

Process Address Spaces and Binary Formats

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Background

- We've talked some about processes
- This lecture: discuss overall virtual memory organization
 - Key abstraction: Address space
- We will learn about the mechanics of virtual memory later

Review

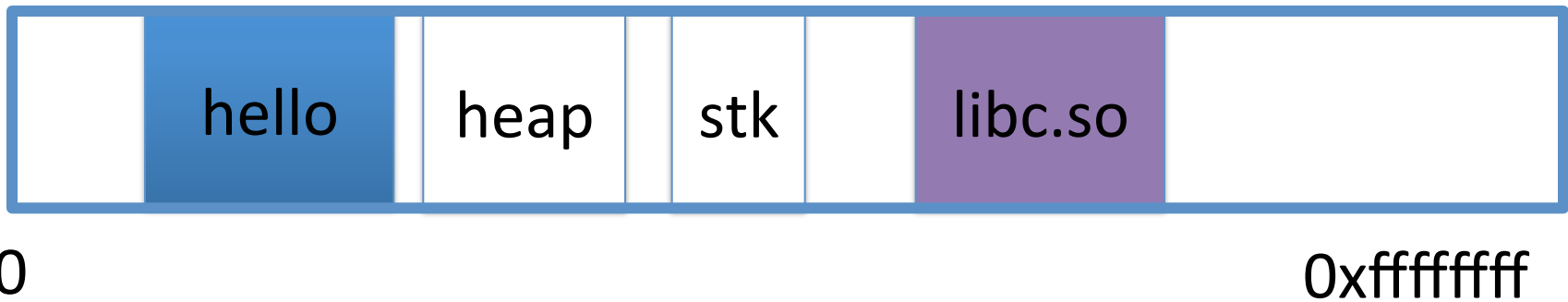
- Process includes a virtual address space
- An address space is composed of:
 - Memory-mapped files
 - Includes program binary
 - Anonymous pages: no file backing
 - When the process exits, their contents go away

Address Space Layout

- Determined (mostly) by the application
- Determined at compile time
 - Link directives can influence this
- 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

Virtual Address Space



- “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

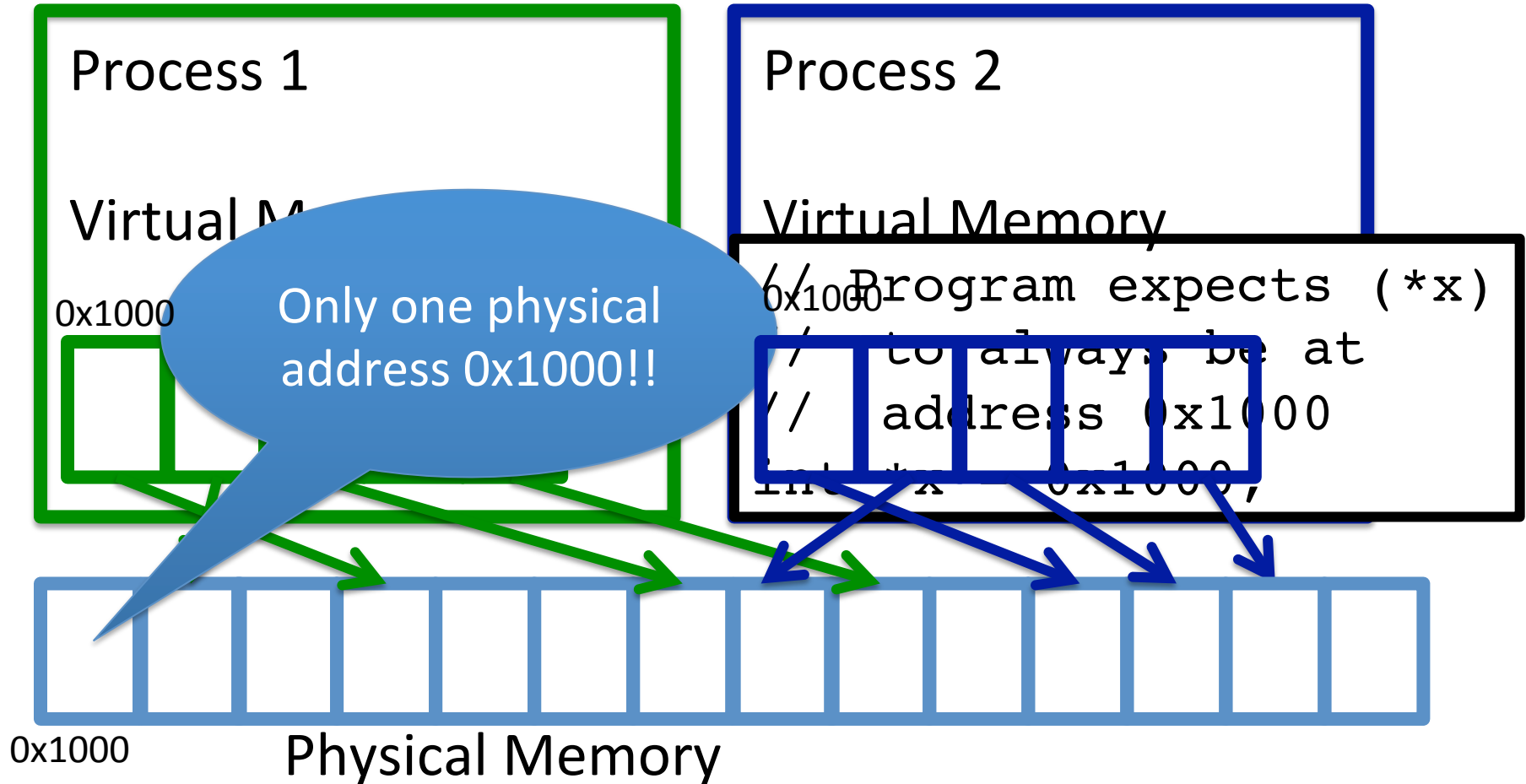
- You can see (part of) the requested memory layout of a program using `ldd`:

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

Many address spaces

- What if every program wants to map libc at the same address?
- No problem!
 - Every process has the abstraction of its own address space
- How does this work?

Memory Mapping



Two System Goals

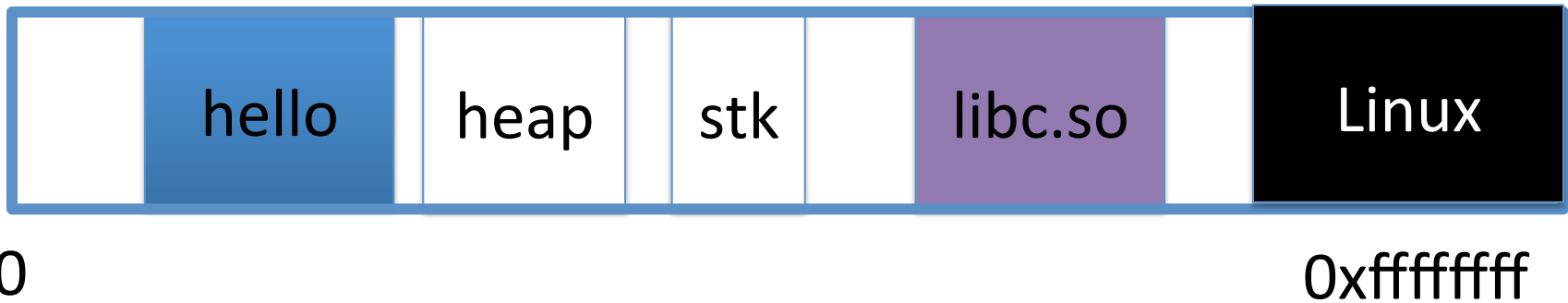
- 1) Provide an abstraction of contiguous, isolated virtual memory to a program
 - We will study the details of virtual memory later
- 2) Prevent illegal operations
 - Prevent access to other application
 - No way to address another application's memory
 - Detect failures early (e.g., segfault on address 0)

What about the kernel?

- Most OSes reserve part of the address space in every process by convention
 - Other ways to do this, nothing mandated by hardware

Example Redux

Virtual Address Space



- Kernel always at the “top” of the address space
- “Hello world” binary specifies most of the memory map
- Dynamically asks kernel for “anonymous” pages for its heap and stack

Why a fixed mapping?

- Makes the kernel-internal bookkeeping simpler
- Example: Remember how interrupt handlers are organized in a big table?
 - How does the table refer to these handlers?
 - By (virtual) address
 - Awfully nice when one table works in every process

Kernel protection?

- So, I protect programs from each other by running in different virtual address spaces
- But the kernel is in every virtual address space?

Protection rings

- Intel's **hardware-level** permission model
 - Ring 0 (supervisor mode) – can issue any instruction
 - Ring 3 (user mode) – no privileged instructions
 - Rings 1&2 – mostly unused, some subset of privilege
- Note: this is not the same thing as superuser or administrator in the OS
 - Similar idea
- Key intuition: Memory mappings include a ring level and read only/read-write permission
 - Ring 3 mapping – user + kernel, ring 0 – only kernel

Putting protection together

- Permissions on the memory map protect against programs:
 - Randomly reading secret data (like cached file contents)
 - Writing into kernel data structures
- The only way to access protected data is to trap into the kernel. How?
 - Interrupt (or syscall instruction)
- Interrupt table entries protect against jumping into unexpected code

Outline

- Basics of process address spaces
 - Kernel mapping
 - Protection
- How to dynamically change your address space?
- Overview of loading a program

Linux APIs

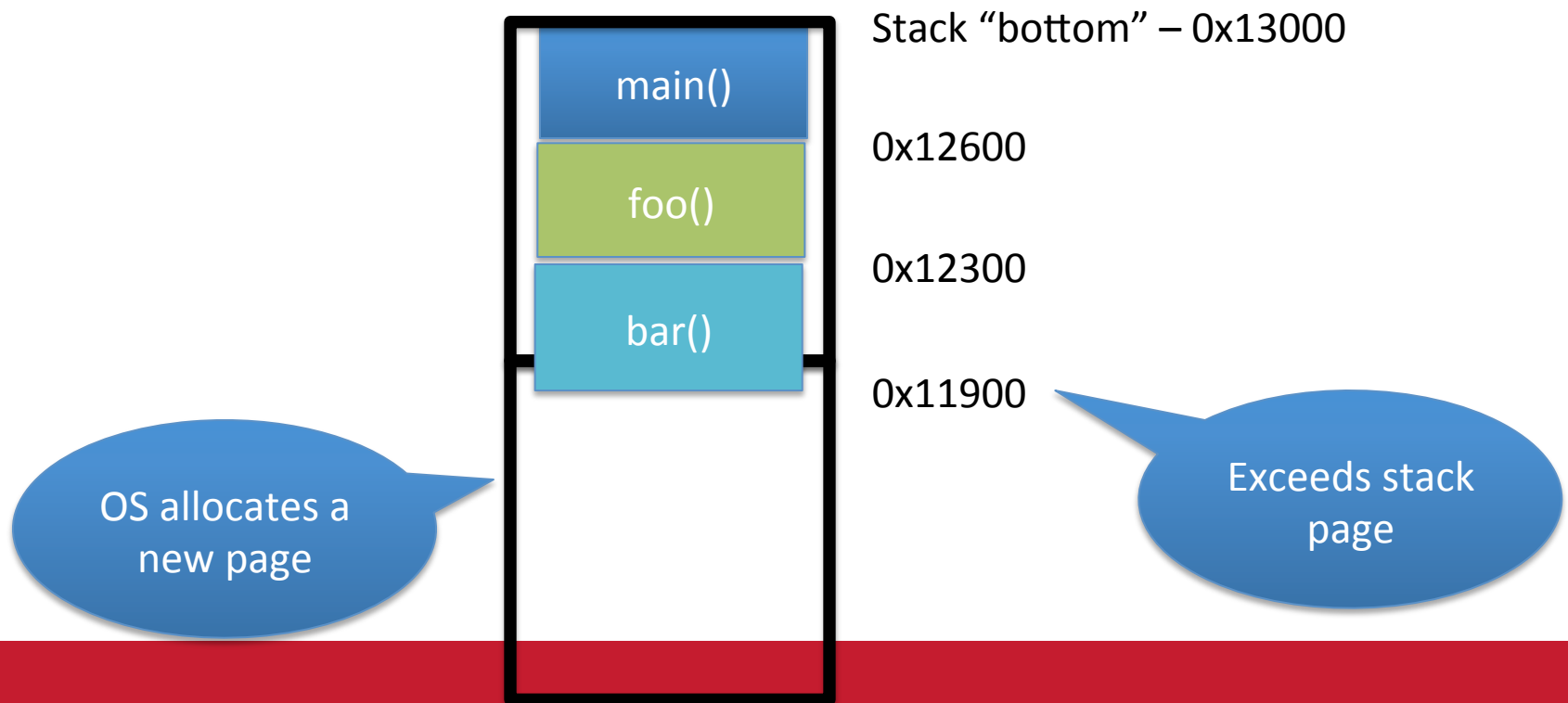
- `mmap(void *addr, size_t length, int prot, int flags, int fd, off_t offset);`
- `munmap(void *addr, size_t length);`
- How to create an anonymous mapping?
- What if you don't care where a memory region goes (as long as it doesn't clobber something else)?

Example:

- 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?

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
 - Data segment abstraction (we'll see more about segments later)
 - Unix solution:



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

brk() system call

- Brk points to the end of the heap
- `sys_brk()` changes this pointer



Relationship to malloc()

- malloc, or any other memory allocator (e.g., new)
 - Library (usually libc) inside application
 - Takes in gets large chunks of anonymous memory from the OS
 - Some use brk,
 - Many use mmap instead (better for parallel allocation)
 - Sub-divides into smaller pieces
 - Many malloc calls for each mmap call

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Linux: ELF

- Executable and Linkable Format
- Standard on most Unix systems
- 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 Sections

- `.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 sections

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()

Key point

- Most program loading work is done *by the loader in user space*
 - If you ‘`strace`’ any substantial program, there will be beaucoup `mmap` calls early on
 - Nice design point: the kernel only does very basic loading, `ld.so` does the rest
 - Minimizes risk of a bug in complicated ELF parsing corrupting the kernel

Other formats?

- The first two bytes of a file are a “magic number”
 - Kernel reads these and decides what loader to invoke
 - ‘#!’ says “I’m a script”, followed by the “loader” for that script
 - The loader itself may be an ELF binary
- Linux allows you to register new binary types (as long as you have a supported binary format that can load them)

Recap

- Understand the idea of an address space
- Understand how a process sets up its address space, how it is dynamically changed
- Understand the basics of program loading