CS344 - Assignment -3

Group - 12

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Part A : Lazy Memory Allocation

Whenever the current process needs extra memory than its assigned value, it indicates this requirement to the xv6 OS using sbrk system call. sbrk uses growproc() defined inside proc.c to cater to this requirement. A closer look at the implementation of growproc() shows that growproc() calls allocuvm() which is responsible for allocating the desired extra memory by allocating extra pages and mapping the virtual addresses to their corresponding physical addresses inside page tables. In this assignment, our objective is to refrain giving memory as soon as it is requested. Rather, we give the memory when it is accessed. This is known as Lazy Memory Allocation. We do this by commenting out the call to growproc() inside the sbrk system call. We change the size variable associated with the current process to the desired value which gives the process a false feel that the memory has been allocated. When this process tries to access the page (which it thinks has been already brought inside memory), it encounters a PAGE FAULT, thus generating a T_PGFLT trap to the kernel. This is handled in trap.c by calling handlePageFault().

C trap 〉 No Selection

```c
int handlePageFault(){
  int addr=rcr2();
  int rounded_addr = PGROUNDDOWN(addr);
  char *mem=kalloc();
  if(mem!=0){
    memset(mem, 0, PGSIZE);
    if(mappages(myproc()->pgdir, (char*)rounded_addr, PGSIZE, V2P(mem),
        PTE_W|PTE_U)<0)
      return -1;
    return 0;
  } else
    return -1;
}
```

C trap

C trap 〉 No Selection

```c
  case T_PGFLT:
    if(handlePageFault()<0){
      cprintf("Could not allocate page. Sorry.\n");
      panic("trap");
    }
```

In this, rcr2() gives the virtual address at which the page fault occurs. rounded _addr points to the starting address to the page where this virtual address resides. Then we call kalloc() which returns a free page from a linked list of free pages (freelist inside kmem) in the system. Now we have a physical page at our disposal. Now we need to map it to the virtual address rounded_addr which is done using mappages().

C vm 〉 f mappages(pgdir, va, size, pa, perm)

```c
int
mappages(pde_t *pgdir, void *va, uint size, uint pa, int perm)
{
  char *a, *last;
  pte_t *pte;

  a = (char*)PGROUNDDOWN((uint)va);
  last = (char*)PGROUNDDOWN(((uint)va) + size - 1);
  for(;;){
    if((pte = walkpgdir(pgdir, a, 1)) == 0)
      return -1;
    if(*pte & PTE_P)
      panic("remap");
    *pte = pa | perm | PTE_P;
    if(a == last)
      break;
    a += PGSIZE;
    pa += PGSIZE;
  }
  return 0;
}
```

To use mappages() in trap.c, we remove the static keyword in front of it in vm.c and declare its prototype in trap.c. mappages() takes the page table of the current process, virtual address of the start of the data, size of the data, physical memory at which the physical page resides (we give this parameter by using V2P macro which converts our virtual address to physical address by subtracting KERNBASE from it) and permissions corresponding to the page table entry as parameters. Now let's have a deeper look at mappages(). In this, ‘a’ denotes the first page and ‘last’ denotes the last page of the data that has to be loaded. It then runs a loop until all the pages from the first to last have been loaded successfully. For every page, it loads it into the page table using walkpgdir().

C vm 〉 walkpgdir(pgdir, va, alloc)

Find Text

```c
static pte_t *
walkpgdir(pde_t *pgdir, const void *va, int alloc)
{
  pde_t *pde;
  pte_t *pgtab;

  pde = &pgdir[PDX(va)];
  if(*pde & PTE_P){
    pgtab = (pte_t*)P2V(PTE_ADDR(*pde));
  } else {
    if(!alloc || (pgtab = (pte_t*)kalloc()) == 0)
      return 0;
    // Make sure all those PTE_P bits are zero.
    memset(pgtab, 0, PGSIZE);
    // The permissions here are overly generous, but they can
    // be further restricted by the permissions in the page table
    // entries, if necessary.
    *pde = V2P(pgtab) | PTE_P | PTE_W | PTE_U;
  }
  return &pgtab[PTX(va)];
}
```

walkpgdir() takes a page table and a virtual address as input and returns the page table entry corresponding to that virtual address inside the page table. Since it is a two-level page table, it uses the first 10 bits (using PDX macro) of the virtual address to obtain the page directory entry which points to the page table. It then uses the next 10 bits (using PTX macro) to get the corresponding entry in the page table and returns it. If the page table corresponding to the page directory entry is already present in memory, we store the pointer to its first entry in pgtab (We use PTE_ADDR macro to unset the last 12 bits thereby making the offset zero). If the page table isn't present in memory, we load it and set the permission bits in the page directory. After this, we return a pointer to the page table entry corresponding to the virtual address. Now, the mappages() knows the entry to which the current virtual address has to be mapped. It checks if the PRESENT bit of that entry is already set indicating that it is already mapped to some virtual address. If yes, it generates an error telling that remap has occurred. If no error takes place, it associates the page table entry to the virtual address, sets the permission bits and sets its PRESENT bit indicating that the current page table entry has been mapped to a virtual address.

Part B

Task 1:

The **create_kernel_process()** function was created in **proc.c**. The kernel process will remain in kernel mode the whole time. Thus, **we do not need to initialise its trapframe** (trapframes store userspace register values), user space and the user section of its page table. The eip register of the process` context stores the address of the next instruction. We want the process to start executing at the entry point (which is a function pointer). Thus, we set the eip value of the context to entry point (Since entry point is the address of a function). **allocproc** assigns the process a spot in ptable. setupkvm sets up the kernel part of the process page table that maps virtual addresses above **KERNBASE** to physical addresses between 0 and **PHYSTOP**.

proc.c :

C proc 〉 No Selection

```c

void create_kernel_process(const char *name, void (*entrypoint)()){

  struct proc *p = allocproc();

  if(p == 0)
    panic("create_kernel_process failed");

  //Setting up kernel page table using setupkvm
  if((p->pgdir = setupkvm()) == 0)
    panic("setupkvm failed");

  //This is a kernel process. Trap frame stores user space registers. We don't need to initialise tf.
  //Also, since this doesn't need to have a userspace, we don't need to assign a size to this process.

  //eip stores address of next instruction to be executed
  p->context->eip = (uint)entrypoint;

  safestrcpy(p->name, name, sizeof(p->name));

  acquire(&ptable.lock);
  p->state = RUNNABLE;
  release(&ptable.lock);

}
```

Task 2:

This task has various parts. First, we need a process queue that keeps track of the processes that were refused additional memory since there were no free pages available. We created a **circular queue struct** called **rq**. And the specific queue that holds processes with **swap out requests** is **rqueue**. We have also created the functions corresponding to rq, namely **rpush()** and **rpop()**. The queue needs to be accessed with a lock that we have initialised in pinit. We have also initialised the initial values of s and e to zero in **userinit**. Since the queue and the functions relating to it are needed in other files too, we added prototypes in defs.h too.

proc.c:

C proc 〉 No Selection

```c
struct rq{
  struct spinlock lock;
  struct proc* queue[NPROC];
  int s;
  int e;
};
```

C proc 〉 No Selection

```c
struct rq rqueue;

struct proc* rpop(){

  acquire(&rqueue.lock);
  if(rqueue.s==rqueue.e){
    release(&rqueue.lock);
    return 0;
  }
  struct proc *p=rqueue.queue[rqueue.s];
  (rqueue.s)++;
  (rqueue.s)%=NPROC;
  release(&rqueue.lock);

  return p;
}
```

C proc 〉 No Selection

```c
int rpush(struct proc *p){

  acquire(&rqueue.lock);
  if((rqueue.e+1)%NPROC==rqueue.s){
    release(&rqueue.lock);
    return 0;
  }
  rqueue.queue[rqueue.e]=p;
  rqueue.e++;
  (rqueue.e)%=NPROC;
  release(&rqueue.lock);

  return 1;
}
```

C proc 〉 No Selection

```c
static void wakeup1(void *chan);

void
pinit(void)
{
  initlock(&ptable.lock, "ptable");
  initlock(&rqueue.lock, "rqueue");
  initlock(&sleeping_channel_lock, "sleeping_channel");
  initlock(&rqueue2.lock, "rqueue2");
}
```

C proc 〉 No Selection

```c
// Set up first user process.
void
userinit(void)
{
  acquire(&rqueue.lock);
  rqueue.s=0;
  rqueue.e=0;
  release(&rqueue.lock);
```

defs.h :

```
struct rq;
```

*Note: rqueue2 (and correspondingly rpush2 and rpop2) is used in Task 3.

h defs 〉 No Selection

```
extern int swap_out_process_exists;
extern int swap_in_process_exists;
extern struct rq rqueue;
extern struct rq rqueue2;
int rpush(struct proc *p);
struct proc* rpop();
struct proc* rpop2();
int rpush2(struct proc* p);
```

Now, whenever **kalloc** is not able to allocate pages to a process, it returns zero. This notifies **allocuvm** that the requested memory wasn't allocated (mem=0). Here, we first need to change the process state to sleeping. (*Note: The process sleeps on a special sleeping channel called sleeping_channel that is secured by a lock called sleeping_channel_lock. **sleeping_channel_count** is used for corner cases when the system boots) Then, we need to add the current process to the swap out request queue, **rqueue:**

vm.c :

C vm 〉 No Selection

```
struct spinlock sleeping_channel_lock;
int sleeping_channel_count=0;
char * sleeping_channel;
```

allocuvm:

C vm 〉 No Selection

```
    if(mem == 0){
      // cprintf("allocuvm out of memory\n");
      deallocuvm(pgdir, newsz, oldsz);

      //SLEEP
      myproc()->state=SLEEPING;
      acquire(&sleeping_channel_lock);
      myproc()->chan=sleeping_channel;
      sleeping_channel_count++;
      release(&sleeping_channel_lock);

        rpush(myproc());
      if(!swap_out_process_exists){
        swap_out_process_exists=1;
        create_kernel_process("swap_out_process", &swap_out_process_function);
      }

      return 0;
```

Next, we create a mechanism by which whenever free pages are available, all the processes sleeping on sleeping_channel are woken up. We edit kfree in **kalloc.c** in the following way: Basically, all processes that were preempted due to lack of availability of pages were sent sleeping on the sleeping channel. We wake all processes currently sleeping on sleeping_channel by calling the **wakeup()** system call.

C kalloc 〉 No Selection

```c
void
kfree(char *v)
{

  struct run *r;
  // struct proc *p=myproc();

  if((uint)v % PGSIZE || v < end || V2P(v) >= PHYSTOP){
    panic("kfree");
  }

  // Fill with junk to catch dangling refs.
  // memset(v, 1, PGSIZE);
  for(int i=0;i<PGSIZE;i++){
    v[i]=1;
  }

  if(kmem.use_lock)
    acquire(&kmem.lock);
  r = (struct run*)v;
  r->next = kmem.freelist;
  kmem.freelist = r;
  if(kmem.use_lock)
    release(&kmem.lock);

  //Wake up processes sleeping on sleeping channel.
  if(kmem.use_lock)
    acquire(&sleeping_channel_lock);
  if(sleeping_channel_count){
    wakeup(sleeping_channel);
    sleeping_channel_count=0;
  }
  if(kmem.use_lock)
    release(&sleeping_channel_lock);

}
```

Now, I will explain the swapping out process. The entry point for the **swapping out** process in **swap_out_process_function**. Since the function is very long, I have attached two screenshots:

C proc 〉 swap_out_process_function()

```c
void swap_out_process_function(){

  acquire(&rqueue.lock);
  while(rqueue.s!=rqueue.e){
    struct proc *p=rpop();

    pde_t* pd = p->pgdir;
    for(int i=0;i<NPDENTRIES;i++){

      //skip page table if accessed. chances are high, not every page table was accessed.
      if(pd[i]&PTE_A)
        continue;
      //else
      pte_t *pgtab = (pte_t*)P2V(PTE_ADDR(pd[i]));
      for(int j=0;j<NPTENTRIES;j++){

        //Skip if found
        if((pgtab[j]&PTE_A) || !(pgtab[j]&PTE_P))
          continue;
        pte_t *pte=(pte_t*)P2V(PTE_ADDR(pgtab[j]));

        //for file name
        int pid=p->pid;
        int virt = ((1<<22)*i)+((1<<12)*j);

        //file name
        char c[50];
        int_to_string(pid,c);
        int x=strlen(c);
        c[x]='_';
        int_to_string(virt,c+x+1);
        safestrcpy(c+strlen(c),".swp",5);

        // file management
        int fd=proc_open(c, O_CREATE | O_RDWR);
        if(fd<0){
          cprintf("error creating or opening file: %s\n", c);
          panic("swap_out_process");
        }

        if(proc_write(fd,(char *)pte, PGSIZE) != PGSIZE){
          cprintf("error writing to file: %s\n", c);
          panic("swap_out_process");
        }
        proc_close(fd);

        kfree((char*)pte);
        memset(&pgtab[j],0,sizeof(pgtab[j]));
```

The process runs a loop until the swap out requests queue (rqueue1) is non empty. When the queue is empty, a set of instructions are executed for the termination of swap_out_process.

C proc 〉 swap_out_process_function()

```c
        kfree((char*)pte);
        memset(&pgtab[j],0,sizeof(pgtab[j]));

        //mark this page as being swapped out.
        pgtab[j]=((pgtab[j])^(0x080));

        break;
      }
    }

  }

  release(&rqueue.lock);

  struct proc *p;
  if((p=myproc())==0)
    panic("swap out process");

  swap_out_process_exists=0;
  p->parent = 0;
  p->name[0] = '*';
  p->killed = 0;
  p->state = UNUSED;
  sched();
}
```

The loop starts by popping the first process from rqueue and uses the LRU policy to determine a victim page in its page table.

We iterate through each entry in the process page table (pgdir) and extracts the physical address for each secondary page table. For each secondary page table, we iterate through the page table and look at the accessed bit (A) on each of the entries (The accessed bit is the sixth bit from the right. We check if it is set by checking the bitwise & of the entry and PTE_A (which we defined as 32 in mmu.c)).

C proc 〉 userinit()

```c
for(int i=0;i<NPDENTRIES;i++){
  //If PDE was accessed

  if(((p->pgdir)[i])&PTE_P && ((p->pgdir)[i])&PTE_A){

    pte_t* pgtab = (pte_t*)P2V(PTE_ADDR((p->pgdir)[i]));

    for(int j=0;j<NPTENTRIES;j++){
      if(pgtab[j]&PTE_A){
        pgtab[j]^=PTE_A;
      }
    }

    ((p->pgdir)[i])^=PTE_A;
  }
}

// Switch to chosen process.  It is the process's job
// to release ptable.lock and then reacquire it
// before jumping back to us.
c->proc = p;
switchuvm(p);
p->state = RUNNING;

swtch(&(c->scheduler), p->context);
switchkvm();
```

This code resides in the scheduler and it basically unsets every accessed bit in the process page table and its secondary page tables.

Now, back to swap_out_process_function. As soon as the function finds a secondary page table entry with the accessed bit unset, it chooses this entries physical page number (using macros mentioned in part A report) as the victim page. This page is then swapped out and stored to drive.

We use the process pid (**pid, line 267** in image) and virtual address of the page to be eliminated (**virt, line 268** in image) to name the file that stores this page. We have created a new function called **int_to_string** that copies an integer into a given string. We use this function to make the filename using integers pid and virt. Here is that function (declared in **proc.c**):

C proc 〉 userinit()

```c
void int_to_string(int x, char *c){
  if(x==0)
  {
    c[0]='0';
    c[1]='\0';
    return;
  }
  int i=0;
  while(x>0){
    c[i]=x%10+'0';
    i++;
    x/=10;
  }
  c[i]='\0';

  for(int j=0;j<i/2;j++){
    char a=c[j];
    c[j]=c[i-j-1];
    c[i-j-1]=a;
  }

}
```

We need to write the contents of the victim page to the file with the name **<pid>_<virt>.swp**. But we encounter a problem here. We store the filename in a string called c. File system calls cannot be called from proc.c. The solution was that we copied the **open, write, read, close** etc. functions from **sysfile.c** to **proc.c**, modified them since the sysfile.c functions used a different way to take arguments and then renamed them to **proc_open, proc_read, proc_write, proc_close** etc. so we can use them in proc.c.

Some examples:

C proc 〉 userinit()

```c
int
proc_write(int fd, char *p, int n)
{
  struct file *f;
  if(fd < 0 || fd >= NOFILE || (f=myproc()->ofile[fd]) == 0)
    return -1;
  return filewrite(f, p, n);
}
```

C proc 〉 userinit()

```c
int
proc_close(int fd)
{
  struct file *f;

  if(fd < 0 || fd >= NOFILE || (f=myproc()->ofile[fd]) == 0)
    return -1;

  myproc()->ofile[fd] = 0;
  fileclose(f);
  return 0;
}
```

There are many more functions (proc open, proc_fdalloc etc.) and you can check them out in proc.c. I can't paste all of them here.

Now, using these functions, we write back a page to storage. We open a file (using proc_open) with **O_CREATE** and **O_RDWR** permissions (we have imported **fcntl.h** with these macros). O_CREATE creates this file if it doesn't exist and O_RDWR refers to read/write. The file descriptor is stored in an integer called fd. Using this file descriptor, we write the page to this file using proc_write. Then, this page is added to the free page queue using kfree so it is available for use (remember we also wake up all processes sleeping on sleeping_channel when kfree adds a page to the free queue). We then clear the page table entry too using memset.

After this, we do something important: **for Task 3, we need to know if the page that caused a fault was swapped out or not. In order to mark this page as swapped out, we set the 8th bit from the right (2^7) in the secondary page table entry. We use xor to accomplish this task (LINE 295 in image)**.

Suspending kernel process when no requests are left:
When the queue is empty, the loop breaks and suspension of the process is initiated. While exiting the kernel processes that are running, we can't clear their **kstack** from within the process because after this, they will not know which process to execute next. We need to clear their kstack from outside the process. For this, we first preempt the process and wait for the scheduler to find this process. **When the scheduler finds a kernel process in the UNUSED state, it clears this process kstack and name. The scheduler identifies the kernel process in unused state by checking its name in which the first character was changed to '*' when the process ended**.

Thus the ending of kernel processes has two parts:

1. From within process:

C proc 〉 userinit()

```c
  struct proc *p;
  if((p=myproc())==0)
    panic("swap out process");

  swap_out_process_exists=0;
  p->parent = 0;
  p->name[0] = '*';
  p->killed = 0;
  p->state = UNUSED;
  sched();
}
```

2. From scheduler

C proc 〉 scheduler()

```c
    for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){

      //If the swap out process has stopped running, free its stack and name.
      if(p->state==UNUSED && p->name[0]=='*'){

        kfree(p->kstack);
        p->kstack=0;
        p->name[0]=0;
        p->pid=0;
      }
```

Note:

All check marks in assignment accomplished:

1) The swapping out process must support a request queue for the swapping requests. (**page 1 and 2 of this report**).

2) Whenever there are no pending requests for the swapping out process, this process must be suspended from execution. (**page 5 of this report, just above this**)

3) Whenever there exists at least one free physical page, all processes that were suspended due to lack of physical memory must be woken up. (**page 3 of this report: kfree and sleeping_channel**)

4) Only user-space memory can be swapped out (this does not include the second level page table) (**since we are iterating all top tables from to bottom and all user space entries come first (until KERNBASE), we will swap out the first user space page that was not accessed in the last iteration.)**

Task 3:

We first need to create a **swap in request queue**. We used the same struct (rq) as in Task 2 to create a swap in request queue called rqueue2 in proc.c. We also declare an extern prototype for rqueue2 in defs.h. Along with declaring the queue, we also created the corresponding functions for rqueue2 (rpop2() and rpush2()) in proc.c and declared their prototype in defs.h. We also initialised its lock in pinit. We also initialised its s and e variables in userinit.
Since all the functions/variables are similar to the ones shown in Task 2, I am not attaching their screenshots here.

Next, we add an additional entry to the **struct proc** in **proc.h** called **addr (int)**. This entry will tell the swapping in function at which virtual address the page fault occurred:

proc.h (in struct proc):

h proc 〉 No Selection

```
char name[16];               // Process name (debugging)
int addr;                    // ADDED: Virtual address of pagefault
```

Next, we need to handle page fault (**T_PGFLT**) traps raised in trap.c. We do it in a function called **handlePageFault()**:

trap.c:

C trap 〉 tvinit()

```
void handlePageFault(){
  int addr=rcr2();
  struct proc *p=myproc();
  acquire(&swap_in_lock);
  sleep(p,&swap_in_lock);
  pde_t *pde = &(p->pgdir)[PDX(addr)];
  pte_t *pgtab = (pte_t*)P2V(PTE_ADDR(*pde));

  if((pgtab[PTX(addr)])&0x080){
    //This means that the page was swapped out.
    //virtual address for page
    p->addr = addr;
    rpush2(p);
    if(!swap_in_process_exists){
      swap_in_process_exists=1;
      create_kernel_process("swap_in_process", &swap_in_process_function);
    }
  } else {
    exit();
  }
}
```

In **handlePageFault**, just like **Part A**, we find the virtual address at which the page fault occurred by using **rcr2()**. We then put the current process to sleep with a new lock called **swap_in_lock** (initialised in trap.c and with extern in defs.h). We then obtain the page table entry corresponding to this address (the logic is identical to **walkpgdir**). Now, we need to check whether this page was swapped out. In Task 2, whenever we swapped out a page, we set its page table entries bit of 7th order (2^7). This is mentioned at the beginning of the 5th page of this report. Thus, in order to check whether the page was swapped out or not, we check its 7th order bit using **bitwise & with 0x080**. If it is set, we initiate **swap_in_process** (if it doesn't already exist - check using swap_in_process_exists). Otherwise, we safely suspend the process using exit() as the assignment asked us to do.

Now, we go through the **swapping in process**. The entry point for the swapping out process is **swap_in_process_function (declared in proc.c)** as you can see in handlePageFault. Note: swap_in_process_function is shown on the next page since it is long. Refer to the next page for the actual function.

I have already mentioned how we have implemented file management functions in proc.c in the Task 2 part of the report. I will just mention which functions I used and how I used them here. The function runs a loop until **rqueue2** is not empty. In the loop, it pops a process from the queue and extracts its **pid** and **addr** value to get the file name. Then, it creates the filename in a string called "c" using **int_to_string** (described in Task 2, page 4 of this report). Then, it used **proc_open** to open this file in read only mode (**O_RDONLY**) with file descriptor fd. We then allocate a free frame (mem) to this process using kalloc. We read from the file with the fd file descriptor into this free frame using proc_read. We then make mappages available to proc.c by removing the static keyword from it in Ym.c and then declaring a prototype in proc.c. We then use mappages to map the page corresponding to addr with the physical page that got using kalloc and read into (mem). Then we wake up, the process for which we allocated a new page to fix the page fault using wakeup. Once the loop is completed, we run the kernel process termination instructions that were described on page 5 of this report.

In Task 3 too, all the check marks were accomplished.

```
int mappages(pde_t *pgdir, void *va, uint size, uint pa, int perm);
```

C proc 〉 swap_in_process_function()

```c
void swap_in_process_function(){

    acquire(&rqueue2.lock);
    while(rqueue2.s!=rqueue2.e){
        struct proc *p=rpop2();

        int pid=p->pid;
        int virt=PTE_ADDR(p->addr);

        char c[50];
        int_to_string(pid,c);
        int x=strlen(c);
        c[x]='_';
        int_to_string(virt,c+x+1);
        safestrcpy(c+strlen(c),".swp",5);

        int fd=proc_open(c,O_RDONLY);
        if(fd<0){
            release(&rqueue2.lock);
            cprintf("could not find page file in memory: %s\n", c);
            panic("swap_in_process");
        }
        char *mem=kalloc();
        proc_read(fd,PGSIZE,mem);

        if(mappages(p->pgdir, (void *)virt, PGSIZE, V2P(mem), PTE_W|PTE_U)<0){
            release(&rqueue2.lock);
            panic("mappages");
        }
        wakeup(p);
    }

    release(&rqueue2.lock);
    struct proc *p;
    if((p=myproc())==0)
      panic("swap_in_process");

    swap_in_process_exists=0;
    p->parent = 0;
    p->name[0] = '*';
    p->killed = 0;
    p->state = UNUSED;
    sched();
```

Task 4 : Sanity Test

In this part our aim is to create a testing mechanism ignorer to test the functionalities created by us in the previous parts we will implement a user space program named **memtest** that will do this job for us. The implementation of memtest is given below.

C memtest 〉 main(argc, argv)

```c
#include "types.h"
#include "stat.h"
#include "user.h"

int math_func(int num){
    return num*num - 4*num + 1;
}

int
main(int argc, char* argv[]){

    for(int i=0;i<20;i++){
        if(!fork()){
            printf(1, "Child %d\n", i+1);
            printf(1, "Iteration Matched Different\n");
            printf(1, "--------- ------- ---------\n\n");

            for(int j=0;j<10;j++){
                int *arr = malloc(4096);
                for(int k=0;k<1024;k++){
                    arr[k] = math_func(k);
                }
                int matched=0;
                for(int k=0;k<1024;k++){
                    if(arr[k] == math_func(k))
                        matched+=4;
                }
                if(j<9)
                    printf(1, "    %d       %dB       %dB\n", j+1, matched, 4096-matched);
                else
                    printf(1, "   %d       %dB       %dB\n", j+1, matched, 4096-matched);
            }
            printf(1, "\n");

            exit();
        }
    }
    while(wait()!=-1);
    exit();

}
```

We can make the following observations by looking at the implementations :

-> The main process creates 20 child processes using fork( ) system call.
-> Each child process executes a loop with 10 iterations

-> At each iteration,4096B (4KB) of memory is being allocated using malloc( )
-> The value stored at index I of the array is given by mathematical expression i^2 - 4i +1 which is computed using math_func( )

-> A counter named matched is maintained which stores the number of bytes that contain the right value. This is done by checking the value stored at every index with the value returned by the function for that index.

Inorder to run meatiest , we need to include it in the main file under UPROGS and EXTRA to make it accessible to the Xv6 user.
On running memtest, we obtain the following output.

```
$ memtest
Child 1
Iteration Matched Different
--------- ------- ---------

    1      4096B      0B
    2      4096B      0B
    3      4096B      0B
    4      4096B      0B
    5      4096B      0B
    6      4096B      0B
    7      4096B      0B
    8      4096B      0B
    9      4096B      0B
   10      4096B      0B

Child 2
Iteration Matched Different
--------- ------- ---------

    1      4096B      0B
    2      4096B      0B
    3      4096B      0B
    4      4096B      0B
    5      4096B      0B
    6      4096B      0B
    7      4096B      0B
    8      4096B      0B
    9      4096B      0B
   10      4096B      0B

Child 3
Iteration Matched Different
--------- ------- ---------

    1      4096B      0B
    2      4096B      0B
    3      4096B      0B
    4      4096B      0B
    5      4096B      0B
    6      4096B      0B
    7      4096B      0B
    8      4096B      0B
    9      4096B      0B
   10      4096B      0B
```

As can be seen in the output our implementation passes the sanity test s all the indices store the correct value.
Now , to test our implementation even further , we run the tests on different values of **PHYSTOP** (defined in the memlayout.h). The default value of PHYSTOP is 0xE000000 (224MB).

We changed its value to 0x0400000 (4MB)
We choose 4MB because this is the minimum memory needed by Xv6 to execute **kinit1**. On running memtest, **the obtained output is identical to previous output** indicating that the implementation is correct.