1. Draw a picture of how this struct is laid out in memory, labeling the byte offset of each field (starting with `a` at offset `+0`);



2. Modify your picture to show how much space a single element of this struct would take if used as an element of an array (e.g., the total size).



3. Rearrange the fields of the struct to minimize wasted space. Draw the new offsets and the total size.