Process Address Spaces and Binary Formats

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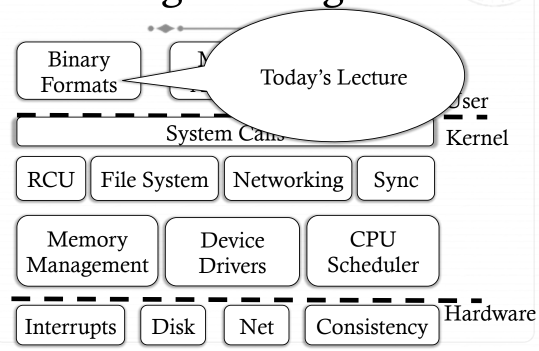
Logical Diagram



Review

- We've seen how paging and segmentation work on x86
  - Maps logical addresses to physical pages
  - These are the low-level hardware tools
- This lecture: build up to higher-level abstractions
- Namely, the process address space

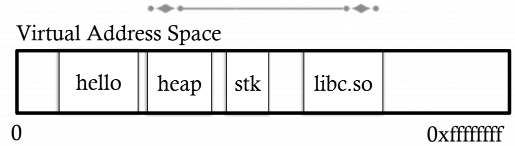
Definitions (can vary)

- Process is a virtual address space
  - 1+ threads of execution work within this address space
- A process is composed of:
  - Memory-mapped files
    - Includes program binary
  - Anonymous pages: no file backing
    - When the process exits, their contents go away

Address Space Layout

- Determined (mostly) by the application
- Determined at compile time
  - Link directives can influence this
    - See kern/kernel.ld in JOS; specifies kernel starting address
- OS usually reserves part of the address space to map itself
  - Upper GB on x86 Linux
- Application can dynamically request new mappings from the OS, or delete mappings

Simple Example



- "Hello world" binary specified load address
- Also specifies where it wants libc
- Dynamically asks kernel for "anonymous" pages for its heap and stack

In practice

- You can see (part of) the requested memory layout of a program using ldd:

```
$ ldd /usr/bin/git
 linux-vdso.so.1 =>  (0x00007fff197be000)
 libz.so.1 => /lib/libz.so.1 (0x00007f31b9d4e000)
 libpthread.so.0 => /lib/libpthread.so.0
                              (0x00007f31b9b31000)
 libc.so.6 => /lib/libc.so.6 (0x00007f31b97ac000)
 /lib64/ld-linux-x86-64.so.2 (0x00007f31b9f86000)
```

Problem 1: How to represent in the kernel?

- What is the best way to represent the components of a process?
  - Common question: is mapped at address x?
    - Page faults, new memory mappings, etc.
- Hint: a 64-bit address space is seriously huge
- Hint: some programs (like databases) map tons of data
  - Others map very little
- No one size fits all

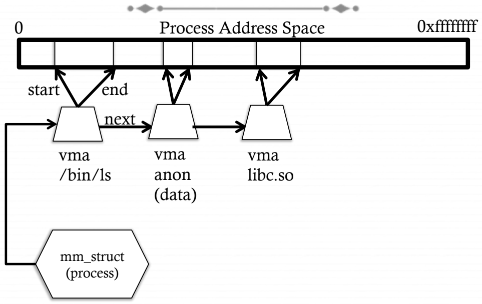
Sparse representation

- Naïve approach might make a big array of pages
  - Mark empty space as unused
  - But this wastes OS memory
- Better idea: only allocate nodes in a data structure for memory that is mapped to something
  - Kernel data structure memory use proportional to complexity of address space!

Linux: vm_area_struct

- Linux represents portions of a process with a vm_area_struct, or vma
- Includes:
  - Start address (virtual)
  - End address (first address after vma) – why?
    - Memory regions are page aligned
  - Protection (read, write, execute, etc) – implication?
    - Different page protections means new vma
  - Pointer to file (if one)
  - Other bookkeeping

Simple list representation



Simple list

- Linear traversal – O(n)
  - Shouldn't we use a data structure with the smallest O?
- Practical system building question:
  - What is the common case?
  - Is it past the asymptotic crossover point?
- If tree traversal is O(log n), but adds bookkeeping overhead, which makes sense for:
  - 10 vmas: log 10 =~ 3; 10/2 = 5; Comparable either way
  - 100 vmas: log 100 starts making sense

Common cases

- Many programs are simple
  - Only load a few libraries
  - Small amount of data
- Some programs are large and complicated
  - Databases
- Linux splits the difference and uses both a list and a red-black tree

Red-black trees

- (Roughly) balanced tree
- Read the wikipedia article if you aren't familiar with them
- Popular in real systems
  - Asymptotic == worst case behavior
    - Insertion, deletion, search: log n
    - Traversal: n

Optimizations

- Using an RB-tree gets us logarithmic search time
- Other suggestions?
- Locality: If I just accessed region x, there is a reasonably good chance I'll access it again
  - Linux caches a pointer in each process to the last vma looked up
  - Source code (mm/mmap.c) claims 35% hit rate

Memory mapping recap

- VM Area structure tracks regions that are mapped
  - Efficiently represent a sparse address space
  - On both a list and an RB-tree
    - Fast linear traversal
    - Efficient lookup in a large address space
  - Cache last lookup to exploit temporal locality

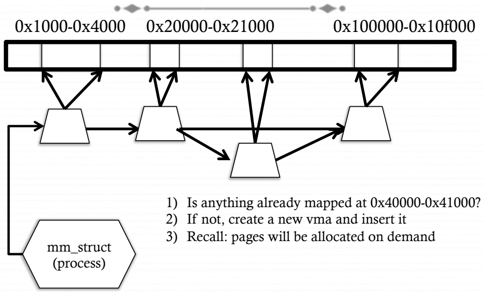
Linux APIs

- mmap(void *addr, size_t length, int prot, int flags, int fd, off_t offset);
- munmap(void *addr, size_t length);
- How to create an anonymous mapping?
- What if you don't care where a memory region goes (as long as it doesn't clobber something else)?

Example 1:

- Let's map a 1 page (4k) anonymous region for data, read-write at address 0x40000
- mmap(0x40000, 4096, PROT_READ|PROT_WRITE, MAP_ANONYMOUS, -1, 0);
  - Why wouldn't we want exec permission?

Insert at 0x40000

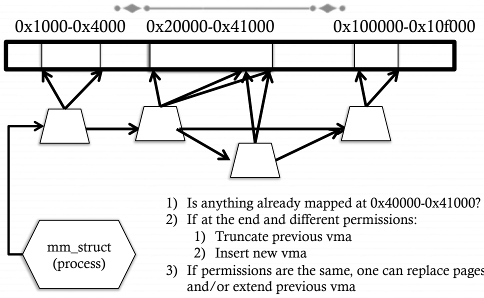


1) Is anything already mapped at 0x40000-0x41000?
2) If not, create a new vma and insert it
3) Recall: pages will be allocated on demand

Scenario 2

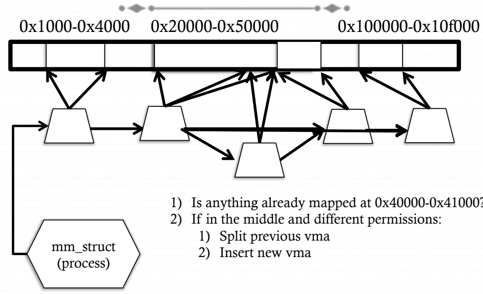
- What if there is something already mapped there with read-only permission?
  - Case 1: Last page overlaps
  - Case 2: First page overlaps
  - Case 3: Our target is in the middle

Case 1: Insert at 0x40000



1) Is anything already mapped at 0x40000-0x41000?
2) If at the end and different permissions:
   1) Truncate previous vma
   2) Insert new vma
3) If permissions are the same, one can replace pages and/or extend previous vma

Case 3: Insert at 0x40000



1) Is anything already mapped at 0x40000-0x41000?
2) If in the middle and different permissions:
   1) Split previous vma
   2) Insert new vma

Demand paging

- Creating a memory mapping (vma) doesn't necessarily allocate physical memory or setup page table entries
  - What mechanism do you use to tell when a page is needed?
- It pays to be lazy!
  - A program may never touch the memory it maps.
    - Examples?
      - Program may not use all code in a library
  - Save work compared to traversing up front
  - Hidden costs? Optimizations?
    - Page faults are expensive; heuristics could help performance

Unix fork()

- Recall: this function creates and starts a copy of the process; identical except for the return value
- Example:

```
int pid = fork();
if (pid == 0) {
      // child code
} else if (pid > 0) {
      // parent code
} else // error
```

Copy-On-Write (COW)

- Naïve approach would march through address space and copy each page
  - Most processes immediately `exec()` a new binary without using any of these pages
  - Again, lazy is better!

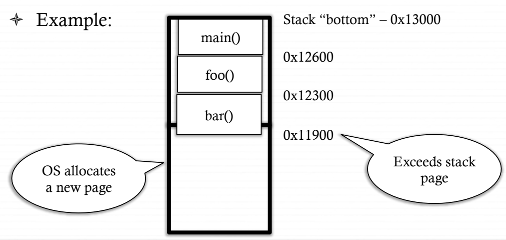
How does COW work?

- Memory regions:
  - New copies of each vma are allocated for child during fork
  - As are page tables
- Pages in memory:
  - In page table (and in-memory representation), clear write bit, set COW bit
    - Is the COW bit hardware specified?
    - No, OS uses one of the available bits in the PTE
  - Make a new, writeable copy on a write fault

New Topic: Stacks

Idiosyncrasy 1: Stacks Grow Down

- In Linux/Unix, as you add frames to a stack, they actually decrease in virtual address order
- Example:

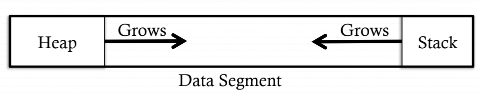


Problem 1: Expansion

- Recall: OS is free to allocate any free page in the virtual address space if user doesn't specify an address
- What if the OS allocates the page below the "top" of the stack?
  - You can't grow the stack any further
  - Out of memory fault with plenty of memory spare
- OS must reserve stack portion of address space
  - Fortunate that memory areas are demand paged

Feed 2 Birds with 1 Scone

- Unix has been around longer than paging
  - Remember data segment abstraction?
  - Unix solution:



- Stack and heap meet in the middle
  - Out of memory when they meet

But now we have paging

- Unix and Linux still have a data segment abstraction
  - Even though they use flat data segmentation!
- sys_brk() adjusts the endpoint of the heap
  - Still used by many memory allocators today

Windows Comparison

- LPVOID VirtualAllocEx(__in HANDLE hProcess,
  __in_opt LPVOID lpAddress,
  __in SIZE_T dwSize,
  __in DWORD flAllocationType,
  __in DWORD flProtect);
- Library function applications program to
  - Provided by ntdll.dll – the rough equivalent of Unix libc
  - Implemented with an undocumented system call

Windows Comparison

- LPVOID VirtualAllocEx(__in HANDLE hProcess,
  __in_opt LPVOID lpAddress,
  __in SIZE_T dwSize,
  __in DWORD flAllocationType,
  __in DWORD flProtect);
- Programming environment differences:
  - Parameters annotated (__out, __in_opt, etc), compiler checks
  - Name encodes type, by convention
  - dwSize must be page-aligned (just like mmap)

Windows Comparison

- LPVOID VirtualAllocEx(__in HANDLE hProcess,
  __in_opt LPVOID lpAddress,
  __in SIZE_T dwSize,
  __in DWORD flAllocationType,
  __in DWORD flProtect);
- Different capabilities
  - hProcess doesn't have to be you! Pros/Cons?
  - flAllocationType – can be reserved or committed
    - And other flags

Reserved memory

- An explicit abstraction for cases where you want to prevent the OS from mapping anything to an address region
- To use the region, it must be remapped in the committed state
- Why?
  - My speculation: Gives the OS more information for advanced heuristics than demand paging

Part 1 Summary

- Understand what a vma is, how it is manipulated in kernel for calls like mmap
- Demand paging, COW, and other optimizations
- brk and the data segment
- Windows VirtualAllocEx() vs. Unix mmap()

Part 2: Program Binaries

- How are address spaces represented in a binary file?
- How are processes loaded?

Linux: ELF

- Executable and Linkable Format
- Standard on most Unix systems
  - And used in JOS
  - You will implement part of the loader in lab 3
- 2 headers:
  - Program header: 0+ segments (memory layout)
  - Section header: 0+ sections (linking information)

Helpful tools

- readelf - Linux tool that prints part of the elf headers
- objdump – Linux tool that dumps portions of a binary
  - Includes a disassembler; reads debugging symbols if present

Key ELF Segments

- For once, not the same thing as hardware segmentation
  - Similar idea, though
- .text – Where read/execute code goes
  - Can be mapped without write permission
- .data – Programmer initialized read/write data
  - Ex: a global int that starts at 3 goes here
- .bss – Uninitialized data (initially zero by convention)
- Many other segments

Sections

- Also describe text, data, and bss segments
- Plus:
  - Procedure Linkage Table (PLT) – jump table for libraries
  - .rel.text – Relocation table for external targets
  - .symtab – Program symbols

How ELF Loading Works

- execve("foo", …)
- Kernel parses the file enough to identify whether it is a supported format
  - Kernel loads the text, data, and bss sections
- ELF header also gives first instruction to execute
  - Kernel transfers control to this application instruction

Static vs. Dynamic Linking

- Static Linking:
  - Application binary is self-contained
- Dynamic Linking:
  - Application needs code and/or variables from an external library
- How does dynamic linking work?
  - Each binary includes a "jump table" for external references
  - Jump table is filled in at run time by the linker

Jump table example

- Suppose I want to call foo() in another library
- Compiler allocates an entry in the jump table for foo
  - Say it is index 3, and an entry is 8 bytes
- Compiler generates local code like this:
  - `mov rax, 24(rbx) // rbx points to the`
    `// jump table`
  - `call *rax`
- Linker initializes the jump tables at runtime

Dynamic Linking (Overview)

- Rather than loading the application, load the linker (ld.so), give the linker the actual program as an argument
- Kernel transfers control to linker (in user space)
- Linker:
  - 1) Walks the program's ELF headers to identify needed libraries
  - 2) Issue mmap() calls to map in said libraries
  - 3) Fix the jump tables in each binary
  - 4) Call main()

Recap

- Understand basics of program loading
- OS does preliminary executable parsing, maps in program and maybe dynamic linker
- Linker does needed fixup for the program to work

Summary

- We've seen a lot of details on how programs are represented:
  - In the kernel when running
  - On disk in an executable file
  - And how they are bootstrapped in practice
- Will help with lab 3