CS250B: Modern Computer Systems

Bluespec Introduction – More Topics

Sang-Woo Jun

UCI

Many slides adapted from
Arvind's MIT "6.175: Constructive Computer Architecture"
and Hyoukjun Kwon's Gatech "Designing CNN Accelerators"

More Topics

- Rule Scheduling
- Static Elaboration
- Polymorphism
- Nested Interfaces

Rule Scheduling In Bluespec

- For each rule, the compiler adds two signals
  - CAN_FIRE: Explicit and implicit guards are all met (rule -> scheduler)
  - WILL_FIRE: The rule will fire in the current cycle (rule <- scheduler)
- If there is no conflict between all rules, CAN_FIRE == WILL_FIRE for all
- If there are conflicts, some rules will be scheduled less urgent
  - CAN_FIRE == True, but WILL_FIRE == False for some rules that wait until conflicting rules' CAN_FIRE becomes false

XXX.sched example

```
Rule: pcieCtrl_relayTLPm
Predicate: pcieCtrl_sendTLPQ.i_notFull &&
>       pcieCtrl_sendTLPm_mb_outQ.i_notEmpty &&
>       (pcieCtrl_dataWordsRemain == 10'd0)
Blocking rules: pcieCtrl_generateHeaderTLP
```

Valid Concurrent Rules

- Simplified story: Rules that write to the same state can’t fire together
  - Except when they can
  - Also, sometimes rules that don’t write to same state can’t fire together
  - Still safe guideline to try to follow

Conflict? **No!**

```
Reg#(Bit#(32)) x <- mkReg(0);

rule rule1;
  x <= x + 1;
endrule
rule rule2;
  x <= 3;
endrule
```

Conflict? **Yes…**

```
Reg#(Bit#(32)) x <- mkReg(0);
Reg#(Bit#(32)) y <- mkReg(0);

rule rule1;
  x <= y;
endrule
rule rule2;
  y <= x;
endrule
```

Valid Concurrent Rules

- “A set of rules r_i can fire concurrently if there exists a total order between the rules such that all the method calls within each of the rules can happen in that given order”
  - Rules r_1, r_2, r_3 can fire concurrently if there is an order r_i, r_j, r_k such that $r_i < r_j$, $r_j < r_k$, and $r_i < r_k$ are all valid
- What does it mean for rules to be ordered?

Conflict Matrix for an Interface

- Methods can have a "happens" before relationship between them
  - **f** < **g** : **f** happens before **g** (effects of **g** do not affect **f**)
  - **f** C **g** : **f** and **g** conflict, and cannot be called together
  - **f** CF **g** : **f** and **g** are conflict-free, and can be called together
- Conflict Matrix (CM) defines which methods of a module can be called concurrently
  - e.g., Conflict matrix of a register

	Reg.r	Reg.w
Reg.r	CF	<
Reg.w	>	CF*

Conflict-free if called from different rules, conflict if called within same rule

Valid Concurrent Rules

	Reg.r	Reg.w
Reg.r	CF	<
Reg.w	>	CF*

```
Reg#(Bit#(32)) x <- mkReg(0);

rule rule1;
  x <= x + 1;
endrule
rule rule2;
  x <= x + 3;
endrule
```

rule1 can’t fire before rule2
(rule1’s x.write > rule2’s x.read)
rule2 can’t fire before rule1
(rule2’s x.write > rule1’s x.read)

Conflict!

```
Reg#(Bit#(32)) x <- mkReg(0);

rule rule1;
  x <= x + 1;
endrule
rule rule2;
  x <= 3;
endrule
```

rule1 can fire before rule2
rule2 can’t fire before rule1
(rule2’s x.write > rule1’s x.read)

Conflict free! (rule1 < rule2)

```
Reg#(Bit#(32)) x <- mkReg(0);
Reg#(Bit#(32)) y <- mkReg(0);

rule rule1;
  x <= y;
endrule
rule rule2;
  y <= x;
endrule
```

rule1 can’t fire before rule2
(rule1’s x.write > rule2’s x.read)
rule2 can’t fire before rule1
(rule2’s y.write > rule1’s y.read)

Conflict!

Example: Up/Down Counter

Problem

```
Reg#(Bit#(32)) counter <- mkReg(0);

rule countUp;
  srcQ.deq;
  counter <= counter + 1;
endrule
rule countDown;
  destQ.deq;
  counter <= counter - 1;
endrule
```

Conflict!

This would be terrible for performance

(Duty cycle is half!)

Simple Solution

```
Reg#(Bit#(32)) counterUp <- mkReg(0);
Reg#(Bit#(32)) counterDn <- mkReg(0);

rule countUp;
  srcQ.deq;
  counterUp <= counterUp + 1;
endrule
rule countDown;
  destQ.deq;
  counterDn <= counterDn + 1;
endrule
rule displayCount;
  $display( “%d”, counterUp-counterDn );
endrule
```

Conflict free!

More elegant solutions exist, for another day

More Topics

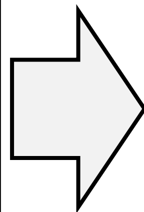
- ❑ Rule Scheduling
- ❑ Static Elaboration
- ❑ Polymorphism
- ❑ Nested Interfaces

Static Elaboration

- Code that generates other code during compile time
  - Efficient way to write code – “Hardware Generator”
  - Example: Parallelizing high-latency GCD calculation

```
GCDIfc gcd1 <- mkGCD;
GCDIfc gcd2 <- mkGCD;

rule rule1;
  cmdQ.deq;  let cmd = cmdQ.first;
  gcd1.start(tpl_1(cmd), tpl_2(cmd));
endrule
rule rule2;
  cmdQ.deq;  let cmd = cmdQ.first;
  gcd2.start(tpl_1(cmd), tpl_2(cmd));
endrule
```



```
typedef 2 GCDCount;
Vector#(GCDCount, GCDIfc) gcd1 <- replicateM(mkGCD);

for (Integer idx = 0; idx < valueOf(GCDCount); idx=idx+1) begin
  rule rule1;
    cmdQ.deq;  let cmd = cmdQ.first;
    gcd[idx].start(tpl_1(cmd), tpl_2(cmd));
  endrule
endrule
```

Note: Many rules competing for cmdQ is not good.
More elegant solutions later!

Static Elaboration

- Also used within rules
  - Example: Parsing an array of values from a single large blob

```
rule rule1;
  Bit#(128) rawdata = inQ.first; inQ.deq;
  Vector#(8, Int#(8)) parsed;
  for (Integer i = 0; i < 8; i=i+1 ) begin
    parsed[i] = unpack(truncate(rawdata>>(i*8)));
  end
  outQ.enq(parsed);
endrule
```

- Not only for loops, but if statements can be used as well
- As long as they all use variables/literals available at compile time

Static Elaboration

- Powerful way to define complex modules
  - A lot of things can be statically elaborated! (Interface, etc)
  - More to come!
- Very complex modules can be defined recursively
  - Example: **MergeSort**#(fanIn, type) NToOneMerge <- mkMergesorter;
  - But in order to give an example of recursive module definition, we must first cover polymorphic modules

More Topics

- Rule Scheduling
- Static Elaboration
- Polymorphism
- Nested Interfaces

Polymorphism – Parameterized Intefaces

- Interface parameterized with types: “#” syntax
  - Bit#(32) data;
  - FIFO#(Bit#(32)) exampleQ <- mkFIFO;
  - Vector#(4, Int#(64)) exampleVector = newVector();

```
interface GCDIfc#(type valType);
  method Action start(valType a, valType b);
  method valType result();
endinterface
```

```
GCDIfc#(Bit#(32)) gdc32 <- mkGCD;
GCDIfc#(Bit#(48)) gdc48 <- mkGCD;
...etc
```

```
module mkGCD (GCDIfc#(valType));
   …
 method Action start(valType a, valType b);
   …
 endmethod
 method valType result();
   …
 endmethod
endmodule
```

Polymorphism – Compiler Errors!

```
module mkGCD (GCDIfc#(valType));
  Reg#(valType) x <- mkReg(?);
  Reg#(valType) y <- mkReg(0);
  rule step1 (x > y && y != 0);
    x <= y; y <= x;
  endrule
  rule step2 (x <= y && y != 0);
    y <= y – x;
  endrule
  method Action start(valType a, valType b) if (y==0);
    …
  endmethod
  method valType result() If (y==0);
    …
  endmethod
endmodule
```

```
compiling Top.bsv
Error: "Top.bsv", line 23, column 8: (T0030)
  The provisos for this expression are too general.
  Given type:
    _m__#(Top::GDCIfc#(valType))
  With the following proviso:
    IsModule#(_m__, _c__)
  The following additional provisos are needed:
    Arith#(valType)
      Introduced at the following locations:
        "Top.bsv", line 39, column 23
    Bits#(valType, a__)
      Introduced at the following locations:
        "Top.bsv", line 33, column 28
        "Top.bsv", line 32, column 28
    Eq#(valType)
      Introduced at the following locations:
        "Top.bsv", line 47, column 38
        "Top.bsv", line 44, column 56
        "Top.bsv", line 38, column 37
        "Top.bsv", line 35, column 35
    Ord#(valType)
      Introduced at the following locations:
        "Top.bsv", line 38, column 25
        "Top.bsv", line 35, column 24
  The type variables are from the following positions:
    "a__" at "Top.bsv", line 32, column 28
Makefile:6: recipe for target 'all' failed
make: *** [all] Error 1
```

Polymorphism – Provisos

Compiles and works with provisos telling compiler about valType

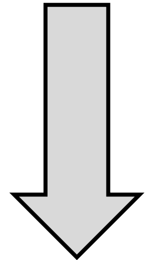
```
module mkGCD (GCDIfc#(valType))
  provisos(Bits#(valType, valTypeSz), Literal#(valType), Arith#(valType), Eq#(valType), Ord#(valType));
  Reg#(valType) x <- mkReg(?);
  Reg#(valType) y <- mkReg(0);
  …
endmodule
```

Now “valTypeSz” is a numeric type available in the module

- valType can be anything, Bit#, Int#, Vector#, typedef struct, as long as the provisos are satisfied.
  - Literal#, Arith#, Ord# not satisfied for Vector#, struct, …

Polymorphism – numeric type

```
interface GCDIfc#(type valType);
  method Action start(valType a, valType b);
  method valType result();
endinterface
```



If we know valType is Bit#,
and we only care about width

```
interface GCDIfc#(numeric type valSz);
  method Action start(Bit#(valSz) a, Bit#(valSz) b);
  method Bit#(valSz) result();
endinterface
```

```
GCDIfc#(32) gdc32 <- mkGCD;
 …etc
```

Don’t need provisos because Bit# satisfies everything

Polymorphism – More Provisos

Say, the output has to be 32 bits

```
interface GCDIfc#(numeric type valSz);
  method Action start(Bit#(valSz) a, Bit#(valSz) b);
  method Bit#(32) result();
endinterface
```

```
module mkGCD (GCDIfc#(valSz));
  Reg#(start(Bit#(valSz)) x <- mkReg(?);
  Reg#(start(Bit#(valSz)) y <- mkReg(0);

  …

  method Bit#(32) result() If (y==0);
    return truncate(x);
  endmethod
endmodule
```

```
Error: "Top.bsv", line 23, column 8: (T0065)
  The provisos for this expression are too general.
  Given type:
    _m__#(Top::GDCIfc#(valType))
  With the following provisos:
    IsModule#(_m__, _c__)
  The following additional proviso is needed:
    Add#(a__, 32, valType)
  This proviso was introduced by an extend or truncate operation, which
  requires that the extended size be larger.
  The extend or truncate occurs in or at the following locations:
    "Top.bsv", line 43, column 24
Makefile:6: recipe for target 'all' failed
make: *** [all] Error 1
```

Requires Add# provisos to tell compiler valType is larger than or equal to 32

Side effect: a__ = valType – 32 available in module

Polymorphism – Arithmetic Provisos

- Used to assert relationships between interface parameters
- Also used like typedefs inside module context
  - Regular typedef not allowed in module
  - Provisos creates a type name if an argument does not exist in context already

Class	Proviso	Description
Add	Add#(n1,n2,n3)	Assert $n1 + n2 = n3$
Mul	Mul#(n1,n2,n3)	Assert $n1 * n2 = n3$
Div	Div#(n1,n2,n3)	Assert ceiling $n1/n2 = n3$
Max	Max#(n1,n2,n3)	Assert $\max(n1, n2) = n3$
Min	Min#(n1,n2,n3)	Assert $\min(n1, n2) = n3$
Log	Log#(n1,n2)	Assert ceiling $\log_2(n1) = n2$.

Example module with valType1 and valType2 available as interface parameters

```
provisos(Log#(valType1, valTypeLog), Max#(valType1, valType2, valTypeMax));
// Types valTypeLog, valTypeMax now available within module context
```

Polymorphism – Type Operations

- Say, we want to correctly handle multiplication overflows
  - Return value needs to be double the width of the input
  - Use "Type Functions": Types as input, type as output

Type Function	Size Relationship	Description
TAdd	TAdd#(n1,n2)	Calculate $n1 + n2$
TSub	TSub#(n1,n2)	Calculate $n1 - n2$
TMul	TMul#(n1,n2)	Calculate $n1 * n2$
TDiv	TDiv#(n1,n2)	Calculate ceiling $n1/n2$
TLog	TLog#(n1)	Calculate ceiling $\log_2(n1)$
TExp	TExp#(n1)	Calculate 2^{n1}
TMax	TMax#(n1,n2)	Calculate $max(n1, n2)$
TMin	TMin#(n1,n2)	Calculate $min(n1, n2)$

"TXxx" naming convention

```
interface SafeMultIfc#(numeric type valSz);
  method Action put(Bit#(valSz) a, Bit#(valSz) b);
  method Bit#(TMul#(2,valSz)) result();
endinterface
```

```
Reg#(Bit#(TMul#(2, valSz)) res <- mkReg(0);
```

Type Arithmetic Examples

- **Int**#(**TAdd**#(5,n)) a;
  - n must be in scope somewhere
- **typedef TAdd**#(vsize, 8) Bigsize#(**numeric type** vsize);
  - typedef parameterized with numeric type vsize
  - Usage example: **Bit**#(Bigsize#(32)) is a 40-bit Bit variable
- **typedef Bit**#(**TLog**#(n)) CBToken#(**numeric type** n);
  - typedef parameterized with numeric type n
  - Usage example: CBToken#(8) is a 3-bit variable
- **typedef** 8 Wordsize; **typedef TAdd**#(Wordsize, 1) Blocksize;

Simple Example: Maybe# types

- Maybe# is a polymorphic tagged union type
  - Parameterized with type t
  - isValid, fromMaybe are helper functions

```
typedef union tagged {
   void Invalid; // void is a zero-bit type
   t    Valid;
} Maybe#(type t) deriving (Eq, Bits);
```

```
case (x) matches
      tagged Valid .a : return a;
      tagged Invalid : return 0;
endcase
```

Polymorphic Functions

- We have seen parameterized interface/modules and types
- Functions can be parameterized as well
  - Requires usual provisos, etc

```
function Bool equal (valType x, valType y)
  provisos( Eq#(valType) );
      return (x==y);
endfunction
// Now equal(x,y) used with any type satisfying Eq
```

More Topics

- Rule Scheduling
- Static Elaboration
- Polymorphism
- Nested Interfaces

Nested Interfaces

- Interfaces can be hierarchical
  - Interfaces in other interfaces
- Syntax Example:

```
interface SubIfc;
  method Bit#(64) getResult;
endinterface

interface TestIfc;
  method Action put(Bit#(32) data);
  method Bit#(32) result();
  interface SubIfc sub;
endinterface
```

```
module mkTest;
  …
  interface TestIfc;
    method Action put(Bit#(32) data);
    …
    endmethod
    method Bit#(32) result();
    …
    endmethod
    interface SubIfc sub;
      method Bit#(64) getResult;
      …
      endmethod
    endinterface
endmodule
```

```
TestIfc test <- mkTest;

rule …
  result = test.sub.getResult;
endrule
```

Nested Vector Interfaces

- Nested interfaces can be a vector of interfaces
- Static elaboration to populate

```
interface SubIfc;
  method Bit#(64) getResult;
endinterface

interface TestIfc;
  method Action put(Bit#(32) data);
  interface Vector#(8, SubIfc) sub;
endinterface
```

```
module mkTest;
  …
  interface TestIfc;
  …
  Vector#(8,SubIfc) sub_;
  for (Integer i = 0; i < 8; i=i+1) begin
    sub_[i] = interface SubIfc;
      method Bit#(64) getResult;
        …
      endinterface
    endinterface;
  end
  interface sub = sub_;
endmodule
```

Tested Interface Use Cases

- N-to-1, N-to-N connections between modules
  - e.g., Switch connected to multiple clients:
    - interface SwitchIfc has a parameterized vector of N ClientConnectionIfc
    - Each module mkClient instance takes as argument one ClientConnectionIfc
  - e.g., Data sink has multiple sources
    - interface SinkIfc has multiple interfaces SinkSubIfc
    - Multiple rules, statically elaborated, call each SinkSubIfc

Connectables

- Concise way to connect interfaces of two modules together
  - Needs “import Connectable::*”
  - Can connect value and action method pairs
    - Cannot deal with ActionValue methods!

```
interface SourceIfc;
  method Bit#(64) getResult;
endinterface

interface SinkIfc;
  method Action put(Bit#(64) data);
endinterface
```

Option 1: Cumbersome with many pairs

```
rule ...;
  sink.put(source.getResult);
endrule
```

Option 2: Concise!

```
mkConnection(sink.put, source.getResult);
```

Connectables – GetPut

- Get# and Put# interfaces can be used to use ActionValue methods
  - Needs to "import GetPut::*;"
  - **Get**#(t) has one method, "ActionValue#(t) get"
  - **Put**#(t) has one method, "Action put(t data)"

```
interface SourceIfc;
  interface Get#(Bit#(64)) getins;
endinterface

interface SinkIfc;
  interface Put#(Bit#(64)) putins;
endinterface
```

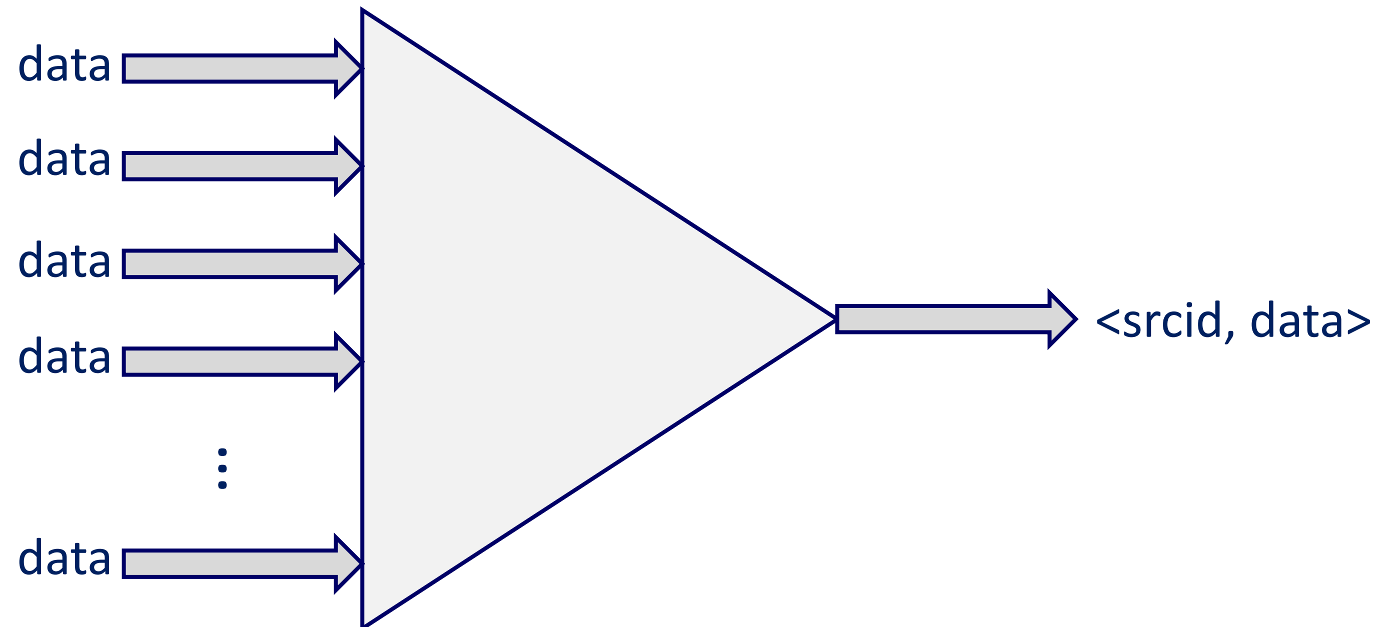
```
module mkSource (SourceIfc);
  interface Get getins;
    method ActionValue#(Bit#(64)) get;
    …
```

```
module mkSink (SinkIfc);
  interface Put putins;
    method Action get(Bit#(64) d);
    …
```

```
mkConnection(sink.putins,source.getins);
```

Putting It All Together: Recursive Module Definition

- Example use case: “MergeN” module
  - Collects data from N sources and funnels it into one stream, tagged with the source index
  - Can be recursively defined using a tree of Merge2’s



MergeN Recursive Definition

```
interface MergeEnqIfc#(type t);
    method Action enq(t d);
endinterface
```

```
interface MergeNIfc#(numeric type n, type t);
    interface Vector#(n, MergeEnqIfc#(t)) enq;

    method Action deq;
    method t first;
endinterface
```

Parameterized with n and t:
Variable number of sources,
Any type (satisfying Bits),

```
module mkMergeN (MergeNIfc#(n,t))
    provisos(Bits#(t, a__));
```

```
    if ( valueOf(n) == 1 ) begin
        FIFO#(t) inQ <- mkFIFO;
        Vector#(n,MergeEnqIfc#(t)) enq_;
        enq_[0] = interface MergeEnqIfc;
            method Action enq(t d);
                inQ.enq(d);
            endmethod
        endinterface;
        interface enq = enq_;
        method Action deq;
            inQ.deq;
        endmethod
        method t first;
            return inQ.first;
        endmethod
    end
```

MergeN Recursive Definition

```
else if ( valueOf(n) == 2 ) begin
    Merge2Ifc#(t) mb <- mkMerge2;
    Vector#(n, MergeEnqIfc#(t)) enq_;
    for ( Integer i = 0; i < valueOf(n); i = i + 1) begin
        enq_[i] = interface MergeEnqIfc;
            method Action enq(t d);
                mb.enq[i].enq(d);
            endmethod
        endinterface;
    end
    interface enq = enq_;
    method Action deq;
        mb.deq;
    endmethod
    method t first;
        return mb.first;
    endmethod
end
```

Continued

```
>   else begin
>   >   Vector#(2,MergeNIfc#(TDiv#(n,2), t)) ma <- replicateM(mkMergeN);
>   >   Merge2Ifc#(t) mb <- mkMerge2;
>   >   for ( Integer i = 0; i < 2; i = i +1 ) begin
>   >   >   rule ma1;
>   >   >   >   ma[i].deq;
>   >   >   >   mb.enq[i].enq(ma[i].first);
>   >   >   endrule
>   >   end

>   >   Vector#(n, MergeEnqIfc#(t)) enq_;
>   >   for ( Integer i = 0; i < valueOf(n); i = i + 1) begin
>   >   >   enq_[i] = interface MergeEnqIfc;
>   >   >   >   method Action enq(t d);
>   >   >   >   >   if ( i < valueOf(n)/2 ) begin
>   >   >   >   >   >   ma[0].enq[i%(valueOf(n)/2)].enq(d);
>   >   >   >   >   end else begin
>   >   >   >   >   >   ma[1].enq[i-(valueOf(n)/2)].enq(d);
>   >   >   >   >   end
>   >   >   >   endmethod
>   >   >   endinterface;
>   >   end
>   >   interface enq = enq_;
>   >   method Action deq;
>   >   >   mb.deq;
>   >   endmethod
>   >   method t first;
>   >   >   return mb.first;
>   >   endmethod
>   end
endmodule
```