Chisel Bootcamp

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Logging into EC2

```
ssh xxx@yyy
password: bootcamp
```

Using Screen

to prevent lossage of state if disconnected ... when you first log in, type

```
screen
```

when you log back into the instance, type

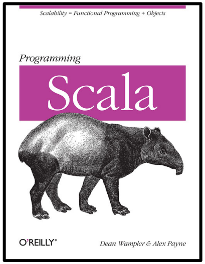
```
screen -r
```

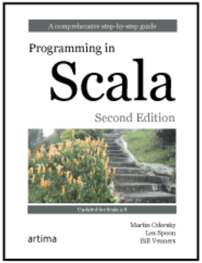
Getting the Latest

```
cd chisel
git pull
```

The Scala Programming Language

- Compiled to JVM
  - Good performance
  - Great Java interoperability
  - Mature debugging, execution environments
- Object Oriented
  - Factory Objects, Classes
  - Traits, overloading etc
- Functional
  - Higher order functions
  - Anonymous functions
  - Currying etc
- Extensible
  - Domain Specific Languages (DSLs)


Scalability = Functional Programming + Objects
Programming
Scala
O'REILLY
Dean Wampler & Alex Payne



Scala Functional

```
def f (x: Int) = 2 * x

def g (xs: List[Int]) =  xs.map(f)
```

Scala Object Oriented

```
object Blimp {
  var numBlimps = 0
  def apply(r: Double) = {
    numBlimps += 1
    new Blimp(r)
  }
}

Blimp.numBlimps
Blimp(10.0)

class Blimp(r: Double) {
  val rad = r
  println("Another Blimp")
}

class Zep(r: Double) extends Blimp(r)
```

Scala Collections

```
// Array’s
val tbl = new Array[Int](256)
tbl(0) = 32
val y = tbl(0)
val n = tbl.length

// ArrayBuffer’s
val buf = new ArrayBuffer[Int]()
buf += 12
val z = buf(0)
val l = buf.length

// List’s
val els = List(1, 2, 3)
val a :: b :: c :: Nil = els
val m = els.length
```

Scala Iteration

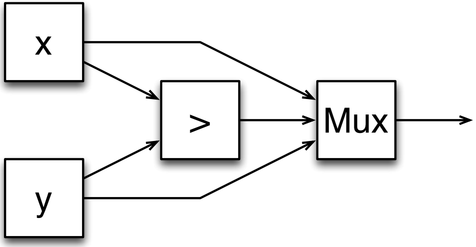
```
val tbl = new Array[Int](256)

// loop over all indices
for (i <- 0 until tbl.length)
  tbl(i) = i

// loop of each sequence element
for (e <- tbl)
  tbl(i) += e

// nested loop
for (i <- 0 until 16; j <- 0 until 16)
  tbl(j*16 + i) = i

// create second table with doubled elements
val tbl2 = for (i <- 0 until 16) yield tbl(i)*2
```

Scala Console

```
scala
1 + 2
def f (x: Int) = 2 * x
f(4)
```

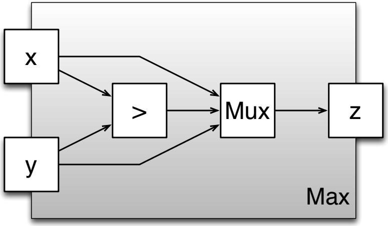
Algebraic Graph Construction

```
Mux(x > y, x, y)
```



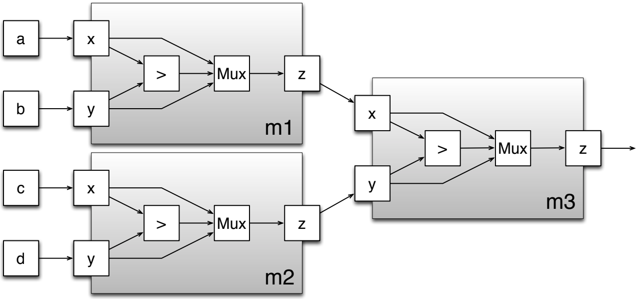
Creating Component

```
class Max2 extends Component {
  val io = new Bundle {
    val x = UFix(width = 8).asInput
    val y = UFix(width = 8).asInput
    val z = UFix(width = 8).asOutput }
  io.z := Mux(io.x > io.y, io.x, io.y)
}
```



Connecting Components

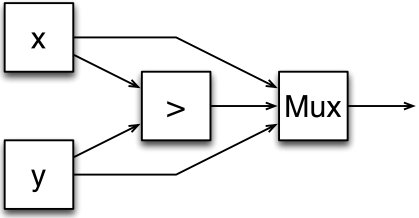
```
val m1 = new Max2()
m1.io.x := a
m1.io.y := b
val m2 = new Max2()
m2.io.x := c
m2.io.y := d
val m3 = new Max2()
m3.io.x := m1.io.z
m3.io.y := m2.io.z
```



Defining Construction Functions

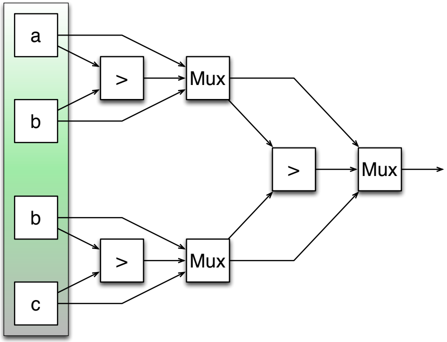
```
def Max2 = Mux(x > y, x, y)
```

```
Max2(x, y)
```



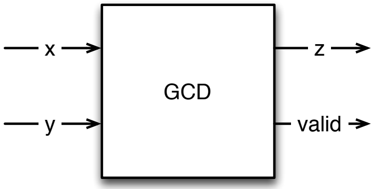
Functional Construction

```
Reduce(Array(a, b, c, d), Max2)
```



Example

```
class GCD extends Component {
  val io = new Bundle {
    val a     = UFix(16, INPUT)
    val b     = UFix(16, INPUT)
    val z     = UFix(16, OUTPUT)
    val valid = Bool(OUTPUT) }
  val x = Reg(resetVal = io.a)
  val y = Reg(resetVal = io.b)
  when (x > y) {
    x := x - y
  } .otherwise {
    y := y - x
  }
  io.z     := x
  io.valid := y === UFix(0)
}
```



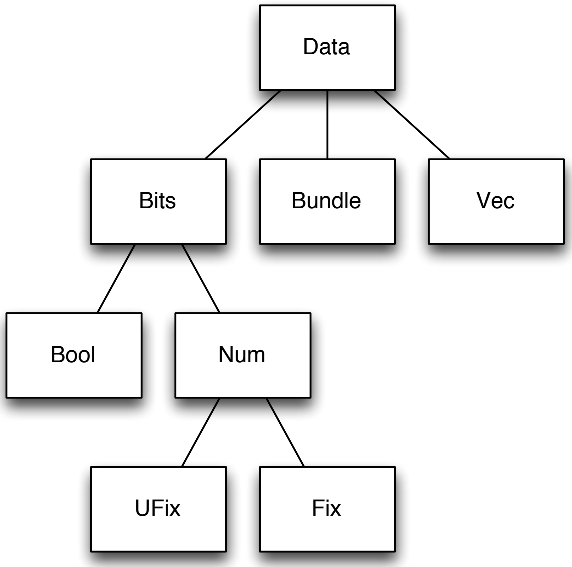
Literals

```
Bits(1)        // decimal 1-bit literal from Scala Int.
Bits("ha")     // hexadecimal 4-bit literal from string.
Bits("o12")    // octal 4-bit literal from string.
Bits("b1010") // binary 4-bit literal from string.

Fix(5)         // signed decimal 4-bit literal from Scala Int.
Fix(-8)        // negative decimal 4-bit literal from Scala Int.
UFix(5)        // unsigned decimal 3-bit literal from Scala Int.

Bool(true)     // Bool literals from Scala literals.
Bool(false)
```

Literals

```
Bits("h_dead_beef") // 32-bit literal of type Bits.
Bits(1)             // decimal 1-bit literal from Scala Int.
Bits("ha", 8)       // hexadecimal 8-bit literal of type Bits.
Bits("o12", 6)      // octal 6-bit literal of type Bits.
Bits("b1010", 12)   // binary 12-bit literal of type Bits.

Fix(5, 7)           // signed decimal 7-bit literal of type Fix.
UFix(5, 8)          // unsigned decimal 8-bit literal of type UFix.
```

Type Hierarchy

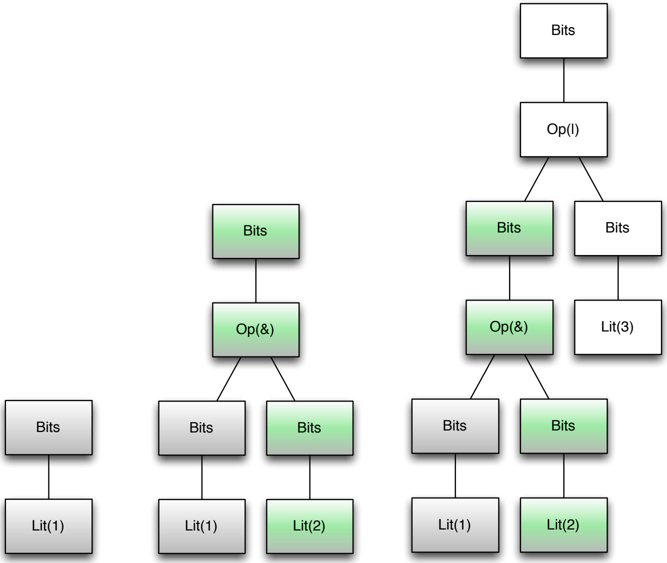


Combinational Circuits

```
(a & b) | (~c & d)
```

```
val sel = a | b
val out = (sel & in1) | (~sel & in0)
```

Building Graphs



`a = Bits(1)` `b = a & Bits(2)` `b | Bits(3)`

Bitwise operators

Valid on Bits, Fix, UFix, Bool.

```
// Bitwise-NOT
val invertedX = ~x
// Bitwise-AND
val hiBits    = x & Bits("h_ffff_0000")
// Bitwise-OR
val flagsOut  = flagsIn | overflow
// Bitwise-XOR
val flagsOut  = flagsIn ^ toggle
```

Bitwise reductions

Valid on Bits, Fix, and UFix. Returns Bool.

```
// AND-reduction
val allSet = andR(x)
// OR-reduction
val anySet = orR(x)
// XOR-reduction
val parity = xorR(x)
```

Equality comparison

Valid on Bits, Fix, UFix, and Bool. Returns Bool.

```
// Equality
val equ = x === y
// Inequality
val neq = x != y
```

Shifts

Valid on Bits, Fix, and UFix.

```
// Logical left shift.
val twoToTheX = Fix(1) << x
// Right shift (logical on Bits & UFix, arithmetic on Fix).
val hiBits    = x >> UFix(16)
```

Bitfield manipulation

Valid on Bits, Fix, UFix, and Bool.

```
// Extract single bit, LSB has index 0.
val xLSB       = x(0)
// Extract bit field  from end to start bit pos.
val xTopNibble = x(15,12)
// Replicate a bit string multiple times.
val usDebt     = Fill(3, Bits("hA"))
// Concatenates bit fields, w/ first arg on left
val float      = Cat(sgn,exp,man)
```

Logical Operations

Valid on Bools.

```
// Logical NOT.
val sleep = !busy
// Logical AND.
val hit   = tagMatch && valid
// Logical OR.
val stall = src1busy || src2busy
// Two-input mux where sel is a Bool.
val out   = Mux(sel, inTrue, inFalse)
```

Arithmetic operations

Valid on Nums: Fix and UFix.

```
// Addition.
val sum  = a + b
// Subtraction.
val diff = a - b
// Multiplication.
val prod = a * b
// Division.
val div  = a / b
// Modulus
val mod  = a % b
```

Arithmetic comparisons

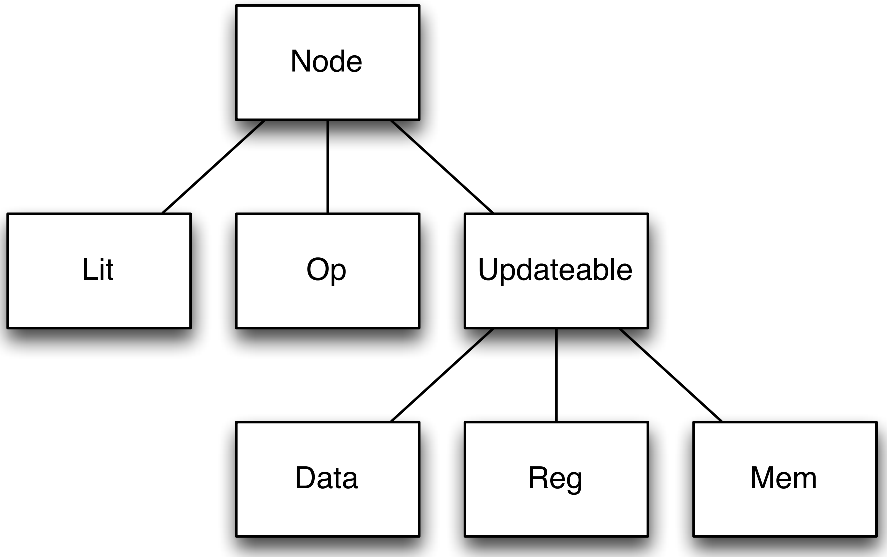
Valid on Nums: Fix and UFix. Returns Bool.

```
// Greater than.
val gt  = a > b
// Greater than or equal.
val gte = a >= b
// Less than.
val lt  = a < b
// Less than or equal.
val lte = a <= b
```

Bitwidth Inference

operation	bit width
`z = x + y`	`wz = max(wx, wy)`
`z = x - y`	`wz = max(wx, wy)`
`z = x & y`	`wz = max(wx, wy)`
`z = Mux(c, x, y)`	`wz = max(wx, wy)`
`z = w * y`	`wz = wx + wy`
`z = x << n`	`wz = wx + maxNum(n)`
`z = x >> n`	`wz = wx - minNum(n)`
`z = Cat(x, y)`	`wz = wx + wy`
`z = Fill(n, x)`	`wz = wx * maxNum(n)`

Node Class Hierarchy



chisel repo

```
src                          # chisel scala source code
csrc                         # chisel emulator source code
doc                          # documentation
www                          # web sources
tutorial                     # tutorial project
tutorial/src                 # tutorial source code
tutorial/sbt                 # tutorial sbt files
tutorial/emulator            # tutorial emulator build products
tutorial/emulator/Makefile # Makefile for emulator products
tutorial/verilog             # tutorial verilog build products
tutorial/verilog/Makefile  # Makefile for verilog products
```

Combinational – tutorial/src/combinational.scala

```
package Tutorial

import Chisel._

class Combinational extends Component {
  val io = new Bundle {
    val x = UFix(16, INPUT)
    val y = UFix(16, INPUT)
    val z = UFix(16, OUTPUT)
  }
  io.z := io.x + io.y
}
```

Tutorial Main – tutorial/src/tutorial.scala

```
package Tutorial

import Chisel._

object Tutorial {
  def main(args: Array[String]) = {
    val args = args.slice(1, args.length)
    args(0) match {
      case "combinational" =>
        chiselMain(args, () => new Combinational())
      ...
    }
  }
}
```

Emitting C++ and Compiling

```
def main(args: Array[String]) = {
 val args = args.slice(1, args.length)
  args(0) match {
    case "combinational" => chiselMain(args, () => new Combinational())
} }
```

get into sbt directory:

```
cd $CHISEL/tutorial/sbt
```

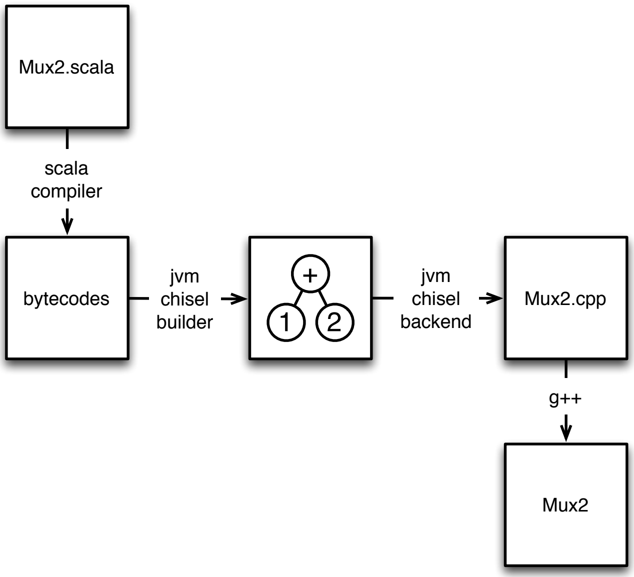
emit C++ and compile `tutorial/emulator/Combination-*` to produce combinational circuit app named `tutorial/emulator/Combination`:

```
bash> sbt
sbt> project tutorial
sbt> compile
sbt> run Combinational --backend c --targetDir ../emulator --compile --genHarness
sbt> exit
```

or on one line

```
sbt "project tutorial" "run Combinational --backend c --targetDir ../emulator --compile --genHarness"
```

Chisel Workflow

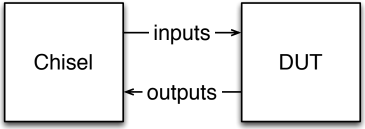


Defining a Tester

```
package Tutorial
import Chisel._
import scala.collection.mutable.HashMap
import scala.util.Random

class Combinational extends Component {
  val io = new Bundle {
    val x = UFix(16, INPUT)
    val y = UFix(16, INPUT)
    val z = UFix(16, OUTPUT) }
  io.z := io.x + io.y
}

class CombinationalTests(c: Combinational)
    extends Tester(c, Array(c.io)) {
  defTests {
    var allGood = true
    val vars    = new HashMap[Node, Node]()
    val rnd     = new Random()
    val maxInt  = 1 << 16
    for (i <- 0 until 10) {
      vars.clear()
      val x          = rnd.nextInt(maxInt)
      val y          = rnd.nextInt(maxInt)
      vars(c.io.x) = UFix(x)
      vars(c.io.y) = UFix(y)
      vars(c.io.z) = UFix((x + y)&(maxInt-1))
      allGood      = step(vars) && allGood
    }
    allGood
} }
```

```
class Tester[T <: Component]
  (val c: T, val testNodes: Array[Node])

def defTests(body: => Boolean)

def step(vars: HashMap[Node, Node]): Boolean
```

- user subclasses `Tester` defining DUT and `testNodes` and tests in `defTests` body
- `vars` is mapping from `testNodes` to literals, called bindings
- `step` runs test with given bindings, where var values for input ports are sent to DUT, DUT computes next outputs, and DUT sends next outputs to Chisel
- finally `step` compares received values against var values for and returns false if any comparisons fail output ports



Binding Tester to Component

```
object chiselMainTest {
  def apply[T <: Component]
    (args: Array[String], comp: () => T)(tester: T => Tester[T]): T
}
```

and used as follows:

```
chiselMainTest(args + "--test", () => new Combinational()){
  c => new CombinationalTests(c)
}
```

Running Tests Examples

```
cd $CHISEL/tutorial/sbt
sbt "project tutorial" "run Combinational ... --compile --test"
...
PASSED
```

or through makefile

```
cd $CHISEL/tutorial/emulator
make combinational
...
PASSED
```

Functional Abstraction

```
def clb(a: Bits, b: Bits, c: Bits, d: Bits) =
  (a & b) | (~c & d)

val out = clb(a,b,c,d)
```

Functional Scala

```
class Functional extends Component {
  def clb(a: Bits, b: Bits, c: Bits, d: Bits) =
    (a & b) | (~c & d)
  val io = new Bundle {
    val x = Bits(16, INPUT)
    val y = Bits(16, INPUT)
    val z = Bits(16, OUTPUT)
  }
  io.z := clb(io.x, io.y, io.x, io.y)
}
```

Bundles

```
class MyFloat extends Bundle {
  val sign        = Bool()
  val exponent    = UFix(width = 8)
  val significand = UFix(width = 23)
}

val x  = new MyFloat()
val xs = x.sign
```

Vecs

```
// Vector of 5 23-bit signed integers.
val myVec = Vec(5) { Fix(width = 23) }

// Connect to one static element of vector.
val reg3  = myVec(3)
reg3     := data3
myVec(4) := data4

// Connect to one dynamic element of vector.
val reg       = myVec(addr)
reg          := data1
myVec(addr2) := data2
```

Ports

Data object with directions assigned to its members

```
class FIFOInput extends Bundle {
  val ready = Bool(OUTPUT)
  val bits  = Bits(32, INPUT)
  val valid = Bool(INPUT)
}
```

Direction assigned at instantiation time

```
class ScaleIO extends Bundle {
  val in    = new MyFloat().asInput
  val scale = new MyFloat().asInput
  val out   = new MyFloat().asOutput
}
```

Component

- inherits from `Component`,
- contains an interface stored in a port field named `io`, and
- wires together subcircuits in its constructor.

```
class Mux2 extends Component {
  val io = new Bundle{
    val sel = Bits(1, INPUT)
    val in0 = Bits(1, INPUT)
    val in1 = Bits(1, INPUT)
    val out = Bits(1, OUTPUT)
  }
  io.out := (io.sel & io.in1) | (~io.sel & io.in0)
}
```

chiselMain Command Line Arguments

```
sbt
sbt> project tutorial
sbt> compile                     // compiles Chisel Scala code
sbt> run Combinational           // produces C++ files
sbt> run Combinational --compile // produces C++ files and compiles
sbt> run Combinational --test    // produces C++ files, compiles, tests
sbt> exit
```

with a complete set of command line arguments being:

`--targetDir`	target pathname prefix
`--genHarness`	generate harness file for C++
`--debug`	put all wires in C++ class file
`--compile`	compiles generated C++
`--test`	runs tests using C++ app
`--backend v`	generate verilog
`--backend c`	generate C++ (default)
`--vcd`	enable vcd dumping

Creating Verilog

```
cd $CHISEL/tutorial/sbt; sbt "project tutorial" "run Mux2 --backend v ..."
```

or through makefile:

```
cd $CHISEL/tutorial/verilog; make Mux2
```

producing `Mux2.v`:

```
module Mux2(
    input  io_sel,
    input  io_in0,
    input  io_in1,
    output io_out);

  wire T0;
  wire T1;
  wire T2;
  wire T3;

  assign io_out = T0;
  assign T0 = T3 | T1;
  assign T1 = T2 & io_in0;
  assign T2 = ~ io_sel;
  assign T3 = io_sel & io_in1;
endmodule
```

Producing VCD

```
cd $CHISEL/tutorial/sbt
sbt "project tutorial" "run Mux2 --backend c ... --vcd --compile --test"
```

which then produces

```
$CHISEL/tutorial/emulator/Mux2.vcd
```

which you can view with a vcd viewer

Component Hierarchy Problem – `Mux4.scala`

- child components stored in fields of parent
- now write 4-to-1 mux out of 3 2-to-1 mux's

```
class Mux4 extends Component {
  val io = new Bundle {
    val in0 = Bits(1, INPUT)
    val in1 = Bits(1, INPUT)
    val in2 = Bits(1, INPUT)
    val in3 = Bits(1, INPUT)
    val sel = Bits(2, INPUT)
    val out = Bits(1, OUTPUT)
  }
  val m0 = new Mux2()
  m0.io.sel := io.sel(0); m0.io.in0 := io.in0; m0.io.in1 := io.in1

  // flush this out ...

  io.out := io.in0 & io.in1 & io.in2 & io.in3 & io.sel
}
```

Doing Mux4 Problem – `Mux4.scala`

- loop
  - edit and flush out Mux4.scala
  - make Mux4
- until PASSES

```
cd $CHISEL/tutorial/emulator
make Mux4
...
PASSED
```

State Elements

```
Reg(in)
```

```
def risingEdge(x: Bool) = x && !Reg(x)
```

Counter

```
def wrapAround(n: UFix, max: UFix) =
  Mux(n > max, UFix(0), n)

def counter(max: UFix) = {
  val x = Reg(resetVal = UFix(0, max.getWidth))
  x := wrapAround(x + UFix(1), max)
  x
}
```

Sequential Circuits

```
// Produce pulse every n cycles.
def pulse(n: UFix) = counter(n - UFix(1)) === UFix(0)
```

```
// Flip internal state when input true.
def toggle(p: Bool) = {
  val x = Reg(resetVal = Bool(false))
  x := Mux(p, !x, x)
  x
}
```

```
// Square wave where each half cycle has given period.
def squareWave(period: UFix) = toggle(pulse(period))
```

Sequential Circuit Problem – `Accumulator.scala`

- write sequential circuit that sums `in` values

```
class Accumulator extends Component {
  val io = new Bundle {
    val in  = UFix(1, INPUT)
    val out = UFix(8, OUTPUT)
  }

  // flush this out ...

  io.out := UFix(0)
}
```

Forward Declarations

```
val pcPlus4      = UFix()
val branchTarget = UFix()
val pcNext       = Mux(io.ctl.pcSel, branchTarget, pcPlus4)
val pcReg        = Reg(data = pcNext, resetVal = UFix(0, 32))
pcPlus4         := pcReg + UFix(4)
...
branchTarget    := addOut
```

Conditional Updates

```
val r = Reg() { UFix(16) }
when (c === UFix(0) ) {
  r := r + UFix(1)
}
```

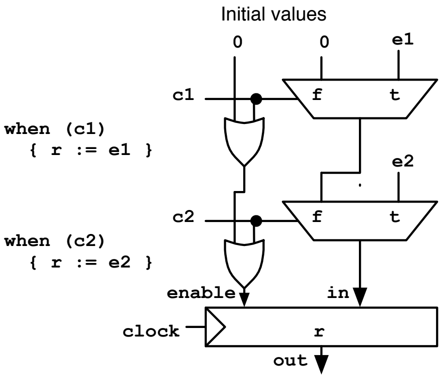
Conditional Updates Priority

```
when (c1) { r := Bits(1) }
when (c2) { r := Bits(2) }
```

Conditional Update Order:

c1	c2	r	
0	0	r	`r` unchanged
0	1	2	
1	0	1	
1	1	2	`c2` takes precedence over `c1`

Conditional Update Synthesized Hardware



- Each `when` statement adds another level of data mux and ORs the predicate into the enable chain and
- the compiler effectively adds the termination values to the end of the chain automatically.

Targetting Multiple Registers

```
r := Fix(3)
s := Fix(3)
when (c1) { r := Fix(1); s := Fix(1) }
when (c2) { r := Fix(2) }
```

leads to `r` and `s` being updated according to the following truth table:

c1	c2	r	s	
0	0	3	3	
0	1	2	3	
1	0	1	1	`r` updated in `c2` block, `s` updated using default
1	1	2	1	

Conditional Update Nesting

```
when (a) { when (b) { body } }
```

which is the same as:

```
when (a && b) { body }
```

Conditional Update Chaining

```
when (c1) { u1 }
.elsewhen (c2) { u2 }
.otherwise { ud }
```

which is the same as:

```
when (c1) { u1 }
when (!c1 && c2) { u2 }
when (!(c1 || c2)) { ud }
```

Switch Statement

```
switch(idx) {
 is(v1) { u1 }
 is(v2) { u2 }
}
```

which is the same as:

```
when (idx === v1) { u1 }
when (idx === v2) { u2 }
```

Finite State Machines

```
class Parity extends Component {
  val io = new Bundle {
    val in  = Bool(dir = INPUT)
    val out = Bool(dir = OUTPUT) }
  val s_even :: s_odd :: Nil = Enum(2){ UFix() }
  val state  = Reg(resetVal = s_even)
  when (io.in) {
    when (state === s_even) { state := s_odd  }
    .otherwise              { state := s_even }
  }
  io.out := (state === s_odd)
}
```

FSM Problem – VendingMachine.scala

- write vending machine which needs accepts 20 cents or more before raising valid high

```
class VendingMachine extends Component {
  val io = new Bundle {
    val nickel = Bool(dir = INPUT)
    val dime   = Bool(dir = INPUT)
    val valid  = Bool(dir = OUTPUT) }
  val sIdle :: s5 :: s10 :: s15 :: sOk :: Nil = Enum(5){ UFix() }
  val state = Reg(resetVal = sIdle)

  // flush this out ...

  io.valid := (state === sOk)
}
```

ROM

```
def Vec[T <: Data](elts: Seq[T])(data: => T): Vec[T]
def Vec[T <: Data](elts: T*)(data: => T): Vec[T]
```

```
val i = Array(UFix(1), UFix(2), UFix(4), UFix(8))
val m = Vec(i){ UFix(width = 32) }
val r = m(counter(UFix(3)))
```

Mul Lookup Table Problem – `Mul.scala`

- write 16x16 multiplication table using `Vec`

```
class Mul extends Component {
  val io = new Bundle {
    val x   = UFix(4, INPUT)
    val y   = UFix(4, INPUT)
    val z   = UFix(8, OUTPUT)
  }
  val muls = new Array[UFix](256)

  // flush this out ...

  io.z := UFix(0)
}
```

Memories

```
def object Mem {
  def apply[T <: Data](n: Int, resetVal: T = null)(type: => T): Mem
}

class Mem[T <: Data]
    (val n: Int, val resetVal: T, val inits: Seq[T], type: () => T)
      extends Updateable {
  def apply(addr: UFix): T
}
```

Register File

```
val regs = Mem(32){ Bits(width = 32) }
when (wr_en) {
  regs(wr_addr) := wr_data
}
val idat = regs(iaddr)
val mdat = regs(maddr)
```

Table Problem – Memo.scala

- write read/write table using `Mem`

```
class Memo extends Component {
  val io = new Bundle {
    val isWr    = Bool(INPUT)
    val wrAddr  = UFix(8, INPUT)
    val wrData  = UFix(8, INPUT)
    val isRd    = Bool(INPUT)
    val rdAddr  = UFix(8, INPUT)
    val rdData  = UFix(8, OUTPUT)
  }
  val mem = Mem(256){ UFix(width = 8) }

  // flush this out ...

  io.rdData := UFix(0)
}
```

Port Classes, Subclasses, and Nesting

```
class LinkIO extends Bundle {
  val data  = Bits(16, OUTPUT)
  val valid = Bool(OUTPUT)
}
```

We can then extend `SimpleLink` by adding parity bits using bundle inheritance:

```
class PLinkIO extends LinkIO {
  val parity = Bits(5, OUTPUT)
}
```

In general, users can organize their interfaces into hierarchies using inheritance.

Filter Example

From there we can define a filter interface by nesting two `LinkIO`s into a new `FilterIO` bundle:

```
class FilterIO extends Bundle {
  val in  = new LinkIO().flip
  val out = new LinkIO()
}
```

where `flip` recursively changes the “gender” of a bundle, changing input to output and output to input.
We can now define a filter by defining a filter class extending component:

```
class Filter extends Component {
  val io  = new FilterIO()
  io.out.valid := io.in.valid
  io.out.data  := io.in.data
}
```

where the `io` field contains `FilterIO`.

Even Filter Problem – `Filter.scala`

- write filter that filters out even numbers

```
class Filter extends Component {
  val io  = new FilterIO()

  // flush this out ...

  io.out.valid := Bool(true)
  io.out.data  := Bits(0)
}
```

Testing Decoupled Circuits

```
class GCDTests(c: GCD) extends Tester(c, Array(c.io)) {
  defTests {
    val (a, b, z) = (64, 48, 16)
    val svars = new HashMap[Node, Node]()
    val ovars = new HashMap[Node, Node]()
    var t = 0
    do {
      svars(c.io.a) = UFix(a)
      svars(c.io.b) = UFix(b)
      step(svars, ovars)
      t += 1
    } while (t <= 1 || ovars(c.io.v).litValue() == 0)
    ovars(c.io.z).litValue() == z
  }
}
```

Bundle Vectors

```
class CrossbarIO extends Bundle {
  val in  = Vec(2){ new LinkIO() }
  val sel = UFix(2, INPUT)
  val out = Vec(2){ new LinkIO() }
}
```

where `Vec` takes a size as the first argument and a block returning a port as the second argument.

Bundle Vectors Cloning

```
class CrossbarIO(n: Int) extends Bundle {
  val in  = Vec(n){ new LinkIO() }
  val sel = UFix(log2Up(n), INPUT)
  val out = Vec(n){ new LinkIO() }
  override def clone() = new CrossbarIO(n).asInstanceOf[this.type]
}
```

where `clone` definition fixes cloning, by incorporating the crossbar construction argument `n` in cloning.

Bulk Connections

We can now compose two filters into a filter block as follows:

```
class Block extends Component {
  val io = new FilterIO()
  val f1 = new Filter()
  val f2 = new Filter()

  f1.io.in  <> io.in
  f1.io.out <> f2.io.in
  f2.io.out <> io.out
}
```

where <> bulk connects interfaces.

- Bulk connections connect leaf ports of the same name to each other.
- After all connections are made and the circuit is being elaborated, Chisel warns users if ports have other than exactly one connection to them.

Parameterized Functions

```
def Mux[T <: Bits](c: Bool, con: T, alt: T): T

Mux(c, UFix(10), UFix(11))
```

yields a `UFix` wire because the `con` and `alt` arguments are each of type `UFix`.

Parameterized Signal Processing

$$y[t] = \sum_j w_j * x_j[t-j] \tag{1}$$

```
def innerProductFIR[T <: Num] (w: Seq[T], x: T) = {
  val delays = Range(0, w.length).map(i => w(i) * delay(x, i))
  delays.foldRight(_ + _)
}

def delay[T <: Bits](x: T, n: Int): T =
  if (n == 0) x else Reg(delay(x, n - 1))
```

Parameterized Classes

```
class FilterIO[T <: Data]()(data: => T) extends Bundle {
  val in  = data.asInput.flip
  val out = data.asOutput
}

class Filter[T <: Data]()(data: => T) extends Component {
  val io = new FilterIO(){ data }
  ...
}
```

Parameterized Classes Continued

```
class FIFOIO[T <: Data]()(data: => T) extends Bundle {
  val ready = Bool(INPUT)
  val valid = Bool(OUTPUT)
  val bits  = data.asOutput
}

class PipeIO[+T <: Data]()(data: => T) extends Bundle {
  val valid = Bool(OUTPUT)
  val bits  = data.asOutput
}
```

Decoupled GCD Problem – `RealGCD.scala`

```scala
class RealGCDInput extends Bundle {
  val a = Bits(width = 16)
  val b = Bits(width = 16)
}

class RealGCD extends Component {
  val io  = new Bundle {
    val in  = new FIFOIO(){ new RealGCDInput() }.flip()
    val out = new PipeIO(){ Bits(width = 16) }
  }

  // flush this out ...
}
```

Object Oriented FIFOIO

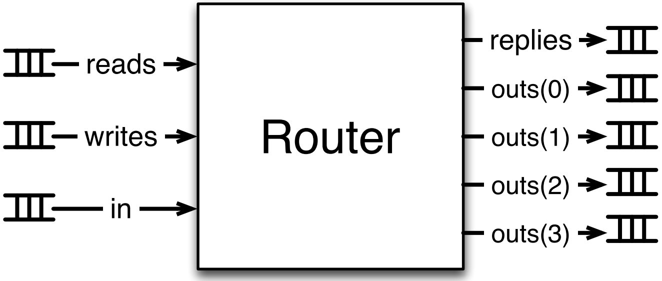
```
class EnqIO[T <: Data]()(data: => T) extends FIFOIO()(data) {
  def enq(dat: T): T = { valid := Bool(true); data := dat; dat }
  valid := Bool(false);
  for (io <- data.flatten.map(x => x._2))
    io := UFix(0, io.getWidth());
}

class DeqIO[T <: Data]()(data: => T) extends FIFOIO()(data) {
  flip()
  ready := Bool(false);
  def deq(b: Boolean = false): T = { ready := Bool(true); data }
}

class Filter[T <: Data]()(data: => T) extends Component {
  val io = new Bundle {
    val in  = new DeqIO(){ data }
    val out = new EnqIO(){ data }
  }
  when (io.in.valid && io.out.ready) {
    io.out.enq(io.in.deq())
  }
}
```

Router Interface

```
class ReadCmd extends Bundle {
  val addr = UFix(width = 32)
}

class WriteCmd extends ReadCmd {
  val data = UFix(width = 32)
}

class Packet extends Bundle {
  val header = UFix(width = 8)
  val body   = Bits(width = 64)
}

class RouterIO(n: Int) extends Bundle {
  override def clone = new RouterIO(n).asInstanceOf[this.type]
  val reads   = new DeqIO(){ new ReadCmd() }
  val replies = new EnqIO(){ UFix(width = 8) }
  val writes  = new DeqIO(){ new WriteCmd() }
  val in      = new DeqIO(){ new Packet() }
  val outs    = Vec(n){ new EnqIO(){ new Packet() } }
}
```

Router Problem – Router.scala

```
class Router extends Component {
  val depth = 32;
  val n     = 4;
  val io    = new RouterIO(n);
  val tbl   = Mem(depth){ UFix(width = sizeof(n)) };

  // flush it out ...
}
```



Advanced Topics

- git
- sbt
- project directory structure
- project file
- installation

git

```
cd ${HOME}
git clone git@github.com:ucb-bar/chisel.git
export CHISEL=${HOME}/chisel
git pull
git status
git log
git add filename
git commit -m "comment"
git push
```

sbt

```
cd ${CHISEL}/tutorial/sbt
sbt
project tutorial
compile
run
console
```

Project Directory Structure

```
chisel/
  tutorial/
  src/
gpu/
  chisel -> ../chisel
  sbt/
    project/build.scala # edit this as shown below
    chisel/src/main/scala -> $CHISEL/src
    gpu/src/main/scala -> ../../../../src
  src/                  # your source files go here
    gpu.scala
  emulator/             # your C++ target can go here
```

Project File

```
import sbt._
import Keys._

object BuildSettings {
  val buildOrganization = "edu.berkeley.cs"
  val buildVersion = "1.1"
  val buildScalaVersion = "2.9.2"

  val buildSettings = Defaults.defaultSettings ++ Seq (
    organization := buildOrganization,
    version      := buildVersion,
    scalaVersion := buildScalaVersion
  )
}

object ChiselBuild extends Build {
  import BuildSettings._

  lazy val chisel =
    Project("chisel", file("chisel"),
      settings = buildSettings)
  lazy val gpu =
    Project("gpu", file("gpu"), settings = buildSettings)
      dependsOn(chisel)
}
```

Installation

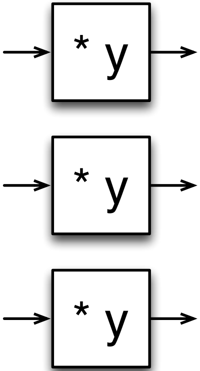
- on mac install:
  - XCODE console tools
  - http://www.macports.org
- on windows install:
  - cygwin
- everywhere install:
  - git
  - g++
  - java
- everywhere
  - export $CHISEL=...
  - git clone https://github.com/ucb-bar/chisel.git

Projects Ideas

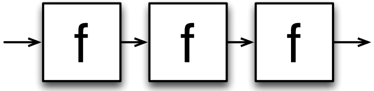
audio processing	`Echo.scala`
image processing	`Darken.scala`
risc processor	`Risc.scala`
game of life	`Life.scala`
router	`Router.scala`
map/reduce	*see next slide*
network	
fft	
cryptography	
serial multiplier	
pong	

Functional Composition

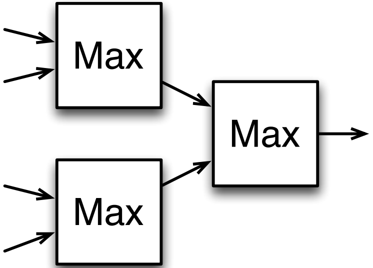
```
Map(ins, x => x * y)
```



```
Chain(n, in, x => f(x))
```



```
Reduce(data, Max)
```



Keep in Touch

website	`chisel.eecs.berkeley.edu`
mailing list	`groups.google.com/group/chisel-users`
github	`https://github.com/ucb-bar/chisel/`
me	`jrb@pobox.com`

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