1 Introduction

This document is a manual for using the advanced parameter library within Chisel. For more general information regarding Chisel as a hardware construction language, please see the Getting Started documentation.

As hardware designs grow in complexity, modularity becomes necessary for maintenance and verification. The primary use case for Chisel is describing diverse and highly-parameterized hardware generators, and we quickly realized that the traditional parameterization method forces brittleness into a design’s source code and limits component reuse.

The outline of this document is as follows: in Section 2.1, we describe the basic objects and methods for the advanced parameterization mechanism, as well as the required boilerplate to use it. In Section 2.2, a series of increasingly complex examples of design patterns are described. For each example, we propose the simplest parameterization scheme which solves the problem. As the examples build in complexity, so do the parameterization requirements, until we arrive at the described advanced parameterization mechanism. The next section, Section 2.3, introduces the concept of Knobs and their relationship to design constraints and the Parameters object. Finally, in Section 2.4, we explain multiple design heuristics which should be followed when using advanced parameterization.

2 Advanced Parameterization

Every Chisel Module has a member params of class Parameters that provides the mechanism for passing parameters between modules.

This section describes the following features: (1) the Parameters class and associated methods/members; (2) the basic usage model; (3) syntactic sugar; (4) boilerplate code for exposing parameters to external users/programs; (5) advanced functionality via Views (site, here, up).

2.1 Classes and Methods

The Parameters class has the following base methods:

```java
class Parameters {
  // returns a value of type T
  def apply[T](key:Any):T

  // returns new Parameters class
  def alter[mask:(Any,View,View,View)=>Any]:Parameters

  // returns a Module's Parameters instance
  def params:Parameters
}
```

View is a class containing a base method:

```java
class View {
  // returns a value of type T
  def apply[T](key:Any):T
}
```

Parameters has a factory object containing one basic method:

```java
object Parameters {
  // returns an empty Parameters instance
  def empty:Parameters
}
```

The Module factory object now has an additional apply method:

```java
object Module {
  // returns a new Module of type T, initialized with a Parameters instance if _p !=None.
  def apply[T <: Module](c:()=>T)(implicit _p:Option[Parameters] = None):T
}
```

2.2 Basic Usage Model

This example shows the simplest usage of (1) querying params, (2) altering a Parameters object, and (3) passing a Parameters object to a Module:
Within the Module Tile, the params member is queried by calling Parameters.apply with the key and return value type.

In Top, an empty parameters is created by calling Parameters.empty; then it is altered with a function of type (Any,View,View,View) => Any to return a new Parameters instance, which is assigned to tile_parameters.

After wrapping tile_parameters within Some:Option[Parameters], it is passed as a second argument to the Module object when passed to chiselMain.

### 2.3 Syntactic Sugar: Field[T]

The simple example requires the return type Int must be included as an argument to the apply method, otherwise the Scala compiler will throw an error:

```scala
class Tile extends Module {
  val width = params[Int]('width')
}
```

Alternatively, one can create a case object for each key which extends Field[T] and pass that directly into params apply method. Because Field contains the return type information, the type does not need to be passed:

```scala
case object Width extends Field[Int]
class Tile extends Module {
  val width = params(Width)
}
```

For the rest of the document, assume the key to every query is a case class that extends Field[T] with the correct return type.

### 2.4 Syntactic Sugar: Passing and Altering

As a module hierarchy is formed, Parameters objects are passed between a parent module and a child module. If specified by the programmer, these objects can be copied and altered prior to instantiating the child.

Anytime an alteration is performed, Chisel internally copies the existing chain of key/value mappings and attaches the provided key/value mappings to the bottom of this chain. When a query is evaluated, it first queries the chain’s bottom key/value mapping. If there is no match, the query is then evaluated on the next key/value mapping in the chain, and so forth. If a query reaches the top of the chain with no matches, Chisel triggers a ParameterUndefinedException.

When instantiating a child, the parent can pass its Parameters object one of two ways:

1. Explicitly pass its Parameters object to its child via a second argument to the Module factory, wrapped in Option[Parameters]:

   ```scala
class Tile extends Module {
  val width = params[Width]
  val core = Module(new Core)(Some(params))
  // Explicit passing of Tile's params to Core
}
```

2. Implicitly pass its Parameters object to its child:

   ```scala
class Tile extends Module {
  val width = params[Width]
  val core = Module(new Core)
  // Implicit passing of Tile's params to Core
}
```

---

**Figure 1:** An example of Memory’s key/value chain and flat map.
If a parent wants to copy/alter the child’s dictionary, the parent has two methods to do so:

1. Provide a PartialFunction mapping as an argument to the Module factory. Internally, Chisel will copy the parent’s Parameters object and apply the alteration:

```scala
class Tile extends Module {
  val width = params(Width)
  val core = Module(new Core,{case Width => 32})
  // Provide PartialFunction to Module factory
  constructor to alter Core's 
  \code{Parameters} object
}
```

2. Call the Parameter.alter function, which returns a new Parameters object. This approach gives the programmer access to the new Parameters object, as well as the ability to use site, here, and up (see Sections ??, ??, ??):

```scala
class Tile extends Module {
  val width = params(Width)
  val core_params = params.alter(
    (pname,site,here,up) => pname match {
      case Width => 32
    })
  val core = Module(new Core)(Some(core_params))
  // Use the Parameter.alter method to return an 
  altered Parameter object. Only use when 
  site, here, or up mechanisms are needed
}
```

A more complicated example of an alteration chain is shown in Figure ?? and describe below:

```scala
class Tile extends Module {
  ...
  val core = Module(new Core, {case FPU => true; case 
  @Depth => 20; case Width => 64})
}
class Core extends Module {
  val fpu = params(FPU)
  val width = params(Width)
  val depth = params(Depth)
  val queue = Module(new Queue,{case Depth => depth*2;
  case Width => 32})
}
class Queue extends Module {
  val depth = params(Depth)
  val width = params(Width)
  val mem = Module(new Memory,{case Size => depth * 
  width})
}
class Memory extends Module {
  val size = params(Size)
  val width = params(Width)
}
```

### 2.5 ChiselConfig and Boilerplate

Chisel’s mechanism to seed the top-level parameters is through a ChiselConfig object. ChiselConfig.topDefinitions contains the highest parameter definitions and is of the following form:

```scala
case object Width extends Field[Int]
class DefaultConfig extends ChiselConfig {
  val topDefinitions:World.TopDefs = {
    (pname,site,here) => pname match {
      case Width => 32
    }
  }$
}
```

Normally, a design calls chiselMain.apply to instantiate a design. To use Chisel’s parameterization mechanism and correctly seed a ChiselConfig, one should instead call chiselMain.run with the design NOT surrounded by the Module factory. The reason for this change is to preserve backwards compatibility with existing designs, although we intend to fix this in future releases.

An example of calling chiselMain.run is as follows:

```scala
object Run {
  def main(args: Array[String]): Unit = {
    chiselMain.run(args, () => new Tile())
  }
}
```

To instantiate a design with a specific ChiselConfig, simply call the Chisel compiler with the --configInstance project_name.configClass_name argument.

### 2.6 Using site

To help the designer express dependencies between parameters, we added the site mechanism. To understand its function, remember that conceptually, a queried Module’s params member first looks at the bottom key/value mapping in its chain of key/value mappings. If there is no match, the query moves up the chain.

Suppose we have some modules which have following form:

```scala
class Core extends Module {
  val data.width = params(Width)
  ...
}
class Cache extends Module {
  val line.width = params(Width)
  ...
}
Unfortunately, both have identical queries for `width` but, for this example’s sake, have different semantic meaning. Inside a core, `width` means the word size, while in the cache, `width` means the width of a cache line. We want to be able to easily tailor the parameter’s response to either query.

The `site` mechanism allows a key/value mapping in the middle of the chain to make its own queries that start at the bottom of the chain.

Consider the following example:

```scala
class DefaultConfig extends ChiselConfig {
  val top:World.TopDefs = {
    (pname,site,here) => pname match {
      case Width => site(Location) match {
        case 'core' => 64 // data width
        case 'cache' => 128 // cache line width
      }
    }
  }
}
```

The top-level key/value mapping is using `site` to query the bottom of the chain for `Location`. Depending on what value returns (either ‘core’ or ‘cache’), the top-level key/value mapping produces a different value (Figure 2).

### 2.7 Using `here`

If a parameter is a deterministic function of other parameters expressed at the same group in the key/value mapping chain, one does not want to duplicate a value, as giving a new value would require multiple changes. Instead, one can use the `here` mechanism to query the same group of key/value mappings that `here` was called:

```scala
class Tile extends Module {
  val cache_params = params.alter {
    (pname, site, here, up) => pname match {
      case Sets => 128
      case Ways => 4
      case Size => here(Sets)*here(Ways)
    }
  }
  val cache = Module(new Cache)(cache_params)
}
```

Figure 3: Instead of using 128 or 4 directly, we can access it via `here(Sets)` and `here(Ways)`, respectively.

### 2.8 Using `up`

The `up` mechanism enables the user to query the parent group of key/value mappings. It is equivalent to calling `Parameters.apply` directly, but can be done within calling `Parameters.alter`. For an example use, see Section 2.

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*Figure 2: For (a), `site(Location)` will return Core, while in (b) `site(Location)` will return Cache.*

*Figure 3: Instead of using 128 or 4 directly, we can access it via `here(Sets)` and `here(Ways)`, respectively.*
3 Examples

The three goals of any parameterization scheme are: (1) all searchable parameters are exposed at the top level; (2) source code must never change when evaluating different points; (3) adding new parameters requires little source code change. After each example is described, we present the simplest parameterization scheme that supports the desired design space without violating any of the three goals. As examples grow in complexity, so too must the simplest parameterization scheme, until we arrive at the current advanced parameterization method.

3.1 Simple Parameters

Figure 4: For a few number of parameters, the simplest scheme is to pass them directly via constructor arguments.

In this simple design, we only vary core and cache-specific parameters. The most straightforward parameterization scheme is passing all parameters via arguments to Tile’s constructor. These values are then passed to Core and Cache via their respective constructors:

```scala
class Tile (val fpu:Boolean, val ic_sets:Int, val ic_ways:Int, val dc_sets:Int, val dc_ways:Int) extends Module {
  val core = Module(new Core(fpu))
  val icache = Module(new Cache(ic_sets,ic_ways))
  val dcache = Module(new Cache(dc_sets,dc_ways))
  ...
}
class Core (val fpu:Boolean) {...}
class Cache(val sets:Int, val ways:Int) extends Module {...}
```

No source code changes are necessary to explore our parameter space, and all searchable parameters are exposed at the top. In addition, adding a new parameter, because this example is simple, requires very few changes to our source code.

3.2 Disjoint Parameter Sets

Figure 5: For disjoint parameter sets, we can group sets of parameters into configuration objects to pass as constructor arguments.

In this next design, we are designing a chip which could instantiate different cores, each with its own set of parameters. If we apply our simple solution, the number of arguments to Tile’s constructor would be huge as it must contain all parameters for all possible cores (which would likely be much greater than two cores!).

One could propose that a better solution would be to group parameters into configuration objects. For example, we could group all BigCore parameters into a BigCoreConfig case class, and all SmallCore parameters into a SmallCoreConfig class, both of which extend CoreConfig. In addition, we have our caches and Tile accept a CacheConfig and TileConfig, respectively, within their constructors.

```scala
abstract class CoreConfig {}
case class BigCoreConfig(iq_depth:Int, lsq_depth:Int) extends CoreConfig
case class SmallCoreConfig(fpu:Boolean) extends CoreConfig
case class CacheConfig(sets:Int, ways:Int)
case class TileConfig(cc:CoreConfig, icc:CacheConfig, dcc:CacheConfig)
class Tile (val tc:TileConfig) extends Module {
  val core = tc.cc match {
    case bcc:BigCoreConfig => Module(new BigCore(bcc))
    case scc:SmallCoreConfig => Module(new SmallCore(scc))
  }
}
```
val icache = Module(new Cache(tc.icc))
val dcache = Module(new Cache(tc.dcc))

3.3 Location-Independent Parameters

Figure 6: For location-independent parameters, every module has a parameter dictionary, which they can copy and alter before passing to each child module.

The subtle reason why nested configuration objects are extremely brittle is the structure of the nested configuration objects encodes the module hierarchy. Given a new design described in Figure ??, we assume that BigCore’s IQ and LSQ, as well as the icache and dcache, instantiate a Memory module. This Memory module contains a width parameter, and in order for the design to function correctly, all of Memory widths must be set to the same value. To ensure this requirement, the follow code might be written:

```scala
case class MemConfig(size:Int, banks:Int, width:Int)
case class CacheConfig(sets:Int, ways:Int, mc:MemConfig)
case class QueueConfig(depth:Int, mc:MemConfig)
case class BigCoreConfig(iqc:QueueConfig, lsqc:QueueConfig, mc:MemConfig)
case class TileConfig(cc:CoreConfig, icc:CacheConfig, dcc:CacheConfig)
class Tile { val core = cc match {
  case bcc:BigCoreConfig => Module(new BigCore(bcc))
  case scc:SmallCoreConfig => Module(new SmallCore(scc))
}
val icache = Module(new Cache(icc)
val dcache = Module(new Cache(dcc))
require(dcc.mc.width == icc.mc.width)
require(bcc.iqc.mc.width == bcc.lsqc.mc.width)
require(dcc.mc.width == bcc.lsqc.mc.width)
...}
```

The series of require statements is extremely brittle, as any change in our design’s hierarchy requires massive rewrites of all of these statements. Omitting the require statements is not a viable option; these statements are necessary to enforce this fundamental design requirement.

This flaw in configuration objects leads us towards the first functionality of our custom parameterization solution, namely a copy/alter dictionary of type Parameters. We use this key-value structure (map or dictionary) to store a module’s parameters.

To parameterize the design in Figure ??, we implicitly pass the Parameters object and, if an alter is needed, provide a `PartialFunction` to the `Module` factory. Recall from Section ?? that the class `MyConfig` (extends `ChiselConfig`) must be passed to the `Chisel` compiler via the `--configInstance` flag to seed the top-level parameters:

```scala
case class DefaultConfig() extends ChiselConfig {
  val top:World.TopDefs = {
    (pname,site,here) => pname match {
      case IQ_depth => 10
      case LSQ_depth => 10
      case Ic_sets => 128
      case Ic_ways => 2
      case Dc_sets => 512
      case Dc_ways => 4
      case Width => 64
        // since any module querying Width should return 64, the name should NOT be unique to modules
    }
  }...
}
class Tile { val core = Module(new Core)(params)
  val ic_sets = params(Ic_sets)
  val ic_ways = params(Ic_ways)
  val icache = Module(new Cache, {case Sets => ic_sets;
    case Ways => ic_ways})
  ...
}
```

6
// we can rename Ic_sets to Sets, effectively
isolating Cache's query keys from any design
hierarchy dependence
val dc_sets = params(Dc_sets)
val dc_ways = params(Dc_ways)
val dcache = Module(new Cache, {case Sets => dc_sets;
   case Ways => dc_ways})
// similarly we rename Dc_sets to Sets and Dc_ways to
Ways
}
class Core extends Module {
val iqdepth = params(IQ_depth)
val iq = Module(new Queue, {case Depth => iqdepth})
val lsqdepth = params(LSQ_depth)
val lsq = Module(new Queue, {case Depth => lsqdepth})
...
}
class Queue extends Module {
val depth = params(Depth)
val mem = Module(new Memory,{case Size => depth})
...
}
class Cache extends Module {
val sets = params(Sets)
val ways = params(Ways)
val mem = Module(new Memory,{case Size => sets*ways})
}
class Memory extends Module {
val size = params(Size)
val width = params(Width)
}

Although this parameterization method is rea-
sonably verbose, it scales well with adding parame-
ters, requires no source changes, and allows a single
parameter, such as width, to change all leaf modules.

3.4 Location-Specific Parameters

As we saw in the previous section, copying and
altering a Parameters object can be verbose. If we
wanted to add an ECC parameter to our Memory mod-
ule, which depends on where the Memory is instan-
tiated, we would change source code in multiple
parents to rename each parameter (e.g. ECC_iocache
=> ECC).

In the example depicted in Figure 7, we instead
use the site functionality of our Parameters object
to obtain location-specific information, and tailor
the value we return to that location-specific value.
After adding the location-specific information, we
drastically reduce the amount of code changes nec-

Figure 7: For location-dependent parameters, we
can use the site mechanism to customize these pa-
rameters at the top level.

case 'd' => 512
}
case Ways => site(Cache.type) match {
   case 'i' => 2
   case 'd' => 4
}
case Width => 64
// since any module querying Width should return 64, the name should NOT be
unique to modules
case ECC => site(Location) match {
   'incore' => false
   'incache' => true
}
}
}
class Tile (val params:Parameters) extends Module {
   val core = Module(new Core,(Location => 'incore'))
   // we can give core and its child modules a location
dentifier
   val cacheparams = params.alter({Location => 'incache'})
   // we can give both caches and all their child
modules a location identifier
   val icache = Module(new ICache)(cacheparams)
   val dcache = Module(new DCache)(cacheparams)
}
class Core extends Module {
    val iq = Module(new IQ)
    val lsq = Module(new LSQ)
    ...
}
class IQ extends Module {
    val depth = params(Depth)
    val mem = Module(new Memory, {Size = depth})
    // in some cases, using copy/alter is preferred
    // instead of `site` (see Design Heuristics
    // for more details)
    ...
} class LSQ extends Module {
    val depth = params(Depth)
    val mem = Module(new Memory, {Size = depth})
    ...
} class ICache extends Module {
    val sets = params(Sets)
    val ways = params(Ways)
    val mem = Module(new Memory, {Size => sets*ways})
} class DCache extends Module {
    val sets = params(Sets)
    val ways = params(Ways)
    val mem = Module(new Memory, {Size => sets*ways})
} class Memory extends Module {
    val size = params(Size)
    val ecc = params(ECC)
}

3.5 Derivative Parameters

In Figure 8, we always want our ROB to be four-thirds the size of the difference between the number of physical registers and the number of architectural registers. If we express this in MyConfig.top, it could look like the following:

case object NUM.arch.reg extends Field[Int]
case object NUM.phy.reg extends Field[Int]
case object ROB.size extends Field[Int]
class DefaultConfig() extends ChiselConfig {
    val top:World.TopDefs = {
        (pname,site,here) => pname match {
            case NUM.arch.reg => 32
            case NUM.phy.reg => 64
            case ROB.size => 4*(here(NUM.phy.reg) - here(NUM.arch.reg))/3
        } ...
    }
}

However, if we later increase the number of physical registers, we need to remember to update the value in the derivation of the ROB size. To avoid this potential error, one should use the ‘here’ functionality to query the same group of parameters:

class DefaultConfig() extends ChiselConfig {
    val top:World.TopDefs = {
        (pname,site,here) => pname match {
            case NUM.arch.reg => 32
            case NUM.phy.reg => 64
            case ROB.size => 4*(here(NUM.phy.reg) - here(NUM.arch.reg))/3
        } ...
    }
}

3.6 Renaming Parameters

In Figure 9, both cache modules query for a sets parameter. However, Tile has ic_sets and dc_sets as parameters. To rename the parameters, we can read the parent value and alter the child’s Parameters object:

class Tile extends Module {
    val ic_sets = params(Ic_sets)
    val ic = Module(new Cache, {case Sets => ic_sets})
}
val dc_sets = params(Ic_sets)
val dc = Module(new Cache,{case Sets => dc_sets})
...

Alternatively, we can use the 'up' mechanism within the Parameters.alter method to query the parent module’s Parameter object:

class Tile extends Module {
  val ic_params = params.alter(
    (pname,site,here,up) => pname match {
      case Sets => up(Ic_sets)
    }
  )
  val ic = Module(new Cache)(ic_params)
...
}

In general one should never use the up mechanism as it is more verbose. However, it can be useful if the parent is making significant changes to a child’s Parameters object, as all changes can be contained the Parameter.alter method because one has access to all three central mechanisms (up, site, and here).

4 External Interface

So far, this document has only describe mechanisms to manipulate parameters at a top-level class (ChiselConfig). However, to actually generate multiple C++ or Verilog designs, we need to manually change these parameters.

One would prefer to express design constraints (parameter ranges, dependencies, constraints) and leave the actual instantiation of a specific design separate from the expression of the valid design space.

With that motivation, Chisel has an additional feature based around the concept of “Knobs,” or parameters that are created specifically to explore a design space. This section will describe Knobs and their uses, the Dump Object, adding constraints to parameters/Knobs, and the two modes to running the Chisel compiler: –configCollect and –configInstance.

4.1 Knobs

A generator has some parameters that are fixed, and others that dictate the specific design point being generated. These generator-level parameters, called Knobs, have an additional key-value mapping to allow external programs and users to easily overwrite their values.

Knobs can only be instantiated within a ChiselConfig subclass’s topDefinitions:

```scala
package example
class MyConfig extends ChiselConfig {
  val topDefinitions:World.TopDefs = {
    (pname,site,here) => pname match {
      case NTiles => Knob('NTILES')
      case .... => .... // other non-generator parameters go here
    }
  }
  override val knobValues:Any=>Any = {
    case 'NTILES' => 1 // generator parameter assignment
  }
}
```

When the query NTiles matches within topDefinitions, the Knob('NTILES') is returned. Internally, Chisel will lookup 'NTILES' within MyConfig.knobValues and return 1. As described in Section ??, the flag required to execute a generator with this specific config is:

```sh
sbt run ... --configInstance example.MyConfig
```

Suppose we wanted to instantiate a new design that had two tiles: simply use Scala's class inheritance and overwrite the knobValues method:

```scala
package example
class MyConfig2 extends MyConfig {
  override val knobValues:Any=>Any = {
    case 'NTILES' => 2 // will generate new design with 2 tiles
  }
}
```

Notice that both classes can exist in the source code, so both designs can be instantiated from the commandline. For the new design with two tiles, simply call:

```sh
sbt run ... --configInstance example.MyConfig2
```

4.2 Dump

Downstream from Chisel, other tools might need to know specific parameter/Knob assignments. If so, just pass the Knob/value to the Dump object, which will write the name and value to a file, then return the Knob/value:

```scala
package example
class MyConfig extends ChiselConfig {
  val topDefinitions:World.TopDefs = {
    (pname,site,here) => pname match {
      case Width => Dump('Width',64) // will return 64.
      case NTiles => Dump(Knob('NTILES')) // will return Knob('NTILES'), no name needed
    }
  }
  override val knobValues:Any=>Any = {
    case 'NTILES' => 1 // generator parameter assignment
  }
}
```
The name and value of each dumped parameter will be written to a *knb file located in the directory set by --targetDir path.

4.3 Constraints

Now that external programs/users can easily overwrite a configuration’s knobValue method, we have provided a mechanism for defining legal ranges for Knobs. Within a ChiselConfig, one can overwrite another method called topConstraints:

```scala
package example
class MyConfig extends ChiselConfig {
  val topDefinitions:World.TopDefs = {
    (pname,site,here) => pname match {
      case NTiles => Knob('NTILES')
    }
  }
  override val topConstraints:List[ViewSym=>Ex[Boolean]] = List( { ex => ex(NTiles) > 0 }, { ex => ex(NTiles) <= 4 })
  override val knobValues:Any=>Any = {
    case 'NTILES' => 1 // generator parameter assignment
  }
}
```

Now, if someone tried to instantiate our design with the following configuration and command, it would fail:

```scala
package example
class BadConfig extends ChiselConfig {
  override val knobValues:Any=>Any = {
    case 'NTILES' => 5 // would violate our constraint, throws an error
  }
}
```

// throws 'Constraint failed' error
sbt run ... --configInstance example.BadConfig

Constraints can be declared anywhere in the design, not just at the top level, by calling a Parameter’s constrain method:

```scala
package example
class MyConfig extends ChiselConfig {
  val topDefinitions:World.TopDefs = {
    (pname,site,here) =>pname match {
      case NTiles => Knob('NTILES')
    }
  }
  override val knobValues:Any=>Any = {
    case 'NTILES' => 1 // generator parameter assignment
  }
}
```

```scala
class Tile extends Module {
  params.constrain( ex => ex(NTiles) > 0 )
  params.constrain( ex => ex(NTiles) <= 4 )
}
```

```scala
object Run {
  def main(args: Array[String]): Unit = {
    chiselMain.run(args, () => new Tile())
  }
}
```

5 Design Heuristics

TODO

References

