Logistics

Reading Bryant/O’Hallaron
Ch 4: Architectures
  ▶ Skimming is OK
  ▶ Lecture: high-level coverage
Ch 6: Memory (Next)

Goals
  ▶ Circuits that Compute
  ▶ Basics of Processor Arch
  ▶ Pipelining

Lab / HW 10
  ▶ Time C code using time command
  ▶ Observe strange results that raise questions
  ▶ Answer questions in lecture

Project 4
  ▶ Post Next Week
  ▶ Optimization + Performance
  ▶ Use knowledge of Arch / Memory to improve / explain execution speed

You are filled with determination.
Machines that Compute

- Humans can perform algorithms, sadly **slow and error-prone**
- Want a machine which can do this faster with fewer errors
- Variety of machines have been built over time and technology to implement them has changed rapidly
- The following are high-level principles that haven’t changed much
Logic Gates

- Abstract physical device that implements a boolean function
- May be implemented with a variety of components including **transistors**, vacuum tubes, mechanical devices, and **water pressure**
- Physical implementations have many trade-offs: cost, speed, difficulty to manufacture, wetness

![Logic Gates Diagram]

- OR
- AND
- XOR
- NOR
- NAND
- NOT
Combinatorial Circuits

- Combination of wires/gates with output solely dependent on input
- No storage of information involved / stateless
- Distinguished from sequential circuits which involve storage
- Can compute any Boolean functions of inputs
  - Set inputs as 0/1
  - After a delay, outputs will be set accordingly
- Examples: AND, OR, NOT are obvious
Exercise: Example Combinatorial Circuit

Calculate the Truth Table for the circuit

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>?</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>?</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>?</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>?</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>?</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>?</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>?</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>?</td>
</tr>
</tbody>
</table>

Speculate on the “meaning” of this circuit
**Answer:** Example Combinatorial Circuit

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

A “majority” circuit: Out is 1 when two or more of A,B,C are 1
Exercise: Comparing Majority-3 Circuits

- Both upper and lower circuits implement Majority-3: Same truth table
- Which is better?
- What criteria for “better” seems appropriate?
Answer: Comparing “Majority-3” Circuits

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Upper</th>
<th>Lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate Kinds</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Gate Count</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Gate “Depth”</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>“Scalability”</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

- “Scalability” is not well-defined, roughly how to “scale up” to majority 64
- Hardware designers spend time trying to design “better” circuits where “better” involves many criteria
Adders

- Obviously want computers to add stuff
- An adder is a circuit that performs addition

1-bit Half Adder

- “Adds” A and B
- S is the sum
- C is the carry
- Construct a **Truth Table** for the circuit

1-bit Full Adder

- “Adds” A, B, and $C_{in}$
- S is the sum
- $C_{out}$ is the carry out
- Carry In/Out used to string adders together
Multi-bit Addition

Combine 4 full adders to get a 4-bit ripple carry adder

Easily extends to 32- or 64-bit adders
Multiplexers: MUX

- Used to “select” output from several inputs
- $2^N$ Inputs A, B, C, ...
- $N$ selection bits $S_0, S_1, ...$
- Output will be one of inputs “chosen” by selection bits
- Block diagram is a rectangle or trapezoid with inputs/outputs
- Will prove useful momentarily

- 4-to-1 MUX
- 8-to-1 MUX
- 16-to-1 MUX
Variety of ways to design a MUX

One shown uses NAND gates exclusively

Note output is true when selected input is true
Arithmetic Logic Unit ALU: Select an Operation

2-bit ALU with 4 Operations

- Combine some gates, an adder, and a MUX
- Start having something that looks useful
- Input for multiple ops like AND, OR, XOR, ADD are simultaneously computed
- Select an “operation” with selection bits, really just selecting which output to pass through
ALU and FLAGS

- Block diagram for ALUs are usually a wedge shape
- Along with arithmetic/logic, ALU usually produces condition codes
  - ZF: zero flag
  - OF: overflow flag
  - SF: sign flag
- Used in other parts of CPU for conditional jumps/moves
Hardware Design in the Old Days

- Hardware design originally done by hand
- Draw all the gates, transfer it to technical drawing material, peel, send, hope to heaven that nothing gets munged...
- Required tremendous discipline, still had bugs

Ted Jenkins remembers working on the first Intel product, the 3101 64-bit RAM. Actually, the first version was only a 63-bit RAM due to a simple error peeling one layer on the rubylith (drawing medium).¹

¹Andrew Volk, Peter Stoll, Paul Metrovich, “Recollections of Early Chip Development at Intel”, Intel Technology Journal Q1, 2001
Modern Hardware Design: Specification Languages

- Modern design uses **hardware description languages**
- Verilog and VHDL pervasive, describe **behavior** of circuit
- **Synthesis**: convert description to gate layout with constraints like “use only NAND”
- **Verification**: simulate circuit to ensure correctness
- The invention of computers greatly accelerated development of better computers

---

**VHDL for 4-bit ALU**

```vhdl
library IEEE;
entity alu is
  Port(A_IN : in signed(3 downto 0);
       B_IN : in signed(3 downto 0);
       OPER : in STD_LOGIC_VECTOR(1 downto 0);
       OUTP : out signed(3 downto 0));
end alu;

architecture Behavioral of alu is
begin
  process(A_IN, B_IN, OPER)
  begin
    case OPER is
      when "00" =>
        OUTP <= A_IN xor B_IN; --XOR gate
      when "01" =>
        OUTP <= A_IN and B_IN; --AND gate
      when "10" =>
        OUTP <= A_IN or B_IN; --OR gate
      when "11" =>
        OUTP <= A_IN + B_IN; --addition
    end case;
  end process;
end Behavioral;
```
Combinatorial vs Sequential Circuits

- Combinatorial circuits can do lots of things BUT don’t constitute a complete programming system
- Need to represent **state**: store values, make future values depend on past state
- **Sequential circuits** introduce the notion of time and state to allow actual computation
- Most actual machines are state machines in some class like push-down automata or Turing machines (studied in 2011 and 4011)

*The class of problems that can be solved grows with more powerful machines.*
To move beyond combinatorial circuits, need a way to measure time

A **Clock Circuit** does this

Provides an oscillating signal of high/low voltages at a fixed frequency

Physical device: often **quartz crystal** which contracts when voltage is applied (*electrostriction*), expands when released

Manufactured to have different periods/frequencies

Circuitry attached to crystal causes oscillation at crystal’s resonant frequency; circuitry can increase/decrease output frequency
A Strange Circuit: SR Latch

- This one should **bug you** a little - why?
- Try computing a Truth Table for it...
A Strange Circuit: SR Latch

- SR Latch uses **feedback to store one bit** which is output as Q
- Truth Tables less relevant than **State Transition Table**
- Shows what the next state will be based on previous state
- Inputs and Outputs
  - S is for “SET”
  - R is for “RESET”
  - Q is current stored value
  - \( Q_{\text{next}} \) is new stored value

**State Transition Table**

<table>
<thead>
<tr>
<th>S</th>
<th>R</th>
<th>( Q_{\text{next}} )</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Q</td>
<td>hold state</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>reset</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>set</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>X</td>
<td>not allowed</td>
</tr>
</tbody>
</table>
Storage via Latches ≈ Flip-Flops

Specific combinations of latches yield the following nice properties:

- Store a bit of information so long as power is supplied (not shown in diagrams)
- Constantly output the stored bit
- Change the bit on certain inputs
- **Only change stored bit** during the rising edge of an input signal - **the clock tick**
- Often referred to as a **Flip Flop**, commonly a **rising edge flip-flop**
- Latches/Flip Flops can serve as a basis **registers**

---

2 There is no agreement on whether latches and flip-flops are the same or different so take care to understand context if going deeper. Relation above is adopted from some textbooks on digital design.
**Example: Master Slave SR Flip-Flop and Timing**

- Shows how a flip-flop (combination of two latches) stores a bit
- Set to 1: $S=1$, $R=0$
- Set to 0: $S=0$, $R=1$

### State Transition Table

<table>
<thead>
<tr>
<th>$S$</th>
<th>$R$</th>
<th>$Q_{next}$</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Q</td>
<td>hold state</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>reset</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>set</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>X</td>
<td>not allowed</td>
</tr>
</tbody>
</table>
Registers: a form of Static RAM (SRAM)

- Combine 4 flip-flops (each storing one bit) and one has an 4-bit register: circuitry that holds a changeable multi-bit quantity
- Combine more flip-flops to get larger registers, 8-16-32-64-bit
- Combine several registers with some access control circuitry (multiplexers) and one has a register file containing %rax %rbx ... %r15

Typical register file allows simultaneous
- read from two regs
- write to one reg

Register File with 4 registers, each with 4 bits

24
Register File with 16 Regs X 16 Bits + I/O

Source: Mostafa Khatib “Aging Analysis of Datapath Sub-blocks Based on CET Map Model for Negative Bias Temperature Instability (NBTI)”, Masters of Science Thesis, Center for Materials and Microsystems, Trento, Italy January 2014
Other Registers/CPU Memory of Note (SRAM)

Instruction Memory/Cache
Fast access to binary opcodes of program text

Program Counter (rip)
Position in instruction memory

Intermediate Results
For internal communication between different parts of the CPU to facilitate pipelining, usually accessible in assembly language

Some Memory Caches
Small, fast cache of main memory close to the CPU has similar circuitry to register file

NOT Main Memory
- While fast, **SRAM is expensive** in terms of transistors/space
- DRAM (dynamic RAM) is slower but compact and cheap enough to scale to gigabytes (will discuss DRAM soon)
The Full Shebang

- Connect an Clock, ALU, and Register file, and you’ve got a quasi-computer
- Add some instruction decoding, a place to store instructions, and perhaps some main memory and a full computer is born
- Must specify exact encoding of instructions so that signals between gates/units are routed correctly
- Note that processor design to the right is broken into stages to help understanding
Exercise: Timing Problems

- Each gate creates a delay: time before output to stabilizes based on new inputs
- Inputs are “allowed” to change on the clock signal’s rising edge
- Simplest sequential implementation sets clock frequency slow enough for outputs to stabilize each cycle (tick)
- Easy to do, but… it’s slow

Increasing Efficiency
Propose two ways that a complex, multi-part process can be completed faster
- Draw from experience/knowledge
- Think manufacturing, group projects, car wash, Chipotle…
**Answer: Timing Problems**

General solutions to process speed are familiar to all of us

**Assembly Line**

- Break single instruction into multiple “stages” which must all complete
- **Pipelined** processors execute stages simultaneously

**Multiple Resources**

- Implement multiple functional units and do instructions in parallel
- **Superscalar** processors (and parallel processors)
Pipelining for Efficiency

- Break up processor into “stages” which feed into each other
- Individual instructions like `addl %ecx, %eax` go through each stage
- Instruction completes (retires) when all stages complete
- **Begin next instruction when previous clears first stage**
- Some multi-cycle operations like **multiplication** may be pipelined as well

![3-Stage Pipeline Diagram](image)
Textbook Processor SEQ vs PIPE

- Textbook discusses 5-stages of a simple CPU design
  1. Fetch next PC
  2. Decode instruction
  3. Execute instruction
  4. Main Memory operations
  5. Write-back to register file

- Diagrams and Hardware Description Language for
  - SEQ: sequential implementation
  - PIPE: pipelined version of processor

**PIPE Version**

- Each of 5 stages happens in parallel
- Up to 5 instructions in flight
- Introduces internal registers to facilitate pipeline
Y86-64 SEQ sequential

Y86-64 PIPE 5-stage pipeline
Pipelines Aren’t All that and a Bag of Chips

- Pipelining is effective with predictable control flow and independent instructions
- Cases exist in which this doesn’t play out: pipeline hazards

**Data Interdependencies**

# INDEPENDENT
imull $3, %eax  # mul and add
addl $1, %edx  # different reg

# DEPENDENT: "Hazard"
imull $3, %eax  # mul and add
addl $1, %eax  # same reg

- Dependencies between register results break the pipeline
- Must serialize instructions (sequential execution)

**Branching**

.LOOP:
  addl %edx,%eax
  addl $1, %ecx
  cmp %esi,%ecx
  jl .LOOP  # which instruction
  popq %rbx  # next? "hazard"

- Modern Processors use branch prediction to guess the next instruction
- Incorrect guesses lead to restarting the pipeline
Superscalar Block Diagram

Source: Kilo-Instruction Processors: Overcoming the Memory Wall by Cristal et al.

Note several ALUs, separate queues for different instructions, asynchronous execution of instructions
Superscalar Processing

- Modern processors may have several **functional units** to do arithmetic, logic, other ops

- Allows **instruction-level parallelism**: do two things simultaneously

- Example:
  ```
  # SEQ 1: Multiply only
  imull $3, %eax
  
  # SEQ 2: Multiply and Add
  imull $3, %eax
  addl $5, %edx
  ```

- SEQ 1 and SEQ 2 may take the same amount of time

- Separate mult/add units used simultaneously

- Instruction parallelism automatically done at the hardware level leading to naming conventions for processors:
  - “Scalar”: sequential only, one thing at a time
  - **“Superscalar”**: automatic instruction parallelism, no explicit control
  - “Parallel”: explicit instructions that do multiple things simultaneously

- Modern processors are an amalgam of the above
Modern Processors are Weird

Assembly Code as an Interface

- Assembly/Binary Opcodes are a target for high level languages
- Modern processors execute these, guarantee correctness BUT make no guarantees about how or in what order
- Most use very deep pipelines which must be “fed” to keep speed high
- Has led to exotic processor designs with speculative and out of order execution: keep things in the pipeline
- This hasn’t always gone well: Meltdown / Spectre

Lab10 + HW10: Timing Arithmetic Codes

- Leads to surprising results
- Explainable by considering CPU is pipelined and superscalar
- Timing results vary with different CPUs
Additional Resources the Architecture-Inclined

Building an 8-bit breadboard computer! by Ben Eater (Youtube)

- Discusses many components we briefly touched on in more detail with a very practical bent of using them
- Results in a full CPU + Memory system that you can “see”
- A great introduction to components, breadboards, and general small electronics work

MIT 6.004 Computation Structures, Spring 2017 (Youtube)

- Much deeper detail on many aspects of CPU design
- Includes discussion of Multiplier circuits, power considerations, etc.