Virtual Memory - giving the illusion of more physical memory than there really is (via demand paging).

Pure Paging - The total program is kept in memory as sets of (non-contiguous) pages.
- No illusion of virtual memory.

Demand Paging - A program’s “working set” is kept in memory, reference outside WS causes corresponding code to be retrieved from disk (“page fault”).
- Provides the illusion of virtual memory.

Processes (programs) are divided into fixed size pieces called Pages.
- Main memory is divided into fixed size partitions called Blocks (Page Frames).
- Pure Paging - entire program is kept in memory during execution, but pages are not kept in contiguous blocks.
- Demand paging - only parts of program kept in memory during execution, pages are not kept in contiguous blocks.

A virtual address is represented as <page, offset> where the page is determined by dividing each process into fixed size pages, the offset is a number in the range 0 - (page_size-1).
- Memory is divided into fixed size blocks (or page frames) and accommodates a process’ pages. The physical address (PA) then is (block_number * page_size + offset).
- In pure paging systems the entire VA space of a process must reside in physical memory during execution, but pages are not kept in contiguous blocks.

Virtual Address to Physical Address Mapping

<table>
<thead>
<tr>
<th>Page</th>
<th>VA to PA mapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Page 0</td>
<td>0 - p-1</td>
</tr>
<tr>
<td>Page 1</td>
<td>p - 2p-1</td>
</tr>
<tr>
<td>Page 2</td>
<td>2p - 3p-1</td>
</tr>
<tr>
<td>Page 3</td>
<td>3p - 4p-1</td>
</tr>
<tr>
<td>Page 4</td>
<td>4p - 5p-1</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Program divided into Pages of size “p”.
**Key Idea in Paging Systems**

- **CPU**
  - Compiled Address
- **Address Translator**
  - Determines VA
  - Maps VA to PA
- **Memory**
  - PA

Assume 256 bytes per page:

<table>
<thead>
<tr>
<th>VA</th>
<th>Page number</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8 bits</td>
<td></td>
</tr>
</tbody>
</table>

**Addressing Scheme**

- **Base addr of PMT**
- **Page Number**
- **Displacement**
- **Virtual Address** $v = (p, d)$
- **Physical Address** $PA = (b \times \text{page size}) + d$

**Paging Mapping Example**

<table>
<thead>
<tr>
<th>PMT’s Page Block</th>
<th>MBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job 1</td>
<td></td>
</tr>
<tr>
<td>0 3</td>
<td>OS</td>
</tr>
<tr>
<td>1 5</td>
<td>J1 P2</td>
</tr>
<tr>
<td>2 1</td>
<td>J2 P0</td>
</tr>
<tr>
<td>Job 2</td>
<td></td>
</tr>
<tr>
<td>0 2</td>
<td>J1 P0</td>
</tr>
<tr>
<td>1 6</td>
<td>J3 P0</td>
</tr>
<tr>
<td>Job 3</td>
<td></td>
</tr>
<tr>
<td>0 4</td>
<td>J1 P1</td>
</tr>
<tr>
<td>1 8</td>
<td>J2 P1</td>
</tr>
<tr>
<td>2 7</td>
<td>J3 P1</td>
</tr>
</tbody>
</table>

**Page Management**

**Page Map Table (PMT):**
- Contains VA page to PA block mapping

<table>
<thead>
<tr>
<th>Page</th>
<th>Block</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
</tr>
</tbody>
</table>

**Page Map Table Address Register (PMTAR):**

- Length of program in pages (entries)
- Base address of current PMT

- Points to PMT for currently executing job
  - 1 PMTAR / System
Maps each block of main memory either to a process id and page number or to "free"

- Memory Block Table (MBT)
  - 1 MBT / System
  - 1 Entry / Block

Process (Job) Control Block (PCB)
- Contains information about all jobs in the system
  - Stores: Job Size
  - Location of PMT
  - 1 PCB / system
  - 1 entry / job

Page Addressing - Let's get REAL
- VA = < page, offset >
- PA = block size * block + offset
- Assume:
  - 1 word PMT entries;
  - byte addressable MM
- Example:
  - page & block size = 4 K bytes
  - VA = < 1, 1234 >
  - PA = 4096 * 16 + 1234

Determining Virtual Address <Page, Offset> from the Compiled Address
- Compiled Address (relative to 0): 18087
- Page size: 2K (2048 bytes)
- Memory is byte addressable
- Virtual Address:
  - Page = Div (Compiled Address, Page Size)
  - Offset = MOD (Compiled Address, Page Size)
  - <8, 1703>

Review Questions
- Assume:
  - 2 bytes PMT entries; byte addressable MM
  - page & block size = 4 K bytes
1) What is the maximum size for any program?
2) What VA corresponds to compiled address 220945?
3) What is the MBT length if MM size is 80M?
   (Assume MBT entries are 2 bytes long.)
4) What is the PMT length if compiled size = 300K?

Allocating Pages
- procedure allocation (int Size) {
  NPpgm := ceiling ( Size / WS );
  NPPmt := ceiling ( (NPPgm * WS) / P );
  NPTot := NPPgm + NPPmt;
  If ( NPTot > MaxBlocks ) Then ERROR
  Else If ( NPTot blocks are not free in MBT )
  Then Add job to HOLDQ;
  Else {
    Allocate pages to blocks;
    Update MBT, PCB;
    Create, initialize PMT;
  }
}
Sharing Pages of Reentrant Code or Data Between Processes

Advantages:
- Efficient memory usage
- Simple partition management due to discontiguous loading and fixed partition size
- No compaction necessary
- Easy to share pages

Disadvantages:
- Job Size <= Memory Size
- Internal fragmentation (half the page size on the average)
- Need special hardware for address translation
- Some main memory space used for PMT's
- Address translation lengthens memory cycle times

Pros/Cons of Paging

Pros/Cons of Paging...

Disadvantages:
- Job Size <= Memory Size
- Internal fragmentation (half the page size on the average)
- Need special hardware for address translation
- Some main memory space used for PMT's
- Address translation lengthens memory cycle times

Demand Paging

Jobs are paged, but not all pages have to be in memory at the same time

VIRTUAL MEMORY
- The operating system creates the illusion of more memory
- Job size can exceed main memory size

- Pages are only brought in when referenced (on demand)
- Often page 0 is loaded initially when a job is scheduled

Demand Paging Motivation

Terminology

Page fault:
- Interrupt that arises upon a reference to a page that is not in main memory.

Page swapping:
- Replacement of one page in memory by another page in response to a page fault.
When a Page Fault Occurs

- Select a page to be removed
- Copy it to disk if it has been changed **
- Update old page's PMT **
- Copy new page to main memory
- Update new page's PMT
- Update MBT **

Thrashing occurs when a job continuously references pages which are not in main memory

Demand Page Management

Page Map Table (PMT)
Maps page to blocks
Status: Pointer to Main Memory Block
Indicator Main|Secondary Memory PMT for the Disk

Memory Block Table (MBT)
Maps block to page
Contains: Job/Page Number Reference bit Change bit

File Map Table (FMT)
Maps a job's pages to secondary memory
1 FMT / job
1 entry / page

Demand Paging Schematic

Demand Paging Data Structures

Summary of Data Structures

1) Page Map Table (PMT): Maps page to block
   Fields:
   - Page number (which page in memory)
   - In, Memory <- New
2) Memory Block Table (MBT): Maps block to either process id and page number or to "free"
   Fields:
   - New!
   - Reference Count
   - Change Bit
3) File Map Table (FMT): Maps a job's pages to secondary memory (like a PMT for the disk) <- New!
   1 FMT / job, 1 entry / page

Page Replacement

Now we consider the decision of selecting which page to replace upon a page fault.

Local versus Global Page Replacement

Local
Requires that each process remove a page from its own set of allocated blocks

Global
A replacement page may be selected from the set of all blocks
Question: Does a program need all its pages in main memory at all times?

The Principle of Locality

At any time, the locality of a process is the set of pages that are actively being used together.

Spatial
- There is a high probability that once a location is referenced, the one after it will be accessed in the near future.
  - Sequential code, Array processing, Code within a loop

Temporal
- A referenced location is likely to be accessed again in the near future.
  - Loop indices, Single data elements

More on Locality

Does a linked list help or hurt locality?

Does a recursive function display spatial or temporal locality?

Working Set Theory (Formalizes "Locality")

- A process' working set is the number of pages currently being referenced during \((t, t + \Delta)\) for some small \(\Delta\).
- The working set size is an estimate of degree of locality.
- A job should not be scheduled unless there is room for its entire working set.
  - Why?

Idea Behind Working Set

Motivation: Page Replacement Algorithms

Which page replacement rule should we use to give the minimum page fault rate?

Page fault rate = \# faults / \#refs
Page Replacement Algorithm: Optimal Replacement
- Replace the page which will not be used for the longest period of time
- Lowest page fault rate of all algorithms
- Requires knowledge of the future

Example:
MM has 3 blocks containing 3, 5, 2.
Current and future refs: 4, 3, 3, 4, 2, 3, 4, 5, 1, 3, 4
OPT replaces 5

Optimal Replacement Algorithm

Replacement Algorithm: FIFO
- Replace the "oldest" page
- A frequently used page may be swapped out

Belady's Anomaly:
For some page replacement algorithms, the page fault rate may increase as the number of blocks increase

FIFO Page Replacement

Replacement Algorithms: Least Recently Used (LRU)
- Uses the recent past as an approximation of the near future
- Stack algorithm
  - Does NOT suffer from Belady's Anomaly
- Hardware / Overhead intensive

Least Recently Used (LRU)
Replacement Algorithms:
**LRU Approximation**

- Uses reference bits in the MBT and a static reference pointer (RP)
- The reference pointer is not reinitialized between calls to LRU Approximation
- Set referenced bit to 1 when loading a page
- Set referenced bit to 1 on a R/W
- Set referenced bit to 0 if currently a 1 and scanning for a replacement page
- Replace page with reference bit = 0

**LRU Approximation Algorithm...**

Initially: RP = -1

begin
RP := (RP + 1) mod MBTSize;
While (MBT[RP].Referenced = 1) Do
Begin
MBT[RP].Referenced := 0
RP := (RP + 1) mod MBTSize;
End
return(RP);
end

Note: referenced bit is set to 1 when a page is
(a) referenced, and
(b) when first loaded into memory
RP always points to last page replaced

---

**LRU Approximation**

<table>
<thead>
<tr>
<th>Page Trace</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block Number</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

# Page Faults = 
Page Fault Rate =

---

**Replacement Algorithms: Least Frequently Used (LFU)**

- Keep a reference count, select page with lowest count
- Reference count is number of times a page has been referenced over its current stay in memory, **not** over the lifetime of the program

<table>
<thead>
<tr>
<th>Page Trace</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block Number</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

# Page Faults =

---

**Pros/Cons of Demand Paging**

**Advantages:**
- Can run program larger than physical memory
- Allows higher multiprogramming level than pure paging
- Efficient memory usage
- No compaction is required
- Portions of process that are never called are never loaded
- Simple partition management due to discontinuous loading and fixed partition size
- Easy to share pages

**Disadvantages:**
- Internal fragmentation
- Program turnaround time increases each time a page is replaced, then reloaded
- Need special address translation hardware