

# Virtual Memory

CSE 220: Systems Programming

Ethan Blanton & Carl Alphonse

Department of Computer Science and Engineering  
University at Buffalo



# Virtual Memory

Virtual memory is a mechanism by which a system divorces the address space in programs from the physical layout of memory.

Virtual addresses are locations in program address space.

Physical addresses are locations in actual hardware RAM.

With virtual memory, the two need not be equal.

# Process Layout

As previously discussed:

- Every process has unmapped memory near NULL
- Processes may have access to the **entire address space**
- Each process is **denied access** to the memory used by other processes

Some of these statements seem **contradictory**.

Virtual memory is the **mechanism** by which this is accomplished.

Every address in a process's address space is a **virtual address**.

# Physical Layout

The **physical layout** of hardware RAM may vary significantly from machine to machine or platform to platform.

- Sometimes certain locations are **restricted**
- **Devices** may appear in the memory address space
- Different amounts of RAM may be present

Historically, programs were **aware of these restrictions**.

Today, **virtual memory** hides these details.

The **kernel must still be aware** of physical layout.

# The Memory Management Unit

The **Memory Management Unit (MMU)** **translates** addresses.

It uses a **per-process mapping structure** to transform **virtual addresses** into **physical addresses**.

The MMU is physical hardware between the CPU and the memory bus.

This translation must **typically be very fast**, but occasionally has a **large performance penalty**.

Managing the translation mappings requires **tight integration** between the kernel and hardware.

# Address Spaces

Both **virtual** and **physical addresses** are in **address spaces**.

An **address space** is a range of **potentially valid locations**.

These spaces **need not be the same!**

- For example, on x86-64, the **virtual address space** is all locations from 0 to  $2^{64} - 1$ .
- Current x86-64 processors only allow **48 of those bits**.<sup>1</sup>
- A **given piece of hardware** may support **much less** memory.

---

<sup>1</sup>...in a somewhat strange fashion

# Linear Address Spaces

Many modern machines use a **linear address space**.

Linear addresses map to a small number of (sometimes one) **contiguous blocks of memory** in the **same address space** that are **address-disjoint**.

*In other words:*

- A particular address represents a **unique location** in the address space.
- **Every location in the address space** can be named with a single address.

# Segmented Address Spaces

Many older systems, and some modern systems, use **segmented address spaces**.

In a **segmented address space**, an address is divided into two (or more) parts:

- A **segment identifier**
- An **offset within the segment**

Each **segment** is often a **linear address space**.

The **segment identifier** may be **implicit** or **provided separately** from the address within the segment.

We will not consider segmented addresses further.



# Address Locations

The addresses we have used are **byte addresses**.

This is **not necessary**, however!

Some machines use **word addresses**, in particular.<sup>2</sup>

On a **word addressed** machine, **every address** is a word.

*E.g.*, address 0x1 would be the **second word**, or the **fifth byte**, on a 32-bit word machine!

We will not consider word addressing further.

---

<sup>2</sup>Early Unix was developed on a word-addressed machine (the PDP-7).

# The MMU

Every time the CPU accesses an address:

- The MMU intercepts that address
- It converts the **virtual address** from the **virtual address space** into a **physical address space**
- The converted address is used to access physical RAM

We call this **address translation**.

These address spaces **may not use the same addressing model**.

# Paging

There are **many possible virtual memory models**.

The x86-64 architecture offers several!

Linux on x86-64 uses **paging**.

In paged virtual memory, the **MMU** breaks memory into fixed-sized **pages**.

- There may be **several page sizes** in a system
- Page sizes are **typically powers of two**
- x86-64 small pages are 4 kB

# Page Metadata

**Metadata** stored in page tables defines features like:

- Whether a virtual page is readable/writable
- If executing code from a virtual page is allowable
- Whether a virtual page is **currently present in memory**
- ...

If a memory access **violates this metadata**, this is a **page fault** (e.g., a write to a page that is not writable):

- the MMU **notifies the processor**
- the processor **jumps to a particular kernel routine**
- the kernel:
  - **fixes** the problem, or
  - **notifies** the offending process

# Page Backing

Virtual pages can be **backed** by files, physical pages, or both.

A **backed page** is **based on the contents** of its backing.

Backed pages may not need to be stored in memory at all times.

If it is:

- **clean**: it is **identical to its backing**
- **dirty**: it is **different from its backing**

Clean pages can be **recreated from the backing** at any time.

# Demand Paging

In some cases, a virtual page may be **backed** but **not present**.

Such a page will be **marked as not present** in the page tables.

Attempts to access this page will **notify the kernel**.

(This is a type of **page fault**.)

The kernel will **page in** the page by:

- finding an unused **physical page**
- locating the virtual page's **backing**
- reading the **backing data** into the physical page

# Demand Paging Benefits

Demand paging allows physical memory to be **allocated quickly** by simply updating page tables.

It also speeds **loading of executable files** as programs:

- pages are marked as **not present** but **backed by the file**
- access to pages causes the file to be **read into memory**
- **unused pages** are **never loaded**

# The Program Break

Calling `brk()` or `sbrk()` modifies a process memory map.

Additional pages **adjacent to the old break** will be marked as:

- **Not** present
- Readable and writable

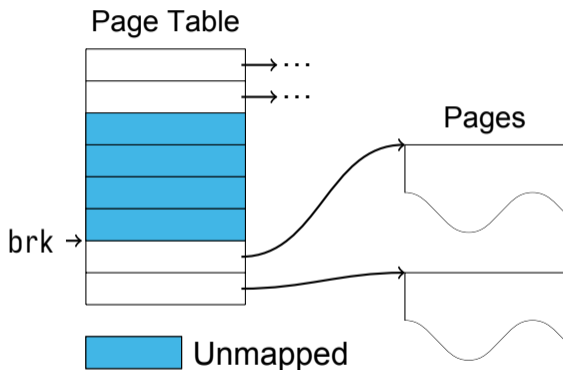
However, **this affects only the page table metadata**, the pages are **not actually allocated!**

When the process tries to use a new page:

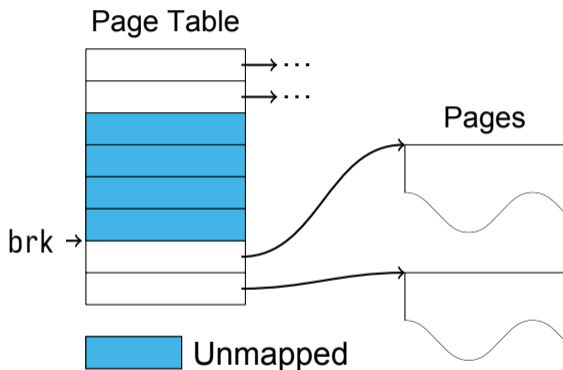
- The MMU will notify the processor
- The kernel will find an unused page
- The kernel will **clear the unused page**
- The kernel will insert the page into the process's page



# Moving the Program Break (Page Fault)

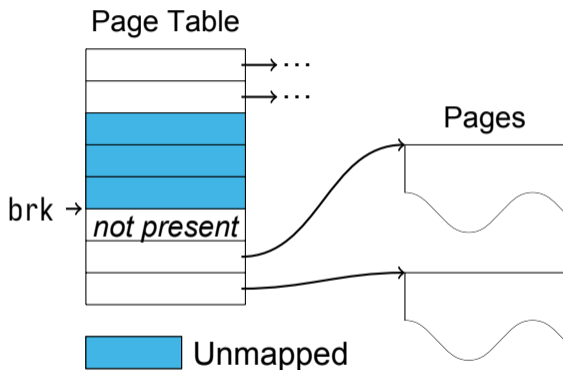


# Moving the Program Break (Page Fault)



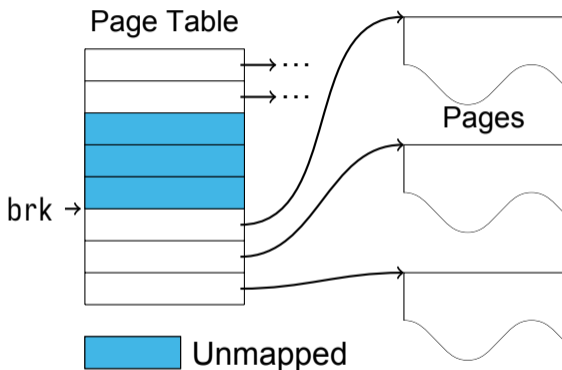
`sbrk(PAGE_SIZE)` is called by the program.

# Moving the Program Break (Page Fault)



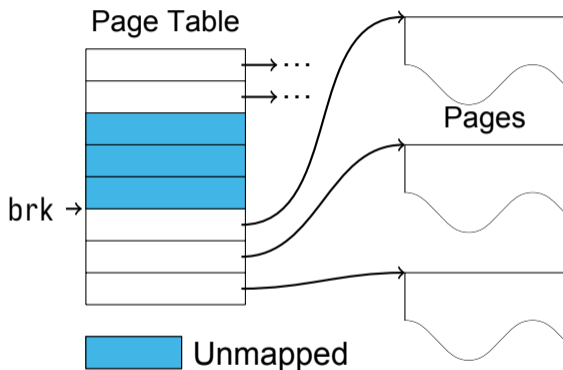
The break is moved, the new page is marked **not present**.

# Moving the Program Break (Page Fault)



Some time later, the process **attempts to access** the page. The MMU notifies the kernel, which allocates a page.

# Moving the Program Break (Page Fault)



The process's access to the page continues as normal.

# The C Stack

We previously said that [the kernel manages the program stack](#):

- It grows as necessary (to some point)
- The program need not explicitly size it (cf. the break)

More correctly, the [kernel configures the MMU](#) to manage the program stack.

Similar to newly-allocated memory at the page break, at process creation the kernel will:

- Determine how large the program's stack should be
- Mark stack pages as [not present](#) but [readable and writeable](#)

As the [program stack grows](#), [page faults](#) will allocate new pages.

# Page Eviction

If the system is **low on memory**, it can **evict** a page.

A page is **evicted** by:

- **clean**: simply remove it from the map
- **dirty**: **write it to its backing** and remove it

A **special backing**, **swap**, can back un-backed dirty pages.

Coupled with **demand paging**, page eviction **can simulate extra memory**.

1. A page is needed
2. No page is free
3. A page is evicted (maybe written to **swap**)
4. The evicted page is remapped

# Summary

- **Virtual memory:**
  - uses a **memory management unit**
  - allows the CPU to operate in a **virtual address space** that may be different from the **physical address space**
  - the MMU **translates** virtual addresses to physical addresses
- **Paging** is a common model for virtual memory.
- Paged systems break **both address spaces** into **pages**.
- Pages can be **mapped individually** between virtual and physical addresses.
- **Page tables** allow the MMU to translate addresses.
- **Page faults** bring mapped but unallocated pages into memory.



# References I

## Required Readings

- [2] Ian Weinand. *Computer Science from the Bottom Up*. Chapter 6: parts 1–4; part 7; part 8, 8.1 and 8.2. URL: <https://www.bottomupcs.com/index.html>.

## Optional Readings

- [1] Randal E. Bryant and David R. O'Hallaron. *Computer Science: A Programmer's Perspective*. Third Edition. Chapter 1: 1.7.3; Chapter 9: Intro, 9.1-9.4. Pearson, 2016.

# License

Copyright 2018–2023 Ethan Blanton, All Rights Reserved.  
Copyright 2022, 2023 Carl Alphonse, All Rights Reserved.  
Copyright 2019 Karthik Dantu, All Rights Reserved.

Reproduction of this material without written consent of the author is prohibited.

To retrieve a copy of this material, or related materials, see <https://www.cse.buffalo.edu/~eblanton/>.