Lab 1: Combinational Circuits

CSE 4190.308 Computer Architecture
5 Exercises (Total 60 Points)

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TA Office Hours: 7:00 - 8:00 p.m., 4/1, 4/2

1 Introduction

You will build up a barrel shifter from gate primitives. First, you will build a 1-bit multiplexer. Next, you will write a polymorphic multiplexer using for-loops. Using the gate-level multiplexer function, you will then construct a combinational barrel-shifter. Finally, we will add a simple gate-level modification to the barrel shifter to support the arithmetic right shift operation. This allows us to use the barrel shifter for both logical and arithmetic operations.

The left shift (`<<`) and right shift (`>>`) operations are employed in computer programs to manipulate bits and to simplify multiplication and division in some special cases. Shifting is considered a simple operation because shift has a relatively small and fast implementation in hardware; shift can typically be implemented in a single processor cycle, while multiplication and division take multiple cycles.

Shifts are inexpensive in hardware because their functional implementation involves wiring, rather than transistors. For example, a shift by a constant value is implemented with wires, as shown in Figure 1a. Variable Shifting is more complicated, but still efficient.

The barrel shifter (shown in Figure 1b) is more general than the wired shifter, but requires more hardware. The shift amount (`shiftAmt`) determines how far the input is shifted.

The microarchitecture of the barrel shifter is a logarithmic circuit for variable length shifting. The key observation in this microarchitecture is that any shift can be done by applying a sequence of smaller shifts. For example, a left shift by three can be decomposed into a shift by one and a shift by two. At each level of the shifter, the shifter conditionally shifts the data, using a multiplexer to select the data for the next stage.

In this lab we will implement the right shift operation, for which there are two possible meanings, logical and arithmetic which differ in preservation of the two's complement sign bit.

2 Getting Started

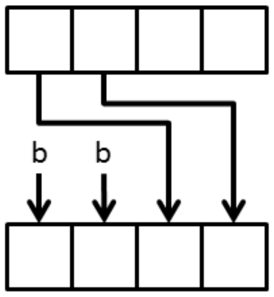
2.1 How to Download the Source Code

컴퓨터 구조 과목에서 사용하게 될 모든 실습은 Lab 0에서도 언급되었듯이 eTL을 통해 관리됩니다. Lab1의 실습 코드를 받으시기 위해서는 수업 홈페이지에 올라와 있는 Lab 1 과제란에서 다운로드 받아 본인의 로컬 환경에서 수행하시면 됩니다.

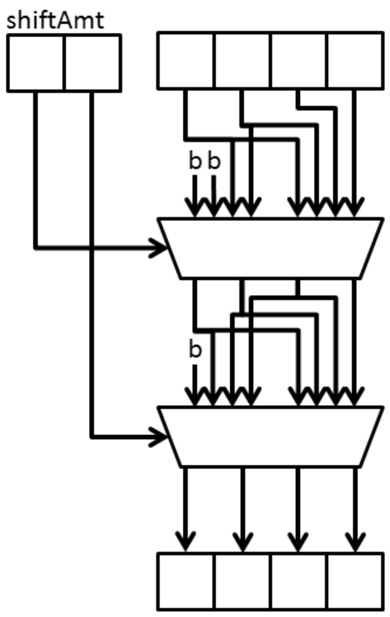
2.2 Directory Structure of Lab1

Lab1 실습의 디렉토리 구조는 다음과 같습니다.

`build`
: 컴파일 시 생성되는 파일들이 위치하는 폴더입니다.



(a) Wired Shifting by a Constant Value



(b) Variable Shifting by a Register Value

Figure 1: Different Types of Shifters

```
lab1/
    build/
    lib/
        TestBench.bsv
        ...
    src/
        BarrelShifterRight.bsv
        Multiplexer.bsv
        Makefile
        test
```

Figure 2: Directory structure of Lab1

`lib`
: 실습에 사용되는 library 파일들이 위치하는 폴더입니다.

`lib/TestBench.bsv`
: Multiplexer 및 barrel shifter 모듈을 시뮬레이션 할 수 있는 Bluespec 코드 입니다.

`src/Multiplexer.bsv`
: 삼항연산자를 사용하는 multiplexer 함수들을 가지고 있습니다. 이 파일을 수정하여 multiplexer 관련 숙제를 진행합니다.

`src/BarrelShifterRight.bsv`
: '>>' 연산자를 사용하는 기본적인 barrel shifter 초기 모듈을 가지고 있습니다. 이 파일을 수정하여 barrel shifter 관련 숙제를 진행합니다.

`src/Makefile`
: Lab 1 코드의 컴파일 관련 명령 및 세부적인 사항이 정의되어 있습니다. *make* 명령을 통해 bluespec 코드의 컴파일 가능하게 해줍니다.

`src/test`
이 파일을 이용하여 컴파일이 완료된 Lab 1을 실행시켜 볼 수 있습니다.

2.3 How to Test the Design

실습에서 제공되는 test-bench는 여러분이 구현할 multiplexer 및 combinational barrel-shifter의 동작을 확인합니다. 먼저 모듈의 컴파일은

```
$ make mul  or  $ make rl  or  $ make ra  or  $ make all
```

와 같은 명령을 통해 수행할 수 있습니다. 컴파일을 통해 생성된 실행파일을 `test` 파일을 통해 테스트하여 여러분이 구현한 모듈의 동작을 확인할 수 있습니다.

```
$ ./test mul  or  $ ./test rl  or  $ ./test ra  or  $ ./test all
```

컴파일 및 테스트에 대한 자세한 내용은 연관된 Exercise에 설명되어 있습니다.

2.4 How to Submit Your Design

lab1폴더를 압축하여 수업 홈페이지에 올라와 있는 Lab 1 과제제출란에 제출하면됩니다.

3 Building a Barrel Shifter in Bluespec

3.1 Multiplexers

The first step in constructing or barrel shifter is to build a basic multiplexer from gates. Let's first examine Multiplexer.bsv.

```
function Bit#(1) multiplexer1(Bit#(1) sel, Bit#(1) a, Bit#(1) b);
```

This begins a definition of a new function called multiplexer1. This multiplexer function takes several arguments which will be used in defining the behavior of the multiplexer. This multiplexer operates on single bit values, the concrete type `Bit#(1)`. Later we will learn how to implement polymorphic functions, which can handle arguments of any width.

This function uses C-like constructs in its definition. Simple code, such as the multiplexer can be defined at the high level without implementation penalty. However, because hardware compilation is a dificult, multi-dimensional problem, tools are limited in the kinds of optimizations that they can do. As we shall see later with the high-level barrel shifter, high-level constructs can sometimes result in inefficient hardware. As a result, even complicated designs like processors may be implemented at the gate-level (or even transistor-level) to achieve maximum performance.

```
  return (sel == 0)? a: b;
endfunction
```

The `return` statement, which constitutes the entire function, takes two input and selects between them using `sel`. The `endfunction` keyword completes the definition of our multiplexer function. You should be able to compile the module.

Exercise 1 (10 Points): Using the and, or, and not gates, re-implement the function `multiplexer1` in Multiplexer.bsv. How many gates are needed? (The required functions, called `and1`, `or1` and `not1`, respectively, are provided)

3.2 Static Elaboration

The data path width of the Y86-64 processor is 64 bits, so we will need multiplexers that are larger than a single bit. However, writing the code to manually instantiate 64 single-bit multiplexers to form a 64-bit multiplexer would be tedious. Fortunately, Bluespec provides constructs for powerful static elaboration which we can use to make writing the code easier. Static elaboration refers to the process by which the Bluespec compiler evaluates expressions at compile time, using the results to generate the hardware. Static elaboration can be used to express extremely flexible designs in only a few lines of code.

In Bluespec we can use bracket notation (`[]`) to index individual bits in a wider Bit type, for example `bitVector[1]`. We can use a for-loop to copy many lines of code which have the same form. For example, to aggregate the multiplexer1 function to form a larger multiplexer, we could write:

```
function Bit#(64) multiplexer64(Bit#(1) sel, Bit#(64) a, Bit#(64) b);
  Bit#(64) aggregate;
  for(Integer i = 0; i < 64; i = i + 1)
    aggregate[i] = multiplexer1(sel, a[i], b[i]);
  return aggregate;
endfunction
```

The Bluespec compiler, during its static elaboration phase, will replace this for-loop with its fully unrolled version.

```
aggregate[0] = multiplexer1(sel, a[0], b[0]);
aggregate[1] = multiplexer1(sel, a[1], b[1]);
aggregate[2] = multiplexer1(sel, a[2], b[2]);
...
aggregate[63] = multiplexer1(sel, a[63], b[63]);
```

Exercise 2 (10 Point): Complete the implementation of the function `multiplexer64` in Multiplexer.bsv using for-loops (in other words, copy the above code).

Check the correctness of the code by running the multiplexer testbench:

```
$ make mul
$ ./test mul
```

3.3 Polymorphism and Higher-order Constructors

So far, we have implemented two versions of the multiplexer function, but it is easy to imagine needing an n-bit multiplexer. It would be nice if we did not have to completely re-implement the multiplexer whenever we want to use a different width. Using the for-loops introduced in the previous section, our multiplexer code is already somewhat parametric because we use a constant size and the same type throughout. We can do better by giving a name (`N`) to the size of the multiplexer using `typedef`. Our new multiplexer code looks like:

```
typedef 64 N;
function Bit#(N) multiplexerN(Bit#(1) sel, Bit#(N) a, Bit#(N) b);
  Bit#(N) aggregate;
  for(Integer i = 0; i < valueOf(N); i = i + 1)
    aggregate[i] = multiplexer1(sel, a[i], b[i]);
  return aggregate;
endfunction
```

The `typedef` gives us the ability to change the size of our multiplexer at will. The `valueOf` function introduces a small subtlety in our code: `N` is not an Integer but a *numeric type* and must be converted to an Integer before being used in an expression. Even though it is improved, our implementation is still missing some flexibility. All instantiations of the multiplexer must have the same type, and we still have to produce new code each time we want a new multiplexer. However, in Bluespec, we can further parameterize the module to allow different instantiations to have instantiation-specific parameters. This sort of module is polymorphic, the implementation of the hardware changes automatically based on compile time configuration. Polymorphism is the essence of design-space exploration in Bluespec.

The truly polymorphic multiplexer will be as follows:

```
//typedef 64 N; // Not needed
function Bit#(n) multiplexer_n(Bit#(1) sel, Bit#(n) a, Bit#(n) b);
```

The variable `n` represents the width of the multiplexer, replacing the concrete value `N` (=64). In Bluespec *type variables* (`n`) start with a lower case whereas concrete types (`N`) start with an upper case.

Exercise 3 (10 Points): Complete the definition of the function `multiplexer_n`. Verify that this function is correct by replacing the original definition of multiplexer64 to only have:
`return multiplexer_n(sel, a, b);`.
This redefinition allows the test benches to test your new implementation without modication.

3.4 Building a Barrel Shifter

We will now use the multiplexers that we implemented in the previous section to build a logical barrel shifter. To build this shifter we need a logarithmic number of multiplexers. At each stage, we will shift over twice as many bits as the previous stage, based on the control value, as shown in Figure 1b.

The implementation for the barrel-shifters can be found in BarrelShifterRight.bsv. Notice that all the barrel-shifters are declared as modules, as opposed to as functions. This is a subtle, but important distinction. In Bluespec, functions are inlined by the compiler automatically, while modules must be explicitly instantiated using the '`<-`' notation. If we made the barrel shifter a function, using it in multiple locations would instantiate multiple barrel shifters. One purpose of this lab was to build shift algorithms that share as much logic as possible, so we make the barrel shifter a module.

There are three modules inside BarrelShifterRight.bsv, `mkBarrelShifterRight`, `mkBarrelShifterRightLogical`, and `mkBarrelShifterRightArithmetic`. All three modules contain a method named `rightShift`, which implements the right shift. Notice that `rightShift` in `mkBarrelShifterRight` takes three arguments while `rightShift` in the others take only two. The third argument, `shiftValue`, specifies whether 0 or 1 is shifted in. In the logical barrel shifter, we always shift in 0 to the high-order bits. The arithmetic right shift preserves sign, so we need to examine the two's complement sign (high-order) bit and the shift mode to fill in the correct bits. The `mkBarrelShifterRightLogical` and `mkBarrelShifterRightArithmetic` should instantiate the basic `mkBarrelShifterRight`, and should supply the appropriate arguments to the `shiftRight` in `mkBarrelShifterRight` to implement the logical and arithmetic shifters, respectively.

Exercise 4 (20 Points): Complete an implementation of the 64-bit barrel shifter in `mkBarrelShifterRight`. Use exactly six 64-bit multiplexers in a for-loop. With the `mkBarrelShifterRight`, complete an implementation of the 64-bit logical shifter in `mkBarrelShifterRightLogical`, using `mkBarrelShifterRight` that you have implemented already. Check the correctness of the code by running the logical shifter testbench:

```
$ make rl
$ ./test rl
```

Exercise 5 (10 Points): Complete an implementation of the 64-bit arithmetic shifter in `mkBarrelShifterRightArithmetic`, using `mkBarrelShifterRight` that you have implemented already.

Check the correctness of the code by running the arithmetic shifter testbench:

```
$ make ra
$ ./test ra
```