Lab 7: Memory Management

1. **Outcomes:** After this lab, learner able to:
   The purpose of this lab is to study the memory layout of a process. Unix/Linux is a particularly good environment to show you memory management, as there are often hundreds of running processes (started by dozens of people) that each require memory in order to work.
   Unix/Linux must distribute the pages of available memory fairly and equitably. Methods such as demand paging, page sharing and the Least Recently Used victim page selection scheme are used to manage the memory.
2. **Prepare:**
   2.1. Install Virtual computer and Ubuntu operating system
   2.2. Read most common commands linux
3. **Facilities**
   3.1. Computer with Ubuntu operating system
4. **Duration:** 4 hours
5. **Introduction:**
   As with most high-level languages, C creates space for your declared variables when your program is compiled, so you don't have to manually do anything before you use your variables.
   Global variables live in the data-segment of your process, and local variables live in the stacksegment.
   However, often you need to allocate memory space **dynamically**, for example, when you are building linked lists with pointers. In C, the routines to do this are *malloc* and *free*.
   5.1. malloc Library Routine:

   char *malloc(unsigned size)

The function **malloc** allocates a region of memory large enough to hold an object whose size (as measured by the **sizeof** operator) is size. A pointer to the beginning of the region is returned. If it is impossible for some reason to perform the requested allocation, or if size is 0, a NULL pointer is returned. The region of memory is not specially initialized in any way and the caller must assume that it will contain garbage information. Notice that **malloc** returns a **char** pointer. Often you don't want to **malloc** characters, but structures etc. You therefore must *coerce* the pointer returned from **malloc** into the type you need. For example:

```
/* Type Declarations */
struct client
{
char *name;              /* Pointer to the string holding the name */
int age;                 /* Client's age */
int size;                /* Client's size;
struct client *next;     /* Pointer to the next element in the list */
}
 ----
 ---
 struct client *c;       /* A pointer to a client structure. */
```

```
/* Initially, it points to nothing */
/* Create enough memory to hold a client */
c= (struct client *) malloc( sizeof(struct client));
if (c==NULL)
printf("Could not malloc a client\n");
else
{
c->name= "Ahmed";
c->age= 25;
c->size= 160;
c->next= NULL;
}
```

5.2. free Library Routine:

void free(char *ptr)

The function **free** deallocates a region of memory previously allocated by **malloc**. The argument to **free** must be a pointer that is equivalent (except for possible intermediate type casting) to a pointer previously returned by **malloc**. (If the argument to *free* is a null pointer then no action should occur, but this is known to cause trouble in some C implementations.)

Once a region of memory has been explicitly freed it must not be used for any other purpose.

To free the client struct **malloc**'d above, you would do **free(c)**

5.3. Using ps to see Memory Allocation:

In the first lab you saw that **ps** could give you details of all of the processes running on the UNIX machine. After logging into **Unix server**, run the following **ps** command:

$ ps -o user,vsz,rss,pmem,fname -e | more

user:

The user who started the process running.

vsz:

The total size of the process in (virtual) memory in kilobytes as a decimal integer.

rss:

The resident set size of the process, in kilobytes as a decimal integer.

pmem:

The ratio of the process's resident set size to the physical memory on the machine, expressed as a percentage.

fname:

The first few character's of the process' name.

One reason why the resident set is smaller than the process size is that UNIX processes use ***shared libraries***, similar to DLLs on Windows systems. The operating system doesn't include the size of any shared libraries in the resident set, because the libraries are **loaded** into memory only once.

5.4. Using df to see Swap Usage:

With a paging virtual memory system using LRU, those least recently used pages are swapped out to disk until they are required again (if ever). Under Solaris this **swap space**

is also used to keep temporary files in the directory */tmp*. To see the amount of **swap space** in use, use the command:

$ df /tmp

Remember that if the **swap space is too small**, then there is not enough room to keep the unused pages, and **thrashing** is likely to occur. On the other hand, if the **swap space is too large**, you waste disk space as it cannot be used to store files (except temporary files in */tmp*)

5.5. Monitoring Paging Activity:

The vmstat program is the best utility to monitor paging activity.

$ vmstat 2 5

will give 5 vmstat reports, one every 2 seconds, and the first report is an average since the system was started. Read the manual on **vmstat** to see what information it provides. The main memory stats columns are:

swap:

Amount of swap space currently available in Kbytes.

free:

Size of the free list of pages in Kbytes.

pi:

Kilobytes paged in per second. These are pages which are required for processes to continue execution.

po:

Kilobytes paged out per second. These are LRU unused pages which can be paged to the disk.

fr:

Kilobytes freed due to pageouts or to process termination.

The page out column is often zero. Therefore, there must be many pages in memory which are unused but are not paged out to disk.

6. Components of a Process:

A UNIX process has several memory components:

- ✓ A text section which holds the process' machine code.
- ✓ A data section which holds the process' global variables. Initially, some of the global variables have values, and some do not. The latter are kept in a section known as the bss section.
- ✓ A heap section which is where newly created global variables are kept.
- ✓ A stack section which is where newly created local variables are kept, as well as function parameters and function return information

The **size** program shows the sizes of the text, data and bss sections in a program's disk image. For example:

```
$ which ls                    # Where on disk is ls kept?
/bin/ls
$ size /bin/ls
15678 + 1241 + 1963 = 18882  # code + data + bss == total
```

6.1. Sharing Memory:

Because UNIX runs on page architectures, it can use page protections to share sections of memory **read-only** between processes. For example, the text section for all *ksh*s is shared readonly. Another use of page sharing is for **shared libraries**. These are subroutines, which are common to many programs. The *printf()* function is used by nearly all C programs, and so it makes sense to load it once into memory, and share its page amongst all C processes. The *ldd* command can show you what shared libraries each program uses:

```
$ which ls              # Where on disk is ls kept?
/bin/ls
$ ldd /bin/ls           # Show the shared libraries used
libc.so.1 => /usr/lib/libc.so.1
libdl.so.1 => /usr/lib/libdl.so.1
$ size /usr/lib/libc.so.1 # Size of the shared library?
670256 + 25284 + 6500 = 702040
$ ldd a.out
libpthread.so.1 => /usr/lib/libpthread.so.1
libc.so.1 => /usr/lib/libc.so.1
libdl.so.1 => /usr/lib/libdl.so.1
libthread.so.1 => /usr/lib/libthread.so.1
```

6.2. Memory Structure:

This section is an introduction to memory as we see it in UNIX.

Memory is like a huge array with (say) 0xffffffff elements. A pointer in C is an index to this array. Thus when a C pointer is 0xefffe034, it points to the 0xefffe035th element in the memory array (memory being indexed starting with zero).

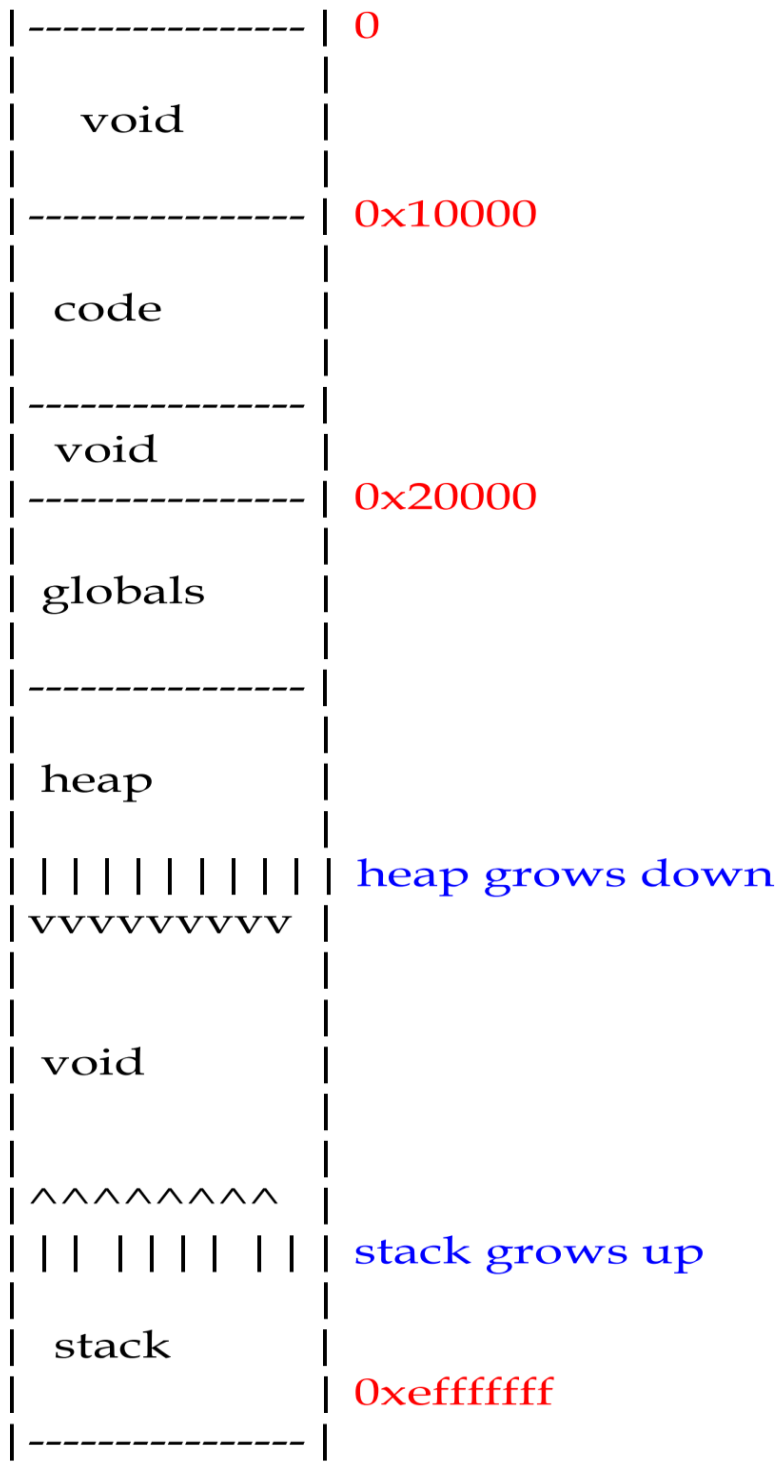
Unfortunately, you cannot access all elements of memory. One example that we have seen a lot is element 0. If you try to dereference a pointer with a value of 0, you will get a segmentation violation. This is UNIX's way of telling you that that memory location is illegal. For example, the following code will generate a segmentation violation:

```
/* Lab0.c */
main( )
{
char *s;
char c;
s = (char *) 0;
c = *s;
}
```

As it turns out, there are 4 regions of memory that are legal. They are:

1. The code (or "text"): These are the instructions of your program.
2. The globals: These are your global variables.
3. The heap: This is memory that you get from malloc( ).
4. The stack: This contains your local variables and procedure arguments.

If we view memory as a big array, the regions (or ``segments'') look as follows:



Note, the heap grows down as you make more malloc( ) calls, and the stack goes up as you make nested procedure calls

6.3. Paging:

On most machines, memory is broken up into 8192-byte chunks. These are called pages. On some machines, pages are 4096 bytes -- this is something set by the hardware. The way memory works is as follows: The operating system allocates certain pages of memory for you. Whenever you try to read to or write from an address in memory, the hardware first checks with the operating system to see if that address belongs to a page that has been **allocated for you. If so, then it goes ahead and performs the read/write. If not, you'll get a segmentation violation**

- ✓ This is what happens when you do:
  s = (char *) 0;
  c = *s;
- ✓ When you say "c = *s", the hardware sees that you want to read memory location zero. It checks with the operating system, which says "I haven't allocated the page containing location zero for you". This results in a segmentation violation.
- ✓ As it turns out, the first 8 pages on our machines are void. This means that trying to read to or write from any address from 0 to 0xffff will result in a segmentation violation.
- ✓ The next page (starting with address 0x10000) starts the code segment. This segment ends at the variable &etext. The globals segment starts at page 0x20000. It goes until the variable &end. The heap starts immediately after &end, and goes up to sbrk(0). The stack ends with address 0xeffffffff. Its beginning changes with the different procedure calls you make. Every page between the end of the heap and the beginning of the stack is void, and will generate a segmentation violation upon accessing.

6.4. &etext and &end:

These are two external variables that are defined as follows:

```
extern etext;
extern end;
```

Note that they are typeless. You never use just "etext" and "end". Instead, you use their addresses-- these point to the end of the text and globals segments respectively. Look at the program lab1.c. This prints out the addresses of etext and end. Then it prints out 6 values:

```
/* Lab1.c*/
#include <stdio.h>
extern end;
extern etext;
extern int I;
extern int J;
int I;
main(int argc, char **argv)
{
int i;
int *ii;
printf("&etext = 0x%lx\n", &etext);
printf("&end = 0x%lx\n", &end);
printf("\n");
ii = (int *) malloc(sizeof(int));
printf("main = 0x%lx\n", main);
printf("&I = 0x%lx\n", &I);
printf("&i = 0x%lx\n", &i);
printf("&argc = 0x%lx\n", &argc);
printf("&ii = 0x%lx\n", &ii);
```

```
printf("ii = 0x%lx\n", ii);
}
```

main is a pointer to the first instruction of the main() procedure. This is simply a location in the code segment. I is a global variable. Thus &I should be an address in the globals segment. i is a local variable. Thus &i should be an address in the stack. argc is an argument to main(). Thus, &argc should be an address in the stack. ii is another local variable. Thus, &ii should be an address in the stack. However, ii is a pointer to memory that has been malloc'd. Thus, ii should be an address in the heap.

When we run Lab1.c, we get something like the following:

```
$ testaddr1
&etext = 0x10b64
&end = 0x20cf0
main = 0x1095c
&I = 0x20ce8
&i = 0xffbefbac
&argc = 0xffbefc04
&ii = 0xffbefba8
ii = 0x20d00
```

So, what this says is that the code segment goes from 0x10000 to 0x10b64. The globals segment goes from 0x20000 to 0x20cf0. The heap goes from 0x20cf0 to some address greater than 0x20d00 (since ii allocated 4 bytes starting at 0x20d00). The stack goes from some address less than 0xefffe8f8 to 0xeffffff. All values that are printed by lab12_1.c make sense.

6.5. Now, look at Lab2.c

```
/* Lab2.c*/
#include <stdio.h>
extern end;
extern etext;
main( )
{
char *s;
char c;
printf("&etext = 0x%lx\n", &etext);
printf("&end = 0x%lx\n", &end);
printf("\n");
printf("Enter memory location in hex (start with 0x): ");
fflush(stdout);
scanf("0x%x", &s);
printf("Reading 0x%x: ", s);
fflush(stdout);
c = *s;
printf("%d\n", c);
printf("Writing %d back to 0x%x: ", c, s);
```

```
fflush(stdout);
*s = c;
printf("ok\n");
}
```

This is the first really gross piece of C code that you'll see. What it does is print out &etext and &end, and then prompt the user for an address in hexidecimal. It puts that address into the pointer variable s. You should never do this unless you are writing code like this which is testing memory. The first thing that it does with s is try to read from that memory location (c = *s).

Then it tries to write to the memory location (*s = c). This is a way to see which memory locations are legal.

So, let's try it out with an illegal memory value of zero:

```
$ Lab2
&etext = 0x10c0c
&end = 0x20ee8
Enter memory location in hex (start with 0x): 0x0
Reading 0x0: Segmentation Fault
```

When we tried to read from memory location zero, we got a Segmentation fault. This is because memory location zero is in the void -- the hardware recognized this by asking the operating system, and then generating a segmentation violation.

Memory locations 0x0 to 0xffff are illegal -- if we try any address in that range, we will get a segmentation violation:

```
$ Lab2
&etext = 0x10c0c
&end = 0x20ee8
Enter memory location in hex (start with 0x): 0xffff
Reading 0xffff: Segmentation Fault
$ Lab2
&etext = 0x10c0c
&end = 0x20ee8
Enter memory location in hex (start with 0x): 0x4abc
Reading 0x4abc: Segmentation Fault
```

Memory location 0x10000 is in the code segment. This should be a legal address:

```
$ Lab2
&etext = 0x10c0c
&end = 0x20ee8
Enter memory location in hex (start with 0x): 0x10000
Reading 0x10000: 127
Writing 127 back to 0x10000: Segmentation Fault
```

You'll note that we were able to read from 0x10000 -- it gave us the byte 127, which begins some instruction in the program. However, we got a segmentation fault when we wrote to 0x10000. This is by design: The code segment is read-only. You can read from it, but you can't write to it. This makes sense, because you can't change your program while it's

running – instead you have to recompile it, and rerun it.
Now, what if we try memory location 0x11fff? This is above &etext, so it should be outside of the code segment:

```
$ Lab2
&etext = 0x10c0c
&end = 0x20ee8
Enter memory location in hex (start with 0x): 0x11fff
Reading 0x11fff: 0
Writing 0 back to 0x11fff: Segmentation Fault
```

You'll note that even though 0x11fff is an address outside the code segment, we're still allowed to read from it. This is because the hardware checks the with operating system to see if an address's page has been allocated. Since page 8 (0x10000 - 0x11fff) has been allocated for the code segment, the hardware treats any address between 0x10000 and 0x11fff as a legal address.
You can read from it, but its value is meaningless.
Now, pages 9 to 15 are unreadable again:

```
$ Lab2
&etext = 0x10c0c
&end = 0x20ee8
Enter memory location in hex (start with 0x): 0x12000
Reading 0x12000: Segmentation Fault
$ Lab2
&etext = 0x10c0c
&end = 0x20ee8
Enter memory location in hex (start with 0x): 0x1f000
Reading 0x1f000: Segmentation Fault
```

The globals starts at 0x20000, so we see that the 16th page is readable and writable:

```
$ Lab2
&etext = 0x10c0c
&end = 0x20ee8
Enter memory location in hex (start with 0x): 0x20000
Reading 0x20000: 127
Writing 127 back to 0x20000: ok
```

We can read from and write to any location (0x20000 to 0x21fff) in this page. The next page (starting at 0x22000) is unreachable:

```
$ Lab2
&etext = 0x10c0c
&end = 0x20ee8
Enter memory location in hex (start with 0x): 0x21dff
Reading 0x21dff: 0
Writing 0 back to 0x21dff: ok
$ Lab2
&etext = 0x10c0c
```

```
&end = 0x20ee8
Enter memory location in hex (start with 0x): 0x22000
Reading 0x22000: Segmentation Fault
```

What this tells us is that the globals go from 0x20000 to 0x20ee8. The heap goes from 0x20ee8 up to some higher address in the same page

6.6. Sbrk(0):

sbrk( ) is a system call. sbrk(0) returns to the user the current end of the heap. Since we can keep calling malloc(), sbrk(0) can change over time. testaddr3.c shows the value of sbrk(0) -- note it is in page 16 (0x20000 - 0x21fff). Since the hardware performs its check in 8192-byte intervals, we can get at any byte in page 16, even though sbrk(0) returns 0x20c78:

```
/* Lab3.c */
#include <stdio.h>
extern end;
extern etext;
main( )
{
char *s;
char c;
printf("&etext = 0x%lx\n", &etext);
printf("&end = 0x%lx\n", &end);
printf("sbrk(0)= 0x%lx\n", sbrk(0));
printf("&c = 0x%lx\n", &c);
printf("\n");
printf("Enter memory location in hex (start with 0x): ");
fflush(stdout);
scanf("0x%x", &s);
printf("Reading 0x%x: ", s);
fflush(stdout);
c = *s;
printf("%d\n", c);
printf("Writing %d back to 0x%x: ", c, s);
fflush(stdout);
*s = c;
printf("ok\n");
}
```

$ Lab3

```
&etext = 0x10c84
&end = 0x20f68
sbrk(0)= 0x20f68
&c = 0xffbefbab
Enter memory location in hex (start with 0x): 0x21fff
Reading 0x21fff: 0
Writing 0 back to 0x21fff: ok
```

We haven't called malloc() in Lab3.c. This is the reason why &end and sbrk(0) return the same value. In Lab3a.c we make a malloc() call in the beginning of the program, and as you see, &end and sbrk(0) return different values:

6.7. Lab3a.c

```
/* Lab3a.c */
#include <stdio.h>
extern end;
extern etext;
main( )
{
char *s;
char c;
char *buf;
buf = (char *) malloc(1000);
printf("&etext = 0x%lx\n", &etext);
printf("&end = 0x%lx\n", &end);
printf("sbrk(0)= 0x%lx\n", sbrk(0));
printf("&c = 0x%lx\n", &c);
printf("\n");
printf("Enter memory location in hex (start with 0x): ");
fflush(stdout);
scanf("0x%x", &s);
printf("Reading 0x%x: ", s);
fflush(stdout);
c = *s;
printf("%d\n", c);
printf("Writing %d back to 0x%x: ", c, s);
fflush(stdout);
*s = c;
printf("ok\n");
}
```

$ Lab3a

```
&etext = 0x10cc4
&end = 0x20fb8
sbrk(0)= 0x22fb8
&c = 0xffbefbab
Enter memory location in hex (start with 0x): 0x23fff
Reading 0x23fff: 0
Writing 0 back to 0x23fff: ok
```

$ Lab3a

```
&etext = 0x10cc4
&end = 0x20fb8
sbrk(0)= 0x22fb8
&c = 0xffbefbab
```

Enter memory location in hex (start with 0x): 0x24000
Reading 0x24000: Segmentation Fault

7. **The Stack:**

So, where's the beginning of the stack? If we try addresses above 0xffbee103 in Lab3.c, we see that most of them are legal:

$ Lab3
&etext = 0x10c84
&end = 0x20f68
sbrk(0)= 0x20f68
&c = 0xffbefbab
Enter memory location in hex (start with 0x): 0xffb00000
Reading 0xffb00000: 0
Writing 0 back to 0xffb00000: ok
$ Lab3
&etext = 0x10c84
&end = 0x20f68
sbrk(0)= 0x20f68
&c = 0xffbefbab
Enter memory location in hex (start with 0x): 0xff3f0000
Reading 0xff3f0000: 0
Writing 0 back to 0xff3f0000: ok
$ Lab3
&etext = 0x10c84
&end = 0x20f68
sbrk(0)= 0x20f68
&c = 0xffbefbab
Enter memory location in hex (start with 0x): 0xff3effff
Reading 0xff3effff: Segmentation Fault

What gives? As it turns out, the operating system allocates all pages from 0xff3f0000 to the bottom of the stack. Where is the bottom of the stack? Let's probe:

$ Lab3
&etext = 0x10c84
&end = 0x20f68
sbrk(0)= 0x20f68
&c = 0xffbefbab
Enter memory location in hex (start with 0x): 0xffbeffff
Reading 0xffbeffff: 0
Writing 0 back to 0xffbeffff: ok
$ Lab3
&etext = 0x10c84
&end = 0x20f68
sbrk(0)= 0x20f68
&c = 0xffbefbab

Enter memory location in hex (start with 0x): 0xffbf0000
Reading 0xffbf0000: Segmentation Fault
So the stack goes from 0xff3f0000 to 0xffbeffff. That is roughly 8 megabytes you can print out the default stack size, and change it using the limit command (read the man page):

```
$ limit
cputime unlimited
filesize unlimited
datasize unlimited
stacksize 8192 kbytes
coredumpsize 0 kbytes
descriptors 64
memorysize unlimited
```

Whenever you call a procedure, it allocates local variables and arguments (plus a few other things) on the stack. Whenever you return from a procedure, those variables are popped off the stack.
So, look at Lab4.c. It has main() call itself recursively as many times as there are arguments. You'll see that at each recursive call, the addresses of argc and argv and the local variable i are smaller addresses -- this is because each time the procedure is called, the stack grows downward to allocate its arguments and local variables.

```
/* Lab4.c */
#include <stdio.h>
extern end;
extern etext;
main(int argc, char **argv)
{
int i;
printf("argc = %d. &argc = 0x%x, &argv = 0x%x, &i = 0x%x\n", argc, &argc, &argv, &i);
if (argc > 0) main(argc-1, argv);
}
$ Lab4
argc = 1. &argc = 0xffbefc04, &argv = 0xffbefc08, &i = 0xffbefbac
argc = 0. &argc = 0xffbefb8c, &argv = 0xffbefb90, &i = 0xffbefb34
$ Lab4 v
argc = 2. &argc = 0xffbefbfc, &argv = 0xffbefc00, &i = 0xffbefba4
argc = 1. &argc = 0xffbefb84, &argv = 0xffbefb88, &i = 0xffbefb2c
argc = 0. &argc = 0xffbefb0c, &argv = 0xffbefb10, &i = 0xffbefab4
$ Lab4 v o l s
argc = 5. &argc = 0xffbefbec, &argv = 0xffbefbf0, &i = 0xffbefb94
argc = 4. &argc = 0xffbefb74, &argv = 0xffbefb78, &i = 0xffbefb1c
argc = 3. &argc = 0xffbefafc, &argv = 0xffbefb00, &i = 0xffbefaa4
argc = 2. &argc = 0xffbefa84, &argv = 0xffbefa88, &i = 0xffbefa2c
argc = 1. &argc = 0xffbefa0c, &argv = 0xffbefa10, &i = 0xffbef9b4
argc = 0. &argc = 0xffbef994, &argv = 0xffbef998, &i = 0xffbef93c
```

Now, lets break the stack. Writing a program that allocates too much stack memory can do this. One such program is in breakstack.c. It performs infinite recursion, and at each recursive step it allocates 10000 bytes of stack memory in the variable iptr. When you run this, you'll see that you get a segmentation violation when the recursive call is made and the stack is about to dip below 0xff3f0000:

```
/* breakstack.c */
#include <stdio.h>
extern end;
extern etext;
main( )
{
char c;
char iptr[10000];
printf("&c = 0x%lx, iptr = 0x%x ... ", &c, iptr);
fflush(stdout);
c = iptr[0];
printf("ok\n");
main( );
}
```

```
$ breakstack
...
&c = 0xff3fa347, iptr = 0xff3f7c30 ... ok
&c = 0xff3f7bbf, iptr = 0xff3f54a8 ... ok
&c = 0xff3f5437, iptr = 0xff3f2d20 ... ok
Segmentation Fault
```

8.