

**15-213 Introduction to Computer Systems**

**Exam 2**

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Recitation Section: \_\_\_\_\_

- This is an open-book exam.
- Notes and calculators are permitted, but not computers.
- Write your answer legibly in the space provided.
- You have 80 minutes for this exam.
- We will drop your lowest score among questions 1–6.

| <b>Problem</b> | <b>Max</b> | <b>Score</b> |
|----------------|------------|--------------|
| 1              | 15         |              |
| 2              | 15         |              |
| 3              | 15         |              |
| 4              | 15         |              |
| 5              | 15         |              |
| 6              | 15         |              |
| <b>Total</b>   | <b>75</b>  |              |

## 1. Symbols and Linking (15 points)

Consider the following three files, `main.c`, `fib.c`, and `bignat.c`:

```
/* main.c */
void fib (int n);
int main (int argc, char** argv) {
    int n = 0;
    sscanf(argv[1], "%d", &n);
    fib(n);
}

/* fib.c */
#define N 16

static unsigned int ring[3][N];

static void print_bignat(unsigned int* a) {
    int i;
    for (i = N-1; i >= 0; i--)
        printf("%u ", a[i]);      /* print a[i] as unsigned int */
    printf("\n");
}

void fib (int n) {
    int i, carry;
    from_int(N, 0, ring[0]);      /* fib(0) = 0 */
    from_int(N, 1, ring[1]);      /* fib(1) = 1 */
    for (i = 0; i <= n-2; i++) {
        carry = plus(N, ring[i%3], ring[(i+1)%3], ring[(i+2)%3]);
        if (carry) { printf("Overflow at fib(%d)\n", i+2); exit(0); }
    }
    print_bignat(ring[n%3]);
}
```

Furthermore assume that a file `bignat.c` defines functions `plus` and `from_int` of the form

```
int plus (int n, unsigned int* a, unsigned int* b, unsigned int* c);
void from_int (int n, unsigned int k, unsigned int* a);
```

A possible definition of these functions is given in Problem 6, although this is not relevant here.

1. (9 points) Fill in the following tables by stating for each name whether it is local or global, and whether it is strong or weak. Cross out any box in the table that does not apply. For example, cross out the first box in a line if the symbol is not in the symbol table, or cross out the second box in a line if the symbol is not global (and therefore neither weak nor strong). Recall that in C, external functions do not need to be declared.

main.c

|      | Local or Global? | Strong or Weak? |
|------|------------------|-----------------|
| fib  |                  |                 |
| main |                  |                 |

fib.c

|              | Local or Global? | Strong or Weak? |
|--------------|------------------|-----------------|
| ring         |                  |                 |
| print_bignat |                  |                 |
| fib          |                  |                 |
| plus         |                  |                 |

2. (3 points) Now assume that the file `bignat.c` is compiled to a static library in archive format, `bignat.a` exporting the symbols `plus` and `from_int`.

For each of the following calls to `gcc`, state if it

- (A) compiles and links correctly, or
- (B) linking fails due to undefined references, or
- (C) linking fails due to multiple definitions .

| Command                                       | Result (A, B, or C) |
|---|---------------------|
| <code>gcc -o fib main.c fib.c bignat.a</code> |                     |
| <code>gcc -o fib bignat.a main.c fib.c</code> |                     |
| <code>gcc -o fib fib.c main.c bignat.a</code> |                     |

3. (3 points) Consider the case where the programmer accidentally declared the variable `ring` in the file `fib.c` with

```
static int ring[3][N];
```

instead of `static unsigned int ring[3][N]`. Mark each of the following statements as true or false.

- The files all still compile correctly.    True    False
- The files can all still be linked correctly.    True    False
- The resulting executable will still run correctly.    True    False

## 2. Virtual Address Translation (15 points)

We consider a virtual address system with the following parameters.

- The memory is byte addressable.
- Virtual addresses are 16 bits wide.
- Physical addresses are 16 bits wide.
- The page size is 1024 bytes.
- The TLB is fully associative with 16 total entries.

Recall that a fully associative cache has just one set of entries. In the following tables, all numbers are given in hexadecimal. The contents of the TLB and the page table for the first 16 virtual pages are as follows. If a VPN is not listed in the page table, assume it generates a page fault.

| Tag | PPN | Valid |
|-----|-----|-------|
| 03  | 1B  | 1     |
| 06  | 06  | 0     |
| 28  | 23  | 1     |
| 01  | 18  | 0     |
| 31  | 01  | 1     |
| 12  | 00  | 0     |
| 07  | 3D  | 1     |
| 0B  | 11  | 1     |
| 2A  | 2C  | 0     |
| 11  | 1C  | 0     |
| 1F  | 03  | 1     |
| 08  | 14  | 1     |
| 09  | 2A  | 1     |
| 3F  | 30  | 0     |
| 10  | 0D  | 0     |
| 32  | 11  | 0     |

| VPN | PPN | Valid |
|-----|-----|-------|
| 00  | 27  | 1     |
| 01  | 0F  | 1     |
| 02  | 19  | 1     |
| 03  | 1B  | 1     |
| 04  | 06  | 0     |
| 05  | 03  | 0     |
| 06  | 06  | 0     |
| 07  | 3D  | 0     |
| 08  | 14  | 1     |
| 09  | 2A  | 1     |
| 0A  | 21  | 1     |
| 0B  | 11  | 1     |
| 0C  | 1C  | 1     |
| 0D  | 2D  | 0     |
| 0E  | 0E  | 0     |
| 0F  | 04  | 1     |

1. (5 points) In the four rows below, mark the bits that constitute the indicated part of the virtual address with an X. Leave the remaining bits of each row blank.

Virtual Page Number

|     |    |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |
|-----|----|----|----|----|----|----|---|---|---|---|---|---|---|---|---|---|
|     | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| VPN |    |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |

Virtual Page Offset

|     |    |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |
|-----|----|----|----|----|----|----|---|---|---|---|---|---|---|---|---|---|
|     | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| VPO |    |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |

TLB Tag

|      |    |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |
|------|----|----|----|----|----|----|---|---|---|---|---|---|---|---|---|---|
|      | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| TLBT |    |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |

2. (5 points) For the virtual address 0xC7A4, indicate the physical address and various results of the translation. If there is a page fault, enter “—” for the PPN and Physical Address. All answers should be given in hexadecimal.

Virtual Address (one bit per box)

|    |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |
|----|----|----|----|----|----|---|---|---|---|---|---|---|---|---|---|
| 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|    |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |

| Parameter         | Value |
|-------------------|-------|
| VPN               |       |
| TLB Tag           |       |
| TLB Hit? (Y/N)    |       |
| Page Fault? (Y/N) |       |
| PPN               |       |
| Physical Address  |       |

3. (5 points) For the virtual address 0x05DD, indicate the physical address and various results of the translation. If there is a page fault, enter “—” for the PPN and Physical Address. All answers should be given in hexadecimal.

Virtual Address (one bit per box)

|    |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |
|----|----|----|----|----|----|---|---|---|---|---|---|---|---|---|---|
| 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|    |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |

| Parameter         | Value |
|-------------------|-------|
| VPN               |       |
| TLB Tag           |       |
| TLB Hit? (Y/N)    |       |
| Page Fault? (Y/N) |       |
| PPN               |       |
| Physical Address  |       |

### 3. Process Control (15 points)

Consider the following C program. For space reasons, we do not check return codes, so assume that all functions return normally. Also assume that `printf` is unbuffered.

```
int main() {
    pid_t pid1, pid2;

    pid1 = fork();
    pid2 = fork();
    if (pid1 && pid2) printf("A\n");
    if (pid1 || pid2) printf("B\n");
    exit(0);
}
```

Mark each column that represents a valid possible output of this program with 'Yes' and each column which is impossible with 'No'.

|   |   |   |   |   |
|---|---|---|---|---|
|   |   |   |   |   |
| A | B | B | B | B |
| B | A | B | B | B |
| B | B | A | B | B |
| B | B | B | A | B |



## 4. Signals (15 points)

Consider the following code.

```
int i = 1;

void handler (int sig) {
    i++;
}

int main() {
    pid_t pid;
    sigset_t s;
    sigemptyset(&s);
    sigaddset(&s, SIGUSR1);
    signal(SIGUSR1, handler);
    sigprocmask(SIG_BLOCK, &s, 0);
    pid = fork();
<LINE A>
    if (pid != 0) {
        i = 2;
<LINE B>
    } else {
        i = 3;
<LINE C>
    }
    sigprocmask(SIG_UNBLOCK, &s, 0);
    pause(); /* pause to allow all signals to arrive */
    printf("%d\n", i);
    exit(0);
}
```

We assume that `pause()` ; pauses long enough that all signals in a process arrive before the following `printf` command is executed and that concurrently running processes proceed to their `pause()` ; command if they are not already there. We also assume that `fork()` ; is successful and that all processes run to successful completion.

Now consider the effect of adding the command

```
kill(pid, SIGUSR1);
```

either at <LINE A>, <LINE B>, or <LINE C>. Recall that if the first argument to `kill` is 0, it sends the signal to all processes in the current process group. For each resulting program, list the possible values that may be printed for any given run. You may assume that no other process sends a `SIGUSR1` signal.

1. (5 pts) <LINE A>

2. (5 pts) <LINE B>

3. (5 pts) <LINE C>

## 5. Garbage Collection (15 points)

In this problem we consider a tiny list processing machine in which each memory word consists of two bytes: the first byte is a pointer to the tail of the list and the second byte is a data element. The end of a list is marked by a pointer of 0x00. We assume that the data element is never a pointer.

- (8 points) In the first question we consider a copying collector.

We start with the memory state on the left, where the range 0x10–0x1F is the from-space and the range 0x20–0x2F is the to-space. All addresses and values in the diagram are in hexadecimal.

Write in the state of memory after a copying collector is called with root pointers 0x12 and 0x1A and answer the subsequent question. You may leave cells that remain unchanged blank.

| Before GC |     |      | After GC |     |      |
|-----------|-----|------|----------|-----|------|
| Addr      | Ptr | Data | Addr     | Ptr | Data |
| 10        | 12  | 2C   | 10       |     |      |
| 12        | 18  | FF   | 12       |     |      |
| 14        | 12  | 0E   | 14       |     |      |
| 16        | 1C  | AB   | 16       |     |      |
| 18        | 16  | 10   | 18       |     |      |
| 1A        | 00  | 00   | 1A       |     |      |
| 1C        | 12  | 1D   | 1C       |     |      |
| 1E        | 1A  | 00   | 1E       |     |      |
|           |     |      | 20       |     |      |
|           |     |      | 22       |     |      |
|           |     |      | 24       |     |      |
|           |     |      | 26       |     |      |
|           |     |      | 28       |     |      |
|           |     |      | 2A       |     |      |
|           |     |      | 2C       |     |      |
|           |     |      | 2E       |     |      |

After garbage collection, free space starts as address \_\_\_\_\_

2. (7 points) In the second question we consider a mark and sweep collector.

We use the lowest bit of the pointer as the mark bit, because it is normally always zero since pointers must be word-aligned.

Assume the garbage collector is once again called with root pointers 0x12 and 0x1A. Write in the state of memory after the mark phase, and then again after the sweep phase and answer the subsequent question. You may leave cells that remain unchanged blank.

| Before GC |     |      | After Marking Phase |     |      | After Sweep Phase |     |      |
|-----------|-----|------|---------------------|-----|------|-------------------|-----|------|
| Addr      | Ptr | Data | Addr                | Ptr | Data | Addr              | Ptr | Data |
| 10        | 12  | 2C   | 10                  |     |      | 10                |     |      |
| 12        | 18  | FF   | 12                  |     |      | 12                |     |      |
| 14        | 12  | 0E   | 14                  |     |      | 14                |     |      |
| 16        | 1C  | AB   | 16                  |     |      | 16                |     |      |
| 18        | 16  | 10   | 18                  |     |      | 18                |     |      |
| 1A        | 00  | 00   | 1A                  |     |      | 1A                |     |      |
| 1C        | 12  | 1D   | 1C                  |     |      | 1C                |     |      |
| 1E        | 1A  | 00   | 1E                  |     |      | 1E                |     |      |

The free list now starts at address \_\_\_\_\_.

## 6. Cyclone (15 points)

Now consider the file `bignat.c` that implements addition and conversion of an unsigned integer to a `bignat` representation as we assumed in Problem 1.

```
typedef unsigned int uint;

int plus (int n, uint* a, uint* b, uint* c) {
    int i;
    int carry = 0;
    for (i = 0; i < n; i++) {
        c[i] = a[i] + b[i];
        if (carry) {
            c[i]++;
            carry = (c[i] <= a[i]);
        } else {
            carry = (c[i] < a[i]);
        }
    }
    return carry;
}

void from_int (int n, uint k, uint* a) {
    int i;
    a[0] = k;
    for (i = 1; i < n; i++)
        a[i] = 0;
    return;
}
```

1. (3 points) Is it legal for `a`, `b`, and `c` to be pointers to different regions of memory?  
Circle one

Yes                      No

2. (4 points) Assume `a`, `b`, and `c` are declared as fat pointers. Use the notation  $\text{curr}(p)$ ,  $\text{lower}(p)$ , and  $\text{upper}(p)$  to denote the current value of a fat pointer  $p$  and its lower and upper bounds. The bounds are *inclusive*:  $\text{lower}(p) \leq \text{curr}(p) \leq \text{upper}(p)$ , and you may assume all fat pointers will always satisfy this invariant. Under which conditions on `n`, `a`, `b`, and `c` will this code execute without an illegal pointer access exception?

In order to avoid the still possible overflow, we would like to implement arbitrarily large unsigned integers as linked lists of unsigned integers. In order to avoid always using linked lists, we represent bignats as a tagged union, either consisting just of an integer or a pointer to a linked list representation.

```
struct List {
    unsigned int head;
    struct List* tail;
};

@tagged union Bignat {
    unsigned int x;
    struct List* l;
};
```

4. (5 points) Recall that Cyclone translates its source into C code. Give a representation of the tagged union construct above that would be a plausible result of a translation from Cyclone to C.

5. (3 points) Give a plausible translation of the following Cyclone code fragment using your translation of the tagged union.

```
union Bignat a;
a.x = 15213;
```