Build Your Own Transistor Logic Circuits

Workshop Manual
v1.0

VCF East 7.0
May 14-15, 2011

Build Your Own Transistor Logic Circuits

1. **Introduction**

   This workshop allows you to build a modular, plugin card containing an array of transistors which allows you to customize your own transistor logic circuits. This plug-in card is a kind of experimenter board which can be used over again by changing the connections to build different logic circuits using the same transistors.

   There are various examples included in this manual which can be made with this. Larger projects can be made using several of these circuit cards, such as a transistor computer.

   This is the first revision of the manual for this workshop. Any feedback on the contents of this manual to help make it better is always welcome.

2. **Overview**

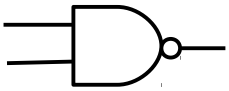
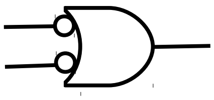
   The experimenter card will contain up to 42 transistors which can be configured with several different options, NAND gates, AND-OR-INVERT gates, or combination of both. Within each transistor circuit are breadboarding connections to let you wire the logic gates together to build larger circuits. Below is a list of the possible Logic circuits that are possible which you can build.

   There is room for a pair of transistors on board for wiring a Schmitt Trigger Logic gate. This allows additional features such as edge-triggered clocking when making Flip-Flops, Accumulators, etc. Also, you can wire a Clock circuit using a Crystal oscillator.

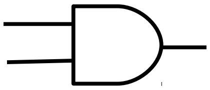
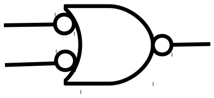
3. Theory

DeMorgan's Theorem

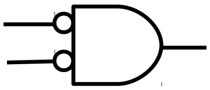
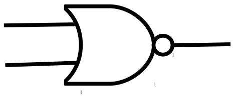
$$\overline{AB} = \overline{A} + \overline{B}$$

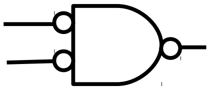
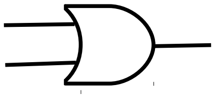
$$A\,B = \overline{\overline{A} + \overline{B}}$$

$$\overline{A}\,\overline{B} = \overline{A + B}$$

$$\overline{\overline{A}\,\overline{B}} = A + B$$

This theorem says that any logical binary expression remains unchanged if these steps are followed:

1. Change all variables to their complements.
2. Change all AND operations to OR's.
3. Change all OR operations to AND's.
4. Take the complement of the entire expression.

A practical operational way to look at DeMorgan's Theorem is that the inversion bar of an expression may be broken at any point and the operation at that point replaced by its opposite (i.e., AND replaced by OR or vice versa).

4. Assembly

The assembly is not at all sophisticated for this hobby project. There's basically a few different types of logic gates which are repeated many times to build up your logic circuit. It takes a lot of patience as there's an abundance of intricate point to point wiring that you need to solder. Unfortunately, this doesn't have a ready made pcb normally found in kits. Making a pcb is a possible future step to take this workshop further.

A. Select Your Logic Circuit

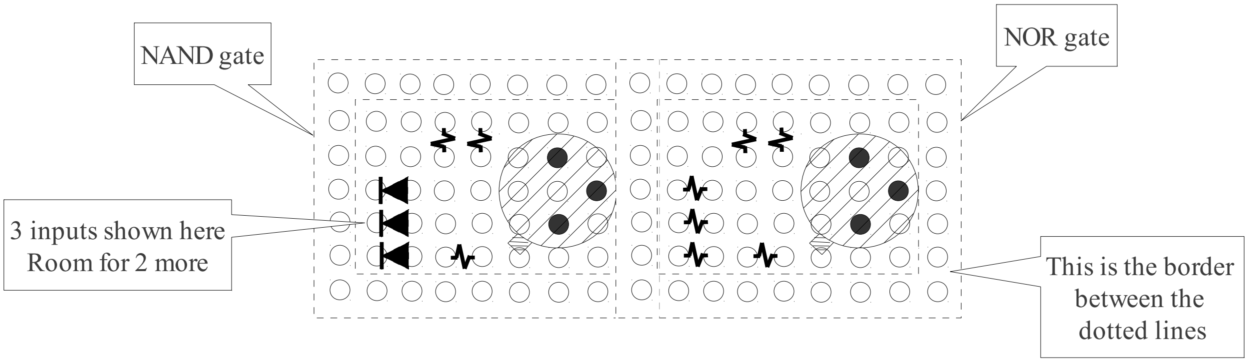
You first want to select a logic circuit to build. The circuit card can hold up to 42 transistors so there's a good selection to choose from. Because this is made on a plug-in card, you can expend this even further in the future with using a backplane and several cards.

B. Add up the Transistors

You can see in the examples how any transistors are used in different ways. If you have an idea for some other circuit, you can draw your circuit on a sheet of paper to get an overview of how to connect everything. Once you know what circuit you're going to build, add up all transistors that you need.

C. Layout the Parts

The diagram shows how to allot the minimum space need for each transistor. This is how you can fit 42 of these on one card.



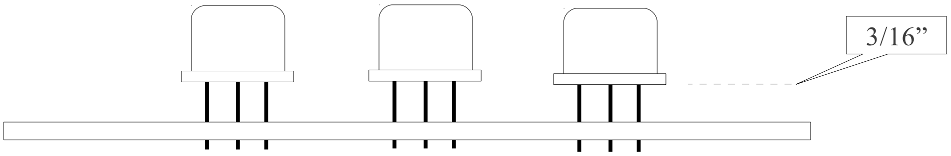
After you determine the amount needed for your logic circuit, start to layout the space needed for the transistors on your experimenter card. On the grid of the experimenter card, you want to make a border which divides the board into sections for each transistor. Use a black sharpie marker to make lines on the experimenter card. You can see an example of one here at the workshop, a photo is also available online.

D. Layout Description

The space in each section provides up to 5 digital inputs for each logic gate, the kit supplies enough for 3 inputs for all 42 transistors. If you need any more, the parts list shows where you can find more of these parts online. There's another method for adding additional inputs for other circuits using the extra breadboard space at the edge of the card. This is explained in the Advanced section.

E. Solder Transistors

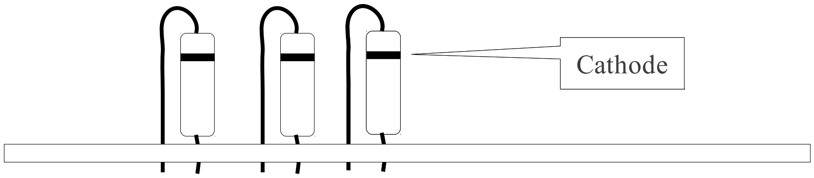
You first want to solder all the transistors that are needed for your circuit. It's recommended that you leave a gap of approx 3/16" above the board in case you need to troubleshoot your circuit. This space should be enough to access the pins of the transistors. I limited the gap to this distance on my project to allow them to be installed in a card rack with a backplane.



You can eyeball the distance at first, then bend the legs wider underneath the board so the transistor doesn't fall out when you flip the board over to solder them. Just solder one leg first, check the height, reheat the leg in case you need to slide the transistor up or down. Straighten out the transistor's case so they all look good sitting in a row. Then solder the remaining legs.

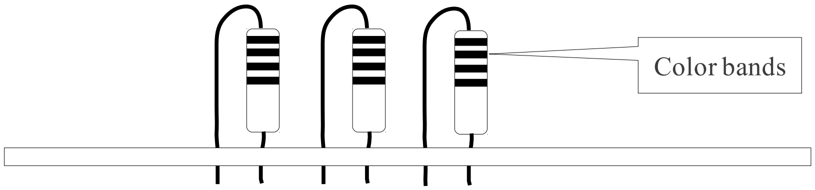
F. Solder Diodes

Next, you want to prepare the diodes and resistors for each transistor. All of the passive components are mounted vertically to save space. The legs of each part are bent in half to allow this. The diodes are mounted with the cathode end(band) on top. Bend the leg of the diode on this end only. With the cathode at the top, it doubles as a testpoint when you have to troubleshoot the circuit. This give you direct access to the input of the logic gate.



G. Solder Resistors

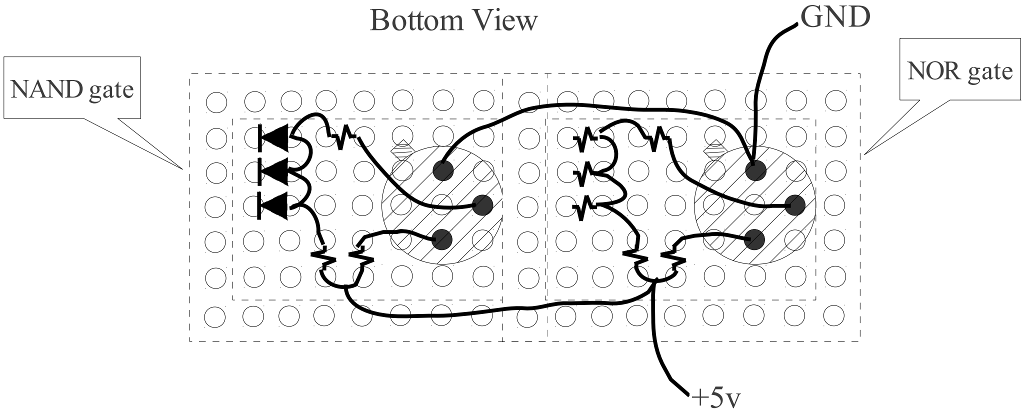
The resistors are mounted with the color bands starting at the top. This helps you to read the value easily – in case you make a mistake and mixup the parts :) Bend the leg of the resistor on end where the color bands start.



H. Connecting the Parts

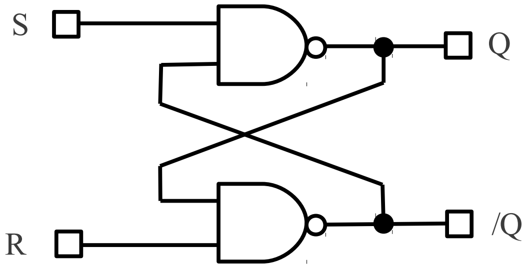
Now that the parts are all soldered in and all the leads have been cut – I hope you didn't throw out the clipped ends ?! This is what you can use to connect between the transistor, diode and resistors for each section.

It takes some patience to do this without creating solder shorts. But it also saves a lot of space versus using ordinary insulated wire. You can see a prototype in the workshop as an example. Below is a diagram to illustrate the technique.



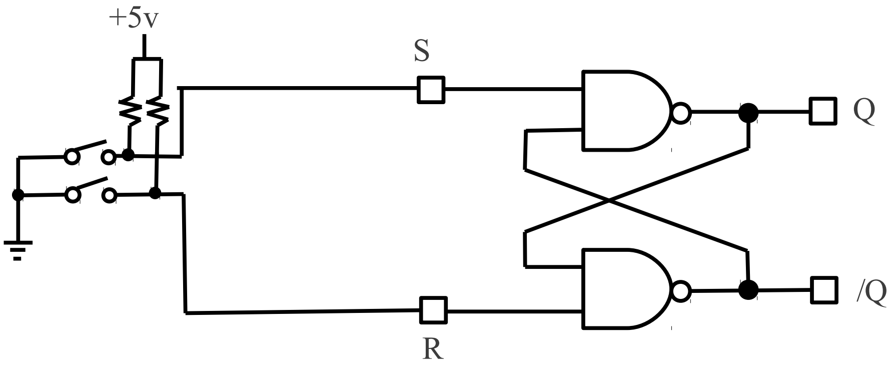
I. Connecting the Logic Circuit

The schematic below is an example of a RS Flip-Flop. Now that you have your logic gates prepared, you can begin to connect your circuit.



In this case, one of the inputs of the top NAND gate is reserved as the 'R' input (Reset). The other NAND gate has one input reserved as the 'S' input (Set). Then the second input of one NAND gate is connected to the output of the other NAND gate. The same is done for the other NAND gate.

The Q and /Q outputs are where you can connect your LEDs to have a visual indication of the Flip-Flop states when it's running. This is explained in the next section. The R,S inputs can be connected using the DIP switch. One DIP switch can be wired to the 'R' input and the another can be wired to the 'S' input. Below is the truth table for a RS Flip-Flop.



S	R	Q state
0	0	N/A
0	1	1
1	0	0
1	1	state

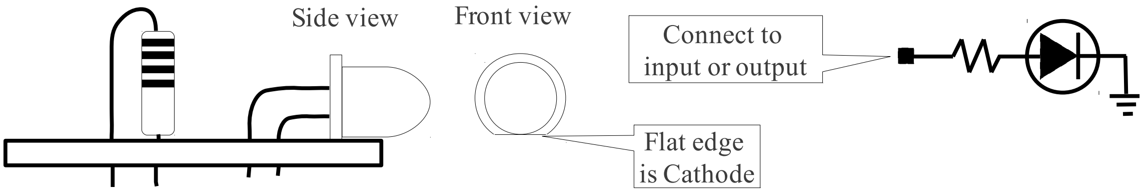
NOTE:

The state labeled N/A indicates this is a condition which is not allowable. This condition results in a state where both Q and /Q are at a logic HI level. A Flip Flop is not allowed to have both outputs at the same logic level.

J. Adding the LEDs

You like to have some visual indication of the logic circuit when it's operating. You can decide where you like to add any LEDs, either the green or red, to any points in the circuit.

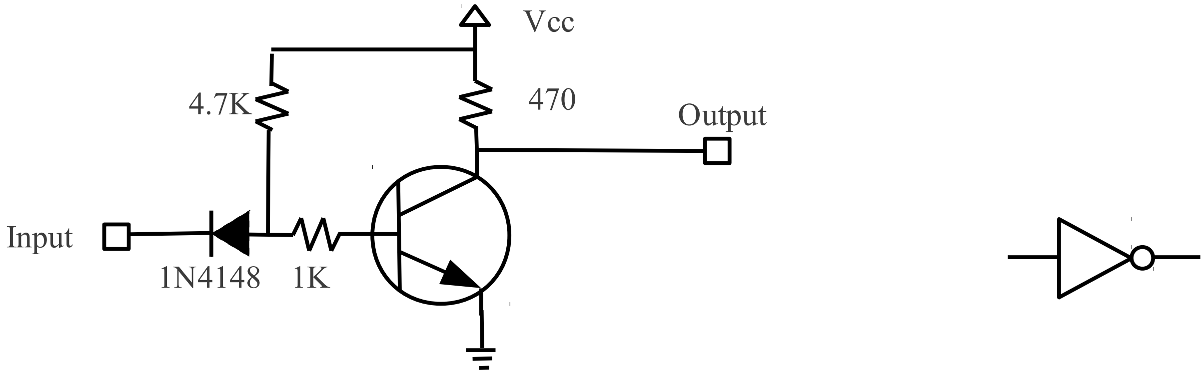
The edge of the card is reserved for LEDs. Since this is a plug in card, it's common to mount the LEDs at a right angle. The diagram below shows the best way to mount the LEDs. This saves space and allows room for more LEDs – you can never have enough LEDs !



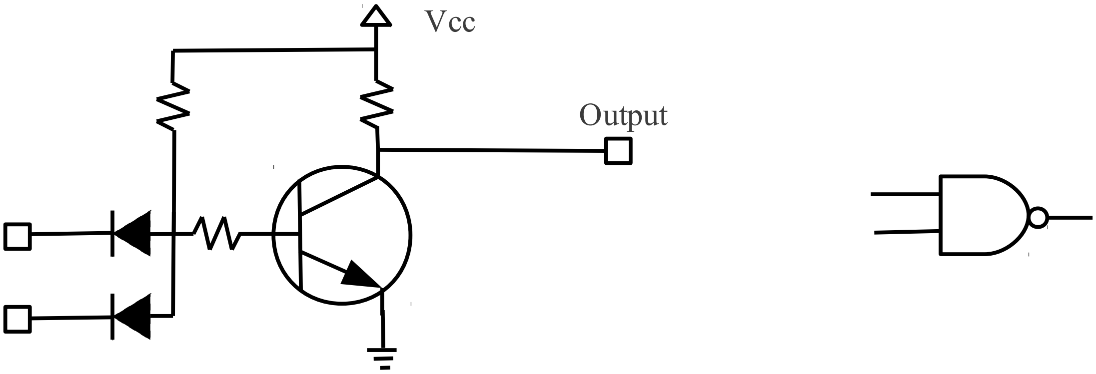
You can use the 220ohm resistors for the LEDs. These are also mounted vertically. And these can be soldered in the extra breadboard area near the edge of the card behind the LEDs. You can use the telephone wire to connect the LEDs to the resistors. Then add another connection to the point in the circuit where you would like to see the LED turn on. The cathode end of the LED would be connected to ground.

5. Examples

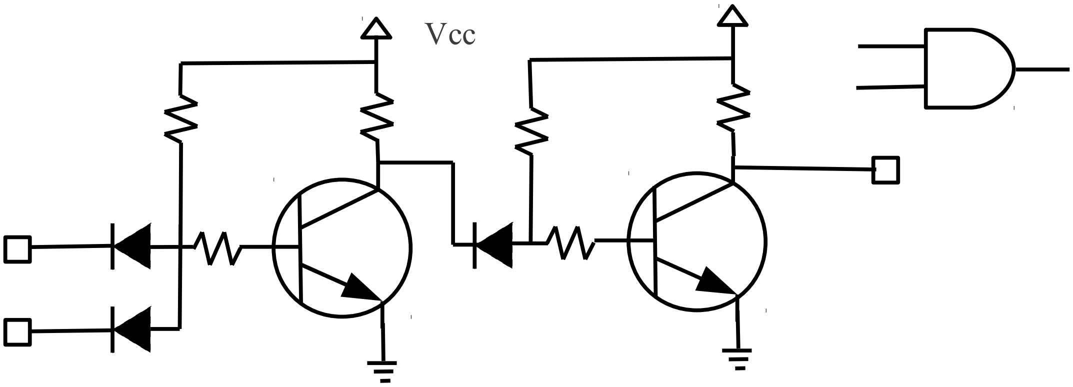
- INVERTER gate



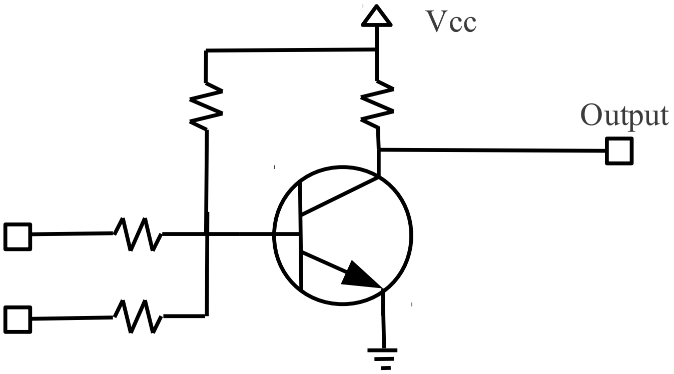
- NAND gate

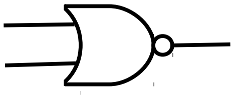


- AND gate

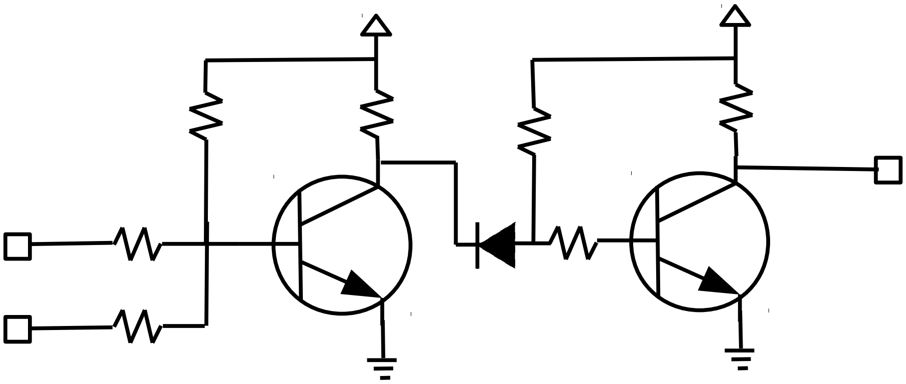


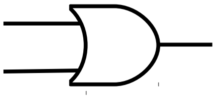
- NOR gate





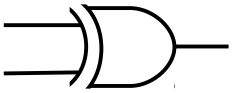
- OR gate





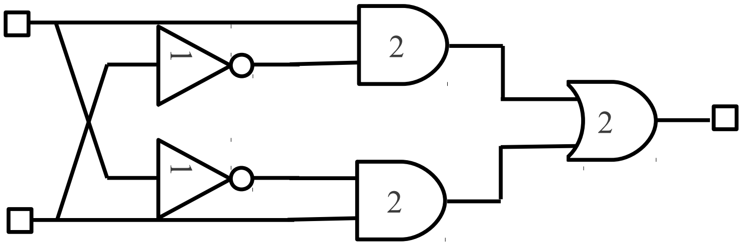
- XOR gate

symbol:



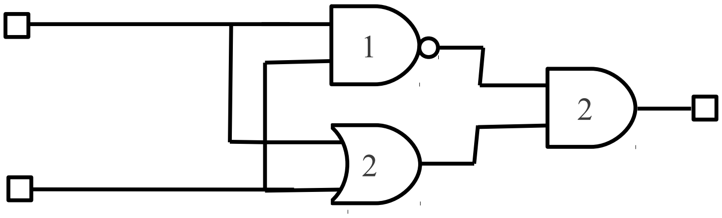
Version 1: 8 transistors

$$A*B = (\bar{A}\ B) + (A\ \bar{B})$$



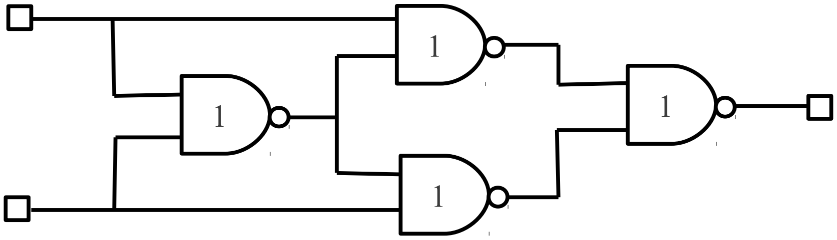
Version 2: 5 transistors

$$A*B = (\overline{AB})(A+B)$$



Version 3: 4 transistors & all gates are the same !

$$A*B = \overline{(A(\overline{AB}))}\,\overline{(B(\overline{AB}))}$$



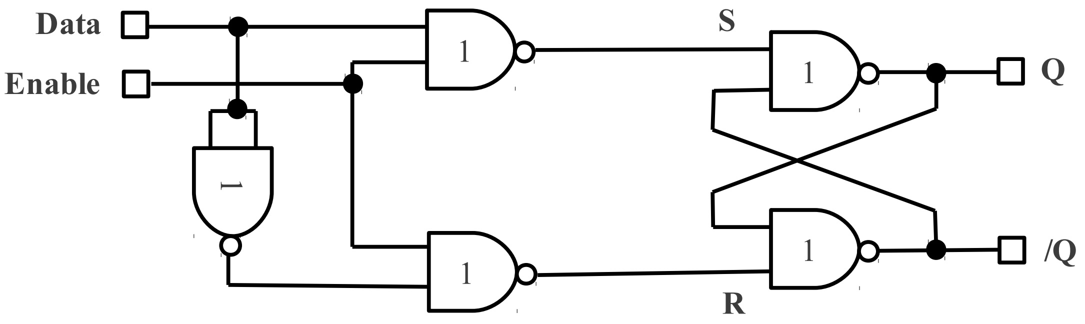
- Flip Flop:

D type Flip Flop:

Features:

- Enable Input(Active Hi)
- Data Input
- Q and /Q Outputs
- only 5 Transistors
- Used in Registers and Accumulators.

D	E	Q state
0	1	0
1	1	1
x	0	No Change

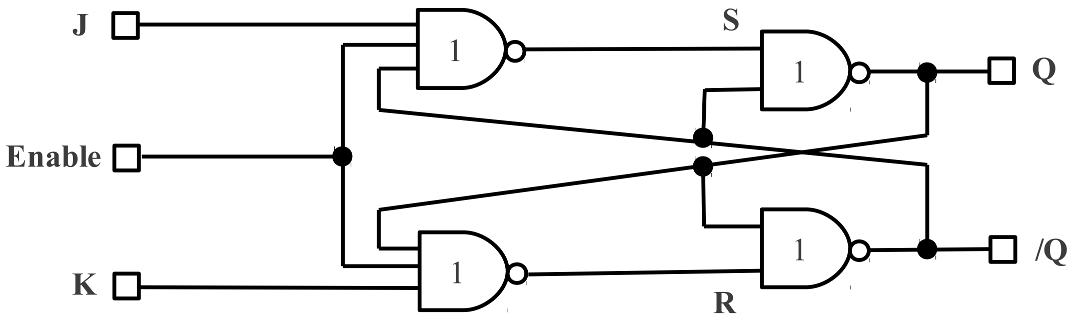


J/K type Flip Flop:

Features:

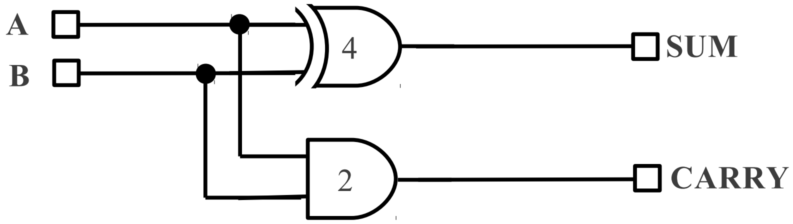
- Enable Input(Active Hi)
- J and K Inputs
- Q and /Q Outputs
- only 4 Transistors
- Used in Shift Registers, Serial Data, Counters, Dividers.

J	K	Q state
0	0	No Change
0	1	1
1	0	0
1	1	Toggles



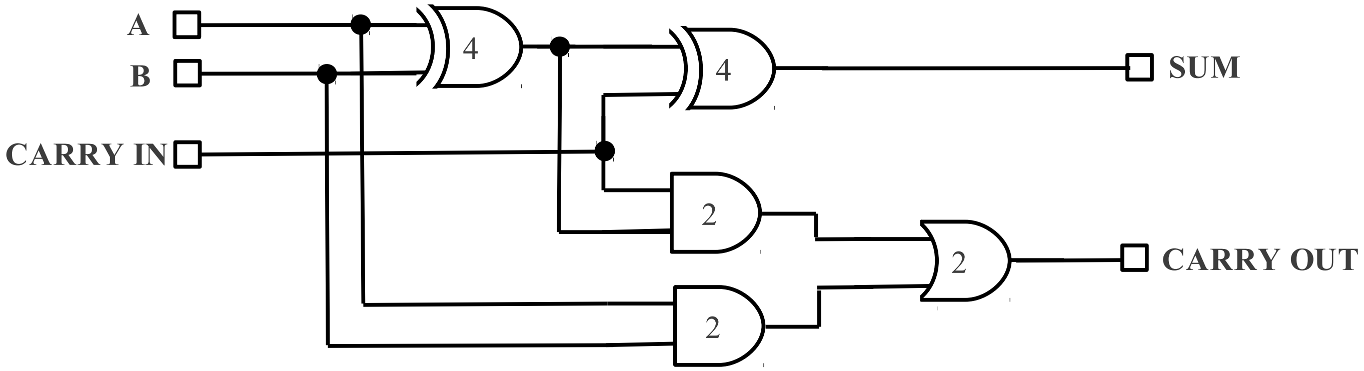
- Half Adder:

  Features:
  - Adds 2 single bit numbers
  - Carry Output available
  - only 6 Transistors
  - Used in Arithmetic Logic Units.



- Full Adder:

  Features:
  - Adds 2 single bit numbers
  - Carry Input & Output available
  - only 14 Transistors
  - Used in Arithmetic Logic Units.



- Clock Circuit - Pierce Oscillator:

  This is a basic oscillator which can be used in many instances. The configuration uses a simple inverter to provide 180° of phase shift, with the additional 180° supplied by two "pi" capacitors. Loop gain is optimized by specifying a lower output capacitance value than that of the input.

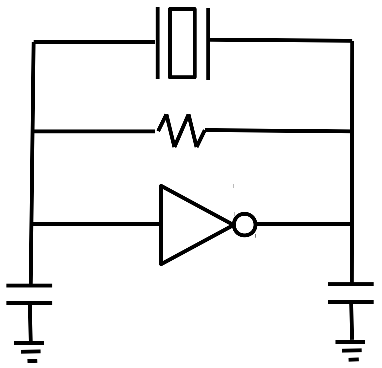
  The crystal parallel-resonates with the series combination of capacitors as the load. A resistor connecting the input and output of the circuit adds linearity to the gate and adjusts amplification.

  Bandwidth can be adjusted to a limited extent by changing the feedback resistor (usually from 2.2K to 100K). On the next page are some examples which you can experiment.

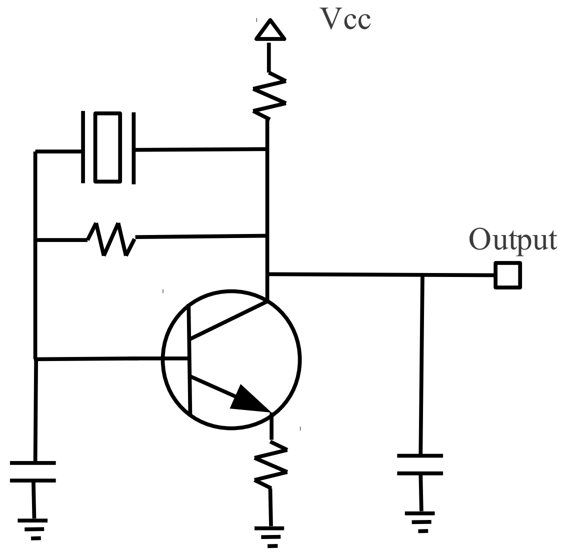
Clock Circuit (cont'd)

Schematic

common configuration:

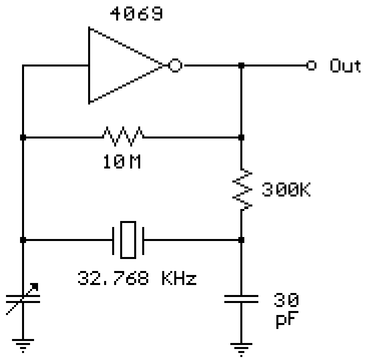


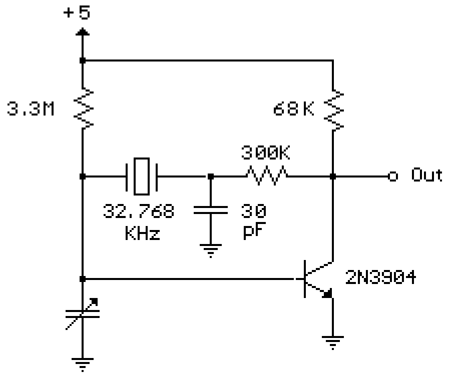
transistor configuration:

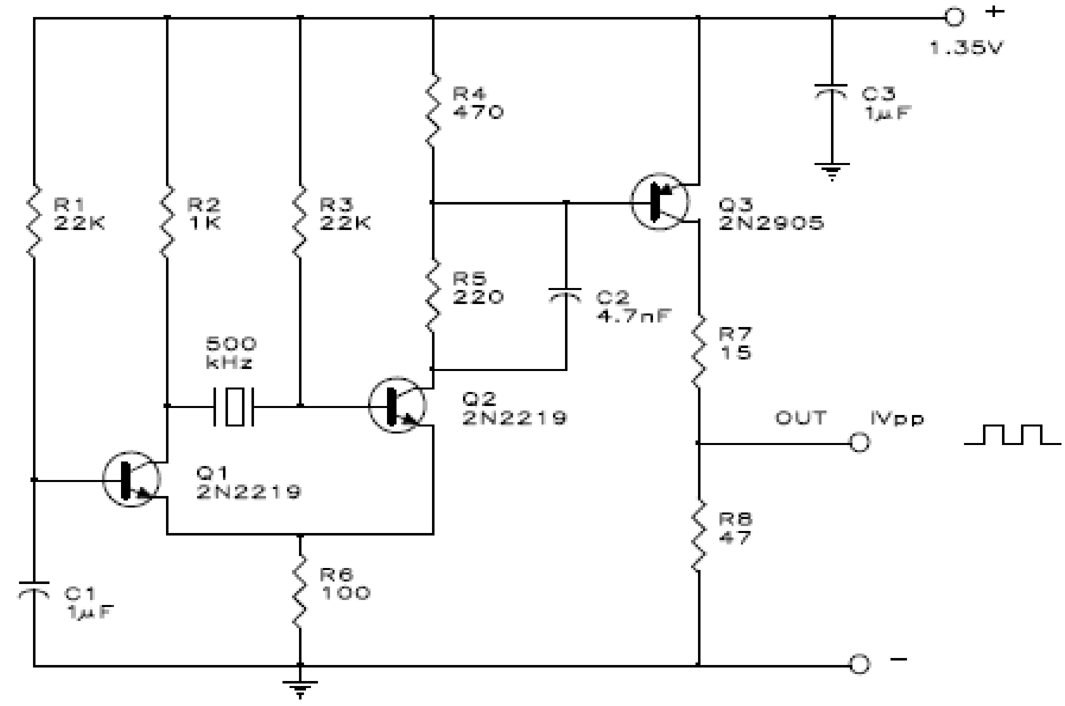


Clock Circuit (cont'd)

Schematic



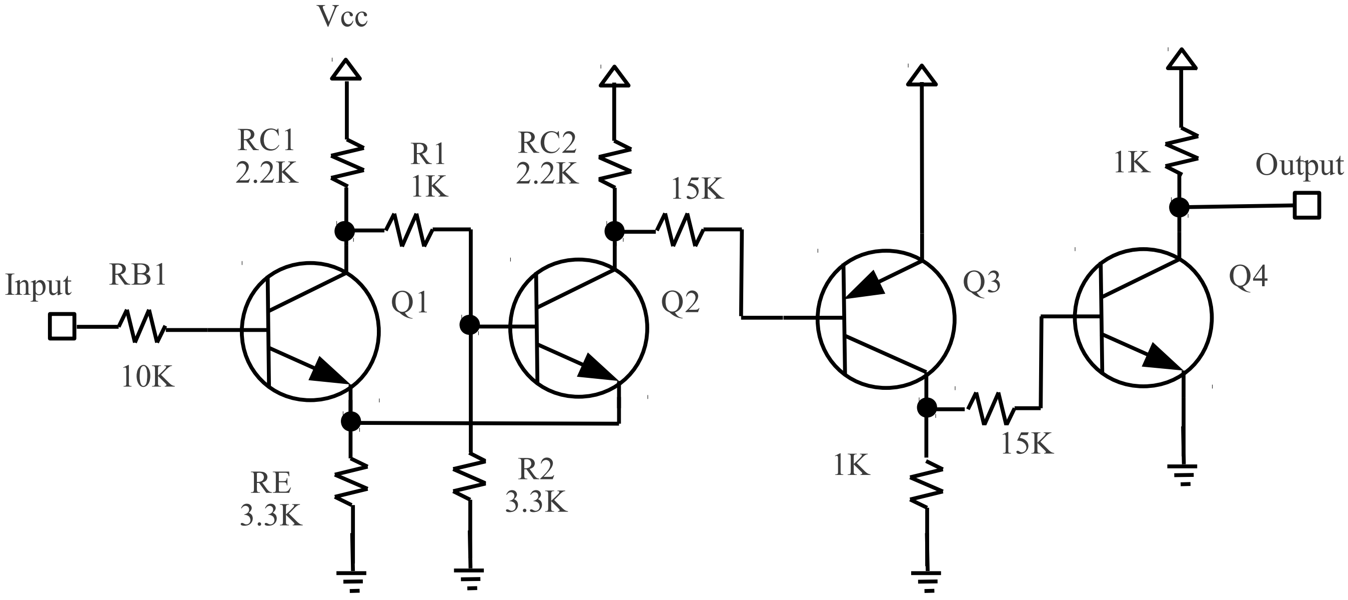




- Schmitt Trigger Buffer

The *Schmitt Trigger* takes an input signal which may not be clean or even a sinewave and it will “clean-up” and force it to a digital logic level signal on the output.

Some kind of signals may have slow rise and/or fall times, or may have some signal noise embedded which could affect the circuitry. It may even be an analog signal with a frequency you like to measure, such as, 60hz. It has two possible states just like an Inverter gate. The trigger for this relies on the input voltage level instead of a digital pulse.



Theory:
The Schmitt Trigger makes its feedback connection through the emitters of the transistors as shown in the schematic diagram to the right.

The input starts at ground, or 0 volts. Transistor Q1 is necessarily turned off, and has no effect on this circuit.

Therefore, RC1, R1, and R2 form a voltage divider across the 5 volt power supply to set the base voltage of Q2 to a value of:

$$(5 \times R2)/(RC1 + R1 + R2).$$

As long as the input voltage remains significantly less than the base voltage of Q2, Q1 will remain off and the circuit operation will not change.

While Q1 is off, Q2 is on. Its emitter and collector current are essentially the same, and are set by the value of RE and the emitter voltage, which will be less than the Q2 base voltage by V_{BE}.

If Q2 is in saturation, the output voltage will be within a fraction of the threshold voltage set by RC1, R1, and R2.

The output voltage of this circuit cannot drop to zero volts, “logic 0”. There is an additional stage to take care of this.

When the input voltage rises until it approaches the threshold voltage on Q2's base, then Q1 begins to conduct.

Since it now carries some collector current, the current through RC1 increases and the voltage at the collector of Q1 decreases.

But this also affects our voltage divider, reducing the base voltage on Q2.

But since Q1 is now conducting it carries some of the current flowing through RE, and the voltage across RE doesn't change as rapidly.

Therefore, Q2 turns off and the output voltage rises to +5 volts.

This is how the circuit changes states.

As the input voltage rises further, it will simply keep Q1 turned on and Q2 turned off.

Theory(cont'd):

However, if the input voltage starts to fall back towards zero, there is a point at which this circuit will reset itself.

The falling threshold voltage is when Q1's base becomes more negative than Q2's base. This will make Q2 conduct again.

This differs from the rising threshold voltage, since Q1 affects the behavior of the voltage divider.

When V_{IN} is equal to Q2's base voltage, Q2's base voltage will be:

$$V_{B2} = \frac{5 + V_{BE}\dfrac{RC2}{RE}}{\mathbf{1} + \dfrac{RC1}{RE} + \dfrac{RC1 + R1}{R2}}$$

As V_{IN} approaches this value, Q2 begins to conduct, taking emitter current away from Q1.

This reduces the RC1 current and raises Q2's base voltage more, increasing Q2's forward bias and decreasing Q1's forward bias.

This will turn off Q1, and the circuit will switch back to its original state.

Theory(cont'd):

Three factors in the Schmitt Trigger.

First,

The circuit changes states as V_{IN} *approaches* V_{B2}, not when the two voltages are equal. Therefore V_{B2} is very close to the threshold voltage, but is not precisely equal to it.

For example,

V_{B2} will be 2.54V when Q1 is off,

and 2.06v as V_{IN} is falling towards this value.

Second,

RE must be large enough to provide the requisite amount of feedback, but not too large where there's little current for the circuit.

If RE is out of range, the circuit will not operate properly, and may not operate as anything more than a high-gain amplifier over a narrow input voltage range, instead of switching states.

Third,

Since the 2nd stage output cannot switch between logic levels, the 3rd and 4th stage compensates for this. This circuit is basically two RTL inverters, except that one uses a PNP transistor.

This works because when Q2 is off, it will hold a Q3(pnp) off. But when Q2 is on, the Q3(pnp) is on. Then Q4(npn) is the second inverter to re-invert the signal and to restore it to active pull-down.

Note:

Traditional circuit analysis of this circuit would include the forward current gain, h_{FE}, of the two transistors.

This was very important in the early days of transistors when a signal transistor having a current gain of 30 was considered to be very good !

Modern transistors have a much higher gain, so they don't have the same limitations as older transistors. So you can ignore the effects of transistor base current

eg. 2N3904/2N3906 h_{FE} 160, 2N4124/2N4126 h_{FE} 200

6. **Advanced Work**

Several of the options below are also possible. They will contain many more transistors in the circuit, so it's important to plan the layout properly.

As I continue with experimenting with my project and improving this manual, I will include this information online. You can then find more info about building these circuits to include in your project. You can eventually find it here on my website, www.rogtronics.net/blog.

- Accumulator
- Shift/Rotate Register
- Arithmetic Logic Unit
- Discrete DRAM
- Control Store Logic
- Multiplier
- PCB - to speed up wiring

7. Parts List

- Experimenter Card, plug-in, Qty= 1

  Electronics Express, Prototyping board, 6-1/2" x 4-1/2", 22/44pin card edge, model PB-4
  http://www.elexp.com/pro_2pb4.htm

- Edge connectors, Qty= 2 , Part no. 39117

  JAMECO, 22/44, 0.156”(3.96mm) Edge Connector, $3.55, qty=10+
  http://www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_39117_-1

- Transistors, QTY= 35, Part no. 38228

  JAMECO, General Purpose BJT NPN 40 Volt 0.8A 3-Pin TO-39, qty= 100+, $0.35ea
  http://www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_38228_-1

- Crystal, 5Mhz, Qty= 1, Part no. 324427
  JAMECO, CRYSTAL,5.00MHZ,HC-49/UA, Qty= 10+ $0.29ea.
  http://www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_324427_-1

- Card Guides, Qty= 4
  Mouser, Card Guide, 6″ length, plastic nylon, Qty= 4, $0.68ea
  part# 561-CG600

  Below are some passive components with the basic values to get started. Some of the additional examples in this manual will use other values. Those can always be found at any parts supplier.

- Resistor - value= 1K
- Resistor - value= 4.7K
- Resistor - value= 470
- Resistor - value= 220
- Diodes – 1N4148
- Crystal, 5Mhz

  These are some additional parts to provide a way to connect the inputs and outputs of the logic gates.

- DIP Switch, 8 position
- LED - Red
- LED - Green

END OF LINE