Memory Management
Memory Management

Memory – a linear array of bytes
- Holds O.S. and programs (processes)
- Each cell (byte) is named by a unique memory address

Recall, processes are defined by an *address space*, consisting of text, data, and stack regions

Process execution
- CPU fetches instructions from the text region according to the value of the program counter (PC)
- Each instruction may request additional operands from the data or stack region
Addressing Memory

Cannot know ahead of time where in memory a program will be loaded!

Compiler produces code containing embedded addresses
these addresses can’t be absolute (physical addresses)

Linker combines pieces of the program
Assumes the program will be loaded at address 0

We need to **bind** the compiler/linker generated addresses
to the actual memory locations
Relocatable Address Generation

Compilation

Assembly

Linking

Loading
Address Binding

Address binding
  - fixing a physical address to the logical address of a process’ address space

Compile time binding
  - if program location is fixed and known ahead of time

Load time binding
  - if program location in memory is unknown until run-time AND location is fixed

Execution time binding
  - if processes can be moved in memory during execution
  - Requires hardware support!
Base and Limit Registers

Simple runtime relocation scheme
  - Use 2 registers to describe a partition

For every address generated, at runtime...
  - Compare to the limit register (& abort if larger)
  - Add to the base register to give physical memory address
Dynamic Relocation

Memory Management Unit (MMU)
- Dynamically converts logical to physical address
- Contains base address register for running process

Relocation register for process $i$

Program generated address + MMU

Max Mem

Max addr

Physical memory address

process $i$

Operating system
Protection

Memory protection
- **Base** register gives starting address for process
- **Limit** register limits the offset accessible from the relocation register
### Multiprogramming

Multiprogramming: a separate partition per process

What happens on a context switch?

- Store process `base` and `limit` register values
- Load new values into `base` and `limit` registers

<table>
<thead>
<tr>
<th>Partition E</th>
<th>Partition D</th>
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</thead>
<tbody>
<tr>
<td>Partition C</td>
<td>Partition B</td>
</tr>
<tr>
<td>Partition A</td>
<td>OS</td>
</tr>
</tbody>
</table>
Swapping

When a program is running...
   The entire program must be in memory
   Each program is put into a single partition

When the program is not running...
   May remain resident in memory
   May get “swapped” out to disk

Over time...
   Programs come into memory when they get swapped in
   Programs leave memory when they get swapped out
Swapping

Benefits of swapping:

- Allows multiple programs to be run concurrently
- ... more than will fit in memory at once
Fragmentation
Dealing With Fragmentation

Compaction – from time to time shift processes around to collect all free space into one contiguous block
  - Memory to memory copying overhead
  - Memory to disk to memory for compaction via swapping!
How Big Should Partitions Be?

Programs may want to grow during execution
  - More room for stack, heap allocation, etc

Problem:
  - If the partition is too small, programs must be moved
  - Requires copying overhead
  - Why not make the partitions a little larger than necessary to accommodate “some” cheap growth?
Allocating Extra Space Within

![Diagram](image)
Management Data Structures

Each chunk of memory is either
- Used by some process or unused (free)

Operations
- **Allocate** a chunk of unused memory big enough to hold a new process
- **Free** a chunk of memory by returning it to the free pool after a process terminates or is swapped out
Management With Bit Maps

Problem - how to keep track of used and unused memory?

Technique 1 - Bit Maps

A long bit string
One bit for every chunk of memory
  1 = in use
  0 = free

Size of allocation unit influences space required

Example: unit size = 32 bits
  overhead for bit map: 1/33 = 3%
Example: unit size = 4Kbytes
  overhead for bit map: 1/32,769
Management With Bit Maps

(a) 

(b) 

(c)
Management With Linked Lists

Technique 2 - Linked List

Keep a list of elements
Each element describes one unit of memory
  - Free / in-use Bit ("P=process, H=hole")
  - Starting address
  - Length
  - Pointer to next element
Management With Linked Lists

(a)

(b)

(c)

Hole Starts at 18 Length 2

Process
Management With Linked Lists

Searching the list for space for a new process

First Fit

Next Fit
   Start from current location in the list

Best Fit
   Find the smallest hole that will work
   Tends to create lots of really small holes

Worst Fit
   Find the largest hole
   Remainder will be big

Quick Fit
   Keep separate lists for common sizes
Fragmentation Revisited

Memory is divided into partitions
Each partition has a different size
Processes are allocated space and later freed
After a while memory will be full of small holes!
- No free space large enough for a new process even though there is enough free memory in total
If we allow free space within a partition we have fragmentation
  - External fragmentation = unused space between partitions
  - Internal fragmentation = unused space within partitions
Solutions to Fragmentation

Compaction requires high copying overhead
Why not allocate memory in non-contiguous equal fixed size units?
- No external fragmentation!
- Internal fragmentation < 1 unit per process

How big should the units be?
- The smaller the better for internal fragmentation
- The larger the better for management overhead

The key challenge for this approach
How can we do secure dynamic address translation?
Non-Contiguous Allocation (Pages)

Memory divided into fixed size \textit{page frames}
- Page frame size $= 2^n$ bytes
- Lowest $n$ bits of an address specify byte offset in a page

But how do we associate page frames with processes?
- And how do we map memory addresses within a process to the correct memory byte in a page frame?

Solution – address translation
- Processes use \textit{virtual addresses}
- CPU uses \textit{physical addresses}
- Hardware support for virtual to physical \textit{address translation}
Virtual Addresses

Virtual memory addresses (what the process uses)

Page number plus byte offset in page

Low order n bits are the byte offset

Remaining high order bits are the page number

Example: 32 bit virtual address

Page size = \(2^{12} = 4\)KB

Address space size = \(2^{32}\) bytes = 4GB
Physical Addresses

Physical memory addresses (what the CPU uses)
Page “frame” number plus byte offset in page
Low order n bits are the byte offset
Remaining high order bits are the frame number

Example: 24 bit physical address
Frame size = $2^{12} = 4$KB
Max physical memory size = $2^{24}$ bytes = 16MB
Address Translation

Hardware maps page numbers to frame numbers

Memory management unit (MMU) has multiple registers for multiple pages
  - Like a base register except its value is substituted for the page number rather than added to it
  - Why don’t we need a limit register for each page?
Memory Management Unit (MMU)

The CPU sends virtual addresses to the MMU.

The MMU sends physical addresses to the memory.
Virtual Address Spaces

Here is the virtual address space (as seen by the process)

Lowest address

Virtual Addr Space

Highest address
Virtual Address Spaces

The address space is divided into “pages”

In BLITZ, the page size is 8K

Virtual Addr Space

Page 0

Page 1

Page N

A Page
Virtual Address Spaces

In reality, only some of the pages are used.
Physical Memory

Physical memory is divided into “page frames”
(Page size = frame size)
Virtual & Physical Address Spaces

Some frames are used to hold the pages of this process

Virtual Addr Space

Physical memory

These frames are used for this process
Virtual & Physical Address Spaces

Some frames are used for other processes

Virtual Addr Space

Physical memory

Used by other processes
Virtual & Physical Address Spaces

Address mappings say which frame has which page
Page Tables

Address mappings are stored in a *page table* in memory
1 entry/page: is page in memory? If so, which frame is it in?
Address Mappings

Address mappings are stored in a page table in memory
- Typically one page table for each process

Address translation is done by hardware (ie the MMU)

How does the MMU get the address mappings?
- Either the MMU holds the entire page table (too expensive) or it knows where it is in physical memory and goes there for every translation (too slow)
- Or the MMU holds a portion of the page table and knows how to deal with TLB misses
  - MMU caches page table entries
  - Cache is called a translation look-aside buffer (TLB)
Address Mappings & TLB

What if the TLB needs a mapping it doesn’t have?

Software managed TLB
- It generates a **TLB-miss fault** which is handled by the operating system (like interrupt or trap handling)
- The operating system looks in the page tables, gets the mapping from the right entry, and puts it in the TLB

Hardware managed TLB
- It looks in a pre-specified physical memory location for the appropriate entry in the page table
- The hardware architecture defines where page tables must be stored in physical memory
- OS must load current process page table there on context switch!
The BLITZ Architecture

Page size
8 Kbytes

Virtual addresses ("logical addresses")
24 bits --> 16 Mbyte virtual address space
2^{11} Pages --> 11 bits for page number
The BLITZ Architecture

Page size
8 Kbytes

Virtual addresses ("logical addresses")
24 bits --> 16 Mbyte virtual address space
$2^{11}$ Pages --> 11 bits for page number

An address:

```
   23 13 12 0
11 bits 13 bits
```

- **page number**
- **offset**
The BLITZ Architecture

Physical addresses

32 bits --> 4 Gbyte installed memory (max)

$2^{19}$ Frames --> 19 bits for frame number
The BLITZ Architecture

Physical addresses

- 32 bits \(\rightarrow\) 4 Gbyte installed memory (max)
- \(2^{19}\) Frames \(\rightarrow\) 19 bits for frame number

\[
\begin{array}{c|c|c}
31 & 19 \text{ bits} & 13 \text{ bits} \\
\hline
& & 0 \\
\end{array}
\]

frame number

offset
The BLITZ Architecture

The page table mapping:
Page --> Frame

Virtual Address:

Physical Address:
The BLITZ Page Table

An array of “page table entries”
  Kept in memory

2^{11} pages in a virtual address space?
  ---> 2K entries in the table

Each entry is 4 bytes long
  19 bits The Frame Number
  1 bit Valid Bit
  1 bit Writable Bit
  1 bit Dirty Bit
  1 bit Referenced Bit
  9 bits Unused (and available for OS algorithms)
The BLITZ Page Table

Two page table related registers in the CPU
- Page Table Base Register
- Page Table Length Register

These define the “current” page table
- This is how the CPU knows which page table to use
- Must be saved and restored on context switch
- They are essentially the Blitz MMU

Bits in the CPU status register
- System Mode
- Interrupts Enabled
- Paging Enabled
  1 = Perform page table translation for every memory access
  0 = Do not do translation
The BLITZ Page Table

31

1312

frame number

unused

D R W V

19 bits

dirty bit

referenced bit

writable bit

valid bit
The BLITZ Page Table

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>2K</th>
</tr>
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<tbody>
<tr>
<td></td>
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<td>unused</td>
<td>D</td>
<td>R</td>
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Indexed by the page number

Page table base register

Indexed by the page number
The BLITZ Page Table

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page table base register

virtual address
The BLITZ Page Table

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- **Page Table Base Register**:虚地址
- **Virtual Address**: 31 1312 0
- **Frame Number**
  - 0: unused, D R W V
  - 1: unused, D R W V
  - 2: unused, D R W V
  - 2K: unused, D R W V

- **Physical Address**
  - 31 0
The BLITZ Page Table

- Page number
- Offset
- Frame number
- Physical address
- Virtual address
- Frame number
- Unused
- D R W V

Page table base register

Virtual address

Physical address
The BLITZ Page Table

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Page table base register

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Quiz

What is the difference between a virtual and a physical address?
What is address binding?
Why are programs not usually written using physical addresses?
Why is hardware support required for dynamic address translation?
What is a page table used for?
What is a TLB used for?
How many address bits are used for the page offset in a system with 2KB page size?