Cool Things VM Provides

- Learning Objectives
  - Explain how virtual memory provides abstractions such as:
    - Contiguous allocation of memory
    - Processes
    - Fork
    - Mmap
  - Explain how virtual memory enables process isolation using:
    - Per-process page tables
    - Protection bits in PTEs
    - Faults
    - Validating user addresses (avoid the confused deputy problem)

Pointer Arithmetic (It's all Lies!)

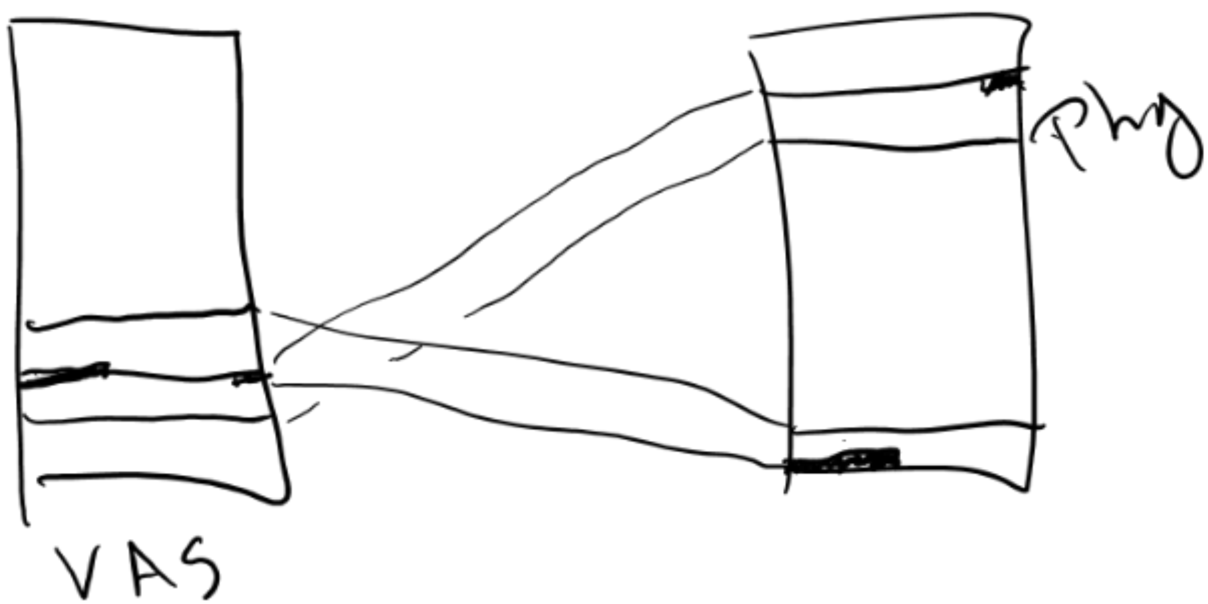
- Recall how nicely we can calculate the addresses of data.
- For example

```
int array[10];
```

- Let's say that this array is allocated at address 0x1FFFC.
- What is `&array[6]`?
- We know that C allocates this array contiguously.
- BUT – it is only contiguous in the virtual address space.
- Need it be contiguous in physical memory?

No!

- We've learned that virtual pages map individually to physical pages, so your address space might look like this:

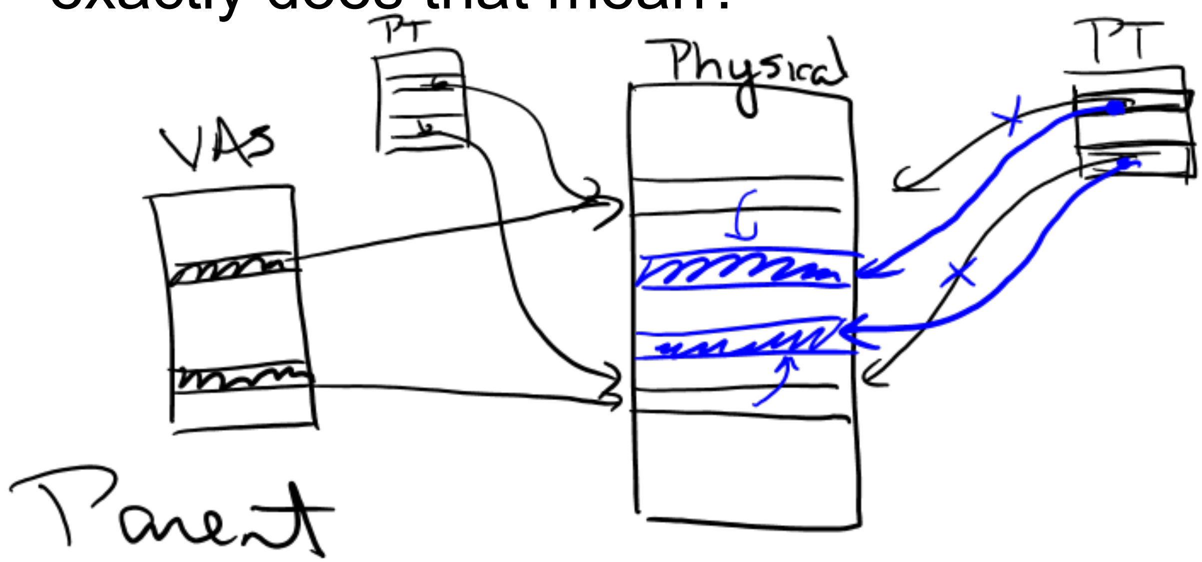


Moving on: Address Spaces

- At the very beginning of the semester, we introduced an address space. In the context of virtual memory, what exactly is an address space?

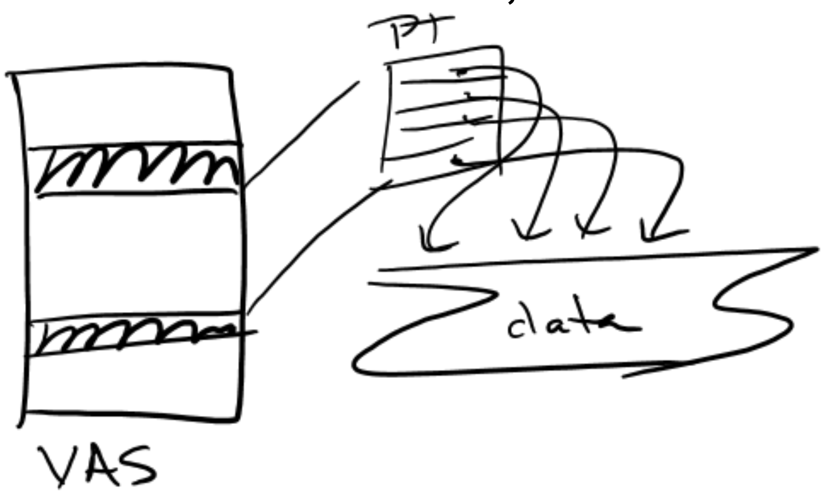
Next up: `fork`

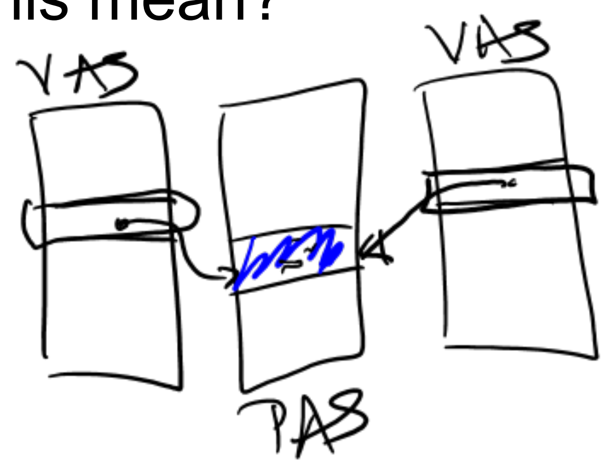
- When we introduced `fork`, we said that it "creates a new process with its own address space."
- Now that we understand virtual memory – what exactly does that mean?



And … `mmap`

- In assignment 3, we introduced `mmap` and we saw that it:
  - Allows us to pretend that a file's data is directly accessible in a process's address space, and
  - Allows us to share memory between two processes.
- In the context of VM, what does this mean?





Let's Talk About Process Isolation

- How does virtual memory protect processes from one another and the kernel from user processes?
- Protect processes from one another:
- Protect kernel from processes:

Let's Talk About Process Isolation

- How does virtual memory protect processes from one another and the kernel from user processes?
- Protect processes from one another:
  - Each has its own page table.
  - The operating system must ensure that a process's pages are not accessible from another process's page table (unless they are intended to be share).
- Protect kernel from processes:

Let's Talk About Process Isolation

- How does virtual memory protect processes from one another and the kernel from user processes?
- Protect processes from one another:
- Protect kernel from processes:
  - The kernel (OS) runs in privileged mode
  - The kernel's memory is marked as being accessible only to code that runs in privileged mode.

Bad Processes

- If the OS sets everything up correctly, when a process tries to violate process isolation:
  - Touch kernel memory
  - Touch another process's memory
  - Write hardware registers it's not supposed to
- What happens?

Bad Processes

- If the OS sets everything up correctly, when a process tries to violate process isolation:
  - Touch kernel memory
  - Touch another process's memory
  - Write hardware registers it's not supposed to
- What happens?
  - The processor generates a fault.
  - When the processor takes a fault, the OS gains control.
  - The OS could do whatever it wants:
    - Kill the process
    - Skip the instruction

The Confused Deputy Problem

- When privileged code acts on behalf of unprivileged code and the unprivileged code tricks the privilieged code into doing something bad.
- Who is the deputy here?

  OS

- How could a process confuse the deputy?

The Confused Deputy Problem

- When privileged code acts on behalf of unprivileged code and the unprivileged code tricks the privilieged code into doing something bad.
- Who is the deputy here?
  - The OS
- How could a process confuse the deputy?
  - While a process can't write into privileged memory, the OS can.
  - What if a process could somehow convince the OS to write something bad into a location that the process cannot write, but the kernel can!?
  - How do we avoid that?

Verifying Process Addresses

- Whenever a process passed an address to the operating system (e.g., a buffer, a string, etc), the operating system must verify that the process has the proper permissions to use the address in the way the kernel is being asked to.
- Examples:
  - Ensure that the address is a valid address in the process's address space.
  - Ensure that if the process is trying to write the location, the page is writable.

PTEs: The heart of VM protection

- Page table entries are at the heart of the operating system and hardware's ability to maintain process isolation.
- Recall a virtual address (on 32-bit x86)

20 bit (virtual) page number	12-bit offset

- The PTE must contain a page number; in addition it contains special bits.

20 bit (physical) page number	12 bits of metadata

PTE Meta-Data

- Both L1 and L2 page tables have three critical bits that provide protection:
- Bit 0: Present Bit
  - 0 indicates that the entire entry is invalid
  - 1 indicates the entry is valid
- Bit 1: Read/Write Bit
  - 0 indicates that the page (or entire set of pages represented by the referenced L2 page table) is read only.
  - 1 indicates that the page(s) are writable.
- Bit 2: User/Supervisor bit
  - 0 indicates that the page is accessible only to privileged code.
  - 1 indicates that the page is accessible to unprivileged code.

Wrapping Up

- Virtual memory is a cooperative arrangement between the OS and the hardware.
- Process isolation is provided by proper management of virtual memory.
  - Each process has its own page table
  - Pages in the page table are described by present, read/write, and privilege bits. Setting these bits correctly prevents processes from doing bad things.
  - Whenever a process sends an address to the OS, the OS must ensure that the address is valid for the intended operation.