# 1 2015 Paper 2 Question 4

https://www.cl.cam.ac.uk/teaching/exams/pastpapers/y2015p2q4.pdf

(a) What is a page fault?

A page fault is when a program attempts to access a page which is not in memory.

(b) What is a segment fault? What might be a sensible response to a segment fault on a stack segment?

When a process attempts to access memory outside it's allocated memory. A sensible response would be to terminate the process – access cannot be given for security reasons and the program may not (is unlikely to) work correctly without the required data – also it is obviously buggy if it is trying to access memory it has not been allocated.

(c) Describe the actions that follow after a page fault occurs. You should include those performed in hardware prior to a handler being started, and those that are taken within the handler. Your answer should include how segment faults might be detected and handled.

The hardware will raise a trap. The trap should find the page the program tried to access. It now needs a free frame. If there is one in the free frame list then we can simply take the head from the list. If the free frame list is empty then we must free a page. We do this by selecting a victim (based on criteria discussed below). We should then write the victim page to disk *if it has been modified* and mark the page as invalid. We then read the page the program tried to access from memory into the free page frame.

(d) What is page thrashing and how might it be avoided?

Page thrashing is when a system spends more time paging than executing. This occurs when the number of pages allocated to a system is less than it's working set.

There are two simple ways to avoid page thrashing:

- Reduce the degree of multiprocessing (kill or shelve some processses so that each process can have more memory).
- Give a process more pages either via prioritising it or assigning more pages from other less used processes.

Note that a better page replacement algorithm will not help – we are simply bottlenecked by the number of pages. If we have 2 pages and use 5 constantly and another 10 occasionally (ie has a working set of size 15) then we will be inundated with page faults whatever algorithm we use.

(e) Why is handling a page fault more complex than handling an interrupt or software trap?

Handling a page fault requires at least two memory accesses and a write while interrupts often require 0 and exceptions are the same. Assuming that main memory is full, we have to free a space, which in some implementations of page-faults requires passing throug every pages. At this point we have done $1 \leq n \leq k+1$ accesses where $k \leq n$ to find the desired page to remove. Then we must write it to memory and load the new page in from memory. This is a very expensive operation.

Exceptions and Interrupts do not require this level of memory access. Often they involve only one memory access (to load the handler).

# 2 2013 Paper 2 Question 4

https://www.cl.cam.ac.uk/teaching/exams/pastpapers/y2013p2q4.pdf

(a) What is the difference between a *logical* or *virtual* memory address and a physical memory address?

A physical memory address is the whole address in memory which is specific to the one time which a program was loaded into memory. A logical memory address is an offset from an unknown base which sum to give the physical memory address. Logical addresses are independent of loading. This means that pages know a relative position and do not need to know their absolute memorya ddress..

(b) Consider a variable which is bound to a single logical address for the duration of process execution. How is it possible for the variable to be bound to different physical addresses during process execution?

The process is swapped to disk midway through execution and then paged back in but to a different physical location. The variable itself has not been changed and so will keep the same logical address throughout, however since the program is stored in a new physical location, the variable has a new physical location (ie the base changes but offset stays the same so base + offset is different).

(c) In a demand paging system, what are the factors that can be taken into account when deciding which valid page should be made a victim?

Optimal victim-selection would select the page which will not be used for the longest amount of time in the future. We can approximate this fairly well by using "Least Recently Used" (LRU) paging to select the page which was used the longest ago. We can approximate LRU in several ways.

Depending on the specific implementation of demand-paging there are several features to take into account:

If we implement LRU using clock times then we should consider only the last time the clock accessed it (and whether that was before or after the most recent clock reset).

If we implement LRU by putting the most recently used node at the top of a stack each turn then all we need to consider whether the page is at the bottom of the stack to page it. This pagew will be the one which was used the least recently.

If LRU is approximated using the reference-bit / dirty-bit technique; we should consider:

- Whether the page was accessed in the last $\tau$ms where $\tau$ is a system-dependant constant.
- Whether the page has been written to since it was last loaded from/saved to memory (how expensive paging it out would be). This is signified by the reference bit being 1.

If we use the method where we record every $\tau$ milli-seconds whether a page has been accessed then the only factor that we need to put into consideration is the size of the reference integer. This integer should have its msb set to 1 whenever the page is accessed. Every $\tau$ milli-seconds this should then be bit-shifted to the right. This enables us to have an integer representation of how much a page has been used historically. When selecting the victim we should search for the page with the lowest reference integer.

If we use the "second-chance" method then the only consideration should be whether the page has a reference bit or not. If the page has a reference-bit then we should remove it and move onto the next page. If it does not have a reference-bit then we should select it as the victim.

(d) Consider a demand paging system in which hardware can trap unauthorised read or write accesses, but cannot perform any update to *use counts* or *written/dirty* bits. How can these be performed efficiently in software?

We can use Second-Chance FIFO to efficiently count with software. Second-Chance FIFO is a low-maintenance method to simulate Least-Recently-Used which can be implemented in software with minimal or no hardware support.

In Second-Chance FIFO, each page frame has a single bit to say whether it has been updated. Since we are only writing one bit to a page when we are accessing it – this is fast (unlike other methods where all pages must be updated every $\tau$ms etc). We maintain a single pointer to one element in the cyclic linked list. When searching for the victim page we pass through the list in one direction. For each page we check to see whether its reference bit is set to 0 or 1. If it set to 0 then it has not been accessed since the last check and the OS should trap and make it the victim page. If it is 1 then it has been accessed and we should change the bit to 0 and go onto the next page. This method guarantees that we will find a victim page after at most one pass through the linked list.

(e) What is copy-on-write? How can it be implemented in a demand paging system?

When a process forks, the new process requires access ot it's parents state. However, when we create this process we do not know whether it will be read-only or read-write. We assume that all shared memory is read-only until it requests to write to this memory. When this happens we should copy the page into memory and we will no longer share it. We should do this for each program sharing the memory.

This reduces the amount of memory copying that we have to do (since we no longer have to copy shared read-only data). Copy-on-Write also allows for lazy-shared memory – which can also reduce copying if for example one of the processes terminates without writing.

## 3 2009 Paper 2 Question 3

https://www.cl.cam.ac.uk/teaching/exams/pastpapers/y2009p2q3.pdf

(a) Operating systems typically provide each process with a virtual address space.

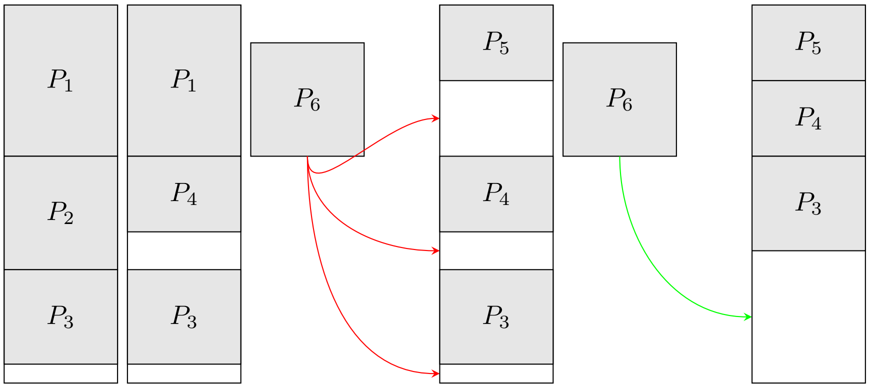
(i) Give *three* advantages of this.

- Programs never need to know their exact memory locations. This makes programming and compilation easier since we only need to consider our own address-space and not all the contents of a dynamic main memory.
- It is now far easier to determine whether a process is trying to access memory outside its address-space and it is significantly less likely for a program to attempt to do so accidentally. Note also that adding the base to the offset is very fast since it is supported by hardware and so the overhead is negligible.
- Since we do not need to know our exact memory location, we can page programs out of memory and reload them into different places without affecting execution (since the base registers remain the same and pages are abstracted from the program). Along the vein of loading programs into different memory locations; we never have to (or can) hardcode memory addresses and so programs can run on a wider range of machines with different sizes of RAM. For example if 95% of computers have 8GB of RAM then almost all programs would be programmed to work in that range. Hence having 16GB of RAM would be pointless since very few programs would use half of it.

(ii) In which circumstances does external fragmentation occur? How can it be managed?

We use segments, segments are removed. They are then partially filled. This leaves small spaces. We can use a heuristic memory allocation like best-fit to reduce the rate at which this happens and intermittently use compaction to solve this.

Below is an illustration of external fragmentation followed by compaction to resolve it.




(iii) In which circumstances does internal fragmentation occur?

Internal fragmentation happens in two situations: a very small program is allocated a page frame which is larger than itself. So a program which needs say 1kB takes up a 4kB page frame. Secondly when a larger program is split into multiple page frames – ie a 10kB program occupies three 4kB page frames (12kB total).

The second situation is more meaningful since when the large program is being executed, it will frequently refer to variables and code stored in the other page frames. This means that its working set will be multiple frames and so it will need to access a lot of data from multiple frames. If too many programs have large working sets this could cause issues with thrashing.

(iv) Design a multi-level page table for a computer with a 48-bit virtual address space, 48-bit physical address space, and a 4K page size. You should explain its operation, and justify your design decisions.

Since pages are 16KB, we require 16 bits to access each page. Since the higher levels are still pages of the same size, the overall page table must have three levels. We could implement a page table with a different number of levels – say 4, where the first three levels had 12 bit addressing and the last had 16. However this would mean that we would waste a lot of memory in the higher level tables and have much more complicated logic. So my implementation will have 3 tiers each with 16 bit addresses.

The first 16 bits of the address will access the page on the first level, the next 16 will access the page on the second level and the final 16 bits will be the offset in the page in which data is stored.

When we access one of the two highest pages, we will get the base address for the next page table. The address of that table will then be added as an offset. IE say our address is 150 100 90 (obviously addresses would actually be far higher and in binary). We will access position 150 in the first page table. This gives us a base for the next page table. Say 8192. So we now access position 8192 + 100 for the second table. This gives us another position. Say 4096. So we now access position 4096 + 90 and return the value stored there.

This system means that programs can hold up to $2^{48}$ bits of memory – allowing all realistic programs to run on all realistic home-computers. Note that the virtual address space (16TB) is far greater than the likely actual memory of the computer. This is okay since we do not allocate most of the pages. Most entries in the two higher page tables are null, meaning that we can use the memory for other programs (and only allocate memory in 4kB chunks). If the program tries to access unallocated memory then they will face a nullpointerexception – as they should. More memory can easily be allocated at the programs request by allocating new pages and filling in more pointers. In practice, the majority of programs the first page table will have one non-null entry leading to the second page table which will have several non-null entries.

This page table system means that we can abstract between where pages are physically stored and the address that the program asks for. This enables dynamic loading. In addition since the entries are null and the program only accesses memory through the page system, we are guaranteed that the program can only access its own memory. This solves the protection issue as well.