This lecture

To support multiprogramming, we need “Protection”

- Kernel vs. user mode
- What is an address space?
- How to implement it?

<table>
<thead>
<tr>
<th>Physical memory</th>
<th>Abstraction: virtual memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>No protection</td>
<td>Each program isolated from all others and from the OS</td>
</tr>
<tr>
<td>Limited size</td>
<td>Illusion of “infinite” memory</td>
</tr>
<tr>
<td>Sharing visible to programs</td>
<td>Transparent --- can’t tell if memory is shared</td>
</tr>
</tbody>
</table>
The big picture

- To support multiprogramming with protection, we need:
  - dual mode operations
  - translation between virtual address space and physical memory

- How to implement the translation?

Address translation

- Goals
  - implicit translation on every memory reference
  - should be very fast
  - protected from user’s faults

- Options
  - Base and Bounds
  - Segmentation
  - Paging
  - Multilevel translation
  - Paged page tables
Base and Bounds

Each program loaded into contiguous regions of physical memory.
Hardware cost: 2 registers, adder, comparator.

Base and Bounds (cont’d)

- Built in Cray-1
- A program can only access physical memory in \([\text{base}, \text{base}+\text{bound}]\)
- On a context switch: save/restore base, bound registers
- Pros: Simple
- Cons: fragmentation; hard to share (code but not data and stack); complex memory allocation
Segmentation

- **Motivation**
  - separate the virtual address space into several segments so that we can share some of them if necessary

- **A segment is a region of logically contiguous memory**

- **Main idea: generalize base and bounds by allowing a table of base-bound pairs**
  (assume 2 bit segment ID, 12 bit segment offset)

<table>
<thead>
<tr>
<th>virtual segment #</th>
<th>physical segment start</th>
<th>segment size</th>
</tr>
</thead>
<tbody>
<tr>
<td>code (00)</td>
<td>0x4000</td>
<td>0x700</td>
</tr>
<tr>
<td>data (01)</td>
<td>0</td>
<td>0x500</td>
</tr>
<tr>
<td>- (10)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>stack (11)</td>
<td>0x2000</td>
<td>0x1000</td>
</tr>
</tbody>
</table>

Segmentation (cont’d)

- Have a table of (seg, size)
- Protection: each entry has
  - (nil, read, write)
- On a context switch: save/restore the table or a pointer to the table in kernel memory
- Pros: efficient, easy to share
- Cons: complex management and fragmentation within a segment
## Segmentation example

(assume 2 bit segment ID, 12 bit segment offset)

<table>
<thead>
<tr>
<th>v-segment #</th>
<th>p-segment start</th>
<th>segment size</th>
<th>physical memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>code (00)</td>
<td>0x4000</td>
<td>0x700</td>
<td></td>
</tr>
<tr>
<td>data (01)</td>
<td>0</td>
<td>0x500</td>
<td></td>
</tr>
<tr>
<td>- (10)</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>stack (11)</td>
<td>0x2000</td>
<td>0x1000</td>
<td></td>
</tr>
</tbody>
</table>

### virtual memory

- 0
- 6ff
- 1000
- 14ff
- 3000
- 3ff

### physical memory

- 0
- 4ff
- 2000
- 2ff
- 4000
- 46ff

---

## Segmentation example (cont’d)

### Virtual memory for `strlen(x)`

<table>
<thead>
<tr>
<th>Main: 240</th>
<th>store 1108, r2</th>
</tr>
</thead>
<tbody>
<tr>
<td>244</td>
<td>store pc+8, r31</td>
</tr>
<tr>
<td>248</td>
<td>jump 360</td>
</tr>
<tr>
<td>24c</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>strlen: 360</td>
<td>loadbyte (r2), r3</td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>420</td>
<td>jump (r31)</td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>x: 1108</td>
<td>a b c \0</td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>

### physical memory for `strlen(x)`

<table>
<thead>
<tr>
<th>Main: 4240</th>
<th>store 1108, r2</th>
</tr>
</thead>
<tbody>
<tr>
<td>4244</td>
<td>store pc+8, r31</td>
</tr>
<tr>
<td>4248</td>
<td>jump 360</td>
</tr>
<tr>
<td>424c</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>strlen: 4360</td>
<td>loadbyte (r2), r3</td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>4420</td>
<td>jump (r31)</td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>
Paging

- **Motivations**
  - both branch bounds and segmentation still require fancy memory management (e.g., first fit, best fit, re-shuffling to coalesce free fragments if no single free space is big enough for a new segment)
  - can we find something simple and easy

- **Solution**
  - allocate physical memory in terms of fixed size chunks of memory, or *pages*.
  - Simpler because it allows use of a bitmap
    00111110000001100 --- each bit represents one page of physical memory
    1 means allocated, 0 means unallocated

Paging (cont’d)

- Use a page table to translate
- Various bits in each entry
- Context switch: similar to the segmentation scheme
- What should be the page size?
- Pros: simple allocation, easy to share
- Cons: big page table and cannot deal with internal fragmentation easily
Paging example

Virtual memory

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>f</td>
<td>g</td>
<td>h</td>
</tr>
<tr>
<td>i</td>
<td>j</td>
<td>k</td>
<td>l</td>
</tr>
</tbody>
</table>

Physical memory

<table>
<thead>
<tr>
<th>i</th>
<th>j</th>
<th>k</th>
<th>l</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>f</td>
<td>g</td>
<td>h</td>
</tr>
</tbody>
</table>

Page size: 4 bytes

Segmentation with paging

Virtual address

<table>
<thead>
<tr>
<th>Vseg #</th>
<th>VPage #</th>
<th>offset</th>
</tr>
</thead>
</table>

Page table

<table>
<thead>
<tr>
<th>PPage#</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>PPage#</td>
<td>...</td>
</tr>
</tbody>
</table>

Each segment has its own page table!
Two-level paging

Virtual address

<table>
<thead>
<tr>
<th>dir</th>
<th>table</th>
<th>offset</th>
</tr>
</thead>
</table>

Directory

<table>
<thead>
<tr>
<th>dir</th>
<th>dir</th>
<th>dir</th>
</tr>
</thead>
</table>

Each directory entry points to a page table

pte

Two-level paging example

- A logical address (on 32-bit machine with 4K page size) is divided into:
  - a page number consisting of 20 bits.
  - a page offset consisting of 12 bits.
- Since the page table is paged, the page number is further divided into:
  - a 10-bit page number.
  - a 10-bit page offset.
- Thus, a logical address is as follows:

<table>
<thead>
<tr>
<th>page number</th>
<th>page offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_1$</td>
<td>$p_2$</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

where $p_1$ is an index into the outer page table, and $p_2$ is the displacement within the page of the outer page table.
Segmentation with paging - Intel 386

- As shown in the following diagram, the Intel 386 uses segmentation with paging for memory management with a two-level paging scheme.
How many PTEs do we need?

- Worst case for 32-bit address machine
  - # of processes \times 2^{20} (if page size is 4096 bytes)

- What about 64-bit address machine?
  - # of processes \times 2^{52}

Summary: virtual memory mapping

- What?
  - separate the programmer’s view of memory from the system’s view

- How?
  - translate every memory operation using table (page table, segment table).
  - Speed: cache frequently used translations

- Result?
  - each user has a private address space
  - programs run independently of actual physical memory addresses used, and actual memory size
  - protection: check that they only access their own memory
Summary (cont’d)

- Goal: multiprogramming with protection + illusion of “infinite” memory

- Today’s lecture so far:
  - HW-based approach for protection: dual mode operation + address space
  - Address translation: virtual address -> physical address

- Future topics
  - how to make address translation faster? use cache (TLB)
  - demand paged virtual memory

- The rest of today’s lecture:
  - The programming interface
Abstraction: process & file system

- **Problem**
  - Multiple CPU cores, many I/O devices and lots of interrupts
  - Users feel they have machine to themselves

- **Answer**
  - Decompose hard problems into simple ones
  - Deal with one at a time
  - Process is such a unit (reflecting something dynamic)
  - File system is another high-level abstraction (for “data”)

- **Future**
  - How processes differ from threads? What is a process really?
  - Generalizing “processes” to “containers” & “virtual machines”

Simplest process

- **Sequential execution**
  - No concurrency inside a process
  - Everything happens sequentially
  - Some coordination may be required

- **Process state**
  - Registers
  - Main memory
  - I/O devices
    - File system
    - Communication ports
Program vs. process

Program

```c
main()
{
...
foo()
...
}
foo()
{
...
}
```

Process

```
main()
{
...
foo()
...
}
foo()
{
...
}
```

- Program vs. process (cont’d)
  - Process > program
    - Program is just part of process state
    - Example: many users can run the same program (but different processes)
  - Process < program
    - A program can invoke more than one process
    - Example: cc starts up cpp, cc1, cc2, as, ld (each are programs themselves)
Process control block (PCB)

- **Process management info**
  - State
    - Ready: ready to run
    - Running: currently running
    - Blocked: waiting for resources
  - Registers, EFLAGS, and other CPU state
  - Stack, code and data segment
  - Parents, etc

- **Memory management info**
  - Segments, page table, stats, etc

- **I/O and file management**
  - Communication ports, directories, file descriptors, etc

- **How OS takes care of processes**
  - Resource allocation and process state transition

Primitives of processes

- **Creation and termination**
  - Exec, Fork, Wait, Kill

- **Signals**
  - Action, Return, Handler

- **Operations**
  - Block, Yield

- **Synchronization**
  - We will talk about this later
Make a process

◆ Creation
  - Load code and data into memory
  - Create an empty call stack
  - Initialize state to same as after a process switch
  - Make the process ready to run

◆ Clone
  - Stop current process and save state
  - Make copy of current code, data, stack and OS state
  - Make the process ready to run

UNIX process management

◆ UNIX fork - system call to create a copy of the current process, and start it running
  - No arguments!

◆ UNIX exec - system call to change the program being run by the current process

◆ UNIX wait - system call to wait for a process to finish

◆ UNIX signal - system call to send a notification to another process
UNIX process management

```
main () {
...
}
```

```
pid = fork();
if (pid == 0)
   exec(...);
else
   wait(pid);
```

```
pid = fork();
if (pid == 0)
   exec(...);
else
   wait(pid);
```

```
pid = fork();
if (pid == 0)
   exec(...);
else
   wait(pid);
```

```
child_pid = fork();
if (child_pid == 0) {  // I'm the child process
   printf("I am process #\%d\n", getpid());
   return 0;
} else {  // I'm the parent process
   printf("I am parent of process #\%d\n", child_pid);
   return 0;
}
```
Implementing UNIX fork & exec

- Steps to implement UNIX fork
  - Create and initialize the process control block (PCB) in the kernel
  - Create a new address space
  - Initialize the address space with a copy of the entire contents of the address space of the parent
  - Inherit the execution context of the parent (e.g., any open files)
  - Inform the scheduler that the new process is ready to run

- Steps to implement UNIX exec
  - Load the program into the current address space
  - Copy arguments into memory in the address space
  - Initialize the hardware context to start execution at ``start''

Process context switch

- Save a context (everything that a process may damage)
  - All registers (general purpose and floating point)
  - All co-processor state
  - Save all memory to disk?
  - What about cache and TLB stuff?

- Start a context
  - Does the reverse

- Challenges
  - OS code must save state without changing any state
  - How to run without touching any registers?
    - CISC machines have a special instruction to save and restore all registers on stack
    - RISC: reserve registers for kernel or have way to carefully save one and then continue

Very machine dependent!
Process state transition

Running: executing now
Ready: waiting for CPU
Blocked: waiting for I/O or lock

Which ready process to pick?

0 ready processes: run idle loop
1 ready process: easy!
> 1: what to do?

- FIFO?
  - put threads on back of list, pull them off from front
  - (nachos does this: schedule.cc)
- Pick random? (could result in starvation)
- Priority?
  - give some threads a better shot at the CPU
Scheduling policies

◆ Scheduling issues
  - fairness: don't starve process
  - prioritize: more important first
  - deadlines: must do by time 'x' (car brakes)
  - optimization: some schedules >> faster than others

◆ No universal policy:
  - many variables, can't maximize them all
  - conflicting goals
    * more important jobs vs starving others
    * I want my job to run first, you want yours.

◆ Given some policy, how to get control?

How to get control?

◆ Traps: events generated by current process
  - system calls
  - errors (illegal instructions)
  - page faults

◆ Interrupts: events external to the process
  - I/O interrupt
  - timer interrupt (every 100 milliseconds or so)

◆ Process perspective:
  - explicit: process yields processor to another
  - implicit: causes an expensive blocking event, gets switched
UNIX I/O --- a key innovation ("files")

- **Uniformity**
  - All operations on all files, devices use the same set of system calls: open, close, read, write
- **Open before use**
  - Open returns a handle (file descriptor) for use in later calls on the file
- **Byte-oriented**
- **Kernel-buffered reads/writes**
- **Explicit close**
  - To garbage collect the open file descriptor
- **Pipes** (for interprocess communication → a kernel buffer with two file descriptors, one for reading, one for writing)

UNIX file system interface

- **UNIX file open is a Swiss Army knife:**
  - Open the file, return file descriptor
  - Options:
    - if file doesn't exist, return an error
    - If file doesn't exist, create file and open it
    - If file does exist, return an error
    - If file does exist, open file
    - If file exists but isn't empty, nix it then open
    - If file exists but isn't empty, return an error
    - ...