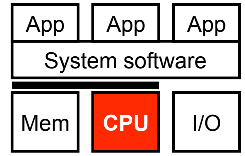
CIS 371
Computer Organization and Design

Unit 2: Digital Logic & Hardware Description

Based on slides by Prof. Amir Roth & Prof. Milo Martin

This Unit: Digital Logic & Hdw Description

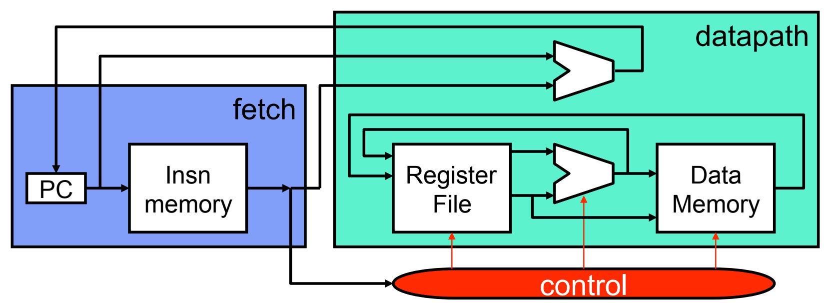


- Transistors & frabrication
- Digital logic basics
  - Focus on useful components
- Hardware design methods
  - Introduction to Verilog

Readings

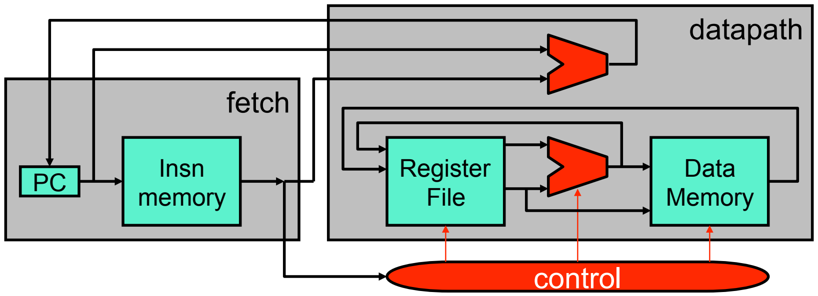
- Digital logic
  - P&H, Appendix C
- Manufacturing
  - P&H, Section 1.7
- See webpage for Verilog HDL resources

Motivation: Implementing an ISA



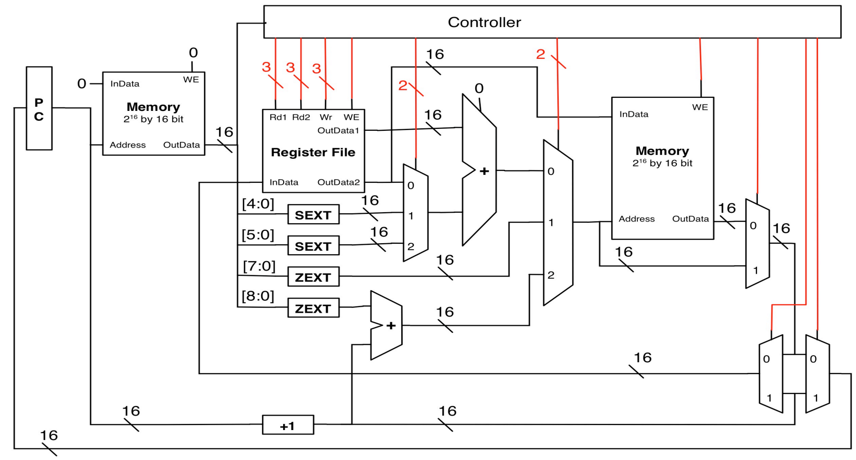
- **Datapath**: performs computation (registers, ALUs, etc.)
  - ISA specific: can implement every insn (single-cycle: in one pass!)
- **Control**: determines which computation is performed
  - Routes data through datapath (which regs, which ALU op)
- **Fetch**: get insn, translate opcode into control
- **Fetch** → **Decode** → **Execute** "cycle"

Two Types of Components

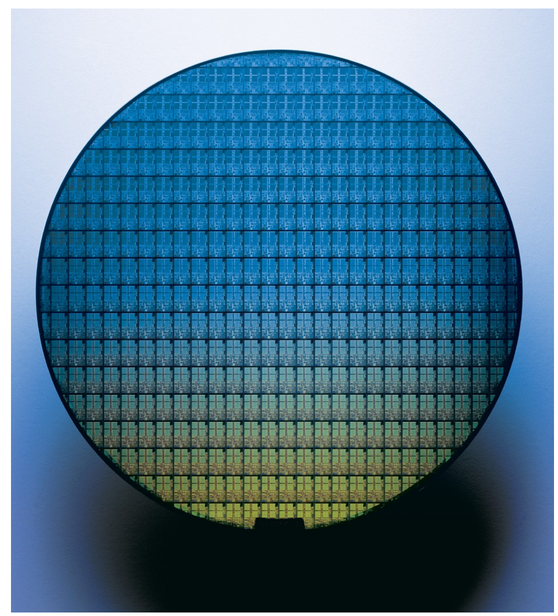


- **Purely combinational**: stateless computation
  - ALUs, muxes, control
  - Arbitrary Boolean functions
- **Combinational/sequential**: storage
  - PC, insn/data memories, register file
  - Internally contain some combinational components

Example Datapath

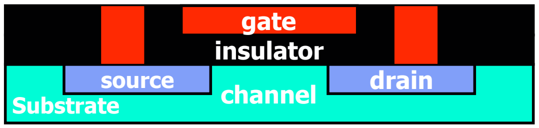


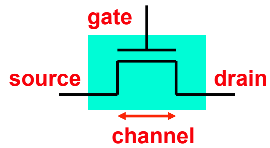
Transistors & Fabrication



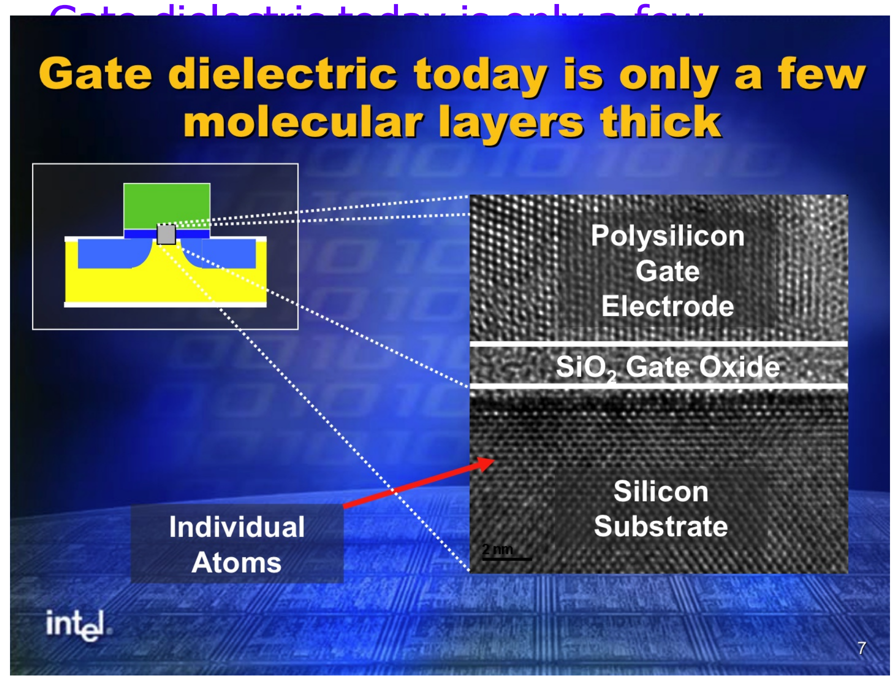
Intel Pentium M Wafer

Semiconductor Technology

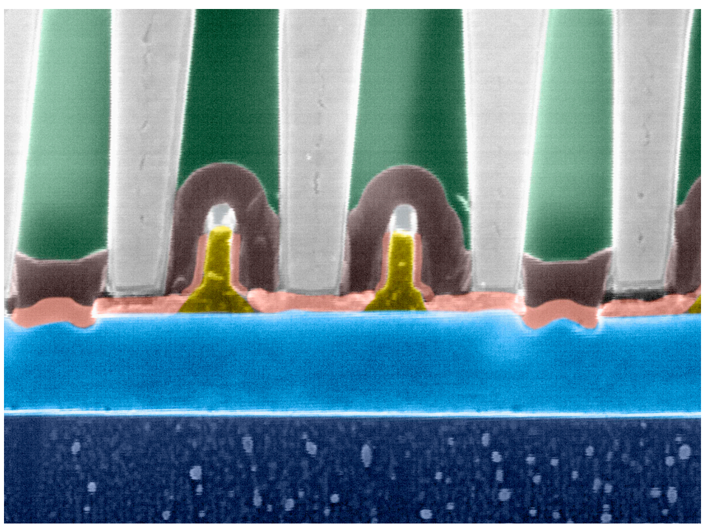




- Basic technology element: **MOSFET**
  - Solid-state component acts like electrical switch
  - **MOS**: metal-oxide-semiconductor
    - Conductor, insulator, semi-conductor
- **FET**: field-effect transistor
  - Channel conducts source→drain only when voltage applied to gate
- **Channel length**: characteristic parameter (short → fast)
  - Aka "feature size" or "technology"
  - Currently: 0.022 micron (μm), 22 nanometers (nm)
  - Continued miniaturization (scaling) known as "**Moore's Law**"
    - Won't last forever, physical limits approaching (or are they?)



Transistors



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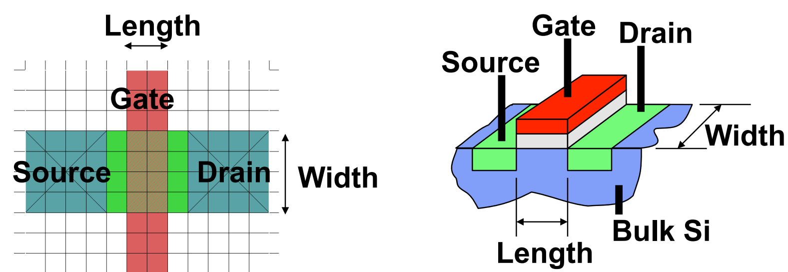
 IBM Power6

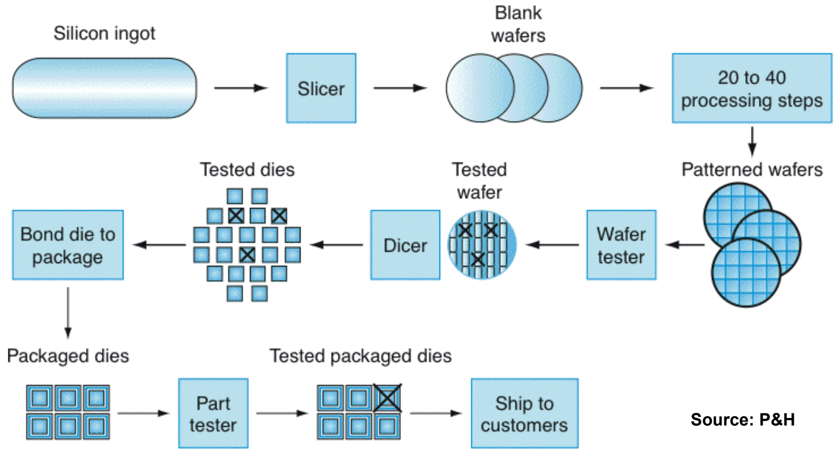
Transistor Geometry: Length & Scaling



Diagrams © Krste Asanovic, MIT

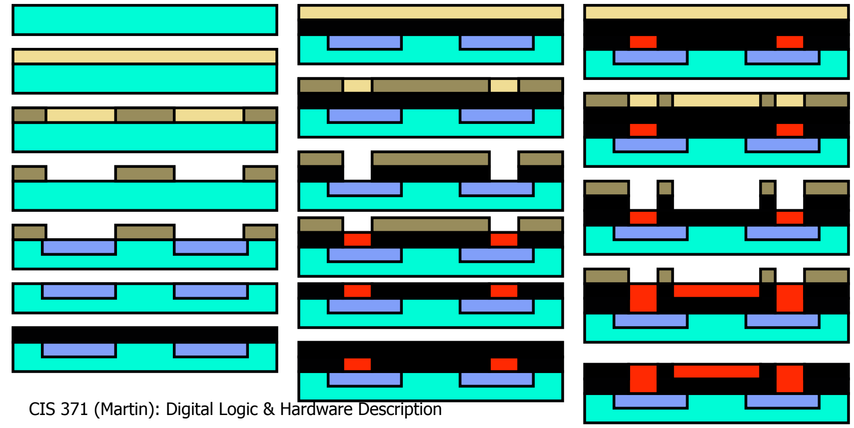
- **Transistor length**: characteristic of "process generation"
  - "22nm" refers to the transistor gate length
- Each process generation shrinks transistor length by 1.4x
  - "Moore's law" -> roughly 2x improvement transistor density
  - Roughly linear improvement in switching speeds (lower resistance)

Manufacturing Steps



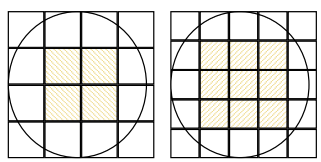
Manufacturing Steps

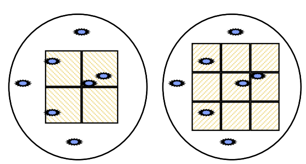
- Multi-step photo-/electro-chemical process
  - More steps, higher unit cost
- \+ Fixed cost mass production ($1 million+ for "mask set")



Integrated Circuit (IC) Costs

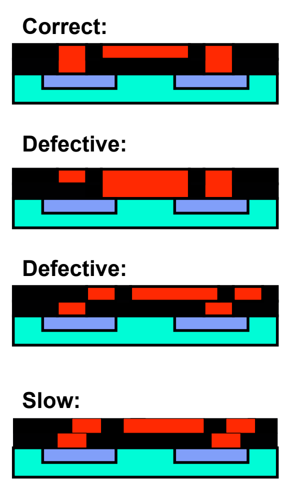
- Chips built in multi-step chemical processes on **wafers**
  - Cost / wafer is constant, f(wafer size, number of steps)
- Chip (die) cost is related to **area**
  - Larger chips means fewer of them
- Cost is more than linear in area
  - Why? random defects
  - Larger chips means fewer working ones
  - Chip cost ~ chip area$^{\alpha}$
    - α = 2 to 3





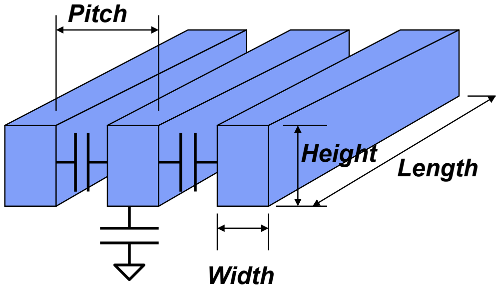
- **Wafer yield**: % wafer that is chips
- **Die yield**: % chips that work
- Yield is increasingly non-binary - fast vs slow chips

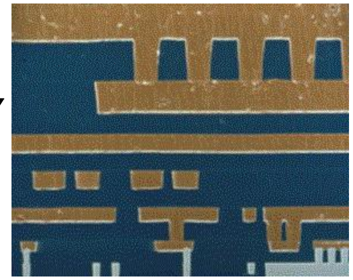
Manufacturing Defects



- Defects can arise
  - Under-/over-doping
  - Over-/under-dissolved insulator
  - Mask mis-alignment
  - Particle contaminants
- Try to minimize defects
  - Process margins
  - Design rules
    - Minimal transistor size, separation
- Or, tolerate defects
  - Redundant or "spare" memory cells
  - Can substantially improve yield

Wires

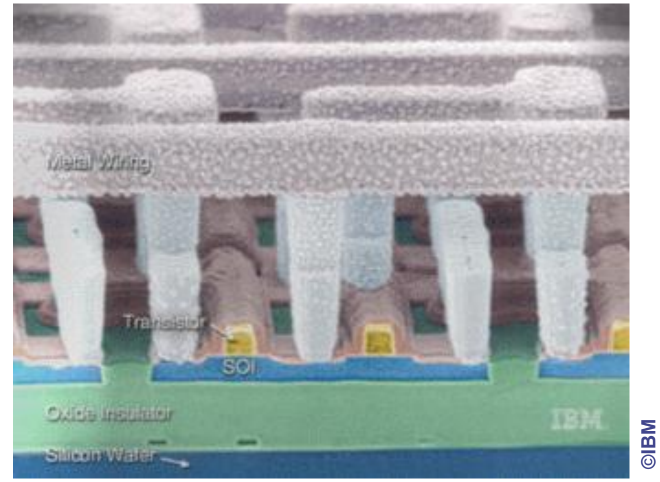




IBM CMOS7, 6 layers of copper wiring

- Transistors 1-dimensional for design purposes: **width**
- Wires 4-dimensional: **length**, **width**, **height**, **"pitch"**
  - Longer wires have more resistance (slower)
  - "Thinner" wires have more resistance (slower)
  - Closer wire spacing ("pitch") increases capacitance (slower)

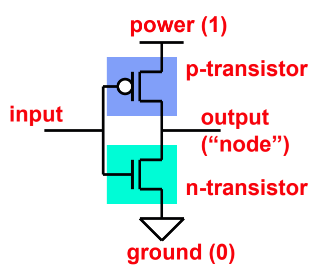
Transistors and Wires



From slides © Krste Asanović, MIT

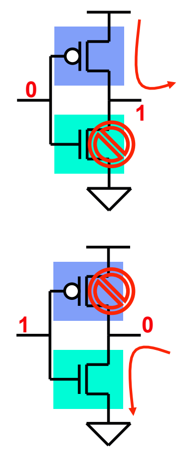
Complementary MOS (CMOS)

- Voltages as values
  - Power (V_{DD}) = "1", Ground = "0"
- Two kinds of MOSFETs
  - **N-transistors**
    - Conduct when gate voltage is 1
    - Good at passing 0s
  - **P-transistors**
    - Conduct when gate voltage is 0
    - Good at passing 1s
- **CMOS**
  - Complementary n-/p- networks form boolean logic (i.e., gates)
  - And some non-gate elements too (important example: RAMs)



Basic CMOS Logic Gate

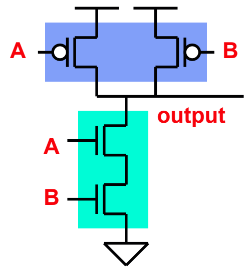
- **Inverter**: NOT gate
  - One p-transistor, one n-transistor
  - Basic operation
  - Input = 0
    - P-transistor closed, n-transistor open
    - Power charges output (1)
  - Input = 1
    - P-transistor open, n-transistor closed
    - Output discharges to ground (0)

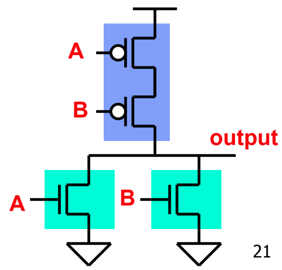


Another CMOS Gate Example

- What is this? Look at **truth table**
  - 0, 0 → 1
  - 0, 1 → 1
  - 1, 0 → 1
  - 1, 1 → 0
  - Result: **NAND** (NOT AND)
  - NAND is "universal"

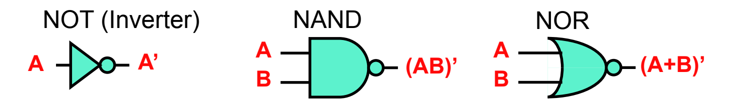
  - What function is this?



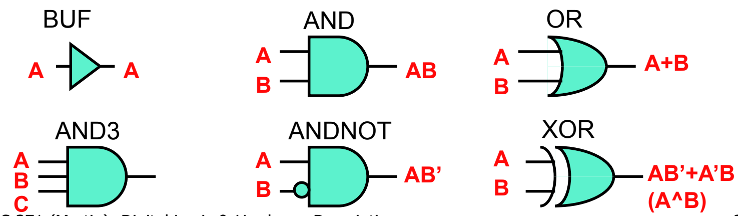


Digital Building Blocks: Logic Gates

- **Logic gates:** implement Boolean functions
  - Basic gates: NOT, NAND, NOR
    - Underlying CMOS transistors are naturally inverting (○ = NOT)



- NAND, NOR are "Boolean complete"



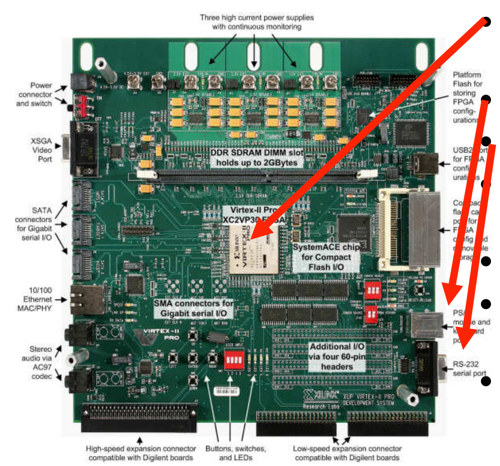
Alternative to Fabrication: FPGA

- We'll use **FPGAs (Field Programmable Gate Array)**
  - Also called Programmable Logic Devices (PLDs)

- An FPGA is a special type of programmable chip
  - Conceptually, contains a grid of gates
  - The wiring connecting them can be reconfigured electrically
    - Using more transistors as switches
  - Once configured, the FPGA can emulate any digital logic design
  - Tool converts **gate-level design** to configuration

- Uses
  - **Hardware prototyping** (what "we" are doing)
  - Low-volume special-purpose hardware
  - New: computational offload

In Our Lab: Digilent XUP-V2P Boards



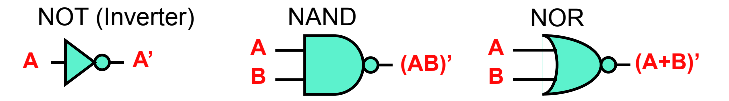
- Program FPGA to run LC4
  - "The project"
- Hook up keyboard
- And VGA
- Game on!

- Boards have many features
- Use some for debugging
  - LEDs, switches
- Other features
  - Ethernet, flash reader
  - 256MB SDRAM, audio in/out
  - Can boot Linux!

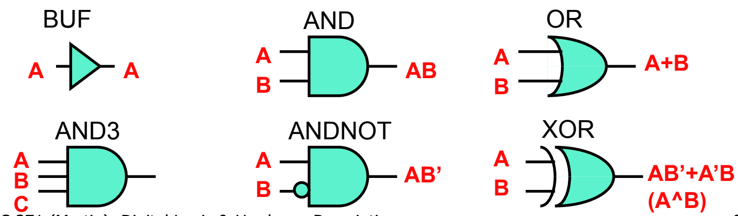
Digital Logic Review

Digital Building Blocks: Logic Gates

- **Logic gates:** implement Boolean functions
  - Basic gates: NOT, NAND, NOR
    - Underlying CMOS transistors are naturally inverting (○ = NOT)



  - NAND, NOR are "Boolean complete"



Boolean Functions and Truth Tables

- Any Boolean function can be represented as a truth table
  - **Truth table**: point-wise input → output mapping
  - Function is disjunction of all rows in which "Out" is 1

```
A,B,C → Out
0,0,0 → 0
0,0,1 → 0
0,1,0 → 0
0,1,1 → 0
1,0,0 → 0
1,0,1 → 1
1,1,0 → 1
1,1,1 → 1
```

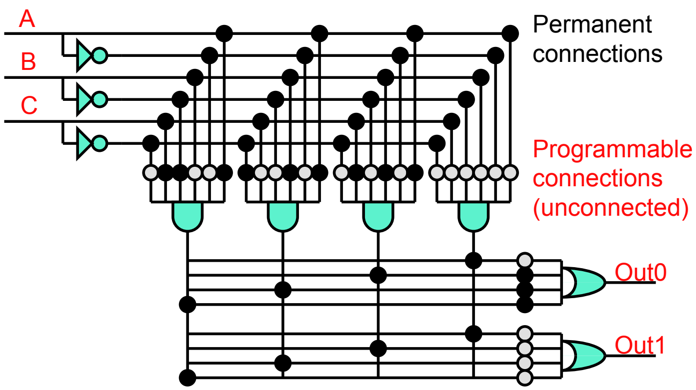
  - Example above: Out = AB'C + ABC' + ABC

Truth Tables and PLAs

- Implement Boolean function by implementing its truth table
  - Takes two levels of logic
    - Assumes inputs and inverses of inputs are available (usually are)
  - First level: ANDs (product terms)
  - Second level: ORs (sums of product terms)
- **PLA (programmable logic array)**
  - Flexible circuit for doing this

PLA Example

- PLA with 3 inputs, 2 outputs, and 4 product terms
  - Out0 = AB′C + ABC′ + ABC



Boolean Algebra

- **Boolean Algebra**: rules for rewriting Boolean functions
  - Useful for simplifying Boolean functions
    - Simplifying = reducing gate count, reducing gate "levels"
  - Rules: similar to logic (0/1 = F/T)
    - **Identity**: A1 = A, A+0 = A
    - **0/1**: A0 = 0, A+1 = 1
    - **Inverses**: (A′)′ = A
    - **Idempotency**: AA = A, A+A = A
    - **Tautology**: AA′ = 0, A+A′ = 1
    - **Commutativity**: AB = BA, A+B = B+A
    - **Associativity**: A(BC) = (AB)C, A+(B+C) = (A+B)+C
    - **Distributivity**: A(B+C) = AB+AC, A+(BC) = (A+B)(A+C)
    - **DeMorgan's**: (AB)′ = A′+B′, (A+B)′ = A′B′

Logic Minimization

- **Logic minimization**
  - Iterative application of rules to reduce function to simplest form
  - There are tools for automatically doing this

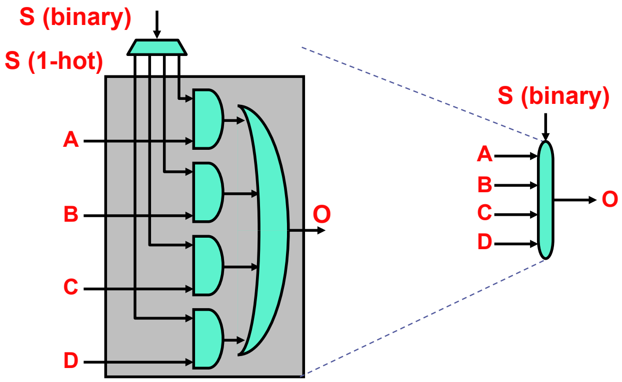
```
Out = AB′C + ABC′ + ABC
Out = A(B′C + BC′ + BC)        // distributivity
Out = A(B′C + (BC′ + BC))      // associativity
Out = A(B′C + B(C′+C))         // distributivity (on B)
Out = A(B′C + B1)              // tautology
Out = A(B′C + B)               // 0/1
Out = A((B′+B)(C+B))           // distributivity (on +B)
Out = A(1(B+C))                // tautology
Out = A(B+C)                   // 0/1
```


Non-Arbitrary Boolean Functions

- PLAs implement Boolean functions point-wise
  - E.g., represent f(X) = X+5 as [0→5, 1→6, 2→7, 3→8, …]
  - Mainly useful for "arbitrary" functions, no compact representation
- Many useful Boolean functions are not arbitrary
  - Have a compact implementation
  - Examples
    - Multiplexer
    - Adder

Multiplexer (Mux)

- **Multiplexer (mux)**: selects output from N inputs
  - Example: 1-bit 4-to-1 mux
  - Not shown: N-bit 4-to-1 mux = N 1-bit 4-to-1 muxes + 1 decoder



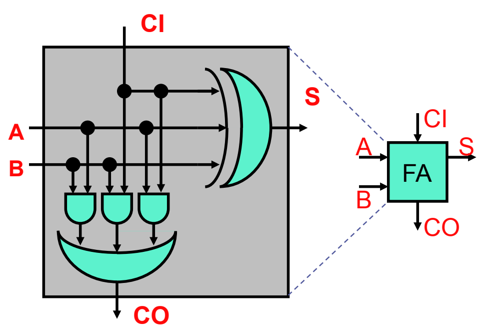
Adder

- **Adder**: adds/subtracts two 2C binary integers
  - **Half adder**: adds two 1-bit "integers", no carry-in
  - **Full adder**: adds three 1-bit "integers", includes carry-in
  - **Ripple-carry adder**: N chained full adders add 2 N-bit integers
  - **To subtract**: negate B input, set bit 0 carry-in to 1

Full Adder

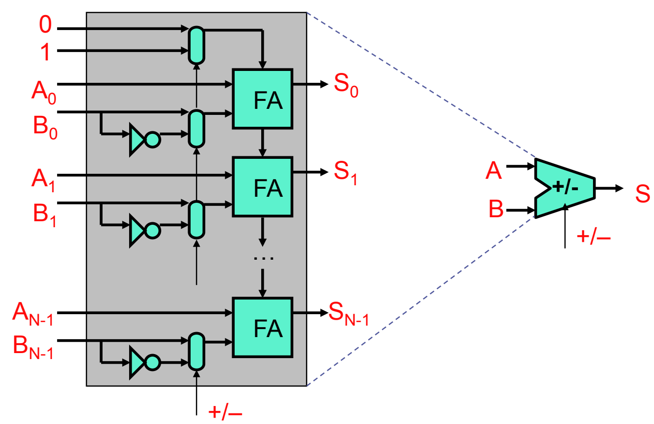
- What is the logic for a full adder?
  - Look at truth table

CI	A	B	→	CO	S
0	0	0	→	0	0
0	0	1	→	0	1
0	1	0	→	0	1
0	1	1	→	1	0
1	0	0	→	0	1
1	0	1	→	1	0
1	1	0	→	1	0
1	1	1	→	1	1



  - **S = C'A'B + C'AB' + CA'B' + CAB = C ^ A ^ B**
  - **CO = C'AB + CA'B + CAB' + CAB = CA + CB + AB**

N-bit Adder/Subtracter



- More later when we cover arithmetic

Hardware Design Methods

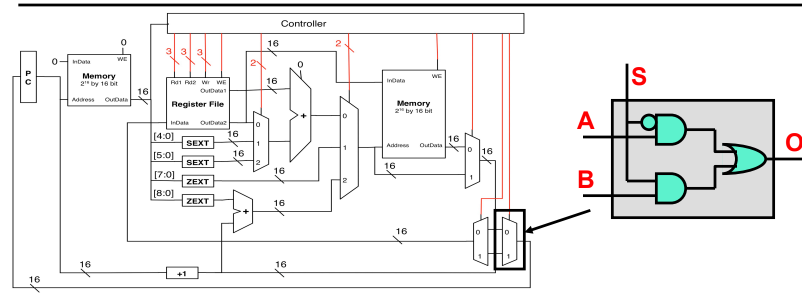
Hardware Design Methodologies

- Fabricating a chip requires a detailed layout
  - All transistors & wires
- How does a hardware designer describe such design?
  - (Bad) Option #1: draw all the masks "by hand"
    - All 1 billion transistors? Umm…
  - Option #2: use computer-aided design (CAD) tools to help
    - Layout done by engineers with CAD tools or automatically
- Design levels – uses **abstraction**
  - Transistor-level design – designer specifies transistors (not layout)
  - Gate-level design – designer specifics gates, wires (not transistors)
  - Higher-level design – designer uses higher-level building blocks
    - Adders, memories, etc.
    - Or logic in terms of and/or/not, and tools translates into gate

Describing Hardware

- Two general options
- Schematics
  - Pictures of gates & wires
- Hardware description languages
  - Use textural descriptions to specify hardware
- Translation process called "synthesis"
  - Textural description -> gates -> full layout
    - Tries to minimizes the delay and/or number of gates
  - Much like process of compilation of software

Schematics



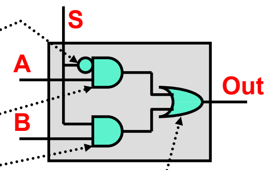
- Draw pictures
  - Use a schematic entry program to draw wires, logic blocks, gates
  - Support hierarchical design (arbitrary nesting)
  - \+ Good match for hardware which is inherently spatial, purty
  - – Time consuming, "non-scalable" (large designs are unreadable)
  - Rarely used in practice ("real-world" designs are big)

Hardware Description Languages (HDLs)

- Write "code" to describe hardware
  - HDL vs. SDL
  - Specify wires, gates, modules (also hierarchical)
  - \+ Easier to create, edit, modify, scales well
  - – Disconnect: must still "think" visually (gets easier with practice)

```
module mux2to1(S, A, B, Out);
   input S, A, B;
   output Out;
   wire S_, AnS_, BnS;

   not (S_, S);
   and (AnS_, A, S_);
   and (BnS, B, S);
   or (Out, AnS_, BnS);
endmodule
```

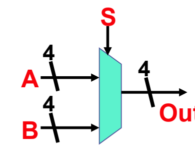


(Hierarchical) HDL Example

- Build up more complex modules using simpler modules
  - Example: 4-bit wide mux from four 1-bit muxes

```
module mux2to1_4(S, A, B, Out);
   input [3:0] A;
   input [3:0] B;
   input S;
   output [3:0] Out;

   mux2to1 mux0 (S, A[0], B[0], Out[0]);
   mux2to1 mux1 (S, A[1], B[1], Out[1]);
   mux2to1 mux2 (S, A[2], B[2], Out[2]);
   mux2to1 mux3 (S, A[3], B[3], Out[3]);
endmodule
```



Verilog HDL

- **Verilog**: HDL we will be using
  - Syntactically similar to C (by design)
  - ± Ease of syntax hides fact that this isn't C (or any SDL)
  - We will use a few lectures to learn Verilog

```
module mux2to1_4(S, A, B, Out);
   input [3:0] A;
   input [3:0] B;
   input S;
   output [3:0] Out;

   mux2to1 mux0 (S, A[0], B[0], Out[0]);
   mux2to1 mux1 (S, A[1], B[1], Out[1]);
   mux2to1 mux2 (S, A[2], B[2], Out[2]);
   mux2to1 mux3 (S, A[3], B[3], Out[3]);
endmodule
```

These aren't variables

These aren't function calls

HDLs are not SDLs (PLs)

- Similar in some (intentional) ways …
  - Syntax
    - Named entities, constants, scoping, etc.
  - Tool chain: synthesis tool analogous to compiler
    - Multiple levels of representation
    - "Optimization"
    - Multiple targets (portability)
  - "Software" engineering
    - Modular structure and parameterization
    - Libraries and code repositories
- … but different in many others
  - One of the most difficult conceptual leaps of this course

Hardware is not Software

- Just two different beasts (or two parts of the same beast)
  - Things that make sense in hardware, don't in software, vice versa
  - One of the main themes of 371
- **Software is sequential**
  - Hardware is inherently parallel, at multiple levels
  - Have to work to get hardware to *not* do things in parallel
- Software atoms are purely functional ("digital")
  - Hardware atoms have quantitative ("analog") properties too
  - Including correctness properties!
- Software mostly about quality ("functionality")
  - Hardware mostly about quantity: performance, area, power, etc.
- One reason that HDLs are not SDLs

HDL: Behavioral Constructs

- HDLs have **low-level structural** constructs
  - Specify hardware structures directly
  - Transistors, gates (`and`, `not`) and wires, hierarchy via modules
- Also have **mid-level behavioral** constructs
  - Specify operations, not hardware to perform them
  - Low-to-medium-level: `&`, `~`, `+`, `*`
- Also **higher-level behavioral** constructs
  - High-level: `if-then-else`, `for` loops
  - Some of these are synthesizable (some are not)
    - Tools try to guess what you want, often highly inefficient
    - – Higher-level → more difficult to know what it will synthesize to!
- HDLs are both high- and low-level languages in one!
  - And the boundary is not clear!

HDL: Simulation

- Another use of HDL: simulating & testing a hardware design
  - Cheaper & faster turnaround (no need to fabricate)
  - More visibility into design ("debugger" interface)
- **HDLs have features just for simulation**
  - Higher level data types: integers, FP-numbers, timestamps
  - Higher level control structures: for-loops, conditionals
  - Routines for I/O: error messages, file operations
  - Obviously, **these cannot be synthesized into circuits**
- Also another reason for HDL/SDL confusion
  - HDLs have "SDL" features for simulation

Verilog HDL

HDL History

- 1970s:
  - First HDLs
- Late 1970s: VHDL
  - VHDL = VHSIC HDL = Very High Speed Integrated Circuit HDL
  - VHDL inspired by programming languages of the day (Ada)
- 1980s:
  - Verilog first introduced
  - Verilog inspired by the C programming language
  - VHDL standardized
- 1990s:
  - Verilog standardized (Verilog-1995 standard)
- 2000s:
  - Continued evolution (Verilog-2001 standard)
- Both VHDL and Verilog evolving, still in use today

Verilog HDL

- Verilog is a (surprisingly) big language
  - Structural constructs at both gate and transistor level
  - Facilities for specifying memories
  - Precise timing specification and simulation
  - Lots of "behavioral" constructs
  - C-style procedural variables, including arrays
  - A pre-processor
  - VPI: Verilog programming interface
  - …

371 Verilog HDL

- **We're going to learn a focused *subset* of Verilog**
  - Focus on synthesizable constructs
  - Focus on avoiding subtle synthesis errors
  - Use as an educational tool
- For synthesis
  - Structural constructs at gate-level only
  - A few behavioral constructs
- Some testing and debugging features

Rule 1: if you haven't seen it in lecture, you can't use it!

Rule 1a: when in doubt, ask!

Basic Verilog Syntax

- Have already seen basic syntax, looks like C
  - C/C++/Java style comments
  - Names are case sensitive, and can use _ (underscore)
  - Avoid: clock, clk, power, pwr, ground, gnd, vdd, vcc, init, reset, rst
    - Some of these are "special" and will silently cause errors

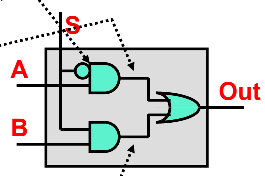
```
/* this is a module */
module mux2to1(S, A, B, Out);
   input S, A, B;
   output Out;
   wire S_, AnS_, BnS;
   // these are gates
   not (S_, S);
   and (AnS_, A, S_);
   and (BnS, B, S);
   or (Out, AnS_, BnS);
endmodule
```

(Gate-Level) Structural Verilog

- Primitive "data type": **wire**
  - Have to declare it

Structural

```
module mux2to1(S, A, B, Out);
  input S, A, B;
  output Out;
  wire S_, AnS_, BnS;
  not (S_, S);
  and (AnS_, A, S_);
  and (BnS, B, S);
  or (Out, AnS_, BnS);
endmodule
```

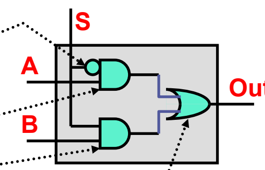


(Gate-Level) Structural Verilog

- Primitive "operators": gates
  - Specifically: **and**, **or**, **xor**, **nand**, **nor**, **xnor**, **not**, **buf**
  - Can be multi-input: e.g., **or (C, A, B, D)** (C= A+B+D)
  - "Operator" **buf** just repeats input signal (may amplify it)

Structural

```
module mux2to1(S, A, B, Out);
  input S, A, B;
  output Out;
  wire S_, AnS_, BnS;
  not (S_, S);
  and (AnS_, A, S_);
  and (BnS, B, S);
  or (Out, AnS_, BnS);
endmodule
```

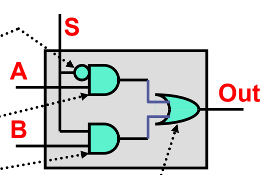


(Gate-Level) Behavioral Verilog

- Primitive "operators": boolean operators
  - Specifically: **&**, **|**, **^**, **~**
  - Can be combined into expressions
  - Can be mixed with structural Verilog

"Behavioral" (Synthesizable)

```
module mux2to1(S, A, B, Out);
  input S, A, B;
  output Out;
  wire S_, AnS_, BnS;
  assign S_ = ~S;
  assign AnS_ = A & S_;
  assign BnS = B & S;
  assign Out = AnS_ | BnS;
endmodule
```

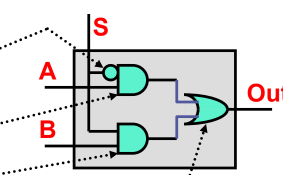


Wire Assignment

- **Wire assignment**:
  - Connect combinational logic block or other wire to wire input
  - **Order of statements not important**, executed totally in parallel
  - When right-hand-side changes, it is re-evaluated and re-assigned
  - Designated by the keyword **assign**

"Behavioral" (Synthesizable)

```
module mux2to1(S, A, B, Out);
  input S, A, B;
  output Out;
  wire S_, AnS_, BnS;
  assign S_ = ~S;
  assign AnS_ = A & S_;
  assign BnS = B & S;
  assign Out = AnS_ | BnS;
endmodule
```



Wire Assignment

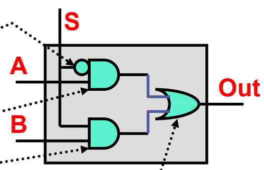
- Assignment can be combined with declaration

```
wire c = a | b;
```

“Behavioral” (Synthesizable)

```
module mux2to1(S, A, B, Out);
  input S, A, B;
  output Out;

  wire S_ = ~S;
  wire AnS_ = A & S_;
  wire BnS = B & S;
  assign Out = AnS_ | BnS;
endmodule
```



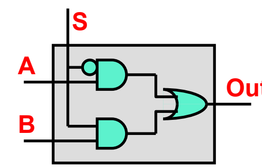
(Gate-Level) Behavioral Verilog

- Primitive “operators”: boolean operators
  - Specifically: `&`, `|`, `^`, `~`
  - **Can be combined into expressions**
  - Can be mixed with structural Verilog

“Behavioral” (Synthesizable)

```
module mux2to1(S, A, B, Out);
  input S, A, B;
  output Out;

  assign Out = (~S & A) | (S & B);
endmodule
```



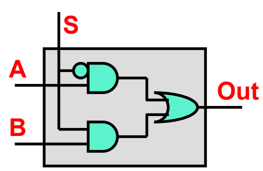
Easiest Way to do a Mux?

- Verilog supports `?:` conditional assignment operator
  - Much more useful (and common) in Verilog than in C/Java

“Behavioral” (Synthesizable)

```
module mux2to1(S, A, B, Out);
  input S, A, B;
  output Out;

  assign Out = S ? B : A;
endmodule
```



Wires Are Not C-like Variables!

- Order of assignment doesn’t matter
  - This works fine

```
module mux2to1(S, A, B, Out);
  input S, A, B;
  output Out;
  wire S_, AnS_, BnS;
  assign Out = AnS_ | BnS;
  assign BnS = B & S;
  assign AnS_ = A & S_;
  assign S_ = ~S;
endmodule
```

- Can’t “reuse” a wire

```
assign temp = a & b;
assign temp = a | b;
```

  - Actually, you can; but doesn’t do what you think it does

Wire Vectors

- Wire vectors: also called "arrays" or "buses"

```
wire [7:0] w1;  // 8 bits, w1[7] is most significant bit
wire [0:7] w2;  // 8 bits, w2[0] is most significant bit
```

- Example:

```
module 8bit_mux2to1 (S, A, B, Out);
  input S;
  input [7:0] A, B;
  output [7:0] Out;
  assign Out = S ? B : A;
endmodule
```

Unlike C, array range is part of type, not variable!

- Operations
  - Bit select: vec[3]
  - Range select: vec[3:2]
  - Concatenate: `assign vec = {x, y, z};`

Repeated Signals

- Concatenation

```
wire vec[2:0] = {x, y, z};
```

- Can also repeat a signal n times

```
wire vec[15:0] = {16{x}}; // 16 copies of x
```

- Example uses (what does this do?):

```
wire [7:0] out;
wire [3:0] A;
assign out = {{4{1'd0}}, A[3:0]};
```

- What about this?

```
assign out = {{4{A[3]}}, A[3:0]};
```


Gate-Level Vector Operators

- Verilog also supports behavioral vector operators
- **Logical bitwise and reduction**: ~,&,|,^

```
wire [7:0] vec1, vec2;
wire [7:0] vec3 = vec1 & vec2; // bitwise AND
wire w1 = ~|vec1;              // NOR reduction
```

- **Integer arithmetic comparison**: +,–,*,/,%,==,!=,<,>

```
wire [7:0] vec4 = vec1 + vec2; // vec1 + vec2
```

  - Important: all arithmetic is unsigned, want signed? "roll your own"
  - Good: in signed/unsigned integers: +, –, * produces same output
    - Just a matter of interpretation
  - Bad: in signed/unsigned integers: /, % is not the same
  - Ugly: Xilinx will not synthesize /, % anyway!
    - Our LC4 won't support DIV and MOD instructions

Why Use a High-Level Operator?

- Abstraction
  - Why write assembly, when you can write C? (not a great example)
- Take advantage of built-in high level implementation
  - Virtex-IIPro FPGAs have integer multipliers on them
  - Xilinx will use these rather than synthesizing a multiplier from gates
    - Much faster and more efficient
  - How hard is it for Xilinx to figure out you were doing a multiply?
    - If you use "*": easy
    - If you "roll your own" using gates: nearly impossible
- Why *not* use high-level operators?
  - Less certain what they will synthesize to
  - Or even if it will synthesize at all: e.g., /, %

Wire and Wire Vector Constants

```
wire [3:0] w = 4'b0101;
```

- The "4" is the number of bits
- The "b" means "binary" - "h" for hex, "o" for octal, "d" for decimal
- The "0101" are the digits (in binary in this case)

```
wire [3:0] w = 4'd5; // same thing, effectively
```

- Here is a single wire constant

```
wire w = 1'b0;
```

- A useful example of wire-vector constants:

```
module mux4to1(Sel, A, B, C, D, Out);
  input [1:0] Sel;
  input A, B, C, D;
  output Out = (Sel == 2'd0) ? A :
               (Sel == 2'd1) ? B :
               (Sel == 2'd2) ? C : D;
endmodule
```


Hierarchical Design using Modules

- Interface specification

```
module mux2to1(Sel, A, B, Out);
  input Sel, A, B;
  output Out;
```

  - Can also have `inout`: bidirectional wire (we will not need)
- Alternative: Verilog 2001 interface specification

```
module mux2to1(input Sel, A, B, output Out);
```

- Declarations
  - Internal wires, i.e., "locals"
  - Wires also known as "nets" or "signals"

```
wire S_, AnS_, BnS;
```

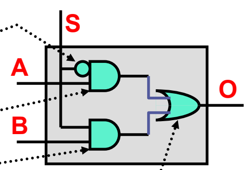
- Implementation: primitive and module instantiations

```
and (AnS_, A, S_);
```


Verilog Module Example

```
module mux2to1(S, A, B, O);
  input S, A, B;
  output O;
  wire S_, AnS_, BnS;

  not (S_, S);
  and (AnS_, A, S_);
  and (BnS, B, S);
  or (O, AnS_, BnS);
endmodule
```



- Instantiation: `mux2to1 mux0 (cond, in1, in2, out);`
  - Non-primitive module instances must be named (helps debugging)
- Operators and expressions can be used with modules
  - `mux2to1 mux0 (cond1 & cond2, in1, in2, out);`

Hierarchical Verilog Example

- Build up more complex modules using simpler modules
- Example: 4-bit wide mux from four 1-bit muxes
  - Again, just "drawing" boxes and wires

```
module mux2to1_4(Sel, A, B, O);
  input [3:0] A;
  input [3:0] B;
  input Sel;
  output [3:0] O;

  mux2to1 mux0 (Sel, A[0], B[0], O[0]);
  mux2to1 mux1 (Sel, A[1], B[1], O[1]);
  mux2to1 mux2 (Sel, A[2], B[2], O[2]);
  mux2to1 mux3 (Sel, A[3], B[3], O[3]);
endmodule
```

Connections by Name

- Can (should?) specify module connections by name
  - Helps keep the bugs away
  - Example

```
mux2to1 mux0 (.S(Sel), .A(A[0]), .B(B[0]), .O(O[0]));
```

  - Also, then order doesn't matter

```
mux2to1 mux1 (.A(A[1]), .B(B[1]), .O(O[1]), .S(Sel));
```


Per-Instance Module Parameters

- Module parameters: useful for defines varying bus widths
  - But for widths, not "types" (in HDL "width" == "type")

```
module Nbit_mux2to1 (Sel, A, B, Out);
   parameter N = 1;
   input [N-1:0] A, B;
   input Sel;
   output [N-1:0] Out;
   assign Out = Sel ? B : A;
endmodule
```

  - Two ways to instantiate: implicit

```
Nbit_mux2to1 #(4) mux1 (S, in1, in2, out);
```

  - And explicit

```
Nbit_mux2to1 mux1 (S, in1, in2, out);
defparam mux1.N = 4;
```

  - Multiple parameters per module allowed

Verilog Pre-Processor

- Like the C pre-processor
  - But uses ` (back-tick) instead of #
  - Constants: `` `define ``
    - No parameterized macros
    - Use ` before expanding constant macro

```
`define letter_A 8'h41
wire w[7:0] = `letter_A;
```

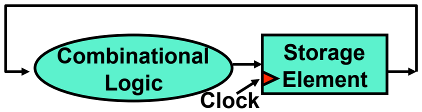
  - Conditional compilation: `` `ifdef ``, `` `endif ``
  - File inclusion: `` `include ``
- Parameter vs `define
  - Parameter only for "per instance" constants
  - `define for "global" constants

Sequential Logic

Two Types of Digital Circuits

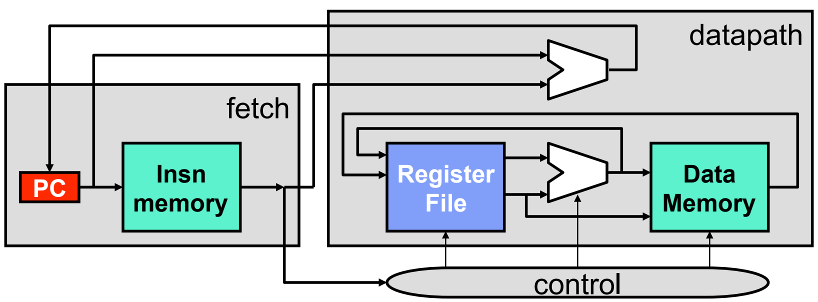
- Combinational Logic
  - Logic **without state** variables
  - Examples: adders, multiplexers, decoders, encoders
  - **No clock involved**
- Sequential Logic
  - Logic **with state** variables
  - State variables: latches, flip-flops, registers, memories
  - **Clocked**
  - State machines, multi-cycle arithmetic, processors
- Sequential Logic in Verilog
  - Special idioms using behavioral constructs that synthesize into latches, memories

Sequential Logic & Synchronous Systems



- Processors are complex fine state machines (FSMs)
  - Combinational (compute) blocks separated by storage elements
    - State storage: memories, registers, etc.
- **Synchronous systems**
  - **Clock**: global signal acts as write enable for all storage elements
    - Typically marked as triangle
  - All state elements write together, values move forward in lock-step
  - \+ Simplifies design: design combinational blocks independently
- Aside: asynchronous systems
  - Same thing, but … no clock
  - Values move forward using explicit handshaking
  - ± May have some advantages, but difficult to design

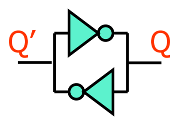
Datapath Storage Elements



- Three main types of storage elements
  - **Singleton registers**: PC
  - **Register files**: ISA registers
  - **Memories**: insn/data memory

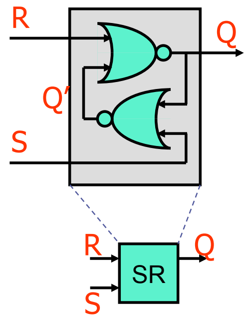
Cross-Coupled Inverters (CCIs)

- **Cross-coupled inverters (CCIs)**
  - **Primitive "storage element" for storing state**
  - Most storage arrays (regfile, caches) implemented this way
  - Where is the input and where is the output?



S-R Latch

- **S-R (set-reset) latch**
  - Cross-coupled NOR gates
  - Distinct inputs/outputs



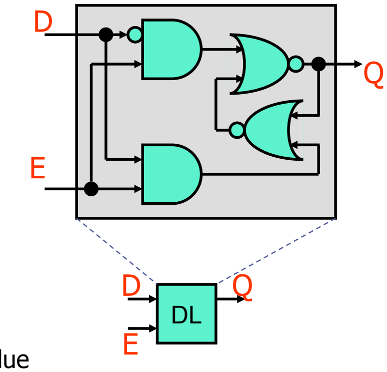

```
S,R → Q
0,0 → oldQ
0,1 → 0
1,0 → 1
1,1 → 0
```

  - S=0, R=0? circuit degenerates to cross-coupled INVs
  - S=1, R=1? not very useful
  - Not really used … except as component in something else

D Latch

- **D latch**: S-R latch + …
  - control that makes S=R=1 impossible

```
E,D → Q
0,0 → oldQ
0,1 → oldQ
1,0 → 0
1,1 → 1
```



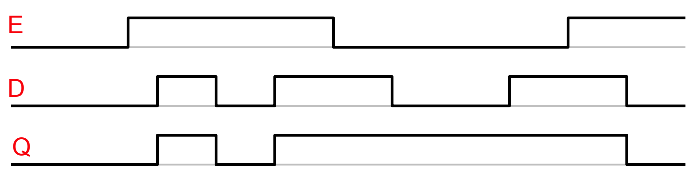
  - In other words

```
0,D → oldQ
1,D → D
```

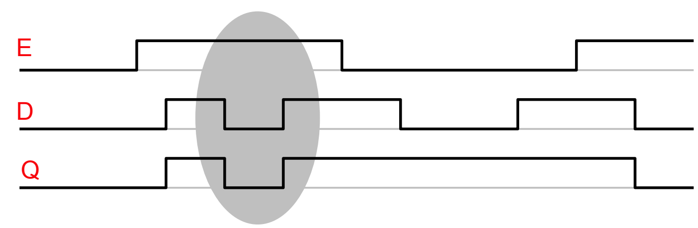
  - In words
    - When E is 1, Q gets D
    - When E is 0, Q retains old value

Timing Diagrams

- Voltage {0,1} diagrams for different nodes in system
  - "Digitally stylized": changes are vertical lines (instantaneous?)
  - Reality is analog, changes are continuous and smooth
- Timing diagram for a D latch



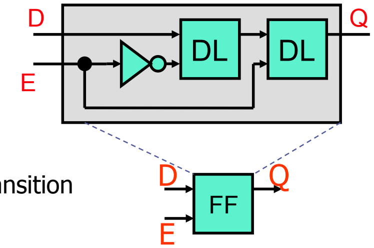
Triggering: Level vs. Edge

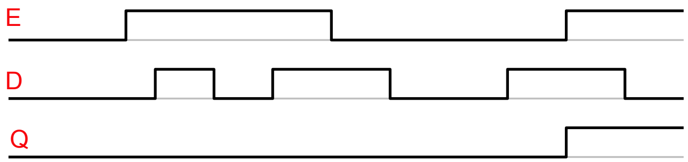


- The D-latch is **level-triggered**
  - The latch is open for writing as long as E is 1
  - If D changes continuously, so does Q
  - – May not be the functionality we want
- Often easier to reason about an **edge-triggered** latch
  - The latch is open for writing only on E transition (0 → 1 or 1 → 0)
  - \+ Don't need to worry about fluctuations in value of D

D Flip-Flop

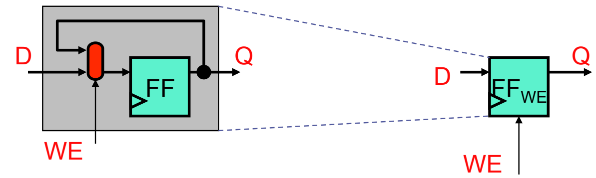
- **D Flip-Flop**:
  - Sequential D-latches
  - Enabled by inverse signals
  - First latch open when E = 0
  - Second latch open when E = 1
  - Overall effect?
    - D flipflop latches D on 0→1 transition
  - E is the "clock" signal input





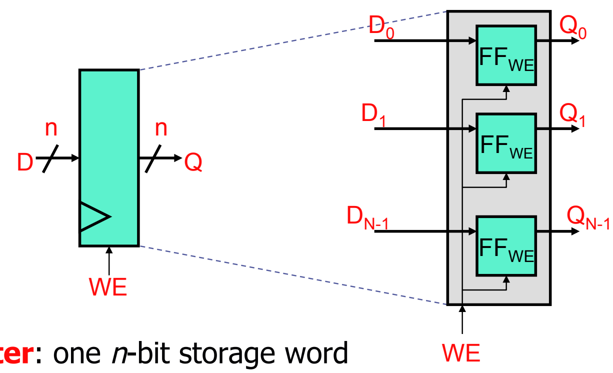
FF_{WE}: FF with Separate Write Enable

- **FF_{WE}**: FF with separate write enable
  - FF D(ata) input is MUX of D and Q, WE selects



- Bad idea: why not just AND the CLK and WE?
  - + Fewer gates
  - – Creates timing problems
    - Do not try to do logic on CLK in Verilog
    - No, really. Never do this.

N-bit Register

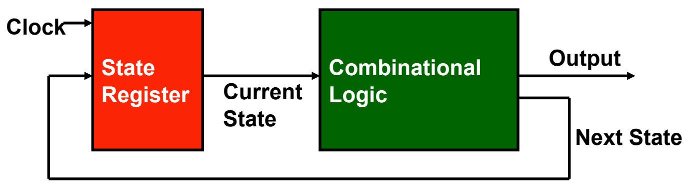


- **Register**: one *n*-bit storage word
  - Non-multiplexed input/output: data buses write/read same word
- Implementation: FF_{WE} array with shared write-enable (WE)
  - FFs written on CLK edge if WE is 1 (or if there is no WE)

Sequential Logic in Verilog

Designing Sequential Logic

- CIS371 design rule: separate combinational logic from sequential state elements
  - Not enforced by Verilog, but a very good idea
  - Possible exceptions: counters, shift registers
- We'll give you a flip-flop module (see next slide)
  - Edge-triggered, not a transparent latch
  - Parameterized to create a *n*-bit register
- Example use: state machine

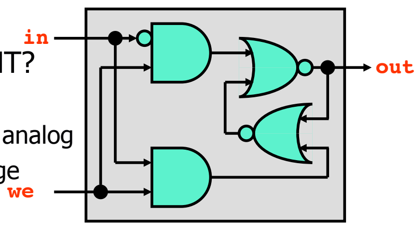


Sequential Logic In Verilog

- How are state-holding variables specified in Verilog?
  - First instinct: structurally
  - After all, real latches and flip-flops are made from gates…

```
module latch(out, in, we);
   output out; input in, we;
   wire not_out = ~(out | (we & ~in));
   assign out = ~(not_out | (we & in));
endmodule
```

- This should work, right? RIGHT?
  - Logically, yes… in practice, no
    - Storage elements are highly analog
    - FPGAs have dedicated storage



Verilog Flipflop (Behavioral Magic)

- How do we specify state-holding constructs in Verilog?

```
module dff (out, in, wen, rst, clk);

  output out;
  input in;
  input wen, rst, clk;

  reg out;
  always @(posedge clk)
    begin
      if (rst)
        out = 0;
      else if (wen)
        out = in;
    end
endmodule
```

wen = write enable
rst = reset
clk = clock

- **reg**: interface-less storage bit
- **always @ ()**: synthesizable behavioral sequential Verilog
  - Tricky: hard to know exactly what it will synthesize to
  - **We will give this to you, don't write your own**
  - "Creativity is a poor substitute for knowing what you're doing"

Verilog Register (Behavioral Magic)

- How do we specify state-holding constructs in Verilog?

```
module register (out, in, wen, rst, clk);
  parameter n = 1;
  output [n-1:0] out;
  input [n-1:0] in;
  input wen, rst, clk;

  reg [n-1:0] out;
  always @(posedge clk)
    begin
      if (rst)
        out = 0;
      else if (wen)
        out = in;
    end
endmodule
```

wen = write enable
rst = reset
clk = clock

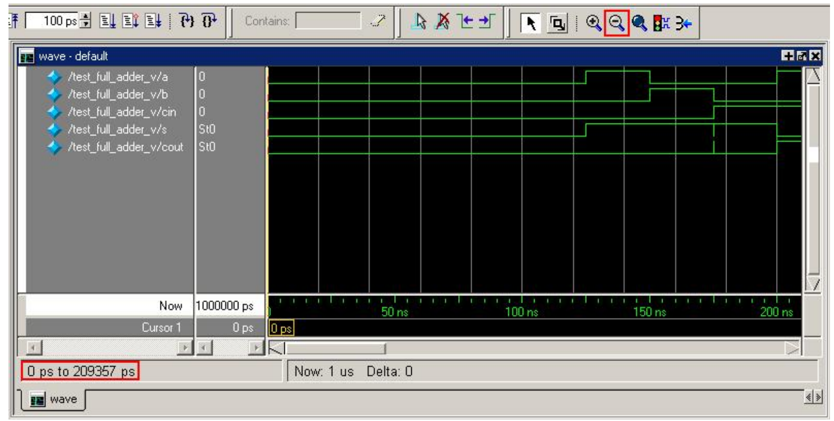
- **reg**: interface-less storage bit
- **always @ ()**: synthesizable behavioral sequential Verilog
  - Tricky: hard to know exactly what it will synthesize to
  - **We will give this to you, don't write your own**
  - "Creativity is a poor substitute for knowing what you're doing"

Clocks Signals

- Clocks & reset signals are ***not*** normal signals
- Travel on dedicated "clock" wires
  - Reach all parts of the chip
  - Special "low-skew" routing
- Ramifications:
  - Never do logic operations on the clocks
  - If you want to add a "write enable" to a flip-flop:
    - Use a mux to route the old value back into it
    - (or use the flip-flop with write enable we give you!)
    - Do not just "and" the write-enable signal with the clock!
- Messing with the clock can cause a errors
  - Often can only be found using detail low-level simulation

Simulation

- One way to test and debug designs
- Graphical output via waveforms



Testbenches

- A more effective way to test & debug designs
- In C/Java?
  - Write test code in C/Java to test C/Java
  - "Test harness", "unit testing"
- For Verilog/VHDL?
  - Write test code in Verilog to test Verilog
  - Verilog has advanced "behavioral" commands to facilitate this:
    - Delay for *n* units of time
    - Full high-level constructs: if, while, sequential assignment, ints
    - Input/output: file I/O, output to display, etc.

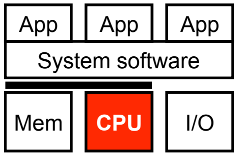
Common Errors

- Tools are from a less gentle time
  - More like C, less like Java
  - Assume that you mean what you say
- Common errors:
  - Not assigning a wire a value
  - Assigning a wire a value more than once
  - Implicit wire declarations (default to type "wire" 1-bit wide)
- Avoid names such as:
  - clock, clk, power, pwr, ground, gnd, vdd, vcc, init, reset, rst
  - Some of these are "special" and will silently cause errors

Additional Verilog Resources

- Elements of Logic Design Style by Shing Kong, 2001
  - Dos, do-nots, tips
  - http://www.cis.upenn.edu/~milom/elements-of-logic-design-style/
- Verilog HDL Synthesis: A Practical Primer
  - By J. Bhasker, 1998
  - To the point (<200 pages)
- Advanced Digital Design with the Verilog HDL
  - By Michael D. Ciletti, 2003
  - Verilog plus lots of digital logic design (~1000 pages)
- Verilog tutorial from textbook (posted on course web page)

Summary



- Transistors & frabrication
- Digital logic basics
  - Focus on useful components
- Hardware design methods
  - Introduction to Verilog
- Next unit: single-cycle datapath