

15-213 Introduction to Computer Systems

Final Exam

May 3, 2006

Name: _____

Andrew User ID: _____

Recitation Section: _____

- This is an open-book exam.
- Notes and calculators are permitted, but not computers.
- Write your answers legibly in the space provided.
- You have 180 minutes for this exam.

Assignment Project Exam Help

<https://eduassistpro.github.io/>

Add WeChat edu_assist_pro

Out-of-Order Execution

Pointer Arithmetic

Caching

Signals

Semaphores

Servers

System-Level I/O

3	10	
4	20	
5	15	
6	30	
7	20	
8	20	
Total	150	

1. Assembly Language (15 points)

Consider the following declaration of a binary search tree data structure.

```
struct TREE {  
    int data;  
    struct TREE* left;  
    struct TREE* right;  
};
```

Describe the layout of this structure on an x86-64 architecture.

1. (3 pts) If a is the address of the beginning of the structure, then

- _____ is the address of the `data` field,
- _____ is the address of the `left` field, and
- _____ is the address of the `right` field.

Give your address

2. (1 pts) a will be

3. (1 pts) The total size of a `TREE` structure will _____.

Assignment Project Exam Help

<https://eduassistpro.github.io/>

Add WeChat edu_assist_pro

Next we consider the tree as a binary search tree, where elements to the left of a node are smaller and elements to the right of a node are larger than the data stored in the node. The following function checks whether a given integer x is stored in the global tree root.

```
typedef struct TREE tree;
tree* root;
```

```
int member(int x) {
    tree* t = root;
    while (t != NULL) {
        if (x == t->data)
            return 1;
        if (x < t->data)
            t = t->left;
        else
            t = t->right;
    }
    return 0;
}
```

This function might compile to the following piece of assembly code, omitting some code alignment directives and three lines for you to fill in.

member:

```

    movq    root, %rax
    testq   %rax, %rax
    je      .L9
.L14:
    je      .L13
    jle     .L5
    movq    8(%rax), %rax
.L11:
    testq   %rax, %rax
    jne     .L14
.L9:
    ret
.L5:
    movq    16(%rax), %rax
    jmp     .L11
.L13:
    ret
```

Assignment Project Exam Help

<https://eduassistpro.github.io/>

Add WeChat edu_assist_pro

4. (4 pts) Complete the following table, associating C variables with machine registers or assembly expressions.

C variable	Assembly expression
x	
root	
t	
<i>return value</i>	

5. (6 pts) Fill in the missing three lines of assembly code.

Assignment Project Exam Help

<https://eduassistpro.github.io/>

Add WeChat edu_assist_pro

2. Out-of-Order Execution (20 points)

We continue the code from the previous problem

1. (15 pts) On a machine with pipelining and out-of-order execution as the machines used in this course, the efficiency of the inner loop can be improved by the use of conditional move instructions. Rewrite the code between `.L14` and `.L9` by using only instructions from the original program, ordinary move instructions, and one or more of the following conditional move instructions.

```
cmovl    S,D
cmovle   S,D
cmove    S,D
cmovge   S,D
cmovg    S,D
```

As usual, *S* stands for the source, *D* for the destination, and the suffix `l`, `le`, `e`, `ge`, `g` has the same meaning as for conditional branches.

`.L14:`

Assignment Project Exam Help

<https://eduassistpro.github.io/>

Add WeChat edu_assist_pro

```
testq    %rax, %rax
jne      .L14
```

2. (5 pts) Explain why the code with conditional moves can be more efficient than the original code produced by the compiler.

3. Pointer Arithmetic (10 points)

A desperate student decided to write a dynamic memory allocator for an x86-64 machine in which each block has the following form:

Header	Id string	Payload	Footer
--------	-----------	---------	--------

where

- *Header* is a 4 byte header
- *Id string* is an 8 byte string
- *Payload* is arbitrary size, including padding
- *Footer* is a 4 byte footer

Assume the student wants to print the Id string with the following function

```
void print_block(void *bp) {  
    printf("Found block ID: %s\n", GET_ID(bp));  
}
```

where bp points to the beginning of the block. The Id string is 8 bytes long. Circle each of the following letters.

- A #define GET_ID(bp) ((char *)((
B #define GET_ID(bp) ((char *)((
C #define GET_ID(bp) ((char *)(((char)bp)-8))
D #define GET_ID(bp) ((char *)(((long *)bp)-1))
E #define GET_ID(bp) ((char *)(((int *)bp)-2))
F #define GET_ID(bp) ((char *)(((char *)bp)-8))
G #define GET_ID(bp) ((char *)(((char**)bp)-1))
H #define GET_ID(bp) ((char *)(((char**)bp)-2))
I #define GET_ID(bp) ((char *)(((char**)bp)-4))
J #define GET_ID(bp) ((char *)(((char**)bp)-8))

4. Caching (20 points)

Assume the following situation.

- All caches are fully associative, with LRU eviction policy.
- The cache is write-back, write-allocate.
- All caches are empty at the beginning of an execution.
- Variables i , j , and k are stored in registers.
- A float is 4 bytes.

The function `mm_ijk` multiplies two $N \times N$ arrays A and B and puts the result in R . For simplicity, we assume R is initialized to all zeros.

```
void mm_ijk (float A[N][N], float B[N][N], float R[N][N]) {  
    int i,j,k;  
    for (i = 0; i < N; i++)  
        for (j = 0; j < N; j++)  
            for (k = 0; k < N; k++)  
                R[i][j] += A[i][k] * B[k][j];  
}
```

1. (6 pts) Consider the experiment on a 4-byte fully associative LRU cache with 4-byte lines (the cache holds 4 lines). Fill in the table below with the number of cache misses caused by each of the arrays A , B , and R , assuming that the argument arrays are 16-byte aligned.

N	A	B	R
2			
4			

2. (6 pts) Now suppose we consider the previous experiment on a 64-byte fully associative LRU cache with 16 byte lines (the cache holds 4 lines). Fill in the table below with the number of cache misses due to each array, assuming that the argument arrays are 16 byte aligned.

N	A	B	R
2			
4			

3. (5 pts) Even if R is initialized to all zeros, and even if the program is single-threaded and no signals occur, after the execution of the `mm_ij` function, R will not necessarily contain the product of A and B . Give a concrete counterexample.

Assignment Project Exam Help

4. (3 pts) Under which conditions?
<https://eduassistpro.github.io/>
Add WeChat edu_assist_pro

5. Signals (15 points)

For each code segment below, give the **largest** value that could be printed to stdout. Remember that when the system executes a signal handler, it blocks signals of the type currently being handled (and no others).

```
/* Version A */
int i = 0;

void handler(int s) {
    if (!i) {
        kill(getpid(), SIGINT);
    }
    i++;
}

int main() {
    signal(SIGINT, handler);
    kill(getpid(), SIGINT);
    printf("%d\n", i);
    return 0;
}
```

1. (5 pts) **Largest** <https://eduassistpro.github.io/>

```
/* Version B */
int i = 0;

void handler(int s) {
    if (!i) {
        kill(getpid(), SIGINT);
        kill(getpid(), SIGINT);
    }
    i++;
}

int main() {
    signal(SIGINT, handler);
    kill(getpid(), SIGINT);
    printf("%d\n", i);
    return 0;
}
```

2. (5 pts) **Largest** value for version B: _____.

```

/* Version C */
int i = 0;

void handler(int s) {
    if (!i) {
        kill(getpid(), SIGINT);
        kill(getpid(), SIGUSR1);
    }
    i++;
}

int main() {
    signal(SIGINT, handler);
    signal(SIGUSR1, handler);
    kill(getpid(), SIGUSR1);
    printf("%d\n", i);
    return 0;
}

```

3. (5 pts) ~~largest value for version C: _____.~~ **Assignment Project Exam Help**

<https://eduassistpro.github.io/>

Add WeChat edu_assist_pro

6. Semaphores (30 points)

We would now like to use binary search trees with (long) integer data to represent sets of integers.

```
struct TREE {
    long int data;
    struct TREE* left;
    struct TREE* right;
};
typedef struct TREE tree;
tree* root = NULL;          /* tree is initially empty */

int member(long int x); /* returns 1 if x is in *root, 0 otherwise */
void insert(long int x); /* insert x into tree at *root */
```

We assume that the functions `member` and `insert` are straightforward (as `member` in an earlier problem) and are not thread-safe. In this problem we explore how to write wrappers so they can be used in a thread-safe manner.

We would like to allow any number of concurrent readers (via the `member` function), since simultaneously reading the data structure is safe. On the other hand, we would like to ensure that a writer (via the `insert` function) has exclusive access to the data structure (no other writers or readers).

To implement this, we need to count the number of currently executing readers, and use a semaphore to ensure exclusive access to the readers variable, and w to ensure that a writer has exclusive access to the data structure stored in the `root` variable.

```
int readers = 0;
sem_t w;
sem_t r;
```

1. (15 pts) Below is the skeleton of the wrapper functions. Fill in the missing lines from the following selection. Note that you may need some commands more than once while others may remain unused.

```
P(&r);
V(&r);
P(&w);
V(&w);
readers++;
readers--;
if (readers == 1) P(&w);
if (readers == 1) V(&w);
if (readers == 0) P(&w);
if (readers == 0) V(&w);
```

```

int member_safe(long int x) {
    int b;

    b = member(x);

    return(b);
}

void insert_safe(long int x) {

```

Assignment Project Exam Help

```

insert(x)

```

<https://eduassistpro.github.io/>

Add WeChat edu_assist_pro

2. (5 pts) Which code is needed to initialize the semaphores. Circle all needed initialization.

- `sem_init(&r, 0, 0);` Yes No
- `sem_init(&r, 0, 1);` Yes No
- `sem_init(&w, 0, 0);` Yes No
- `sem_init(&w, 0, 1);` Yes No

3. (5 pts) Note that it is possible for a write request never to succeed by having certain read patterns. Precisely explain the circumstances under which this may happen.

4. (5 pts) Propose a simple solution to avoid this problem so that every write request is eventually honored (in words—no need to show code).

Assignment Project Exam Help

<https://eduassistpro.github.io/>

Add WeChat edu_assist_pro

7. Servers (20 points)

We now write a server which maintains a do-not-call list of telephone numbers. Tele-marketers who call numbers in this list are subject to heavy fines. Our protocol is much simpler than HTTP. A client connects to the server and then sends either

- $+x\backslash n$ to add the phone number x to the do-not-call list, or
- $?x\backslash n$ to query whether the number x is in the do-not-call list, whereupon the server responds with $0\backslash n$ (not in the list) or $1\backslash n$ (in the list).

Here, a phone number x is just a 10-digit number (no spaces or parentheses). The server spawns a separate thread for each connection. We assume that `serve(connfd)` reads one line of input from `connfd`, parses it, and responds if appropriate according to the protocol above. For conciseness, the code below does not check return codes for system calls.

```
void* thread(void* vargp) {
    int connfd = *((int *) vargp);
    pthread_detach(pthread_self());
    serve(connfd);
    close(connfd);
    return NULL;
}

int main() {
    int listenfd, connfd;
    pthread_t tid;

    /* semaphores are initialized here */
    ...

    listenfd = open_listenfd(15213);
    while (1) {
        connfd = accept(listenfd, NULL, NULL);
        pthread_create(&tid, NULL, thread, &connfd);
    }
}
```

Assignment Project Exam Help

<https://eduassistpro.github.io/>

Add WeChat edu_assist_pro

1. (10 pts) Even if `serve` is thread-safe, the code above exhibits a race condition. Explain this race condition in detail.

2. (10 pts) Correct the code above to avoid the race condition. Your code should not cast integers to pointers or pointers to integers (which would be in poor taste).

<https://eduassistpro.github.io/>

Add WeChat `edu_assist_pro`

8. System-Level I/O (20 points)

We continue the example from the previous question. To complete the `serve` function below, you should use

```
void    rio_readinitb(rio_t* rp, int fd);
ssize_t rio_readlineb(rio_t* rp, char* usrbuf, size_t maxlen);
ssize_t rio_writen(int fd, char* usrbuf, size_t len);
```

from the robust I/O package. The function `long atol(char* s)` converts the beginning of the string `s` to a long int.

1. (10 pts) Complete the following function `serve`.

```
void serve(connfd) {
    long int phone_number;
    rio_t rio;
```

```
    _____;
```

Assignment Project Exam Help

```
    if (_____
```

```
        if (buf[0] == '+')
```

```
            phone
```

```
            if (member_safe(phone_number))
```

```
                _____;
```

Add WeChat edu_assist_pro

```
            else
```

```
                _____;
```

```
        }
```

```
    if (buf[0] == '+') {
```

```
        phone_number = atol(buf+1);
```

```
        insert_safe(phone_number);
```

```
    }
```

```
}
```

```
}
```


2. (5 pts) HTTP 1.1 allows for multiple client requests and server responses on a single connection. Explain why.

3. (5 pts) We would like our protocol to support multiple interactions per connection. Show how to change the code for the `serve` function above to handle multiple requests per connection. [Hint: you don't have to change much.]

Assignment Project Exam Help

<https://eduassistpro.github.io/>

Add WeChat edu_assist_pro