Linux Kernel Compilation & Working of malloc() in Linux

Operating Systems

Group Members

Content & Index

1. Problem

The aim of this project is to understand the compilation process of the Linux kernel and to investigate how malloc () or the dynamic memory allocation works in Linux operating system and the role of kernel in dynamic memory allocation.

2.Introduction

This report describes the step by step process of Linux kernel compilation which involves downloading complete Linux kernel source code, setting the configurations, compiling the kernel source. Also, this report describes about our experience in understanding of working of malloc() in Linux operating system by tracing malloc() function and allocation of virtual memory to the user space processes.

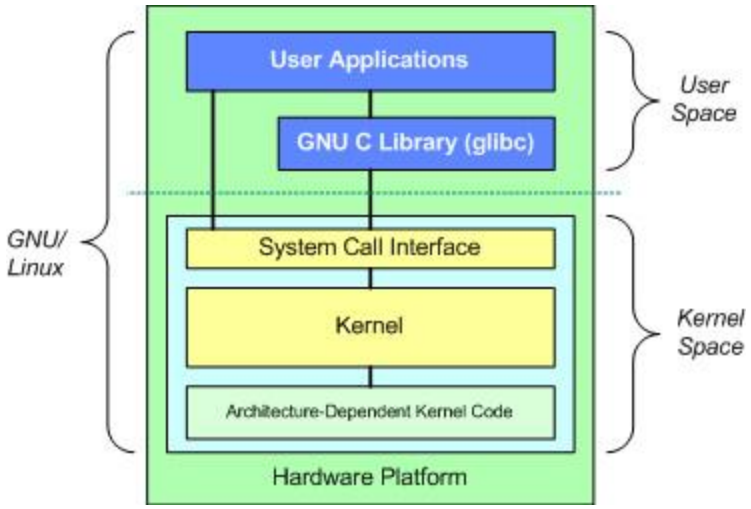
2. Description/Background

Linux is a free and open source operating system. It can be easily used by the developers to understand its internals as against to propriety operating systems like windows. The core of the operating system is called kernel, which our team decided to explore in order to understand its components and functionality.

Kernel is a program which is the main component of the operating system. Kernel interacts with underlying hardware of the computer on one end and user commands on the other end. In Linux, the architecture is divided into user space and kernel space. In user space the user applications are executed and kernel space is where Linux kernel exists. The kernel and user applications occupy different protected address spaces. Each user-space process occupies its own virtual address space and the kernel occupies the single address space.

Also, there is one more important component in the Linux operating system architecture, whichis GNU C Library (glibc). This provides the system call interface that connects to the kernel and provides the mechanism to transition between the user-space application and kernel.

In this project, our main aim was to understand the kernel space , the user space applications and their interaction through system calls. The below diagram gives the high level view of the Linux architecture.



To understand the kernel space, we need to download and install the separate kernel source code on our Linux system. The advantage of installing a separate Linux kernel is that we can easily understand the various components of the Linux kernel. Not only we can understand but we can remove, modify the existing components and we can add our own customized components. These components of the Linux kernels are called as loadable kernel modules (lkm), which are pieces of code written in C language. These modules can be loaded and unloaded into the kernel upon demand dynamically. The reason that not all modules are loaded into kernel and are loaded dynamically on demand is because, it takes up large amount of memory if all the modules are loaded. An example of the kernel module is device driver which allows the kernel to access hardware connected to the computer.

The compiled module in the linux operating system can be found at */lib/modules/kernel-version/* directory. The *modprobe* command can be used to add or remove a module from the Linux kernel. The modprobe command looks in the module directory /lib/modules/$(uname -r) for all the modules and other files, except for the optional /etc/modprobe.conf configuration file and /etc/modprobe.d directory.

Malloc() in Linux Operating System

Background

Malloc() is a c library function, defined in malloc.c file in glibc, is memory allocator that can be used to allocate memory dynamically. Its prototype is as defined in <stdlib.h>

*Void *(size_t size);*

Malloc() takes an argument specifying the size of the memory block that the user wishes to allocate and returns a pointer to a block of memory of that size. If this function fails to allocate the memory because of no memory available, it will return 0.

To deallocate the allocated memory, the free() function of the glibc in linux is used.

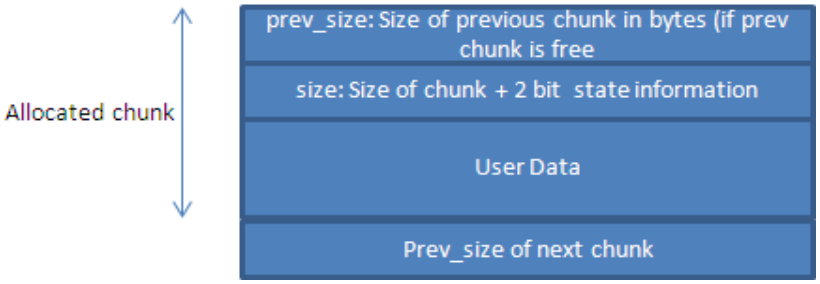
Void free(void*ptr);

How does memory allocator allocate the memory ?

Different operating systems can implement dynamic allocation in their own which they think makes it efficient. In Linux, the memory allocator or malloc() uses the concept of segregated- "free-lists" or bins. Each free-lists or bins contains blocks for a particular range of sizes.

The Linux allocator keeps 128 bins of different sizes. The first half of the bins keep exactly one size in them. These are for smaller sizes, 16 bytes through 512 bytes. The other half of the bins keep the rest of the sizes between 576 bytes and 2^31 bytes. Unlike the first half, these bins don not need exact sizes. The sizes found in the given bin can be between the previous bin size and the current size of the bin. All bins that contain different size blocks are sorted from smallest to largest, making the algorithm always return the best-fit for any given size.

When a block is freed, it is combined with its free neighbors, and the resulting block is placed in the appropriate bin. The allocator keeps track of the location of a block's neighbors by making use of a "size tag." The size tag is four bytes of memory that is allocated along with the block requested by the application. It resides right before the beginning of the user block of memory. This size is also repeated at the end of the block so that it is easy to determine the size of the block right behind any given block as well as the block ahead of any given block.



The allocator uses these size tags to keep track of exactly how much memory is allocated where. That is why we don't specify a size when the memory needs to be free memory — the allocator simply looks back 4 bytes from the given address to determine the size of the block. The size tag at the beginning of the block also keeps a bit reserved to indicate whether the block is free or in use.

The use of these two size tags adds an additional eight bytes to the size of any allocated block. The allocator must also keep the pointers for the list of free blocks for each bin.

In the Linux memory allocator, each bin is a doubly-linked list of free blocks in the given size range. The allocator stores the previous and next pointers for each block in the actual user space of the block that was allocated. By storing two pointers in the freed blocks, the allocator imposes a minimum size of 8 bytes on any allocated user block. Therefore, no matter how few bytes a program allocates, a block of at least 16 bytes will be allocated.

Where is memory being allocated in Linux Operating System ?

Every Linux process has its own dedicated memory address space. The kernel maps these "virtual" addresses in the process address space to actual physical memory addresses as necessary. The data stored at address 0xDEADBEEF in one process is not necessarily the same as the data stored at the same address in another process. When this data is tried to access, the kernel translates the virtual address into an appropriate physical address in order to retrieve the data from memory.

What is Heap ?

In the processes virtual address space, there is an area called as heap from where malloc() allocates memory dynamically to the user processes. The top of the heap is called the break point which specifies the end of the heap area. But if more memory is required by the process, the user application can ask the kernel to increase the heap size by moving up the break point.

How does user space applications tell the kernel to increase the heap size or process memory ?

The user space application or malloc tells the kernel to increase the heap size through brk() system call. When brk() system call is called, the kernel moves the break point of the heap up. There is also sbrk() function which is glibc function that makes increase in the size of heap easy by simply passing the number of bytes the application wishes to increase the size of the heap , as an argument.

brk() system call returns 0 if the new allocation is successful and -1 if not. sbrk() function returns a pointer to the new break point and -1 if the break point could not be moved.

There is an __curbrk is a global variable that keeps track of the current position of the break point . The sbrk()function simply adds the increment passed into it to __curbrk and passes this value to the brk()system call to actually allocate the memory.

What happens when brk() system call is called from userspace ?

When brk() is called, it goes to the kernel at mm/mmap.c where it is defined. The Linux kernel performs a few checks and then allocates the new memory for the process. The

kernel first aligns the old and the new break point to be on page boundaries. After aligning the addresses to fall on a boundary that is divisible by 4096 bytes, the system call checks to see if the amount of memory is decreased. If so, it immediately decreases the amount of heap space for that process with a call to ***do_munmap()*** and returns the new address pointer.

What does kernel do when if the application process wants an increase in memory ?

If the application wants to increase the amount of heap space allocated to it, the kernel performs three checks to make sure the allocation can succeed. The first check verifies that the specified limit of memory for this process will not be exceeded if more more memory is allocated***. setrlimit()*** function sets the limit of the size of the memory in Linux for the processes.

After verifying that a process is not requiring more memory than its limit allows, the kernel then verifies that increasing the memory will not interfere with any of the other parts of memory for that process. For Example, it should not interfere with stack or mmaped files or text area of the virtual address space.

Finally, as a last check, the kernel checks to see if there is enough memory to accommodate the new process. Once kernel verifies it calls the ***do_brk()*** function to increase the memory for the process.

The two basic functions used by the ***sys_brk()*** system call to allocate and deallocate memory are ***do_brk()***and ***do_munmap().*** In fact, the do_brk() function is really just a simplified version of the do_munmap() function. These two functions are similar to the *libc* functions mmap() and munmap().

In the implementation section, we will try to illustrate to see the files containing above functions and system calls to verify the compilation and the dynamic memory allocation process through malloc().

1. Implementation

Compilation of Linux Kernel

Platform used

The Linux operating system which we used for our experiment is Ubuntu 12.10 virtual machine. We allocated RAM of 6 GB and Hard disk size of 80 GB's in order to carry out our experiments uninterrupted.

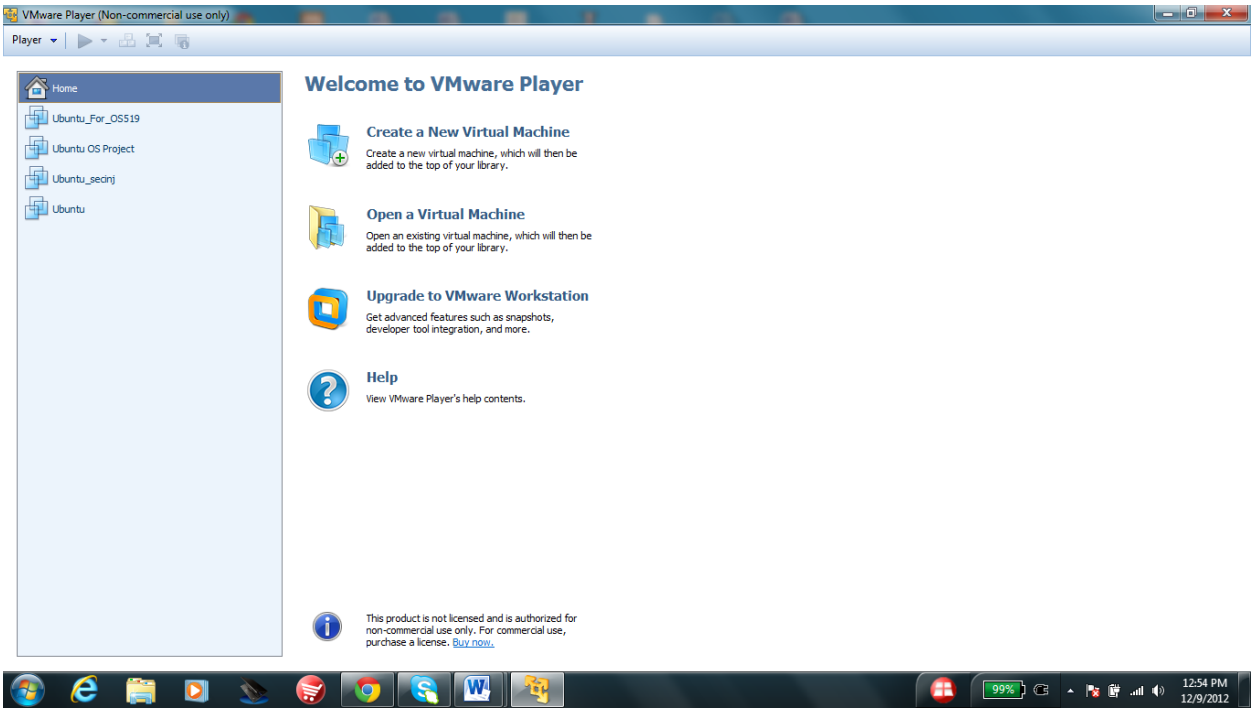
Why we used Virtual Machine

The reason for using virtual machine in our experiment was to make testing of kernel easy. There are chances while playing with kernel source code, something can go wrong and operating systems needs to be installed again. With the use of virtual machine, we can have the backup of the Linux operating system and can be used anytime if something goes wrong with the kernel which we experienced while performing the compilation of Linux kernel.

Proof of Implementation

Installation of virtual machine

1.



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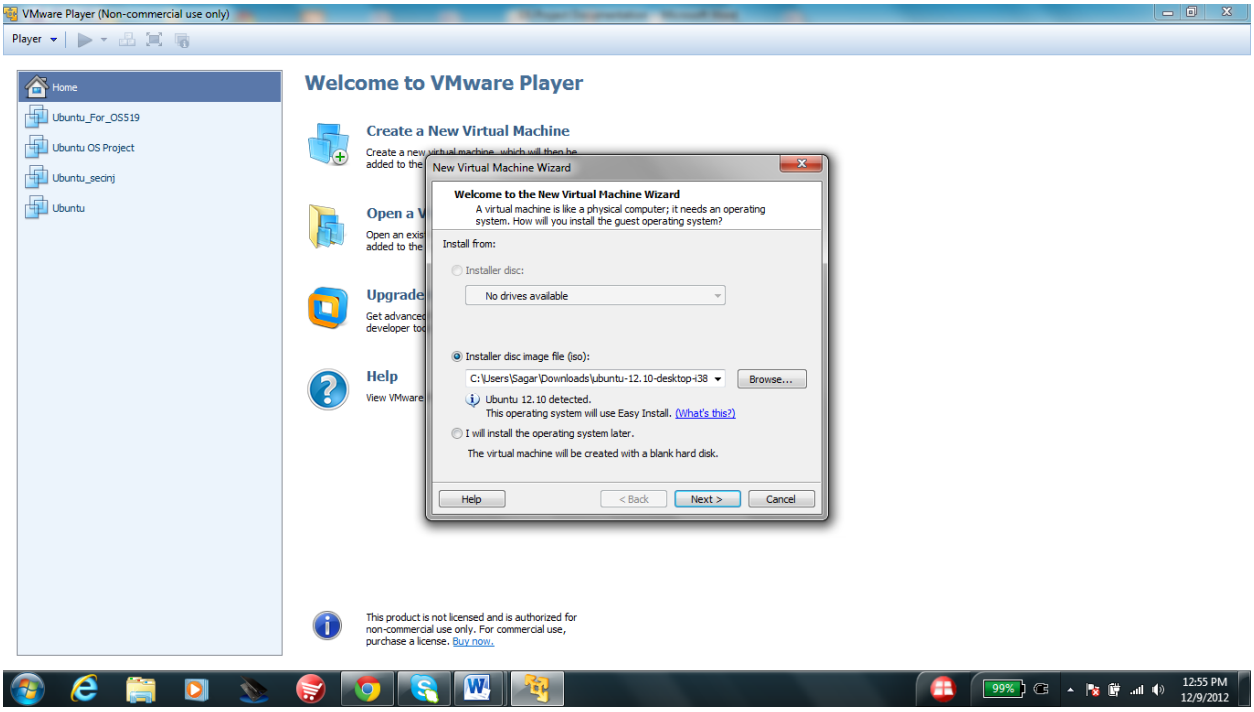
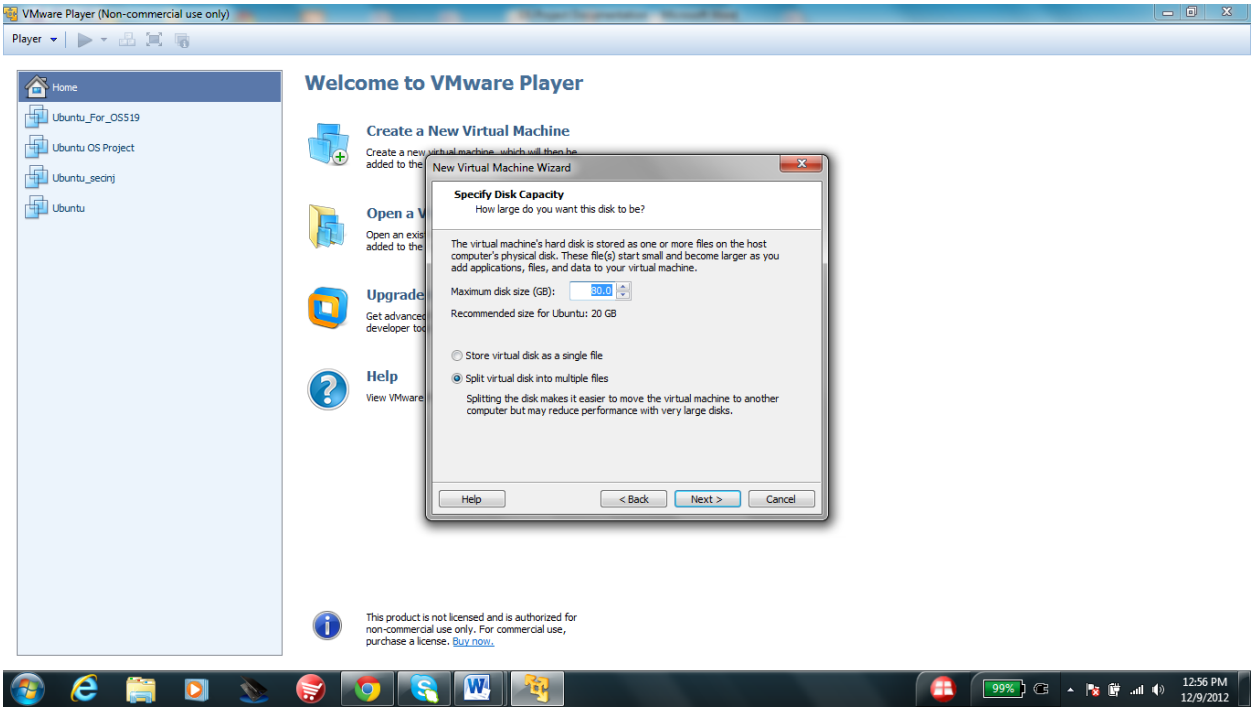


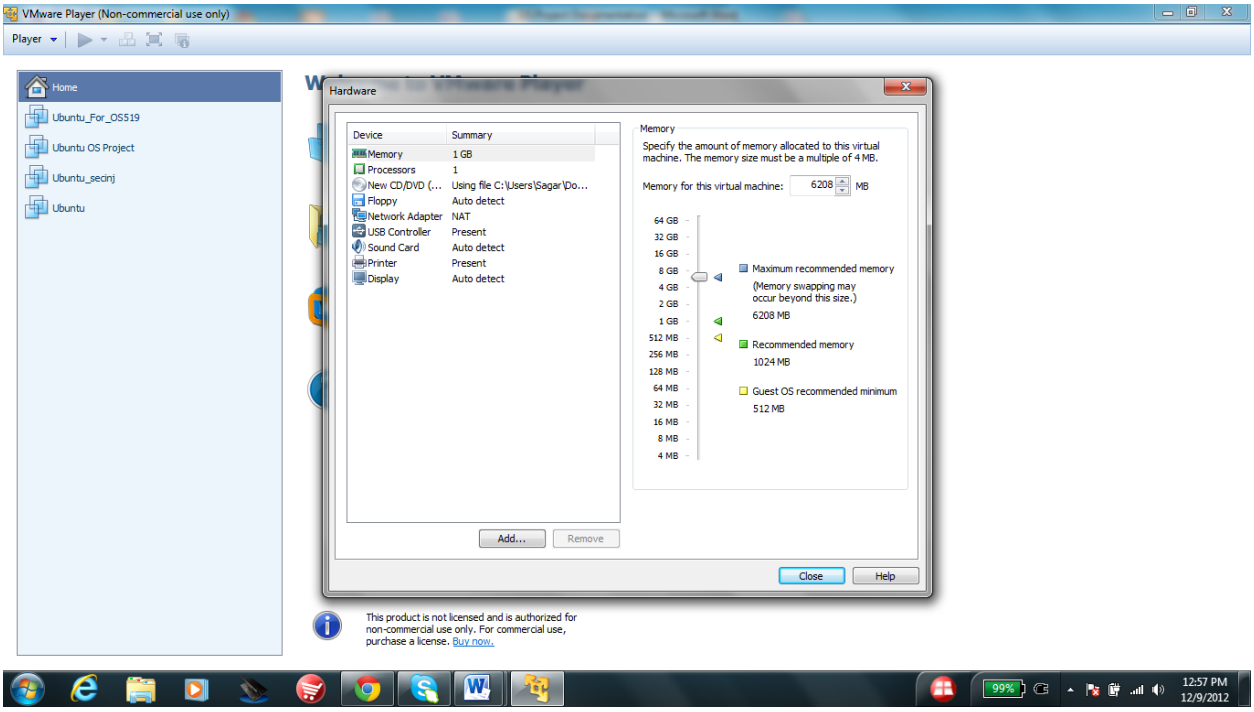
3.

Allocating Hard disk space



4.

Allocating 6 GB of RAM



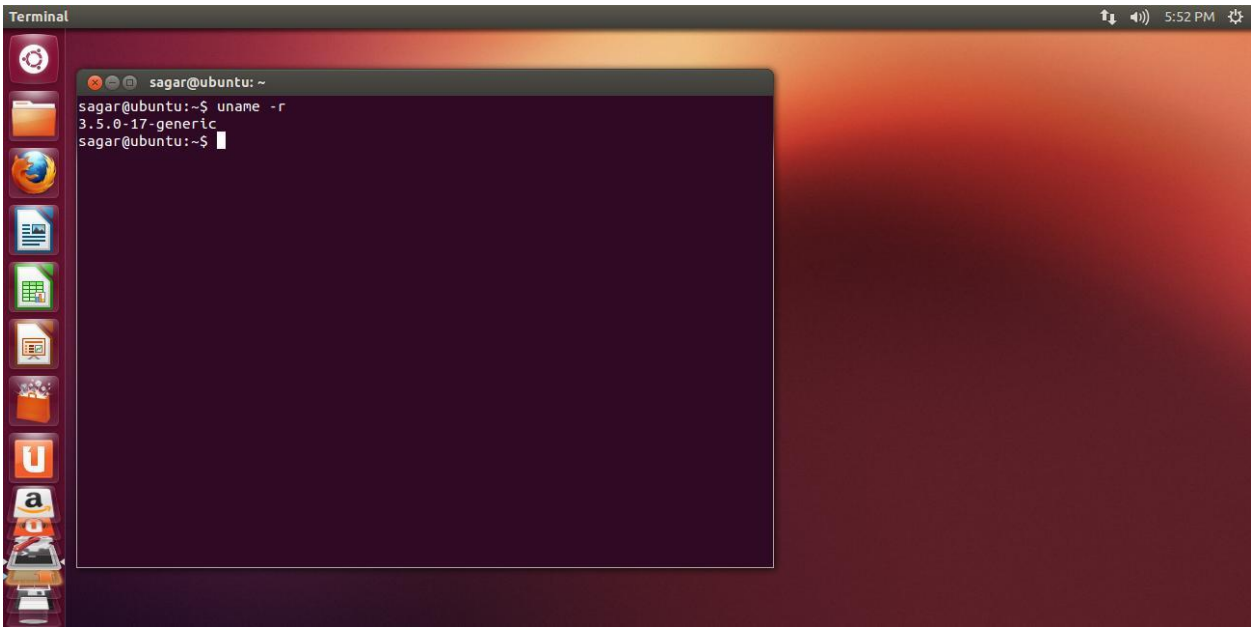
5.

Installation process starts

6.

7.

The Ubuntu 12.10 is installed now on our virtual Machine . We used uname –r command to check our original kernel version which is 3.5.0-17-generic



8.

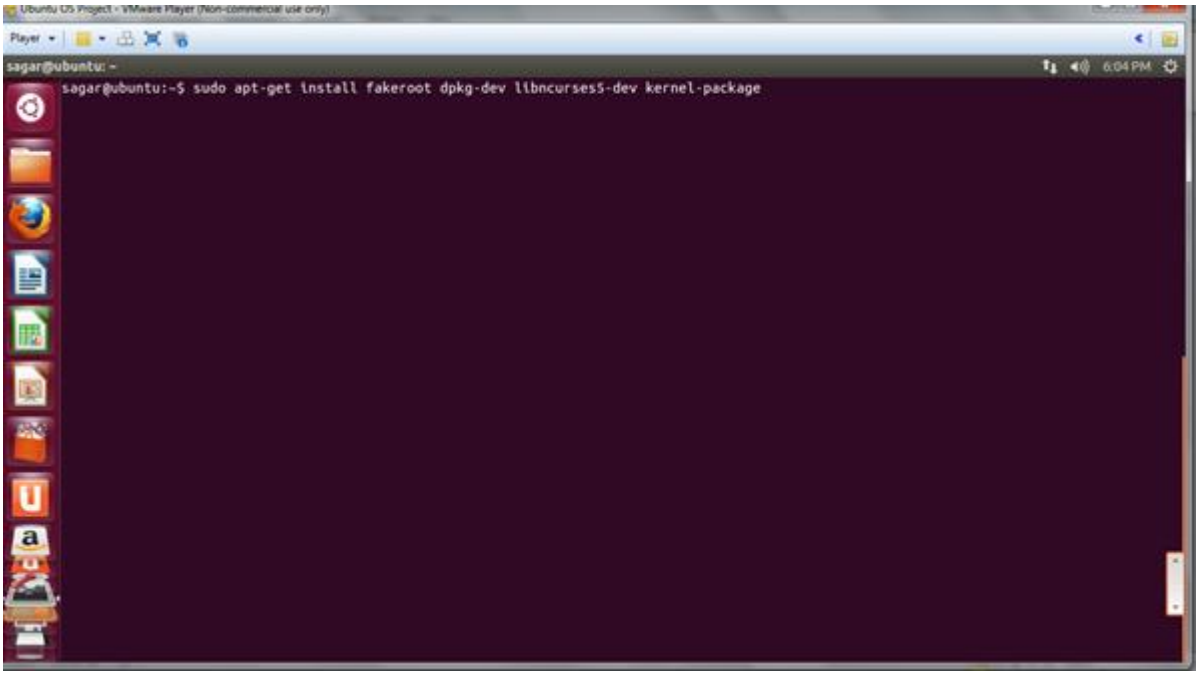
Now we need to install our custom kernel, inorder to carry our experimentations . We will first install the required packages before we actually start installing our custom Linux kernel.

Debian manages the kernel in the form of a package.To compile a Linux kernel the debian way,we need to include libncurses5-dev package, fakeroot package.

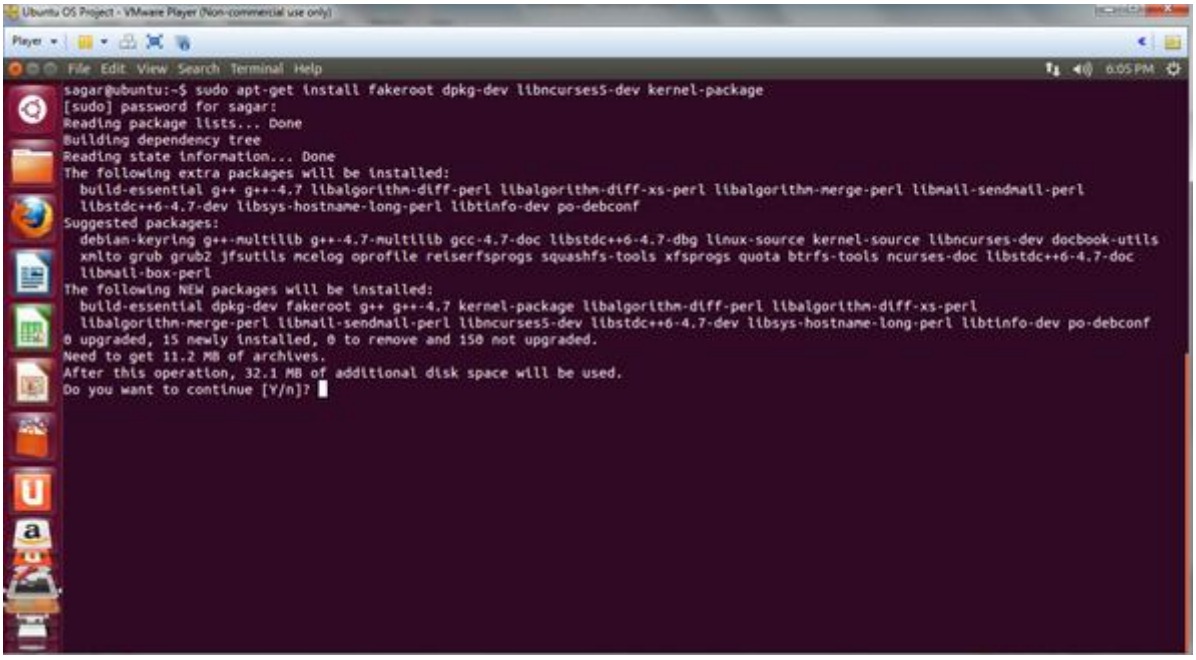
Fakeroot package will enable creation of the Debian package without using administrator's rights.

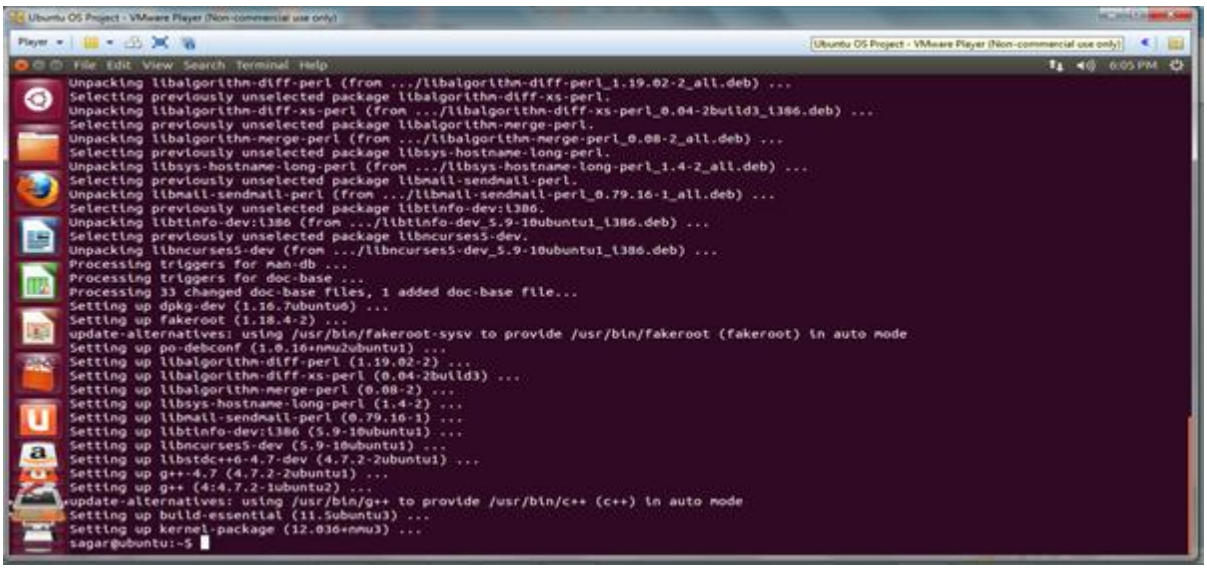
Linux command used:

sudo apt-get install fakeroot dpkg-dev libncurses5-dev kernel-package



Output screen shots of the above command



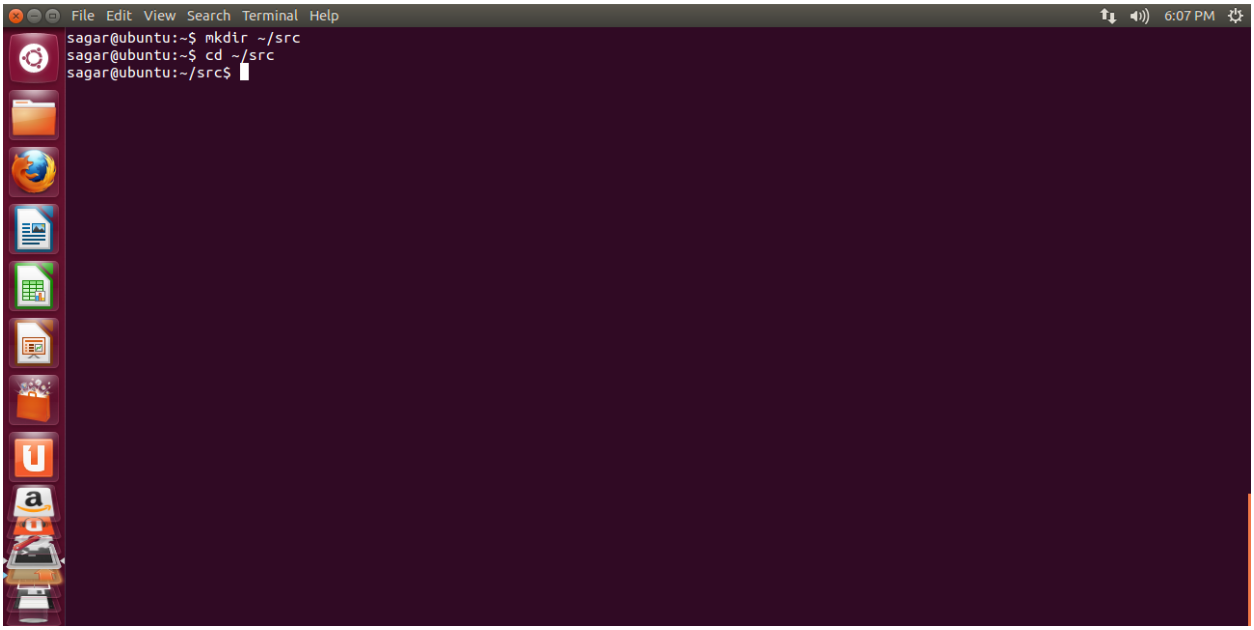


9.

Now we need to create the source directory where we will store of kernel source code.

Linux Command:

mkdir ~/src
cd ~/src

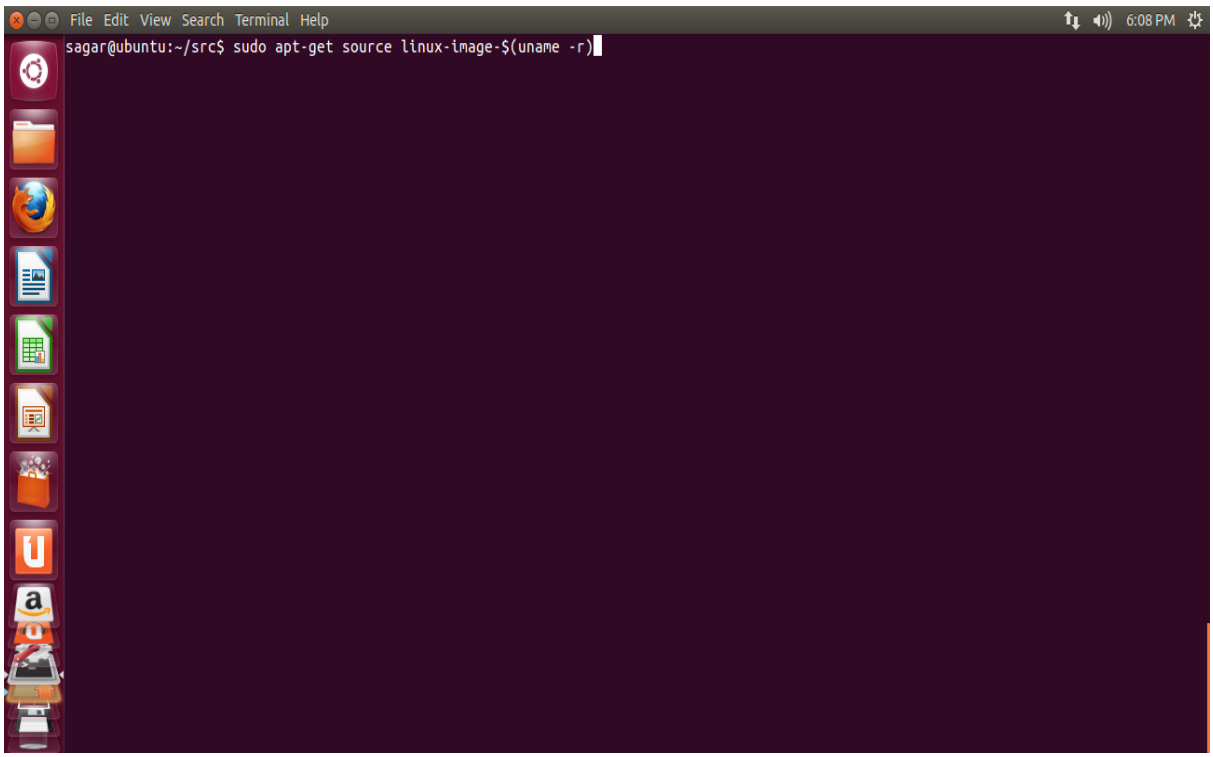


10.

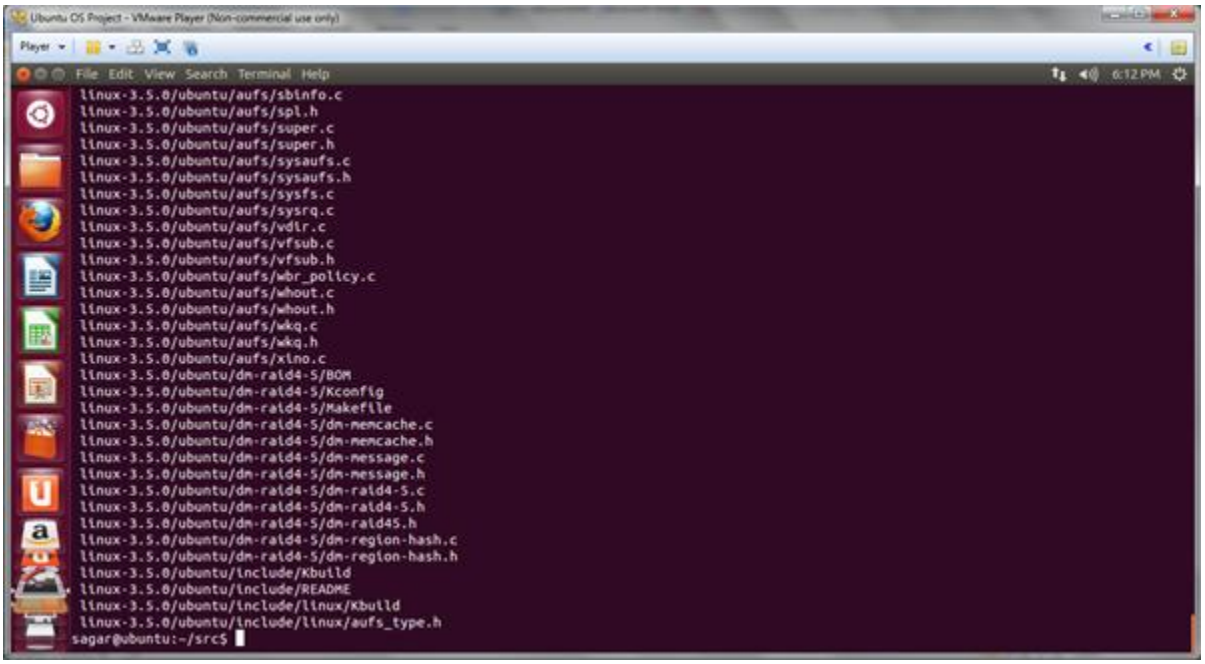
Now we need to download the kernel source code , of the same version which our Ubuntu 12.10 is using currently.

Linux Command used

sudo apt-get source linux-image-$(uname -r)



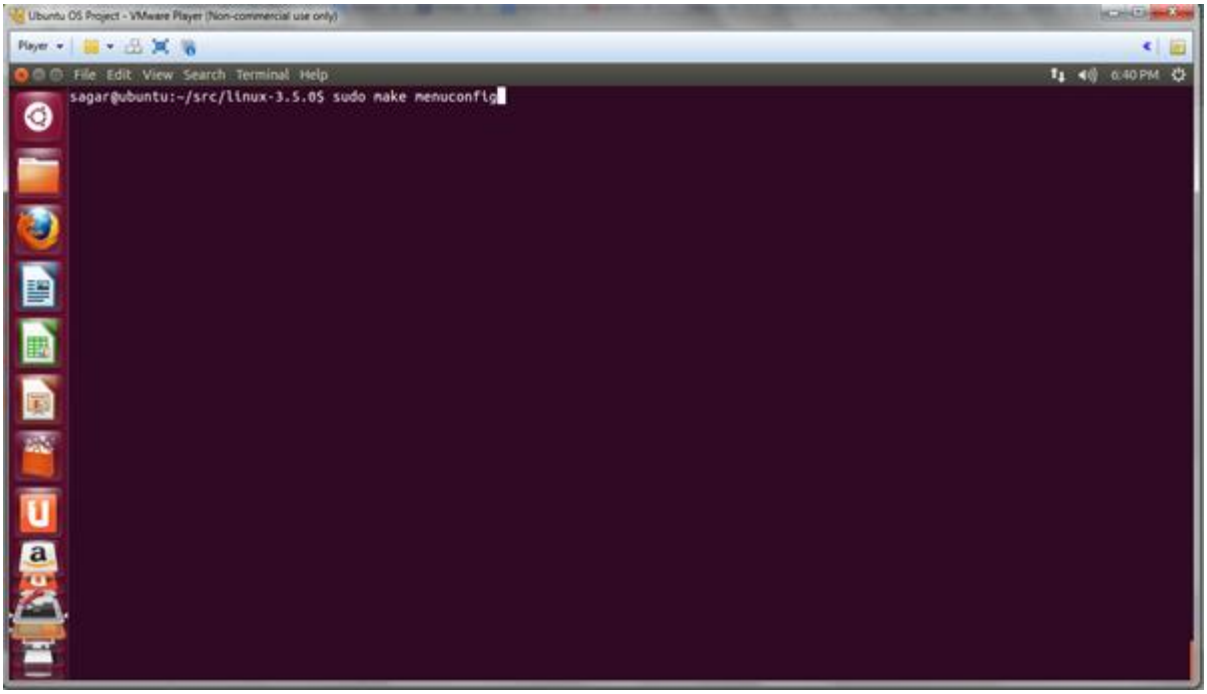
Command Output Screen Shot:



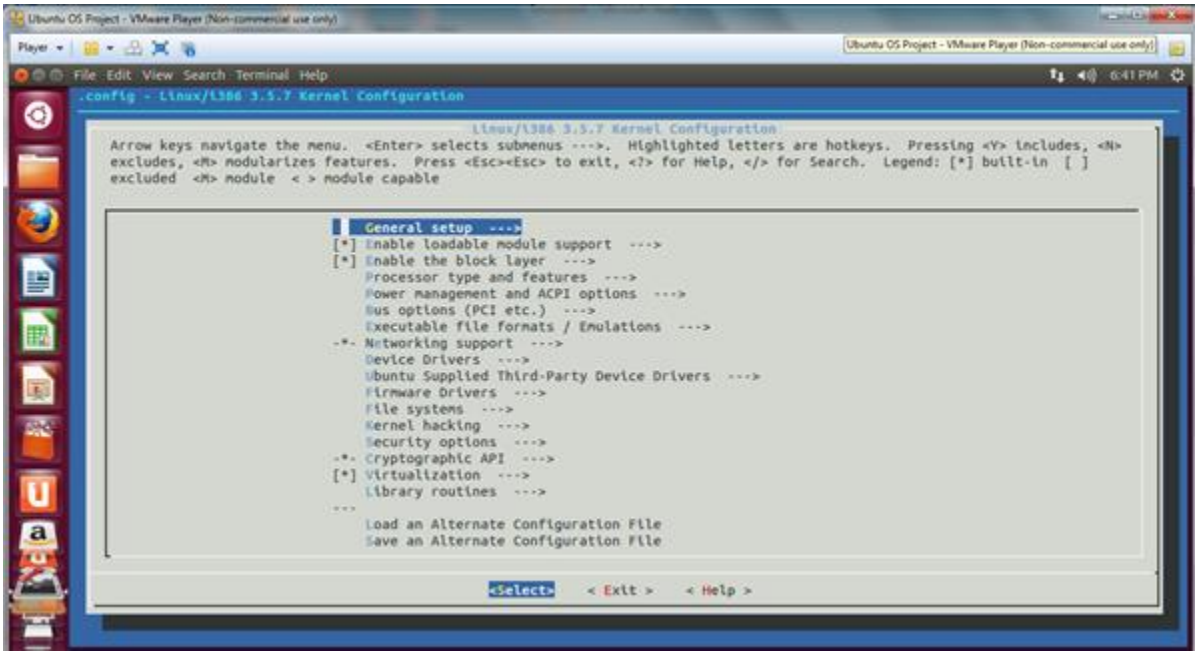
11. Now the next step is to show you, how to do the kernel configurations before the kernel compilation. In this menu you can specify which modules or specific area you want to compile. We will stick with general configurations.

Linux Command Used:

sudo make menuconfig



Output Screen Shots



We will move to Exit in the above menu screen and Exit

12. To speed up the compilation process, we can shoot a command.

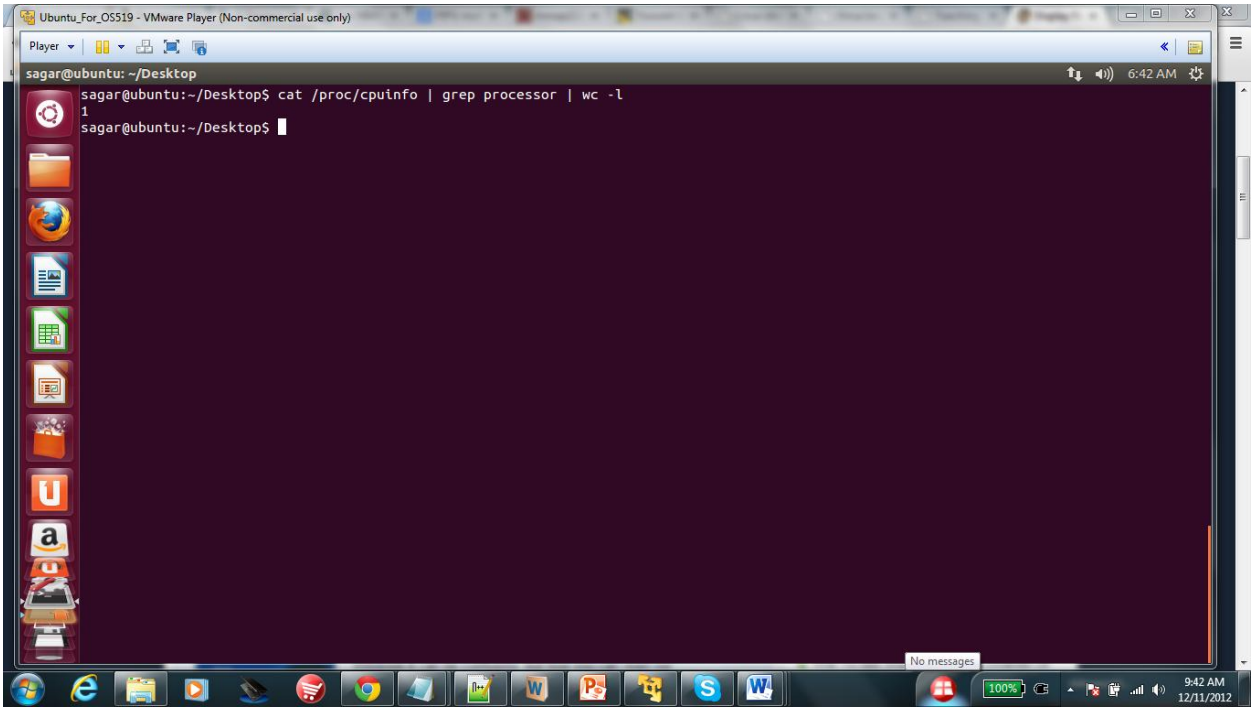
Linux Command used

export CONCURRENCY_LEVEL=2

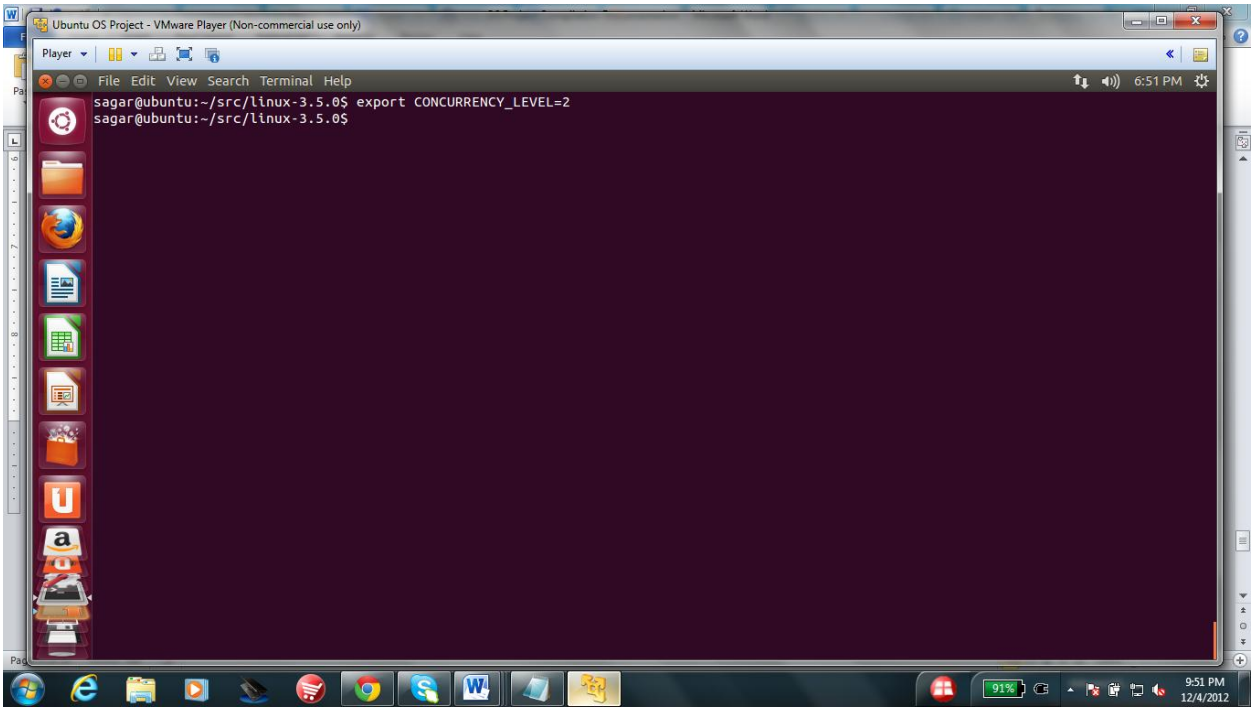
The above command is used depending upon the number of the CPU's your computer is using. The general formula to come up with the number like shown above is – number of CPU's + 1. In our case, we have only one cpu, so we set it to 2.

To verify the number of processors in your computer use the following command

cat /proc/cpuinfo | grep processor | wc –l



Speed up Output Screen shot

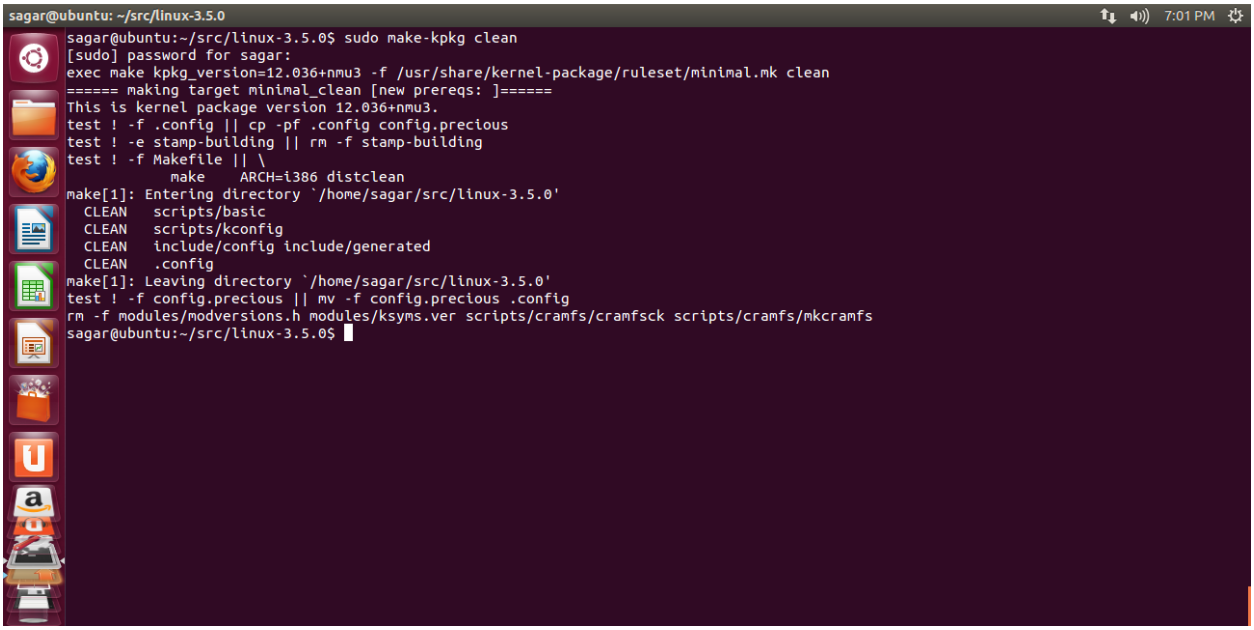


13.

The next step is to clean the temperory files generated if earlier some kernel compilation was done.

Linux command used:

sudo make-kpkg clean



14.

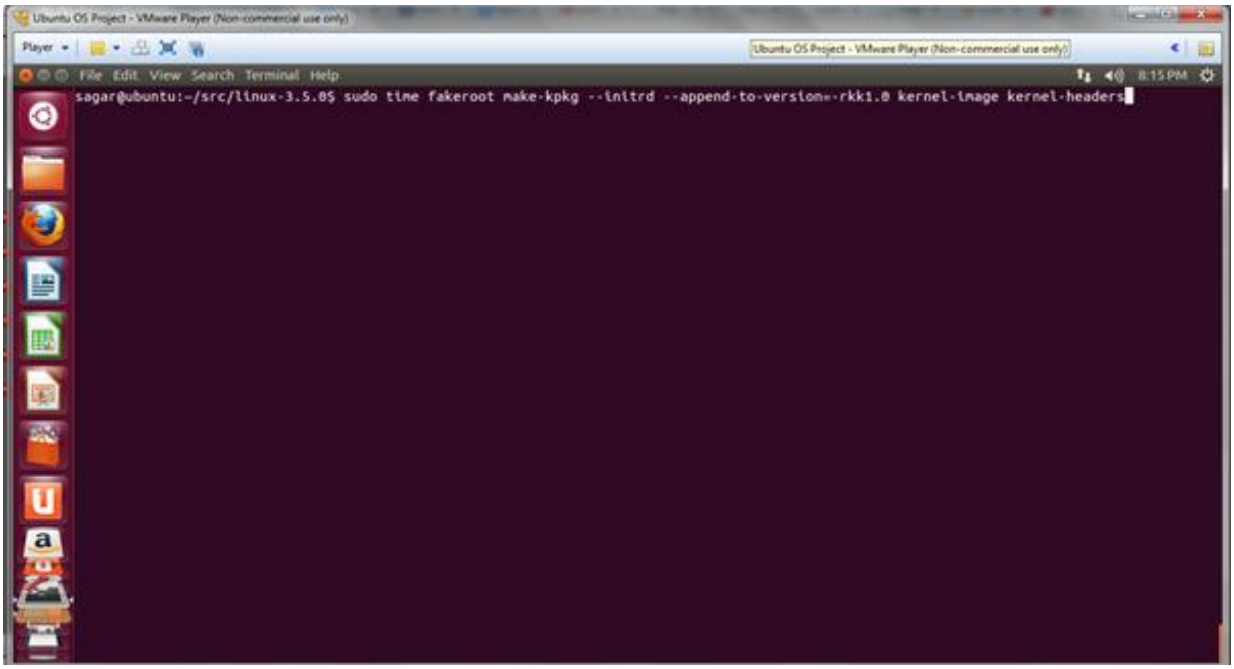
The next step is to compile the kernel. We use make command to compile the kernel. make command runs the Makefile in the src directory which has already configurations described in it.

Linux command used in our case is:

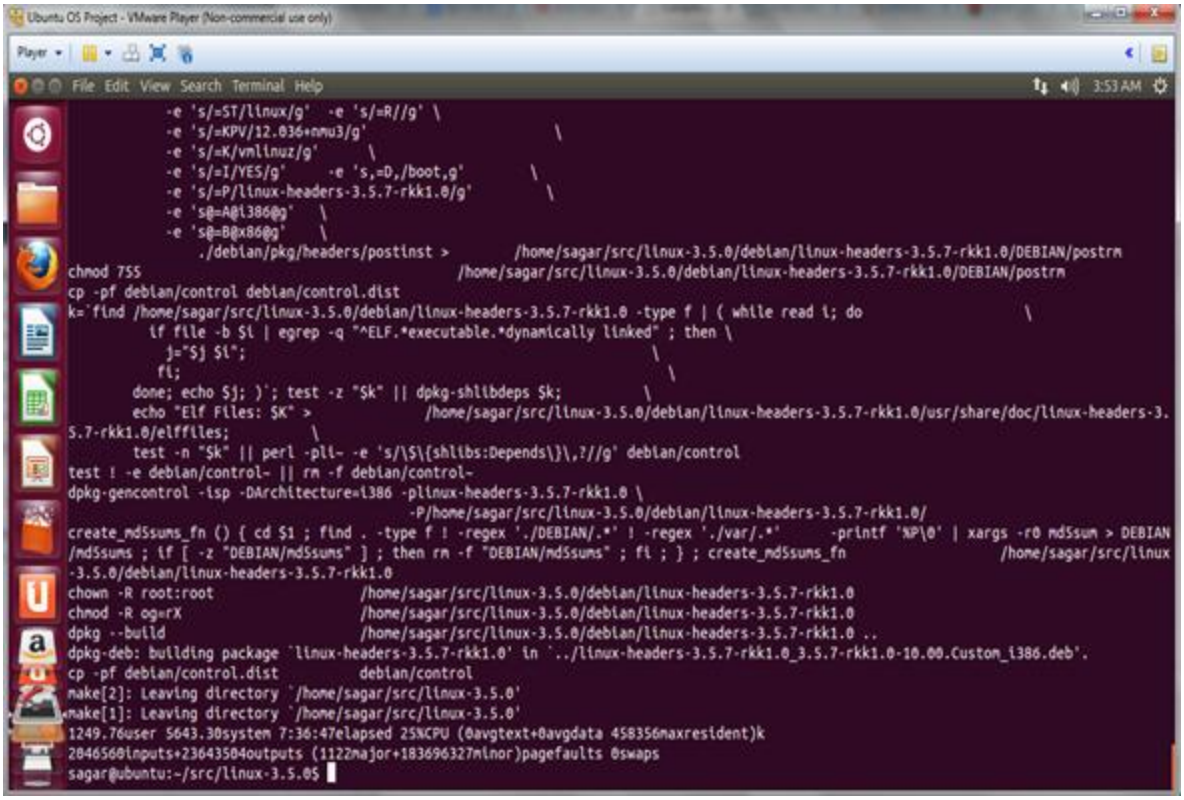
sudo time fakeroot make-kpkg --initrd --append-to-version=-rkk1.0 kernel-image kernel-headers

This command will generate the compiled image and header files appended version number with rkk1.0 our custom name to distinguish it from our previous kernel version.

This is the most time consuming phase in the compilation process of the Linux kernel. For us it took almost 10 – 11 hours to compile the entire kernel. Later when we increased the RAM to 4 GB , the compilation time consumption reduced to 6 hours and again we increased the RAM of virtual Machine to 6 GB. The compilation time reduced to 4 GB’s

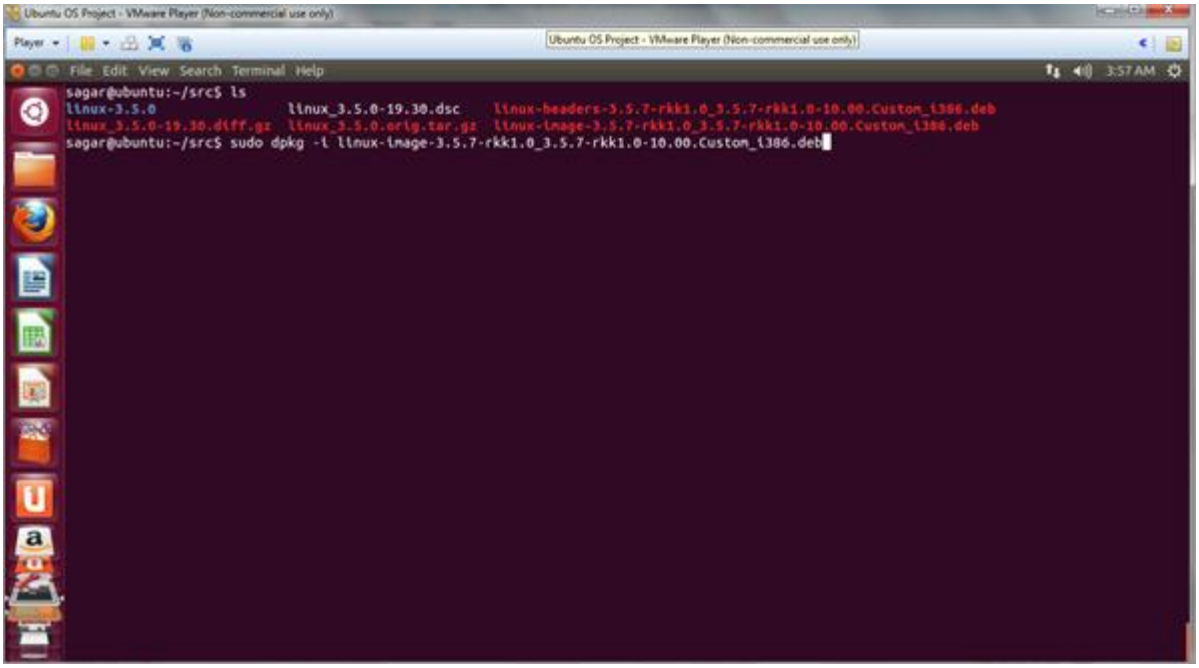


Output screen of this command



15.

If you see your src directory, you will see that the two compiled files got created , one is image file and another one is header file. The below screen shot mentions that.



16.

Now we have got the compiled files, now we need to install the kernel. We will install both the .deb files step by step

Linux command used:

```
cd ~/src
sudo dpkg -i linux-image-3.0.36-rkk1.0_3.0.36-rkk1.0-10.00.Custom_i386.deb
sudo dpkg -i linux-headers-3.0.36-rkk1.0_3.0.36-rkk1.0-10.00.Custom_i386.deb
```

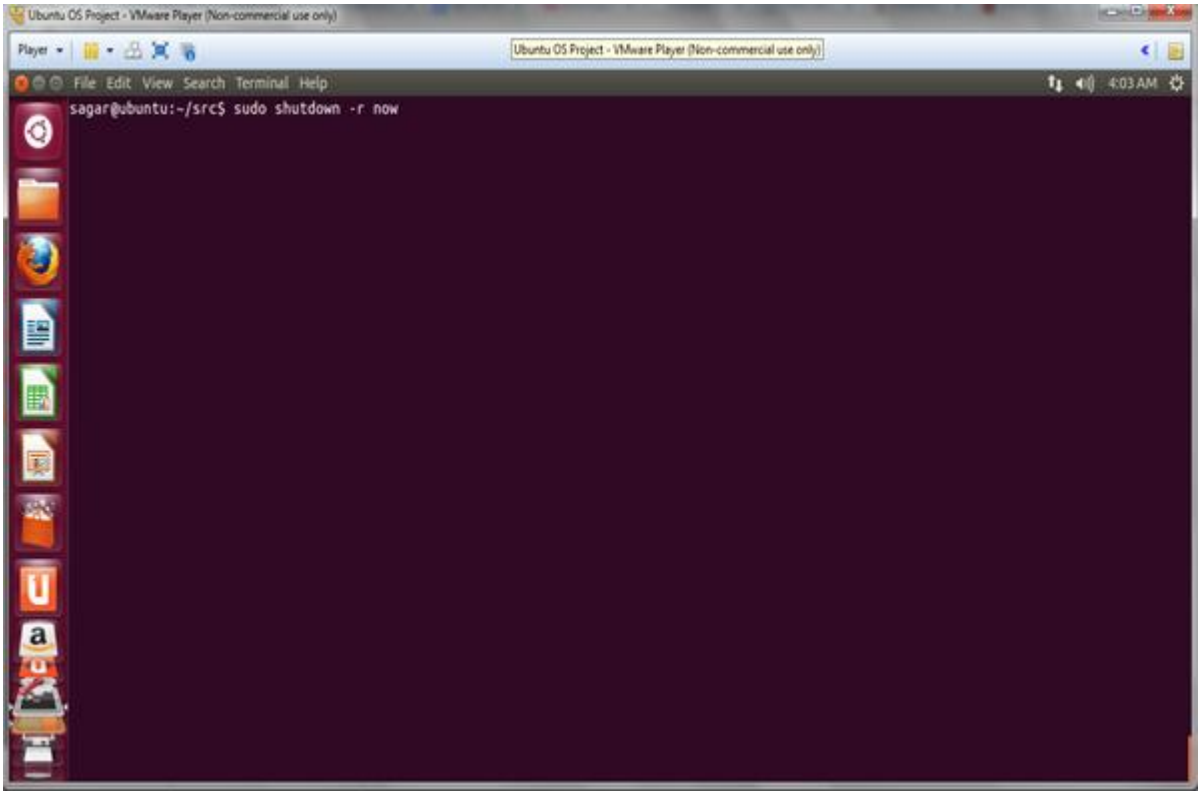
-i option tells to install the files set up in options.

17.

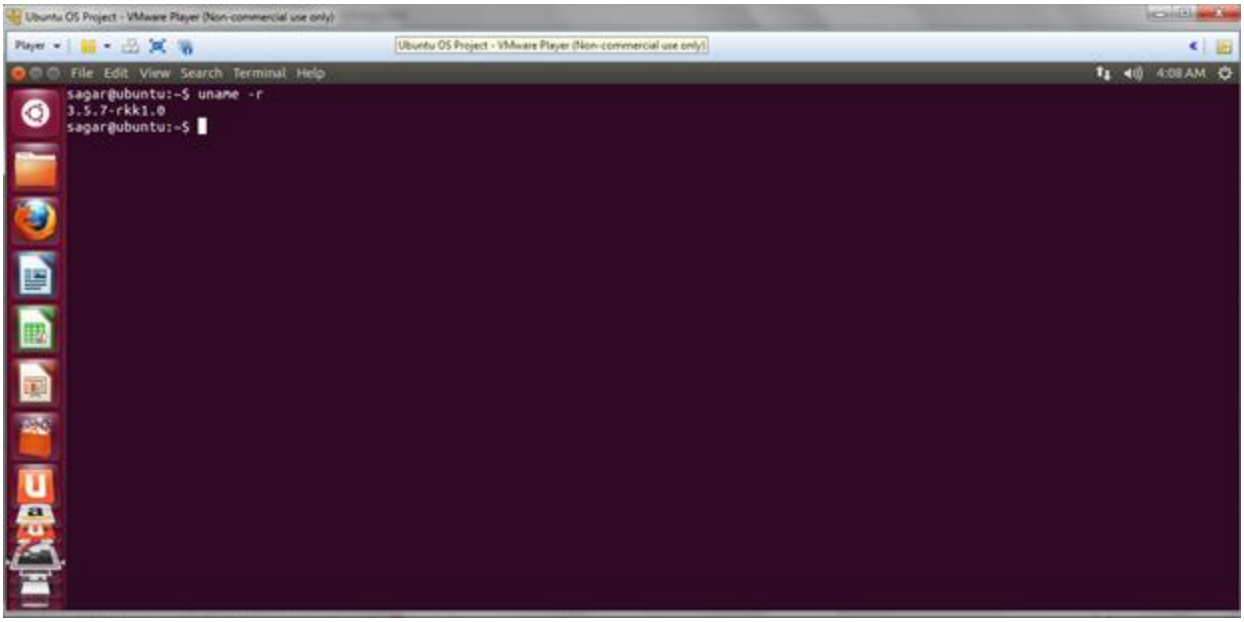
This is last step in Compilation and Installation process, which is to shutdown and restart the Ubuntu after the installation is complete.

Linux command used:

```
sudo shutdown -r now
```



Let's check or verify whether the new kernel has got installed. We will use the same uname –r command to see the version of our new kernel



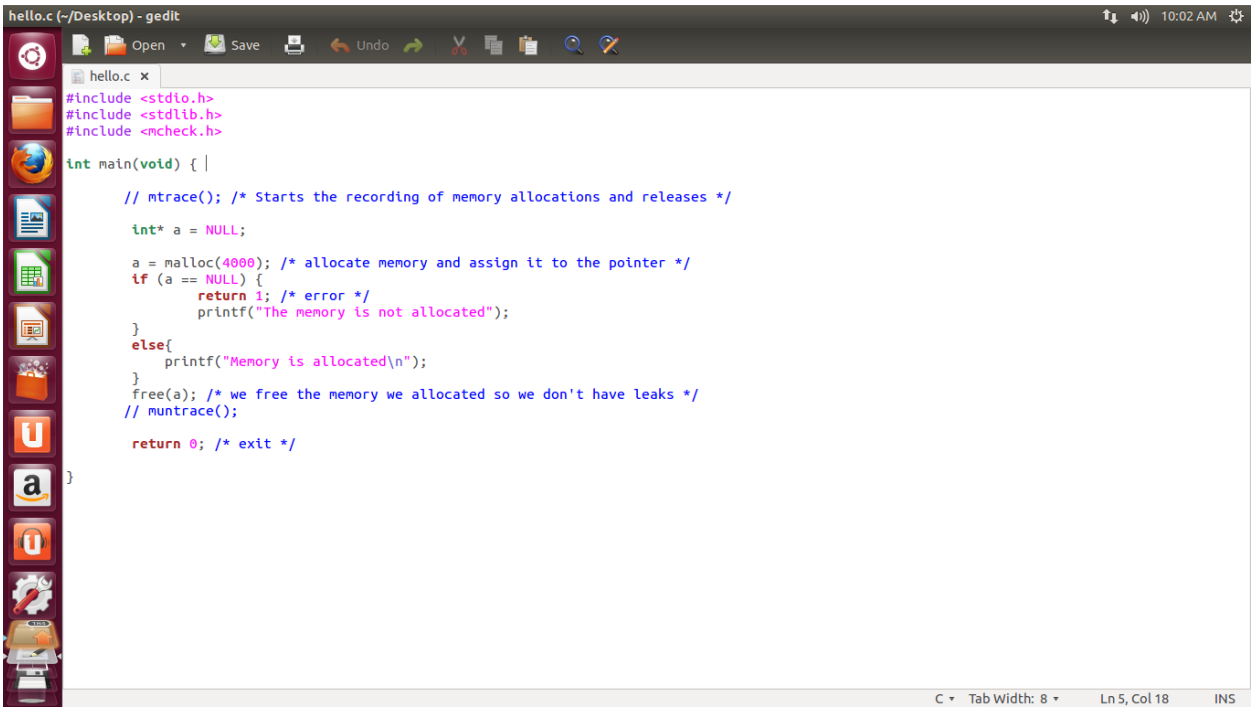
The new kernel has got installed in our system. The kernel version name is 3.5.7-rkk1.0

The Kernel compilation and installation process is complete.

Understanding the malloc() implementation in Linux operating system

malloc() is userspace dynamic memory allocation function for the processes. In linux kernel, it has its own version of malloc() called as kmalloc(). For this project we were only interested in knowing the working of malloc(), which is the userspace function.

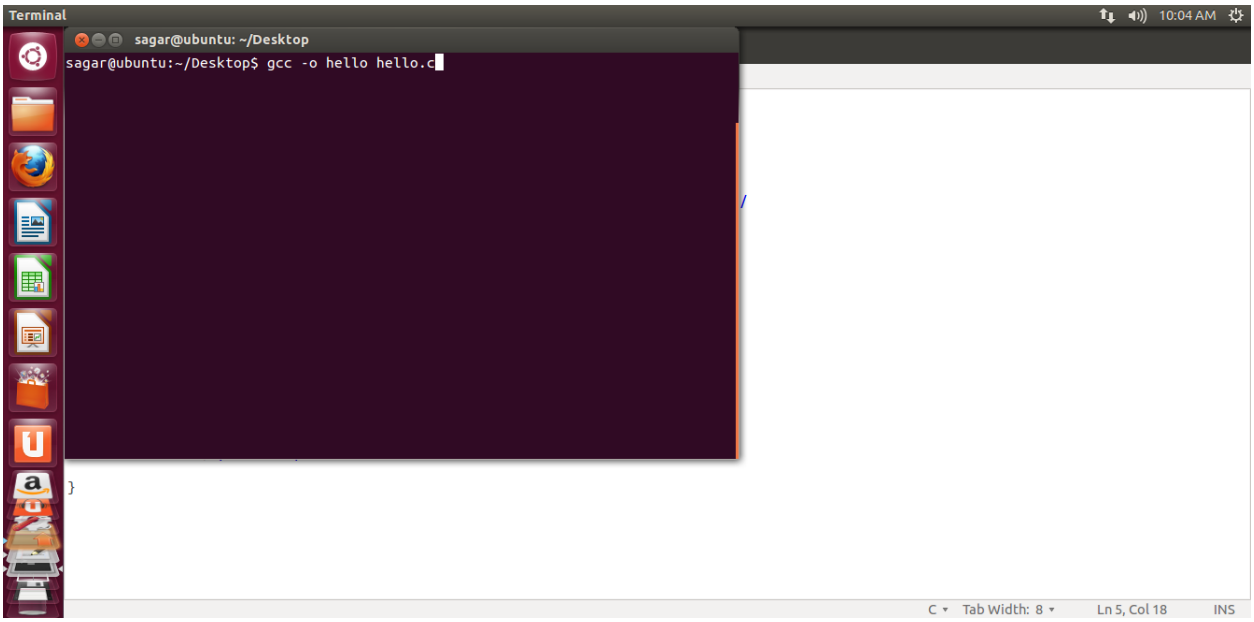
To understand the entire process, we created a small user application program hello.c in C language which uses malloc() function.



The above program wants to assign the memory of 4000 bytes using malloc() function. What ever returned from the malloc() function is a starting address of the memory allocated and stored in a pointer a.

We first need to compile this program. The command used to compile this program is

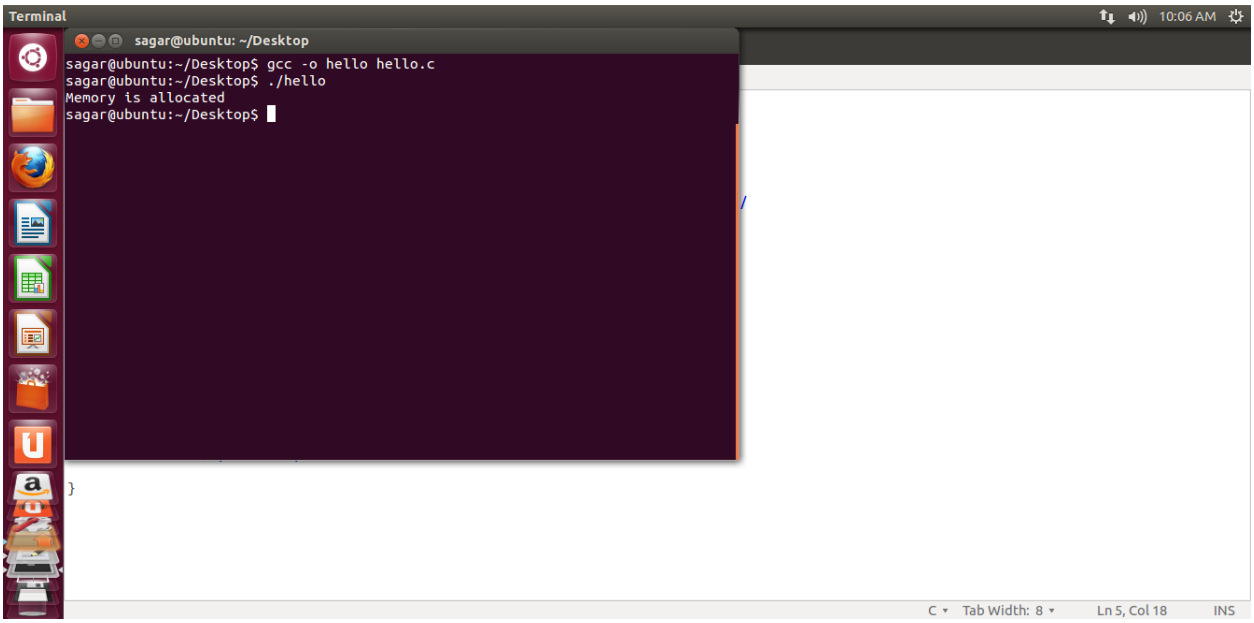
gcc –o hello hello.c



Now let's run this program

Commad used is :

./hello



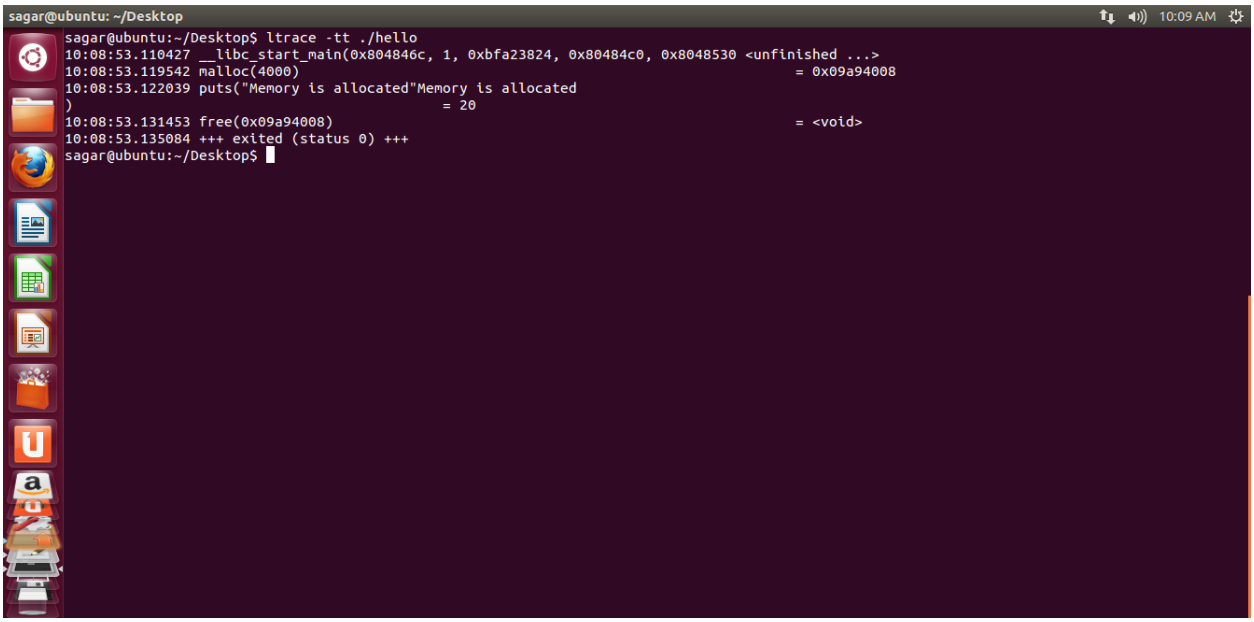
Based on the output the memory of 4000 bytes have been allocated.

We will now try to trace this program using either ltrace command or strace command to see which library functions or system calls are involved while running this hello.c application program.

ltrace command in linux traces all the library functions used by the file specified. When given an option of –S in ltrace command, it traces all the library functions and System calls used while running the hello.c

Linux command

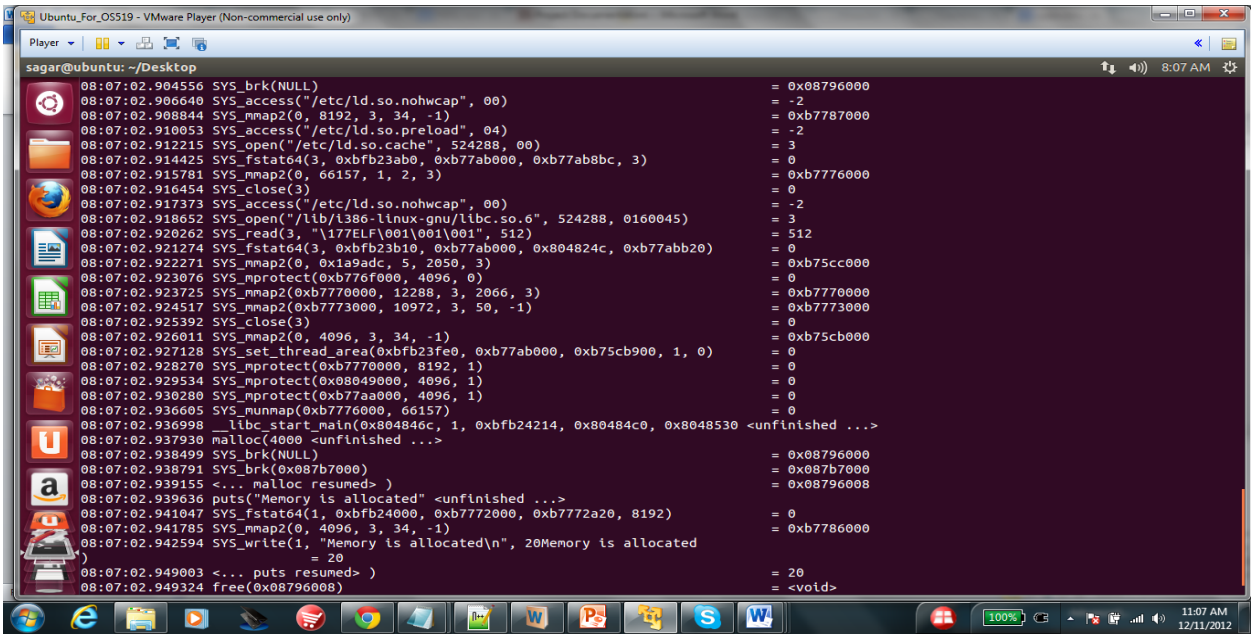
ltrace ./hello



Seeing the output of the above command, we can see that execution accesses the __libc_start_main() shared library function. Then it executes malloc() function. From here we got the clue that, malloc() is defined in glibc shared libraries .

Now we will try to see which system calls are being used while running the hello.c program

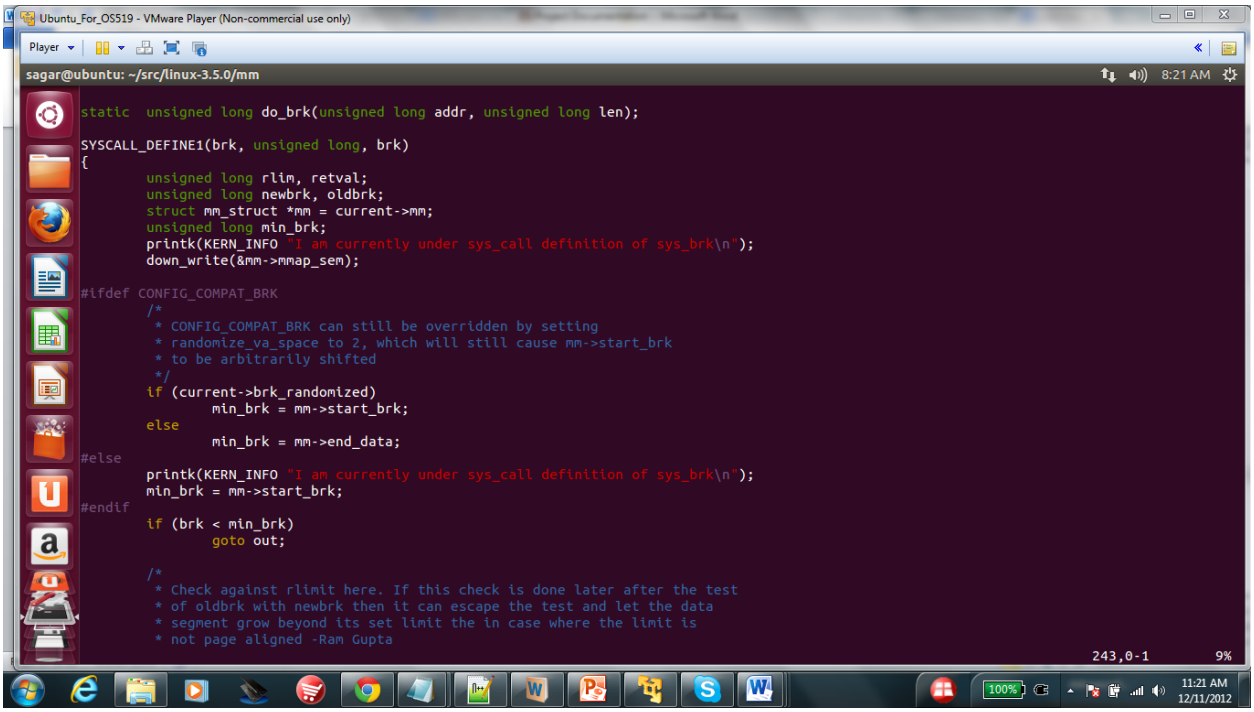
Command used: ltrace –S –t ./hello



The hello.c file uses the system calls as mentioned above in the screen. Now we will go in source to see what these system calls are and what is their purpose.

sys_brk : Location: mm/mmap.c
sys_brk() system call is gives the starting address of the new chunk or block of memory allocated to the process requested by the application from the user space.

Below is the screen shot of the source code



```
static  unsigned long do_brk(unsigned long addr, unsigned long len);

SYSCALL DEFINE1(brk, unsigned long, brk)
{
        unsigned long rlim, retval;
        unsigned long newbrk, oldbrk;
        struct mm_struct *mm = current->mm;
        unsigned long min_brk;
        printk(KERN INFO "I am currently under sys call definition of sys brk\n");
        down_write(&mm->mmap_sem);

#ifdef CONFIG_COMPAT_BRK
        /*
         * CONFIG_COMPAT_BRK can still be overridden by setting
         * randomize va space to 2, which will still cause mm->start brk
         * to be arbitrarily shifted
         */
        if (current->brk_randomized)
                min_brk = mm->start_brk;
        else
                min brk = mm->end data;
#else
        printk(KERN INFO "I am currently under sys call definition of sys brk\n");
        min_brk = mm->start_brk;
#endif
        if (brk < min brk)
                goto out;

        /*
         * Check against rlimit here. If this check is done later after the test
          * of oldbrk with newbrk then it can escape the test and let the data
         * segment grow beyond its set limit the in case where the limit is
         * not page aligned -Ram Gupta
         */
        rlim = rlimit(RLIMIT_DATA);
        if (rlim < RLIM_INFINITY && (brk - mm->start_brk) +
                        (mm->end_data - mm->start_data) > rlim)
                goto out;

        newbrk = PAGE ALIGN(brk);
        oldbrk = PAGE_ALIGN(mm->brk);
        if (oldbrk == newbrk)
                goto set_brk;

        /* Always allow shrinking brk. */
        if (brk <= mm->brk) {
                if (!do_munmap(mm, newbrk, oldbrk-newbrk))
                        goto set_brk;
                goto out;
        }

        /* Check against existing mmap mappings. */
        if (find_vma_intersection(mm, oldbrk, newbrk+PAGE_SIZE))
                goto out;

        /* Ok, looks good - let it rip. */
        if (do brk(oldbrk, newbrk-oldbrk) != oldbrk)
                goto out;
set_brk:
        mm->brk = brk;
out:
        retval = mm->brk;
        up write(&mm->mmap sem);
        printk(KERN_INFO "We are still in sys_brk system call definition under out section\n");
          printk(KERN_INFO "We are still in sys_brk system call definition under out section\n");
        return retval;
}
```

When the brk() is called, the system call checks to see if the amount of memory is decreased. If so, it immediately decreases the amount of heap space for that process with a call to ***do_munmap()*** and returns the new address pointer.

If the application wants to increase the amount of heap space allocated to it, the kernel performs three checks to make sure the allocation can succeed. The first check verifies that the specified limit of memory for this process will not be exceeded if more more memory is allocated***. setrlimit()*** function sets the limit of the size of the memory in Linux for the processes.

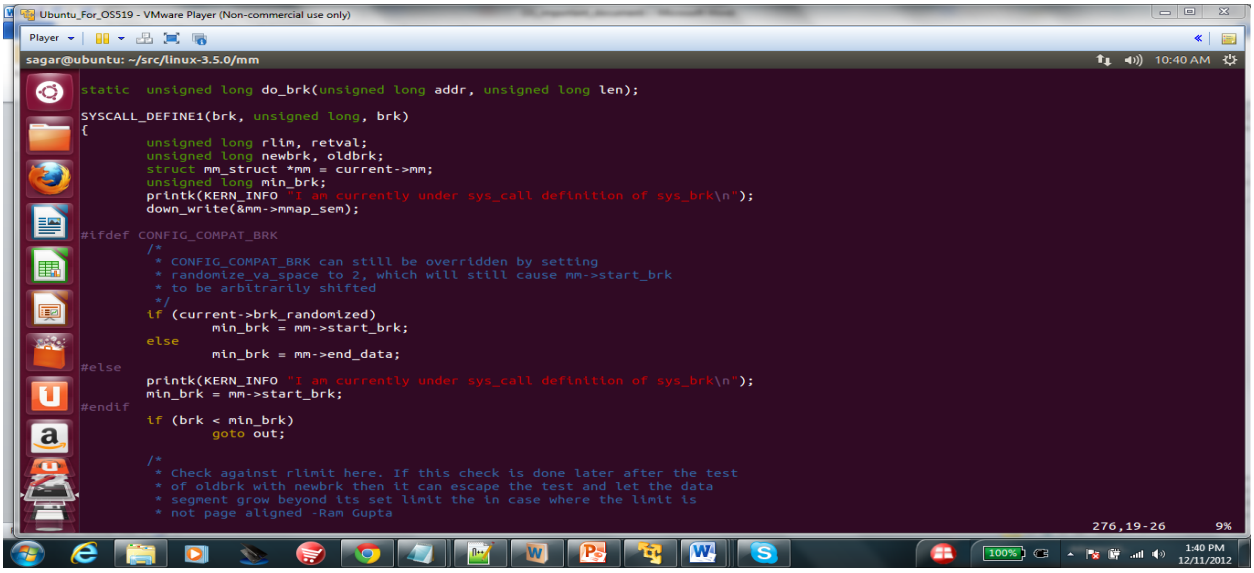
After verifying that a process is not requiring more memory than its limit allows, the kernel then verifies that increasing the memory will not interfere with any of the other parts of memory for that process. For Example, it should not interfere with stack or mmaped files or text area of the virtual address space.

Finally, as a last check, the kernel checks to see if there is enough memory to accommodate the new process. Once kernel verifies it calls the ***do_brk()*** function to increase the memory for the process.

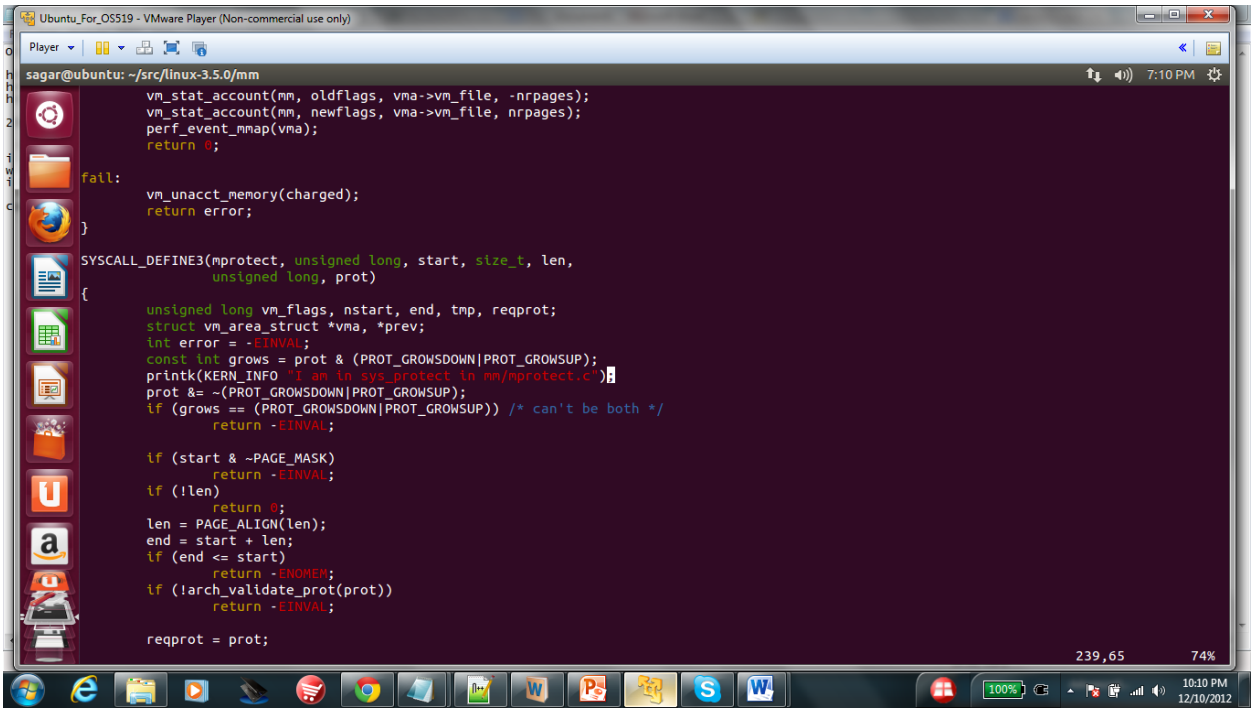
Editing sys_brk() system to add printk statement

To verify if sys_brk is accessed by the shared library functions, we added the printk statement in all the system calls we got from ltrace –S –tt ./hello command

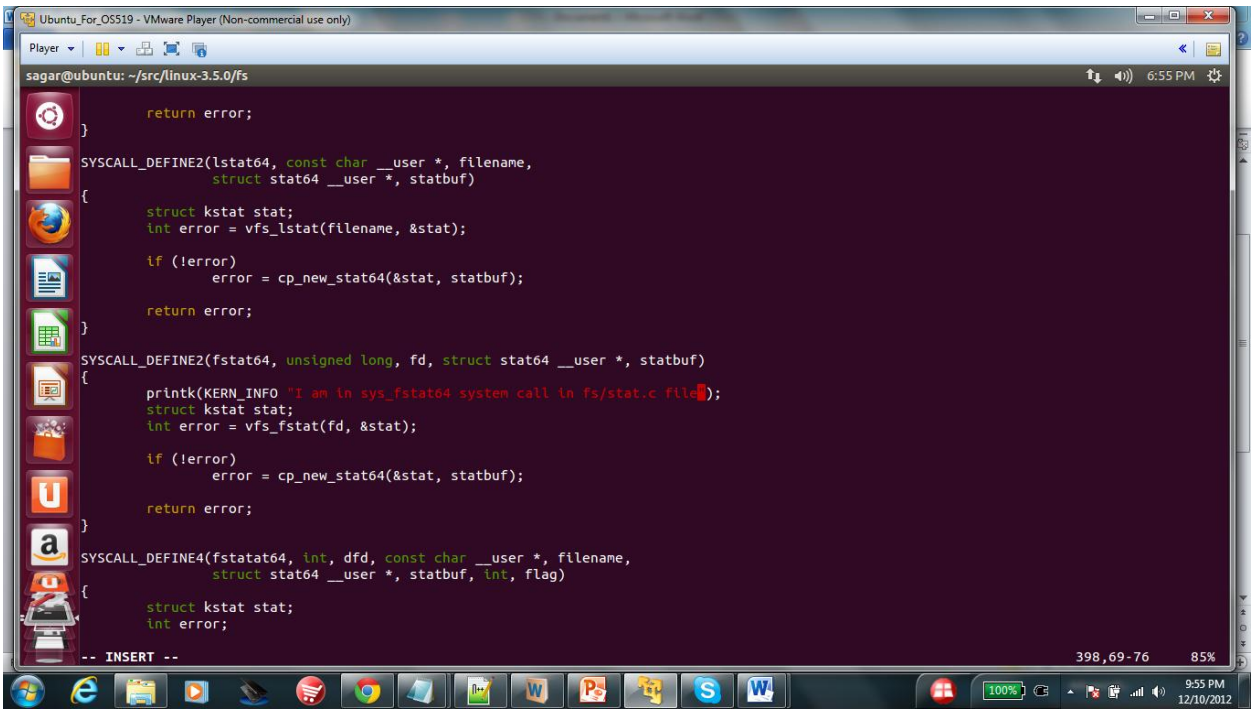
The screen shots are as follows. 1. sys_access in mm/mmap.c file



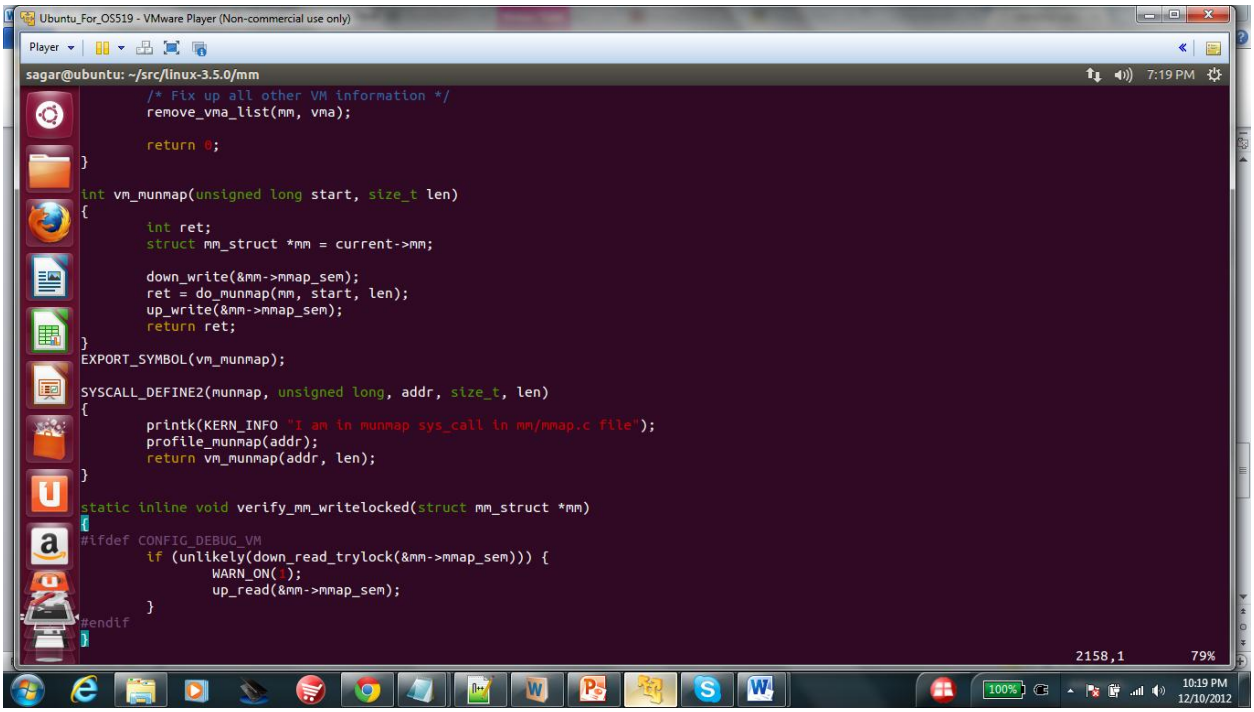
sys_mprotect at mm/mprotect.c



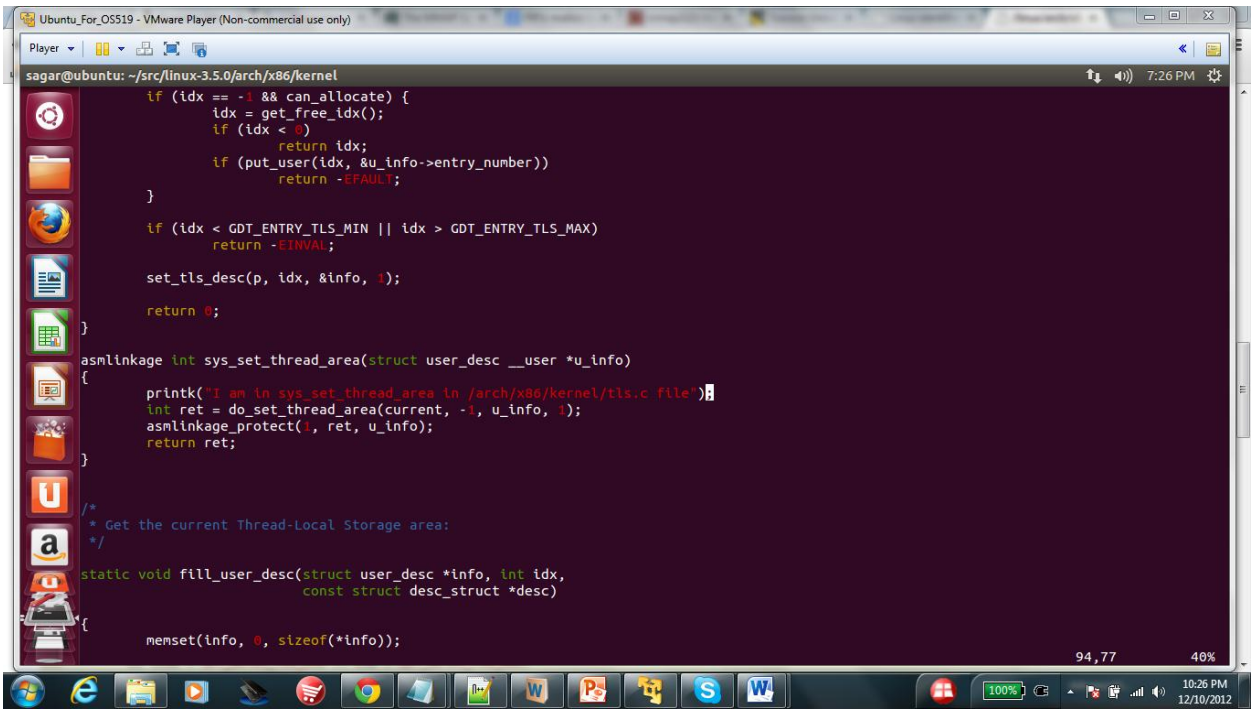
sys_fstat64 at location fs/stat.c



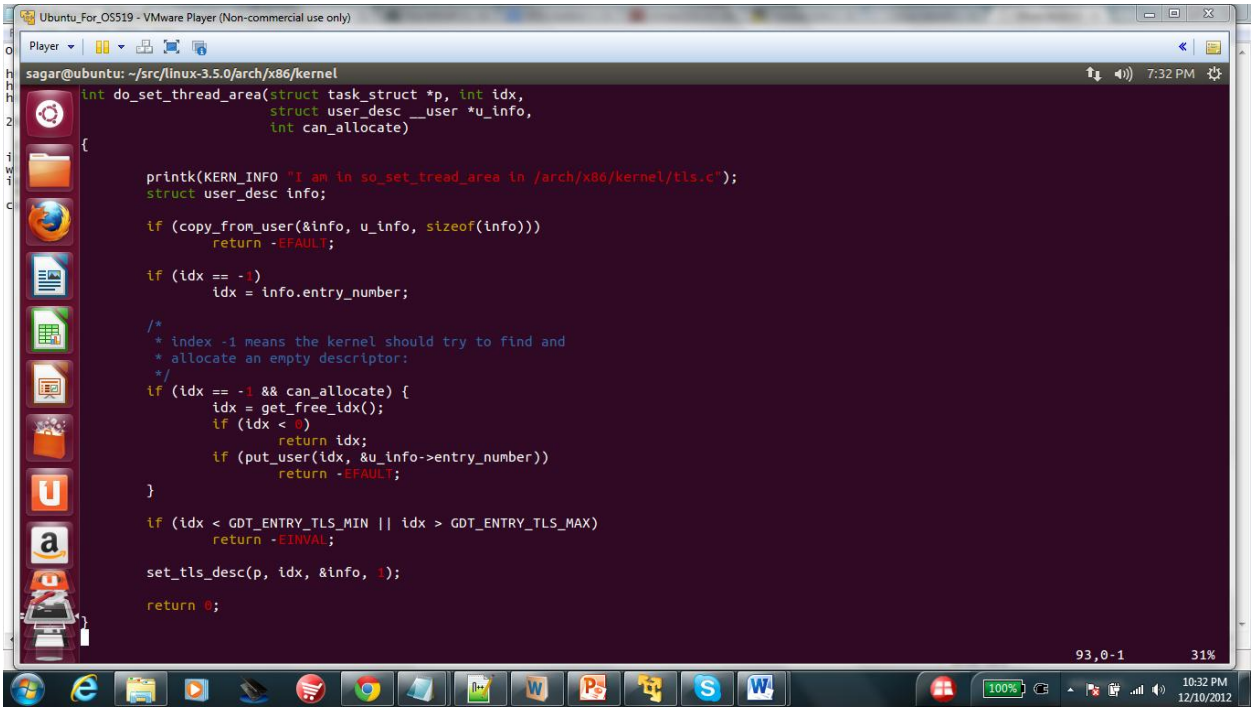
sys_munmap at mm/mmap.c



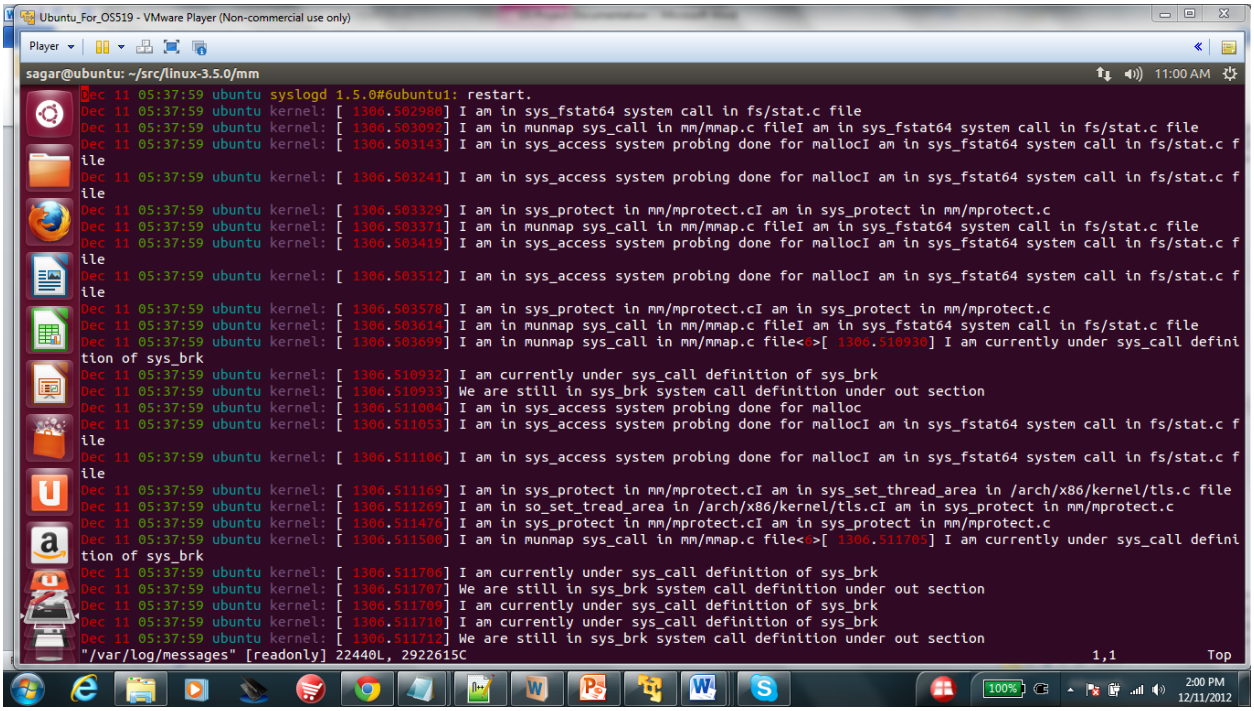
sys_set_thread_area at location /arch/x86/kernel

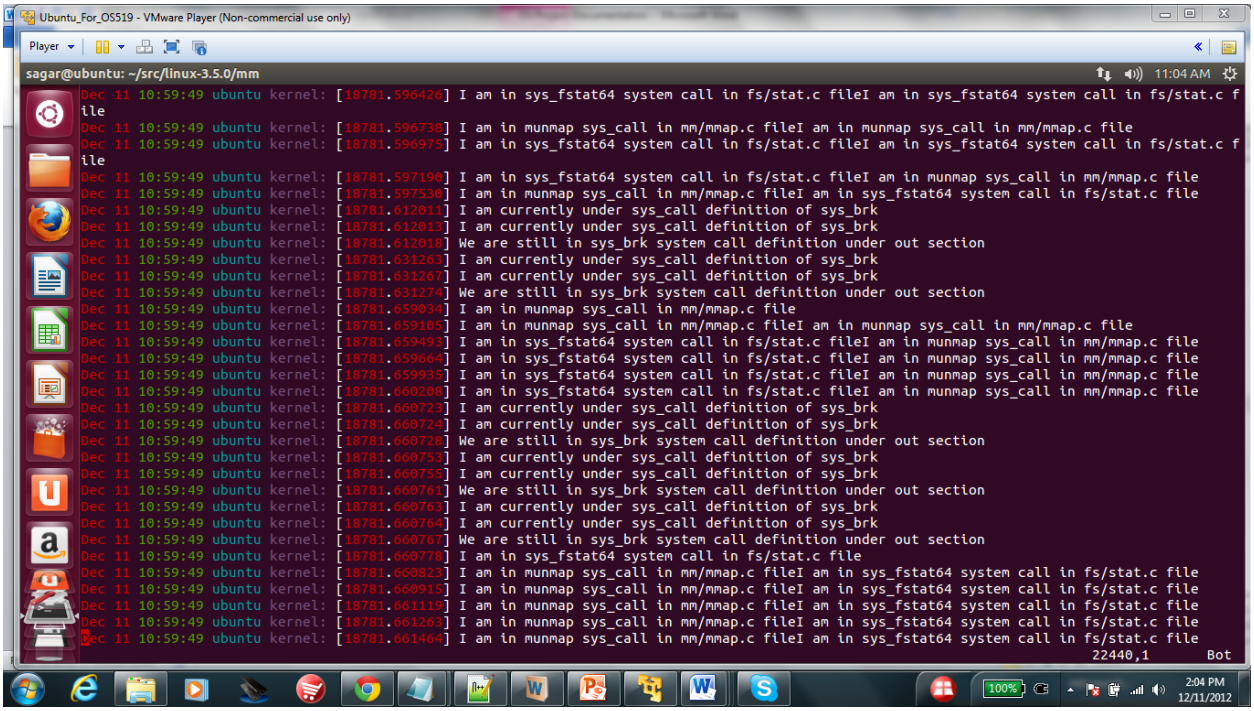


Since the above system call use function do_set_thread_area, the below screen shot includes that function too.



After inserting prink statements as shown above, we compiled our kernel again and checked /var/messages/log as shown below.





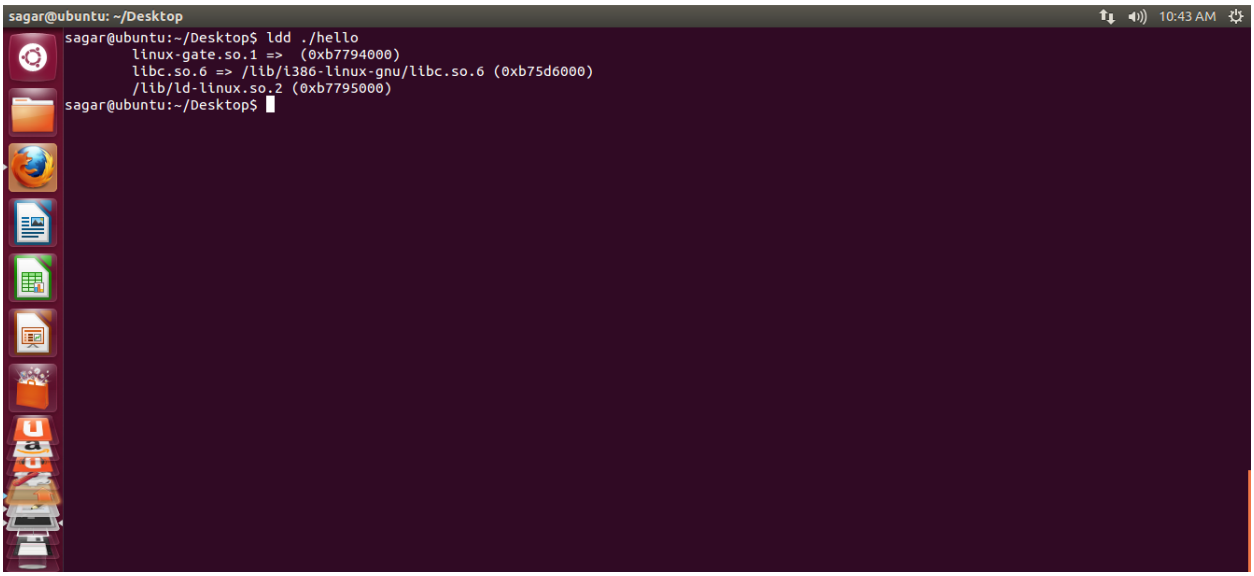
Analyzing the above output , we could see printk statements which we added from sys_brk system call, sys_access ,sys_fstat64,sys_munmap, sys_protect, sys_set_thread_area .

Despite of not running the hello.c program we were still getting so many printk statements, we concluded that not only malloc by many other processes need memory dynamically there these system calls are accessed again and again and hence many printk statement.

To filter out which system calls are accessed by malloc(), we decided to download the glibc source code of the same version our kernel is using. We planned to install the glibc library and put a print statement in malloc () function in malloc.c file

Below are the screen shots of downloading and compilation of glibc but we failed to compile it because it needed some patch files, which we could not locate.

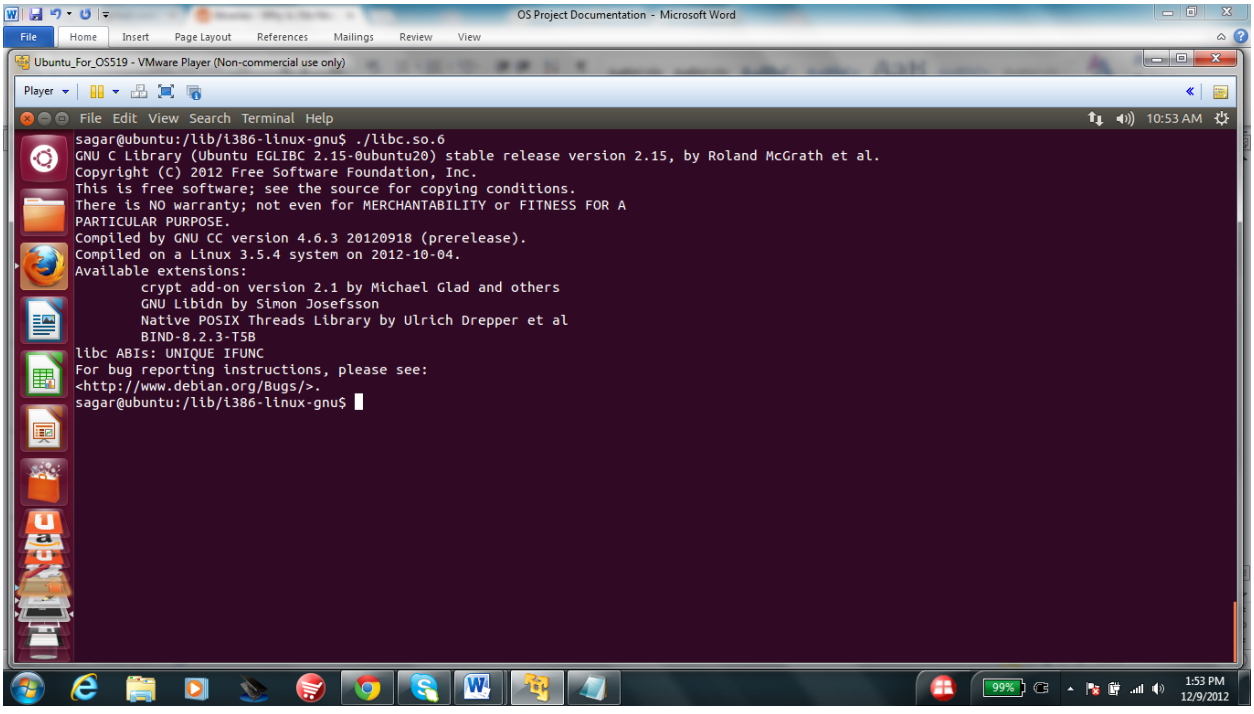
To see which version of glibc file our ./hello program is using we did the following



From the second line of output we can see that libc.so.6 from glibc shared libraries is loaded.

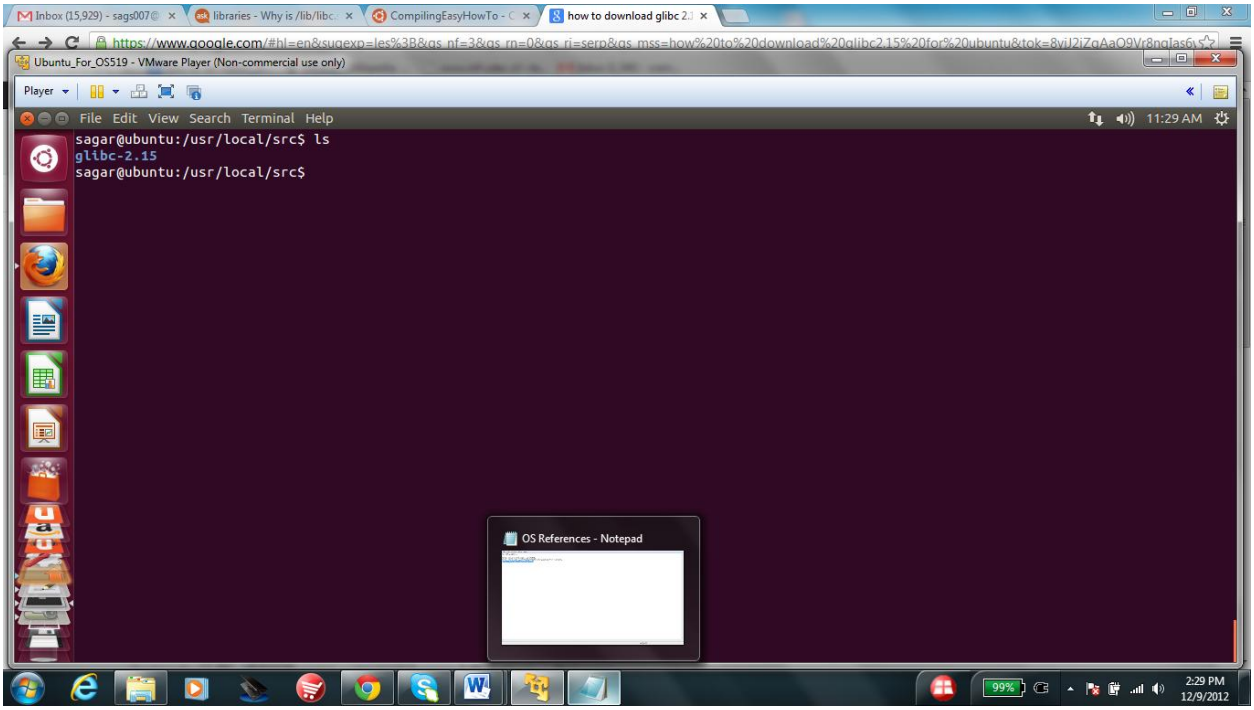
Now to see which version of glibc kernel is using , we need to run libc.so.6 file using the following command

./libc.so.6 at /lib/i386-linux-gnu/ directory

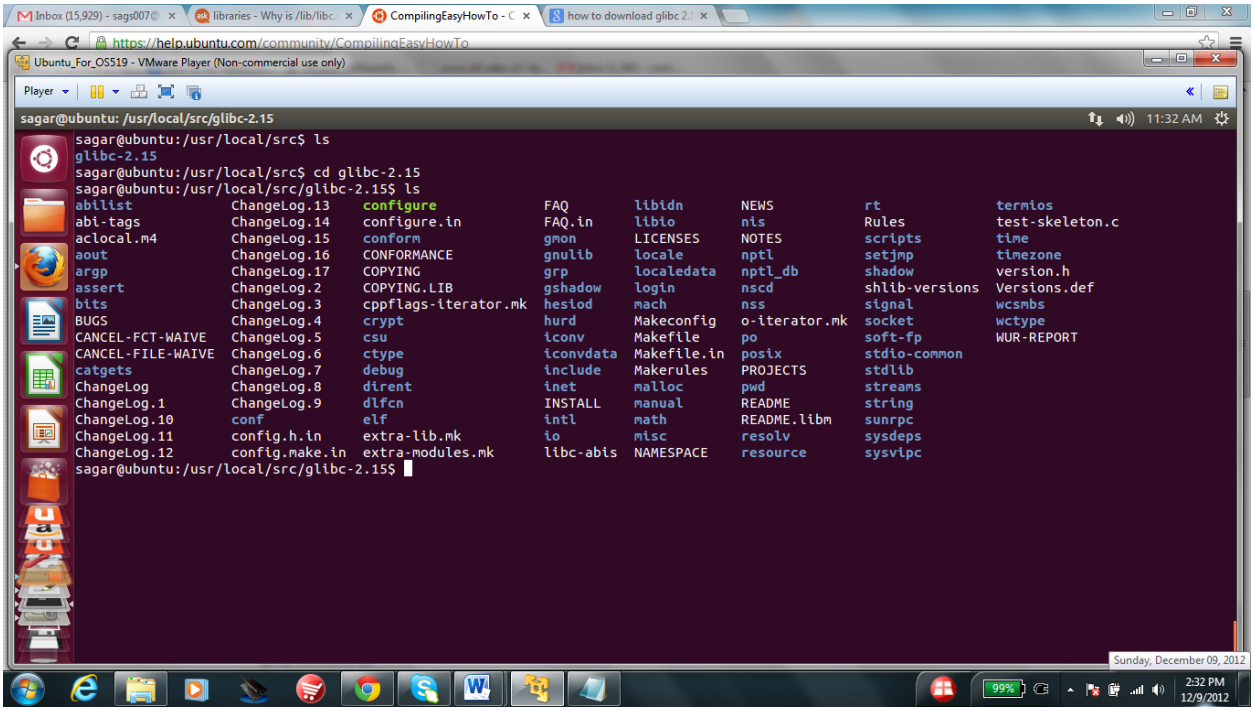


The glibc version which is current used by the kernel is 2.15

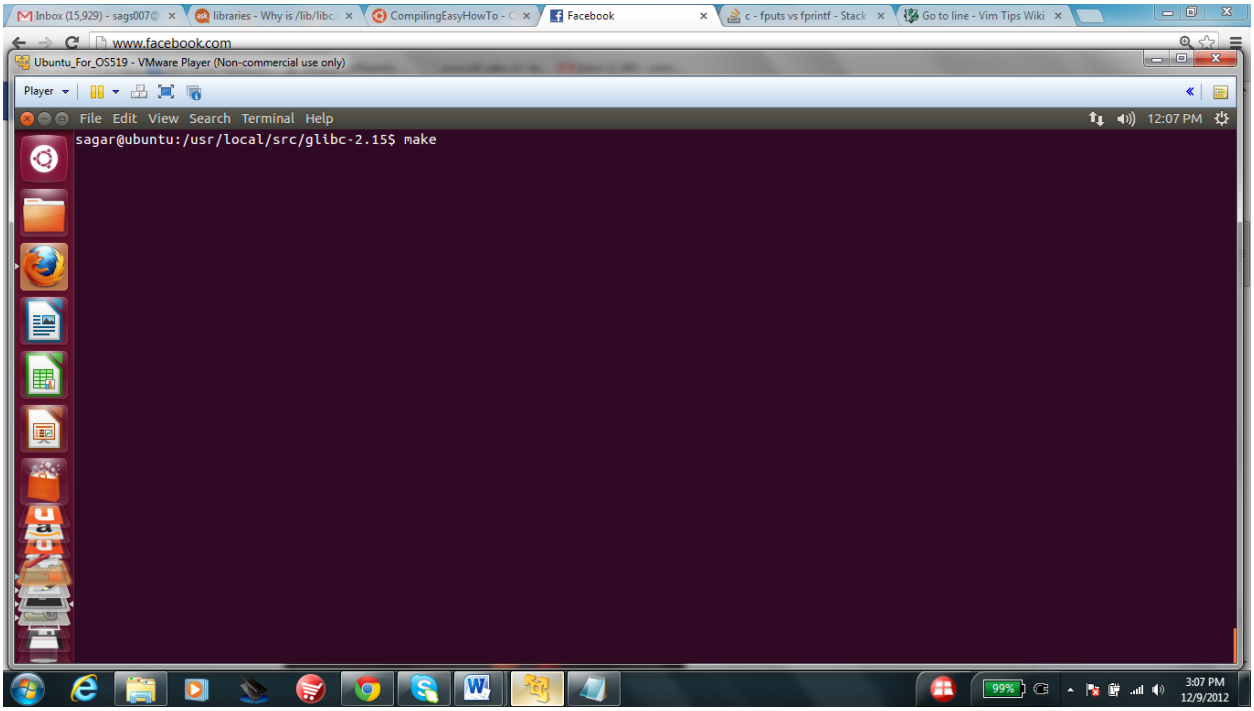
Let’s download, the glibc version 2.15 source code from the following source http://ftp.gnu.org/gnu/glibc/ and store it at /usr/local/src in our linux file system.

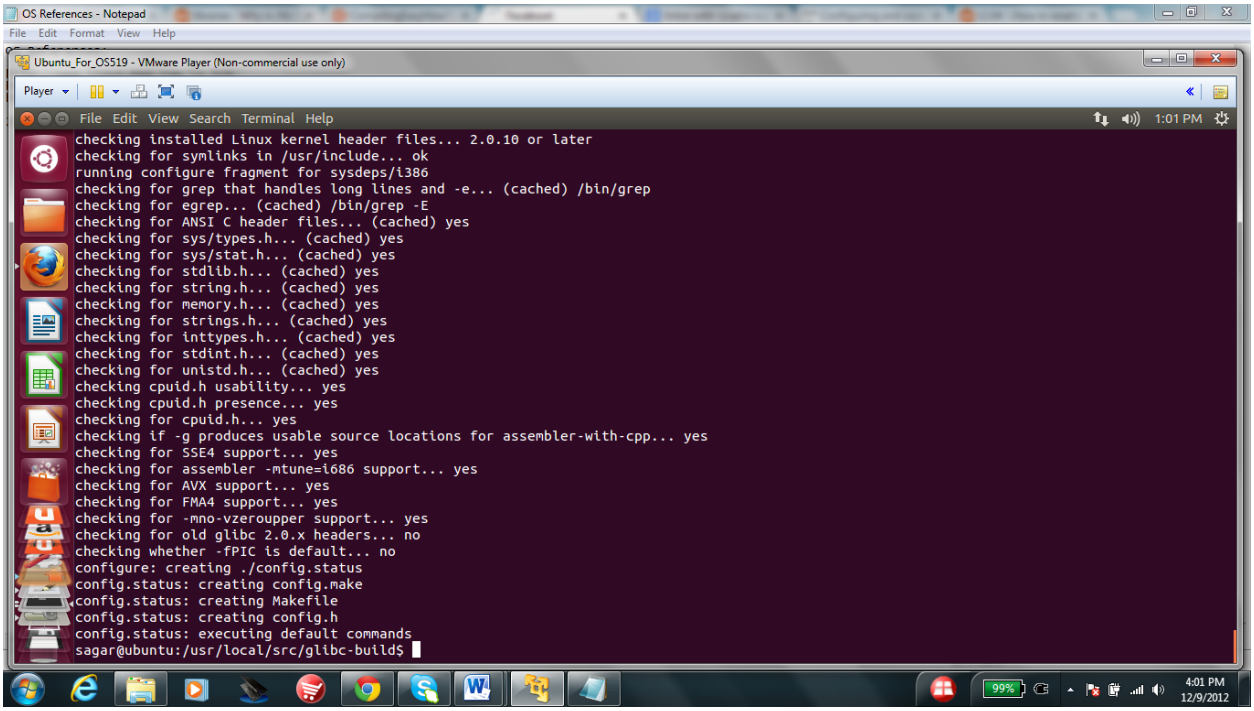


Below screen shot shows the files in glibc library

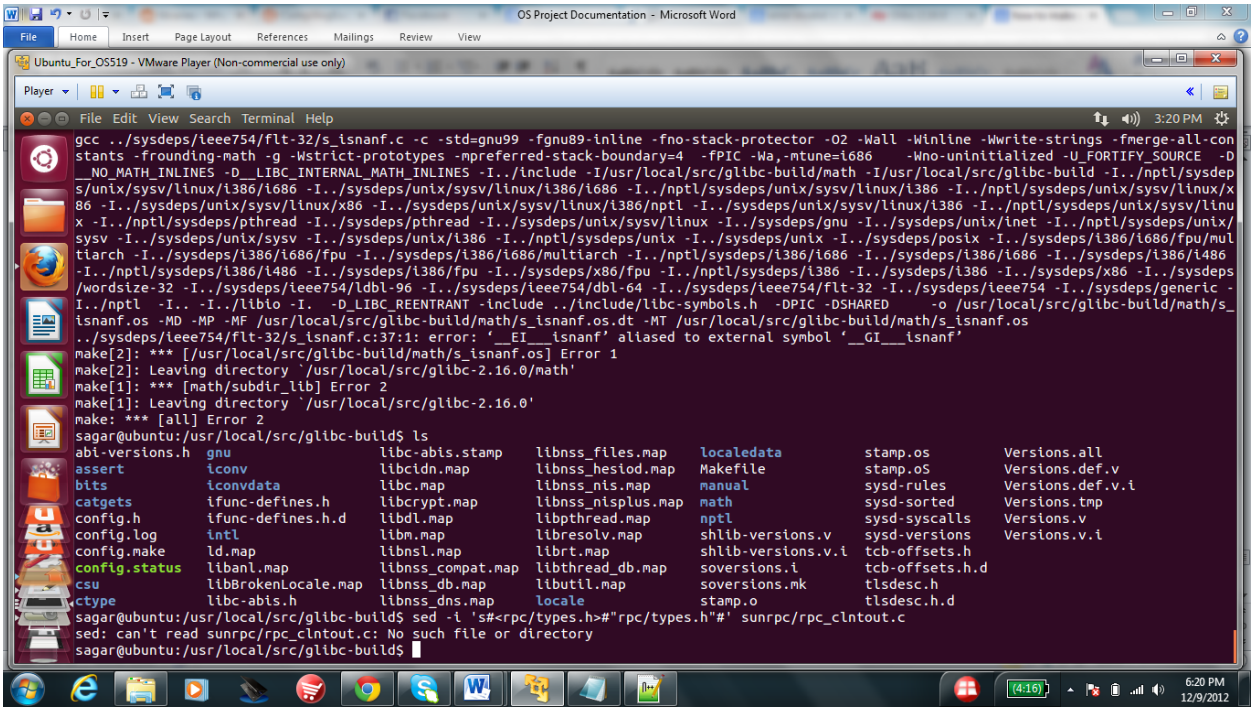


Now we compiled the source code





But we finally got the errors while compiling



Finally we were left to analyze the malloc.c source code in malloc directory in glibc library.

After studying carefully we analyzed that, malloc function allocates the dynamic memory from heap and it only need help from kernel when, processes current memory is over and it needs

more memory. When process needs more memory . malloc() function calls either sys_brk or mmap2 system calls to increase the size of the heap.

The source code for sys_brk() and mmap() is at Appendix at the end of the document.

Conclusion:

Based on our research, we could conclude that malloc() function allocates the dynamic memory from heap and it only needs help from kernel when, processes current memory is over and it needs more memory. When process needs more memory . malloc() function calls either sys_brk or mmap2 system calls to increase or decrease the size of the heap.

Things Learned

1. Our team learned the process of compiling the kernel and during the process we faced many challenges. For Example, Compilation time for getting over 10 hours. We increased the RAM size to 6 GB instead of 2 GB earlier. The compilation time reduced to 3-4 hours. We compiled and installed the Kernel 3 – 4 times and every time we learned something new.
2. Use of Virtual Machine was always helpful. First of all it acted as a backup. We use to save the state of virtual machine every time we start working on the project. Because there were always chances of getting wrong while compiling and installing kernel.
3. We learnt the file structure of the Linux operating system, which gave us confidence to understand Linux related things
4. We learnt how to modify already installed kernel files. For Example we edited various system calls by putting printk statements , to analyse the flow of the program.
5. We learned how malloc() function flow work.

Sources:

http://www.linux-mag.com/id/806/
http://www.linux-mag.com/id/827/
http://lxr.free-electrons.com/
http://www.cs.fsu.edu/~baker/devices/lxr/http/source/linux
http://www.ibm.com/developerworks/linux/library/l-linuxboot/http://en.wikipedia.org/wiki/Linux_startup_process
http://en.wikipedia.org/wiki/Dpkg
http://en.wikipedia.org/wiki/Advanced_Packaging_Tool
http://www.gratisoft.us/sudo/intro.html
http://en.wikipedia.org/wiki/Make_%28software%29
http://en.wikipedia.org/wiki/Topological_sorting
http://www.wlug.org.nz/MakefileHowto
http://linuxdevcenter.com/pub/a/linux/2002/01/31/make_intro.html
http://www.gnu.org/software/make/manual/make.html
http://www.dedoimedo.com/computers/grub.html

Appendix

```
// malloc() This code is glibc/malloc/malloc.c file This part only shows malloc()
//function otherwise this file contains 6000 lines of code

static void*
_int_malloc(mstate av, size_t bytes)
{
  INTERNAL_SIZE_T nb;               /* normalized request size */
  unsigned int    idx;              /* associated bin index */
  mbinptr         bin;              /* associated bin */

  mchunkptr       victim;           /* inspected/selected chunk */
  INTERNAL_SIZE_T size;             /* its size */
  int             victim_index;     /* its bin index */

  mchunkptr       remainder;        /* remainder from a split */
  unsigned long   remainder_size;   /* its size */

  unsigned int    block;            /* bit map traverser */
  unsigned int    bit;              /* bit map traverser */
  unsigned int    map;              /* current word of binmap */

  mchunkptr       fwd;              /* misc temp for linking */
  mchunkptr       bck;              /* misc temp for linking */

  const char *errstr = NULL;

  /*
    Convert request size to internal form by adding SIZE_SZ bytes
    overhead plus possibly more to obtain necessary alignment and/or
    to obtain a size of at least MINSIZE, the smallest allocatable
    size. Also, checked_request2size traps (returning 0) request sizes
    that are so large that they wrap around zero when padded and
    aligned.
  */

  checked_request2size(bytes, nb);

  /*
    If the size qualifies as a fastbin, first check corresponding bin.
    This code is safe to execute even if av is not yet initialized, so we
    can try it without checking, which saves some time on this fast path.
  */

  if ((unsigned long)(nb) <= (unsigned long)(get_max_fast ())) {
    idx = fastbin_index(nb);
    mfastbinptr* fb = &fastbin (av, idx);
    mchunkptr pp = *fb;
    do
      {
      victim = pp;
      if (victim == NULL)
        break;
      }
    while ((pp = catomic_compare_and_exchange_val_acq (fb, victim->fd, victim))
          != victim);
    if (victim != 0) {
      if (__builtin_expect (fastbin_index (chunksize (victim)) != idx, 0))
      {
        errstr = "malloc(): memory corruption (fast)";
```

```
      errout:
        malloc_printerr (check_action, errstr, chunk2mem (victim));
        return NULL;
      }
     check_remalloced_chunk(av, victim, nb);
     void *p = chunk2mem(victim);
     if (__builtin_expect (perturb_byte, 0))
      alloc_perturb (p, bytes);
     return p;
   }
 }

 /*
   If a small request, check regular bin.  Since these "smallbins"
   hold one size each, no searching within bins is necessary.
   (For a large request, we need to wait until unsorted chunks are
   processed to find best fit. But for small ones, fits are exact
   anyway, so we can check now, which is faster.)
 */

 if (in_smallbin_range(nb)) {
   idx = smallbin_index(nb);
   bin = bin_at(av,idx);

   if ( (victim = last(bin)) != bin) {
     if (victim == 0) /* initialization check */
      malloc_consolidate(av);
     else {
      bck = victim->bk;
      if (__builtin_expect (bck->fd != victim, 0))
        {
          errstr = "malloc(): smallbin double linked list corrupted";
          goto errout;
        }
      set_inuse_bit_at_offset(victim, nb);
      bin->bk = bck;
      bck->fd = bin;

      if (av != &main_arena)
        victim->size |= NON_MAIN_ARENA;
      check_malloced_chunk(av, victim, nb);
      void *p = chunk2mem(victim);
      if (__builtin_expect (perturb_byte, 0))
        alloc_perturb (p, bytes);
      return p;
     }
   }
 }

 /*
    If this is a large request, consolidate fastbins before continuing.
    While it might look excessive to kill all fastbins before
    even seeing if there is space available, this avoids
    fragmentation problems normally associated with fastbins.
    Also, in practice, programs tend to have runs of either small or
    large requests, but less often mixtures, so consolidation is not
    invoked all that often in most programs. And the programs that
    it is called frequently in otherwise tend to fragment.
 */

 else {
   idx = largebin_index(nb);
   if (have_fastchunks(av))
```

```
    malloc_consolidate(av);
}

/*
  Process recently freed or remaindered chunks, taking one only if
  it is exact fit, or, if this a small request, the chunk is remainder from
  the most recent non-exact fit.  Place other traversed chunks in
  bins.  Note that this step is the only place in any routine where
  chunks are placed in bins.

  The outer loop here is needed because we might not realize until
  near the end of malloc that we should have consolidated, so must
  do so and retry. This happens at most once, and only when we would
  otherwise need to expand memory to service a "small" request.
*/

for(;;) {

  int iters = 0;
  while ( (victim = unsorted_chunks(av)->bk) != unsorted_chunks(av)) {
    bck = victim->bk;
    if (__builtin_expect (victim->size <= 2 * SIZE_SZ, 0)
       || __builtin_expect (victim->size > av->system_mem, 0))
     malloc_printerr (check_action, "malloc(): memory corruption",
                      chunk2mem (victim));
    size = chunksize(victim);

    /*
      If a small request, try to use last remainder if it is the
      only chunk in unsorted bin.  This helps promote locality for
      runs of consecutive small requests. This is the only
      exception to best-fit, and applies only when there is
      no exact fit for a small chunk.
    */

    if (in_smallbin_range(nb) &&
       bck == unsorted_chunks(av) &&
       victim == av->last_remainder &&
       (unsigned long)(size) > (unsigned long)(nb + MINSIZE)) {

     /* split and reattach remainder */
     remainder_size = size - nb;
     remainder = chunk_at_offset(victim, nb);
     unsorted_chunks(av)->bk = unsorted_chunks(av)->fd = remainder;
     av->last_remainder = remainder;
     remainder->bk = remainder->fd = unsorted_chunks(av);
     if (!in_smallbin_range(remainder_size))
       {
         remainder->fd_nextsize = NULL;
         remainder->bk_nextsize = NULL;
       }

     set_head(victim, nb | PREV_INUSE |
              (av != &main_arena ? NON_MAIN_ARENA : 0));
     set_head(remainder, remainder_size | PREV_INUSE);
     set_foot(remainder, remainder_size);

     check_malloced_chunk(av, victim, nb);
     void *p = chunk2mem(victim);
     if (__builtin_expect (perturb_byte, 0))
       alloc_perturb (p, bytes);
     return p;
    }
```

```
/* remove from unsorted list */
unsorted_chunks(av)->bk = bck;
bck->fd = unsorted_chunks(av);

/* Take now instead of binning if exact fit */

if (size == nb) {
 set_inuse_bit_at_offset(victim, size);
 if (av != &main_arena)
   victim->size |= NON_MAIN_ARENA;
 check_malloced_chunk(av, victim, nb);
 void *p = chunk2mem(victim);
 if (__builtin_expect (perturb_byte, 0))
   alloc_perturb (p, bytes);
 return p;
}

/* place chunk in bin */

if (in_smallbin_range(size)) {
 victim_index = smallbin_index(size);
 bck = bin_at(av, victim_index);
 fwd = bck->fd;
}
else {
 victim_index = largebin_index(size);
 bck = bin_at(av, victim_index);
 fwd = bck->fd;

 /* maintain large bins in sorted order */
 if (fwd != bck) {
   /* Or with inuse bit to speed comparisons */
   size |= PREV_INUSE;
   /* if smaller than smallest, bypass loop below */
   assert((bck->bk->size & NON_MAIN_ARENA) == 0);
   if ((unsigned long)(size) < (unsigned long)(bck->bk->size)) {
     fwd = bck;
     bck = bck->bk;

     victim->fd_nextsize = fwd->fd;
     victim->bk_nextsize = fwd->fd->bk_nextsize;
     fwd->fd->bk_nextsize = victim->bk_nextsize->fd_nextsize = victim;
   }
   else {
     assert((fwd->size & NON_MAIN_ARENA) == 0);
     while ((unsigned long) size < fwd->size)
       {
        fwd = fwd->fd_nextsize;
        assert((fwd->size & NON_MAIN_ARENA) == 0);
       }

     if ((unsigned long) size == (unsigned long) fwd->size)
       /* Always insert in the second position.  */
       fwd = fwd->fd;
     else
       {
        victim->fd_nextsize = fwd;
        victim->bk_nextsize = fwd->bk_nextsize;
        fwd->bk_nextsize = victim;
        victim->bk_nextsize->fd_nextsize = victim;
       }
     bck = fwd->bk;
```

```
          }
        } else
          victim->fd_nextsize = victim->bk_nextsize = victim;
        }

        mark_bin(av, victim_index);
        victim->bk = bck;
        victim->fd = fwd;
        fwd->bk = victim;
        bck->fd = victim;

#define MAX_ITERS   10000
        if (++iters >= MAX_ITERS)
         break;
      }

      /*
        If a large request, scan through the chunks of current bin in
        sorted order to find smallest that fits.  Use the skip list for this.
      */

      if (!in_smallbin_range(nb)) {
        bin = bin_at(av, idx);

        /* skip scan if empty or largest chunk is too small */
        if ((victim = first(bin)) != bin &&
           (unsigned long)(victim->size) >= (unsigned long)(nb)) {

         victim = victim->bk_nextsize;
         while (((unsigned long)(size = chunksize(victim)) <
                (unsigned long)(nb)))
          victim = victim->bk_nextsize;

         /* Avoid removing the first entry for a size so that the skip
            list does not have to be rerouted.  */
         if (victim != last(bin) && victim->size == victim->fd->size)
          victim = victim->fd;

         remainder_size = size - nb;
         unlink(victim, bck, fwd);

         /* Exhaust */
         if (remainder_size < MINSIZE)  {
          set_inuse_bit_at_offset(victim, size);
          if (av != &main_arena)
            victim->size |= NON_MAIN_ARENA;
         }
         /* Split */
         else {
          remainder = chunk_at_offset(victim, nb);
          /* We cannot assume the unsorted list is empty and therefore
             have to perform a complete insert here.  */
          bck = unsorted_chunks(av);
          fwd = bck->fd;
          if (__builtin_expect (fwd->bk != bck, 0))
            {
              errstr = "malloc(): corrupted unsorted chunks";
              goto errout;
            }
          remainder->bk = bck;
          remainder->fd = fwd;
          bck->fd = remainder;
          fwd->bk = remainder;
```

```
        if (!in_smallbin_range(remainder_size))
          {
            remainder->fd_nextsize = NULL;
            remainder->bk_nextsize = NULL;
          }
        set_head(victim, nb | PREV_INUSE |
                 (av != &main_arena ? NON_MAIN_ARENA : 0));
        set_head(remainder, remainder_size | PREV_INUSE);
        set_foot(remainder, remainder_size);
       }
       check_malloced_chunk(av, victim, nb);
       void *p = chunk2mem(victim);
       if (__builtin_expect (perturb_byte, 0))
         alloc_perturb (p, bytes);
       return p;
      }
    }

    /*
      Search for a chunk by scanning bins, starting with next largest
      bin. This search is strictly by best-fit; i.e., the smallest
      (with ties going to approximately the least recently used) chunk
      that fits is selected.

      The bitmap avoids needing to check that most blocks are nonempty.
      The particular case of skipping all bins during warm-up phases
      when no chunks have been returned yet is faster than it might look.
    */

    ++idx;
    bin = bin_at(av,idx);
    block = idx2block(idx);
    map = av->binmap[block];
    bit = idx2bit(idx);

    for (;;) {

      /* Skip rest of block if there are no more set bits in this block.  */
      if (bit > map || bit == 0) {
       do {
         if (++block >= BINMAPSIZE)  /* out of bins */
           goto use_top;
       } while ( (map = av->binmap[block]) == 0);

       bin = bin_at(av, (block << BINMAPSHIFT));
       bit = 1;
      }

      /* Advance to bin with set bit. There must be one. */
      while ((bit & map) == 0) {
       bin = next_bin(bin);
       bit <<= 1;
       assert(bit != 0);
      }

      /* Inspect the bin. It is likely to be non-empty */
      victim = last(bin);

      /*  If a false alarm (empty bin), clear the bit. */
      if (victim == bin) {
       av->binmap[block] = map &= ~bit; /* Write through */
       bin = next_bin(bin);
       bit <<= 1;
```

```
      }

      else {
       size = chunksize(victim);

       /*  We know the first chunk in this bin is big enough to use. */
       assert((unsigned long)(size) >= (unsigned long)(nb));

       remainder_size = size - nb;

       /* unlink */
       unlink(victim, bck, fwd);

       /* Exhaust */
       if (remainder_size < MINSIZE) {
         set_inuse_bit_at_offset(victim, size);
         if (av != &main_arena)
           victim->size |= NON_MAIN_ARENA;
       }

       /* Split */
       else {
         remainder = chunk_at_offset(victim, nb);

         /* We cannot assume the unsorted list is empty and therefore
            have to perform a complete insert here.  */
         bck = unsorted_chunks(av);
         fwd = bck->fd;
         if (__builtin_expect (fwd->bk != bck, 0))
           {
             errstr = "malloc(): corrupted unsorted chunks 2";
             goto errout;
           }
         remainder->bk = bck;
         remainder->fd = fwd;
         bck->fd = remainder;
         fwd->bk = remainder;

         /* advertise as last remainder */
         if (in_smallbin_range(nb))
           av->last_remainder = remainder;
         if (!in_smallbin_range(remainder_size))
           {
             remainder->fd_nextsize = NULL;
             remainder->bk_nextsize = NULL;
           }
         set_head(victim, nb | PREV_INUSE |
                  (av != &main_arena ? NON_MAIN_ARENA : 0));
         set_head(remainder, remainder_size | PREV_INUSE);
         set_foot(remainder, remainder_size);
       }
       check_malloced_chunk(av, victim, nb);
       void *p = chunk2mem(victim);
       if (__builtin_expect (perturb_byte, 0))
         alloc_perturb (p, bytes);
       return p;
      }
    }

  use_top:
    /*
      If large enough, split off the chunk bordering the end of memory
      (held in av->top). Note that this is in accord with the best-fit
```

```
      search rule.  In effect, av->top is treated as larger (and thus
      less well fitting) than any other available chunk since it can
      be extended to be as large as necessary (up to system
      limitations).

      We require that av->top always exists (i.e., has size >=
      MINSIZE) after initialization, so if it would otherwise be
      exhausted by current request, it is replenished. (The main
      reason for ensuring it exists is that we may need MINSIZE space
      to put in fenceposts in sysmalloc.)
    */

    victim = av->top;
    size = chunksize(victim);

    if ((unsigned long)(size) >= (unsigned long)(nb + MINSIZE)) {
      remainder_size = size - nb;
      remainder = chunk_at_offset(victim, nb);
      av->top = remainder;
      set_head(victim, nb | PREV_INUSE |
              (av != &main_arena ? NON_MAIN_ARENA : 0));
      set_head(remainder, remainder_size | PREV_INUSE);

      check_malloced_chunk(av, victim, nb);
      void *p = chunk2mem(victim);
      if (__builtin_expect (perturb_byte, 0))
       alloc_perturb (p, bytes);
      return p;
    }

    /* When we are using atomic ops to free fast chunks we can get
       here for all block sizes.  */
    else if (have_fastchunks(av)) {
      malloc_consolidate(av);
      /* restore original bin index */
      if (in_smallbin_range(nb))
       idx = smallbin_index(nb);
      else
       idx = largebin_index(nb);
    }

    /*
       Otherwise, relay to handle system-dependent cases
    */
    else {
      void *p = sysmalloc(nb, av);
      if (p != NULL && __builtin_expect (perturb_byte, 0))
       alloc_perturb (p, bytes);
      return p;
    }
  }
}
```

Sys_brk() system call , located at mm/mmap.c file

```
static  unsigned long do_brk(unsigned long addr, unsigned long len);

SYSCALL_DEFINE1(brk, unsigned long, brk)
{
        unsigned long rlim, retval;
        unsigned long newbrk, oldbrk;
        struct mm_struct *mm = current->mm;
        unsigned long min brk;
        printk(KERN_INFO "I am currently under sys_call definition of sys_brk\n");
        down write(&mm->mmap sem);

#ifdef CONFIG_COMPAT_BRK
        /*
         * CONFIG_COMPAT_BRK can still be overridden by setting
         * randomize va space to 2, which will still cause mm->start brk
         * to be arbitrarily shifted
         */
        if (current->brk_randomized)
                min brk = mm->start brk;
        else
                min brk = mm->end data;
#else
        printk(KERN_INFO "I am currently under sys_call definition of sys_brk\n");
        min_brk = mm->start_brk;
#endif
        if (brk < min_brk)
                goto out;

        /*
         * Check against rlimit here. If this check is done later after the test
           * of oldbrk with newbrk then it can escape the test and let the data
```

```
         * segment grow beyond its set limit the in case where the limit is
         * not page aligned -Ram Gupta
         */
        rlim = rlimit(RLIMIT_DATA);
        if (rlim < RLIM_INFINITY && (brk - mm->start_brk) +
                        (mm->end_data - mm->start_data) > rlim)
                goto out;

        newbrk = PAGE_ALIGN(brk);
        oldbrk = PAGE_ALIGN(mm->brk);
        if (oldbrk == newbrk)
                goto set_brk;

        /* Always allow shrinking brk. */
        if (brk <= mm->brk) {
                if (!do_munmap(mm, newbrk, oldbrk-newbrk))
                        goto set_brk;
                goto out;
        }

        /* Check against existing mmap mappings. */
        if (find_vma_intersection(mm, oldbrk, newbrk+PAGE_SIZE))
                goto out;

        /* Ok, looks good - let it rip. */
        if (do_brk(oldbrk, newbrk-oldbrk) != oldbrk)
                goto out;
set_brk:
        mm->brk = brk;
out:
        retval = mm->brk;
        up_write(&mm->mmap_sem);
        printk(KERN_INFO "We are still in sys_brk system call definition under out section\n");
          printk(KERN_INFO "We are still in sys_brk system call definition under out section\n");
        return retval;
}
```

sys_mprotect system call defined in mm/mprotect.c file

```
SYSCALL_DEFINE3(mprotect, unsigned long, start, size_t, len,
                unsigned long, prot)
{
        unsigned long vm_flags, nstart, end, tmp, reqprot;
        struct vm_area_struct *vma, *prev;
        int error = -EINVAL;
        const int grows = prot & (PROT_GROWSDOWN|PROT_GROWSUP);
        prot &= ~(PROT_GROWSDOWN|PROT_GROWSUP);
        if (grows == (PROT_GROWSDOWN|PROT_GROWSUP)) /* can't be both */
                return -EINVAL;

        if (start & ~PAGE_MASK)
                return -EINVAL;
        if (!len)
                return 0;
        len = PAGE_ALIGN(len);
        end = start + len;
        if (end <= start)
                return -ENOMEM;
        if (!arch_validate_prot(prot))
                return -EINVAL;

        reqprot = prot;
        /*
         * Does the application expect PROT_READ to imply PROT_EXEC:
```

```
      /*
         * Does the application expect PROT_READ to imply PROT_EXEC:
         */
        if ((prot & PROT_READ) && (current->personality & READ_IMPLIES_EXEC))
                prot |= PROT_EXEC;

        vm_flags = calc_vm_prot_bits(prot);

        down_write(&current->mm->mmap_sem);

        vma = find_vma(current->mm, start);
        error = -ENOMEM;
        if (!vma)
                goto out;
        prev = vma->vm_prev;
        if (unlikely(grows & PROT_GROWSDOWN)) {
                if (vma->vm_start >= end)
                        goto out;
                start = vma->vm_start;
                error = -EINVAL;
                if (!(vma->vm_flags & VM_GROWSDOWN))
                        goto out;
        }
        else {
                if (vma->vm_start > start)
                        goto out;
                if (unlikely(grows & PROT_GROWSUP)) {
                        end = vma->vm_end;
                        error = -EINVAL;
                        if (!(vma->vm_flags & VM_GROWSUP))
                                goto out;
                }
        }
 if (start > vma->vm_start)
                prev = vma;

        for (nstart = start ; ; ) {
                unsigned long newflags;

                /* Here we know that  vma->vm_start <= nstart < vma->vm_end. */

                newflags = vm_flags | (vma->vm_flags & ~(VM_READ | VM_WRITE |
VM_EXEC));

                /* newflags >> 4 shift VM_MAY% in place of VM_% */
                if ((newflags & ~(newflags >> 4)) & (VM_READ | VM_WRITE | VM_EXEC)) {
                        error = -EACCES;
                        goto out;
                }

                error = security_file_mprotect(vma, reqprot, prot);
                if (error)
                        goto out;

                tmp = vma->vm_end;
```

```
                if (tmp > end)
                        tmp = end;
                error = mprotect_fixup(vma, &prev, nstart, tmp, newflags);
                if (error)
                        goto out;
                nstart = tmp;

                if (nstart < prev->vm_end)
                        nstart = prev->vm_end;
                if (nstart >= end)
                        goto out;

                vma = prev->vm_next;
    if (!vma || vma->vm_start != nstart) {
                        error = -ENOMEM;
                        goto out;
                }
        }
out:
        up_write(&current->mm->mmap_sem);
        return error;
}
```

sys_mmap2

Location of file /arch/sh/kernel/sys_sh.c

```
asmlinkage long sys_mmap2(unsigned long addr, unsigned long len,
        unsigned long prot, unsigned long flags,
        unsigned long fd, unsigned long pgoff)
{
        printk(KERN_INFO "I am currently in sys_mmap2 system call in
/arch/sh/kernel/sys_sh.c file");
        /*
         * The shift for mmap2 is constant, regardless of PAGE_SIZE
         * setting.
         */
        if (pgoff & ((1 << (PAGE_SHIFT - 12)) - 1))
                return -EINVAL;

        pgoff >>= PAGE_SHIFT - 12;

        return sys_mmap_pgoff(addr, len, prot, flags, fd, pgoff);
}
```

do_munmap() mm/mmap.c

```
int do_munmap(struct mm_struct *mm, unsigned long start, size_t len)
{
        unsigned long end;
        struct vm_area_struct *vma, *prev, *last;

        if ((start & ~PAGE_MASK) || start > TASK_SIZE || len > TASK_SIZE-start)
                return -EINVAL;

        if ((len = PAGE_ALIGN(len)) == 0)
                return -EINVAL;

        /* Find the first overlapping VMA */
        vma = find_vma(mm, start);
        if (!vma)
                return 0;
        prev = vma->vm_prev;
        /* we have  start < vma->vm_end  */

        /* if it doesn't overlap, we have nothing.. */
        end = start + len;
        if (vma->vm_start >= end)
                return 0;

        /*
         * If we need to split any vma, do it now to save pain later.
         *
         * Note: mremap's move_vma VM_ACCOUNT handling assumes a partially
         * unmapped vm_area_struct will remain in use: so lower split_vma
         * places tmp vma above, and higher split_vma places tmp vma below.
         */
        if (start > vma->vm_start) {
                int error;
```

```
if (start > vma->vm_start) {
                int error;

                /*
                 * Make sure that map_count on return from munmap() will
                 * not exceed its limit; but let map_count go just above
                 * its limit temporarily, to help free resources as expected.
                 */
                if (end < vma->vm_end && mm->map_count >= sysctl_max_map_count)
                        return -ENOMEM;

                error = __split_vma(mm, vma, start, 0);
                if (error)
                        return error;
                prev = vma;
        }

        /* Does it split the last one? */
        last = find_vma(mm, end);
        if (last && end > last->vm_start) {
                int error = __split_vma(mm, last, end, 1);
                if (error)
                        return error;
        }
        vma = prev? prev->vm_next: mm->mmap;

        /*
         * unlock any mlock()ed ranges before detaching vmas
         */
        if (mm->locked_vm) {
                struct vm_area_struct *tmp = vma;
                while (tmp && tmp->vm_start < end) {
                        if (tmp->vm_flags & VM_LOCKED) {
                                mm->locked_vm -= vma_pages(tmp);
munlock_vma_pages_all(tmp);
                        }
                        tmp = tmp->vm_next;
                }
        }

        /*
         * Remove the vma's, and unmap the actual pages
         */
        detach_vmas_to_be_unmapped(mm, vma, prev, end);
        unmap_region(mm, vma, prev, start, end);

        /* Fix up all other VM information */
        remove_vma_list(mm, vma);

        return 0;
}

int vm_munmap(unsigned long start, size_t len)
{
        int ret;
```

```
        struct mm_struct *mm = current->mm;

        down_write(&mm->mmap_sem);
        ret = do_munmap(mm, start, len);
        up_write(&mm->mmap_sem);
        return ret;
}
EXPORT_SYMBOL(vm_munmap);
        /* Does it split the last one? */
        last = find_vma(mm, end);
        if (last && end > last->vm_start) {
                int error = __split_vma(mm, last, end, 1);
                if (error)
                        return error;
        }
        vma = prev? prev->vm_next: mm->mmap;

        /*
         * unlock any mlock()ed ranges before detaching vmas
         */
        if (mm->locked_vm) {
                struct vm_area_struct *tmp = vma;
                while (tmp && tmp->vm_start < end) {
                        if (tmp->vm_flags & VM_LOCKED) {
                                mm->locked_vm -= vma_pages(tmp);
munlock_vma_pages_all(tmp);
                        }
                        tmp = tmp->vm_next;
                }
        }

        /*
         * Remove the vma's, and unmap the actual pages
         */
        detach_vmas_to_be_unmapped(mm, vma, prev, end);
        unmap_region(mm, vma, prev, start, end);

        /* Fix up all other VM information */
        remove_vma_list(mm, vma);
```

```
        return 0;
}

int vm_munmap(unsigned long start, size_t len)
{
        int ret;
        struct mm_struct *mm = current->mm;

        down_write(&mm->mmap_sem);
        ret = do_munmap(mm, start, len);
        up_write(&mm->mmap_sem);
        return ret;
}
```

```
EXPORT_SYMBOL(vm_munmap);
```