VIRTUAL MEMORY MANAGEMENT PART 3

CS124 – Operating Systems

Spring 2024, Lecture 20

Page Allocation Policy

- Previously covered a number of page replacement policies
  - Handle case when a page must be evicted to free up a frame
- The operating system also requires some number of frames…
  - For kernel code and data, I/O buffers, frames for use in interrupt handlers, etc.
- All remaining frames can be allocated to processes, but the OS must do this in an intelligent way
- The operating system can usually control two things:
  - How many frames are allocated to each process
  - The **degree of multiprogramming**: how many processes are currently running on system
- The **page allocation policy** determines how many page frames each running process should be given

Page Allocation Considerations

- The primary goal of the page allocation policy: make sure all processes have "enough" frames to perform their tasks
- Ideally, every process has all the frames it needs
  - Page faults only occur when a process begins accessing new data that isn't already in virtual memory
- Reality: try to keep the page fault rate to a reasonable level, so that we don't lose too much time to paging I/O
- When a given process page-faults, it slows down that process…
- In the context of multitasking, page faults aren't so bad:
  - When one process faults, it becomes blocked on I/O, allowing other ready processes to run
  - As long as I/O due to page faults doesn't become too large, the OS can continue to keep the CPU 100% utilized

Thrashing

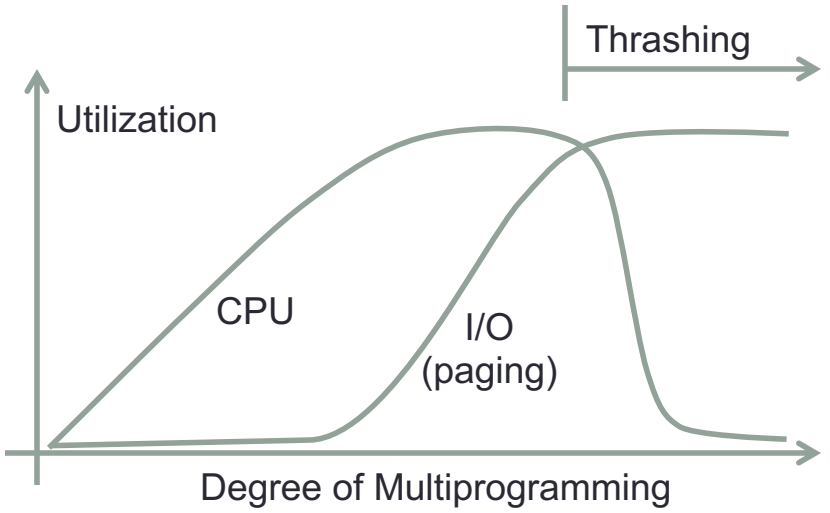
- If the amount of paging I/O grows so high that it begins to impede system performance, the system is **thrashing**
  - This term comes from when tapes were used for external storage
  - Describes the sound they would make when paging I/O was high
- An individual process can also be described as thrashing when it has a high page-fault rate
- Thrashing occurs when the total number of page frames that all processes are using, exceeds the total number of frames available in the system
- Every time a process generates a page fault, the OS evicts a page that some process is still actively using…
  - …which will provoke yet another page-fault again in the near future

Thrashing (2)

- Thrashing can occur unexpectedly as the resource requirements of processes change over time…
- Example: an OS running on a system with 20 physical page-frames available for applications to use
  - Four processes are running: each has a virtual address space of 10 pages, but each is only accessing 5 of those pages regularly
  - Requirement: 20 frames to hold pages. The system won't thrash.
- Then, two processes switch to accessing all 10 pages
  - Now the requirement is for 30 frames, but the system only has 20
  - The I/O overhead from page faults may become so high that CPU utilization may drop precipitously
- Depending on how the OS allocates pages, this scenario can cause all processes' page-fault rates to increase, even ones still only using 5 pages…

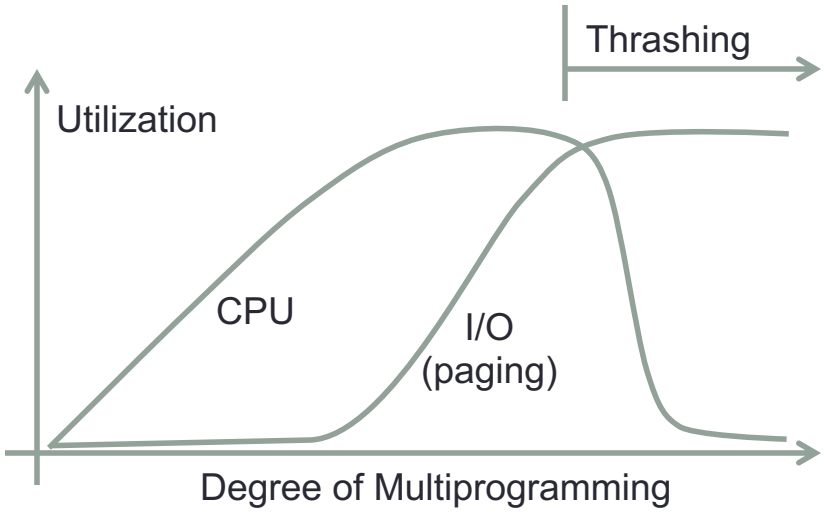
Faults and Degree of Multiprogramming

- Every process has a set of pages it is currently using
  - Called the **working set** of the process
- The “degree of multiprogramming” is the number of processes currently running on the system
- Generally, as we increase degree of multiprogramming, the demand for physical page frames also increases
  - The page fault rate also increases, and the I/O system must handle an increasing rate of page faults
- Eventually the I/O system is saturated, producing thrashing



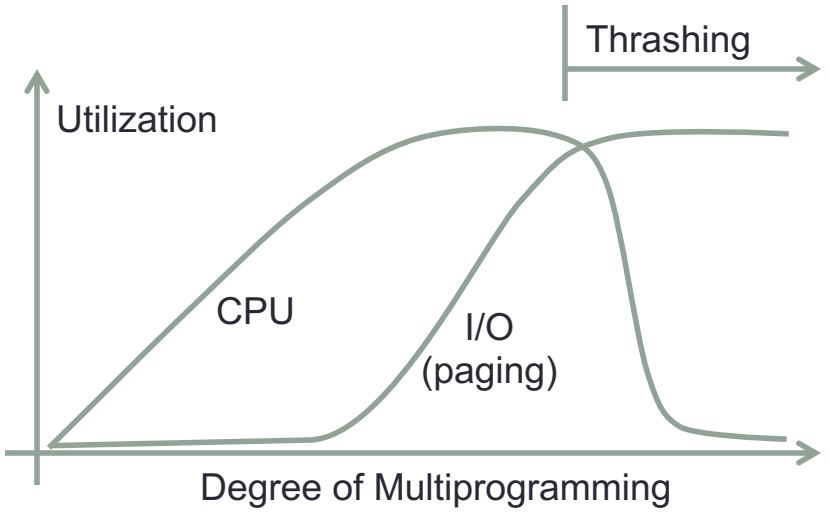
Degree of Multiprogramming (2)

- Some OSes can control the degree of multiprogramming
  - Recall: This is the role of long-term and medium-term scheduling
  - Long-term scheduling controls when new jobs are admitted into the system, and is usually part of batch-processing systems
  - Medium-term scheduling allows the OS to adjust the degree of multiprogramming by suspending running processes, then later resuming them
- Medium-term scheduling can be guided by page-fault rates
  - If system has too high a page-fault rate, remove some processes from memory to free up more frames
  - Later, reintroduce these processes when page-fault rates are lower



Degree of Multiprogramming (3)

- Most widespread operating systems rely on the user to control the degree of multiprogramming
  - The OS only includes a short-term scheduler
- OS allows the user to start whatever processes they want
- If performance becomes unacceptable (e.g. due to thrashing), the user simply terminates some processes



Global vs. Local Allocation Policies

- When a process needs a new frame, the operating system has two options
- A **global replacement** policy: the OS can acquire the new frame from any process that is currently running
  - Example: Process A causes a page fault. The OS evicts a page from Process B's set of pages, and assigns the frame to Process A.
  - The number of frames allocated to a given process can change (both grow and shrink) dynamically over time
- Strength: gives the OS much more flexibility in assigning frames to processes in memory, based on their needs
  - Frames won't be held onto by a process that isn't using them
- Limitation: a process' page-fault rate can be directly affected by other processes in the system
  - The performance of a given program may vary widely over time, simply due to the other programs running on the system

Global vs. Local Allocation Policies (2)

- A **local replacement** policy: the OS will acquire the new frame from the process that suffered the page-fault
  - Example: Process A causes a page fault. The OS evicts a page from Process A's own set of pages.
  - Generally, the set of frames assigned to a given process is much more static; it changes in much more limited ways over time
- Strength: if some process starts page-faulting frequently, it won't affect other processes nearly as much
- Limitation: number of frames assigned to each process isn't nearly as finely tuned as it is with global allocation

- Most operating systems use a global replacement policy

Simple Page Allocation Policies

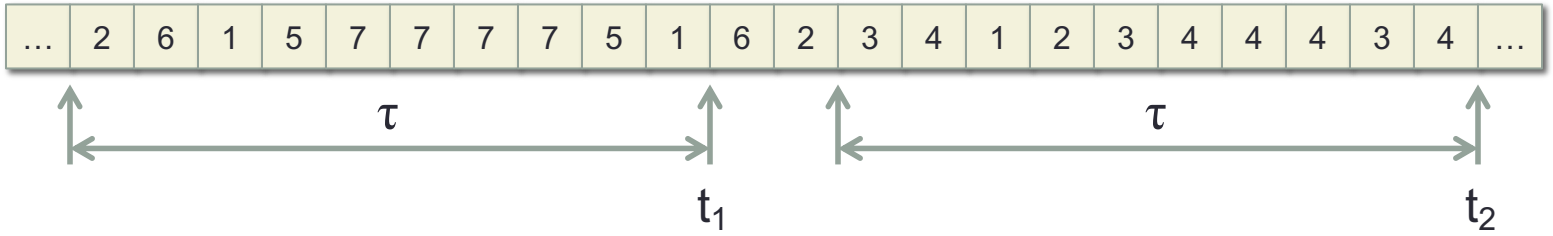
- Some page allocation policies are very simple
  - e.g. given a total of *m* frames available to *n* processes
- An **equal allocation policy** assigns each process roughly *m* / *n* frames
- Some programs have a larger virtual address space than others – equal allocation doesn't always make sense…
  - e.g. a given process p_i has a virtual address space of size s_i
  - The sum of all process virtual memory sizes is $S = \Sigma s_i$
- A **proportional allocation policy** assigns each process a number of frames proportional to its virtual memory size
  - Each process is assigned roughly $m \times s_i / S$ frames
- These policies make most sense with a local replacement policy; each process has basically static frame allocation

Simple Page Allocation Policies (2)

- As degree of multiprogramming increases, each process ends up with fewer and fewer frames to use
  - Equal allocation policy: each process gets m / n frames; n is the degree of multiprogramming
  - Proportional allocation policy: the sum of all process virtual memory sizes S increases as degree of multiprogramming increases; each process gets roughly $m \times s_i / S$ frames
- Frames for new processes must come from somewhere... unfortunately, that's all the other processes
- In these systems, medium-term scheduling can be used to eliminate thrashing
  - Suspend some processes until thrashing issues disappear
  - Resume these processes later when system load is lower

The Working Set Model

- Previous strategies aren't designed to handle variations in process page-frame requirements
- Would prefer to determine the requirements of each process much more dynamically
- One option: quantify the size of each process' working set
  - The set of pages that the process is currently working with
  - As a program runs, its working set changes
- A process' working set is difficult to determine…
- Estimate it by looking at all recent memory accesses within a given window
  - A proper choice of τ is essential for a good estimate



The Working Set Model (2)

- Can estimate a process' working set with a mechanism very similar to the Aging page-replacement policy
  - Requires that the MMU maintains an "accessed" bit for each page
- The OS maintains a *b*-bit value for each page
- On a periodic timer interrupt, the OS traverses all pages in memory, updating this value
  - Shift the value right, store "accessed" bit into topmost bit of value, then clear the page's "accessed" bit
- If a process' page has a nonzero value, it's in the process' working set
  - Can easily count how many pages are in each process' working set
- Main difference between this and the Aging policy is that the timer interval is much longer
  - e.g. might only want 2-4 interrupts during the working set window

The Working Set Model (3)

- Once each process' working set is known (or guessed), OS can use this to set the degree of multiprogramming
  - If the working sets of all processes requires fewer frames than the system has available, add more processes!
  - Or, if the working sets of all processes don't fit within the system's memory, suspend processes until all working sets fit within memory
  - (Can suspend lower-priority processes to allow higher-priority ones to finish more quickly)
- This approach works very well in practice
- This model also does a great job of driving **prepaging** of processes when they are unblocked or resumed
  - Instead of waiting for pages to be demanded, preemptively start loading a process' working set back into physical memory
  - If working-set estimate is good, should greatly reduce page faults

Page-Fault Frequency

- So far, these page allocation policies primarily make sense in the context of medium-term scheduling
  - Operating systems that can control degree of multiprogramming
- Most widespread operating systems don't actually have a long-term or medium-term scheduler
- Instead, they rely on the **page-fault frequency** of various processes to determine when to assign more frames
  - i.e. how often is a given process generating page faults?
- If a process' page-fault frequency is too high, give it more frames
  - Take frames away from processes with a low page-fault frequency
  - Premise: they may have more frames than their working set size

Page-Fault Frequency (2)

- The pager can aim to keep processes' page-fault frequency within a specific "desirable range"
  - Specify a lower- and upper-bound on page-fault rate
- If a process' page-fault rate exceeds the upper bound, the OS assigns it more frames
- If a process is below the lower bound, the OS considers it a candidate for giving up frames
  - e.g. with page buffering, OS might reclaim frames and move them into free page-frame pool
- If the process is in the desirable page-fault frequency range, the OS can use other page replacement policies
  - e.g. LRU, aging, etc.
  - This can be done in a local way, to avoid affecting other processes

Page-Fault Frequency (3)

- Of course, using page-fault frequency approach won't necessarily prevent thrashing…
- The OS may still benefit from medium-term scheduling techniques to free up more frames for processes
  - e.g. if page-fault frequency of many processes is high, just suspend one or more processes and use their frames for other processes

Modern OSes and Page Allocation

- Most widely used operating systems don't have a very sophisticated page allocation policy
- Instead, they rely on a more sophisticated page replacement policy with global replacement
- Just let users run the programs they want to run…
  - When system performance become unacceptable, the user will kill or exit some of the running processes
  - (The user is the medium/long-term scheduler)
- If a process remains blocked for a long time (e.g. waiting for user interaction):
  - If other processes need more frames, they will be taken from the blocked process
  - The process will eventually be completely paged out of memory
  - All of the process' frames will become available to other processes

Example: Linux

- Linux has a straightforward virtual memory policy:
- Pages are never allocated to a process until they are used
  - e.g. programs are referenced in the process' virtual memory mapping, but are demand-paged into physical memory
  - e.g. heap and stack pages aren't allocated to a process until it actually references the page
    - **Demand-zero paging**: a page is taken from the free-page pool and cleared with all zeros
- Linux uses a modified form of the Clock algorithm that maintains an age for every page
  - Pages are periodically traversed, and ages adjusted based on whether or not they have been accessed recently
    - Ages decay to zero; higher ages indicate frequent recent accesses
  - Pages with a low age value will be reclaimed by the system
  - Allows Linux to implement a policy that considers page-access recency *and* frequency

Example: Windows

- Windows generally relies on processes to state their “working set” sizes
  - Windows calls it the “working set,” but it’s actually the **resident set**; the number of pages the process has in physical memory
  - If the process’ actual working set (not the Windows definition) is larger than its resident set, the process will incur many page-faults
- Processes are given a default minimum and maximum “working set” size
  - e.g. default minimum is 50 pages or 200KiB, default maximum is 345 pages or ~1.3MiB
  - A process can have a larger virtual address space than this…
- Processes may also specify their minimum and maximum “working set” sizes
  - Limits are applied, e.g. a hard minimum of 20 pages, etc.

Example: Windows (2)

- If the page-fault rate becomes unacceptably high, Windows will **trim** the "working sets" of all processes
  - (Again, Windows "working set" means the resident set)
- When trimming, Windows sets goal for page reclamation
  - Sets it slightly higher than what is strictly required, so that trimming doesn't have to run multiple times
- Pages in each process' working set are periodically aged based on recent accesses
  - In Windows 7, each page has one of up to 8 age values
- Oldest pages are reclaimed first to avoid further faults
- Trimming culls pages from all processes, even if trim goal is reached partway through the procedure
  - Ensures that page reclamation is fair to all processes

Example: Windows and Linux

- Both Windows and Linux use free page-frame pools
- When pages are reclaimed by the virtual memory system, they are added to clean or modified pools
  - Modified pages are eventually written out, then moved to the clean pool
- If a process page-faults on a page in one of these pools, the page will usually be reassigned back to the process

Next Time

- Start discussing file systems