

# **Pegasus 42 Project**

The goal for this Gambiconf 2025 workshop is to show how the most basic elements of digital computers and videogame work and how they can be combined to create more complex blocks up to a whole computer.

A simulator (called Digital) will be used to allow the workshop participants to experiment for themselves with all the presented circuits.

## **1. Switches, Logic Gates, Combinational Circuits**

These are the basic blocks of digital circuits.

## **2. Sequential Circuits**

More complex circuits need memory.

## **3. Processors**

mcpu16h is a very simple processor with only 4 instructions and is a good introduction while drv32h is more practical, being compatible with the RISC-V standard.

## **4. FPGAs and Shin JAMMA**

With reconfigurable circuits (FPGAs - Field Programmable Gate Arrays) it is possible to see the simulates circuits working in the real world. As there are many different FPGA boards, the Shin JAMMA standard was created so a single project can work on any of them

## **5. Video and Audio**

Though interesting games can be created to use the text terminal, color graphics output and sound like those from the classic NES (Nintendo Entertainment System or Famicom) allow games that are more fun

## **6. Pegasus 42**

With cache memory and high resolution graphics it becomes possible to run the Squeak Smalltalk programming language

### **A. History**

In addition to the material presented in the workshop, a history of the Pegasus project is also included as an appendix.

## 1. Switches, Logic Gates, Combinational Circuits

The goal of this workshop is to build a retro computer (roughly equivalent to what people would have bought in the early 1990s for their home) called Pegasus 42 and use it to program simple games. The idea is that the project can be completely understood from the lowest level to the overall system.

For this we will initially use a simulator, and then move on to a FPGA (Field Programmable Gate Array - a chip which can be reconfigured to implement any digital circuit). For each level of abstraction there are several different simulators we can use. From a high to low level we have:

| Level              | Example Simulators  |
|--------------------|---------------------|
| Architecture       | QEMU, MAME          |
| Micro-architecture | SPIM, SimpleScalar  |
| Register Transfer  | Verilator, ModelSim |
| Logic Gate         | Digital, TkGate     |
| Switches           | IRSIM, MOSSIM       |
| Analog Circuits    | Spice, Xyce         |
| Components         | TCAD, DEVSIM        |
| Physics            | Elmer, Matlab       |

The advantage of using a simulator instead of the real thing is being able to see details that would be very hard, if not impossible, to measure in the actual circuit. The low level simulators show far more details than the high level ones, but are proportionally slower when running on the same computer. So while it would be possible to simulate a whole computer using Spice, it might take minutes for the simulated circuit to execute a single instruction. We might have to wait for weeks to see if it correctly boots or not. Normally we use the low level simulators for small subcircuits and then higher level simulators for the whole system.

When we said that the goal was to understand Pegasus 42 at the lowest level we exaggerated a bit. We will consider the switch level as being the lowest one in this workshop. Even though *Digital* is not optimized for this level, it is sufficient to illustrate the ideas that will be presented. It is also not optimized for the higher levels, mas for the reduced projects that will be studied it is sufficient (though too slow to show the operation of circuits that output video in a usable manner).

An abstract representation of a system is a box with a number of inputs and some outputs. Normally we will show the inputs coming from the left and the outputs going right, but we can ignore this rule if it makes the drawing more confusing.

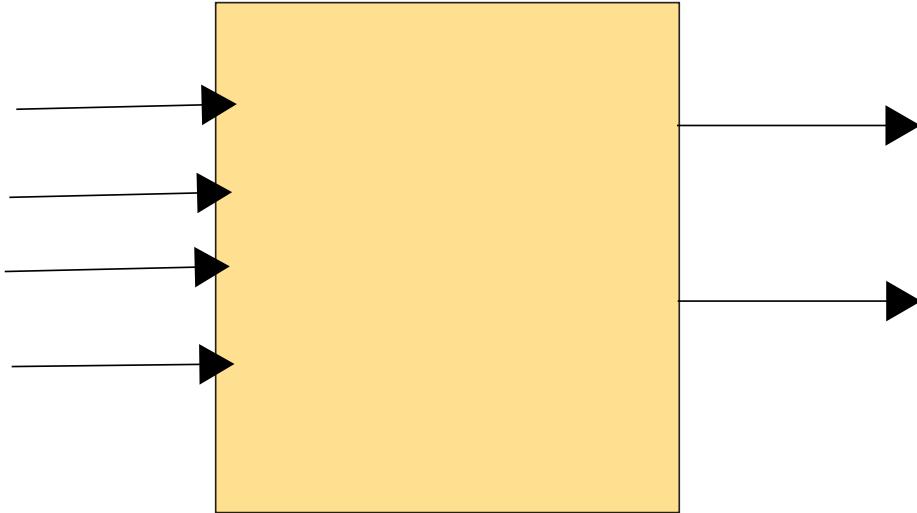


Figure 1: system

### Digital ou Analog

The first choice we need to make is the nature of the inputs and outputs of our system. For the analog inputs and outputs some quantity in our circuit (voltage, current, etc) is analog to some quantity in the world (temperature, brightness, etc). For the digital inputs and outputs several quantities in the circuit represent a single value in the world. This set of quantities can use separate inputs and outputs (a parallel representation) or a single input ou output over time (a serial representation).

| characteristic     | Analog                        | Digital                              |
|--------------------|-------------------------------|--------------------------------------|
| number of circuits | one                           | one per digit                        |
| precision          | depends on circuit quality    | always equal to the number of digits |
| noise              | accumulates at each operation | does not pass from input to output   |

Analog circuits dominated computing until the middle of the 20th century, and telecommunications until the end of the 20th century. The most important factor was the number of circuits since the components were very expensive and their connection was a manual process. With the evolution of integrated circuits the cost became extremely low and the other factors lead to the digitalizations of technology. Our project is digital.

Humanity has used several different digital systems to represent numbers, with the most popular the positional decimal system wth hindu-arabic digits. The

more values each digit can have, the more sensitive to noise it becomes. But the fewer values each digit can have, the more digits are necessary to represent the same number. The best possible protection against noise is when each digit can have only 2 values, like in the positional binary system.

Though the binary system needs more digits (and so, more circuits) than the alternatives, each circuit is simpler so that is the option we shall use.

## Logic Gates

Combinational circuits are those whose output (or outputs) depends only on the combination of the inputs. In the case of binary, each digit can only be either 0 or 1. There are several areas of mathematics which are equivalent when only two values are used.

| Area            |           |       |                 |          |              |
|-----------------|-----------|-------|-----------------|----------|--------------|
| Boolean Algebra | 1         | 0     | inversion       | addition | product      |
| Predicate Logic | true      | false | not             | or       | and          |
| Set Theory      | universal | empty | complement      | union    | intersection |
|                 | set       | set   |                 |          |              |
| Switch Circuits | 5V        | 0V    | normally closed | parallel | series       |

Notations from all of these areas can be used to represent combinational circuits. Yet another possible representation is simply a table with a line for each combination of input values and the corresponding output. We call this a “truth table” even with the values shown are 0 and 1 instead of false and true.

We will not be completely consistent and might talk about a circuit being the in form of “a sum of products” (Boolean Algebra) and another circuit of using “not and” (Predicate Logic). The latter case is why the basic circuits are known as “logic gates”.

To illustrate these ideas we will use *Digital*, the simulator we had previously mentioned. *Digital* was written in Java, so it is necessary to first install this language on your computer. The advantage of this is that *Digital* runs on computers with different operating systems and different processors. The indicated site is where the source code is, but that is only needed by those wanting to modify the simulator. That page includes a “Download” button which will fetch *Digital.zip* with the most recent version of the tool.

## Switches

Since we talked about circuits with switches, lets start there connecting two switches in parallel between a lamp and a power supply. In the “File” menu we select “New”. Using the “Components” menu with “Switches” and “Switch” we

can position two simple switches anywhere we want. Then “Components”, “IO”, “LED” will give us a reasonable approximation of the lamp we wanted (*Digital* has fancier options, but we won’t use them here). Finally in “Components”, “Wires”, “Supply voltage” gets us the power supply we need for our circuito. Note that all circuits need both a power supply and a ground wire, but we normally don’t show those and the simulator works just the same. But if we want to actually build the circuit we need to remember them.

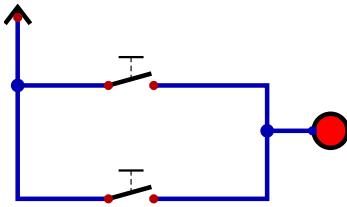


Figure 2: parallel switches

If we imagine two gardens connected using two gates, with one beside the other (in parallel), if one *or* the other is open we can go from one garden to the other. If we simulate this circuit (menu “Simulation”, “Start simulation” ou the button with the simple triangle pointing right) we will see that the LED is off. But if we process the switch on top *or* the switch on the bottom (or both) it turns on.

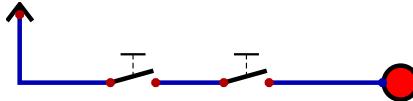


Figure 3: serial switches

If we imagine two gardens connected using two gates, with one after the other with a narrow path between them (in series), it is not enough for one of them to be open. It will only be possible to pass from one garden to the other if the first gate *and* the second gate are open. In this second circuit we connected the switches in series and in the simulation we can see that the LED stays off unless the first *and* the second switch have been pressed.

We have seen two of the three equivalencies between switches and areas of mathematics. The table indicates the remaining equivalency (inversion, not, complement) as being a normally close switch. This kind of switch opens the circuit when pressed. But here we will show an alternative that depends on the device level (the only time we will go down to this level in this project).

We only need one switch here, and in place of the supply we use “Components”, “Wires”, “Pull-Up Resistor”. We also need “Components”, “Wires”, “Ground”. When the switch is open, a current goes through the resistor and into the LED, which shines. As the switch is pressed it offers a path to 0V that draws the current from the resistor instead of the LED, which turns off.

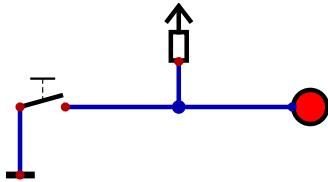


Figure 4: inversion with a switch

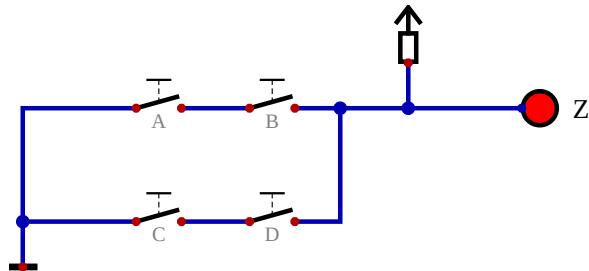


Figure 5: and, or, invert with switches

Here we have a more complex example using the same idea. Normally the AOI gate(and/or/invert) is not considered to be a basic logic gate and we will not see it again in this project, but it is sufficiently useful that it is often included in a library for integrated circuit design. In Boolean algebra we have:

$$Z = !(A \cdot B + C \cdot D)$$

while in predicate logic it would be:

$$Z = \text{not}((A \text{ and } B) \text{ or } (C \text{ and } D))$$

A fourth representation of the AOI circuit (with the first being the figure, or schematic, the second the boolean algebra and the third the logic equation) would be the truth table:

| A      | B      | C      | D      | Z   |
|--------|--------|--------|--------|-----|
| open   | open   | open   | open   | on  |
| open   | open   | open   | closed | on  |
| open   | open   | closed | open   | on  |
| open   | open   | closed | closed | off |
| open   | closed | open   | open   | on  |
| open   | closed | open   | closed | on  |
| open   | closed | closed | open   | on  |
| open   | closed | closed | closed | off |
| closed | open   | open   | open   | on  |
| closed | open   | open   | closed | on  |
| closed | open   | closed | open   | on  |

| A      | B      | C      | D      | Z   |
|--------|--------|--------|--------|-----|
| closed | open   | closed | closed | off |
| closed | closed | open   | open   | off |
| closed | closed | open   | closed | off |
| closed | closed | closed | open   | off |
| closed | closed | closed | closed | off |

The table shows a problem - the input have one nature (they are controlled by a human finger) while the output is of a different nature (light coming from the LED). If we want the outputs of a circuit to be used as inputs of another circuits in order to build larger systems, they need to be of the same kind. Fortunately switches which are controlled using electricity have been invented: relays (1835), vacuum tubes (1904) and transistors (1947). Even though *Digital* can simulate relays in a limited way (like its switches) we will replace the switches in the AOI circuit with MOSFET (Metal/Oxide/Silicon Field Effect Transistors) of the N type (negative) which is used to make integrated circuits.

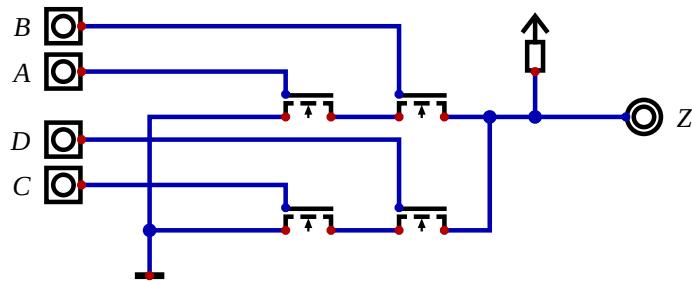


Figure 6: and, or, invert NMOS

Besides replacing the switches with “Components”,“Switches”,“N-Channel FET” we also use “Components”,“IO”,“Input” as well as “Output” from the same menu to show that these signals can come from another circuit and that the result can go to another circuit. While simulating we can change the values of the inputs and observe the value of the output.

In the “Analysis” menu, the “Analysis” item will create a truth table for the circuit and we can verify that it is the same one as for the circuit with switches. A problem with this type of circuit, which we call NMOS, is that whenever the output is 0 there is a current going through the resistor and generating heat (and draining the battery if that is where the power is coming from). Another kind of transistor, the “P-Channel FET”, is the opposite of the N type and conducts current when the input is 0. If we replace the resistor with a complementary circuit of the N transistors using the P transistors (placing them in series where the other is parallel) the circuit will work just the same but without a constant current.

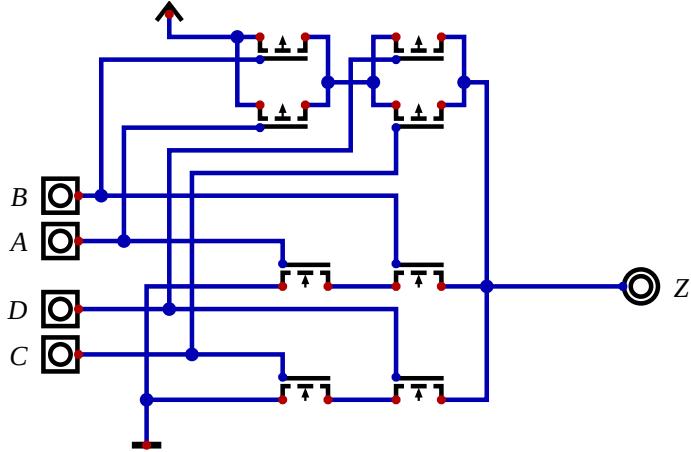


Figure 7: and, or, invert CMOS

The extra complexity of CMOS relegated it to niche applications (like digital watches) in the 1960s and 1970s, but it replaced nearly all other kinds of circuits in the 1980s when the increasing number of transistors per chip (Moore's Law) made having twice as many transistors worth it to reduce power.

### one input Logic Gates

So far we have seen a single logic gate with one input: Not.

With a single input, only two combination of inputs are possible: either 0 or 1. Its truth table will be two lines in size. The output in each line can have two values, so there are  $2^2 = 4$  possible truth tables.

| A | Z |
|---|---|
| 0 | 0 |
| 1 | 0 |

In the first gate the output is always 0. It isn't surprising that we didn't talk about it. In circuit terms we only need to connect the output to the ground wire.

| A | Z |
|---|---|
| 0 | 1 |
| 1 | 0 |

This is the Not gate that we have already seen.

$$\begin{array}{r} \overline{\overline{A}} \quad Z \\ \hline 0 \quad 0 \\ 1 \quad 1 \\ \hline \end{array}$$

Here the output is the same as the input. Just like in the first circuit we can implement this with just a wire.

$$\begin{array}{r} \overline{\overline{A}} \quad Z \\ \hline 0 \quad 1 \\ 1 \quad 1 \\ \hline \end{array}$$

The final gate is an output that is always one. This can also be done with a wire connected to the power supply.

So out of the 4 possible gates, only Not is interesting. Note that if we consider the value of Z in each table as the bits of a binary number with the first line being the least significant digit, we can call these gates “gate 0” ( $Z = 0$ ), “gate 1” ( $Z = !A$ ), “gate 2” ( $Z = A$ ) and “gate 3” ( $Z = 1$ ).

### **two input Logic Gates**

Using the same thinking, a two input gate has 4 possible input combinations and therefore a truth table with 4 lines. Using the same scheme to number them we will have a 4 bit binary number indicating that there are  $2^4 = 15$  possible logic gates.

| outputs | equation            | name |
|---------|---------------------|------|
| 0 0 0 0 | $Z = 0$             |      |
| 0 0 0 1 | $Z = !(A+B)$        | NOR  |
| 0 0 1 0 | $Z = Ax!B$          |      |
| 0 0 1 1 | $Z = !B$            |      |
| 0 1 0 0 | $Z = !AxB$          |      |
| 0 1 0 1 | $Z = !A$            |      |
| 0 1 1 0 | $Z = !(AxB)+(Ax!B)$ | XOR  |
| 0 1 1 1 | $Z = !(AxB)$        | NAND |
| 1 0 0 0 | $Z = AxB$           | AND  |
| 1 0 0 1 | $Z = (AxB)+(!Ax!B)$ | XNOR |
| 1 0 1 0 | $Z = A$             |      |
| 1 0 1 1 | $Z = A+!B$          |      |
| 1 1 0 0 | $Z = B$             |      |
| 1 1 0 1 | $Z = !A+B$          |      |
| 1 1 1 0 | $Z = A+B$           | OR   |
| 1 1 1 1 | $Z = 1$             |      |

| outputs | equation | name |
|---------|----------|------|
|---------|----------|------|

Gates 0000 and 1111 don't actually have any inputs, while 0011, 0101, 1010 and 1100 ignore one of the inputs. They are actually the gates we already saw above.

6 gates have names in the menu “Componentes”, “Logic” as well as a corresponding drawing. There is a special shape for AND (1000), OR (1110) and XOR (exclusive OR - 0110) and for their inverses we just add a little circle to the output and an “N” to the beginning of the name. *Digital* also allows a little circle to be added to any of the inputs which means we can use an AND for gates 0010 and 0100 and an OR for 1011 and 1101.

**Sum of Products** If we look at the line for XOR and XNOR we will notice that they are the most complicated ones. In the case of XOR the first product (AND) is  $\text{!AxB}$  which corresponds directly to the left 1, while  $\text{Ax!B}$  is what generated the right 1.

| outputs | product        |
|---------|----------------|
| 0 0 0 1 | $\text{!Ax!B}$ |
| 0 0 1 0 | $\text{Ax!B}$  |
| 0 1 0 0 | $\text{!AxB}$  |
| 1 0 0 0 | $\text{AxB}$   |

So the XOR is the sum (OR) of the second and third products of this table. This is actually true for any logic gate and can be expanded for any number of inputs. This means that nobody will ever discover a new logic gate in the future that we don't know how to implement. The truth table can be transformed directly into a circuit.

That doesn't mean that the circuit created this way will be very good. Using this method for the next to the last logic gate we would have

$$Z = (\text{Ax!B}) + (\text{!AxB}) + (\text{AxB})$$

But we know that a simple OR gate will do the same thing. Fortunately Boolean algebra has rules for simplification much like the rules in normal algebra, and there is a graphical method (called Karnaugh Map, which is one of the things *Digital* can generate) to reduce the logic to the minimum while keeping the same operation.

## Multiple Bits

One disadvantage of digital circuits relative to analog ones is the repetition of the same circuit for each digit. If we use 32 bits to represent values, we will have

32 copies of each circuit.

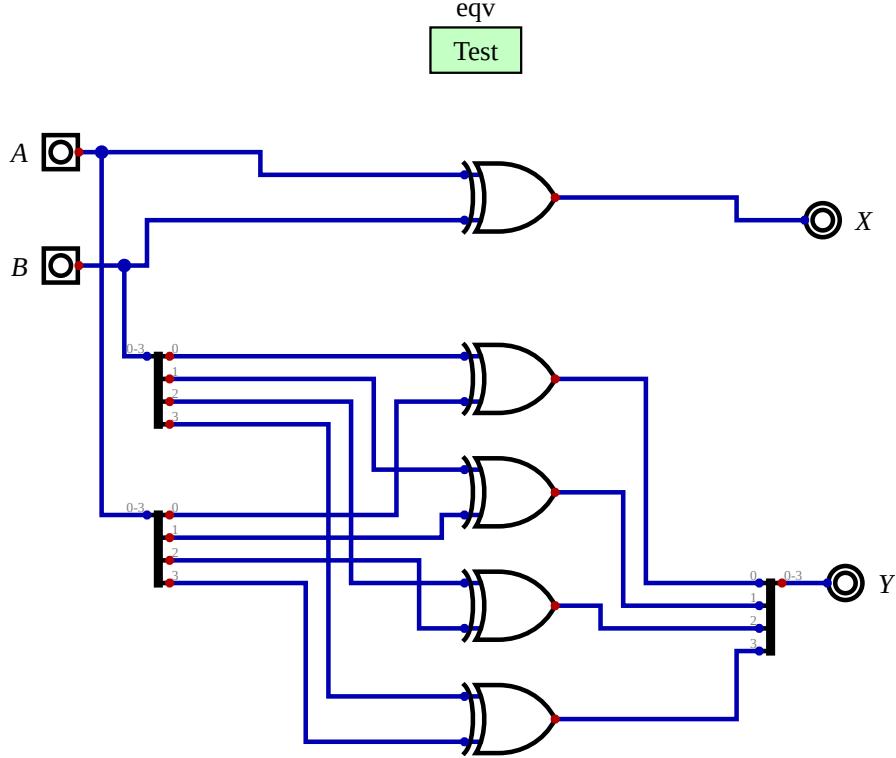


Figure 8: multiple bits

*Digital* has a feature which can reduce this complexity. For each input and output, besides the name we can define a “width” in number of bits. In the above circuit we changed  $A$ ,  $B$ ,  $X$  and  $Y$  to have 4 bits each. In “Components”, “Wires”, “Splitter/Merger” we have a way to connect signals with different numbers of bits. In the two on the left the input was configured as “4” and the output as “1,1,1,1” while the one on the right was configured as the opposite. In addition, each normal component can be configured to have a given width. The exclusive or gate at the top was configured to 4 bits while the four below it as 1 bit each.

Both circuits should be completely equivalent, but the one on top is easier to understand since it is much smaller. And this is for only 4 bits - the gain for, for example, 32 bits is proportionally greater. While editing the circuit, *Digital* does not give any visual indications that the top gate is different than the others, that the inputs and outputs are for multiple bits nor even that the wires connecting them will be carrying multiple bits. During simulation, however, the wires with 1 bit are shown in dark green (for 0) or light green (for 1) while those with several

bits continue dark blue with the current value shown right above the wire. And clicking on a 1 bit input will invert its value while on a multiple bit input this will open a dialog box to define the new value.

Using “Analysis”, “Analysis” we can see the truth table and compare the bits from  $X$  and  $Y$  to check that the circuits are actually equivalent. With 256 lines, however, this confirmation is quite tiring. And if we make any changes to the circuit we will have to repeat this careful examination of the truth table. Fortunately, *Digital* allows us to automate this using “Components”, “Misc”, “Test Case”. We edit the test (which we name “eqv”) to:

```
A B X Y
```

```
loop(a,16)
  loop(b,16)
    (a)  (b)  (a^b)  (a~b)
  end loop
end loop
```

Using “Simulation”, “Run tests”, all 256 combinations of  $a$  and  $b$  are generated for  $A$  and  $B$  and  $X$  and  $Y$  are compared with  $a \text{ XOR } b$ . All tests that pass are shown in green and all tests that fail are shown with a red “x”. It is possible to examine the details to know where a failure happened.

Another way that *Digital* hides complexity is the use of hierarchical projects. Several components can be combined into a circuit that is then shown as a single block in a higher level circuit. Any practical project should make extensive use of this as well as include many tests for each sub-circuit. But since the goal of this workshop is to show the complexity of a computer, the projects that will be shown will be as “flat” as possible. Sub-circuits are often compared with subroutine calls in programming languages but they are actually more like macros.

## Decisions

In programming languages we have constructions like “if A then B else C” to use one input to select between two other inputs.

Looking at the truth table we can see that  $Z = B$  whenever  $A = 1$ , but  $Z = C$  when  $A$  is 0. This means that combinational circuits can make decisions. It is possible to select between more than two alternatives, like in the “switch/case” statements that programming languages have.

This is more complicated to test because with  $8+3 = 11$  inputs there are 2048 possible combinations. The complete test ( $t8x256$ ) is possible:

```
S_2 S_1 S_0  A_7 A_6 A_5 A_4 A_3 A_2 A_1 A_0  Z
loop(s,8)
```

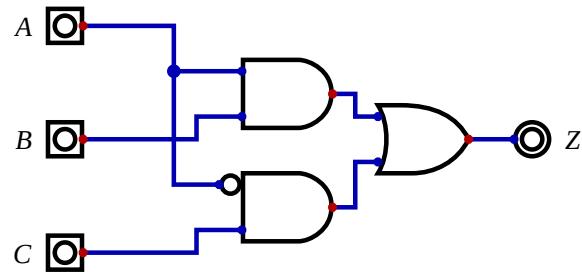


Figure 9: 2 input multiplexer

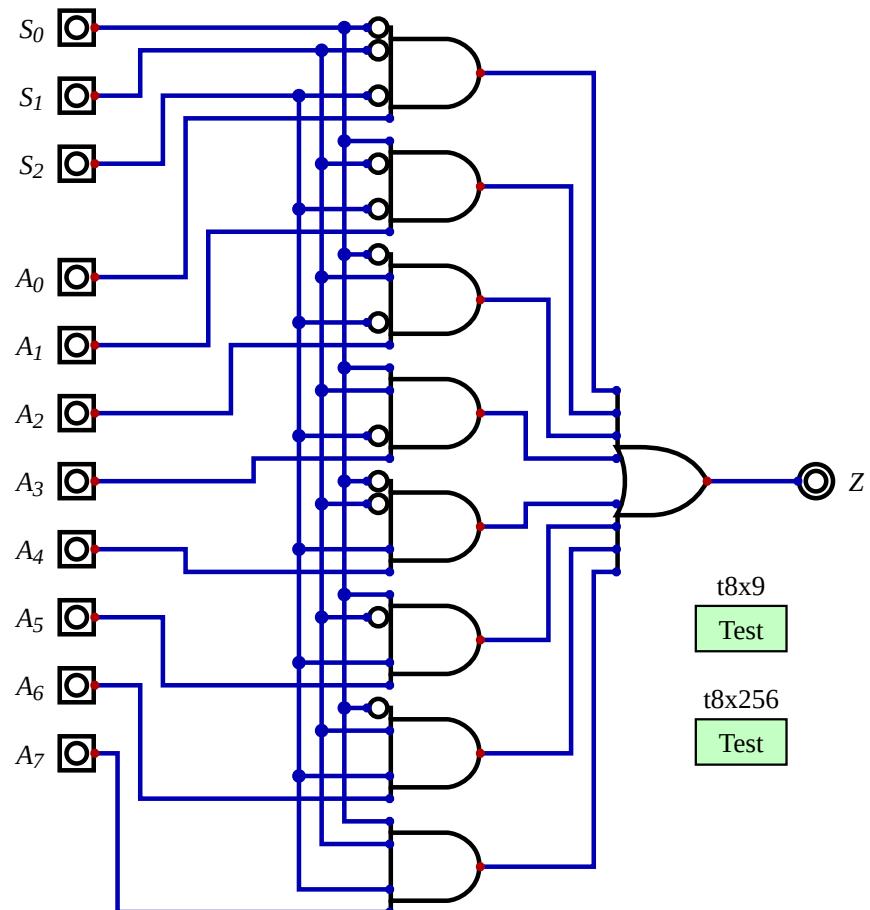


Figure 10: 8 input multiplexer

```

loop(a,256)
    bits(3,s) bits(8,a) bits(1,a>>s)
end loop
end loop

```

Here we are confirming that the output corresponds to the bit selected by  $S$  ( $Z$  is calculated by right shifting so that the least significant bit is the one from the desired input). A more careful test would be to check that when all inputs are 0 the output is also 0 and then to turn on each input, one at a time. The output should remain at 0 except when it is the selected input that goes to 1. Instead of  $8 \times 256$  tests we need only  $8 \times 9$ . In this case the more complete test is actually better, but during the fabrication of some product where part of the cost is the time spent using test equipment the reduced solution would be more interesting.

Our project will use many multiplexers and the circuit above is rather big (and would have to be repeated 32 times to select between 8 values of 32 bits each). At the logic gate level this is the best solution, but if we go down to the switch level we can save transistors.

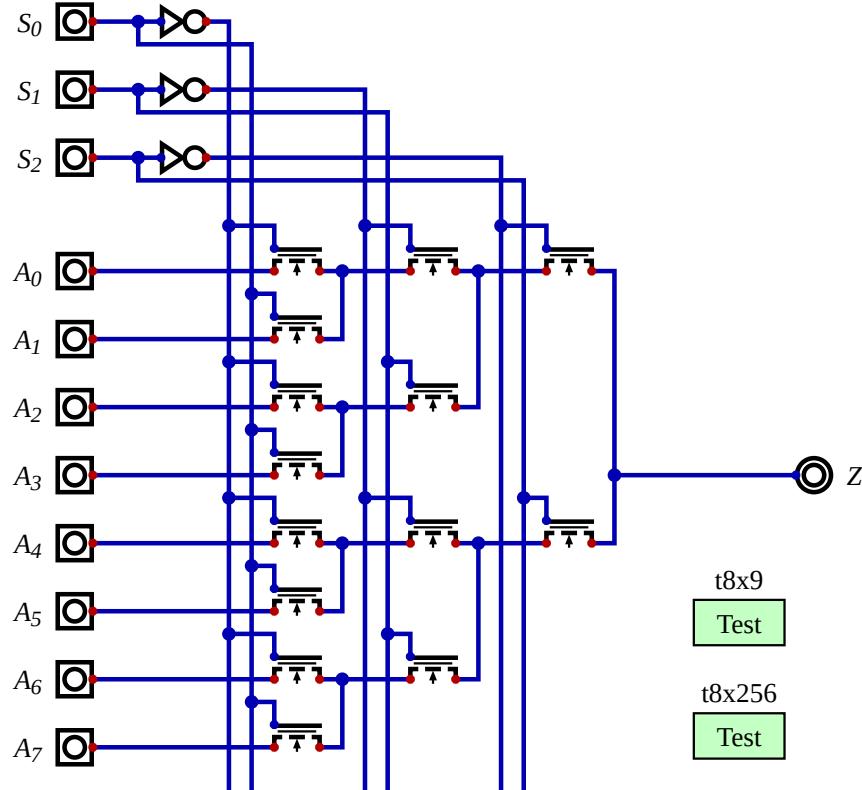


Figure 11: 8 input multiplexer

This circuit passes the same tests as the previous one. In practice this use of NMOS pass transistors reduces the signal level, but adding two inverters to the output will eliminate this problem. Using pairs of NMOS and PMOS pass transistors is another solution, but the wiring becomes a bit more complex. The idea of showing this was so we can use multiplexers in our projects without worrying too much about their cost.

## Numbers

A very popular idea is that computers only manipulate numbers but we can interpret these numbers as being letters, colors, sounds, etc. This is subtly wrong - computers can manipulate representations of many things, including numbers. This is not easy to notice for positive integer numbers, but for negative numbers or floating point numbers this becomes clearer.

The first detail we need to notice is the difference between “+” in Boolean algebra and in binary arithmetic:

| A | B | Boolean A+B | Binary A+B |
|---|---|-------------|------------|
| 0 | 0 | 0           | 0          |
| 0 | 1 | 1           | 1          |
| 1 | 0 | 1           | 1          |
| 1 | 1 | 1           | 10         |

The result in the last line has more digits than the inputs in the case of binary arithmetic. That is also the case for decimal arithmetic: adding two decimal numbers with 5 digits each might generate a result with 6 digits. And for each digit the result will be from 0 to 18, with the last being 2 digits.

We shall call the digits from the addition of binary 1 bit numbers  $S$  (from “sum”) for the least significant and  $C$  (for “carry”) for the most significant.

| A | B | C | S |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 0 | 1 | 0 | 1 |
| 1 | 0 | 0 | 1 |
| 1 | 1 | 1 | 0 |

$C$  has the truth table of the AND logic gate and  $S$  of the Exclusive OR gate. So an adder is:

For the least significant digits of the input numbers this does the job. But for any other digits we need to take into account the “carry” from the digit immediately to the right. That is why we call this circuit a “half adder” and use two of them to create a “full adder”, which is a circuit with 3 inputs and 2 outputs.

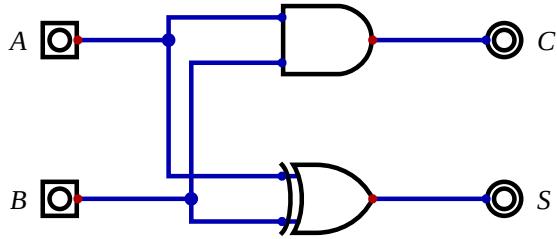


Figure 12: half adder

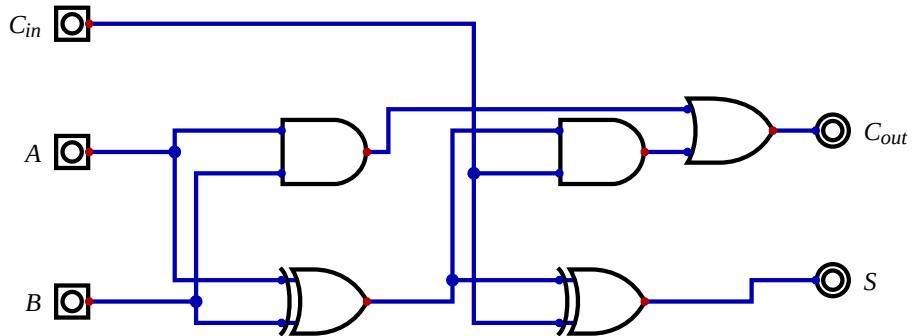


Figure 13: full adder

Repeating the full adder 4 times we can add two binary numbers with 4 bits each. Actually, we could have used a half adder for the least significant digit but doing it this way it becomes easy to combine several of these blocks to handle larger numbers.

We can test that we are actually adding numbers:

C\_in A\_3 A\_2 A\_1 A\_0 B\_3 B\_2 B\_1 B\_0 C\_out S\_3 S\_2 S\_1 S\_0

```

loop(a,16)
  loop(b,16)
    0 bits(4,a) bits(4,b) bits(5,a+b)
    1 bits(4,a) bits(4,b) bits(5,a+b+1)
  end loop
end loop

```

Note that with  $C_{out}$  and  $S_3$  to  $S_0$  the result is 5 bits long, one more digit than the inputs.

This “ripple carry adder” is not very fast. The carry goes from one digit to the next and only arrives at the most significant digit with a long delay. If we double the number of digits the adder will operate at half the speed. There are more complex circuits that reduce this problem, but for our project this simple

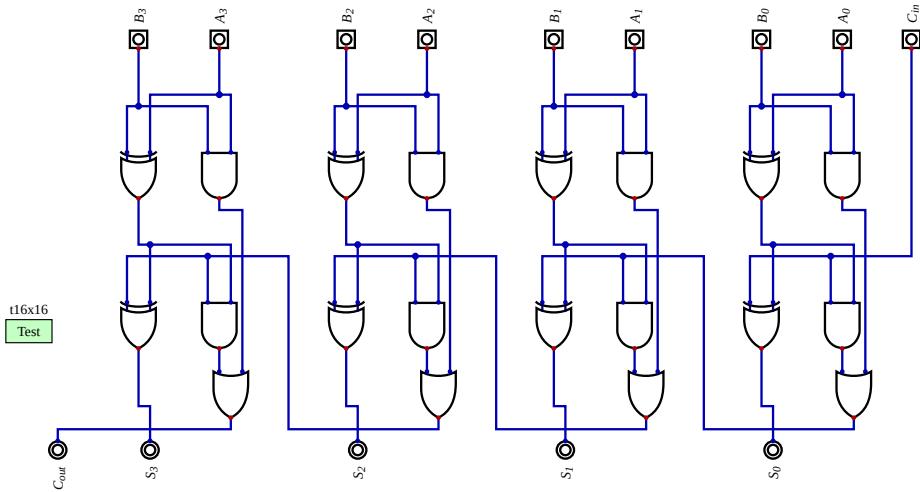


Figure 14: 4 bit adder

solution is good enough.

## 2. Sequential Circuits

## 3. Processors

## 4. FPGAs and Shin JAMMA

## 5. Video and Audio

## 6. Pegasus 42

## A. History