Bluespec-2
Bluespec Compilation Model & Introduction to programming

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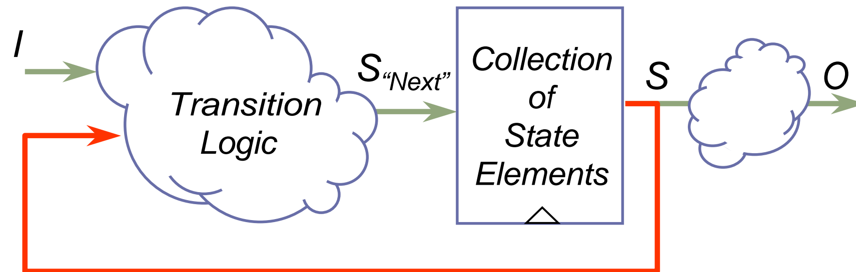
Lecture 18

Outline

- Bluespec compilation ⇐
- Bluespec programming
  - Example: Barrel shifter

From TRS to Synchronous CFSM



TRS Execution Semantics

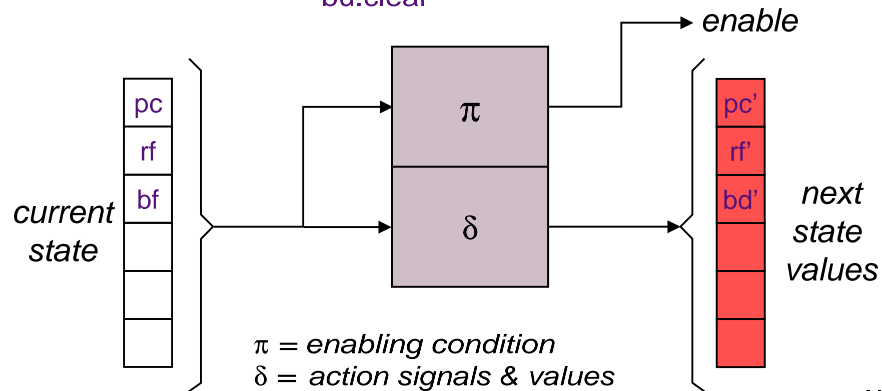
Given a set of rules and an initial term s

While (some rules are applicable to s)
- choose an applicable rule
  (non-deterministic)
- apply the rule atomically to s

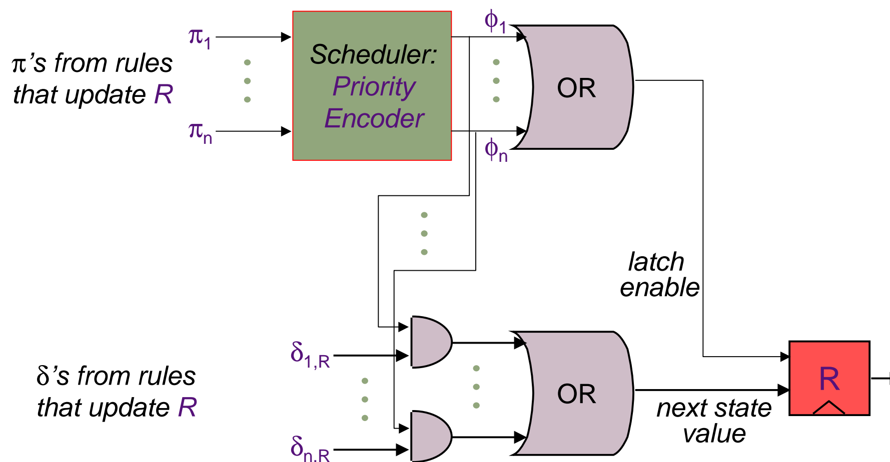
The trick to generating good hardware is to schedule as many rules in parallel as possible without violating the sequential semantics given above

Compiling a Rule

```
"Bz Taken":
  when (Bz rc ra) <- bu.first, rf!rc == 0
    ==> action pc := rf!ra
                bu.clear
```



Combining State Updates



Scheduler ensures that at most one ϕ_i is true

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Executing Multiple Rules Per Cycle

```
"Fetch":
  when True
    ==> action  pc := pc+1
                bu.enq (imem.read pc)
"Add":
  when (Add rd rs rt) <- bu.first
    ==> action  rf!rd := rf!rs + rf!rt
                bu.deq
```

Can these rules be executed simultaneously?

These rules are "conflict free" because they manipulate different parts of the state (i.e., pc and rf), and enq and deq on a FIFO can be done simultaneously.

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Conflict-Free Rules

$Rule_a$ and $Rule_b$ are conflict-free if

$$\forall s\ .\ \pi_a(s) \wedge \pi_b(s) \Rightarrow$$

1. $\pi_a(\delta_b(s)) \wedge \pi_b(\delta_a(s))$
2. $\delta_a(\delta_b(s)) == \delta_b(\delta_a(s))$
3. $\delta_a(\delta_b(s)) == \delta_a(s) \oplus \delta_b(s)$

where $\oplus$ is a sort of LUB operator

Theorem: Conflict-free rules can be executed concurrently without violating TRS's sequential semantics

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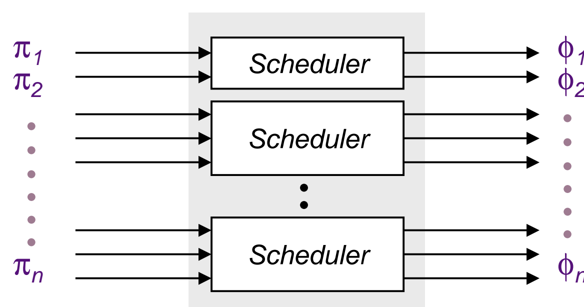
Conflict-Free Scheduler

- Partition rules into maximum number of disjoint sets such that
  - a rule in one set may conflict with one or more rules in the same set
  - a rule in one set is conflict free with respect to all the rules in all other sets

    (Best case: All sets are of size 1!!)
- Schedule each set independently
  - Priority Encoder, Round-Robin Priority Encoder
  - Enumerated Encoder

The state update logic remains unchanged

Multiple-Op-per-Cycle Scheduler



1. $\phi_i \Rightarrow \pi_i$

2. $\pi_1 \vee \pi_2 \vee .... \vee \pi_n \Rightarrow \phi_1 \vee \phi_2 \vee .... \vee \phi_n$

3. *Multiple operations such that*

   $\phi_i \wedge \phi_j \Rightarrow$ *R_i and R_j are conflict-free*

Multiple Rewrites Per Cycle

```
"Fetch":
  when True
       ==> action    pc := pc+1
                     bu.enq (imem.read pc)
"Bz Taken":
  when (pc' , Bz rc ra) <- bu.first, rf!rc == 0
       ==> action    pc := rf!ra
                     bu.clear
```

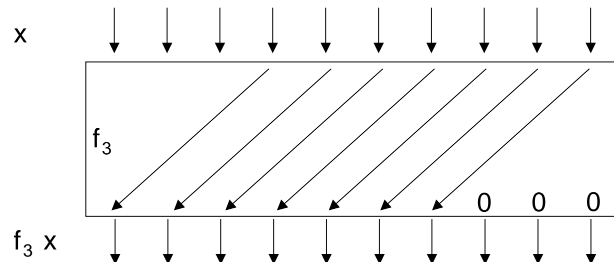
Can these rules be executed simultaneously?

Yes, as long as the action of Bz Taken rule dominates!
many other possibilities for parallel execution ...

Outline

- Bluespec compilation √
- Bluespec programming ⇐
  - Example: Barrel shifter

Left-shifting a value by 3



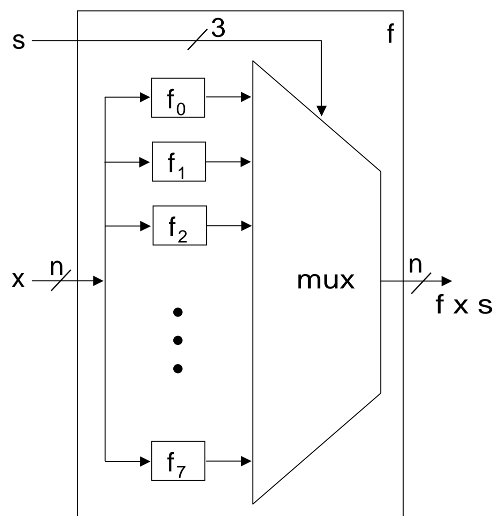
In Bluespec:

```
f3 :: (Bit 10) -> (Bit 10)
f3 x = x << 3
```

More generally:

```
f3 :: (Bit n) -> (Bit n)
```

Shifting by a variable amount (0-7)



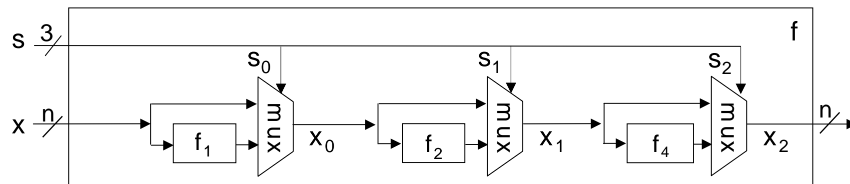

```
f :: (Bit n) -> (Bit 3)
             -> (Bit n)

f0 x = x << 0
 ...
f7 x = x << 7

f x s =
    case s of
         0 -> f0 x
         1 -> f1 x
         2 -> f2 x
         ...
         7 -> f7 x
```

But this is an expensive solution !

Shifting by a variable amount:
solution 2

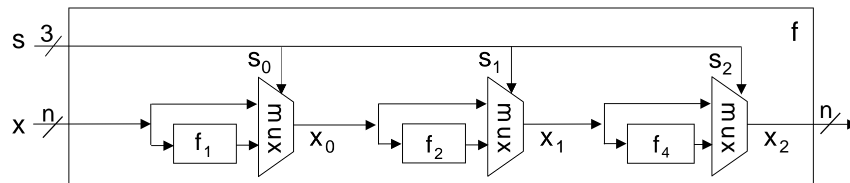


- three cascaded steps such that the jth step shifts by 0 or 2^j depending on the jth bit of s

```
f x s = let
            x0 = if s[0:0] == 0 then x
                   else (x  << (1 << 0))
            x1 = if s[1:1] == 0 then x0
                   else (x0 << (1 << 1))
            x2 = if s[2:2] == 0 then x1
                   else (x1 << (1 << 2))
        in
            x2
```

2^2

Shifting by a variable amount:
generalization




```
f :: (Bit n) -> (Bit 3) -> (Bit n)
f x s = ...
```

m (replacing 3)

generalize to m stages?

- In the jth step shift by 0 or 2^j depending on the jth bit of s

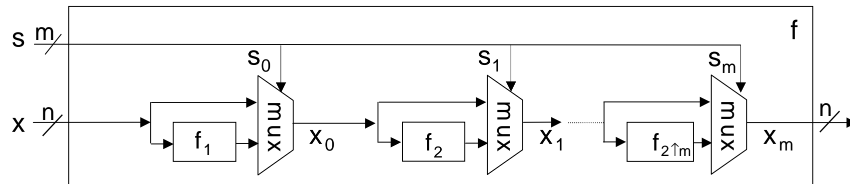
```
step s x j = if s[j:j]==0 then x
                else (x << (1 << j))
```

2^j

- Apply this step m times to the initial value of x

```
f x s = foldl (step s) x (upto 0 (m - 1))
```

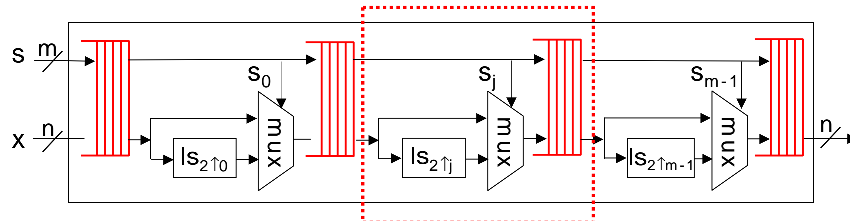
Barrel Shifter: *a "types" issue*




```
f :: (Bit n) -> (Bit m) -> (Bit n)
f x s = let
            step s x j = if s[j:j]==0 then x
                                   else (x << (1 << j))
        in
            foldl (step s) x (upto 0 (m - 1))
                                  valueOf(m)
```

m in (Bit m) has something to do with types. We need to use valueOf(m) for m in expressions.

Pipelined shifter



- In the jth step
  - shift by 0 or 2^j depending on the jth bit of s

```
step s x j = if s[j:j]==0 then x
                      else (x << (1 << j))
```

2^j

  - given the input FIFO fIn, produce the circuit and the FIFO fOut

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Pipelined shifter *continued*

```
mkLsStep:: FIFO (Bit n,Bit m) -> (Bit m) ->
                    -> Module (FIFO (Bit n,Bit m))
mkLsStep fIn j =
      module
        fOut :: FIFO (Bit n,Bit m) <- mkFIFO
        rules
          when (x,s) <- fIn.first
             ==> action fIn.deq
                        fOut.enq (step s x j, s)
        return fOut
```

State → fOut declaration

Internal behavior → rules

External interface → return fOut

- Iterate mkLsStep m times:
  start by supplying the leftmost FIFO

```
mkLs fifo0 =
  foldlM mkLsStep fifo0 (upto 0 (valueOf m - 1))
```

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Pipelined shifter *remarks*

- The program to generate the circuit is parametric
  - n bits represent the datawidth in the FIFO
  - m represents the number of bits needed to specify the shift (= log n)
- The language scaffolding needed to express, for example, iteration disappears after the first phase of compilation
  - no “circuit” penalty for using high-level language constructs

Monadic Fold

```
foldl :: (tz -> tx -> tz) -> tz ->
                        (List tx) -> tz
foldl f z Nil           = z
foldl f z (Cons x xs)   = foldl f (f z x) xs
```

```
foldlM :: (tz -> tx -> Module tz) -> tz ->
                    (List tx) -> (Module tz)

foldlM f z Nil          = return z
foldlM f z (Nil x xs)   = module
                              z' <- (f z x)
                              foldlM f z' xs
```

Unfolding during Compilation

```
foldlM f z Nil      = return z
foldlM f z (Cons x xs)  = module
                              z' <- (f z x)
                              foldlM f z' xs
```

Suppose the list is {x1,x2,x3]. The compiler will unfold foldlM as follows:

```
module
    z1 <- f z x0
    module
        z2 <- f z1 x1
        module
            z3 <- f z2 x2
            return
               z3
```

```
module
    z1 <- f z x0
    z2 <- f z1 x1
    z3 <- f z2 x2
    return
           z3
```

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Compilation of Pipelined shifter

```
mkLs fifo0 =
  foldlM mkLsStep fifo0 (upto 0 (valueOf m - 1))
```

Suppose m is 3. The compiler will unfold foldlM as follows:

```
module
    fifo1 <- mkLsStep fifo0 0
    fifo2 <- mkLsStep fifo1 1
    fifo3 <- mkLsStep fifo2 2
    return
           fifo3
```

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Compilation of Pipelined shifter
continued

```
module
    fifo1 <-
      module
        fOut <- mkFIFO
        rules
          when (x,s) <- fifo0.first
             ==> action fifo0.deq
                        fOut.enq (step s x 0, s)
        return fOut

    fifo2 <- mkLsStep fifo1 1
    fifo3 <- mkLsStep fifo2 2
    return
           fifo3
```

http://www.csg.lcs.mit.edu/6.827

Compilation of Pipelined shifter
continued-2

```
module
    let fifo1 = fOut
    fOut <- mkFIFO
    rules
          when (x,s) <- fifo0.first
             ==> action fifo0.deq
                        fOut.enq (step s x 0, s)

    fifo2 <- mkLsStep fifo1 1
    fifo3 <- mkLsStep fifo2 2
    return
           fifo3
```