Basic Digital Circuits in Chisel

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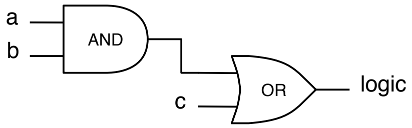
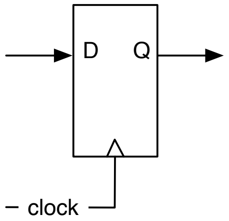
Overview

- Quick recap of last lecture
  - If something is unclear, please ask!
- Basic digital building blocks
- And the coding of it in Chisel
- Some coding style

The Digital Abstraction

- Just two values: 0 and 1, or low and high
- Represented as voltage
- Digital signals tolerate noise
- Digital Systems are *simple*, just:
  - Combinational circuits and
  - Registers

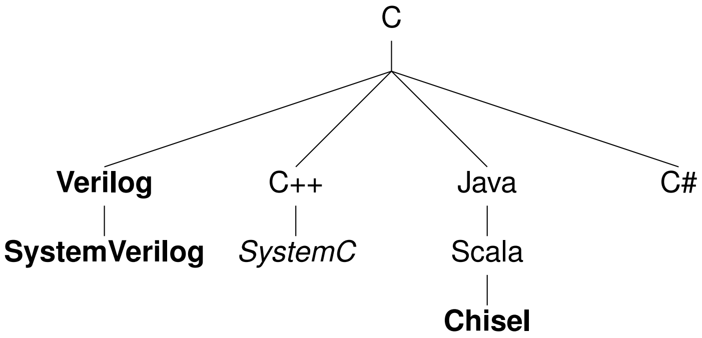




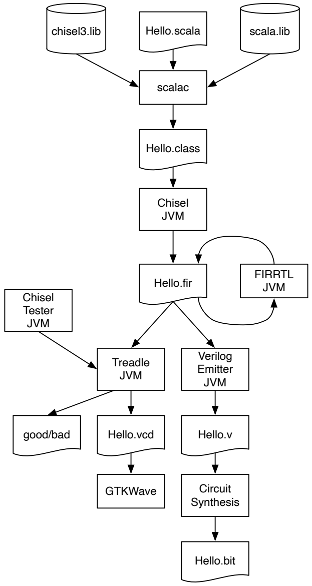
Chisel

- A hardware *construction* language
  - Constructing Hardware In a Scala Embedded Language
  - If it compiles, it is synthesisable hardware
  - Say goodby to your unintended latches
- Chisel is not a high-level synthesis language
- Single source for two targets
  - Cycle accurate simulation (testing)
  - Verilog for synthesis
- Embedded in Scala
  - Full power of Scala available
  - But to start with, no Scala knowledge needed
- Developed at UC Berkeley

Chisel is Part of the C Language Family



Tool Flow for Chisel Defined Hardware



Signal/Wire Types and Width

- All types in hardware are a collection of bits
- The base type in Chisel is `Bits`
- `UInt` represents an unsigned integer
- `SInt` represents a signed integer (in two's complement)
- The number of bits is the width
- The width written as number followed by `.W`

```
Bits(8.W)
UInt(8.W)
SInt(10.W)
```

Constants

- Constants can represent signed or unsigned numbers
- We use `.U` and `.S` to distinguish

```
0.U  // defines a UInt constant of 0
-3.S // defines a SInt constant of -3
```

- Constants can also be specified with a width

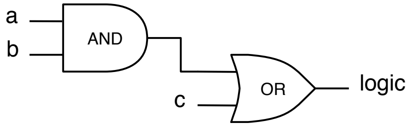
```
3.U(4.W) // An 4-bit constant of 3
```

- Use the string notation for a different base

```
"hff".U        // hexadecimal representation of
   255
"o377".U       // octal representation of 255
"b1111_1111".U // binary representation of 255
```

Combinational Circuits

- Chisel uses Boolean operators, similar to C or Java
- `&` is the AND operator and `|` is the OR operator
- The following code is the same as the schematics
- `val logic` gives the circuit/expression the name `logic`
- That name can be used in following expressions



```
val logic = (a & b) | c
```

Arithmetic and Logic Operations

- Same as in Java or C
- But this is *hardware*

```
val add = a + b // addition
val sub = a - b // subtraction
val neg = -a    // negate
val mul = a * b // multiplication
val div = a / b // division
val mod = a % b // modulo operation

val and = a & b // bitwise and
val or = a | b  // bitwise or
val xor = a ^ b // bitwise xor
val not = ~a    // bitwise negation
```

Operators

- Operators precedence is the same as in Java
  - E.g., * has precedence over +
  - But different in VHDL or Verilog
  - Use parentheses when unsure (especially for logical expressions)
- + and - is relatively cheap
- * is expensive, know what you do
- / and % is VERY expensive, usually no direct use in hardware
  - Implement as a multi-cycle operation

Wires

- A wire (a signal) can be first defined
- And later assigned an expression with `:=`

```
val w = Wire(UInt())

w := a & b
```

Subfields and Concatenation

A single bit can be extracted as follows:

```
val sign = x(31)
```

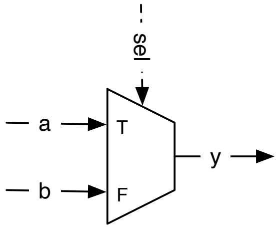
A subfield can be extracted from end to start position:

```
val lowByte = largeWord(7, 0)
```

Bit fields are concatenated with `Cat`:

```
val word = highByte ## lowByte
```

A Multiplexer

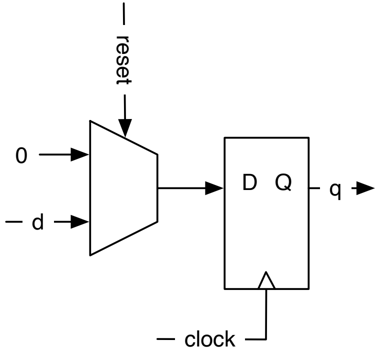


- A Multiplexer selects between alternatives
- So common that Chisel provides a construct for it
- Selects `a` when `sel` is `true.B` otherwise `b`

```
val result = Mux(sel, a, b)
```

Register

- A register is a collection of flip-flops
- Updated on the rising edge of the clock
- May be set to a value on reset



A Register with Reset

Following code defines an 8-bit register, initialized with 0 at reset:

```
val reg = RegInit(0.U(8.W))
```

An input is connected to the register with the `:=` update operator and the output of the register can be used just with the name in an expression:

```
reg := d
val q = reg
```

Reminder: We Construct Hardware

- Chisel code looks much like Java code
- But it is *not* a program in the usual sense
- It represents a circuit
- We should be able to *draw* that circuit
- The “program” constructs the circuit
- All statements are “executed” in parallel
- Statement order has mostly no meaning

Interlude

- Before we look at new material
- Sprinkle in some info on general development tools
- Get better at using your computer
- Learn some tools
- Don't be afraid of the command line ;-)
  - Show `sbt` usage
-
-
- Engineers are power users!

What is `git`?

- `git` is a distributed version-control system
  - What does that mean?
  - Wikipedia on git
- To manage source code or other documents
- Track changes in computer files
- Created by Linus Torvalds for Linux kernel development
- Good tool for cooperation
- Mostly used at the command line
- But graphical clients are available (i.e., with a GUI)
- Show the CLI commands

What is GitHub?

- GitHub is a git repository server
- GitHub is a classic startup, based in San Francisco
- Acquired 2018 by Microsoft for $7.5 billion
- Many open-source projects are on GitHub (e.g., Chisel)
  - 372 million repositories, 28 million public repositories, and 100 million developers
- Our DE2 material is hosted on GitHub
  - Lab material (you have used it)
  - The slides
  - The Chisel book
  - see `https://github.com/schoeberl`
  - Everyone can contribute via GitHub ;-)

Comment on Character Usage and Language

- Computers used for long time ASCII characters
- Show ASCII table
- Does NOT contain the special letters of DK, SE, AT,...
- Only a subset of ASCII was allowed for identifiers
- Languages such as Java or Scala are now more tolerant
  - You could use Chinese characters for your Java program!
- Please do not use any special characters
  - Also not in file names
- Programming is international
  - Use English identifiers and comments
- Avoid spaces in file names and folders

Coding Style

- Similar to Java
- Use readable, meaningful names
  - E.g., `sum` instead of `y`
- Use `camelCase` for identifiers
- `Modules` (classes) start with uppercase
  - E.g., `VendingMachine`
- Mark you register with a postfix `Reg`
  - E.g., `countReg`
- Use consistent indentation
  - Chisel style is 2 spaces (blanks)
- Use ASCII only ;-)

Combinational Circuits

- Simplest is a Boolean expression
- Assigned a name (e)
- This expression can be reused in another expression

```
val e = (a & b) | c
```

Fixed Expression

- Expression is fixed
- Trying to reassign with = results in an error
- Trying the Chisel conditional update := results in runtime error

```
val e = (a & b) | c


e := c & b
```

Combinational Circuit with Conditional Update

- Chisel supports conditional update
- Value first needs to be wrapped into a `Wire`
- Updates with the Chisel update operation `:=`
- With `when` we can express a conditional update
- The resulting circuit is a multiplexer
- The rule is that the last enabled assignment counts
  - Here the order of statements has a meaning

```
val w = Wire(UInt())

w := 0.U
when (cond) {
  w := 3.U
}
```

The “Else” Branch

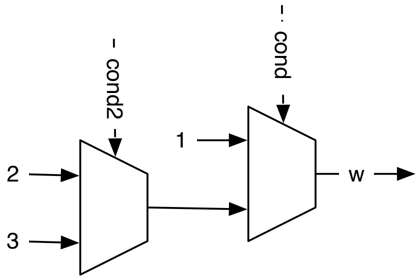
- We can express a form of “else”
- Note the `.` in `.otherwise`

```
val w = Wire(UInt())

when (cond) {
  w := 1.U
} .otherwise {
  w := 2.U
}
```

A Chain of Conditions

- To test for different conditions
- Select with a priority order
- The first that is true counts
- The hardware is a chain of multiplexers

```
val w = Wire(UInt())

when (cond) {
  w := 1.U
} .elsewhen (cond2) {
  w := 2.U
} .otherwise {
  w := 3.U
}
```



Default Assignment

- Practical for complex expressions
- Forgetting to assign a value on all conditions
  - Would describe a latch
  - Runtime error in Chisel
- Assign a default value is good practise

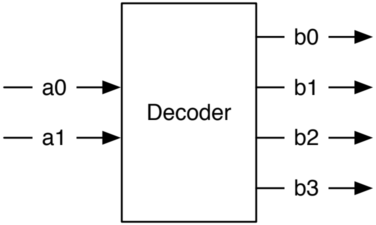
```
val w = WireDefault(0.U)

when (cond) {
  w := 3.U
}
// ... and some more complex conditional
    assignments
```

Logic Can Be Expressed as a Table

- Sometimes more convenient
- Still combinational logic (gates)
- Is converted to Boolean expressions
- Let the synthesize tool do the conversion!
- We use the `switch` statement

```
result := 0.U

switch(sel) {
  is (0.U) { result := 1.U}
  is (1.U) { result := 2.U}
  is (2.U) { result := 4.U}
  is (3.U) { result := 8.U}
}
```

A Decoder



- Converts a binary number of n bits to an m-bit signal, where $m \leq 2^n$
- The output is one-hot encoded (exactly one bit is one)
- Building block for a m-way Mux
- Used for address decoding in a computer system

Truth Table of a Decoder

a	b
00	0001
01	0010
10	0100
11	1000

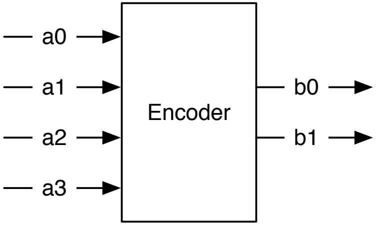
- Does this look like the table we have seen?

Decoder in Chisel

- Binary strings are a clearer representation

```
switch (sel) {
  is ("b00".U) { result := "b0001".U}
  is ("b01".U) { result := "b0010".U}
  is ("b10".U) { result := "b0100".U}
  is ("b11".U) { result := "b1000".U}
}
```

An Encoder



- Converts one-hot encoded signal
- To binary representation

Truth Table of an Encoder

a	b
0001	00
0010	01
0100	10
1000	11
????	??

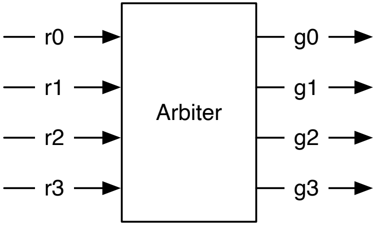
- Only defined for one-hot input

Encoder in Chisel

- We cannot describe a function with undefined outputs
- We use a default assignment of `"b00"`

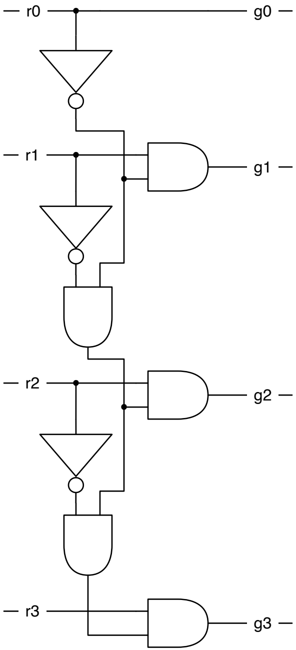
```
b := "b00".U
switch (a) {
  is ("b0001".U) { b := "b00".U}
  is ("b0010".U) { b := "b01".U}
  is ("b0100".U) { b := "b10".U}
  is ("b1000".U) { b := "b11".U}
}
```

An Arbiter for Decisions



- Selects one *winner* for the request of a shared resource
- Here: 4 request lines, 4 grant lines
- The arbiter grants only a single request
- E.g., a request input of `0101` will result in a grant output of `0001`
- This is a priority arbiter (unfair)

The Arbiter Schematic

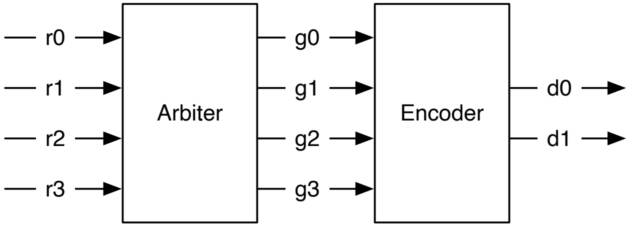


The Arbiter in Chisel

- Example for a 3-bit aribter

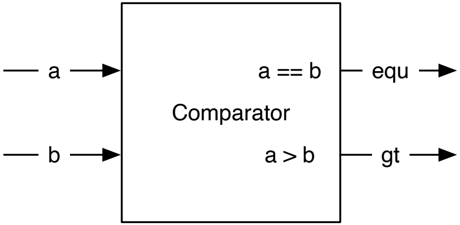
```
val grant = VecInit(false.B, false.B, false.B)
val notGranted = VecInit(false.B, false.B)

grant(0) := request(0)
notGranted(0) := !grant(0)
grant(1) := request(1) && notGranted(0)
notGranted(1) := !grant(1) && notGranted(0)
grant(2) := request(2) && notGranted(1)
```

Priority Encoder



- Combining the arbiter with the encoder
- Solves the problem with multiple bits set for the encoder
- The highest-priority bit from the input is used for the encoding

Comperator

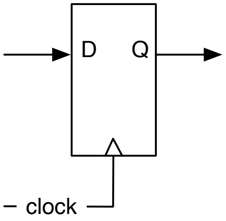


- Needed as component on its own?
- It is just two lines of Chisel code

```
val equ = a === b
val gt = a > b
```

Register (Again)

- Sequential building blocks
  - Contains a register
  - Plus combinational circuits

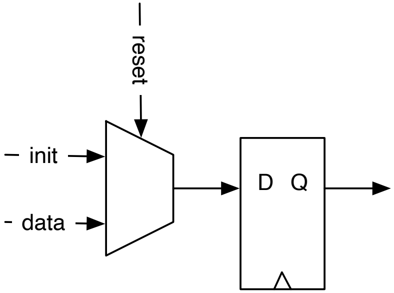


```
val q = RegNext(d)
```

Register in Two Steps

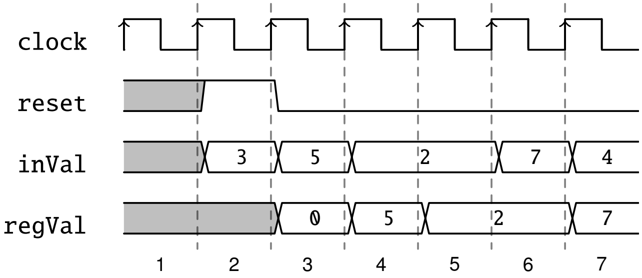
```
val delayReg = Reg(UInt(4.W))

delayReg := delayIn
```

Register With Reset



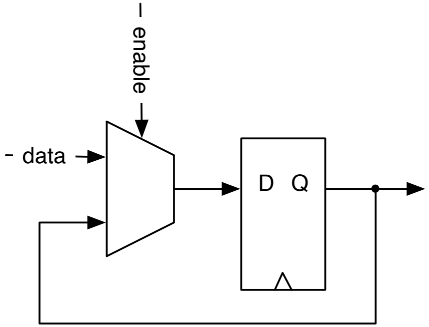
```
val valReg = RegInit(0.U(4.W))

valReg := inVal
```

Timing Diagram of the Register with Reset



- Also called waveform diagram
- Logic function over time
- Can be used to describe a circuit function
- Useful for debugging

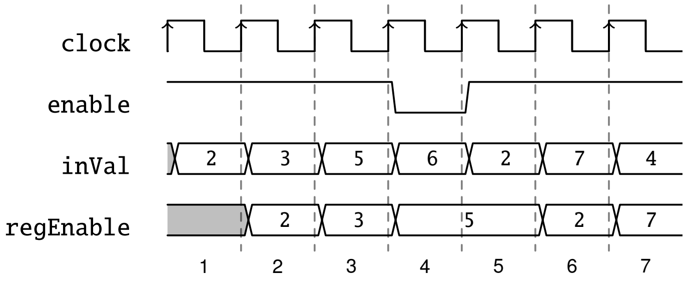
Register with Enable



- Only when `enable` true is a value is stored

```
val enableReg = Reg(UInt(4.W))

when (enable) {
  enableReg := inVal
}
```

Timing Diagram for an Enable Register



More on Register

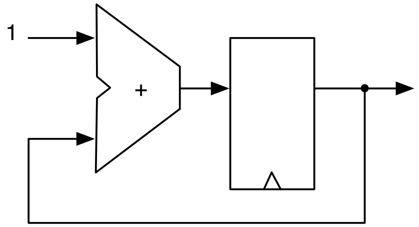
- We can combine initialization and enable

```
val resetEnableReg = RegInit(0.U(4.W))

when (enable) {
  resetEnableReg := inVal
}
```

- A register can also be part of an expression
- What does the following circuit do?

```
val risingEdge = din & !RegNext(din)
```

Combine a Register with an Adder



- Is a free running counter
- 0, 1, ... 14, 15, 0, 1, ...

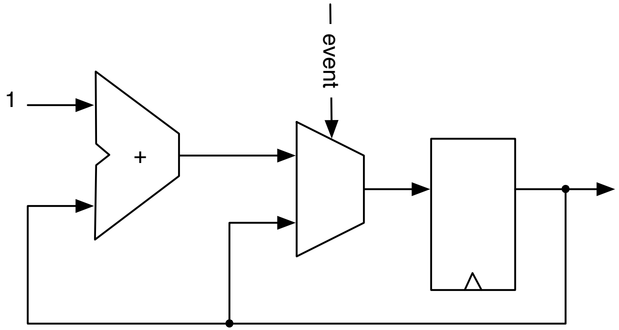
```
val cntReg = RegInit(0.U(4.W))

cntReg := cntReg + 1.U
```

A Counter

```
val cntReg = RegInit(0.U(8.W))

cntReg := Mux(cntReg === 9.U, 0.U, cntReg + 1.U)
```

- This counter counts from 0 to 9
- And starts from 0 again after reaching 9
  - Starting from 0 is common in computer engineering
- A counter is the hardware version of a *for loop*
  - But runs forever (over and over again)
- Often needed
- Can we draw the schematic?

Counting Events



```
val cntEventsReg = RegInit(0.U(4.W))
when(event) {
  cntEventsReg := cntEventsReg + 1.U
}
```

Structure With Bundles

- A `Bundle` to groups signals
- Can be different types
- Defined by a class that extends `Bundle`
- List the fields as `vals` within the block

```
class Channel() extends Bundle {
  val data = UInt(32.W)
  val valid = Bool()
}
```

Using a Bundle

- Create it with `new`
- Wrap it into a `Wire`
- Field access with *dot* notation

```
val ch = Wire(new Channel())
ch.data := 123.U
ch.valid := true.B

val b = ch.valid
```

A Collection of Signals with `Vec`

- Chisel `Vec` is a collection of signals of the same type
- The collection can be accessed by an index
- Similar to an array in other languages

```
val v = Wire(Vec(3, UInt(4.W)))
```

Using a `Vec`

```
v(0) := 1.U
v(1) := 3.U
v(2) := 5.U

val index = 1.U(2.W)
val a = v(index)
```

- Reading from an `Vec` is a multplexer
- We can put a `Vec` into a `Reg`

```
val registerFile = Reg(Vec(32, UInt(32.W)))
```

An element of that register file is accessed with an index and used as a normal register.

```
registerFile(index) := dIn
val dOut = registerFile(index)
```

Mixing Vecs and Bundles

- We can freely mix bundles and vectors
- When creating a vector with a bundle type, we need to pass a prototype for the vector fields. Using our `Channel`, which we defined above, we can create a vector of channels with:

```
val vecBundle = Wire(Vec(8, new Channel()))
```

- A bundle may as well contain a vector

```
class BundleVec extends Bundle {
  val field = UInt(8.W)
  val vector = Vec(4,UInt(8.W))
}
```

Lab Today

- Combinational circuits in Chisel
- Lab 2 Page
- Each exercise contains a test, which initially fails
- `sbt test` runs them all
  - To just run a single test, run e.g.,
    `sbt "testOnly MajorityPrinter"`

  When all test succeed your are done ;-)
- Components contain a comment where you shall add your implementation
- The initial majority example has an optional implementation in an FPGA

Summary

- Think in hardware
    - Draw “boxes”
- Combinational logic (= Boolean function)
    - Logical and arithmetic expressions
    - Conditional update (`when`)
    - Function tables with `switch`
    - Large multiplexer with a `Vec`
- Registers
    - Define as `Reg`, `RegNext`, or `RegInit`

Summary

- We looked at basic digital circuit blocks
- Now you know all you need to build any digital circuit!
  - Digital controller
  - MP3 player
  - Microprocessor
  - Data center accelerator
  - ...
- Will show you some constructs for a more *elegant* style