Learn RISC-V CPU Implementation and **BSV**

(**BSV**: a High-Level Hardware Design Language)

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L17: **BSV**: Tighter Rule scheduling with CRegs

Reminders

Please git clone: `https://github.com/rsnikhil/Learn_Bluespec_and_RISCV_Design`
(git pull for latest version). Repsitory structure:

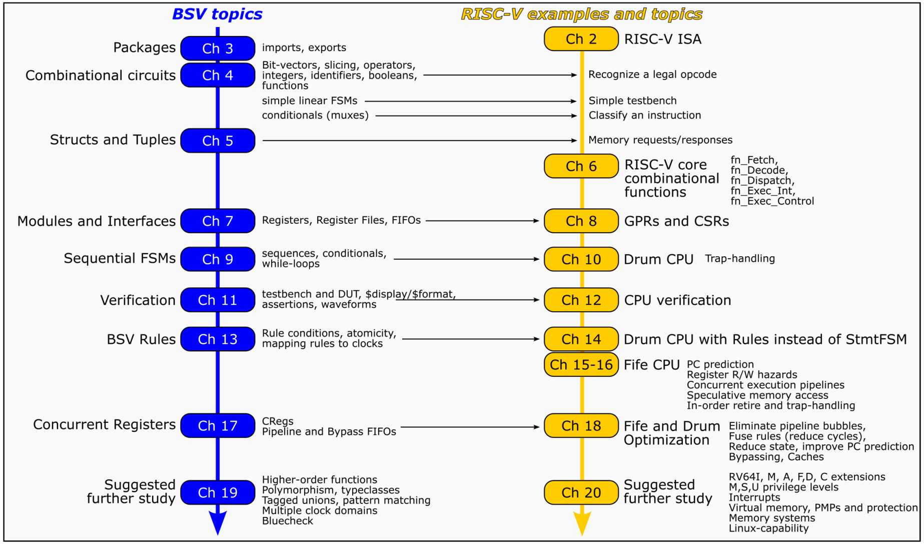
```
./Book_BLang_RISCV.pdf
  Slides/
      Slides_01_Intro.pdf
      Slides_02_ISA.pdf
      ...
  Exercises/
      Ex-03-A-Hello-World/
      Ex-03-B-Top-and-DUT/
      ...
  Code/
      src_Top/
      src_Drum/
      src_Fife/
      src_Common/
      ...
  Doc/Installing_bsc_Verilator_etc.{adoc,html}
```

- Slides and Exercise are numbered in sync with book Chapter numbers.
- For Exercises, please see Appendix E of the book. Some (not all) exercises have associated code in the `Exercises/` directory.

To compile and run the code for exercises, Drum and Fife, please make sure you have installed:

- *bsc* compiler (see `https://github.com/B-Lang-org/bsc`)
- Verilator compiler (see `https://www.verilator.org/`)

Chapter Roadmap



BSV topics
RISC-V examples and topics
Packages
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Bit-vectors, slicing, operators, integers, identifiers, booleans, functions
simple linear FSMs
conditionals (muxes)
Structs and Tuples
Ch 5
Modules and Interfaces
Ch 7
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Sequential FSMs
Ch 9
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Ch 14
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Register R/W hazards
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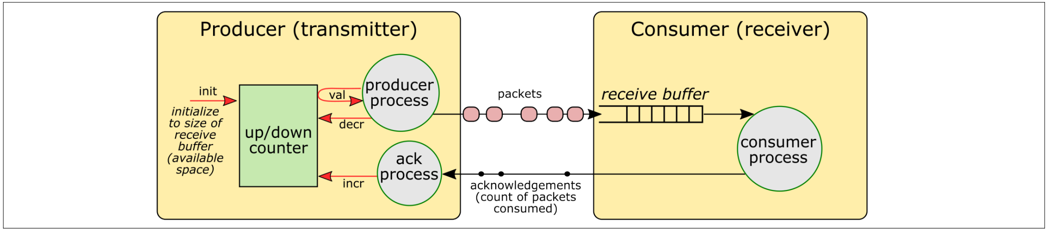
BSV: Tighter Rule Scheduling: Motivation

Tighter Rule Scheduling: An Analogy

	RISC-V ISA	**BSV**
(A) Spec semantics	*RISC-V ISA semantics are abstract: one instruction at a time* *Specifically: register and memory updates in one instruction are visible to the subsequent and later instructions.*	Rule semantics are abstract: one rule at a time *Specifically: effects of* `Action/ActionValues` *in one rule are visible to the subsequent and later rules.*
(B) Implementation	RISC-V instructions can be executed in pipelines, in parallel (superscalar), out-of-order, ... The implementation must ensure that the *order* in which they read and write registers and memory is consistent with (A). In particular, an instruction may be *stalled* to avoid violating (A) (with scoreboards, bypassing, forwarding, ...).	When the *bsc* compiler maps a set of rules to execute simultaneously (in the same clock), all their methods occur at the same instant (clock edge). All "read-values" are from the previous clock edge; all "write-values" (`Action` and `ActionValue` results) are visible only at the next clock edge. *bsc* must ensure that the *ordering* of methods in (B) is consistent with (A). In particular, *bsc* may *stall* a rule to avoid violating (A) (with a combinational control circuit).
	Fused instructions (*e.g.,* Fused Multiply-Add) can avoid this stall.	*Fused* registers ("Concurrent Registers") can avoid this stall.

Tighter Rule Scheduling: Motivational Example: Up-Down Counter (1/2)

Consider this scenario, where a Producer streams packets over a long connection to a Consumer:



```
interface Up_Down_Counter_IFC;
   method Action   init (Bit #(4) init_val);
   method Bit #(4) val;
   method Action   decr;
   method Action   incr;
endinterface
```

To avoid over-running the receive buffer, The producer:

- initializes the counter to the available space in the buffer;
- for every packet sent, decrements the counter (`decr` method);
- stalls (doesn't send) if the counter value (`val` method) is zero (no space available).

As the receiver consumes packets from the buffer, it sends acknowledgements back to indicate the amount of space freed.

In the transmitter, acknowledgements are incremented back into the counter (`incr` method), allowing transmission to continue.

Tighter Rule Scheduling: Motivational Example: Up-Down Counter (2/2)

Here is a possible implementation of the "Up-Down" Counter:

```
module mkUp_Down_Counter_I (Up_Down_Counter_IFC);
   // STATE
   Reg #(Bit #(4)) rg_counter <- mkReg (15);

   // --------------------------------
   // INTERFACE

   method Action init (Bit #(4) init_val);
      rg_counter <= init_val;
   endmethod

   method Bit #(4) val;
      return rg_counter;
   endmethod

   method Action decr () if (rg_counter != 0);
      rg_counter <= rg_counter - 1;
   endmethod

   method Action incr () if (rg_counter != 15);
      rg_counter <= rg_counter + 1;
   endmethod
endmodule
```

Analysis: Rules invoking `.incr()` and `.decr()` cannot execute on the same clock edge.

- (A) In the abstract rule semantics, either `.incr()` precedes `.decr()` or *vice versa*.

  In either case, the latter rule observes the update from the previous rule.

- (B) If they executed on the same clock, neither rule sees the update from the other rule. This is inconsistent with (A).

Thus, this implementation cannot send a packet (decr) and register an ack (incr) in the same clock, even though the two streams are asynchronous and concurrent.

On the average, we can only send (and register ack) on every alternate clock.

Solution:
Use a *Concurrent Register* (`CReg`) for `rg_counter`.

BSV: Concurrent Registers (`CRegs`)

Concurrent Registers (CRegs)

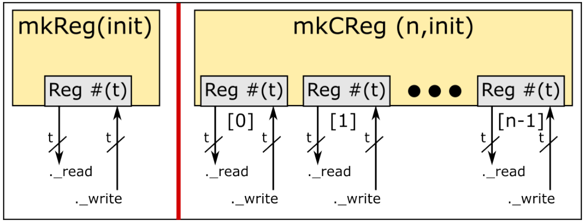
A Concurrent Register, or `CReg`, is a module provided by the *bsc* library. Its interface is an *array* of `Reg#(t)` interfaces:

```
module mkCReg #(parameter Integer n,
                parameter a_type resetval)
              (Reg#(a_type) ifc[])
```

It is instantiated similar to this example:
(This example: register content type: `Bit#(4)`; initial value: 15; three `Reg` interfaces).

```
   // parameter n is 3, resetval is 15
   Array #(Reg #(Bit #(4))) crg_counter <- mkCReg (3, 15);
```

Compare `mkReg` and `mkCReg`:



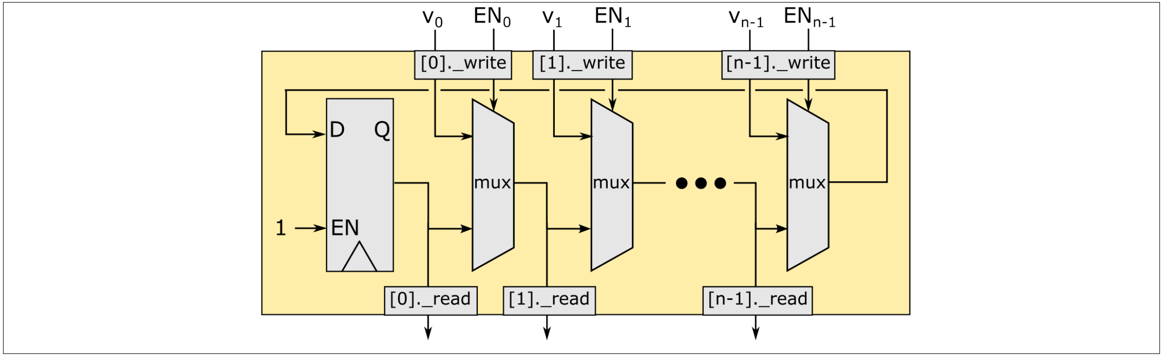
CReg ordering properties

- All the methods can be invoked in the same clock.
- A read at the j'th register interface, *i.e.*, `x[`j`]._read` returns the latest of:
  - the value v_{j-1}, if `x[`$j-1$`]._write(`v_{j-1}`)` is being invoked;
  - else the value v_{j-2}, if `x[`$j-2$`]._write(`v_{j-2}`)` is being invoked;
  - ...
  - else the value v_1, if `x[1]._write(`v_1`)` is being invoked;
  - else the value v_0, if `x[0]._write(`v_0`)` is being invoked;
  - else the value in the register.
- The register value is updated with the latest of:
  - the value v_{n-1}, if `x[`$n-1$`]._write(`v_{n-1}`)` is being invoked;
  - else the value v_{n-2}, if `x[`$n-2$`]._write(`v_{n-2}`)` is being invoked;
  - ...
  - else the value v_1, if `x[1]._write(`v_1`)` is being invoked;
  - else the value v_0, if `x[0]._write(`v_0`)` is being invoked;
  - else the current value in the register.

This ordering corresponds exactly the left-to-right ordering of `Reg#(t)` interfaces in (Slide 10),

and to the left-to-right and top-to-bottom ordering of the methods in the hardware-intuition diagram (Slide 12).

Hardware intuition for a CReg



This has an array of *n* `Reg` interfaces, indexed from 0 to *n*-1.

The *j*'th interface has `[`*j*`]._read()` and `[`*j*`]._write()` methods.

Up-down counter with a CReg

Using mkCReg:

```
module mkUp_Down_Counter_II (Up_Down_Counter_IFC);
   // STATE
   Array #(Reg #(Bit #(4))) crg_counter <- mkCReg (3,15);

   // --------------------------------
   // INTERFACE
   method Action init (Bit #(4) init_val);
      crg_counter [2] <= init_val
   endmethod

   method Bit #(4) val;
      return crg_counter [1];
   endmethod

   method Action decr if (crg_counter [1] != 0);
      crg_counter [1] <= crg_counter [1] - 1;
   endmethod

   method Action incr if (crg_counter [0] != 15);
      crg_counter [0] <= crg_counter [0] + 1;
   endmethod
endmodule
```

Using mkReg:

```
module mkUp_Down_Counter_I (Up_Down_Counter_IFC);
   // STATE
   Reg #(Bit #(4)) rg_counter <- mkReg (15);

   // --------------------------------
   // INTERFACE
   method Action init (Bit #(4) init_val);
      rg_counter <= init_val;
   endmethod

   method Bit #(4) val;
      return rg_counter;
   endmethod

   method Action decr () if (rg_counter != 0);
      rg_counter <= rg_counter - 1;
   endmethod

   method Action incr () if (rg_counter != 15);
      rg_counter <= rg_counter + 1;
   endmethod
endmodule
```

Up-down counter with a CReg

Some questions to ponder:

- What does method `val` return?
  The original value in the register?
  The value after the increment?
  The value after the decrement?
  The value after the increment and decrement?
- What happens if methods `incr` and `decr` are called simultaneously? Which one happens (semantically) "first"?
  Note: `incr` saturates at 15, and `decr` saturates at 0, so the order matters!

Hint: The answers are in the choice of `CReg` indexes in each method.

Example use of a CReg: CSR `mcycle` in RISC-V

CSR `mcycle` (RISC-V CPU cycle counter) is updated by two "processes":

- (A) Standalone infinite loop incrementing `mcycle` on every cycle.
- (B) Instruction execution, when we have a `CSRRxx` instruction that writes to `mcycle`.

The RISC-V spec says that when (B) happens, it should override (A).

We can instantiate a CReg for this:

from src_Common/CSRs.bsv

```
   Array #(Reg #(Bit #(64))) csr_mcycle <- mkCReg (2, 0);
```

(A) Standalone process incrementing it:

from src_Common/CSRs.bsv

```
   rule rl_count_cycles;
      csr_mcycle [0] <= csr_mcycle [0] + 1;
   endrule
```

(B) CSRRxx instruction execution (overrides (A) because of higher CReg index):

from src_Common/CSRs.bsv in function fav_csr_write()

```
   csr_mcycle [1] <= csr_val;
```

BSV: Higher-performance FIFOs (in library `SpecialFIFOs`)

(implemented using Concurrent Registers)

A FIFO implemented with ordinary registers

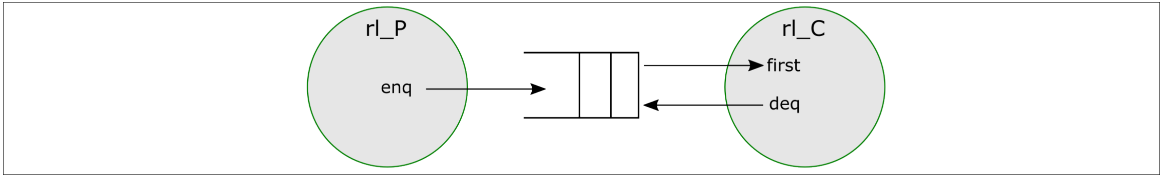
Consider the following module implementing a 1-element FIFO with a FIFOF interface, using ordinary registers (`mkReg`, `mkRegU`):

```
module mkFIFOF_I (FIFOF #(Bit #(32)));
   Reg #(Bit #(32)) rg_data <- mkRegU;
   Reg #(Bool)      rg_full <- mkReg (False);

   // ----------------
   // INTERFACE

   method Bool notEmpty ();
      return rg_full;
   endmethod

   method Bit #(32) first () if (rg_full);
      return rg_data;
   endmethod

   method Action deq () if (rg_full);
      rg_full <= False;
   endmethod
   ...
```

```
   ...
   method Bool notFull ();
      return (! rg_full);
   endmethod

   method Action enq (Bit #(32) x) if (! rg_full);
      rg_data <= x;
      rg_full <= True;
   endmethod

   method Action clear;
      rg_full <= False;
   endmethod
endmodule
```

Analysis of the performance of mkFIFOF_I

Consider a producer rule rl_P that invokes enq, and a consumer rule rl_C that invokes first and deq:



These rules cannot fire at the same instant (on the same clock) because both of them read and write register rg_Full (because both enq and deq read and write the register).

We can use a CReg to relax this constraint, in two different ways, which we call mkPipelineFIFOF and mkBypassFIFOF, respectively.

mkPipelineFIFOF

Instead of mkReg for rg_full, we can use mkCReg:

```
module mkPipelineFIFOF (FIFOF #(Bit #(32)))
   Reg #(Bit #(t))      rg_data  <- mkRegU;
   Array #(Reg #(Bool)) crg_full <- mkCReg (3, False);

   // ----------------
   // INTERFACE

   method Bool notEmpty ();
      return crg_full [0];
   endmethod

   method Bit #(32) first () if (crg_full [0]);
      return rg_data;
   endmethod

   method Action deq () if (crg_full [0]);
      crg_full [0] <= False;
   endmethod
   ...
```

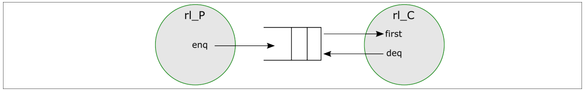
```
   ...
   method Bool notFull ();
      return (! crg_full [1]);
   endmethod

   method Action enq (Bit #(32) x) if (! crg_full [1]);
      rg_data      <= x;
      crg_full [1] <= True;
   endmethod

   method Action clear;
      crg_full [2] <= False;
   endmethod
endmodule
```

Note that the “dequeue” side methods use index [0], “enqueue” side use methods index [1]; and “clear” uses index [2].

These choices affect the ordering semantics of the methods.

Analysis of the performance of mkPipelineFIFOF

Consider again a producer rule `rl_P` that invokes `enq`, and a consumer rule `rl_C` that invokes `first` and `deq`:



Because of `mkPipelineFIFOF`'s CReg indexes, in the equivalent rule-at-a-time semantics, `rl_C` fires *before* `rl_P`. Thus, even if the FIFO was full at the start of the clock, `rl_P` can still `enq` into the FIFO, *provided* `rl_C` is firing on the same clock.

Per the rule-at-a-time semantics, `rl_C` fires first, which empties the FIFO, *i.e.,* `rl_P` sees the FIFO as empty and is therefore able to `enq` into it.

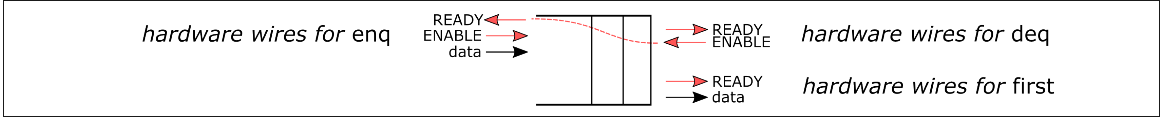
This is why we call it a "PipelineFIFO": it is an ideal candidate for the FIFO between stages of a pipeline, allowing the downstreanm stage (the consumer) and the upstream stage (the producer) to fire on the same clock, advancing data in a piplined manner.

Note also that another rule invoking `clear`, too, can fire on the same clock as `rl_P` and `rl_C`. Because of its CReg index, logically it fires "last", and so will leave the FIFO in a finally empty state.

Analysis of the hardware for `mkPipelineFIFOF`

In the Verilog for `mkPipelineFIFOF`, the READY signal for `enq` incorporates the ENABLE signal of the `deq` method (because if the FIFO is full from the previous clock, in this clock `enq` can only be invoked if `deq` is also being invoked).

Thus, there is a *combinational path* backward through the FIFO (a path that involves only wires and gates and no state-element) from the `deq` method to the `enq` method.



mkBypassFIFOF

What happens if we exchange the [0] and [1] CReg indexes?

```
module mkBypassFIFOF (FIFOF #(Bit #(32)))
   Array #(Reg #(Bit #(32))) crg_data <- mkCRegU (2);
   Array #(Reg #(Bool))      crg_full <- mkCReg (3,
                                                 False);

   // ----------------
   // INTERFACE

   method Bool notEmpty ();
      return crg_full [1];
   endmethod

   method Bit #(32) first () if (crg_full [1]);
      return crg_data [1];
   endmethod

   method Action deq () if (crg_full [1]);
      crg_full [1] <= False;
   endmethod
   ...
```

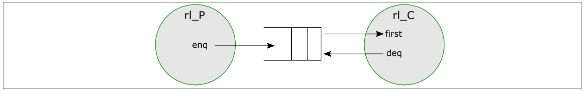
```
   ...
   method Bool notFull ();
      return (! crg_full [0]);
   endmethod

   method Action enq (Bit #(32) x) if (! crg_full [0]);
      crg_data [0] <= x;
      crg_full [0] <= True;
   endmethod

   method Action clear;
      crg_full [0] <= False;
   endmethod
endmodule
```

Now, the “enqueue” side methods use index [0] and the “dequeue” side methods use index [1] (“clear” still uses index [2]).

These choices change the ordering semantics of the methods.

Analysis of the performance of `mkBypassFIFOF`

Consider again a producer rule `rl_P` that invokes `enq`, and a consumer rule `rl_C` that invokes `first` and `deq`:



Because of `mkBypassFIFOF`'s CReg indexes, in the equivalent rule-at-a-time semantics, `rl_C` fires *after* `rl_P`. Thus, even if the FIFO was empty at the start of the clock, `rl_C` can still `deq` from the FIFO, *provided* `rl_P` is firing on the same clock.

Per the rule-at-a-time semantics, `rl_P` fires first, which fills the empty FIFO, *i.e.,* `rl_C` sees the FIFO as full and is therefore able to `deq` from it.

This is why we call it a "BypassFIFO". When used in a pipeline, the enqueued value can be "bypassed" straight through the FIFO to the consumer on the same clock.

Note: So, a `CReg` is needed for the data as well.

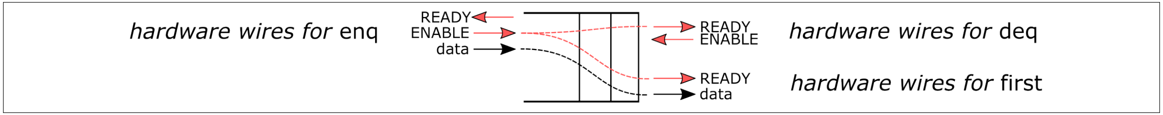
As with `mkPipelineFIFOF`, another rule invoking `clear`, too, can fire on the same clock as `rl_P` and `rl_C`. Because of its CReg index, logically it fires "last", and so will leave the FIFO in a finally empty state.

Analysis of the hardware for `mkBypassFIFOF`

In the Verilog for `mkBypassFIFOF`, the READY signal for `first` and `deq` incorporates the ENABLE signal of the `enq` method (because if the FIFO is empty from the previous clock, in this clock `first` and `deq` can only be invoked if `enq` is also being invoked).

Similarly, for the data to be bypassed through, there has to be a combinational path from the `enq` argument to the `first` result.

Thus, there are *combinational paths* forward through the FIFO (paths that involve only wires and gates and no state-element) from the `enq` method to the `first` and `deq` methods.



Summary of mkFIFOF, mkPipelineFIFOF and mkBypassFIFOF

	mkFIFOF	mkPipelineFIFOF	mkBypassFIFOF
1-tick traversal	Yes	Yes	Yes
# of buffer registers	2	1	1
Scheduling constraints	None	deq before enq	enq before deq
Through combinational circuits	None	deq $\rightarrow$ enq	enq $\rightarrow$ deq
Separate compilation of stages	No	No	No

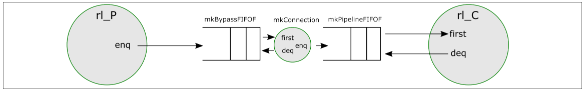
In the next section we'll discuss an alternative: back-to-back composition of mkBypassFIFOF and mkPipelineFIFOF

BSV: Connecting pipeline stages

Back-to-back composition of BypassFIFO and PipelineFIFO (1/2)

An interesting component is a back-to-back composition of the two high-performance FIFOs we have discussed.

Consider this code fragment, illustrated below:



```
module mk... (...);
   FIFOF #(Bit #(32)) f_bypass   <- mkBypassFIFOF;
   FIFOF #(Bit #(32)) f_pipeline <- mkPipelineFIFOF;

   // Producer rule (into f_bypass's enq side)
   rule rl_P;
      ... f_bypass.enq (x);
   endrule

   // Connect f_bypass's first/deq side
   // to f_pipeline's enq side
   mkConnection (to_FIFO_O (f_bypass),
                 to_FIFO_I (f_pipeline));

   // Consumer rule (from f_pipeline's first/deq side)
   rule rl_C;
      let y = f_pipeline.first;
      f_pipeline.deq;
   endrule
endmodule
```

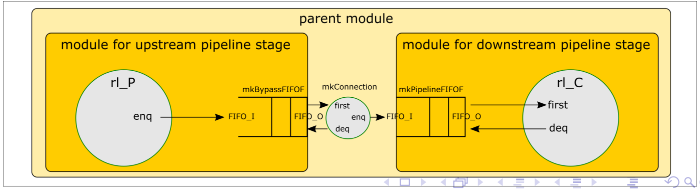
Back-to-back composition of BypassFIFO and PipelineFIFO (2/2)

This has some pleasant properties:

- Despite there being two FIFOs, it takes only one tick to traverse them (because of the nature of BypassFIFOs).
- There are no ordering constraints across the composed FIFOs, *i.e.*, the FIFOs do not induce any ordering constraints between the producer rule `rl_P` and the consumer rule `rl_C` (they are "conflict free"). They can fire in the same clock and can go in either logical order.
- There are no combinational paths through the pair of FIFOs! One can verify this by studying the Verilog. The *bsc* compiler also helpfully reports the absence of combinational paths.
- Enables easier separate compilation (into Verilog) of stage modules: place one of the two component FIFOs in each stage module, and use `mkConnection` in the parent module.

  (Separate compilation is possible with the other FIFOs, but is messier.)

This makes it attractive for connecting stages in a pipeline, enabling a *modular* separation of stages, where each stage can be independently verified and compiled to Verilog. We use this technique everywhere in Fife.



Summary of `mkPipelineFIFOF` and `mkBypassFIFOF` and their composition

	`mkFIFOF`	`mkPipelineFIFOF`	`mkBypassFIFOF`	Composition
1-tick traversal	Yes	Yes	Yes	Yes
# of buffer registers	2	1	1	2
Scheduling constraints	None	`deq` before `enq`	`enq` before `deq`	None
Through combinational circuits	None	`deq` $\rightarrow$ `enq`	`enq` $\rightarrow$ `deq`	None
Separate compilation of stages	No	No	No	Yes

Final comments on CRegs

- CRegs allow us to save a cycle by allowing two rules to run concurrently in the same clock where previously they had to run in separate clocks.

  Effectively, CRegs allow us safely to *fuse* the actions in two different rules into a single composite action (whenever the rule conditions allow)

- It plays a central rule in fine-tuning **BSV** designs for optimal performance, without changing the functional semantics (rule-at-a-time).

  In RISC-V designs, CRegs enable:

  - Isolation of stages (no combinational paths) while preserving pipeline speed (as discussed in Slide 28).
  - Faster PC redirection after a misprediction
  - Faster resolution of register dependencies in the scoreboard
  - Faster reorder buffers in Out-Of-Order processors
  - ... and more ...

Caveat: Before CRegs were available in **BSV***, designs used a facility called "RWires" for the same fusion optimizations. RWires are still available in* **BSV** *(see library documentation), but we recommend using CRegs in new designs. RWires muddy the otherwise clear separation of functional semantics (logical) and clocked semantics (implementation).*

End