Programming Assignment-6 Report
CS3523: Operating Systems-2
Paging

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Part-1: Printing the page table entries

Implementation:

The changes made are:

1. In the file `syscall.c`, added the new system call to the array of system calls (`syscallnames[]` and `syscalls[]`). Also added the statement `extern int sys_pgtprint(void);` which extends to the function `int sys_pgtprint(void)` in the file `sysproc.c` . The extern keyword extends the visibility to the whole program.
2. In the file `sysproc.c`, added definition to the function `int sys_pgtprint(void)` which obtains the page directory and then loops through the entry tables inside the first loop. Inside the second loop, we obtain each page table and print each entry that is valid and has user-mode access.
3. In the file `syscall.h`, added the line `#define SYS_pgtprint 23` which assigns the system call number 23 to `SYS_pgtprint`.
4. In the file `user.h`, added the function definition `int pgtprint(void);` which is called indirectly when user uses the `mypgtPrint` system call.
5. In the file `usys.s`, added `SYSCALL(pgtprint)` for the user to call the function.
6. Created a file named `mypgtPrint.c` which calls the `pgtprint()` function and has the following arrays:
    a. `arrGlobal[10000]` if you uncomment line 5 and comment lines 11 to 16
    b. `arrLocal[10000]` if you comment line 5 and uncomment lines 11 to 16
    Also in `exec.c`, comment line 54 and in line 52 change `ph.filesz` to `ph.memsz`.
7. for the new file to be compiled and included, added `_mypgtPrint\` in the makefile

Output:

(for local array)

```
Booting from Hard Disk..xv6...
cpu1: starting 1
cpu0: starting 0
sb: size 1000 nblocks 941 ninodes 200 nlog 30 logstart 2 inodestart 32 bmap start 58
init: starting sh
$ mypgtPrint
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2027, Physical addr: dee2027
Entry number: 1, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8dedf067, Physical addr: dedf067
$
```

(for global array)

```
Booting from Hard Disk..xv6...
cpu1: starting 1
cpu0: starting 0
sb: size 1000 nblocks 941 ninodes 200 nlog 30 logstart 2 inodestart 32 bmap start 58
init: starting sh
$ mypgtPrint
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2027, Physical addr: dee2027
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dee0007, Physical addr: dee0007
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8dedf007, Physical addr: dedf007
Entry number: 3, pgdir entry num: 0, Pgt entry num: 3, Virtual addr: 8dede007, Physical addr: dede007
Entry number: 4, pgdir entry num: 0, Pgt entry num: 4, Virtual addr: 8dedd007, Physical addr: dedd007
Entry number: 5, pgdir entry num: 0, Pgt entry num: 5, Virtual addr: 8dedc007, Physical addr: dedc007
Entry number: 6, pgdir entry num: 0, Pgt entry num: 6, Virtual addr: 8dedb007, Physical addr: dedb007
Entry number: 7, pgdir entry num: 0, Pgt entry num: 7, Virtual addr: 8deda007, Physical addr: deda007
Entry number: 8, pgdir entry num: 0, Pgt entry num: 8, Virtual addr: 8ded9007, Physical addr: ded9007
Entry number: 9, pgdir entry num: 0, Pgt entry num: 9, Virtual addr: 8ded8007, Physical addr: ded8007
Entry number: 10, pgdir entry num: 0, Pgt entry num: 10, Virtual addr: 8ded7007, Physical addr: ded7007
Entry number: 11, pgdir entry num: 0, Pgt entry num: 12, Virtual addr: 8ded5067, Physical addr: ded5067
$
```

Observations:

1. For the global array, on running the system call `mypgtPrint`, the number of valid entries does not change but the virtual and physical addresses change across multiple executions.
2. For the local array, on running the system call `mypgtPrint`, the number of valid entries does not change but the virtual and physical addresses change across multiple executions.
3. When there is no global/local array, the number of entries is 2. When we have the local array initialized, the number of entries is still 2 whereas when we have the global array, the number of entries is 12 (increases by 10). This is because for the global array, the data is initialized earlier only, and thus, we see an increase in the number of page table entries whereas for the local array, the data is stored on the heap and memory is allocated dynamically. Thus, there is no change in the number of page table entries.

Part-2: Implement demand paging

Implementation:

The changes made are:

1. In the file `exec.c`, modified line 52 so that memory is allocated only for the read-only code/data and not for dynamic variables. We are providing the required memory (line 54) but the memory allocation for the dynamic variables is done on demand.
2. In the file `trap.c`, modified the switch-case to check if the trap corresponds to a page fault and if that's the case, we are handling the fault. The way we handle the fault is to check if the faulting address is a valid address in the virtual memory range of the process or not first (line 86). If the faulting address is invalid, we print a message saying it is invalid address access. If it is valid, we allocate new memory (if it is 0, then there is no memory to allocate) and try to map pages. If this fails, then there are no pages to map meaning we cannot allocate memory. If all goes well, the message "`page fault occurred, doing demand paging for address: <virtual address>`" is printed.
3. In `vm.c`, removed the keyword static from the mappages function and declared the same function with the same argument list in `defs.h` so that the function can be used in `trap.c` while mapping newly allocated memory.
4. Implemented a user program names `mydemandPage.c` to exercise this condition which has a large-sized global array to check for the functioning of demand paging. This file also invokes the `pgtprint()` function periodically to check the number of valid page entries.
5. for the new file to be compiled and included, added `_mydemandPage\` in the makefile

Output:

(for a global array of size 3000)

```
Booting from Hard Disk..xv6...
cpu1: starting 1
cpu0: starting 0
sb: size 1000 nblocks 941 ninodes 200 nlog 30 logstart 2 inodestart 32 bmap start 58
init: starting sh
$ mydemandPage
global addr from user space: B20
page fault occurred, doing demand paging for address: 0x1000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 5, Virtual addr: 8dedf067, Physical addr: dedf067
page fault occurred, doing demand paging for address: 0x2000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 5, Virtual addr: 8dedf067, Physical addr: dedf067
page fault occurred, doing demand paging for address: 0x3000
Printing final page table:
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 3, Virtual addr: 8dfbf067, Physical addr: dfbf067
Entry number: 4, pgdir entry num: 0, Pgt entry num: 5, Virtual addr: 8dedf067, Physical addr: dedf067
Value: 2
$
```

(for a global array of size 5000)

```
Booting from Hard Disk..xv6...
cpu1: starting 1
cpu0: starting 0
sb: size 1000 nblocks 941 ninodes 200 nlog 30 logstart 2 inodestart 32 bmap start 58
init: starting sh
$ mydemandPage
global addr from user space: B20
page fault occurred, doing demand paging for address: 0x1000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 7, Virtual addr: 8dedf067, Physical addr: dedf067
page fault occurred, doing demand paging for address: 0x2000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 7, Virtual addr: 8dedf067, Physical addr: dedf067
page fault occurred, doing demand paging for address: 0x3000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 3, Virtual addr: 8dfbf067, Physical addr: dfbf067
Entry number: 4, pgdir entry num: 0, Pgt entry num: 7, Virtual addr: 8dedf067, Physical addr: dedf067
page fault occurred, doing demand paging for address: 0x4000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 3, Virtual addr: 8dfbf067, Physical addr: dfbf067
Entry number: 4, pgdir entry num: 0, Pgt entry num: 4, Virtual addr: 8dfc0067, Physical addr: dfc0067
Entry number: 5, pgdir entry num: 0, Pgt entry num: 7, Virtual addr: 8dedf067, Physical addr: dedf067
page fault occurred, doing demand paging for address: 0x5000
Printing final page table:
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 3, Virtual addr: 8dfbf067, Physical addr: dfbf067
Entry number: 4, pgdir entry num: 0, Pgt entry num: 4, Virtual addr: 8dfc0067, Physical addr: dfc0067
Entry number: 5, pgdir entry num: 0, Pgt entry num: 5, Virtual addr: 8dfc1067, Physical addr: dfc1067
Entry number: 6, pgdir entry num: 0, Pgt entry num: 7, Virtual addr: 8dedf067, Physical addr: dedf067
Value: 2
$
```

(for a global array of size 10000)

```
Booting from Hard Disk..xv6...
cpu1: starting 1
cpu0: starting 0
sb: size 1000 nblocks 941 ninodes 200 nlog 30 logstart 2 inodestart 32 bmap start 58
init: starting sh
$ mydemandPage
global addr from user space: B20
page fault occurred, doing demand paging for address: 0x1000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 12, Virtual addr: 8dedf067, Physical addr: dedf067
page fault occurred, doing demand paging for address: 0x2000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 12, Virtual addr: 8dedf067, Physical addr: dedf067
page fault occurred, doing demand paging for address: 0x3000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 3, Virtual addr: 8dfbf067, Physical addr: dfbf067
Entry number: 4, pgdir entry num: 0, Pgt entry num: 12, Virtual addr: 8dedf067, Physical addr: dedf067
page fault occurred, doing demand paging for address: 0x4000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 3, Virtual addr: 8dfbf067, Physical addr: dfbf067
Entry number: 4, pgdir entry num: 0, Pgt entry num: 4, Virtual addr: 8dfc0067, Physical addr: dfc0067
Entry number: 5, pgdir entry num: 0, Pgt entry num: 12, Virtual addr: 8dedf067, Physical addr: dedf067
page fault occurred, doing demand paging for address: 0x5000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 3, Virtual addr: 8dfbf067, Physical addr: dfbf067
Entry number: 4, pgdir entry num: 0, Pgt entry num: 4, Virtual addr: 8dfc0067, Physical addr: dfc0067
Entry number: 5, pgdir entry num: 0, Pgt entry num: 5, Virtual addr: 8dfc1067, Physical addr: dfc1067
Entry number: 6, pgdir entry num: 0, Pgt entry num: 12, Virtual addr: 8dedf067, Physical addr: dedf067
page fault occurred, doing demand paging for address: 0x6000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 3, Virtual addr: 8dfbf067, Physical addr: dfbf067
Entry number: 4, pgdir entry num: 0, Pgt entry num: 4, Virtual addr: 8dfc0067, Physical addr: dfc0067
Entry number: 5, pgdir entry num: 0, Pgt entry num: 5, Virtual addr: 8dfc1067, Physical addr: dfc1067
Entry number: 6, pgdir entry num: 0, Pgt entry num: 6, Virtual addr: 8dfc2067, Physical addr: dfc2067
Entry number: 7, pgdir entry num: 0, Pgt entry num: 12, Virtual addr: 8dedf067, Physical addr: dedf067
```

```
page fault occurred, doing demand paging for address: 0x7000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 3, Virtual addr: 8dfbf067, Physical addr: dfbf067
Entry number: 4, pgdir entry num: 0, Pgt entry num: 4, Virtual addr: 8dfc0067, Physical addr: dfc0067
Entry number: 5, pgdir entry num: 0, Pgt entry num: 5, Virtual addr: 8dfc1067, Physical addr: dfc1067
Entry number: 6, pgdir entry num: 0, Pgt entry num: 6, Virtual addr: 8dfc2067, Physical addr: dfc2067
Entry number: 7, pgdir entry num: 0, Pgt entry num: 7, Virtual addr: 8dfc3067, Physical addr: dfc3067
Entry number: 8, pgdir entry num: 0, Pgt entry num: 12, Virtual addr: 8dedf067, Physical addr: dedf067
page fault occurred, doing demand paging for address: 0x8000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 3, Virtual addr: 8dfbf067, Physical addr: dfbf067
Entry number: 4, pgdir entry num: 0, Pgt entry num: 4, Virtual addr: 8dfc0067, Physical addr: dfc0067
Entry number: 5, pgdir entry num: 0, Pgt entry num: 5, Virtual addr: 8dfc1067, Physical addr: dfc1067
Entry number: 6, pgdir entry num: 0, Pgt entry num: 6, Virtual addr: 8dfc2067, Physical addr: dfc2067
Entry number: 7, pgdir entry num: 0, Pgt entry num: 7, Virtual addr: 8dfc3067, Physical addr: dfc3067
Entry number: 8, pgdir entry num: 0, Pgt entry num: 8, Virtual addr: 8dfc4067, Physical addr: dfc4067
Entry number: 9, pgdir entry num: 0, Pgt entry num: 12, Virtual addr: 8dedf067, Physical addr: dedf067
page fault occurred, doing demand paging for address: 0x9000
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 3, Virtual addr: 8dfbf067, Physical addr: dfbf067
Entry number: 4, pgdir entry num: 0, Pgt entry num: 4, Virtual addr: 8dfc0067, Physical addr: dfc0067
Entry number: 5, pgdir entry num: 0, Pgt entry num: 5, Virtual addr: 8dfc1067, Physical addr: dfc1067
Entry number: 6, pgdir entry num: 0, Pgt entry num: 6, Virtual addr: 8dfc2067, Physical addr: dfc2067
Entry number: 7, pgdir entry num: 0, Pgt entry num: 7, Virtual addr: 8dfc3067, Physical addr: dfc3067
Entry number: 8, pgdir entry num: 0, Pgt entry num: 8, Virtual addr: 8dfc4067, Physical addr: dfc4067
Entry number: 9, pgdir entry num: 0, Pgt entry num: 9, Virtual addr: 8dfc5067, Physical addr: dfc5067
Entry number: 10, pgdir entry num: 0, Pgt entry num: 12, Virtual addr: 8dedf067, Physical addr: dedf067
page fault occurred, doing demand paging for address: 0xa000
Printing final page table:
Entry number: 0, pgdir entry num: 0, Pgt entry num: 0, Virtual addr: 8dee2067, Physical addr: dee2067
Entry number: 1, pgdir entry num: 0, Pgt entry num: 1, Virtual addr: 8dfbc067, Physical addr: dfbc067
Entry number: 2, pgdir entry num: 0, Pgt entry num: 2, Virtual addr: 8df76067, Physical addr: df76067
Entry number: 3, pgdir entry num: 0, Pgt entry num: 3, Virtual addr: 8dfbf067, Physical addr: dfbf067
Entry number: 4, pgdir entry num: 0, Pgt entry num: 4, Virtual addr: 8dfc0067, Physical addr: dfc0067
Entry number: 5, pgdir entry num: 0, Pgt entry num: 5, Virtual addr: 8dfc1067, Physical addr: dfc1067
Entry number: 6, pgdir entry num: 0, Pgt entry num: 6, Virtual addr: 8dfc2067, Physical addr: dfc2067
Entry number: 7, pgdir entry num: 0, Pgt entry num: 7, Virtual addr: 8dfc3067, Physical addr: dfc3067
Entry number: 8, pgdir entry num: 0, Pgt entry num: 8, Virtual addr: 8dfc4067, Physical addr: dfc4067
Entry number: 9, pgdir entry num: 0, Pgt entry num: 9, Virtual addr: 8dfc5067, Physical addr: dfc5067
Entry number: 10, pgdir entry num: 0, Pgt entry num: 10, Virtual addr: 8dfc6067, Physical addr: dfc6067
Entry number: 11, pgdir entry num: 0, Pgt entry num: 12, Virtual addr: 8dedf067, Physical addr: dedf067
Value: 2
$
```

Observations:

1. As we increase the size of the global array, the number of page faults increases linearly.
2. As we increase the size of the global array, the number of page table entries increases linearly.
3. The first and last virtual/physical addresses are the same for all sizes of the global array.

Learning:

Through this assignment, I have learnt how to access the page tables and their individual entries of the current process. I also learnt about ELF headers and various terms associated with the same which made me understand how to allocate different amounts of memory for the current process and allocate more memory upon demand for dynamically allocated variables. I also learnt how to trap errors and handle them efficiently.

Note: I have discussed with Dr. Rajesh Kedia, Tanmay Garg (cs20btech11063), and Aayush Patel (cs20btech11001) for part-2 of the above assignment.