CS162
Operating Systems and Systems Programming
Lecture 14

Memory 1: Virtual Memory, Segments and Page Tables

March 5th, 2024
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Recall: Four requirements for occurrence of Deadlock

- **Mutual exclusion**
  - Only one thread at a time can use a resource.

- **Hold and wait**
  - Thread holding at least one resource is waiting to acquire additional resources held by other threads.

- **No preemption**
  - Resources are released only voluntarily by the thread holding the resource, after thread is finished with it.

- **Circular wait**
  - There exists a set \( \{T_1, \ldots, T_n\} \) of waiting threads
    - \( T_1 \) is waiting for a resource that is held by \( T_2 \)
    - \( T_2 \) is waiting for a resource that is held by \( T_3 \)
    - …
    - \( T_n \) is waiting for a resource that is held by \( T_1 \)
Recall: Banker’s Algorithm for Avoiding Deadlock

• Toward right idea:
  – State maximum (max) resource needs in advance
  – Allow particular thread to proceed if:
    (available resources - #requested) ≥ max remaining that might be needed by any thread

• Banker’s algorithm (less conservative):
  – Allocate resources dynamically
    » Evaluate each request and grant if some ordering of threads is still deadlock free afterward
    » Technique: pretend each request is granted, then run deadlock detection algorithm, substituting:

      $$([\text{Max}_n] - [\text{Alloc}_n] \leq [\text{Avail}]) \text{ for } ([\text{Request}_n] \leq [\text{Avail}])$$

  – Grant request if won’t prevent some thread from allocating its maximum and finishing

• Keeps system in a “SAFE” state:
  – There exists a sequence \{T_1, T_2, \ldots, T_n\} with T_1 requesting all remaining resources, finishing, then T_2 requesting all remaining resources, etc..
Recall: Banker’s Algorithm Example

- Banker’s algorithm with dining lawyers
  - “Safe” (won’t cause deadlock) if when try to grab chopstick either:
    » Not last chopstick
    » Is last chopstick but someone will have two afterwards

- What if k-handed lawyers? Don’t allow if:
  » It’s the last one, no one would have k
  » It’s 2\textsuperscript{nd} to last, and no one would have k-1
  » It’s 3\textsuperscript{rd} to last, and no one would have k-2
  » …
Virtualizing Resources

• Physical Reality:
  Different Processes/Threads share the same hardware
  – Need to multiplex CPU (Just finished: scheduling)
  – Need to multiplex use of Memory (starting today)
  – Need to multiplex disk and devices (later in term)

• Why worry about memory sharing?
  – The complete working state of a process and/or kernel is defined by its data in memory (and registers)
  – Consequently, cannot just let different threads of control use the same memory
    » Physics: two different pieces of data cannot occupy the same locations in memory
  – Probably don’t want different threads to even have access to each other’s memory if in different processes (protection)
Important Aspects of Memory Multiplexing

• Protection:
  – Prevent access to private memory of other processes
    » Different pages of memory can be given special behavior (Read Only, Invisible to user programs, etc).
    » Kernel data protected from User programs
    » Programs protected from themselves

• Translation:
  – Ability to translate accesses from one address space (virtual) to a different one (physical)
  – When translation exists, processor uses virtual addresses, physical memory uses physical addresses
  – Side effects:
    » Can be used to avoid overlap
    » Can be used to give uniform view of memory to programs

• Controlled overlap:
  – Separate state of threads should not collide in physical memory. Obviously, unexpected overlap causes chaos!
  – Conversely, would like the ability to overlap when desired (for communication)
Alternative View: Interposing on Process Behavior

• OS interposes on process’ I/O operations
  – How? All I/O happens via syscalls.

• OS interposes on process’ CPU usage
  – How? Interrupt lets OS preempt current thread

• **Question:** How can the OS interpose on process’ memory accesses?
  – Too slow for the OS to interpose every memory access
  – Translation: hardware support to accelerate the common case
  – Page fault: uncommon cases trap to the OS to handle
Recall: Four Fundamental OS Concepts

- **Thread: Execution Context**
  - Fully describes program state
  - Program Counter, Registers, Execution Flags, Stack

- **Address space (with or w/o translation)**
  - Set of memory addresses accessible to program (for read or write)
  - May be distinct from memory space of the physical machine (in which case programs operate in a virtual address space)

- **Process: an instance of a running program**
  - Protected Address Space + One or more Threads

- **Dual mode operation / Protection**
  - Only the “system” has the ability to access certain resources
  - Combined with translation, isolates programs from each other and the OS from programs
THE BASICS: Address/Address Space

- What is \(2^{10}\) bytes (where a byte is abbreviated as “B”)?
  - \(2^{10} \text{B} = 1024 \text{B} = 1 \text{ KB}\) (for memory, \(1 \text{K} = 1024\), not \(1000\))
- How many bits to address each byte of 4KB page?
  - \(4\text{KB} = 4 \times 1\text{KB} = 4 \times 2^{10} = 2^{12} \Rightarrow 12\) bits
- How much memory can be addressed with 20 bits? 32 bits? 64 bits?
  - Use \(2^k\)

"Things" here usually means "bytes" (8 bits)
Address Space, Process Virtual Address Space

• Definition: **Set of accessible addresses and the state associated with them**
  
  – \(2^{32} \approx 4\) billion **bytes** on a 32-bit machine

• How many 32-bit numbers fit in this address space?
  
  – 32-bits = 4 bytes, so \(2^{32}/4 = 2^{30}\) = ~1 billion

• What happens when processor reads or writes to an address?
  
  – Perhaps acts like regular memory
  
  – Perhaps causes I/O operation
    
    » (Memory-mapped I/O)

  – Causes program to abort (segfault)?

  – Communicate with another program

  – …
Recall: Process Address Space: typical structure

Processor registers

PC:
SP:

Code Segment
Static Data
heap

sbrk syscall

Stack Segment

0x000…

0xFFF…
Recall: Uniprogramming

• Uniprogramming (no Translation or Protection)
  – Application always runs at same place in physical memory since only one application at a time
  – Application can access any physical address
  – Application given illusion of dedicated machine by giving it reality of a dedicated machine

![Diagram showing uniprogramming with valid 32-bit addresses: 0x00000000 to 0xFFFFFFFF]
Primitive Multiprogramming

- Multiprogramming without Translation or Protection
  - Must somehow prevent address overlap between threads
    - Use Loader/Linker: Adjust addresses while program loaded into memory (loads, stores, jumps)
      » Everything adjusted to memory location of program
      » Translation done by a linker-loader (relocation)
      » Common in early days (… till Windows 3.x, 95?)

- With this solution, no protection: bugs in any program can cause other programs to crash or even the OS
Binding of Instructions and Data to Memory

Process view of memory

- **data1**: `dw 32
  ...
- **start**: `lw r1,0(data1)
  jal checkit
- **loop**: `addi r1, r1, -1
  bnez r1, loop
  ...
- **checkit**: ...

Physical addresses

Assume 4byte words

- `0x300 = 4 * 0xC0
- `0x0C0 = 0000 1100 0000
- `0x300 = 0011 0000 0000

- `0x0900 8C2000C0
- `0x0904 0C000280
- `0x0908 201FFFFF
- `0x090C 14200242
  ...
- `0x0A00
Binding of Instructions and Data to Memory

Process view of memory

data1: dw 32
start: lw r1,0(data1)
jal checkit
loop: addi r1, r1, -1
bnz r1, loop
... 
checkit: ...

Physical addresses

0x0300 00000020
0x0900 8C2000C0
0x0904 0C000280
0x0908 2021FFFF
0x090C 14200242
... 
0x0A00

Physical Memory

0x0000
0x0300
0x0900
0x090C
0xFFFF

0x2000
0x0030
0x0090
14200242
8C2000C0
0C000340
2021FFFF
Second copy of program from previous example

Process view of memory

```
data1: dw 32
start: lw r1,0(data1)
jal checkit
loop: addi r1, r1, -1
      bnz r1, loop
checkit: ...
```

Physical addresses

```
0x0300 00000020
    ...
0x0900 8C2000C0
0x0904 0C000280
0x0908 2021FFFF
0x090C 14200242
    ...
0xA00
```

Need address translation!
Second copy of program from previous example

Process view of memory

```assembly
data1:  dw 32
start:  lw r1,0(data1)
jal    checkit
loop:  addi r1, r1, -1
bnz    r1, loop
...    ...
checkit: ...```

Physical addresses

```
0x1300  00000020
...    ...
0x1900  8C2004C0
0x1904  0C000680
0x1908  2021FFFF
0x190C  14200642
...    ...
0x1A00
```

• One of many possible translations!
• Where does translation take place?
  Compile time, Link/Load time, or Execution time?
From Program to Process

- Preparation of a program for execution involves components at:
  - Compile time (i.e., “gcc”)
  - Link/Load time (UNIX “ld” does link)
  - Execution time (e.g., dynamic libs)
- Addresses can be bound to final values anywhere in this path
  - Depends on hardware support
  - Also depends on operating system
- Dynamic Libraries
  - Linking postponed until execution
  - Small piece of code (i.e. the stub), locates appropriate memory-resident library routine
  - Stub replaces itself with the address of the routine, and executes routine
Administrivia

• Midterm 2: Thursday 3/14 from 8-10PM
  – A week from tomorrow!!!
  – All material up to Lecture 16 technically in bounds
  – Closed book: with two double-sided handwritten sheets of notes

• Homework 4 coming out
  – Released tomorrow, Wednesday 3/6

• Project 2 design document due this Friday!

• Starting next week – will have an opportunity to get extra credit participation points by attending lecture
  – Details to follow
Administrivia (Con’t)

- You need to know your units as CS/Engineering students!
- Units of Time: “s”: Second, “min”: 60s, “h”: 3600s, (of course)
  - Millisecond: 1ms \( \Rightarrow \) 10^{-3} s
  - Microsecond: 1\(\mu\)s \( \Rightarrow \) 10^{-6} s
  - Nanosecond: 1ns \( \Rightarrow \) 10^{-9} s
  - Picosecond: 1ps \( \Rightarrow \) 10^{-12} s
- Integer Sizes: “b” \( \Rightarrow \) ”bit”, “B” \( \Rightarrow \) “byte” == 8 bits, “W” \( \Rightarrow \)”word”==? (depends. Could be 16b, 32b, 64b)
- Units of Space (memory), sometimes called the “binary system”
  - Kilo: 1KB \( \equiv \) 1KiB \( \Rightarrow \) 1024 bytes \( \Rightarrow \) 2^{10} bytes \( \approx \) 1024 \( \approx \) 1.0 \times 10^{3}
  - Mega: 1MB \( \equiv \) 1MiB \( \Rightarrow \) (1024)^2 bytes \( \Rightarrow \) 2^{20} bytes \( \approx \) 1,048,576 \( \approx \) 1.0 \times 10^{6}
  - Giga: 1GB \( \equiv \) 1GiB \( \Rightarrow \) (1024)^3 bytes \( \Rightarrow \) 2^{30} bytes \( \approx \) 1,073,741,824 \( \approx \) 1.1 \times 10^{9}
  - Tera: 1TB \( \equiv \) 1TiB \( \Rightarrow \) (1024)^4 bytes \( \Rightarrow \) 2^{40} bytes \( \approx \) 1,099,511,627,776 \( \approx \) 1.1 \times 10^{12}
  - Peta: 1PB \( \equiv \) 1PiB \( \Rightarrow \) (1024)^5 bytes \( \Rightarrow \) 2^{50} bytes \( \approx \) 1,125,899,906,842,624 \( \approx \) 1.1 \times 10^{15}
  - Exa: 1EB \( \equiv \) 1EiB \( \Rightarrow \) (1024)^6 bytes \( \Rightarrow \) 2^{60} bytes \( \approx \) 1,152,921,504,606,842,624 \( \approx \) 1.2 \times 10^{18}
- Units of Bandwidth, Space on disk/etc, Everything else…, sometimes called the “decimal system”
  - Kilo: 1KB/s \( \Rightarrow \) 10^3 bytes/s, 1KB \( \Rightarrow \) 10^3 bytes
  - Mega: 1MB/s \( \Rightarrow \) 10^6 bytes/s, 1MB \( \Rightarrow \) 10^6 bytes
  - Giga: 1GB/s \( \Rightarrow \) 10^9 bytes/s, 1GB \( \Rightarrow \) 10^9 bytes
  - Tera: 1TB/s \( \Rightarrow \) 10^{12} bytes/s, 1TB \( \Rightarrow \) 10^{12} bytes
  - Peta: 1PB/s \( \Rightarrow \) 10^{15} bytes/s, 1PB \( \Rightarrow \) 10^{15} bytes
  - Exa: 1EB/s \( \Rightarrow \) 10^{18} bytes/s, 1EB \( \Rightarrow \) 10^{18} bytes
Multiprogramming with Protection

• Can we protect programs from each other without translation?
  – Yes: Base and Bound!
  – Used by, e.g., Cray-1 supercomputer
Recall: Base and Bound (No Translation)

- Still protects OS and isolates program
- Requires relocating loader
- No addition on address path
Recall: General Address translation

- Consequently, two views of memory:
  - View from the CPU (what program sees, virtual memory)
  - View from memory (physical memory)
  - Translation box (Memory Management Unit or MMU) converts between two views
- Translation ⇒ much easier to implement protection!
  - If task A cannot even gain access to task B’s data, no way for A to adversely affect B
- With translation, every program can be linked/loaded into same region of user address space
Recall: Base and Bound (with Translation)

- Hardware relocation
- Can the program touch OS?
- Can it touch other programs?
Issues with Simple B&B Method

• Fragmentation problem over time
  – Not every process is same size ⇒ memory becomes fragmented over time
  – Fragmentation: wasted space both external (between blocks) and internal (inside blocks)

• Missing support for sparse address space
  – Would like to have multiple chunks/program (Code, Data, Stack, Heap, etc)

• Hard to do inter-process sharing
  – Want to share code segments when possible
  – Want to share memory between processes
  – Helped by providing multiple segments per process
More Flexible Segmentation

- Logical View: multiple separate segments
  - Typical: Code, Data, Stack
  - Others: memory sharing, etc
- Each segment is given region of contiguous memory
  - Has a base and limit
  - Can reside anywhere in physical memory
Implementation of Multi-Segment Model

- Segment map resides in processor
  - Segment number mapped into base/limit pair
  - Base added to offset to generate physical address
  - Error check catches offset out of range
- As many chunks of physical memory as entries
  - Segment addressed by portion of virtual address
  - However, could be included in portion of virtual address
    - x86 Example: mov [es:bx],ax.
- What is “V/N” (valid / not valid)?
  - Can mark segments as invalid; requires check as well
Intel x86 Special Registers

• Typical Segment Register
  – Current Priority is RPL of Code Segment (CS)
• Segmentation can’t be just “turned off”
  – What if we just want to use paging?
  – Set base and bound to all of memory, in all segments
Example: Four Segments (16 bit addresses)

<table>
<thead>
<tr>
<th>Seg ID #</th>
<th>Base</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (code)</td>
<td>0x4000</td>
<td>0x0800</td>
</tr>
<tr>
<td>1 (data)</td>
<td>0x4800</td>
<td>0x1400</td>
</tr>
<tr>
<td>2 (shared)</td>
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Virtual Address Format

Virtual Address Space

Physical Address Space
Example: Four Segments (16 bit addresses)

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- **Virtual Address Format**
  - SegID = 0

- **Physical Address Space**
  - 0x0000 to 0x4000

- **Virtual Address Space**
  - 0x0000 to 0xC000
Example: Four Segments (16 bit addresses)

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Virtual Address Format

Physical Address Space
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<td>0x3000</td>
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Virtual Address Format

- Seg ID
- Offset

Virtual Address Space

- Seg ID = 0
- Seg ID = 1

Physical Address Space

- Might be shared
- Space for Other Apps
- Shared with Other Apps
Let's simulate a bit of this code to see what happens (PC=0x240):

1. Fetch 0x0240 (0000 0010 0100 0000). Virtual segment #? 0; Offset? 0x240
   Physical address? Base=0x4000, so physical addr=0x4240
   Fetch instruction at 0x4240. Get “la $a0, varx”
   Move 0x4050 → $a0, Move PC+4 → PC
Let’s simulate a bit of this code to see what happens (PC=0x240):

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   Fetch instruction at 0x4240. Get “la $a0, varx”
   Move 0x4050 → $a0, Move PC+4→PC

2. Fetch 0x0244. Translated to Physical=0x4244. Get “jal strlen”
   Move 0x0248 → $ra (return address!), Move 0x0360 → PC
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   Fetch instruction at 0x4240. Get “la $a0, varx”
   Move 0x4050 → $a0, Move PC+4→PC

2. Fetch 0x0244. Translated to Physical=0x4244. Get “jal strlen”
   Move 0x0248 → $ra (return address!), Move 0x0360 → PC

3. Fetch 0x0360. Translated to Physical=0x4360. Get “li $v0, 0”
   Move 0x0364 → $t0, Move PC+4→PC

Let's simulate a bit of this code to see what happens (PC=0x240):

1. Fetch 0x0240 (0000 0010 0100 0000). Virtual segment #? 0; Offset? 0x240
   Physical address? Base=0x4000, so physical addr=0x4240
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3. Fetch 0x0360. Translated to Physical=0x4360. Get “li $v0, 0”
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   Fetch instruction at 0x4240. Get “la $a0, varx”
   Move 0x4050 $a0, Move PC+4 → PC

2. Fetch 0x0244. Translated to Physical=0x4244. Get “jal strlen”
   Move 0x0248 $ra (return address!), Move 0x0360 → PC

3. Fetch 0x0360. Translated to Physical=0x4360. Get “li $v0, 0”
   Move 0x0000 $v0, Move PC+4 → PC

4. Fetch 0x0364. Translated to Physical=0x4364. Get “lb $t0, ($a0)”
   Since $a0 is 0x4050, try to load byte from 0x4050
   Translate 0x4050 (0100 0000 0101 0000). Virtual segment #? 1; Offset? 0x50
   Physical address? Base=0x4800, Physical addr = 0x4850,
   Load Byte from 0x4850 → $t0, Move PC+4 → PC
Observations about Segmentation

• Translation on every instruction fetch, load or store
• Virtual address space has holes
  – Segmentation efficient for sparse address spaces
• When it is OK to address outside valid range?
  – This is how the stack (and heap?) allowed to grow
  – For instance, stack takes fault, system automatically increases size of stack
• Need protection mode in segment table
  – For example, code segment would be read-only
  – Data and stack would be read-write (stores allowed)
• What must be saved/restored on context switch?
  – Segment table stored in CPU, not in memory (small)
  – Might store all of processes memory onto disk when switched (called “swapping”)
What if not all segments fit in memory?

- Extreme form of Context Switch: **Swapping**
  - To make room for next process, some or all of the previous process is moved to disk
    » Likely need to send out complete segments
  - This greatly increases the cost of context-switching
- What might be a desirable alternative?
  - Some way to keep only active portions of a process in memory at any one time
  - Need finer granularity control over physical memory
Problems with Segmentation

• Must fit variable-sized chunks into physical memory

• May move processes multiple times to fit everything

• Limited options for swapping to disk

• **Fragmentation**: wasted space
  – **External**: free gaps between allocated chunks
  – **Internal**: don’t need all memory within allocated chunks
Recall: General Address Translation

Translation Map 1

Translation Map 2

Physical Address Space

OS heap & Stacks
OS data
OS code

Heap 2
Stack 2
Data 1
Code 2

Heap 1
Stack 1
Data 1
Code 1

Heap
Stack
Data
Code

Prog 2
Virtual Address Space 2

Prog 1
Virtual Address Space 1

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Paging: Physical Memory in Fixed Size Chunks

• Solution to fragmentation from segments?
  – Allocate physical memory in **fixed size chunks** ("pages")
  – Every chunk of physical memory is equivalent
    » Can use simple vector of bits to handle allocation:
      00110001110001101 ... 110010
    » Each bit represents page of physical memory
      1 ⇒ allocated, 0 ⇒ free

• Should pages be as big as our previous segments?
  – No: Can lead to lots of internal fragmentation
    » Typically have small pages (1K-16K)
  – Consequently: need multiple pages/segment
How to Implement Simple Paging?

- Page Table (One per process)
  - Resides in physical memory
  - Contains physical page and permission for each virtual page (e.g. Valid bits, Read, Write, etc)
- Virtual address mapping
  - Offset from Virtual address copied to Physical Address
    » Example: 10 bit offset ⇒ 1024-byte pages
  - Virtual page # is all remaining bits
    » Example for 32-bits: 32-10 = 22 bits, i.e. 4 million entries
    » Physical page # copied from table into physical address
  - Check Page Table bounds and permissions
Simple Page Table Example

Example (4 byte pages)

Virtual Memory

<table>
<thead>
<tr>
<th>0x00</th>
<th>0x04</th>
<th>0x06?</th>
<th>0x08</th>
<th>0x09?</th>
</tr>
</thead>
<tbody>
<tr>
<td>abc</td>
<td>cde</td>
<td>efgh</td>
<td>ijkl</td>
<td>lijk</td>
</tr>
</tbody>
</table>

Page Table

<table>
<thead>
<tr>
<th>0x00</th>
<th>0x04</th>
<th>0x08</th>
<th>0x0C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000 0000</td>
<td>0000 0100</td>
<td>0000 1000</td>
<td>0000 1000</td>
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</table>

Physical Memory

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<tr>
<td>0x00 0010</td>
<td>0x00 1100</td>
<td>0x00 0100</td>
<td>0x00 0100</td>
</tr>
</tbody>
</table>

Example:
- 0x06? maps to 0x08 (efgh)
- 0x09? maps to 0x10 (abcd)

0x05! maps to 0x06 (ijkl)
0x0E! maps to 0x0A (efgh)
What about Sharing?

Virtual Address (Process A):

<table>
<thead>
<tr>
<th>Virtual Page #</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>page #0</td>
<td>V,R</td>
</tr>
<tr>
<td>page #1</td>
<td>V,R</td>
</tr>
<tr>
<td>page #2</td>
<td>V,R,W</td>
</tr>
<tr>
<td>page #3</td>
<td>V,R,W</td>
</tr>
<tr>
<td>page #4</td>
<td>N</td>
</tr>
<tr>
<td>page #5</td>
<td>V,R,W</td>
</tr>
</tbody>
</table>

Virtual Address (Process B):

<table>
<thead>
<tr>
<th>Virtual Page #</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>page #0</td>
<td>V,R</td>
</tr>
<tr>
<td>page #1</td>
<td>N</td>
</tr>
<tr>
<td>page #2</td>
<td>V,R,W</td>
</tr>
<tr>
<td>page #3</td>
<td>N</td>
</tr>
<tr>
<td>page #4</td>
<td>V,R</td>
</tr>
<tr>
<td>page #5</td>
<td>V,R,W</td>
</tr>
</tbody>
</table>

This physical page appears in address space of both processes.
Where is page sharing used?

- The “kernel region” of every process has the same page table entries:
  - The process cannot access it at user level
  - But on U->K switch, kernel code can access it AS WELL AS the region for THIS user
    » What does the kernel need to do to access other user processes?
- Different processes running same binary:
  - Execute-only, but do not need to duplicate code segments
- User-level system libraries (execute only)
- Shared-memory segments between different processes:
  - Can actually share objects directly between processes
    » Must map page into same place in address space!
  - This is a limited form of the sharing that threads have within a single process
Memory Layout for Linux 32-bit (Pre-Meltdown patch!)

1GB

Kernel space
User code CANNOT read from or write to these addresses, doing so results in a Segmentation Fault

Stack (grows down)

Memory Mapping Segment
File mappings (including dynamic libraries) and anonymous mappings. Example: /lib/libc.so

3GB

Heap

BSS segment
Uninitialized static variables, filled with zeros. Example: static char *userName;

Data segment
Static variables initialized by the programmer. Example: static char *gonzo = "God's own prototype";

Text segment (ELF)
Stores the binary image of the process (e.g., /bin/gonzo)

http://static.duarte.org/img/blogPosts/linuxFlexibleAddressSpaceLayout.png
Some simple security measures

• Address Space Randomization
  – Position-Independent Code ⇒ can place user code anywhere in address space
    » Random start address makes much harder for attacker to cause jump to code that it
      seeks to take over
  – Stack & Heap can start anywhere, so randomize placement

• Kernel address space isolation
  – Don’t map whole kernel space into each process, switch to kernel page table
  – Meltdown⇒map none of kernel into user mode!
Summary: Paging
What happens if stack grows to 1110 0000?

Summary: Paging
Summary: Paging

Virtual memory view:
- Stack: 1111 1111
- Heap: 1110 0000
- Data: 1100 0000
- Code: 0100 0000

Offset:
- Page #

Page Table:
- 1111 1111
  - 1111 1110
  - 1111 1110
  - 1111 1110
  - 1111 1110
- 1110 0000
  - 1110 0000
  - 1110 0000
  - 1110 0000
  - 1110 0000
- 1000 0000
  - 1000 0000
  - 1000 0000
- 0100 0000
  - 0100 0000
  - 0100 0000
  - 0100 0000
  - 0100 0000
- 0000 0000
  - 0000 0000
  - 0000 0000
  - 0000 0000
  - 0000 0000

Physical memory view:
- Stack: 1110 0000
- Heap: 0101 0000
- Data: 0011 0000
- Code: 0010 0000

Allocate new pages where room!
Conclusion

• Segment Mapping
  – Segment registers within processor
  – Segment ID associated with each access
    » Often comes from portion of virtual address
    » Can come from bits in instruction instead (x86)
  – Each segment contains base and limit information
    » Offset (rest of address) adjusted by adding base

• Page Tables
  – Memory divided into fixed-sized chunks of memory
  – Virtual page number from virtual address mapped through page table to physical page number
  – Offset of virtual address same as physical address
  – Large page tables can be placed into virtual memory

• Next Time: Multi-Level Tables
  – Virtual address mapped to series of tables
  – Permit sparse population of address space