Virtual Memory

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Announcements

• A4 is due 11:59pm, Thursday, November 18

• Remember to let us know about slip days

• Also remember to type the dot when running the turn-in script

• The first commercially produced microprocessor, the Intel 4004, was released 50 years ago today!
Multiprocessing Illustration

Memory

Process 1
- Stack
- Heap
- Data
- Code

Process 2
- Stack
- Heap
- Data
- Code

Process N
- Stack
- Heap
- Data
- Code

CPU
- Registers
Problem 1: Space

Memory

Process 1
- Stack
- Heap
- Data
- Code

Process 2
- Stack
- Heap
- Data
- Code

Process N
- Stack
- Heap
- Data
- Code
Problem 1: Space

- **Space:**
  - Each process’s address space is huge (64-bit): can memory hold it (16GB is just 34-bit)?
  - $2^{48}$ bytes is 256 TB
  - There are multiple processes, increasing the storage requirement further
Recall: Memory Hierarchy

• Solution: store all the data in disk (several TBs typically), and use memory only for most recently used data
  
  • Of course if a process uses all its address space that won’t be enough, but usually a process won’t use all 64 bits. So it’s OK.
Recall: Memory Hierarchy

Solution: store all the data in disk (several TBs typically), and use memory only for most recently used data

Of course if a process uses all its address space that won’t be enough, but usually a process won’t use all 64 bits. So it’s OK.

Challenge: who is moving data back and forth between the DRAM/main memory/physical memory and the disk?
Problem 2: Security

- Different programs/processes will share the same physical memory
  - Or even different uses. A CSUG machine is accessed by all students, but there is one single physical memory!
- What if a malicious program steals/modifies data from your program?
  - If the malicious program get the address of the memory that stores your password, should it be able to access it? If not, how to prevent it?
- We need isolation.
One Way to Isolate: Segments

Different processes will have exclusive access to just one part of the physical memory. This is called **Segments**.

Need a base register and a bound register for each process. Not widely used today. x86 still supports it (backward compatibility!)

Fast but not flexible. Makes benign sharing hard.

![Diagram](image-url)
Problem 3: Fragmentation (with Segments)

- Each process gets a continuous chunk of memory. Inflexible.
- What if a process requests more space than any continuous chunk in memory but smaller than the total free memory?
  - This is called “fragmentation”; will talk about this more later.
- Need to allow assigning discontinuous chunks of memory to processes.
Problem 4: Benign Sharing (with Segments)

- Different programs/processes will share same data: files, libraries, etc.
- No need to have separate copies in the physical memory.
- Would be good to let other processes access part of the current’s process’ memory based on the “permission”.

![Diagram showing CPU, Registers, Cache, Main/Physical Memory, and Hard Disk/SSD with stdlib.so shared between Program 1 and Program 2]
The Big Idea: Virtual Memory

Virtual Memory of Process 1

Virtual Memory of Process 2

Process 1

Process 2

Hard Drive

Physical/Main Memory
“Cache” Data in Physical Memory

Virtual Memory of Process 1

99
100
101
102
103
104
105

Data 1
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Allow Using Discontinuous Allocation

Virtual Memory of Process 1

Virtual Memory of Process 2

Physical/Main Memory

Hard Drive
Allow Using Discontinuous Allocation
Page Table

Virtual Memory of Process 1

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Virtual Memory of Process 2

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Physical/Main Memory

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Hard Drive

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Demand Paging

Virtual Memory of Process 1

99
Unallocated
100
Data 1
101
Data X
102
Data 2
103 ...
104 ...
105 ...

Page Table

Invalid
1
A
4
B
C
D

Physical/Main Memory

1
Data 1
2
3
4
Data 2

Virtual Memory of Process 2

99 ...
100 ...
101 ...
102 ...
103 ...
104 ...
105 ...

Hard Drive

A
Data X
B ...
C ...
D ...

Process 1

Process 2
Demand Paging

Virtual Memory of Process 1

| 99 | Unallocated |
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| 101 | Data X |
| 102 | Data 2 |
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| 104 | ... |
| 105 | ... |

Virtual Memory of Process 2

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| 104 |
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Page Table

| 1 |
| A |
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Physical/Main Memory

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| A |
| B |
| C |
| D |

Hard Drive

A | Data X |
B | ... |
C | ... |
D | ... |
Demand Paging

Virtual Memory of Process 1

Process 1

Virtual Memory of Process 2

Process 2

Page Table

Physical/Main Memory

Hard Drive
Demand Paging

Virtual Memory of Process 1

- 99: Unallocated
- 100: Data 1
- 101: Data X
- 102: Data 2
- 103:
- 104:
- 105:

Page Table

- Invalid
- 1
- 2
- 4
- B
- C
- D

Virtual Memory of Process 2

- 99
- 100
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- 102
- 103
- 104
- 105

Physical/Main Memory

- 1: Data 1
- 2: Data X
- 3
- 4: Data 2

Hard Drive

- A: Data X
- B:
- C:
- D:

Process 1

- Arrow pointing to 102: Data 2

Process 2
Prevent Unwanted Sharing
Prevent Unwanted Sharing
Enable Benign Sharing

Virtual Memory of Process 1

<table>
<thead>
<tr>
<th>99</th>
<th>Unallocated</th>
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<tbody>
<tr>
<td>100</td>
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Virtual Memory of Process 2

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<td>100</td>
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<td>102</td>
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Page Table of Process 1

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Page Table of Process 2

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Physical/Main Memory

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Hard Drive

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Analogy for Virtual Memory: A Secure Hotel
Analogy for Virtual Memory: A Secure Hotel

• Call a hotel looking for a guest; what happens?
  • Front desk routes call to room, does not give out room number
  • Guest’s name is a virtual address
  • Room number is physical address
  • Front desk is doing address translation!
Analogy for Virtual Memory: A Secure Hotel

• Call a hotel looking for a guest; what happens?
  • Front desk routes call to room, does not give out room number
  • Guest’s name is a virtual address
  • Room number is physical address
  • Front desk is doing address translation!

• Benefits
  • **Ease of management**: Guest could change rooms (physical address). You can still find her without knowing it
  • **Protection**: Guest could have block on calls, block on calls from specific callers (permissions)
  • **Sharing**: Multiple guests (virtual addresses) can share the same room (physical address)
A System Using Physical Memory Only

- Used in “simple” systems like embedded microcontrollers in devices like cars, elevators, and digital picture frames
A System Using Virtual Memory

Used in all modern servers, laptops, and smart phones
One of the great ideas in computer science (back in the 60s)
The Big Idea: Virtual Memory
The Big Idea: Virtual Memory

• What Does a Programmer Want?
  • Infinitely large, infinitely fast memory
  • Strong isolation between processes to prevent unwanted sharing
  • Enable wanted sharing
The Big Idea: Virtual Memory

• What Does a Programmer Want?
  • Infinitely large, infinitely fast memory
  • Strong isolation between processes to prevent unwanted sharing
  • Enable wanted sharing

• Virtual memory to the rescue
  • Present a large, uniform memory to programmers
  • Data in virtual memory by default stays in disk
  • Data moves to physical memory (DRAM) “on demand”
  • Disks (~TBs) are much larger than DRAM (~GBs), but 10,000x slower.
  • Effectively, virtual memory system transparently share the physical memory across different processes
  • Manage the sharing automatically: hardware-software collaborative strategy (too complex for hardware alone)
Today

• VM basic concepts and operation
• Other critical benefits of VM
• Address translation
VM Concepts

- **Virtual memory** is an array of N contiguous pages (each page has a certain amount of continuous bytes).
- Physical memory is also divided into pages. Each physical page (sometimes called frames) has the same size as a virtual page. Physical memory has way fewer pages.
- A page can either be on the (“uncached”) disk or in the physical memory (“cached”).

![Diagram showing virtual and physical memory concepts]
VM Concepts

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**What programmers see**

![Diagram showing relationship between virtual pages (VPs) and physical pages (PPs).](image-url)
VM Concepts

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- Physical memory is also divided into pages. Each physical page (sometimes called frames) has the same size as a virtual page. Physical memory has way fewer pages.
- A page can either be on the (“uncached”) disk or in the physical memory (“cached”).

### What programmers see

- **Virtual memory**
  - VP 0: Unallocated
  - VP 1: In-memory
  - VP 1: On-disk
  - VP 7: Unallocated
  - VP 7: In-memory
  - VP 7: On-disk

- **Physical memory**
  - Physical pages (PPs) cached in DRAM
  - Physical memory size is 16B
  - Assuming page size is 4B
  - Virtual memory size is 32B

- Physical pages (PPs)
  - PP 0
  - PP 1
  - PP 2
  - PP 3
  - Unoccupied
VM Concepts

- **Virtual memory** is an array of N contiguous pages (each page has a certain amount of continuous bytes).
- Physical memory is also divided into pages. Each physical page (sometimes called frames) has the same size as a virtual page. Physical memory has way fewer pages.
- A page can either be on the ("uncached") disk or in the physical memory ("cached").

What programmers see

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<thead>
<tr>
<th>Virtual pages (VPs)</th>
<th>Physical pages (PPs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VP 0 Unallocated</td>
<td>PP 0 Unoccupied</td>
</tr>
<tr>
<td>VP 1 In-memory</td>
<td>PP 1 Unoccupied</td>
</tr>
<tr>
<td>VP 1 On-disk</td>
<td>PP 2 Unoccupied</td>
</tr>
<tr>
<td>VP 7 Unallocated</td>
<td>PP 3 Unoccupied</td>
</tr>
<tr>
<td>VP 7 In-memory</td>
<td></td>
</tr>
<tr>
<td>VP 7 On-disk</td>
<td></td>
</tr>
</tbody>
</table>
```

Assuming page size is 4B
Virtual memory size is 32B
Physical memory size is 16B

- Virtual page number
- Offset

Physical memory

- 3-bit
- 2-bit

Virtual memory

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- On-disk
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</tr>
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<td>PP 0</td>
</tr>
<tr>
<td>VP 1</td>
<td>PP 1</td>
</tr>
<tr>
<td>VP 7</td>
<td>PP 2</td>
</tr>
<tr>
<td></td>
<td>PP 3</td>
</tr>
</tbody>
</table>

- **Virtual page number**
- **offset**

Physical pages (PPs) cached in DRAM

- **Physical page number**
- **offset**

Assuming page size is 4B
- Virtual memory size is 32B
- Physical memory size is 16B

- Offset: 2-bit
- Physical page number: 2-bit
- Virtual page number: 3-bit

---

**offset**

- Virtual page number: 3-bit
- Physical page number: 2-bit

---

**Virtual page number**

- Offset: 2-bit
- Physical page number: 2-bit

---

**Physical page number**

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- Virtual page number: 3-bit
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  • Per-process data structure; managed by the OS kernel
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<table>
<thead>
<tr>
<th>PTE 0</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>null</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>null</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PTE 7</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>●</td>
<td></td>
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Memory resident page table (DRAM)
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Page Hit

- *Page hit:* reference to VM word that is in physical memory
Page Hit

- **Page hit**: reference to VM word that is in physical memory
Page Fault

- **Page fault**: reference to VM word that is not in physical memory
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Handling Page Fault

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- Page fault **handler** selects a victim to be evicted (here VP 4)
- Offending instruction is restarted: page hit!

**Key point:** Waiting until the miss to copy the page to DRAM is known as **demand paging**
Allocating Pages

• Allocating a new page (VP 5) of virtual memory.

<table>
<thead>
<tr>
<th>PTE 0</th>
<th>PTE 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valid</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>null</td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>null</td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Physical page number or disk address

Physical memory (DRAM)

PP 0
- VP 1
- VP 2
- VP 7
- VP 3

PP 3

Disk
- VP 1
- VP 2
- VP 3
- VP 4
- VP 5
- VP 6
- VP 7

Memory resident page table (DRAM)
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![Diagram showing memory resident page table (DRAM) and physical memory (DRAM) with allocated pages VP 1, VP 2, VP 3, VP 4, VP 5, VP 6, VP 7, and VP 8. The memory resident page table has entries for physical page number or disk address with valid bit and null entry.]
Virtual Memory Exploits Locality (Again!)

- Virtual memory seems terribly inefficient, but it works because of locality.

- At any point in time, programs tend to access a set of active virtual pages called the *working set*
  - Programs with better temporal locality will have smaller working sets

- If \( \text{working set size} < \text{main memory size} \)
  - Good performance for one process after initial misses

- If \( \text{SUM(working set sizes)} > \text{main memory size} \)
  - *Thrashing*: Performance meltdown where pages are swapped (copied) in and out continuously
VM Concepts Summary

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• ~MBs of a page table per process
  • Too big for on-chip SRAM (c.f., a L1 cache is ~32 KB)
  • Too slow to access in disk
  • Put the page table in DRAM, with its start address stored in a special register (Page Table Base Register). More on this later.