Assignment 3

Group No:	G31
Chandrabhushan Reddy	200101027
Billa Pramodh	200101025
Sathvika Kalangi	200101048

Part A:

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 as follows:

```
case T_PGFLT:
  {
    char *mem;
    mem = kalloc();
    if (mem == 0)
    {
      cprintf("Out of Memory.\n");
    }
    else
    {
      memset(mem, 0, PGSIZE);

      // creating page table entry
      uint a = PGROUNDDOWN(rcr2());
      mappages(myproc()->pgdir, (char *)a, PGSIZE, V2P(mem), PTE_W | PTE_U);
    }
  }

  break;
```

In this, rcr2() gives the virtual address at which the page fault occurs. "a" 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 "a" which is done using mappages().

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():

```
// Create PTEs for virtual addresses starting at va that refer to
// physical addresses starting at pa. va and size might not
// be page-aligned.
// static int
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;
}
```

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().

Let’s take a closer look at walkpgdir():

```c
// Return the address of the PTE in page table pgdir
// that corresponds to virtual address va.  If alloc!=0,
// create any required page table pages.
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 Question and Answers:

Q1) How does the kernel know which physical pages are used and unused?

A1) xv6 maintains a linked list of free pages in kalloc.c called kmem. Initially, the list is empty so xv6 calls kinit1 through main() which adds 4MB of free pages to the list.

Q2) What data structures are used to answer this question?

A2) A linked list named freelist. Every node of the linked list is a structure defined in kalloc.c namely struct run (pages are typecast to (struct run *) when inserting into freelist in kfree (char *v)).

Q3) Where do these reside?

A3) This linked list is declared inside kalloc¸c inside a structure kmem¸ Every node is of the type struct run which is also defined inside kalloc.c

Q4) Does xv6 memory mechanism limit the number of user processes?

A4) Due to a limit on the size of ptable (a max. of NPROC elements which is set to 64 by default), the number of user processes are limited in xv6. NPROC is defined in param.h

Q5) If so, what is the lowest number of processes xv6 can 'have' at the same time (assuming the kernel requires no memory whatsoever)?

A5) When the xv6 operating system boots up, there is only one process named initproc (this process forks the sh process which forks other user processes). Also, since a process can have a virtual address space of 2GB (KERNBASE) and the assumed maximum physical memory is 240MB (PHYSTOP), one process can take up all of the physical memory (We added this since the question asks from a memory management perspective). Hence, the answer is 1.

There cannot be zero processes after boot since all user interactions need to be done using user processes ƒ which are forked from initproc/sh.

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:

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

//circular request queue for swapping out requests.
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
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;
}
```

```
//PAGEBREAK: 32
// Set up first user process.
void
userinit(void)
{
  acquire(&rqueue.lock);
  rqueue.s=0;
  rqueue.e=0;
  release(&rqueue.lock);

  acquire(&rqueue2.lock);
  rqueue2.s=0;
  rqueue2.e=0;
  release(&rqueue2.lock);

  struct proc *p;
  extern char _binary_initcode_start[], _binary_initcode_size[];

  p = allocproc();

  initproc = p;
  if((p->pgdir = setupkvm()) == 0)
    panic("userinit: out of memory?");
  inituvm(p->pgdir, _binary_initcode_start, (int)_binary_initcode_size);
  p->sz = PGSIZE;
  memset(p->tf, 0, sizeof(*p->tf));
  p->tf->cs = (SEG_UCODE << 3) | DPL_USER;
  p->tf->ds = (SEG_UDATA << 3) | DPL_USER;
  p->tf->es = p->tf->ds;
  p->tf->ss = p->tf->ds;
  p->tf->eflags = FL_IF;
  p->tf->esp = PGSIZE;
  p->tf->eip = 0;  // beginning of initcode.S

  safestrcpy(p->name, "initcode", sizeof(p->name));
  p->cwd = namei("/");

  // this assignment to p->state lets other cores
  // run this process. the acquire forces the above
  // writes to be visible, and the lock is also needed
  // because the assignment might not be atomic.
  acquire(&ptable.lock);

  p->state = RUNNABLE;

  release(&ptable.lock);

}
```

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

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

allocuvm:

```c
// Allocate page tables and physical memory to grow process from oldsz to
// newsz, which need not be page aligned.  Returns new size or 0 on error.
int
allocuvm(pde_t *pgdir, uint oldsz, uint newsz)
{
  char *mem;
  uint a;

  if(newsz >= KERNBASE)
    return 0;
  if(newsz < oldsz)
    return oldsz;

  a = PGROUNDUP(oldsz);
  for(; a < newsz; a += PGSIZE){
    mem = kalloc();
    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;
    }
    memset(mem, 0, PGSIZE);
    if(mappages(pgdir, (char*)a, PGSIZE, V2P(mem), PTE_W|PTE_U) < 0){
      cprintf("allocuvm out of memory (2)\n");
      deallocuvm(pgdir, newsz, oldsz);
      kfree(mem);
      return 0;
    }
  }
  return newsz;
}
```

*Note: create_kernel_process here creates a swapping out kernel process to allocate a page for this process if it doesn't already exist. When the swap out process ends, the swap_out_process_exists (declared as extern in defs.h and initialised in proc.c to 0) variable is set to 0. When it is created, it is set to 1 (as seen above). This is done so multiple swap out processes are not created.

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:

```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);

}
```

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.

Swapping 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]));

        //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 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. 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)).

Important note regarding the Accessed flag: Whenever the process is being context switched into by the scheduler, all accessed bits are unset. Since we are doing this, the accessed bit seen by swap_out_process_function will indicate whether the entry was accessed in the last iteration of the process:

```
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;
  }
}
```

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 entry's 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 and virtual address of the page to be eliminated 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.

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
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;
}

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);
}
```

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 page 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.

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 has changed to '*' when the process ended.

Thus, the ending of kernel processes has two parts:

1) From within the process:

```
  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:

```
      //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: 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 has 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.

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

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
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 entry's bit of 7th order (2^7).

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.

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 (already described in the 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 vm.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.

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:

In this part our aim is to create a testing mechanism in order to test the functionalities created by us in the previous parts. We will implement a user space program that will do this job for us. Following is the code of the test program:

```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();

}
```

As evident from above, the main process creates 20 child processes using fork() system call and each child process executes a loop with 10 iterations. At each iteration, 4KB of memory is being allocated using malloc(). The value stored at index "i" of the array is given by the mathematical expression i^2-4i+1. A counter named matched is maintained which stores the number of bytes that contain the correct values. This is done by checking the value stored at every index with the value returned by the function for that index.

The following is the output obtained after executing the test program:

```
PROBLEMS    OUTPUT    DEBUG CONSOLE    TERMINAL

init: starting sh
$ 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

Child 4
Iteration Matched Different
--------- ------- ---------
```

As evident from the above image, our implementation passes the sanity test as all the indices store the correct value.

In order to check the paging mechanism, we run the test on different values of PHYSTOP. We reduce the value of PHYSTOP to 4MB. The choice is based on the fact that 4MB is the minimum memory required by xv6 to execute kinit1.

On executing the test program again, the output which we obtained is exactly the same as the previous output, which indicates that our implementation is correct.