Virtual Memory Wrap Up
Multi-Level Page Tables

- Multiple levels of tables are used to look up a physical memory address.
Multi-Level Page Tables

- Each virtual address can now be divided into \( (n+1) \) different pieces for an \( (n) \) level page table.
  - **Example:** Two Level Page Table:
    - First Level Page Number (directory)
    - Second Level Page Number (page)
    - Page Offset (offset)
Multi-Level Page Tables: class exercise

- Given
  - 32-bit Virtual Addresses
  - 4 KB Pages
  - 12-bit First Level Page Number (directory)

- What are the components of the address: 0x48503423
Given
- 32-bit Virtual Addresses
- 4 KB Pages
- 12-bit First Level Page Number (directory)

What are the components of the address: \(0x48503423\)

- 0x485 (directory), 0x03 (page), 0x423 (offset)
Multi-Level Page Tables: class exercise

- Given
  - 32-bit Virtual Addresses
  - 64 KB Pages
  - 8-bit First Level Page Table Number (directory)

- What are the components of the address: 

  \(0x48503423\)
Multi-Level Page Tables: class exercise

- Given
  - 32-bit Virtual Addresses
  - 64 KB Pages
  - 8-bit First Level Page Table Number (directory)

- What are the components of the address: 0x48503423
  - 0x48 (directory), 0x50 (page), 0x3423 (offset)
Given
- 32-bit Virtual Addresses
- 4 KB Pages
- 4 B page table entries

If every-level page table fits into a single page:
- How many levels are in the page table?
- How many bits is the index of each level?
Given
- 32-bit Virtual Addresses
- 4 KB Pages
- 4 B page table entries

If every-level page table fits into a single page:
- How many levels are in the page table? 2
- How many bits is the index of each level? 10
### Class exercise

**Given:**
- Each PTE is 16 B
- The pointer to top-level of the page table is 0x1000.
- *: “PTE Content” shows the contents of the memory if it was read as a PTE, and only shows the address field of the PTE.

**Q: On system with a single-level page table and 256 B pages:**
- What is the physical address of the virtual address 0x0241?
Class exercise

Given:
- Each PTE is 16 B
- The pointer to top-level of the page table is 0x1000.
- *: “PTE Content” shows the contents of the memory if it was read as a PTE, and only shows the address field of the PTE.

Q: On system with a single-level page table and 256 B pages:
- What is the physical address of the virtual address 0x0241?
  ➔ physical address: 0x2241
Given:
- Each PTE is 16 B
- The pointer to top-level of the page table is 0x1000.
- *: “PTE Content” shows the contents of the memory if it was read as a PTE, and only shows the address field of the PTE.

Q: On system with a two-level page table where the index of each level is 4-bits:
- What is the physical address of the virtual address 0x1234?
Class exercise

- **Given:**
  - Each PTE is 16 B
  - The pointer to top-level of the page table is **0x1000**.
  - *: “PTE Content” shows the contents of the memory if it was read as a PTE, and only shows the address field of the PTE.

- **Q:** On system with a two-level page table where the index of each level is 4-bits:
  - What is the physical address of the virtual address **0x1234**?
    - physical address: **0x6034**
What is memory trashing?

- Thrashing: as number of page frames per process decreases, the page fault rate increases.
  - Each time one page is brought in, another page, whose contents will soon be referenced, is thrown out.
  - Processes will spend all of their time blocked, waiting for pages to be fetched from disk.
  - I/O utilization at 100% but the system is not getting much useful work done.
  - CPU is mostly idle.
Why Trashing

- Computation has locality

- As number of page frames allocated to a process decreases, the page frames available are not enough to contain the locality of the process.

- The processes experience heavy page faulting
  - Pages that are paged in, are used and immediately paged out.
Level of multiprogramming

- Load control has the important function of deciding how many processes will be resident in main memory
- What are the trade-offs involved?
Level of multiprogramming

- What are the trade-offs involved?
  - If too few processes are resident in memory, it can happen that all processes resident in memory are blocked so swapping is necessary and CPU is left idle.
  - If too many processes are resident, then the average size of the resident set of each process will be insufficient triggering frequent page faults.

![Graph showing CPU Utilization vs. Degree of Multiprogramming with a threshold marked as Thrashing.](image)
Main idea
- figure out how much memory a process needs to keep most of its recent computation in memory with very few page faults

How?
- The working set model assumes temporal locality
- Recently accessed pages are more likely to be accessed again

Thus, as the number of page frames increases above some threshold, the page fault rate will drop dramatically
Working set (1968, Denning)

- What we want to know: collection of pages process must have in order to avoid thrashing
  - This requires knowing the future. And our trick is?

- Intuition of Working Set:
  - Pages referenced by process during last interval of execution are considered to comprise its working set
  - $\Delta$: the working set window

- Usages of working set?
  - Cache partitioning: give each application enough space for WS
  - Page replacement: preferably discard non-WS pages
  - Scheduling: a process is not executed unless its WS is in memory
Page Fault Rate vs. Allocated Frames

Page Rate for System

Trashing

Working Set size

Number of Page Frames

Total number of pages in process

Page Fault Rate

N

Total number of pages in process

W

Working Set size

Trashing

Strategy for sizing the resident set of a process based on Working set

- Keep track of working set of each process
- Periodically remove from the resident set the pages that don’t belong to working set anymore
- A process is scheduled for execution only if its working set is in main memory
Working Set Size

Choosing

- \( \Delta \) too small
  - Will not encompass entire locality

- \( \Delta \) too large
  - Will encompass several localities

- \( \Delta = \infty \)
  - Will encompass entire program
Typical programs have phases

Working sets of real programs
Page Size Considerations

- Page size is a crucial parameter for performance of virtual memory

- Small pages
  - Large page tables
  - Minimizes internal fragmentation
  - Good for locality of reference

- Large pages
  - Small page tables
  - Significant amounts of a page may not be referenced
  - Locality is not well exploited anymore and page fault rate increases

- Real systems (can be reconfigured)
  - Windows: default 8KB
  - Linux: default 4 KB