Constructive Computer Architecture

Sequential Circuits - 2

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Content

- So far we have seen modules with methods which are called by rules outside the body
- Now we will see examples where a module may also contain rules
  - gcd
- A common way to implement large combinational circuits is by *folding* where registers hold the state from one iteration to the next
  - Implementing imperative loops
  - Multiplication

Programming with rules: A simple example

Euclid's algorithm for computing the Greatest Common Divisor (GCD):

15		6	
9		6	*subtract*
3		6	*subtract*
6		3	*swap*
3		3	*subtract*
0	*answer:*	3	*subtract*

GCD module

Euclidean Algorithm

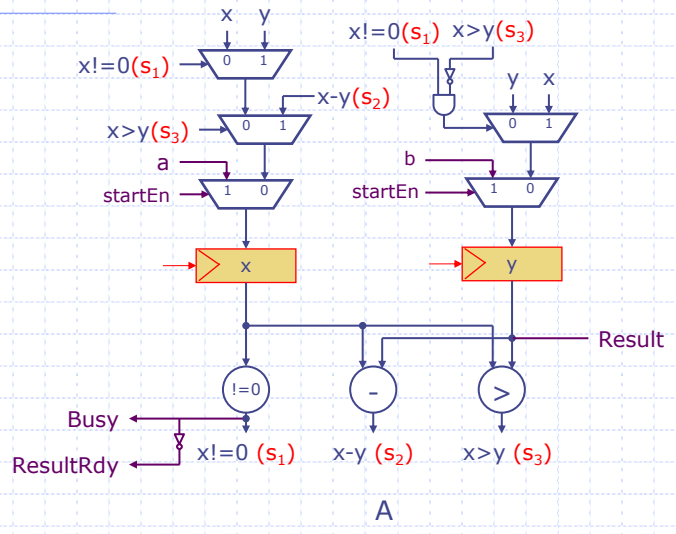
```
Reg#(Bit#(32)) x <- mkReg(0);
Reg#(Bit#(32)) y <- mkReg(0);
rule gcd;
  if (x >= y) begin
    x <= x - y;
  end else if (x != 0) begin
    x <= y; y <= x;
  end
endrule
method Action start(Bit#(32) a, Bit#(32) b);
  x <= a; y <= b;                          endmethod
method Bit#(32) result; return y;          endmethod
method Bool resultRdy;  return x == 0;     endmethod
method Bool busy;       return x != 0;     endmethod
```

A rule inside a module may execute anytime

If x is 0 then the rule has no effect

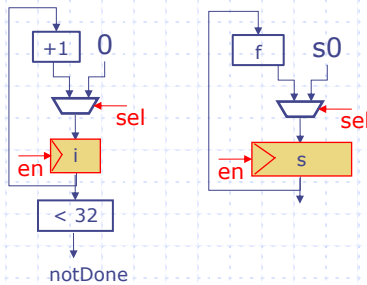
- Start method should be called only if busy is False.
- The result is available only when resultRdy is True.

Circuits for GCD



Expressing a loop using registers

```
int s = s0;
for (int i = 0; i < 32; i = i+1) {
    s = f(s);
  }
return s;                C-code
```



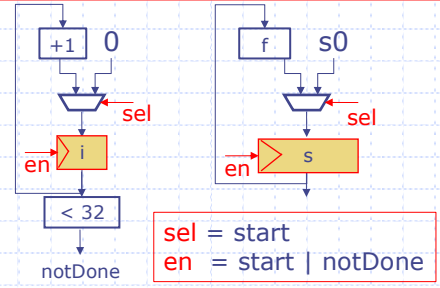
We need two registers to hold s and i values from one iteration to the next.
These registers are initialized when the computation starts and updated every cycle until the computation terminates

```
sel = start
en  = start | notDone
```

Expressing a loop in BSV

- When a rule executes:
  - all the registers are read at the beginning of a clock cycle
  - computations to evaluate the next value of the registers are performed
  - Registers that need to be updated are updated at the end of the clock cycle
- Muxes are need to initialize the registers

```
Reg#(Bit#(32)) s <- mkRegU();
Reg#(Bit#(6))  i <- mkReg(32);
rule step;
  if (i < 32) begin
     s <= f(s); i <= i+1;
  end
endrule
```



sel = start
en = start | notDone

Combinational 32-bit multiply

```
function Bit#(64) mul32(Bit#(32) a, Bit#(32) b);
  Bit#(32) tp = 0;
  Bit#(32) prod = 0;
  for(Integer i = 0; i < 32; i = i+1)
  begin
     Bit#(32) m   = (a[i]==0)? 0 : b;
     Bit#(33) sum = add32(m,tp,0);
     prod[i:i]    = sum[0];
     tp           = sum[32:1];
  end
  return {tp,prod};
endfunction
```

Combinational circuit uses 31 add32 circuits

We can reuse the same add32 circuit if we store the partial results in a *register*

Multiply using registers

```
function Bit#(64) mul32(Bit#(32) a, Bit#(32) b);
  Bit#(32) prod = 0;
  Bit#(32) tp = 0;
  for(Integer i = 0; i < 32; i = i+1)
  begin
     Bit#(32) m = (a[i]==0)? 0 : b;
     Bit#(33) sum = add32(m,tp,0);
     prod[i:i] = sum[0];
     tp = sum[32:1];
  end
  return {tp,prod};
endfunction
```

Combinational version

Need registers to hold a, b, tp, prod and i

Update the registers every cycle until we are done

Sequential Circuit for Multiply

```
Reg#(Bit#(32)) a <- mkRegU();
Reg#(Bit#(32)) b <- mkRegU();
Reg#(Bit#(32)) prod <-mkRegU();
Reg#(Bit#(32)) tp <- mkReg(0);
Reg#(Bit#(6))  i <- mkReg(32);

rule mulStep;
  if (i < 32) begin
     Bit#(32) m = (a[i]==0)? 0 : b;
     Bit#(33) sum = add32(m,tp,0);
     prod[i] <= sum[0];
     tp <= sum[32:1];
     i <= i+1;
  end
endrule
```

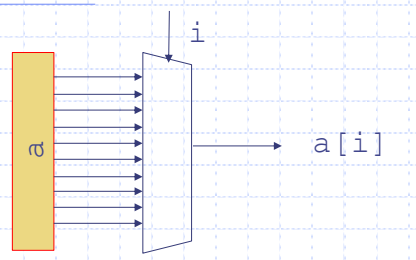
state elements

a rule to describe the dynamic behavior

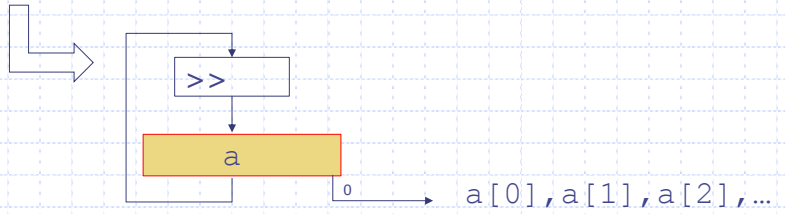
similar to the loop body in the combinational version

So that the rule has no effect until i is set to some other value

Dynamic selection requires a mux



when the selection indices are regular then it is better to use a shift operator (no gates!)

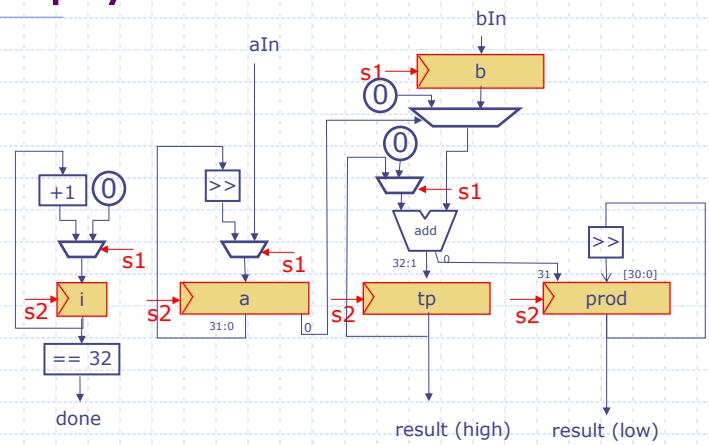


Replacing repeated selections by shifts

```
Reg#(Bit#(32)) a <- mkRegU();
Reg#(Bit#(32)) b <- mkRegU();
Reg#(Bit#(32)) prod <-mkRegU();
Reg#(Bit#(32)) tp <- mkReg(0);
Reg#(Bit#(6))  i <- mkReg(32);

rule mulStep if (i < 32);
   Bit#(32) m = (a[0]==0)? 0 : b;
   a <= a >> 1;
   Bit#(33) sum = add32(m,tp,0);
   prod <= {sum[0], prod[31:1]};
   tp <= sum[32:1];
   i <= i+1;
endrule
```

Circuit for Sequential Multiply



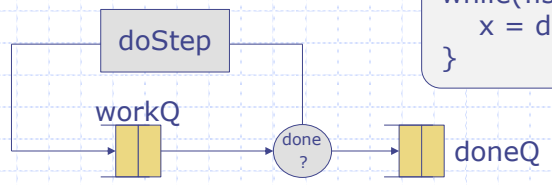
s1 = start_en
s2 = start_en | !done

Circuit analysis

- Number of add32 circuits has been reduced from 31 to one, though some registers and muxes have been added
- The longest combinational path has been reduced from 62 FAs to one add32 plus a few muxes
- The sequential circuit will take 31 clock cycles to compute an answer

A subtle problem

```
while(!isDone(x)) {
   x = doStep(x);
}
```

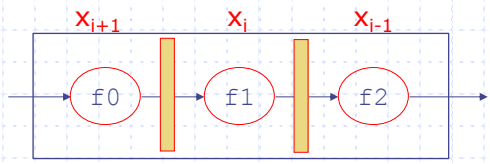



```
let x = workQ.first;
workQ.deq;
if (isDone(x)) begin
  doneQ.enq(x);
end else begin
   workQ.enq(doStep(x));
end
```

Double write problem for previously shown FIFOs

Later we will design FIFOs to permit simultaneous enq and deq

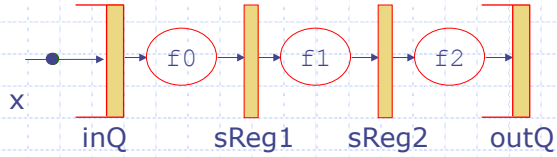
Pipelining Combinational Functions



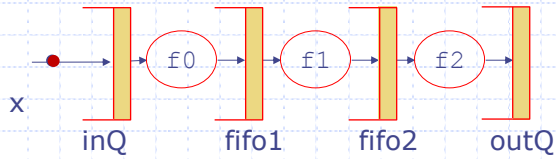
3 different datasets in the pipeline

- Lot of area and long combinational delay
- Folded or multi-cycle version can save area and reduce the combinational delay but throughput per clock cycle gets worse
- Pipelining: a method to increase the circuit throughput by evaluating multiple inputs

Inelastic vs Elastic pipeline



Inelastic: all pipeline stages move synchronously



Elastic: A pipeline stage can process data if its input FIFO is not empty and output FIFO is not Full

Most complex processor pipelines are a combination of the two styles