Address spaces and memory management

• Review of processes
  – Process = one or more threads in an address space
  – Thread = stream of executing instructions
  – Address space = memory space used by threads

• Address space
  – All the memory space the process can use as it runs
  – Hardware interface: one memory of “small” size, shared between processes
  – OS abstraction: each process has its own, larger memory

• Abstractions provided by address spaces
  – Address independence: same numeric address can be used in different address spaces (i.e., different processes), yet remain logically distinct
  – Protection: one process can’t access data in another process’s address space (actually controlled sharing)
  – Large address spaces: an address space can be larger than the machine’s physical memory
Uni-programming

• 1 process runs at a time (viz. one process occupies memory at a time)
• Always load process into same spot in memory (with some space reserved for OS)

<table>
<thead>
<tr>
<th>ffffff</th>
<th>operating system</th>
</tr>
</thead>
<tbody>
<tr>
<td>.</td>
<td></td>
</tr>
<tr>
<td>.</td>
<td></td>
</tr>
<tr>
<td>80000</td>
<td></td>
</tr>
<tr>
<td>7ffff</td>
<td>user process</td>
</tr>
<tr>
<td>.</td>
<td></td>
</tr>
<tr>
<td>.</td>
<td></td>
</tr>
<tr>
<td>00000</td>
<td></td>
</tr>
</tbody>
</table>

• Problems?
Multi-programming and address translation

• Multi-programming: more than 1 process in memory at a time
  – Need to support address translation
  – Need to support protection
• Must translate addresses issued by a process, so they don’t conflict with addresses issued by other processes
  – Static address translation: translate addresses before execution (i.e., translation doesn’t change during execution)
  – Dynamic address translation: translate addresses during execution (i.e., translation can change during execution)
• Is it possible to run two processes at the same time and provide address independence with only static address translation?
• Does static address translation achieve the other address space abstractions?

• Achieving all the address space abstractions requires doing some work on each memory reference
Dynamic address translation

- Translate every memory reference from virtual address to physical address
  - virtual address: an address issued by the user process
  - physical address: an address used to access the physical memory

  ![Diagram](user process → translator (MMU) → physical memory)
  - virtual address
  - physical address

- Translation enforces protection
  - One process can’t refer to another process’s address space

- Translation enables large address spaces
  - A virtual address only needs to be in physical memory when it’s being accessed
  - Change translations on the fly; different virtual addresses occupy the same physical memory
Address translation

- Many ways to implement translator

  - Tradeoffs
    - Flexibility (sharing, growth, large address spaces)
    - Size of data needed to support translation
    - Speed of translation
Base and bounds

- Load each process into contiguous region of physical memory. Prevent each process from accessing data outside its region
  
  ```java
  if (virtual address > bound) {
    trap to kernel; kill process (core dump)
  } else {
    physical address = virtual address + base
  }
  ```

- Process has illusion of dedicated memory [0, bound)
Base and bounds

• Similar to linker-loader, but also protects processes from each other
• Only kernel can change translation data (base and bounds)
• What does it mean to change address spaces?
  – Changing data used to translate addresses (base and bounds registers)

• What to do when address space grows?

• Low hardware cost (2 registers, 1 adder, 1 comparator)
• Low overhead (add and compare on each memory reference)
Base and bounds

• A single address space can’t be larger than physical memory
  – But sum of all address spaces can be larger than physical memory
• Swap current address space out to disk; swap address space for new process in
• Can’t share part of an address space between processes
External fragmentation

• Processes come and go, leaving a mishmash of available memory regions
  — This is called “external fragmentation”: wasted memory between allocated regions

Process 1 start: 100 KB (physical addresses 0–99 KB)
Process 2 start: 200 KB (physical addresses 100–299 KB)
Process 3 start: 300 KB (physical addresses 300–599 KB)
Process 4 start: 400 KB (physical addresses 600–999 KB)

Process 3 exits: physical addresses 300–599 KB now free
Process 5 starts: 100 KB (physical addresses 300–399 KB)
Process 1 exits: physical 0–99 KB now free

Process 6 start: 300 KB. No contiguous space large enough.

• May need to copy memory region to new location
Base and bounds

• Hard to grow address space
Segmentation

- Segment: a region of contiguous memory (contiguous in physical memory and in virtual address space)
- Base and bounds used a single segment. We can generalize this to multiple segments, described by a table of base and bounds pairs

<table>
<thead>
<tr>
<th>Segment #</th>
<th>Base</th>
<th>Bounds</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4000</td>
<td>700</td>
<td>code segment</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>500</td>
<td>data segment</td>
</tr>
<tr>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
<td>unused</td>
</tr>
<tr>
<td>3</td>
<td>2000</td>
<td>1000</td>
<td>stack segment</td>
</tr>
</tbody>
</table>

- In segmentation, a virtual address takes the form: (segment #, offset)
- Many ways to specify the segment #
  - High bits of address
  - Special register
  - Implicit to instruction opcode
Segmentation

- Virtual memory segment 3
  - Stack: 4ff 0

- Virtual memory segment 1
  - Data: 6ff 0

- Virtual memory segment 0
  - Code: 4ff 0

Physical memory

- Code: 46ff
- Stack: 2000
- Data: 4000
Segmentation

• Not all virtual addresses are **valid**
  – Valid means that the region is part of the process’s address space
  – Invalid means the virtual address is illegal to access. Accessing an invalid virtual address causes a trap to OS (usually resulting in core dump)
  – E.g., no valid data in segment 2; no valid data in segment 1 above 4ff)
• Protection: different segments can have different protection
  – E.g., code is usually read only (allows instruction fetch, load)
  – E.g., data is usually read/write (allows instruction fetch, load, store)
  – Protection in base and bounds?

• What must be changed on a context switch?
Segmentation

- Works well for sparse address spaces. Regions can grow independently.
- Easy to share segments, without sharing entire address space
- But complex memory allocation

- Can a single address space be larger than physical memory?

- How to make memory allocation easy; allow address space to grow beyond physical memory?
Paging

- Allocate physical memory in fixed-size units (called pages)
  - Fixed-size unit is easy to allocate
  - Any free physical page can store any virtual page
- Virtual address
  - Virtual page # (high bits of address, e.g., bits 31-12)
  - Offset (low bits of address, e.g., bits 11-0, for 4 KB page size)
- Translation data is the page table

<table>
<thead>
<tr>
<th>Virtual page #</th>
<th>Physical page #</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>invalid</td>
</tr>
<tr>
<td>...</td>
<td>invalid</td>
</tr>
<tr>
<td>1048575</td>
<td>invalid</td>
</tr>
</tbody>
</table>
Paging

• **Translation process**
  
  if (virtual page is invalid or non-resident or protected) {
      trap to OS fault handler
  } else {
      physical page # = pageTable[virtual page #].physPageNum
  }

• **What must be changed on a context switch?**

• Each virtual page can be in physical memory or “paged out” to disk
Paging

• How does processor know that a virtual page is not in physical memory?

• Like segments, pages can have different protections (e.g., read, write, execute)
Valid versus resident

• Valid means a virtual page is legal for the process to access. It is (usually) an error for the process to access an invalid page.
  – Who makes a virtual page valid/invalid?

  – Why would a process want one of its virtual pages to be invalid?

• Resident means a virtual page is in physical memory. It is not an error for a process to access a non-resident page.
  – Who makes a virtual page resident/non-resident?
Paging

• Page size
  – What happens if page size is really small?
  – What happens if page size is really big?
  – Typically a compromise, e.g., 4 KB or 8 KB. Some architectures support multiple page sizes.
• How well does paging handle two growing regions?
Paging

- Simple memory allocation
- Flexible sharing
- Easy to grow address space

- But large page tables

- Summary
  - Base and bound: unit of translation and swapping is an entire address space
  - Segmentation: unit of translation and swapping is a segment (a few per address space)
  - Paging: unit of translation and swapping/paging is a page

- How to modify paging to reduce space needed for translation data?
Multi-level paging

- Standard page table is a simple array. Multi-level paging generalizes this into a tree.
- E.g., two-level page table
  - Index into level 1 page table using virtual address bits 31-22
  - Index into level 2 page table using virtual address bits 21-12
  - Page offset: bits 11-0 (4 KB page)
  - What information is stored in the level 1 page table?
  - What information is stored in the level 2 page table?

- How does this allow the translation data to take less space?
### Multi-level paging

#### Level 1 page table

<table>
<thead>
<tr>
<th>virtual address bits 21-12</th>
<th>physical page #</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

#### Level 2 page tables

<table>
<thead>
<tr>
<th>virtual address bits 21-12</th>
<th>physical page #</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
Multi-level paging

• How to share memory when using multi-level page tables?

• What must be changed on a context switch?

• Space efficient for sparse address spaces
• Easy memory allocation
• Flexible sharing

• But two extra lookups per memory reference
Translation lookaside buffer (TLB)

• Translation when using paging involves 1 or more additional memory references. How to speed up the translation process?

• TLB caches PTEs
  – If TLB contains the entry you’re looking for, you can skip all the translation steps
  – On TLB miss, get the PTE, store in the TLB, then restart the instruction

• Does this change what happens on a context switch?
Replacement policies

• Which page to evict when you need a free page?
  – Goal: minimize page faults

• Random

• FIFO
  – Replace page that was brought into memory the longest time ago
  – But this may replace pages that continue to be frequently used

• OPT
  – Replace page that won’t be used for the longest time in the future
  – This minimizes misses, but requires knowledge of the future
Replacement policies

• LRU (least recently used)
  – Use past reference pattern to predict future (temporal locality)
  – Assumes past is a mirror image of the future. If page hasn’t been used for a long time in the past, it probably won’t be used for a long time in the future.
  – Approximates OPT
  – But still hard to implement exactly
  – Can we make LRU easier to implement by approximating it?
Clock replacement algorithm

- Most MMUs maintain a “referenced” bit for each resident page
  - Set by MMU when page is read or written
  - Can be cleared by OS
- Why maintain reference bit in hardware?
- How to use reference bit to identify old pages?
- How to do work incrementally, rather than all at once?
Clock replacement algorithm

- Arrange resident pages around a clock

- Algorithm
  - Consider page pointed to by clock hand
  - If not referenced, page hasn’t been accessed since last sweep. Evict.
  - If referenced, page has been referenced since last sweep. What to do?
    - Can this infinite loop? What if all pages have been referenced since last sweep?
    - New pages put behind the clock hand and marked referenced
Eviction

• What to do with page when it’s evicted?

• Why not write page to disk on every store?
Eviction optimizations

• While evicted page is being written to disk, the page being brought into memory must wait
  – How might you optimize the eviction system (but don’t use these for Project 3)?
Page table contents

- Physical page number
  - Written by OS; read by MMU
- Resident: is virtual page in physical memory
  - Written by OS; read by MMU
- Protection (readable, writable)
  - Written by OS; read by MMU
- Dirty: has virtual page been written since dirty bit was last cleared?
  - Written by OS and MMU; read by OS
- Referenced: has virtual page been read or written since reference bit was last cleared?
  - Written by OS and MMU; read by OS

- Does hardware page table need to store disk block # for non-resident virtual pages?
MMU algorithm

- MMU does work on each memory reference (load, store)
  
  if (virtual page is non-resident or protected) {
    trap to OS fault handler
    retry access
  } else {
    physical page # = pageTable[virtual page #].physPageNum
    pageTable[virtual page #].referenced = true
    if (access is write) {
      pageTable[virtual page #].dirty = true
    }
    access physical memory
  }

- Project 3 infrastructure implements (a subset of) the MMU algorithm
Software dirty and referenced bits

• Do we need MMU to maintain dirty bit?

• Do we need MMU to maintain referenced bit?
• You can think of (most of) the kernel as a privileged process, with its own address space
Where is translation data stored?

• Page tables for user and kernel address spaces could be stored in physical memory, i.e., accessed via physical addresses

• Page tables for user address spaces could be stored in kernel’s virtual address space

— Benefits?
— Project 3: translation data for user address spaces stored in kernel virtual address space; kernel virtual address space managed by infrastructure (Linux)
Kernel versus user address spaces

• Can you evict the kernel’s virtual pages?

• How can kernel access specific physical memory addresses (e.g., to refer to translation data)?
  – Kernel can issue untranslated address (bypass MMU)
  – Kernel can map physical memory into a portion of its address space (vm_physmem in Project 3)
How does kernel access user’s address space?

- Kernel can manually translate a user virtual address to a physical address, then access the physical address.

- Can map kernel address space into every process’s address space.

  
  7f0000
  | 80000
  | ffff

  trap

  - Trap to kernel doesn’t change address spaces; it just allows computer to access both OS and user parts of that address space.
Kernel versus user mode

• Who sets up data used by translator?

• CPU must distinguish between kernel and user instructions
  – Access physical memory
  – Issue privileged instructions

• How does CPU know kernel is running?
  – Mode bit (kernel mode or user mode)

• Recap of protection
  – Protect address spaces via translation. How to protect translation data?
  – Distinguish between kernel and user mode. How to protect mode bit?
Switching from user process into kernel

• Who can change mode bit?

• What causes a switch from user process to kernel?
System calls

• From C++ program to kernel
  – C++ program calls `cin`
  – `cin` calls `read()`
  – `read()` executes assembly-language instruction `syscall`
  – `syscall` traps to kernel at pre-specified location
  – kernel’s `syscall` handler receives trap and calls kernel’s `read()`

• Trap to kernel
  – Set mode bit to kernel
  – Save registers, PC, SP
  – Change SP to kernel stack
  – Change to kernel’s address space
  – Jump to exception handler
Passing arguments to system calls

• Can store arguments in registers or memory
  – Which address space holds the arguments?

• Kernel must carefully check validity of arguments
Interrupt vector table

• Switching from user to kernel mode is safe(r) because control can only be transferred to certain locations

• Interrupt vector table stores these locations

• Who can modify interrupt vector table?

• Why is this easier than controlling access to mode bit?

• What are administrative processes (e.g., processes owned by root)?
Process creation

• Steps
  – Allocate process control block
  – Initialize translation data for new address space
  – Read program image from executable into memory
  – Initialize registers
  – Set mode bit to “user”
  – Jump to start of program
• Need hardware support for last steps (e.g., “return from interrupt” instruction)
• Switching from kernel to user process (e.g., after system call) is same as last few steps
Multi-process issues

• How to allocate physical memory between processes?
  – Fairness versus efficiency

• Global replacement
  – Can evict pages from this process or other processes

• Local replacement
  – Can evict pages only from this process
  – Must still determine how many pages to allocate to this process
Thrashing

• What would happen if many large processes all actively used their entire address space?

• Performance degrades rapidly as miss rate increases
  – Average access time = hit rate * hit time + miss rate * miss time
  – E.g., hit time = .0001 ms; miss time = 10 ms
    • Average access time (100% hit rate) = .0001 ms
    • Average access time (1% hit rate) =
    • Average access time (10% hit rate) =

• Solutions to thrashing
Working set

- What do we mean by “actively using”?  
- Working set = all pages used in last T seconds  
  - Larger working set \(\Rightarrow\) process needs more physical memory to run well (i.e., avoid thrashing)
- Sum of all working sets should fit in memory  
  - Only run subset of processes that fit in memory

- How to measure size of working set?
Case study: Unix process creation

• Two steps
  – fork: create new process with one thread. Address space of new process is copy of parent process’s address space.
  – exec: replace new process’s address space with data from program executable; start new program
  – Separating process creation into two steps allows parent to pass information to child

• Problems
Copy on write

- Parent virtual address space:
  - Data
  - Code

- Physical memory:
  - Data
  - Code

- Child virtual address space:
  - Data
  - Code
Implementing a shell

- Text and graphical shells provide the main interface to users
- How to write a shell program?