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## 1. Wires

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# Lesson Overview



## ▷ Lesson Overview

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- What is a **wire**?
- What can I do with it?
- How do I build a design?

## Objectives

- To get an initial, basic familiarization with combinational logic
- To learn how to run the tools to build a design
- To get an initial design running on an FPGA board



# First design



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Let's build a simple Verilog design

```
module thruwire(i_sw, o_led);  
    input wire i_sw;  
    output wire o_led;  
  
    assign o_led = i_sw;  
endmodule
```



# First design



Let's build a simple Verilog design

```
module thruwire(i_sw, o_led);  
    input    wire    i_sw;  
    output   wire    o_led;  
  
    assign   o_led = i_sw;  
endmodule
```

- Verilog files contain modules
- This module is named thruwire
- While Verilog allows more than one module per file, I recommend only one module per file.

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Let's build a simple Verilog design

```
module thruwire(i_sw, o_led);  
    input    wire    i_sw;  
    output   wire    o_led;  
  
    assign   o_led = i_sw;  
endmodule
```

- The **module** keyword marks the beginning
- **endmodule** marks the end of the module



# First design



Let's build a simple Verilog design

```
module thruwire(i_sw, o_led);  
    input wire i_sw;  
    output wire o_led;  
  
    assign o_led = i_sw;  
endmodule
```

- This module declare two ports, `i_sw` and `o_led`
- The first is declared to be an **input**
- The second an **output**
- Both are **wire**'s, but we'll get to that later

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Let's build a simple Verilog design

```
module thruwire(i_sw, o_led);  
    input    wire    i_sw;  
    output   wire    o_led;  
  
    assign o_led = i_sw;  
  
endmodule
```

- Our one piece of logic sets o\_led to be the same as i\_sw



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Let's build a simple Verilog design

```
module thruwire(i_sw, o_led);  
    input    wire    i_sw;  
    output   wire    o_led;  
  
    assign   o_led = i_sw;  
endmodule
```

FPGA's are commonly used as:

- Traffic cops  
A programmable/adjustable wire fabric
- Voltage level shifters
- This logic would be appropriate for each  
... it generates a simple "wire" through the chip

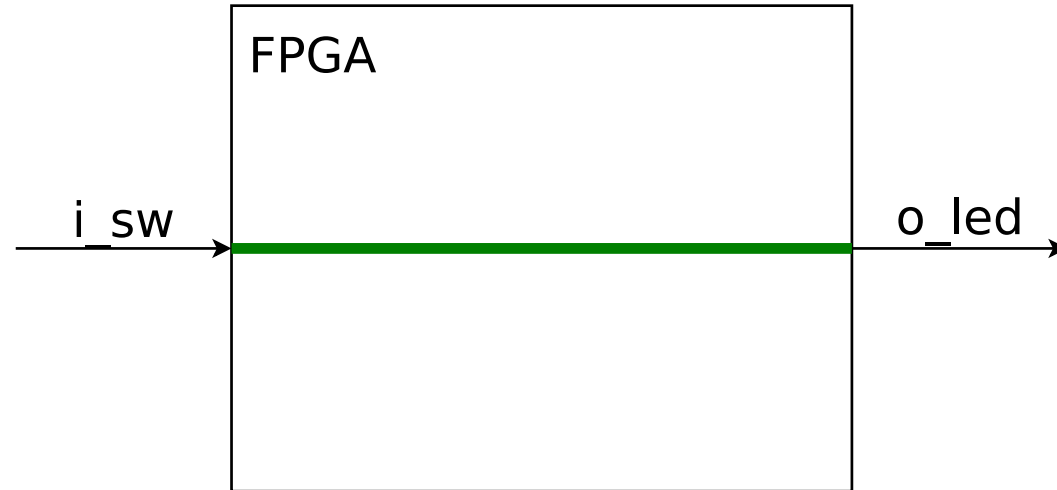




# Schematic



Here's what a schematic of this design would look like



All from this assign statement

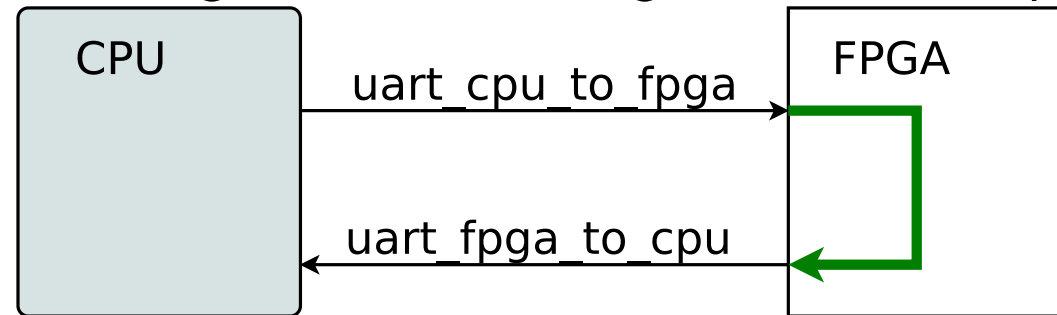
```
assign    o_led = i_sw;
```



# Schematic



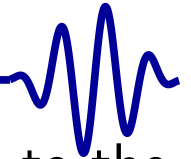
A very similar design would make a good first serial port test



- Your circuit board should pass this test before you try to implement your own serial port within it



# Constraints



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A fundamental part of any FPGA design maps your ports to the pins

- This is the purpose of a *Constraint File*
- Different vendors use different forms for their constraint files
  - PCF: Used by Arachne-PNR and NextPNR
  - UCF: Used by ISE for older Xilinx designs
  - XDC: Used by Vivado for newer Xilinx designs
  - QSF: Used by Quartus for ~~Altera~~ Intel chips
- Your board vendor should provide you with a master constraint file
- You'll still need to
  - Comment-out pins you aren't using
  - Rename pins to match your Verilog



# PCF File



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If you are using nextpnr, you'll need a PCF file

```
set_io    i_sw      P13
set_io    o_led     C8
```

- Maps top-level ports to pins
- You'll find P13 and C8 on the schematic
  - Find the FPGA pins connected to the switch  
... and the LED output
  - If your design has no switches, you can use buttons  
(for now)  
Buttons also bounce, but we'll get to that later



# UCF File



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If you are using ISE, you'll need a UCF file

```
NET "i_sw" LOC = "P9" | IOSTANDARD = LVCMOS33 ;
NET "o_led" LOC = "N3" | IOSTANDARD = LVCMOS33 ;
```

- This would be for the older Xilinx FPGA's
  - Make sure you actually look up the correct pins
    - P13 for one board might be something else on another
- On this board, the switch is on pin P9
- Most development boards use the 3.3V LVCMOS standard
    - Pins are typically grouped in banks
    - All pins in a bank use the same voltage
    - This voltage is usually fixed
    - The master constraint file will help here



# XDC File



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If you are using Vivado, you'll need a XDC file

```
set_property -dict {PACKAGE_PIN E22
                    IOSTANDARD LVCMOS12} [get_ports {i_sw}]
set_property -dict {PACKAGE_PIN T14
                    IOSTANDARD LVCMOS25} [get_ports {o_led}]
```

- This would be for the newer Xilinx FPGA's
- Usually, the vendor will provide a "master XDC" file
- From there, you should be able to
  - Rename the appropriate ports to `i_sw` and `o_led`
  - Comment out every other I/O port



# Build the design



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For an iCE40 design, this will look like:

```
% yosys -p 'synth_ice40 -json thruwire.json' \  
    thruwire.v  
% nextpnr-ice40 --hx8k --package ct256 \  
    --pcf thruwire.pcf --json thruwire.json  
% icepack thruwire.asc thruwire.bin
```

You'll need to do this for every project—get used to this flow.

- A makefile can drastically simplify this process

You should now have a file `thruwire.bin` that you can load onto your board.

- If you aren't using an iCE40, follow your chip vendor's instructions



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Follow your board vendor's instructions for loading this file onto your board.

Notice now that every time you flip the switch, the LED responds





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Follow your board vendor's instructions for loading this file onto your board.

Notice now that every time you flip the switch, the LED responds Yaaaayyyyyy!!! Your first FPGA design.



# Simulation



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Simulation is an important part of design

Simulation	Hardware
Can trace all signals	Can only see some signals
Extended tests cost GB	Extended tests are simple
Easy to debug	<i>Very hard</i> to debug

Because hardware is so hard to debug, simulation is vital

- A successful complex project  
... *requires simulation!*



# Simulation



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Simulation is an important part of design

Simulation	Hardware
Can trace all signals	Can only see some signals
Extended tests cost GB	Extended tests are simple
Easy to debug	<i>Very hard</i> to debug

Because hardware is so hard to debug, simulation is vital

- A successful complex project  
... *requires simulation!*

Do it the easy way:



# Simulation



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Simulation is an important part of design

Simulation	Hardware
Can trace all signals	Can only see some signals
Extended tests cost GB	Extended tests are simple
Easy to debug	<i>Very hard</i> to debug

Because hardware is so hard to debug, simulation is vital

- A successful complex project  
... *requires simulation!*

Do it the easy way: *use the simulator!*



# Verilator



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Let's now build our design using Verilator

```
% verilator -Wall -cc thruwire.v
% cd obj_dir/
% make -f Vthruwire.mk
```

- Verilator compiles Verilog into C++ placed into obj\_dir/
- The make command then builds this converted C++ file into a shared object file we can now use



# Verilator Driver



You'll need a main simulation driver too.

```
#include <stdio.h>
#include <stdlib.h>
#include "Vthruwire.h"
#include "verilated.h"

int main(int argc, char **argv) {
    // Your logic here
}
```

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# Verilator Driver



You'll need a main simulation driver too.

```
// ...  
int main(int argc , char **argv) {  
    // Call commandArgs first!  
    Verilated::commandArgs(argc , argv);  
  
    // Instantiate our design  
    Vthruwire *tb = new Vthruwire;  
  
    // ...  
}
```

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# Verilator Driver



You'll need a main simulation driver too.

```
int main(int argc, char **argv) {  
    // ...  
  
    // Now run the design thru 20 timesteps  
    for(int k=0; k<20; k++) {  
        // We'll set the switch input  
        // to the LSB of our step  
        tb->i_sw = k&1;  
  
        tb->eval();  
  
        // ...  
    }  
}
```





# Verilator Driver



You'll need a main simulation driver too.

```
int main(int argc, char **argv) {  
    // ...  
    for(int k=0; k<20; k++) {  
        // We'll set the switch input  
        // to the LSB of our counter  
        tb->i_sw = k&1;  
  
        tb->eval();  
  
        // Now let's print our results  
        printf("k_=%2d, ", k);  
        printf("sw_=%d, ", tb->i_sw);  
        printf("led_=%d\n", tb->o_led);  
    }  
}
```

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# Building it all



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Last step, let's put it all together:

```
% g++ -I /usr/share/verilator/include \
    -I obj_dir/ \
    /usr/share/verilator/include/verilated.cpp \
    thruwire.cpp obj_dir/Vthruwire__ALL.a \
    -o thruwire
```

(Double check the location of Verilator in your own installation, it might be located in another directory.)

Wow, that's pretty complicated.

You should have a Makefile in your ex-01-thruwire directory with both the code and the build instructions.

```
% cd ex-01-thruwire/
% make
# (Make output skipped for brevity)
%
```



# Simulation



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We can now run our simulator!

```
% thruwire
k = 0, sw = 0, led = 0
k = 1, sw = 1, led = 1
k = 2, sw = 0, led = 0
k = 3, sw = 1, led = 1
k = 4, sw = 0, led = 0
k = 5, sw = 1, led = 1
k = 6, sw = 0, led = 0
k = 7, sw = 1, led = 1
k = 8, sw = 0, led = 0
k = 9, sw = 1, led = 1
# .... (Lines skipped for brevity)
%
```



# Good habits



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Many Verilog problems can be avoided by some simple steps

1. Make **'default\_nettype** none the first line of your Verilog file
  - Before your **module** declaration
  - Otherwise mis-spelled identifiers will be quietly turned into wires

```
module thruwire(i_sw, o_led);  
        input    wire    i_sw;  
        output   wire    o_led;  
  
        assign   o_led = sw;  
endmodule
```

Without **'default\_nettype** none, this design would pass without error



# Good habits



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Many Verilog problems can be avoided by some simple steps

1. Make **'default\_nettype** none the first line of your Verilog file
2. Fix any errors when you verilate -Wall your design
3. Run your design in a simulator
  - Attempt to recreate any hardware bugs ... *in the simulator*

These three rules will save you a lot of heartache!  
... *Get in the habit of using them!*



# Bus Signals



That was one single wire. We can also declare values consisting of many bits.

```
input  wire [8:0] i_sw;  
output wire [8:0] o_led;
```

This defines

- `i_sw` to be 9-input wires, and
- `o_led` to be 9-output wires



# Bit Select



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- Select bits of interest from a bus

```
assign    o_led[7] = i_led[0];  
assign    o_led[6:4] = i_led[5:3];
```

- Bit 7 of o\_led is set to bit 0 of i\_led
- Bits 4 through 6 of o\_led is set to bits 3 through 5 of i\_led

- Concatenate bits together

```
assign    o_led[3:0] = {i_led[7:6], i_led[2:0]};
```

- The {.,.} operator composes a new bit vector from other vectors



# Internal Signals



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You can also declare and work with internal wires

```
wire      [8:0]    w_internal;
```

- Internal wires are neither **input** nor **output**
- These wires can now be used in logic

```
assign    w_internal = 9'h87;  
assign    o_led = i_sw ^ w_internal;
```





# Literals



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A Verilog literal is defined as

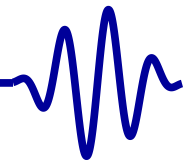
- A width
- An apostrophe
- A numeric type: h (hex), d (decimal), o (octal), b (binary), sd (signed decimal)
- The value: a series of digits, possibly containing underscores  
Underscores can be *very* useful for longer numbers

Examples include:

1'b0   1'b1   2'b01   4'b0101   4'h5   -7'sd124  
32'hdead\_beef   32'd100\_000\_000



# Operators



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The Verilog language supports the following operators

+	Addition	—	Subtraction
<<	Left Shift	>>	Right shift
—	Unary negation	?:	Tertiary operator
~	Bit-wise negation	^	Bit-wise XOR
	Bitwise OR	&	Bitwise AND
	Logical OR	&&	Logical and
!	Logical negation	>>>	Arithmetic right shift
==	Equality	!=	Inequality
<, <=	Less than (Equal)	>, >=	Greater than (Equal)
Limited, use with care		Avoid within logic	
*	Multiplication	/	Division
		%	Remainder

- Some FPGA's support native multiplication
- None support a single clock divide or remainder



# Schematic



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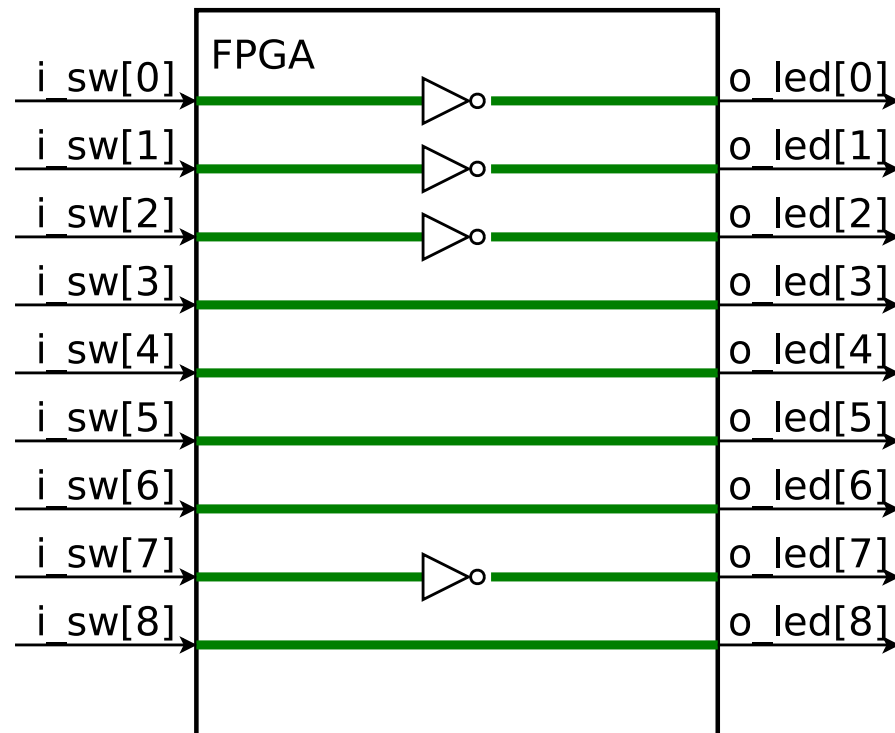
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From this code:

```
assign    w_internal = 9'h87;  
assign    o_led = i_sw ^ w_internal;
```

Get this internal structure:

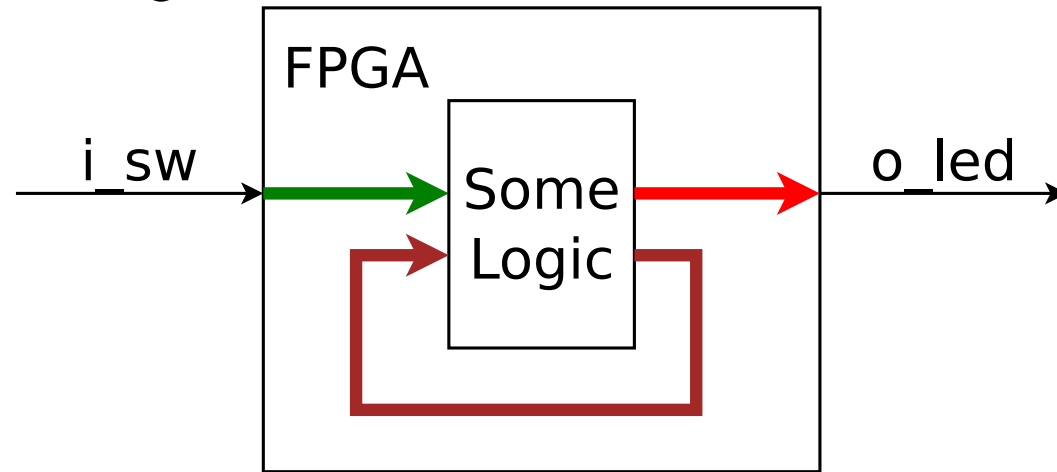




# Circular Logic



Avoid circular logic!



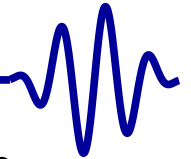
Example:

```
assign    o_led = i_sw + o_led;
```

- This doesn't work in hardware like it might in software
  - This is roughly equivalent to creating a short circuit
  - Most tools will fail to build such designs
- This include Verilator



# Dual Assignment



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You are designing hardware: A value can only be set once  
This is an error:

```
assign    o_led = i_sw + o_led;  
assign    o_led = i_sw + 1;;
```



# Let's build it



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Let's build this design:

```
'default_nettype none

module maskbus(i_sw, o_led);
    input    [8:0]    i_sw;
    output   [8:0]    o_led;

    assign   w_internal = 9'h87;
    assign   o_led = i_sw ^ w_internal;
endmodule
```

... using Verilator



# Updated Driver



Let's update our driver for this wire bus design

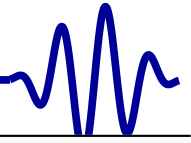
```
int main(int argc, char **argv) {
    // ...
    for(int k=0; k<20; k++) {
        // ...
        // Bottom 9 bits of counter
        tb->i_sw = k&1ff;

        tb->eval();

        // Now let's print our results
        printf("k_=%2d, ", k);
        printf("sw_=%3x, ", tb->i_sw);
        printf("led_=%3x\n", tb->o_led);
    }
}
```



# Sim Result



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```
% ./maskbus
```

```
k = 0, sw = 0, led = 87
```

```
k = 1, sw = 1, led = 86
```

```
k = 2, sw = 2, led = 85
```

```
k = 3, sw = 3, led = 84
```

```
k = 4, sw = 4, led = 83
```

```
k = 5, sw = 5, led = 82
```

```
k = 6, sw = 6, led = 81
```

```
k = 7, sw = 7, led = 80
```

```
k = 8, sw = 8, led = 8f
```

```
k = 9, sw = 9, led = 8e
```

```
# .... (Lines skipped for brevity)
```

```
%
```





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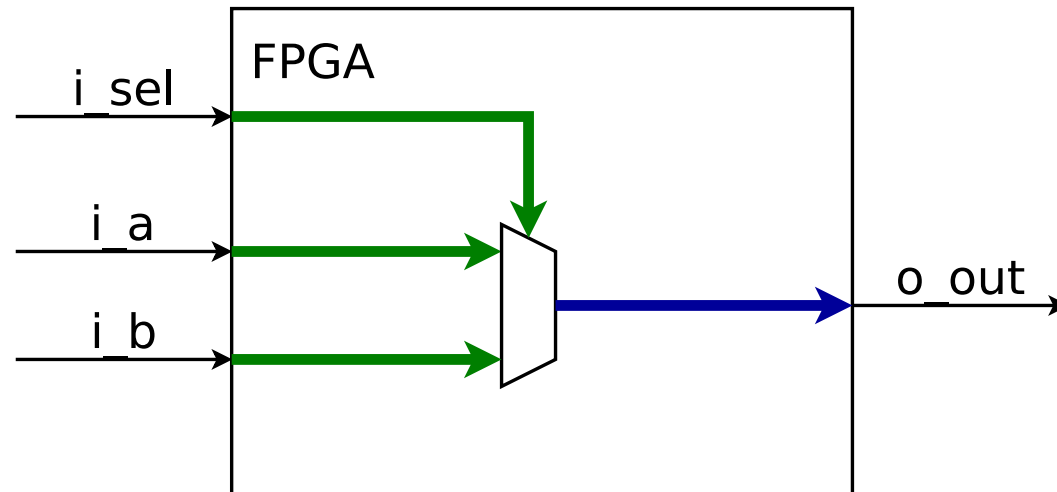
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What can you do with wires and wire logic?

Example: Multiplexer

```
input    wire    i_a, i_b, i_sel;  
output   wire    o_out;  
  
assign   o_out = (i_sel) ? i_a : i_b;
```





# Examples



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What can you do with wires and wire logic?

Example: Multiplexer

```
input      wire      i_a, i_b, i_sel;  
output     wire      o_out;  
  
assign     o_out = (i_sel) ? i_a : i_b;
```

- This is a good example of the tertiary operator
- Interested in making a connection to one of two serial ports?
- How about connecting one of two bus masters to an interconnect?

We'll get to these examples later.



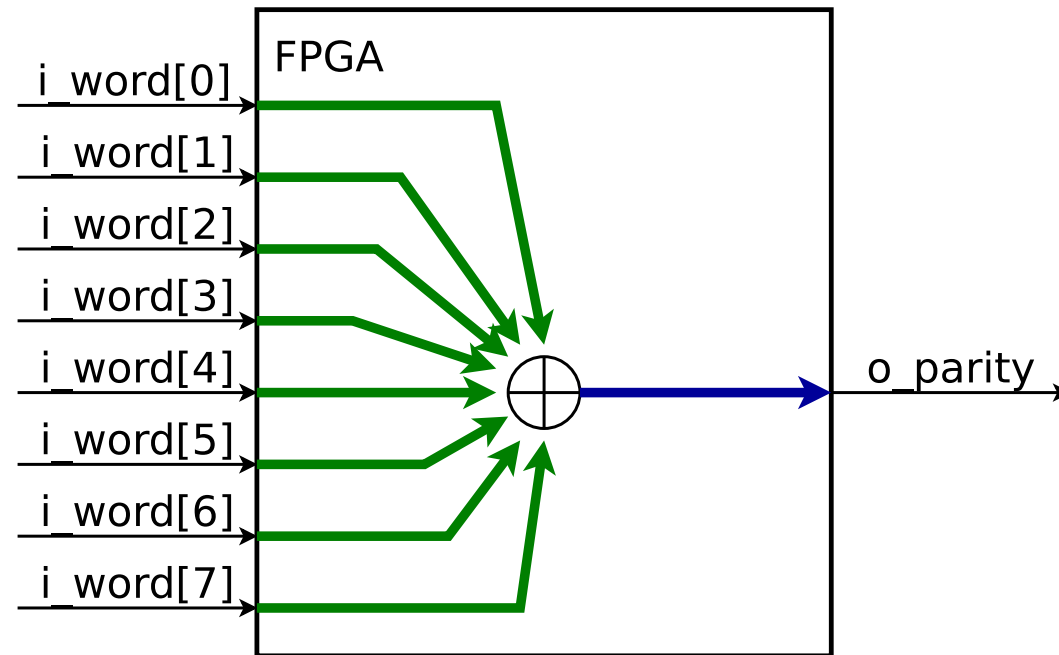
# Examples



What can you do with wires and wire logic?

Example: Parity check

```
input    wire    [7:0]    i_word;  
output   wire                   o_parity;  
  
assign   o_parity = ^i_word;
```





# Examples



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What can you do with wires and wire logic?

Example: Parity check

```
input  wire [7:0] i_word;
output wire      o_parity;

assign o_parity = ^i_word;
```

This form of XOR is a *reduction operator*

- It XORs all the word's bits together
- Other reduction operators include | and &

Error Correction Code (ECC) creation logic is very similar



# Examples



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What can you do with wires and wire logic?

Example: Interrupt detector

```
input    wire    [7:0]    i_irq_source;  
output   wire    o_irq;  
  
assign   o_irq = | i_irq_source;
```

- `i_irq_source` contains eight interrupt sources
- `o_irq` is true if any interrupt source is true



# Examples



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What can you do with wires and wire logic?

Example: CPU stall determination

```
assign    dcd_stall = (dcd_valid)&&(op_stall);
```

From the ZipCPU, the decode stage must stall if

- It has produced a valid result, and
  - The next stage, read operands, is stalled for some reason
- These stalls can back up through the CPU
- Ex. Read operands might be stalled if the ALU is stalled



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What can you do with wires and wire logic?

Example: Determining if there's a phase error in a phase lock loop

```
assign phase_err = (output_phase != input_phase);
```

In this case, the loop will adjust if there are any errors



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This section has two exercises:

1. Build and try the thruwire demo.
  - Toggle the switch.
  - Verify that toggling your switch will toggle the LED
  - Build and run the Verilator simulation
2. Create a test of your serial port connection
  - Connecting the input serial port wire to the output  
Beware: These wires are often marked “TX” and “RX”, but not always from the perspective of the FPGA
  - Turn off any ‘local echo’
  - Turn off any hardware flow control
  - Verify that characters typed into your terminal program show up on the screen





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- Wires represent connections within the design
- Wires can also represent the outputs of combinatorial logic
- Wires have no memory, circular logic or feedback is illegal
- You know how to create constraints for your project!

You can now build and load a design onto an FPGA!