

Components

This section is based on documentation created by Louis Jackowski-Ashley, Sam Russell and Richard Grafton who also created the images used here.

All hex8 wires/ports carry a 4 bit signal. The following kinds of signals exist.

- Clock signal (green in ModuleSim).
- Data signal (red in ModuleSim).
- Control signal (blue in ModuleSim).

ModuleSim uses purple for signals which are a combination of control and data, and gray for everything else. These are not mistakes - you will have purple and gray wires in your processor.

As a rule of thumb, the control port (right hand side) of all registers should be connected to a green wire - if this is not the case, you're probably blocking the reset signal - and apart from passing split/merges these should be the only uses of green wires in your design. Furthermore, the less you pass green wires through fan-outs, the better: it is possible to build a complete hex8 processor without any fan-outs on green wires at all.

When discussing a signal, "bit 0" means the least significant (rightmost) bit, "bit 1" is its neighbour and "bit 3" is the most significant (leftmost) bit. Thus `0010` is a number with bit 1 set (we count from the right, but the first one is bit 0) and `1100` is a number with bits 0 and 1 at zero and bits 2 and 3 set to 1.

Sometimes we use a * to indicate a bit that doesn't matter. Thus when we say a control input of `**1*` resets a register we mean that if bit 1 is set, the register resets whatever the other bits are.

Register



A register stores a 4 bit value and outputs this on its data output port (top). When the control input (right) is $*101$, that is bits 0 and 2 are 1, bit 1 is 0 and bit 3 can be anything, the register copies the value from its data input (bottom) into its storage. When the control input is $**1*$, the register resets its storage to 0000 .

Register storage is erased if the register loses power (i.e. you disconnect all cables).

The control output (left) is always an exact copy of the control input.

Warning: as long as something is connected to the control input, a register operates exactly as described. If the control input is disconnected, the control input defaults to 0101 and not 0000 as one might imagine, i.e. a register with its control input disconnected works as if it were just a wire from data in to data out.

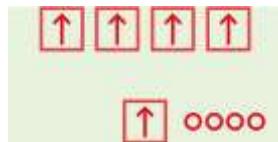
Use

You can chain two registers to make an 8-bit register. Simply connect the control out (left) of the right register to control in (right) of the left register.

The control in of a register should always be either a raw clock signal (either directly from the clock or chained through other registers on the way) or a properly split/merged clock signal. This ensures that pressing the reset button on the clock will reset all registers.

We call bit 0 of a register's control signal the clock bit and bit 2 the enable bit. A register only stores its input if both these bits are set (and bit 1, the reset bit, is zero). This allows us to create registers that only store a value if both a certain clock phase is active and a certain condition is true.

Fanout



A fanout simply takes one input (bottom) and repeats it 4 times (top).

Use

The only thing to say here is **NOT** to use fanouts when you can avoid it. You can often avoid using fanouts by chaining signals. For example, if you want to drive two registers with the same control signal, just connect control out from one register to control in of the other. Similarly, if you want a data signal to activate two chained or modules, chain the signal through the first into the second. That is why they are called chained or after all.

Using fanouts is unavoidable if you have the output value of a register and you want to send it to e.g. two different AUs.

Clock



The clock component has two outputs “A” and “B” and cycles between the following four states:

- A = 0000, B = 0000 (all off)
- A = 0001, B = 0000 (phase “a”)

- A = 0000, B = 0000 (all off)
- A = 0000, B = 0001 (phase “b”)

The switches and buttons control the clock speed and auto/manual mode. In auto mode, the “rate” switch selects “fast” or “slow” and the speed dial allows this to be more finely tuned. In manual mode, which can be selected by changing the auto/manual switch, the clock does not move by itself and you press the “manual” button to advance the clock by one state on each press.

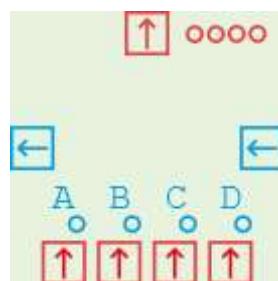
The reset button sends a signal of ****1*** on both outputs, causing any registers connected to either clock output to reset to **0000**. A good processor design must ensure that the reset signal reaches **all** registers whenever the reset button is pressed.

The clock is also a source of power.

Use

Use exactly one clock in your design and make sure all registers are connected to it in such a way that the reset signal works. You will want to create a system that lets you pretend you had a clock with more than 2 phases, details of which will be in the exercises for your computer architecture unit.

Multiplexor



The multiplexor takes 4 data inputs (bottom), selects one of them with the help of a control signal (right) and outputs it (top). The control output on the left is an exact copy of the control input on the right, allowing you to chain two multiplexors to make an 8-bit multiplexor for example.

The multiplexor only cares about the low 2 bits of its control signal and selects the output accordingly:

- **00 selects input A (this is the default).
- **01 selects input B.
- **10 selects input C.
- **11 selects input D.

Use

Multiplexors have two uses. The first is to select one of multiple inputs, e.g. if you have a register that you sometimes want to have connected to another register and sometimes to memory, you place a multiplexor in front of it and use the control signal to select which of the two inputs to pass through.

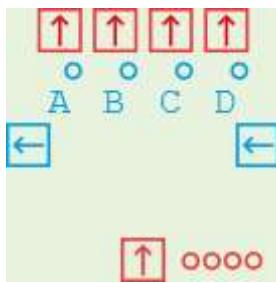
The second use is as a switch. If you want a module to sometimes get input X and sometimes input Y (where both X and Y are 4-bit values), you can set up a multiplexor with X on input A and Y on input B and then use a 1-bit control signal (e.g. you only need to care about bit 0) to switch between X and Y.

A variation of the second use is an “and” switch. If you want a certain wire to be 0001 when both X and Y are 0001 , otherwise 0000 then you can set up a multiplexor with the A, C, D inputs empty, X connected to B and Y to the control input (or the other way round).

- When Y is 0000 , the multiplexor is passing through its A input which is also 0000 .
- When Y is 0001 and X is 0000 then the multiplexor is outputting X, so the output is still 0000 .
- When both X and Y are 0001 then the multiplexor is passing through its B input (as Y is 0001), but that is X so you get an output of 0001 .

This is a useful technique to do the logical “and” of 1-bit control signals. Better still, the Y signal is available for further uses on the control out of the multiplexor so you can save a fan-out in some cases.

Demultiplexor



The complement of a multiplexor. One data input on the bottom, four data outputs on the top of which three are `0000` at any one time and the fourth one is a copy of the data input.

The control signal is passed through from right to left and the low two bits determine the output: `**00 = A, **01 = B, **10 = C, **11 = D.`

Use

The basic use of a demultiplexor is to take a 2-bit input signal, which has 4 possible values, and turn it into a 1-bit signal on any one of four outputs. In this way you can “decode” a signal: if it’s `00` then do this, if it’s `01` then do that etc. In this case the data input can be a fixed input component set to `0001`.

Input



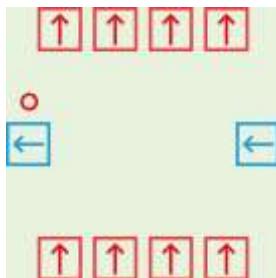
The input component has one data output on which it outputs whatever its switches are set to. It also contains a power source.

Use

The input provides a fixed input value. If you want a loop that always adds 1 to a value on each pass, one way to do this is to use an input set to `0001` connected to an AU somewhere.

Another use of an input is as a power source. All wires carry power as well as their 4 bit value so a component is powered if it is connected to any powered components by any wires, even if the 4-bit signal is not passed through in any way. Until you build something the size of the wall computer, you do not need to worry about power too much.

Chained OR



Performs a logical OR on 1-bit signals.

The control output is `0001` if any of the four data inputs or the control input is `***1`, otherwise (if bit `o` is `0` on all inputs) the control output is `0000`.

The four data outputs are simply the four data inputs passed through unchanged.

Use

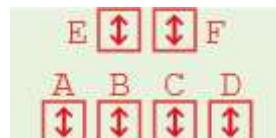
Chained ORs are used to create a stateless control grid in the hex8 machine, a.k.a. “the bit on the bottom” of the wall computer. The basic idea is this. Suppose you want a register to be written two in exactly 5 different machine instructions. You make one signal (one wire) for each instruction. You make a chained OR with at least 5 inputs

(i.e. you chain two of them together) and put these 5 instruction wires in the data inputs, then connect the control output to the place that controls the register in question (together with a clock signal).

Maybe you want two of these instructions, along with a third one that should not activate the register from before, to do something else. You can place another chained OR and feed the wires for the 3 instructions in question into that one. And so on. The wire for a single instruction will take a path through all the chained ORs that are relevant to this instruction, so a “read from memory and write to the B register” instruction would have a wire that passes through the “read from memory” and “write to B” chained ORs.

Chained ORs can be chained in two dimensions. To make a chained OR component with more than 4 data inputs, just chain control out of one chained OR to the control input of another. To make a signal for an instruction activate several different chained ORs, chain a data output of one chained OR to a data input of another.

Split/merge



The Swiss Army Knife component - it has many uses.

On the one hand this is the simplest component (except perhaps the fanout) - it is just a bunch of wires. On the other hand, the pattern of the wires is quite complex.

On a real split/merge component, the bits marked X on the different inputs are not connected to anything and the bits marked A-D are connected to all other bits with the same letter. For example, input “C” (second rightmost of the four ports in a row if you hold the split/merge so that the row of 4 is on the bottom) is marked xxxB and input “F” (rightmost of the two ports on top) is marked DCBA . This means that if you put a signal of $***1$ in input “C”, i.e. any signal where bit 0 is 1 then bit 2 of the “F” port will be 1 (the others will be 0 unless some other port is doing something to them).

Use

The first use is to split or combine two 2-bit signals into one 4-bit signal. Holding the split-merge so that the row of 2 ports is on top, place the wire for the 4-bit signal in port “F” and the two two-bit signals in ports “B” and “D”. This assumes that the 2-bit signals both use bits 0 and 1.

This is the recommended way to control a register. Recall that on the control input of a register, bit 1 is the reset signal and bits 0 (clock) and 2 (enable) together enable writing. Bits 0 and 1 should come from the clock and bit 2 from wherever the register should be controlled from.

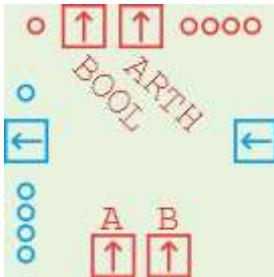
So if you want a register that is enabled for writing in clock phase 4a only, take a split/merge and connect port “F” to the register’s control input. Connect the clock phase “a” to port “D” - this not only sends the clock bit in the “a” clock phases, but also the reset signal whenever you activate it - and connect the “phase 4” signal to port “B”. This way, bit 2 on port “F” will be enabled in clock phases 4a and 4b and bit 0 will be enabled in 1a, 2a, 3a, 4a with the result that both bits 0 and 2 are only on together in 4a - which is exactly when we want our register to write in this example.

To avoid fanouts, you can chain the signals as follows. If you have created a register clocked at 4a with a split-merge, you can chain the register’s control output into another split merge at port “D” to recover the “a” signal, while passing the reset signal through correctly too. The “4” signal you can chain out of the “E” port since the “B” and “E” ports always carry the same signal.

Another use of a split/merge is to combine or split two 1-bit signals into a 2-bit signal. Put the 1-bit signals in “C” and “D” and the two-bit signal in “F”. This relies on the 1-bit signals really being 1-bit, particularly the signal on port “D” can vary between `0000` and `0001` but must never be `**1*` as this conflicts with the “C” port.

To split one 4-bit signal into 4 1-bit signals (or combine them), put the 4-bit signal in port “F” and the 1-bit signals will be on ports A-D.

Arithmetic Unit



This component takes two data inputs A and B, performs arithmetic and comparison operations and outputs the result on two data outputs (top). The result of the arithmetic operation is a 4-bit signal that is also displayed on the group of 4 LEDs; the comparison operation produces a 1-bit output that is also displayed on the single LED in the top left corner.

The operations are controlled by the control input (right). The low two bits select an operation (carry bits will be discussed in a moment):

| bits | arithmetic | comparison |
|-------------|-------------------|-------------------|
| **00 | A+B | $A + B == 0$ |
| **01 | A | $A == 0$ |
| *110 | A - B | $A == B$ |
| *111 | A - B | $A < B$ |

Carry bit

Bit 2 is the carry bit. Bit 3 (the leftmost) you can ignore for now. The control output on the left passes the low 2 bits through from the control input but sets or clears the carry bit depending on whether the arithmetic operation caused a carry out. This way, two chained AUs work as an 8-bit unit.

Use - arithmetic

In addition mode (**00), the actual computation is $A + B + \text{carry_in}$ and the outputs are both the 4-bit value on the arithmetic data output and the carry bit of the control output, set if the computation caused a carry out. For example, $A = 1110$ and $B = 0001$ with carry in at 0 produces 1111 on the arithmetic output and 0 for carry out. If you set carry in to 1, the arithmetic output becomes 0000 and the carry out becomes 1 as you are now computing

$$1110 + 0001 + 1 = 10000$$

The control input *001 ignores the B input and just passes the A input through to the output. This is useful when you just want to send a signal straight through the AU as if it were a wire. The control input *101 (pass through A, carry one) adds 1 to A. This is a quick way to increment a number by 1 without having to create an 0001 data input.

In subtraction mode, the AU by default does one's complement ($A + \text{NOT } B$) but setting the carry bit produces ($A + \text{NOT } B + 1$) which is exactly two's complement subtraction. Therefore to compute $A - B$ you should set the control input to *11* (in practice, 0110).

Use - comparison

The comparison output depends on the arithmetic output. It will be either 0000 or 1111. The most useful control modes are 0001 which checks if the A input (plus a carry, if provided) is all zero and 0111 which checks if $A < B$, to be precise whether bit 3 of $(A - B)$ is set. If B is all zero then this mode simply checks whether bit 3 of A is set. (To check whether the low bit of A is set you could use a split-merge using ports "A" and "F".)

Note - control bit 3

When chaining AUs and comparing say 0000 0001 and 0000 0000 for equality (control input 0000) you might wonder how the "left" AU knows that it should output 0000 not 1111 on the comparison output, since the two inputs are different but the only difference is in the "right" 4 bits and there is no carry. This is what bit 3 of the control output is for: it is used to pass the comparison result up a chain of AUs. Since the right AU sees two

different inputs it will set bit 3 on the control output, causing the left AU to report `0000` as the comparison result whatever its inputs are. The meaning of this bit depends on the comparison mode and you should not need to worry about the exact rules nor should you use this bit for anything except chaining two AUs.

Non-Volatile Memory



A non-volatile memory stores up to 2^{15} 8-bit values. For the 8-bit hex machine we will only be able to address $2^8 = 256$ of these values. For this, we use address inputs “A” and “B” and leave “C” and “D” unconnected.

Like a register, the memory always outputs a stored value on its data outputs and it replaces a stored value with the one on its data inputs if the control signal (blue) is `*1*1`. The memory does not react to the “reset” signal `**1*`. Unlike a register, the memory also has address inputs that select which of the stored values to read/write.

The memory also has a safety feature: it will only allow writing if the two pins forming the “write enable” switch are connected. In the simulator, this can be done by clicking the switch; on a real memory unit use a NAND board cable.

Use

To read a memory value, say the one at location `0000 0001`, set `A = 0001` and `B = 0000`, i.e. `A` is the least significant (rightmost) 4 bits of the address. The 8-bit value appears on the data output (top) ports.

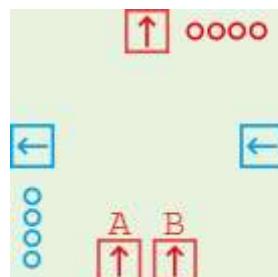
To write a memory value, set the address up the same, put the value to write on the data inputs and then set the control to `0101` - typically this will be a combination of a clock and an enable signal.

Until you come to the point when you are implementing memory writes, leave the write enable switch off - but don't forget to turn it on when you start building the write instruction circuitry.

Programming

To program a memory module in the simulator, right-click it and choose “View / Edit NRAM Data”. In the window that opens you can see the memory contents and changes to memory (writes) will show up in blue as a program executes. The menu lets you save and load hex-encoded data from files.

Logic Unit



The logic unit takes two data inputs, performs a bitwise logical operation and outputs the result. The control signal is passed through from right to left and has the following meaning.

| signal | operation |
|--------|-----------|
|--------|-----------|

| | |
|-------------------|-------|
| <code>**00</code> | NOT A |
|-------------------|-------|

| | |
|-------------------|---------|
| <code>**01</code> | A AND B |
|-------------------|---------|

| | |
|-------------------|--------|
| <code>*110</code> | A OR B |
|-------------------|--------|

| | |
|-------------------|---------|
| <code>*111</code> | A XOR B |
|-------------------|---------|

Bit 3 of the control signal is unused.

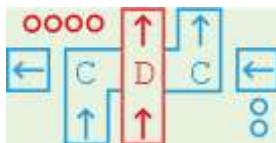
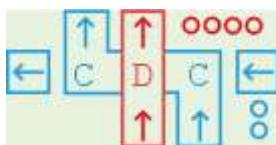
Use

You do not need a LU to build a hex8 computer - it would be useful if there were additional opcodes for logical operations.

A LU is only needed if you want to do an operation on two inputs and the operation you want to do needs to be configurable, i.e. you sometimes want to do A AND B and at other times A OR B. For a fixed operation on 1-bit signals, the most common case in the hex8 machine, you can do the following:

- For an OR of two 1-bit signals, use a chained OR.
- For an AND of two 1-bit signals, use a multiplexor with one signal on the control input and the other on the “B” data input, leaving the “A” data input unconnected (0000).

Shifters



The left and right shift units are not needed to create a hex8 machine. Here is nonetheless an explanation of how they work.

The shifters take a data input, shift it by a number of bits and send it out again. The shift is “logical” not “arithmetic”, i.e. bits shifted in are always 0 - shifting 1111 2 bits to the right gives 0011. The data input/output are

the ports in the middle of the top and bottom of the shifter and marked “D” in the diagram.

The control input on the right of the shifter takes a two-bit signal in the form **xx indicating the number of bits to shift, i.e. **10 shifts by 2 bits.

To chain multiple shifters to produce an 8-bit or higher shifter, two control chains are required: first you connect the left control out of the rightmost shifter to the right control in of the next one etc. This signal is simply passed through. Then, connect the top control output (marked “C” in the diagram) to the bottom control input of the next shifter; for left shifters this control signal flows right to left but for right shifters it flows left to right.

The idea here is as follows. Suppose you want to shift $0011\ 0000$ to the right by 2 bits. The leftmost of the two right shifters takes 0011 , shifts it to the right by two bits producing 0000 and outputs this. But this on its own would forget about the 1s. So the leftmost right shifter tells the one to its right over the “C” control path that goes left to right about these bits (the exact bit pattern is not important for us), resulting in these two bits appearing in the rightmost right shifter’s output to create the result $0000\ 1100$.

Use

Shifters are not required to build a hex8 machine.