Today

- Move on to ...
Hmm... Let's look at this again

L1/L2 cache: 64 B blocks

Throughput:
- 16 B/cycle
- 8 B/cycle
- 2 B/cycle
- 1 B/30 cycles

Latency:
- 3 cycles
- 14 cycles
- 100 cycles
- millions

~4 MB

~4 GB

~500 GB

Disk
Roadmap

- Memory & Data
- Integers/FP
- Machine code
- Assembly programming (x86)
- Procedures/Stacks
- Caches
- Processes (today!)
- Virtual Memory
- Memory Allocation
- Java vs C
- (maybe) a little more on processor HW
Processes and control flow

- Is branches/calls the only way we can get the processor to “go somewhere” in a program?
- What is a process?
Control Flow

- Processors do only one thing:
  - From startup to shutdown, a CPU simply reads and executes (interprets) a sequence of instructions, one at a time
  - This sequence is the CPU’s control flow (or flow of control)

**Physical control flow**

```plaintext
<startup>
inst_1
inst_2
inst_3
...
inst_n
<shutdown>
```
Altering the Control Flow

- **Up to now:** two mechanisms for changing control flow:
  - Jumps and branches
  - Call and return
  
  Both react to changes in *program state*

- **Insufficient for a useful system:**
  **difficult to react to changes in system state**
  - user hits “Ctrl-C” at the keyboard
  - user clicks on a different application’s window on the screen
  - data arrives from a disk or a network adapter
  - instruction divides by zero
  - system timer expires

- **How do we deal with the above? Are branches/calls sufficient?**
Altering the Control Flow

- **Up to now: two mechanisms for changing control flow:**
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  - Call and return
  Both react to changes in *program state*

- **Insufficient for a useful system:**
  difficult to react to changes in *system state*
  - user hits “Ctrl-C” at the keyboard
  - user clicks on a different application’s window on the screen
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  - instruction divides by zero
  - system timer expires

- **System needs mechanisms for “exceptional control flow”!**
Exceptional Control Flow

- Exists at all levels of a computer system
- Low level mechanisms
  - Exceptions
    - change in control flow in response to a system event (i.e., change in system state, user-generated interrupt)
    - Combination of hardware and OS software
- Higher level mechanisms
  - Process context switch
  - Signals – you’ll hear about these in CSE451 and CSE466
  - Implemented by either:
    - OS software (context switch and signals)
    - C language runtime library (nonlocal jumps)
Exceptions

- An exception is transfer of control to the operating system (OS) in response to some event (i.e., change in processor state)

Examples:
- div by 0, arithmetic overflow, page fault, I/O request completes, Ctrl-C

How does the system know where to jump to?
Interrupt Vectors

- Each type of event has a unique exception number $k$
- $k$ = index into exception table (a.k.a. interrupt vector)
- Handler $k$ is called each time exception $k$ occurs
Asynchronous Exceptions (Interrupts)

- **Caused by events external to the processor**
  - Indicated by setting the processor’s interrupt pin(s)
  - Handler returns to “next” instruction

- **Examples:**
  - I/O interrupts
    - hitting Ctrl-C at the keyboard
    - clicking a mouse button or tapping a touch screen
    - arrival of a packet from a network
    - arrival of data from a disk
  - Hard reset interrupt
    - hitting the reset button
  - Soft reset interrupt
    - hitting Ctrl-Alt-Delete on a PC
Synchronous Exceptions

- Caused by events that occur as a result of executing an instruction:
  - **Traps**
    - Intentional
    - Examples: *system calls*, breakpoint traps, special instructions
    - Returns control to “next” instruction
  - **Faults**
    - Unintentional but possibly recoverable
    - Examples: page faults (recoverable), protection faults (unrecoverable), floating point exceptions
    - Either re-executes faulting (“current”) instruction or aborts
  - **Aborts**
    - Unintentional and unrecoverable
    - Examples: parity error, machine check
    - Aborts current program
Trap Example: Opening File

- User calls: `open(filename, options)`
- Function `open` executes system call instruction `int`

```assembly
0804d070 <__libc_open>: 
  ... 
  804d082:  cd 80  int  $0x80 
  804d084:  5b    pop  %ebx 
  ... 
```

- OS must find or create file, get it ready for reading or writing
- Returns integer file descriptor
Fault Example: Page Fault

- User writes to memory location
- That portion (page) of user’s memory is currently on disk

<table>
<thead>
<tr>
<th>int a[1000];</th>
</tr>
</thead>
<tbody>
<tr>
<td>main ()</td>
</tr>
<tr>
<td>{</td>
</tr>
<tr>
<td>a[500] = 13;</td>
</tr>
<tr>
<td>}</td>
</tr>
</tbody>
</table>

User Process

movl
exception: page fault
returns

OS

Create page and load into memory

- Page handler must load page into physical memory
- Returns to faulting instruction
- Successful on second try
Fault Example: Invalid Memory Reference

```c
int a[1000];
main ()
{
    a[5000] = 13;
}
```

User Process

- Page handler detects invalid address
- Sends **SIGSEGV** signal to user process
- User process exits with “segmentation fault”
## Exception Table IA32 (Excerpt)

<table>
<thead>
<tr>
<th>Exception Number</th>
<th>Description</th>
<th>Exception Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Divide error</td>
<td>Fault</td>
</tr>
<tr>
<td>13</td>
<td>General protection fault</td>
<td>Fault</td>
</tr>
<tr>
<td>14</td>
<td>Page fault</td>
<td>Fault</td>
</tr>
<tr>
<td>18</td>
<td>Machine check</td>
<td>Abort</td>
</tr>
<tr>
<td>32-127</td>
<td>OS-defined</td>
<td>Interrupt or trap</td>
</tr>
<tr>
<td>128 (0x80)</td>
<td>System call</td>
<td>Trap</td>
</tr>
<tr>
<td>129-255</td>
<td>OS-defined</td>
<td>Interrupt or trap</td>
</tr>
</tbody>
</table>

Processes

- **Definition:** A *process* is an instance of a running program
  - One of the most important ideas in computer science
  - Not the same as “program” or “processor”

- **Process provides each program with** two key abstractions:
  - Logical control flow
    - Each program seems to have exclusive use of the CPU
  - Private virtual address space
    - Each program seems to have exclusive use of main memory

- **Why are these illusions important?**
- **How are these illusions maintained?**
Processes

- **Definition:** A *process* is an instance of a running program
  - One of the most important ideas in computer science
  - Not the same as “program” or “processor”

- **Process provides each program with two key abstractions:**
  - Logical control flow
    - Each program seems to have exclusive use of the CPU
  - Private virtual address space
    - Each program seems to have exclusive use of main memory

- **How are these Illusions maintained?**
  - Process executions interleaved (multi-tasking)
  - Address spaces managed by virtual memory system – next course topic
Concurrent Processes

- Two processes run *concurrently* (are concurrent) if their instruction executions (flows) overlap in time
- Otherwise, they are *sequential*
- Examples:
  - Concurrent: A & B, A & C
  - Sequential: B & C
User View of Concurrent Processes

- Control flows for concurrent processes are physically disjoint in time

- However, we can think of concurrent processes as executing in parallel (only an illusion?)

![Diagram showing the user view of concurrent processes with time and processes A, B, and C]
Context Switching

- Processes are managed by a shared chunk of OS code called the \textit{kernel}
  - Important: the kernel is not a separate process, but rather runs as part of a user process
- Control flow passes from one process to another via a \textit{context switch}... \textit{(how?)}

\begin{center}
\begin{tikzpicture}
  \node[above] (A) at (3,6) \textit{Process A};
  \node[above] (B) at (9,6) \textit{Process B};
  \node at (3,0) {time};
  \node at (3,-1) {user code};
  \node at (3,-2) {kernel code};
  \node at (3,-3) {user code};
  \node at (9,-3) {user code};
  \node at (9,-2) {kernel code};
  \node at (9,-1) {user code};
  \draw[->, thick] (A) -- (B);
  \draw[->, thick] (A.north west) -- (B.south west);
  \draw[->, thick] (A.north east) -- (B.south east);
  \draw[->, thick] (A.south west) -- (B.north west);
  \draw[->, thick] (A.south east) -- (B.north east);
  \draw[->, thick] (A.center) -- (B.center);
  \node at (9,-4) {\textit{context switch}};
  \node at (3,-4) {\textit{context switch}};
\end{tikzpicture}
\end{center}
fork: Creating New Processes

- **int fork(void)**
  - creates a new process (child process) that is identical to the calling process (parent process)
  - returns 0 to the child process
  - returns child’s process ID (**pid**) to the parent process

```c
pid_t pid = fork();
if (pid == 0) {
    printf("hello from child\n");
} else {
    printf("hello from parent\n");
}
```

- Fork is interesting (and often confusing) because it is called **once** but returns **twice**
Understanding fork

Process n

```c
pid_t pid = fork();
if (pid == 0) {
    printf("hello from child\n");
} else {
    printf("hello from parent\n");
}
```
Understanding fork

**Process n**

```
pid_t pid = fork();
if (pid == 0) {
    printf("hello from child\n");
} else {
    printf("hello from parent\n");
}
```

**Child Process m**

```
pid_t pid = fork();
if (pid == 0) {
    printf("hello from child\n");
} else {
    printf("hello from parent\n");
}
```

pid = m
Understanding fork

**Process n**

```c
 pid_t pid = fork();
 if (pid == 0) {
   printf("hello from child\n");
 } else {
   printf("hello from parent\n");
 }
```

**Child Process m**

```c
 pid_t pid = fork();
 if (pid == 0) {
   printf("hello from child\n");
 } else {
   printf("hello from parent\n");
 }
```

```c
 pid = m
```

Understanding fork

**Process n**

```c
pid_t pid = fork();
if (pid == 0) {
    printf("hello from child\n");
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**Child Process m**

```c
pid_t pid = fork();
if (pid == 0) {
    printf("hello from child\n");
} else {
    printf("hello from parent\n");
}
```

**pid = m**

```c
pid_t pid = fork();
if (pid == 0) {
    printf("hello from child\n");
} else {
    printf("hello from parent\n");
}
```

**pid = 0**

```c
pid_t pid = fork();
if (pid == 0) {
    printf("hello from child\n");
} else {
    printf("hello from parent\n");
}
```
Understanding fork

Process n

```c
pid_t pid = fork();
if (pid == 0) {
    printf("hello from child\n");
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Child Process m

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if (pid == 0) {
    printf("hello from child\n");
} else {
    printf("hello from parent\n");
}
```

Hello from parent Which one is first? Hello from child
Fork Example #1

- Parent and child both run same code
  - Distinguish parent from child by return value from `fork`

- Start with same state, but each has private copy
  - Including shared output file descriptor
  - Relative ordering of their print statements undefined

```c
void fork1()
{
    int x = 1;
    pid_t pid = fork();
    if (pid == 0) {
        printf("Child has x = %d\n", ++x);
    } else {
        printf("Parent has x = %d\n", --x);
    }
    printf("Bye from process %d with x = %d\n", getpid(), x);
}
```
Fork Example #2

- Both parent and child can continue forking

```c
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```
Fork Example #2

- Both parent and child can continue forking

```c
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```
Fork Example #3

- Both parent and child can continue forking

```c
void fork3()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("L2\n");
    fork();
    printf("Bye\n");
}
```
Fork Example #3

- Both parent and child can continue forking

```c
void fork3()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("L2\n");
    fork();
    printf("Bye\n");
}
```
Fork Example #4

- Both parent and child can continue forking

```c
void fork4()
{
    printf("L0\n");
    if (fork() != 0) {
        printf("L1\n");
        if (fork() != 0) {
            printf("L2\n");
            fork();
        }
    }
    printf("Bye\n");
}
```
**Fork Example #4**

- Both parent and child can continue forking

```c
void fork4()
{
    printf("L0\n");
    if (fork() != 0) {
        printf("L1\n");
        if (fork() != 0) {
            printf("L2\n");
            fork();
        }
    }
    printf("Bye\n");
}
```
Fork Example #4

- Both parent and child can continue forking

```c
void fork5()
{
    printf("L0\n");
    if (fork() == 0) {
        printf("L1\n");
        if (fork() == 0) {
            printf("L2\n");
            fork();
        }
    }
    printf("Bye\n");
}
```
Fork Example #4

- Both parent and child can continue forking

```c
void fork5()
{
    printf("L0\n");
    if (fork() == 0) {
        printf("L1\n");
        if (fork() == 0) {
            printf("L2\n");
            fork();
        }
    }
    printf("Bye\n");
}
```
exit: Ending a process

- **void exit(int status)**
  - exits a process
  - Normally return with status 0
  - `atexit()` registers functions to be executed upon exit

```c
void cleanup(void) {
    printf("cleaning up\n");
}

void fork6() {
    atexit(cleanup);
    fork();
    fork();
    exit(0);
}
```
Zombies

- **Idea**
  - When process terminates, still consumes system resources
    - Various tables maintained by OS
  - Called a “zombie”
    - That is, a living corpse, half alive and half dead

- **Reaping**
  - Performed by parent on terminated child (*horror movie!*)
  - Parent is given exit status information
  - Kernel discards process

- **What if parent doesn’t reap?**
  - If any parent terminates without reaping a child, then child will be reaped by *init* process
  - So, only need explicit reaping in long-running processes
    - e.g., shells and servers
Zombie Example

```c
void fork7()
{
    if (fork() == 0) {
        /* Child */
        printf("Terminating Child, PID = %d\n", getpid());
        exit(0);
    } else {
        printf("Running Parent, PID = %d\n", getpid());
        while (1)
            ; /* Infinite loop */
    }
}
```

- `ps` shows child process as “defunct”
- Killing parent allows child to be reaped by `init`
Non-terminating Child Example

```
void fork8()
{
    if (fork() == 0) {
        /* Child */
        printf("Running Child, PID = %d\n", getpid());
        while (1)
            ; /* Infinite loop */
    } else {
        printf("Terminating Parent, PID = %d\n", getpid());
        exit(0);
    }
}
```

- Child process still active even though parent has terminated
- Must kill explicitly, or else will keep running indefinitely
Synchronization!
wait: Synchronizing with Children

- int wait(int *child_status)
  - suspends current process until one of its children terminates
  - return value is the pid of the child process that terminated
  - if child_status != NULL, then the object it points to will be set to a status indicating why the child process terminated
wait: Synchronizing with Children

```c
void fork9() {
    int child_status;
    if (fork() == 0) {
        printf("HC: hello from child\n");
    } else {
        printf("HP: hello from parent\n");
        wait(&child_status);
        printf("CT: child has terminated\n");
    }
    printf("Bye\n");
    exit();
}
```
wait() Example

- If multiple children completed, will take in arbitrary order
- Can use macros WIFEXITED and WEXITSTATUS to get information about exit status

```c
void fork10()
{
    pid_t pid[N];
    int i;
    int child_status;
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            exit(100+i); /* Child */
    for (i = 0; i < N; i++) {
        pid_t wpid = wait(&child_status);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n", wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminated abnormally\n", wpid);
    }
}
```
waitpid(): Waiting for a Specific Process

- **waitpid(pid, &status, options)**
  - suspends current process until specific process terminates
  - various options (that we won’t talk about)

```c
void fork11()
{
    pid_t pid[N];
    int i;
    int child_status;
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            exit(100+i); /* Child */
    for (i = 0; i < N; i++) {
        pid_t wpid = waitpid(pid[i], &child_status, 0);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n", wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminated abnormally\n", wpid);
    }
} 
```
execve: Loading and Running Programs

- int execve(
  char *filename,
  char *argv[],
  char *envp
)

- **Loads and runs**
  - Executable *filename*
  - With argument list *argv*
  - And environment variable list *envp*

- **Does not return** (unless error)

- **Overwrites process, keeps pid**

- **Environment variables:**
  - “name=value” strings
execve: Example

```
envp[n] = NULL
envp[n-1] → "PWD=/homes/iws/luisceze"
...
envp[0] → "USER=luisceze"
```

```
argv[argc] = NULL
argv[argc-1] → "/usr/include"
...
argv[0] → "ls"
```
Summary

- **Exceptions**
  - Events that require non-standard control flow
  - Generated externally (interrupts) or internally (traps and faults)

- **Processes**
  - At any given time, system has multiple active processes
  - Only one can execute at a time, however,
  - Each process appears to have total control of the processor + has a private memory space
Summary (cont’d)

- **Spawning processes**
  - Call to `fork`
  - One call, two returns

- **Process completion**
  - Call `exit`
  - One call, no return

- **Reaping and waiting for Processes**
  - Call `wait` or `waitpid`

- **Loading and running Programs**
  - Call `exec1` (or variant)
  - One call, (normally) no return