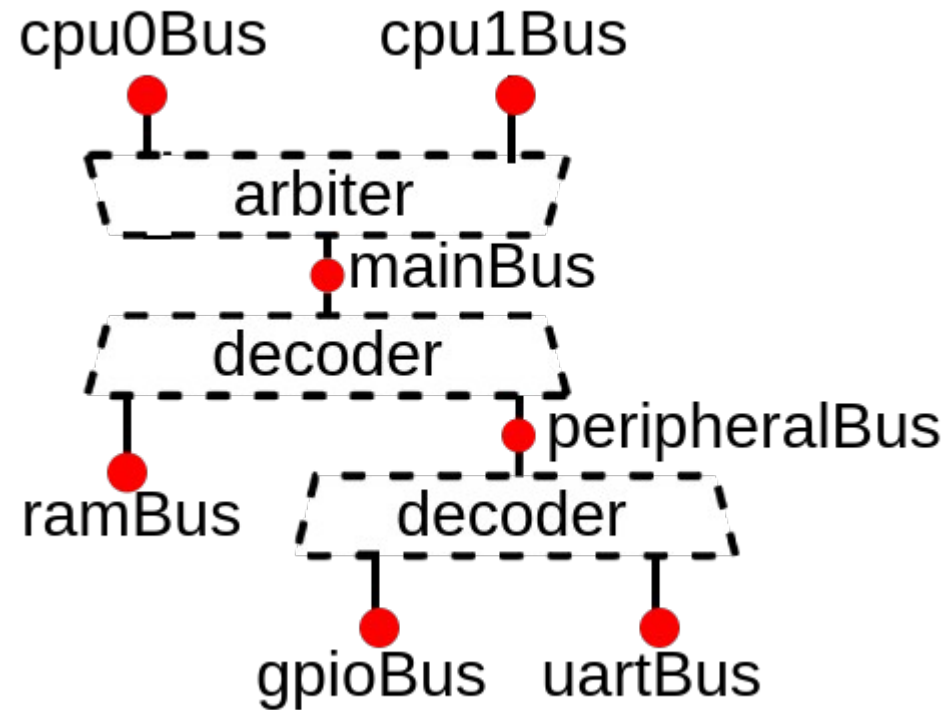


A progressive introduction to memory bus interconnect API in Software-Defined Hardware



Wire sea

```
wire      [19:0]  apb_PADDR;  
wire      [0:0]  apb_PSEL;  
wire      apb_PENABLE;  
wire      apb_PREADY;  
wire      apb_PWRITE;  
wire      [31:0] apb_PWDATA;  
wire      [31:0] apb_PRDATA;
```

Wire sea

```
wire      [19:0]  apb_PADDR;
wire      [0:0]   apb_PSEL;
wire      apb_PENABLE;
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wire      [31:0]  apb_PWDATA;
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```

```
wire      axi_awvalid;
wire      axi_awready;
wire      [19:0]  axi_awaddr;
wire      [3:0]   axi_awid;
wire      [7:0]   axi_awlen;
wire      [2:0]   axi_awsiz;
wire      axi_wvalid;
wire      axi_wready;
wire      [31:0]  axi_wdata;
wire      [3:0]   axi_wstrb;
wire      axi_wlast;
wire      axi_bvalid;
wire      axi_bready;
wire      [3:0]   axi_bid;
wire      [1:0]   axi_bresp;
wire      axi_arvalid;
wire      axi_arready;
wire      [19:0]  axi_araddr;
wire      [3:0]   axi_arid;
wire      [7:0]   axi_arlen;
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wire      axi_rvalid;
wire      axi_rready;
wire      [31:0]  axi_rdata;
wire      [3:0]   axi_rid;
wire      [1:0]   axi_rresp;
wire      axi_rlast;
```

Bus definition

```
case class Apb3(addressWidth: Int,  
                dataWidth : Int) extends Bundle with IMasterSlave {
```

```
  val PADDR      = UInt(addressWidth bits)
```

```
  val PSEL       = Bool()
```

```
  val PENABLE    = Bool()
```

```
  val PREADY     = Bool()
```

```
  val PWRITE     = Bool()
```

```
  val PWDATA     = Bits(dataWidth bits)
```

```
  val PRDATA     = Bits(dataWidth bits)
```

```
  override def asMaster(): Unit = {  
    out(PADDR, PSEL, PENABLE, PWRITE, PWDATA)  
    in(PREADY, PRDATA)
```

```
  }
```

```
}
```

```
val myBus = Apb3(20, 32)
```

```
val myBus = Apb3(  
  addressWidth = 20,  
  dataWidth    = 32  
)
```

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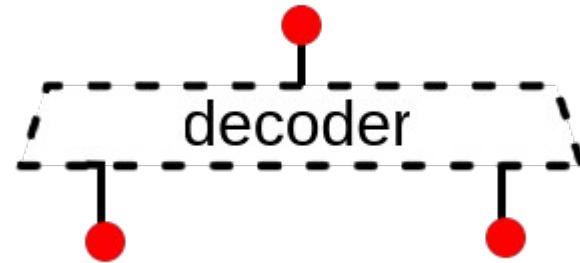
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Software API

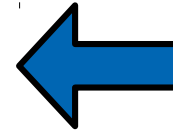
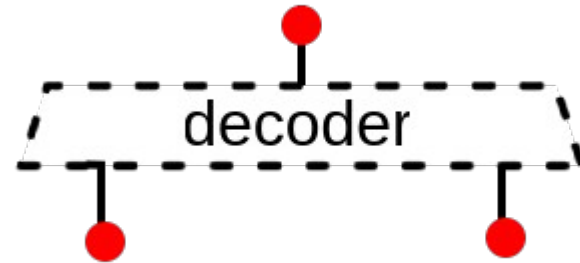
```
val commonBus = Apb3(20, 32)
```



```
val uartBus = Apb3(12, 32)    val gpioBus = Apb3(12, 32)
```

Software API

```
val commonBus = Apb3(20, 32)
```

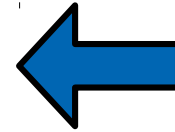
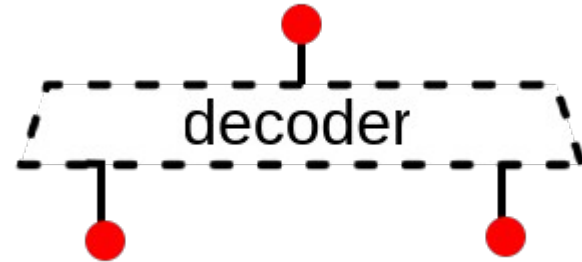


```
val apbDecoder = Apb3Decoder(  
    master = commonBus,  
    slaves = List(  
        gpioBus -> (0x2000, 4 kB),  
        uartBus -> (0x5000, 4 kB)  
    )  
)
```

```
val uartBus = Apb3(12, 32)    val gpioBus = Apb3(12, 32)
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Software API

```
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```

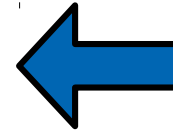
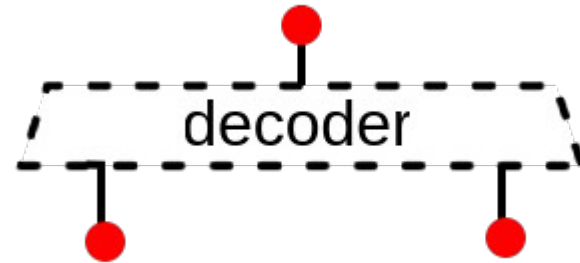


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Software API

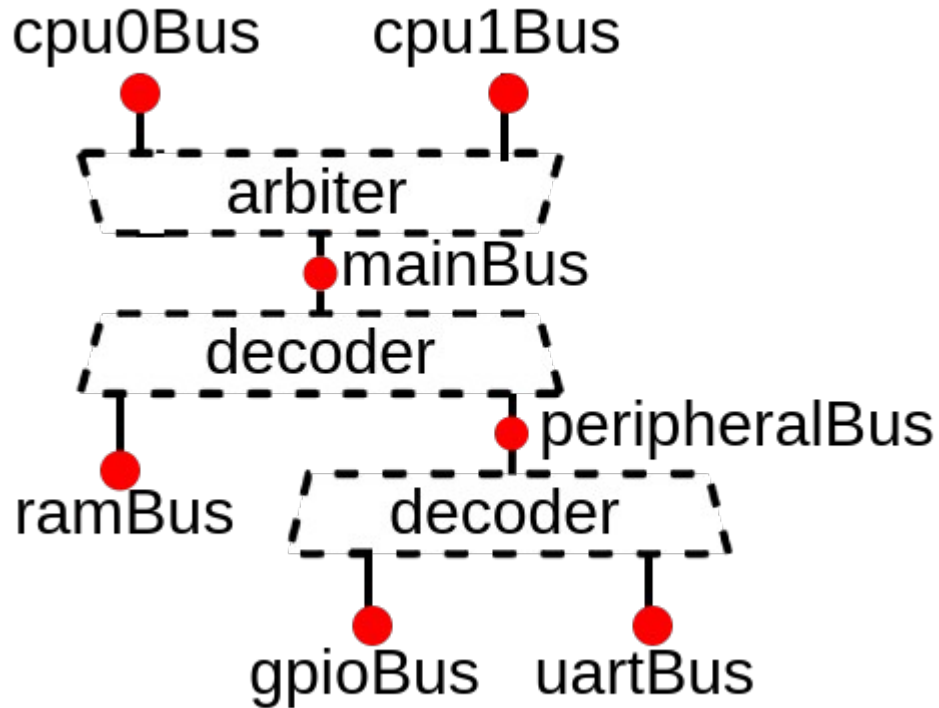
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```



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    )  
)
```

```
val uartBus = Apb3(12, 32)    val gpioBus = Apb3(12, 32)
```

Automation



```
val cpu0Bus, cpu1Bus = Axi4(32, 32, 2)
val mainBus          = Axi4(32, 32, 4)
val ramBus           = Axi4(16, 32, 6)
val peripheralBus     = Axi4(20, 32, 6)
val gpioBus, uartBus = Axi4(12, 32, 8)
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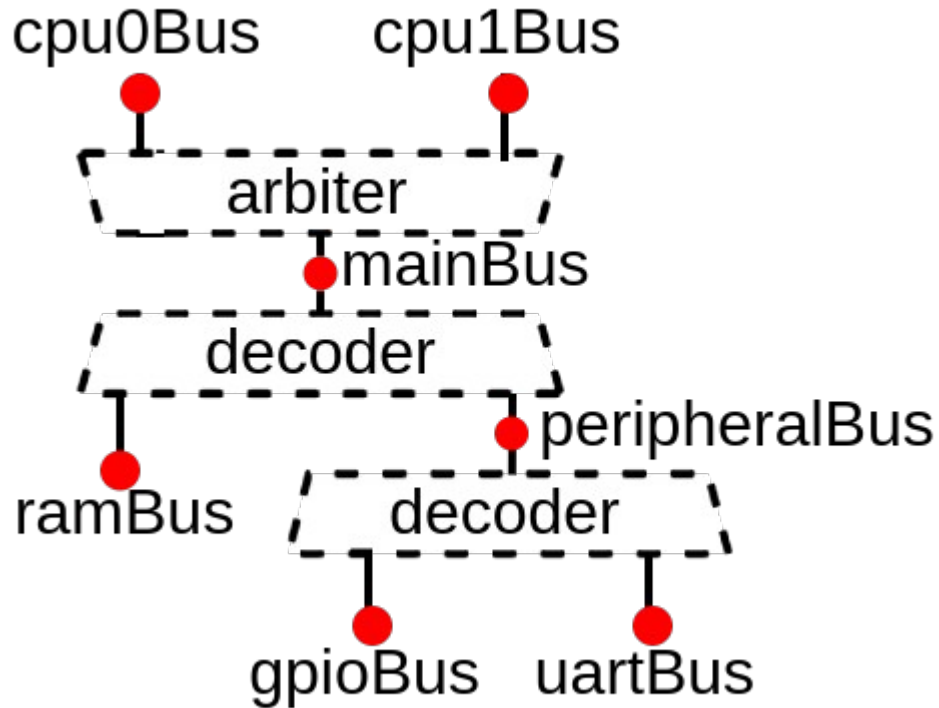
```
val axiCrossbar = Axi4CrossbarFactory()
```

```
axiCrossbar.addSlaves(
  mainBus      -> (0x00000000, 4 GB),
  ramBus       -> (0x80000000, 64 kB),
  peripheralBus -> (0x10000000, 1 MB),
  gpioBus      -> ( 0x2000, 4 kB),
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)
```

```
axiCrossbar.addConnections(
  cpu0Bus      -> List(mainBus),
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  mainBus      -> List(ramBus, peripheralBus),
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)
```

```
axiCrossbar.build()
```

Automation



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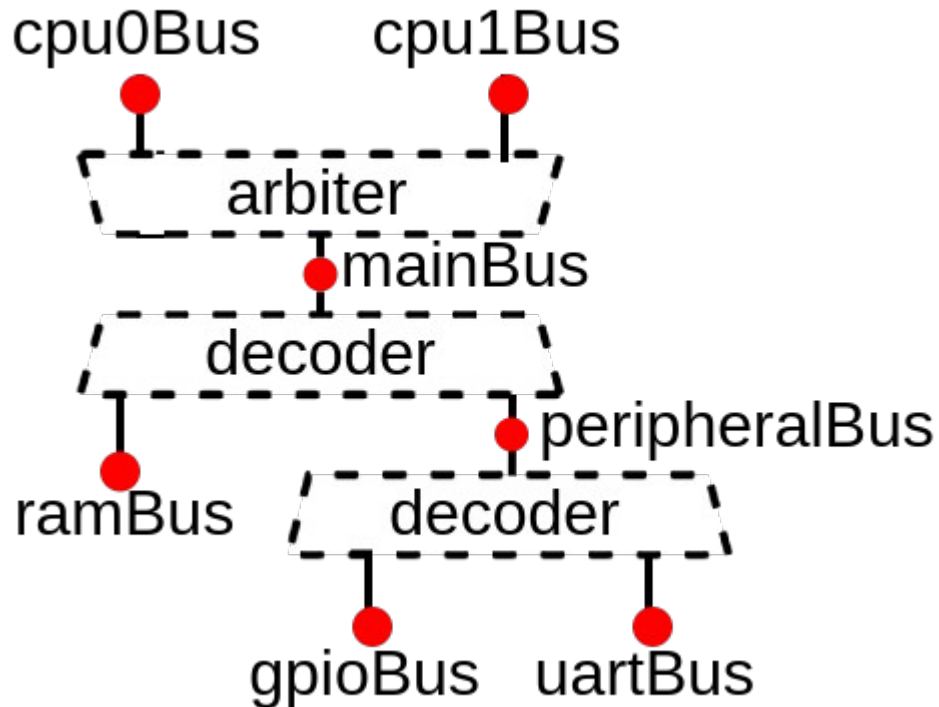
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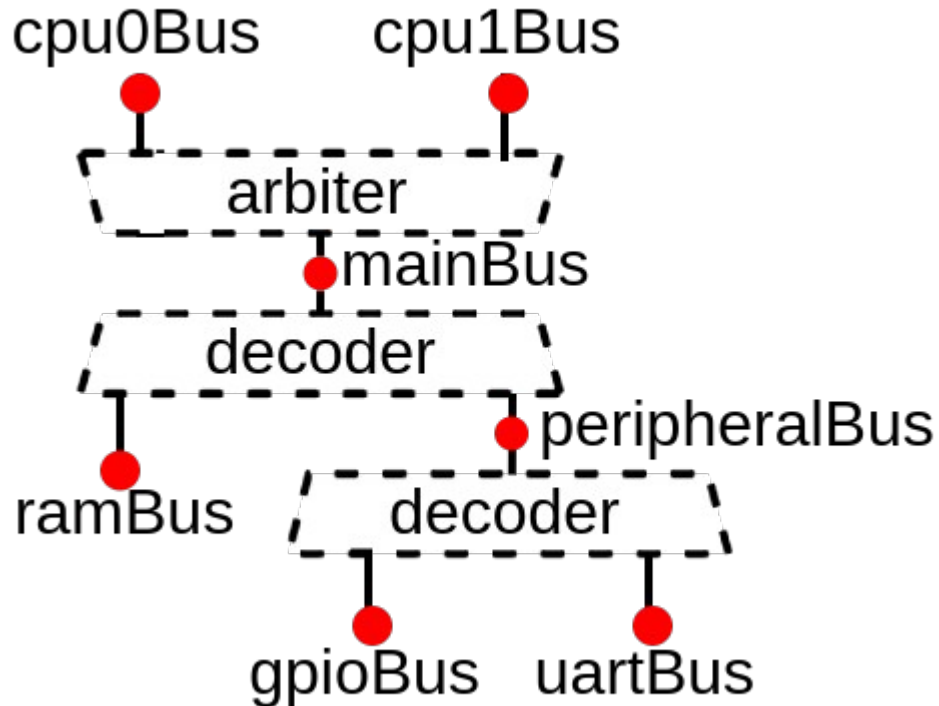
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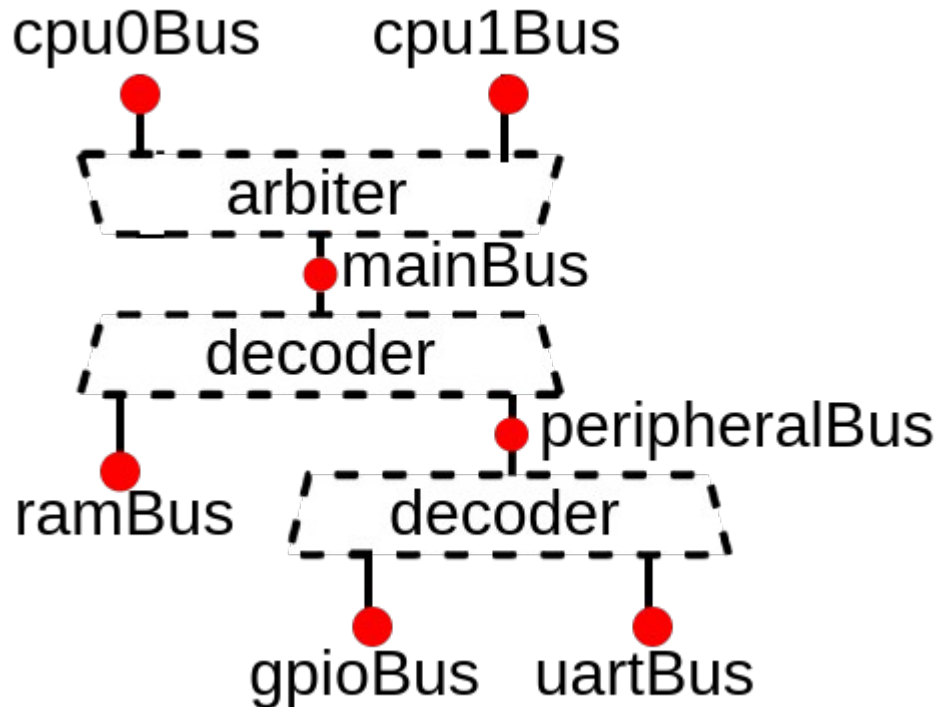
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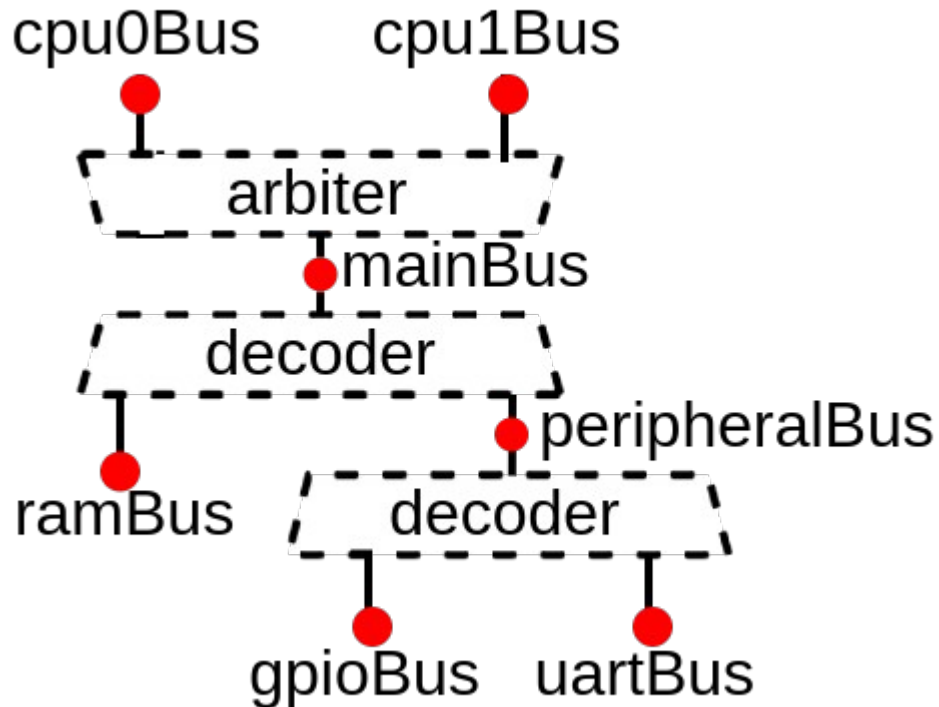
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Issues

- Centralized monolith
 - (You better be happy with what you get)
- No parameter negotiation / propagation
 - Data width
 - Address width
 - Type of accesses (read / write / atomic / ...)
 - ID width
 - ID to master mapping (Tilelink)
- Lack of awareness
 - Memory mapping from a given master perspective
 - Physical memory attributes

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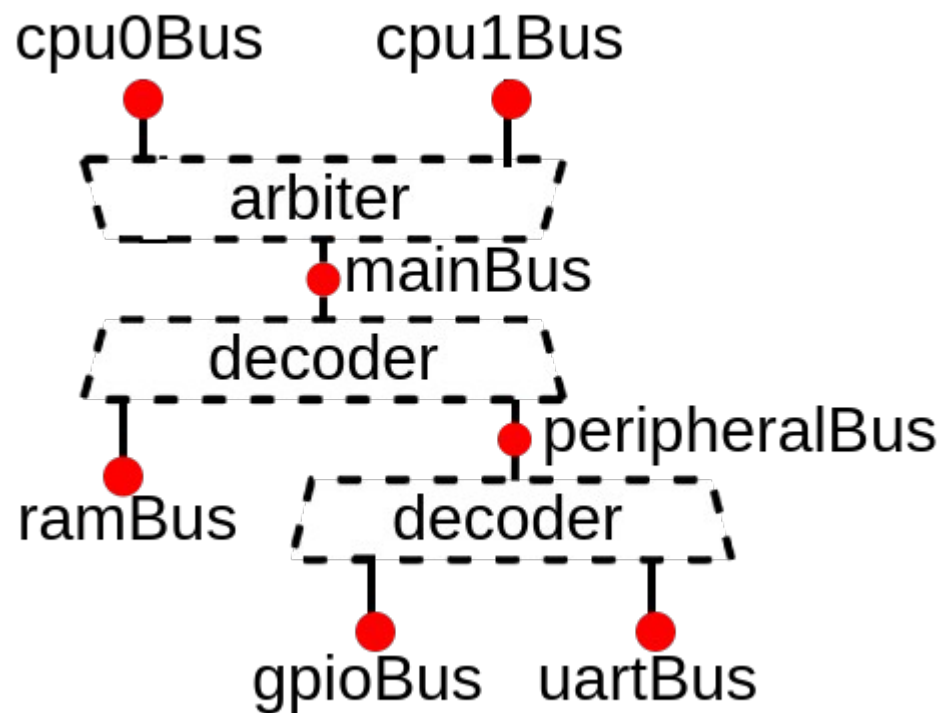
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Decentralization

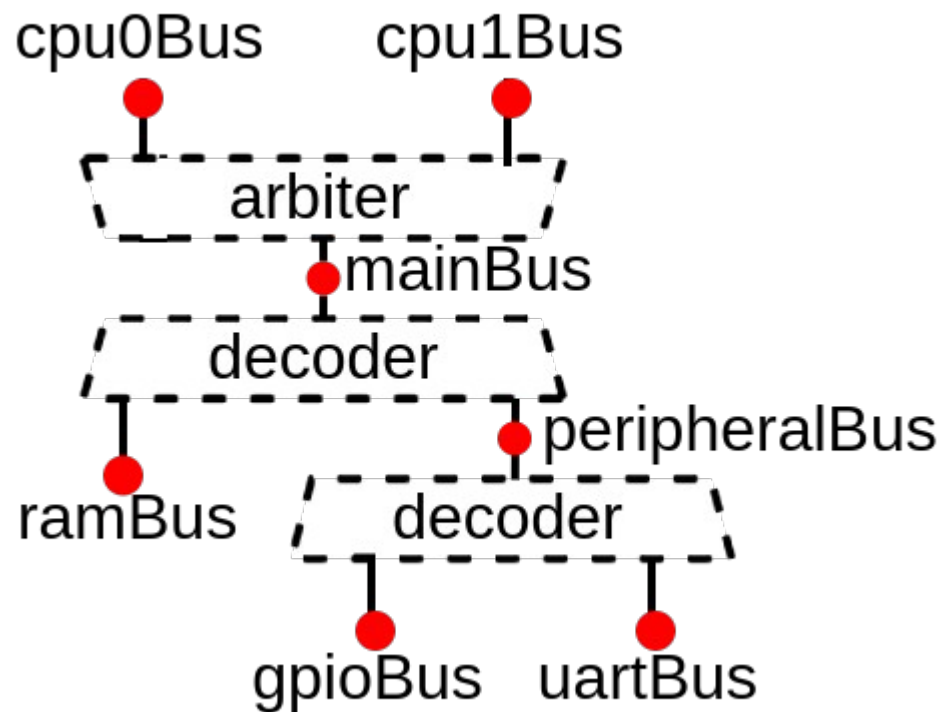


```
import spinal.lib.bus.tilelink.fabric.Node
```

```
val cpu0Bus, cpu1Bus = Node()  
val mainBus          = Node()  
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val peripheralBus     = Node()  
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mainBus << List(cpu0Bus, cpu1Bus)  
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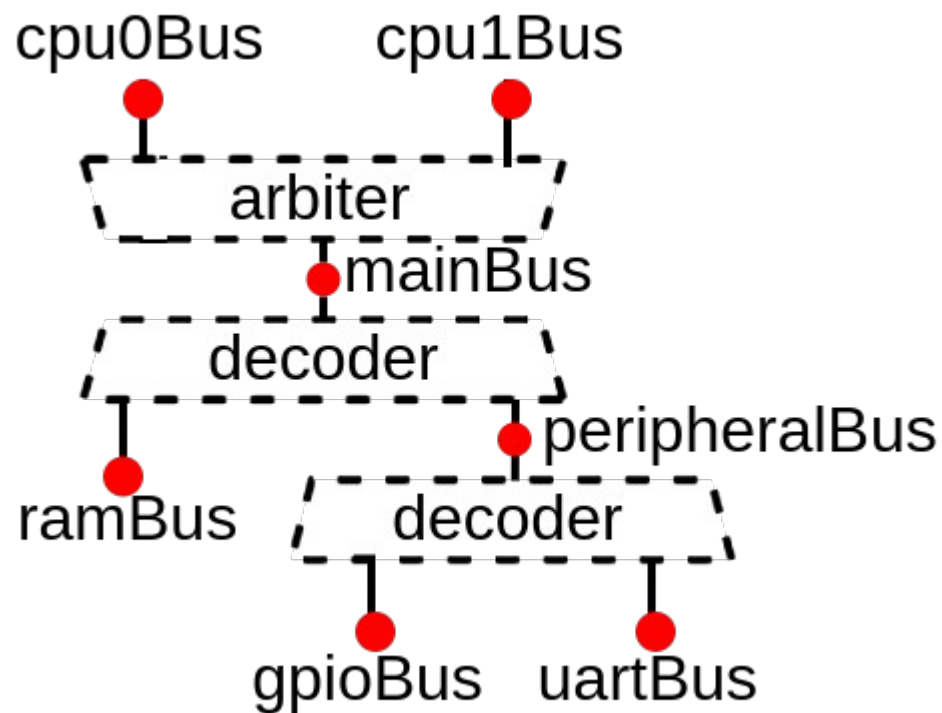


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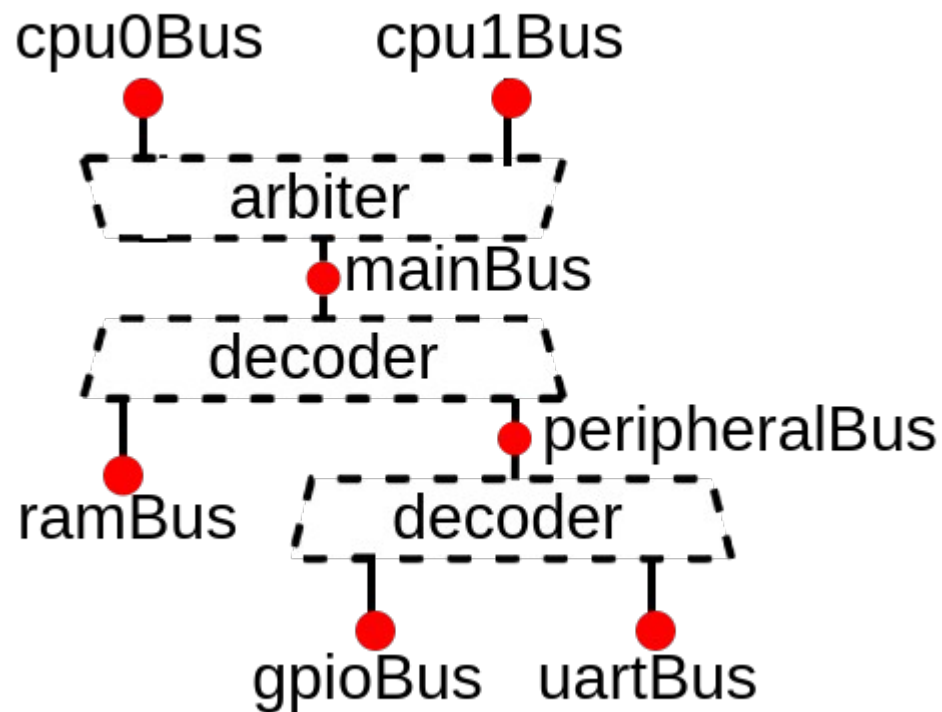


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Decentralization

```
class Node extends Area{
  // Node data model
  val bus    = Handle[tilelink.Bus]()
  val ups    = ArrayBuffer[Connection]()
  val downs  = ArrayBuffer[Connection]()

  //Fork an elaboration thread
  val thread = Fiber build new Area{
    // Generate the required arbiter / decoder logic.
  }
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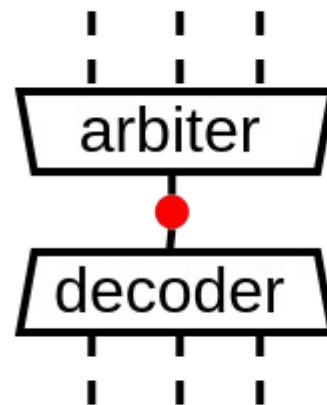
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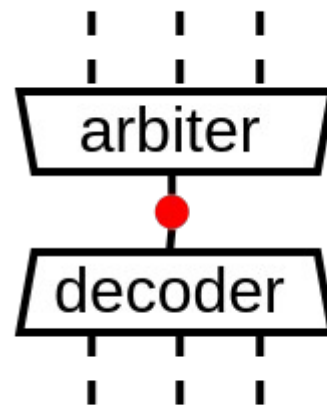
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  }  
}
```

```
class Connection(val m : Node, val s : Node){  
  val thread = Fiber build new Area{  
    // Connect the m.decoder to the s.arbiter  
  }  
}
```

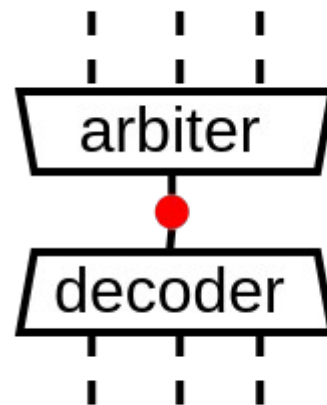



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class Connection(val m : Node, val s : Node){
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  }
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```



Future, Promise, Async, Fibers...

```
val bus = Handle[tilelink.Bus]
```

```
val thread1 = Fiber build new Area{  
  //Will wait on bus.load (from thread 2)  
  bus.a.valid    := False  
  bus.a.address := 42  
}
```

```
val thread2 = Fiber build new Area{  
  //Will allow thread 1 to continue  
  bus load tilelink.Bus(config)  
}
```

Future, Promise, Async, Fibers...

```
val bus = Handle[tilelink.Bus]
```

```
val thread1 = Fiber build new Area{  
  //Will wait on bus.load (from thread 2)  
  bus.a.valid    := False  
  bus.a.address := 42  
}
```

```
val thread2 = Fiber build new Area{  
  //Will allow thread 1 to continue  
  bus load tilelink.Bus(config)  
}
```

Future, Promise, Async, Fibers...

```
val bus = Handle[tilelink.Bus]
```

```
val thread1 = Fiber build new Area{  
  //Will wait on bus.load (from thread 2)  
  bus.a.valid    := False  
  bus.a.address := 42  
}
```

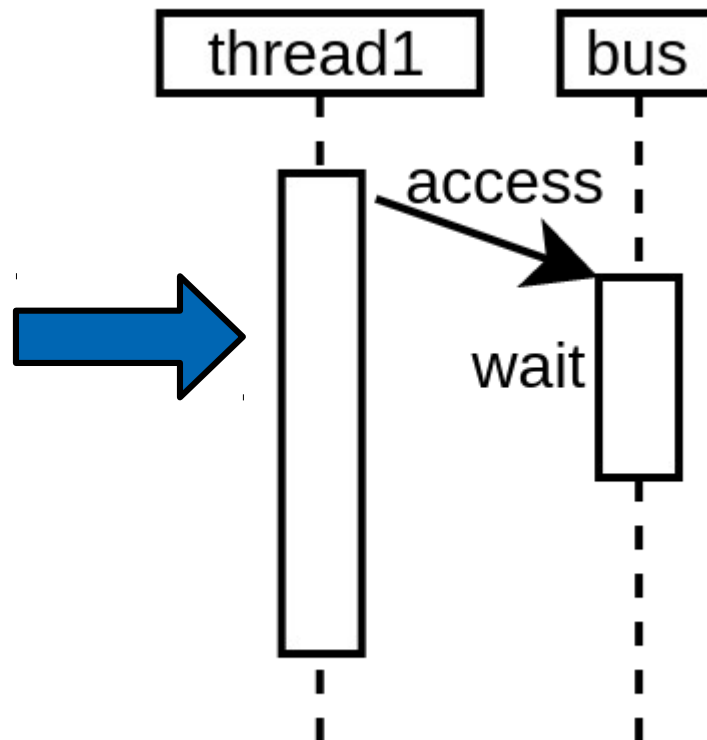
```
val thread2 = Fiber build new Area{  
  //Will allow thread 1 to continue  
  bus load tilelink.Bus(config)  
}
```

Future, Promise, Async, Fibers...

```
val bus = Handle[tilelink.Bus]
```

```
val thread1 = Fiber build new Area{  
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val thread2 = Fiber build new Area{  
  //Will allow thread 1 to continue  
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}
```

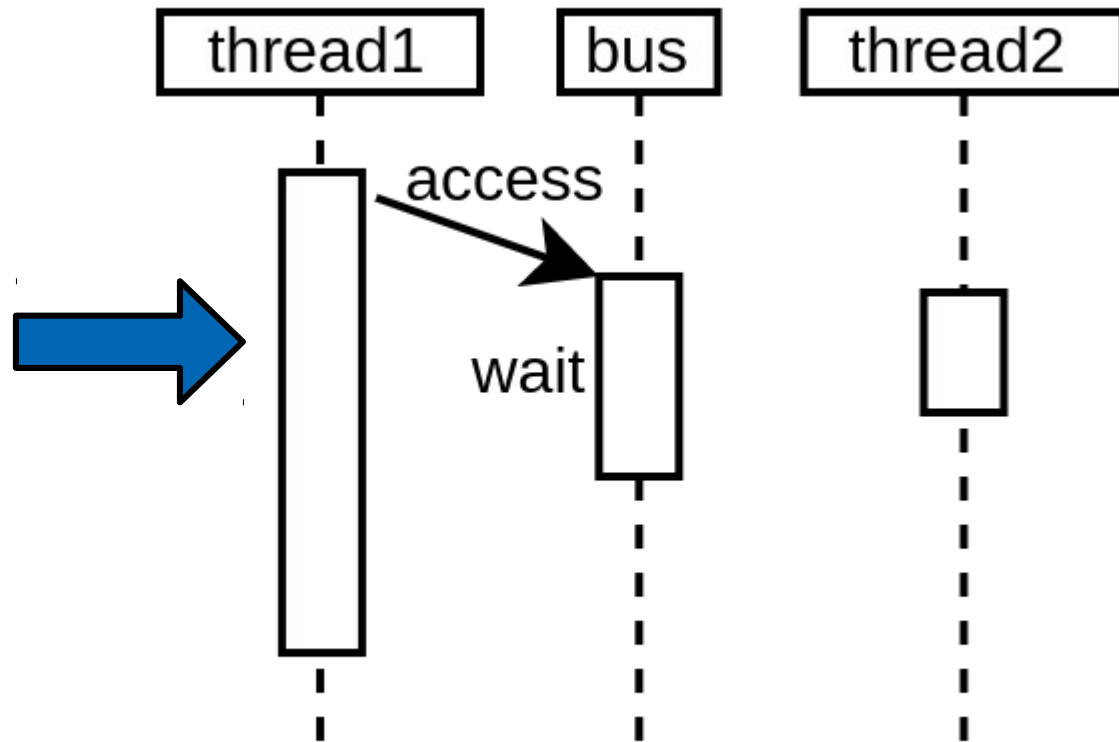


Future, Promise, Async, Fibers...

```
val bus = Handle[tilelink.Bus]
```

```
val thread1 = Fiber build new Area{  
  //Will wait on bus.load (from thread 2)  
  bus.a.valid    := False  
  bus.a.address  := 42  
}
```

```
val thread2 = Fiber build new Area{  
  //Will allow thread 1 to continue  
  bus load tilelink.Bus(config)  
}
```

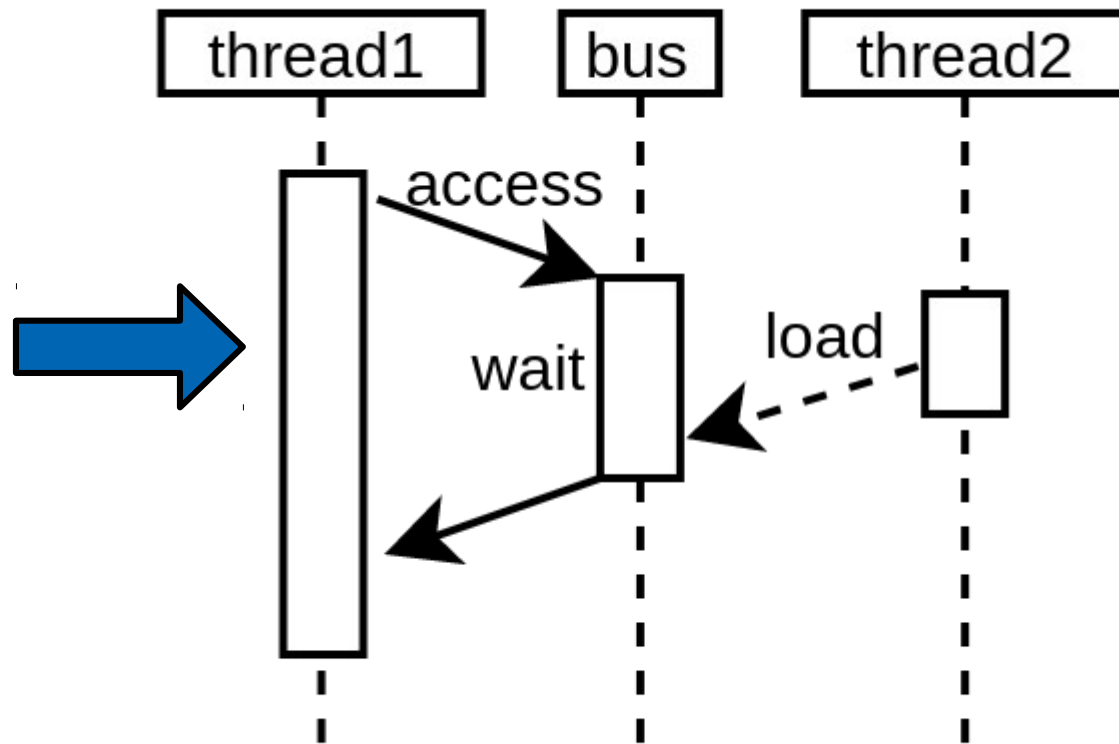


Future, Promise, Async, Fibers...

```
val bus = Handle[tilelink.Bus]
```

```
val thread1 = Fiber build new Area{  
  //Will wait on bus.load (from thread 2)  
  bus.a.valid    := False  
  bus.a.address  := 42  
}
```

```
val thread2 = Fiber build new Area{  
  //Will allow thread 1 to continue  
  bus load tilelink.Bus(...)  
}
```



Negotiation

```
class Node extends Area{
  // Node data model
  val proposed = Handle[M2sSupport]()
  val supported = Handle[M2sSupport]()
  val parameters = Handle[M2sParameters]()

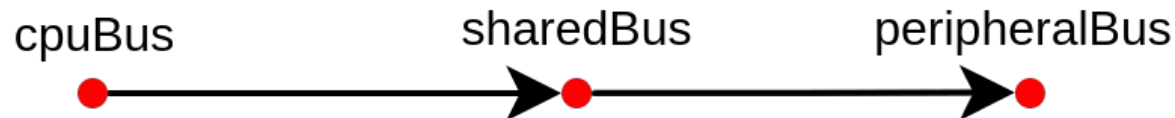
  //Fork an elaboration thread
  val thread = Fiber build new Area{
    // Do the Negotiation
    // Generate the required arbiter / decoder logic.
  }
}
```

Negotiation

```
class Node extends Area{
  // Node data model
  val proposed = Handle[M2sSupport]()
  val supported = Handle[M2sSupport]()
  val parameters = Handle[M2sParameters]()

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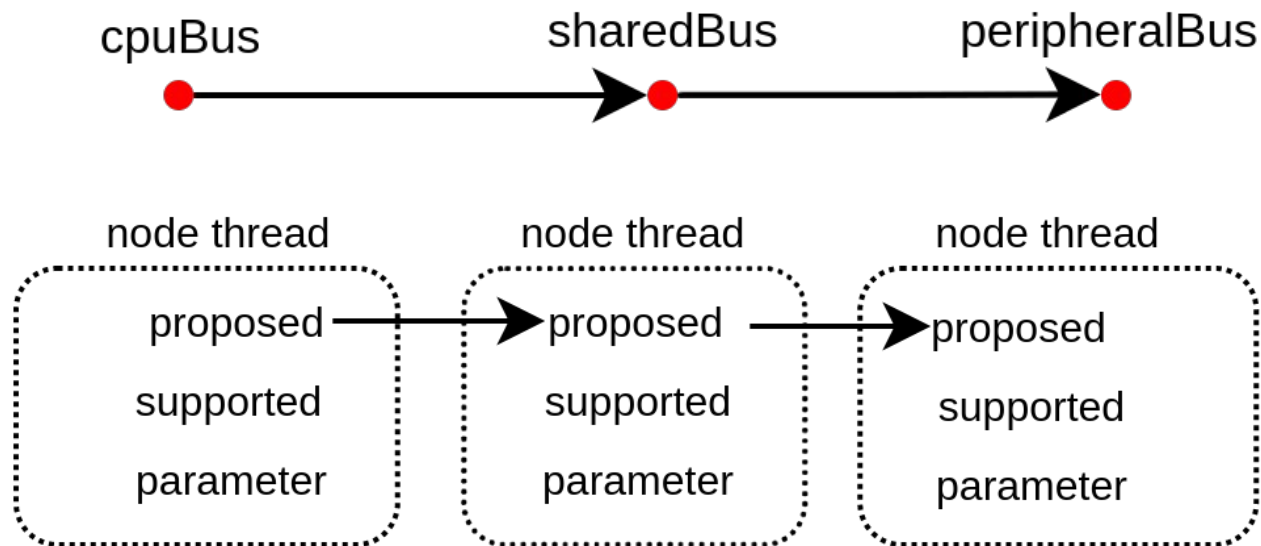

Negotiation



```
class Node extends Area{
  // Node data model
  val proposed = Handle[M2sSupport]()
  val supported = Handle[M2sSupport]()
  val parameters = Handle[M2sParameters]()

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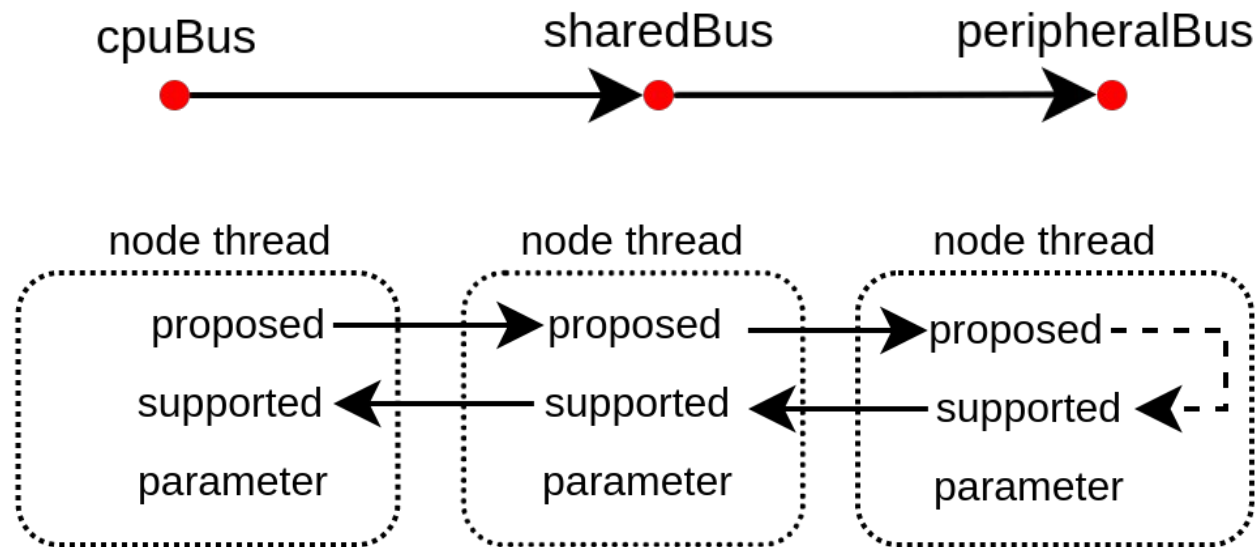
Negotiation



```
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  // Node data model
  val proposed = Handle[M2sSupport]()
  val supported = Handle[M2sSupport]()
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  //Fork an elaboration thread
  val thread = Fiber build new Area{
    // Do the Negotiation
    // Generate the required arbiter / decoder logic.
  }
}
```

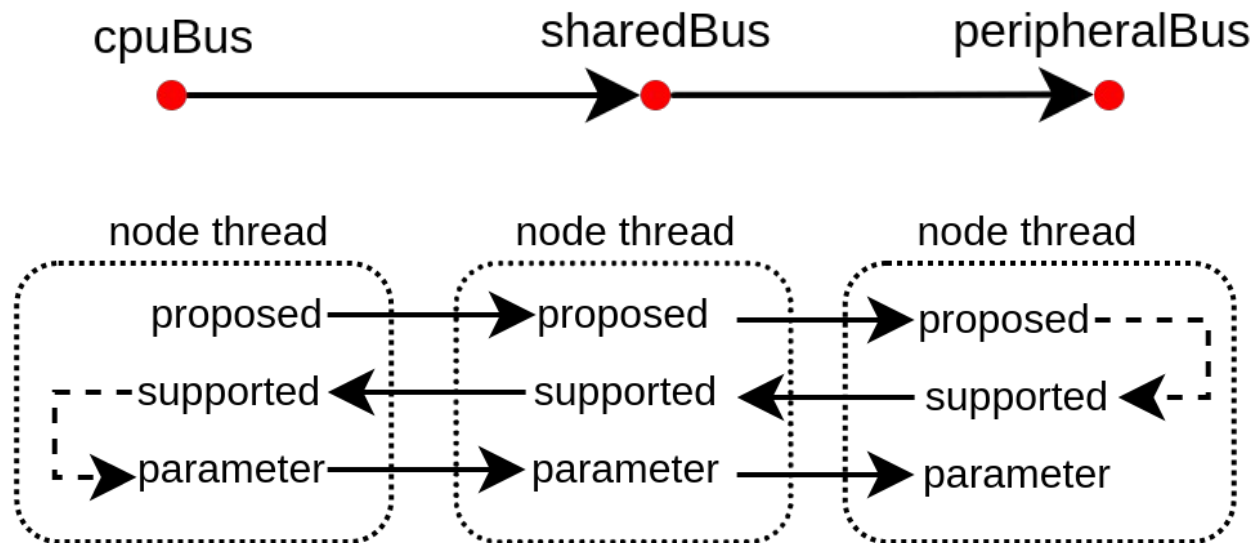
Negotiation



```
class Node extends Area{
  // Node data model
  val proposed = Handle[M2sSupport]()
  val supported = Handle[M2sSupport]()
  val parameters = Handle[M2sParameters]()

  //Fork an elaboration thread
  val thread = Fiber build new Area{
    // Do the Negotiation
    // Generate the required arbiter / decoder logic.
  }
}
```

Negotiation

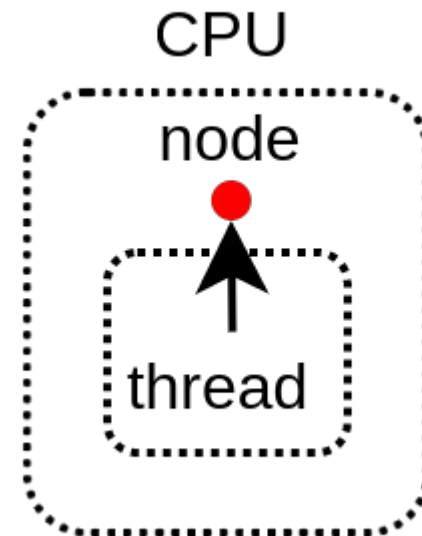


```
class Node extends Area{
  // Node data model
  val proposed = Handle[M2sSupport]()
  val supported = Handle[M2sSupport]()
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  //Fork an elaboration thread
  val thread = Fiber build new Area{
    // Do the Negotiation
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  }
}
```

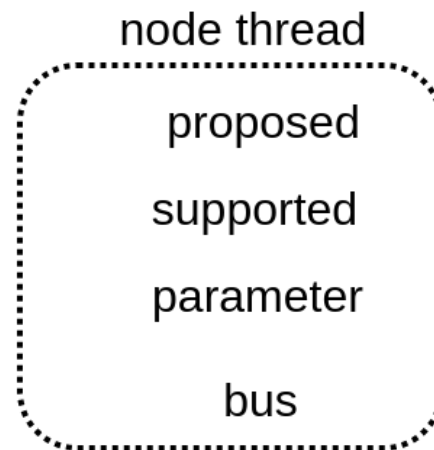
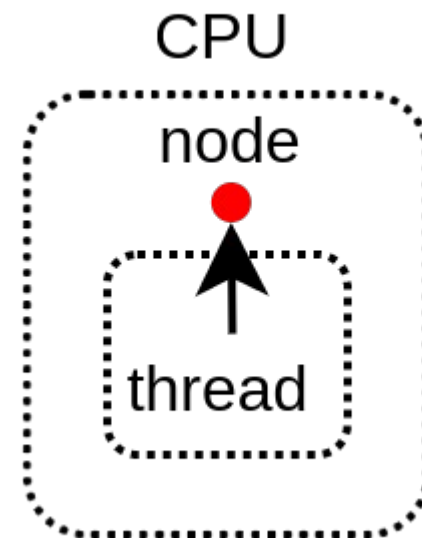
Master example

```
case class Cpu() extends Area {  
  val node = Node.master()  
  
  val thread = Fiber build new Area {  
    // Negotiate things  
    node.proposed load M2sSupport(  
      addressWidth = 32,  
      dataWidth = 64,  
      transfers = ...  
    )  
    node.parameters load M2sParameters(  
      support = node.supported,  
      sourceCount = 4  
    )  
  
    // Implement the actual CPU hardware  
    node.bus.a.valid := False  
    node.bus.a.address := 0x42  
  }  
}
```



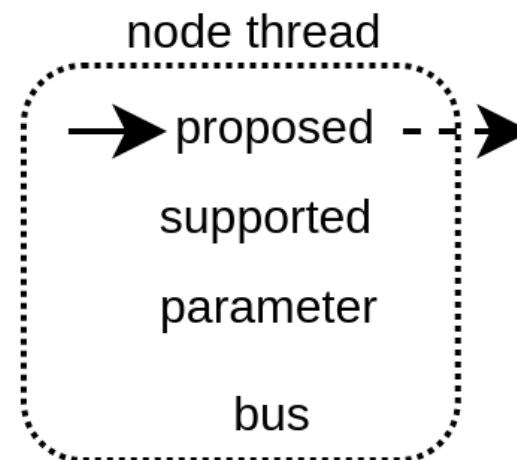
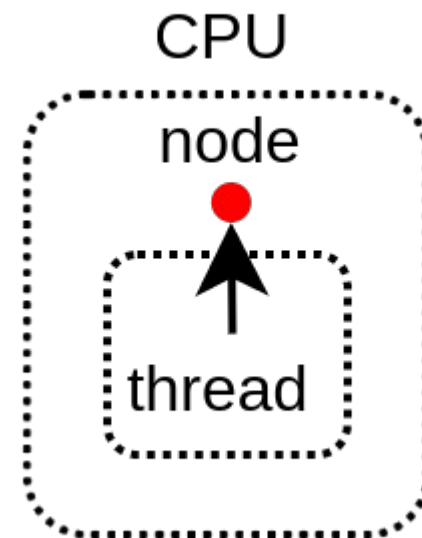
Master example

```
case class Cpu() extends Area {  
  val node = Node.master()  
  
  val thread = Fiber build new Area {  
    // Negotiate things  
    node.proposed load M2sSupport(  
      addressWidth = 32,  
      dataWidth = 64,  
      transfers = ...  
    )  
    node.parameters load M2sParameters(  
      support = node.supported,  
      sourceCount = 4  
    )  
  
    // Implement the actual CPU hardware  
    node.bus.a.valid := False  
    node.bus.a.address := 0x42  
  }  
}
```



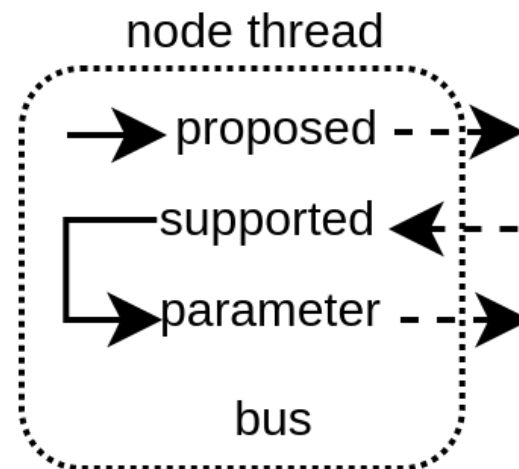
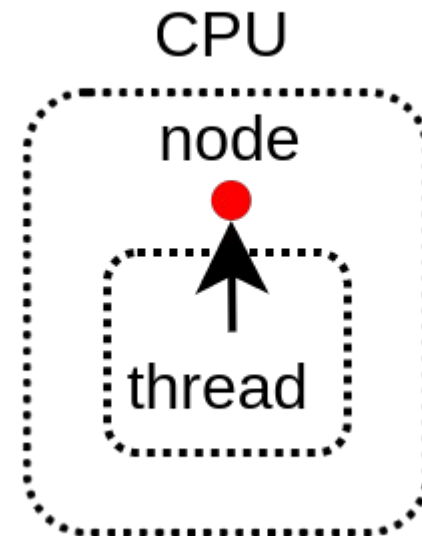
Master example

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case class Cpu() extends Area {  
  val node = Node.master()  
  
  val thread = Fiber build new Area {  
    // Negotiate things  
    node.proposed load M2sSupport(  
      addressWidth = 32,  
      dataWidth = 64,  
      transfers = ...  
    )  
    node.parameters load M2sParameters(  
      support = node.supported,  
      sourceCount = 4  
    )  
  
    // Implement the actual CPU hardware  
    node.bus.a.valid := False  
    node.bus.a.address := 0x42  
  }  
}
```



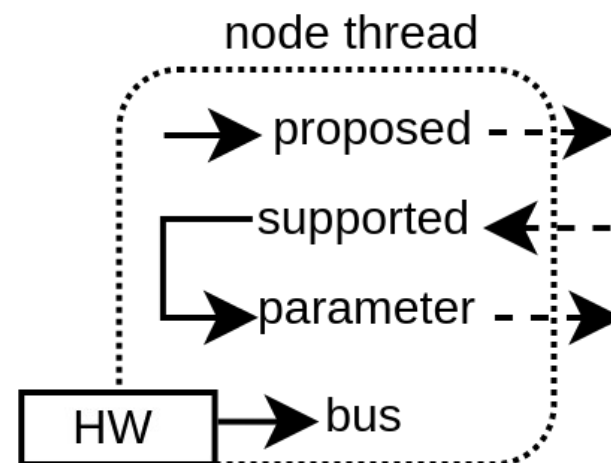
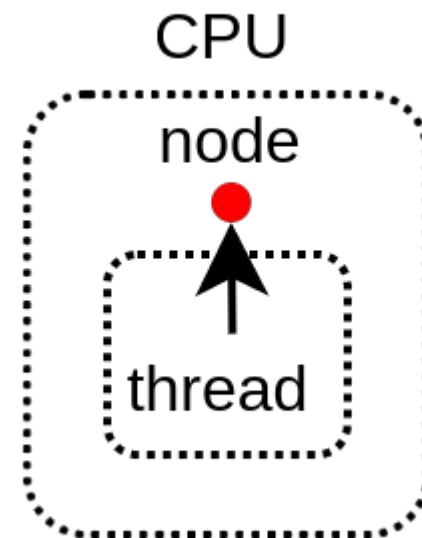
Master example

```
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  val node = Node.master()  
  
  val thread = Fiber build new Area {  
    // Negotiate things  
    node.proposed load M2sSupport(  
      addressWidth = 32,  
      dataWidth = 64,  
      transfers = ...  
    )  
    node.parameters load M2sParameters(  
      support = node.supported,  
      sourceCount = 4  
    )  
  }  
  
  // Implement the actual CPU hardware  
  node.bus.a.valid := False  
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}
```



Master example

```
case class Cpu() extends Area {  
  val node = Node.master()  
  
  val thread = Fiber build new Area {  
    // Negotiate things  
    node.proposed load M2sSupport(  
      addressWidth = 32,  
      dataWidth = 64,  
      transfers = ...  
    )  
    node.parameters load M2sParameters(  
      support = node.supported,  
      sourceCount = 4  
    )  
  }  
  
  // Implement the actual CPU hardware  
  node.bus.a.valid := False  
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}
```



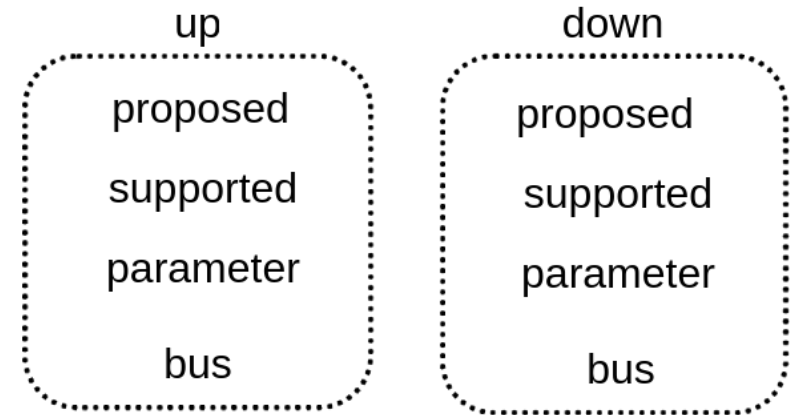
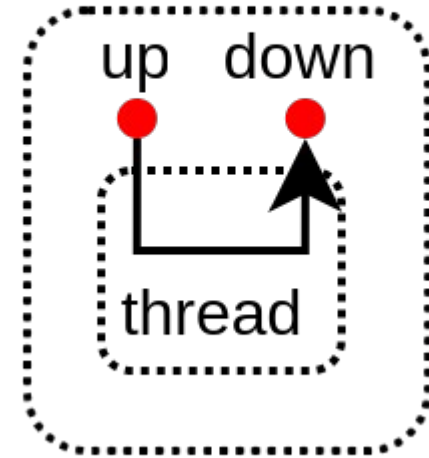
Adapter example

```
class WidthAdapter() extends Area{
  val up = Node.slave()
  val down = Node.master()

  val thread = Fiber build new Area{
    down.proposed load up.proposed
    up.supported load down.supported.copy(
      dataWidth = up.proposed.dataWidth
    )
    down.parameters load up.parameters.copy(
      dataWidth = down.supported.dataWidth
    )
  }

  val bridge = new WidthAdapterHw(up.bus.p, down.bus.p)
  bridge.io.up << up.bus
  bridge.io.down >> down.bus
}
```

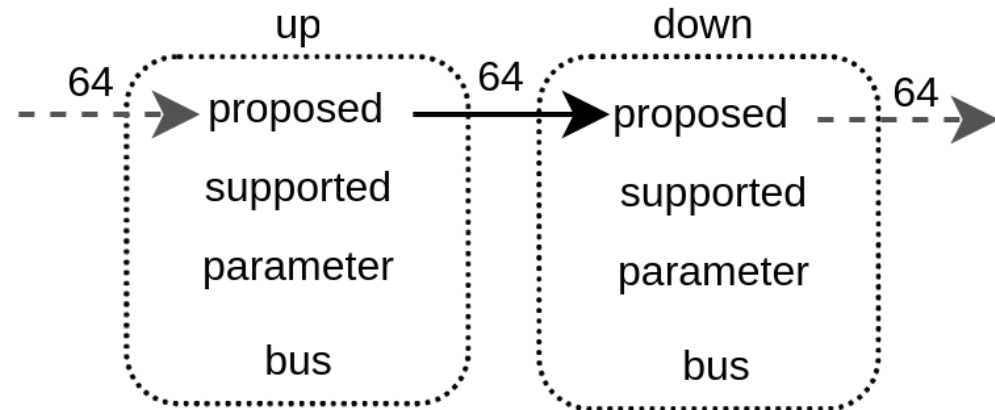
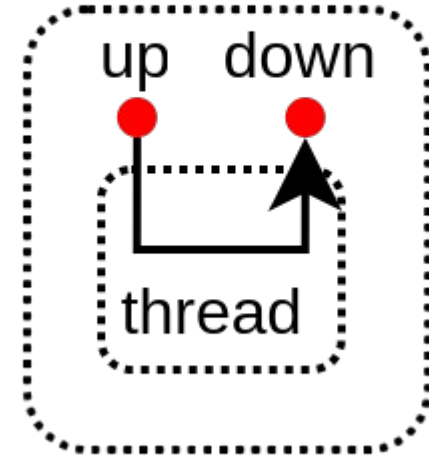
WidthAdapter



Adapter example

```
class WidthAdapter() extends Area{  
  val up = Node.slave()  
  val down = Node.master()  
  
  val thread = Fiber build new Area{  
    down.proposed load up.proposed  
    up.supported load down.supported.copy(  
      dataWidth = up.proposed.dataWidth  
    )  
    down.parameters load up.parameters.copy(  
      dataWidth = down.supported.dataWidth  
    )  
  
    val bridge = new WidthAdapterHw(up.bus.p, down.bus.p)  
    bridge.io.up << up.bus  
    bridge.io.down >> down.bus  
  }  
}
```

WidthAdapter



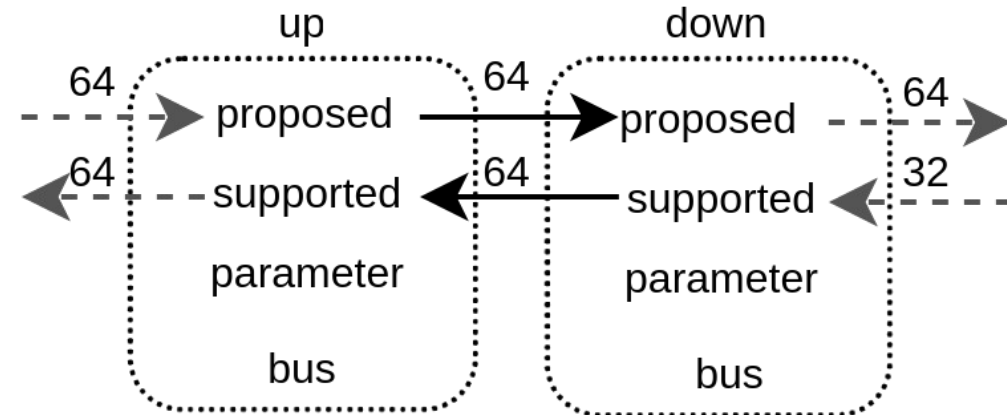
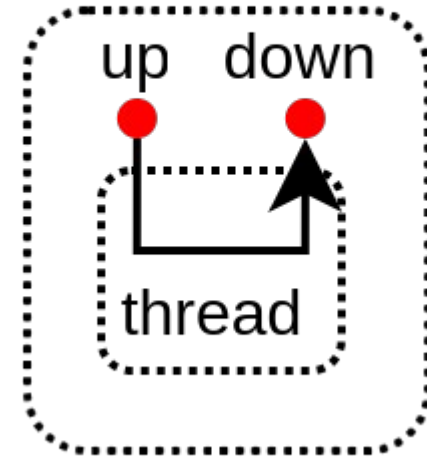
Adapter example

```
class WidthAdapter() extends Area{
  val up = Node.slave()
  val down = Node.master()

  val thread = Fiber build new Area{
    down.proposed load up.proposed
    up.supported load down.supported.copy(
      dataWidth = up.proposed.dataWidth //Will be 64
    )
    down.parameters load up.parameters.copy(
      dataWidth = down.supported.dataWidth
    )
  }

  val bridge = new WidthAdapterHw(up.bus.p, down.bus.p)
  bridge.io.up << up.bus
  bridge.io.down >> down.bus
}
```

WidthAdapter



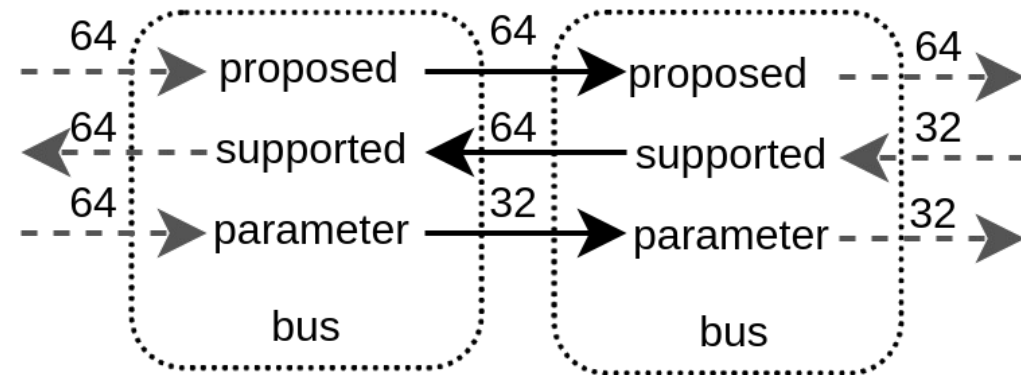
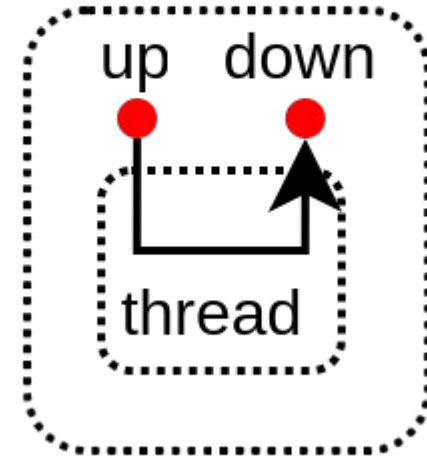
Adapter example

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  val up = Node.slave()
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  val thread = Fiber build new Area{
    down.proposed load up.proposed
    up.supported load down.supported.copy(
      dataWidth = up.proposed.dataWidth
    )
    down.parameters load up.parameters.copy(
      dataWidth = down.supported.dataWidth //Will be 32
    )
  }

  val bridge = new WidthAdapterHw(up.bus.p, down.bus.p)
  bridge.io.up << up.bus
  bridge.io.down >> down.bus
}
```

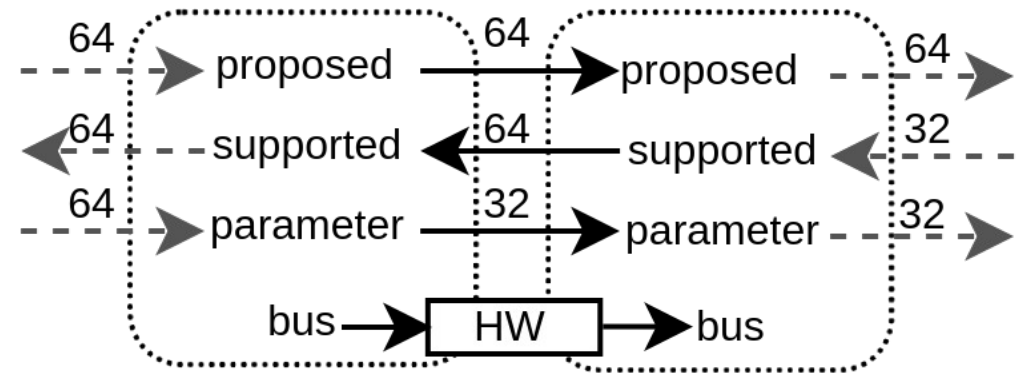
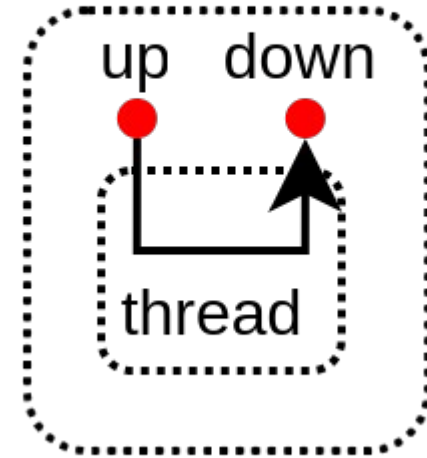
WidthAdapter



Adapter example

```
class WidthAdapter() extends Area{  
  val up = Node.slave()  
  val down = Node.master()  
  
  val thread = Fiber build new Area{  
    down.proposed load up.proposed  
    up.supported load down.supported.copy(  
      dataWidth = up.proposed.dataWidth  
    )  
    down.parameters load up.parameters.copy(  
      dataWidth = down.supported.dataWidth  
    )  
  }  
  
  val bridge = new WidthAdapterHw(up.bus.p, down.bus.p)  
  bridge.io.up << up.bus  
  bridge.io.down >> down.bus  
}
```

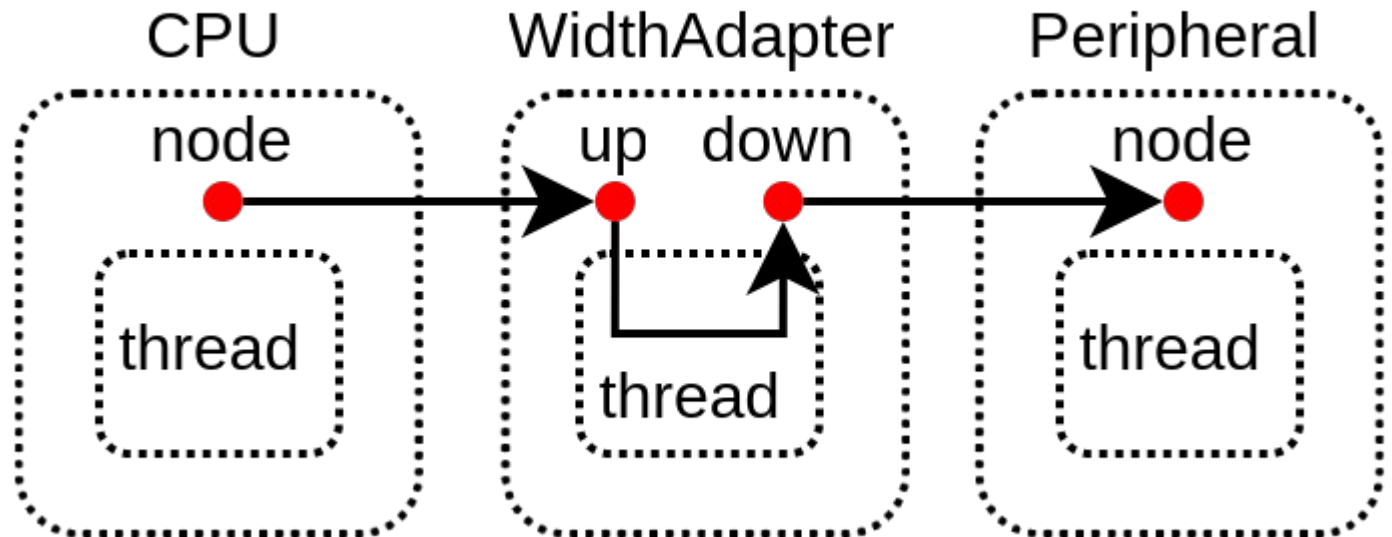
WidthAdapter



Deployment

```
val cpu          = Cpu()  
val adapter      = WidthAdapter()  
val peripheral    = Peripheral()
```

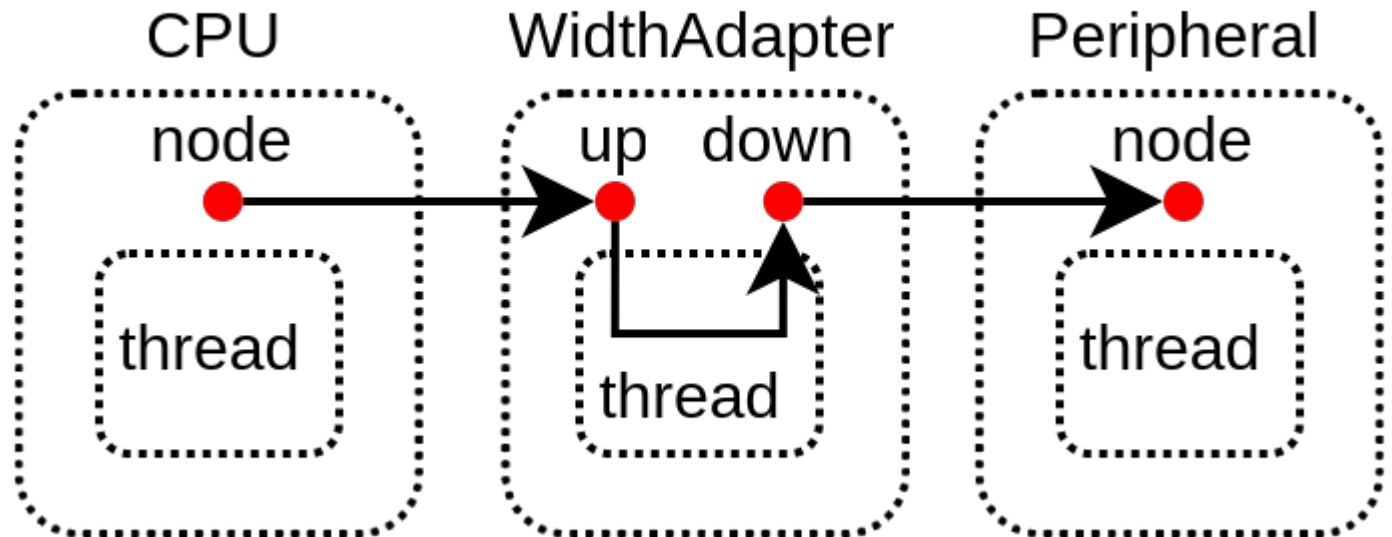
```
adapter.up << cpu.node  
peripheral.node at 0x2000 of adapter.down
```



Deployment

```
val cpu          = Cpu()  
val adapter      = WidthAdapter()  
val peripheral    = Peripheral()
```

```
adapter.up << cpu.node  
peripheral.node at 0x2000 of adapter.down
```



Introspection

```
val counter = Reg(UInt(8 bits))  
counter := counter + 1
```

```
class CustomTag(val str : String) extends SpinalTag
```

```
counter.addTag(new CustomTag("hello"))
```

```
counter.addTag(new CustomTag("miaou"))
```

```
counter.foreachTag{  
  case ct : CustomTag => println(ct.str)  
  case _ =>  
}
```

Introspection

```
val counter = Reg(UInt(8 bits))  
counter := counter + 1
```

```
class CustomTag(val str : String) extends SpinalTag
```

```
counter.addTag(new CustomTag("hello"))  
counter.addTag(new CustomTag("miaou"))
```

```
counter.foreachTag{  
  case ct : CustomTag => println(ct.str)  
  case _ =>  
}
```

Introspection

```
val counter = Reg(UInt(8 bits))
counter := counter + 1

class CustomTag(val str : String) extends SpinalTag

counter.addTag(new CustomTag("hello"))
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counter.foreachTag{
  case ct : CustomTag => println(ct.str)
  case _ =>
}
```

Introspection

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val counter = Reg(UInt(8 bits))  
counter := counter + 1
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```
class CustomTag(val str : String) extends SpinalTag
```

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counter.addTag(new CustomTag("hello"))
```

```
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```

```
counter.foreachTag{  
  case ct : CustomTag => println(ct.str)  
  case _ =>  
}
```



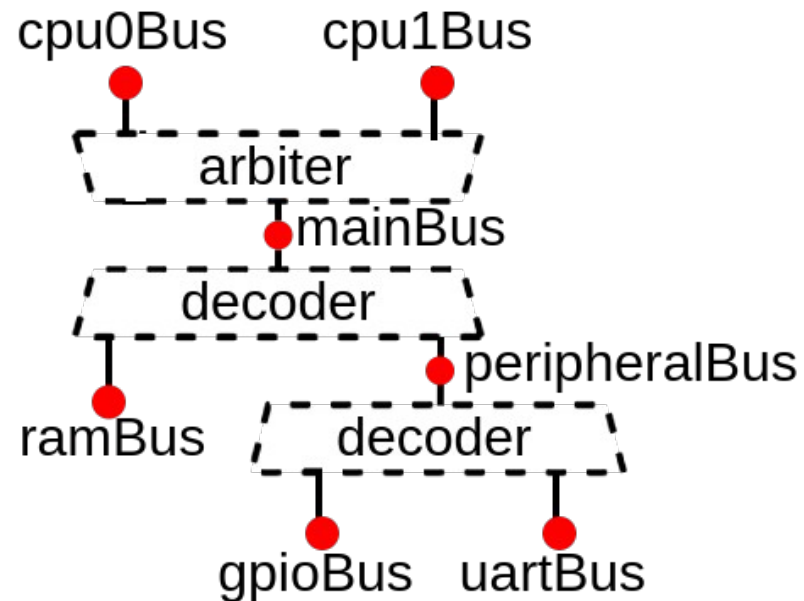
hello
miaou

Introspection

```
trait MemoryConnection extends SpinalTag {  
  def m : SpinalTagReady  
  def s : SpinalTagReady  
  def mapping : SizeMapping  
}
```

Introspection

```
trait MemoryConnection extends SpinalTag {  
  def m : SpinalTagReady  
  def s : SpinalTagReady  
  def mapping : SizeMapping  
  override def toString = s"$m $s $mapping"  
}
```

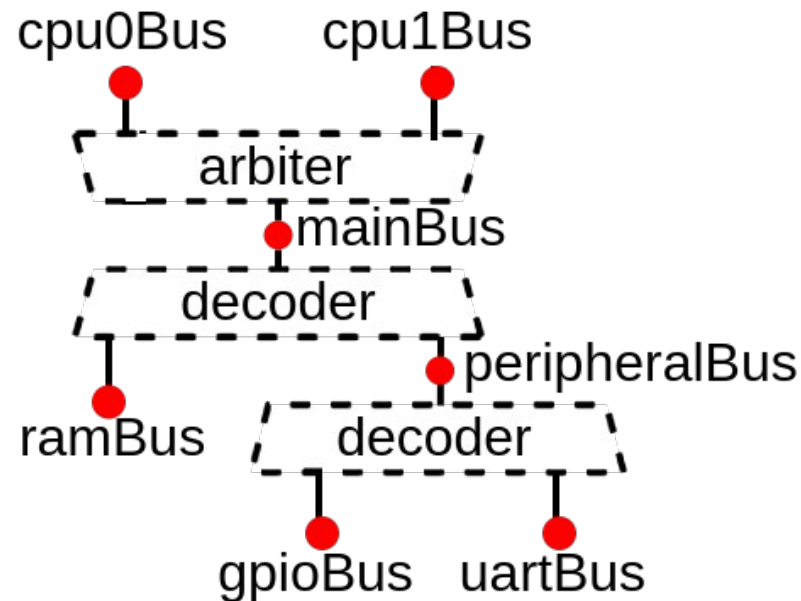
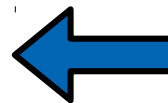


Introspection

```
trait MemoryConnection extends SpinalTag {  
  def m : SpinalTagReady  
  def s : SpinalTagReady  
  def mapping : SizeMapping  
  override def toString = s"$m $s $mapping"  
}
```



```
val tag = new MemoryConnection{  
  def m = peripheralBus  
  def s = gpioBus  
  def mapping = SizeMapping(0x5000, 0x1000)  
}  
peripheralBus.addTag(tag)  
gpioBus.addTag(tag)
```

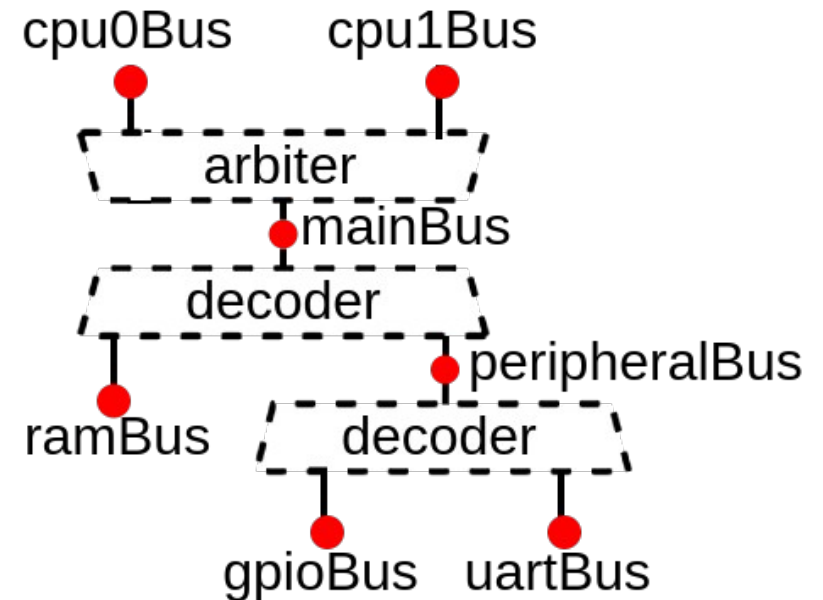
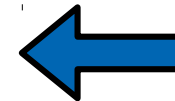
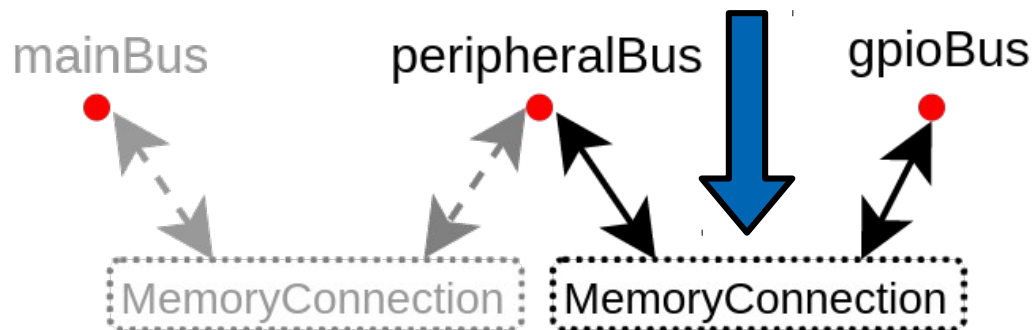


Introspection

```
trait MemoryConnection extends SpinalTag {  
  def m : SpinalTagReady  
  def s : SpinalTagReady  
  def mapping : SizeMapping  
  override def toString = s"$m $s $mapping"  
}
```



```
val tag = new MemoryConnection{  
  def m = peripheralBus  
  def s = gpioBus  
  def mapping = SizeMapping(0x5000, 0x1000)  
}  
peripheralBus.addTag(tag)  
gpioBus.addTag(tag)
```



Introspection

```
def visit(node : SpinalTagReady, level : Int){
  node.foreachTag{
    case mc : MemoryConnection if mc.m == node => {
      println("  " * level + mc)
      visit(mc.s, level + 1)
    }
    case _ =>
  }
}

visit(cpu0Bus, 0)
```

Introspection

```
def visit(node : SpinalTagReady, level : Int){  
  node.foreachTag{  
    case mc : MemoryConnection if mc.m == node => {  
      println("  " * level + mc)  
      visit(mc.s, level + 1)  
    }  
    case _ =>  
  }  
}  
  
visit(cpu0Bus, 0)
```

Introspection

```
def visit(node : SpinalTagReady, level : Int){
  node.foreachTag{
    case mc : MemoryConnection if mc.m == node => {
      println("  " * level + mc)
      visit(mc.s, level + 1)
    }
    case _ =>
  }
}

visit(cpu0Bus, 0)
```

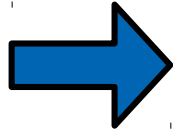
Introspection

```
def visit(node : SpinalTagReady, level : Int){  
  node.foreachTag{  
    case mc : MemoryConnection if mc.m == node => {  
      println("  " * level + mc)  
      visit(mc.s, level + 1)  
    }  
    case _ =>  
  }  
}  
  
visit(cpu0Bus, 0)
```

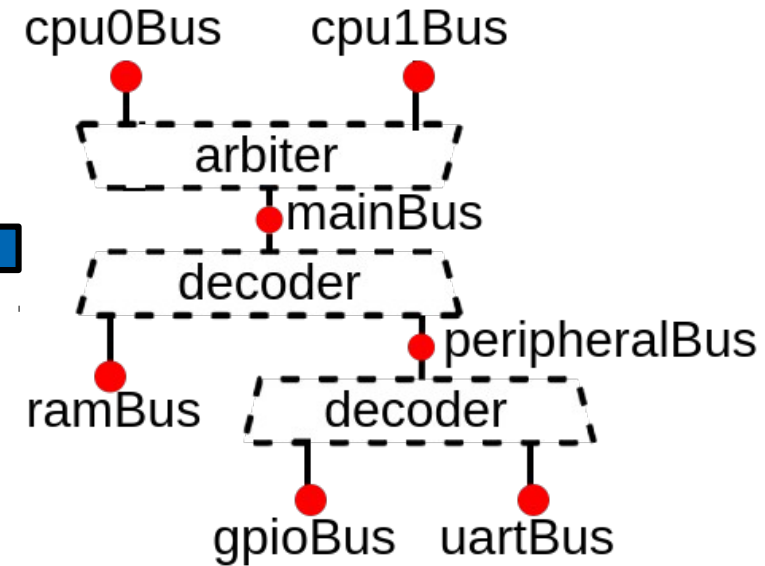
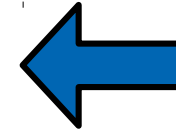
Introspection

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def visit(node : SpinalTagReady, level : Int){  
  node.foreachTag{  
    case mc : MemoryConnection if mc.m == node => {  
      println("  " * level + mc)  
      visit(mc.s, level + 1)  
    }  
    case _ =>  
  }  
}
```

visit(*cpu0Bus*, 0)



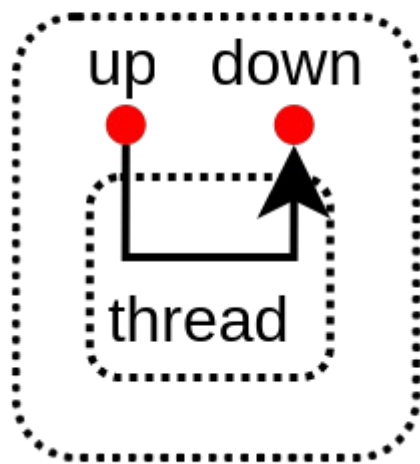
```
cpu0Bus mainBus 0 100000000  
mainBus ramBus 40000000 10000  
mainBus peripheralBus 10000000 100000  
peripheralBus gpioBus 2000 1000  
peripheralBus uartBus 5000 1000
```



Interoperability

```
class TilelinkToAxi4() extends Area{  
  val up    = tilelink.Node.slave()  
  val down  = axi4.Node.master()  
  
  val tag = new MemoryConnection {  
    def m = peripheralBus  
    def s = apbBus  
    def mapping = ...  
  }  
  up.add(tag)  
  down.add(tag)  
  
  val thread = Fiber build new Area{  
    // Handle the negotiation from Tilelink to AXI  
    // ...  
    // Generate the hardware  
    // ...  
  }  
}
```

TilelinkToAxi4



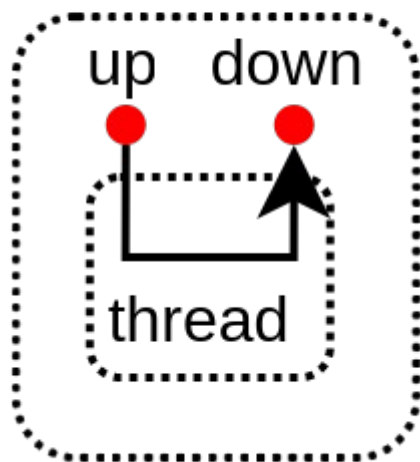
Interoperability

```
class TilelinkToAxi4() extends Area{
  val up    = tilelink.Node.slave()
  val down  = axi4.Node.master()

  val tag = new MemoryConnection {
    def m = peripheralBus
    def s = apbBus
    def mapping = ...
  }
  up.add(tag)
  down.add(tag)

  val thread = Fiber build new Area{
    // Handle the negotiation from Tilelink to AXI
    // ...
    // Generate the hardware
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  }
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TilelinkToAxi4



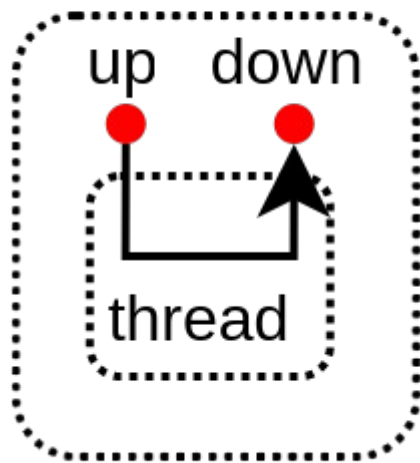
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TilelinkToAxi4



Summarize

- Paradigms (keeps things clean)
- Elaboration thread
- Decentralized negotiation / elaboration
- Introspection
- Interoperability

Question ?

- Open Discussion about the tilelink interconnect API / framework :
 - <https://github.com/SpinalHDL/SpinalHDL/discussions/1115>
- Roadmap
 - Tilelink interconnect with
 - memory coherency
 - L2 cache
 - NaxRiscv with tilelink memory coherency
- Looking for buddies :)