CMOS Music I
// a workshop by Phillip Stearns

Learn how to make 1-bit chiptunes music without the hassle of computer programming. This is a musical introduction to basic electronic concepts through the use of CMOS digital logic chips. From a hand full of components you will create the world's simplest oscillator and 8 note musical rhythm sequencer. No soldering necessary, you'll take your project home on your very own solder-less breadboard!

Quick Review - Electronic Basics

On a rather coarse scale for this day and age, matter is made up of atoms, which comprises electrons, protons and neutrons. Protons and Electrons each have the property of charge, the electrons carry negative charge and protons, positive. Electrons "orbit" a defined nucleus made up of protons and neutrons. Because electrons can go rogue and leave the atom (or otherwise be ejected), we focus on the presence and absence of electrons in the study of electronics.

Electric Charge

Charge is considered a fundamental conserved property. Like energy, it can be neither created nor destroyed. Electrically charged particles produce and are influenced by electromagnetic fields as well as electrostatic fields. [We'll return to electromagnetism later...] A charged object possesses an electric field, a surrounding area that exerts a force on other charged particles. An electrically charged object may be either positive or negative. Similarly charged objects exert repulsive forces on each other, while objects with opposite charges experience an attractive force.

There is another quantity associated with the potential energy of a charged object in an electric field. This quantity is called electric potential and is measured in volts. Voltage is the electric potential difference, typically referring to the electric potential from a point of a highly energized state to a ground or zero potential state. Electric potential is that makes electrons move through space, creating electric current.

Static Discharge and Current

The build up of charge on the surface of an object is called static electricity. Static discharge occurs when charge is transferred from one object to the next resulting in a change in net charge. Current is the flow of electric charge through an object with a change in net charge of zero.

Electric Fields and Capacitance

Potential energy, or charge, may be stored in electric fields due to the property of capacitance. A common device used for storing charge is a capacitor, formed of two parallel plates. In the presence of an electric field, an object with a net charge of zero may polarize. Electrons will be forced to one side of the object, creating positively and negatively charged poles, corresponding with the charge of the field. Parallel-plate capacitors use this principle to store charge. In a closed circuit where a voltage source is connected across both terminals of a capacitor, electrons are forced onto one of the plates. This creates an electric field that forces electrons on the other plate to move away. There is an apparent current that flows momentarily across the capacitor until it can no longer store excess charge. The total amount of charge that can be held between the plates is directly proportional to the area of the plates, and inversely proportional the distance between them, and multiplied by a constant related to the dielectric properties of the material between the plates.

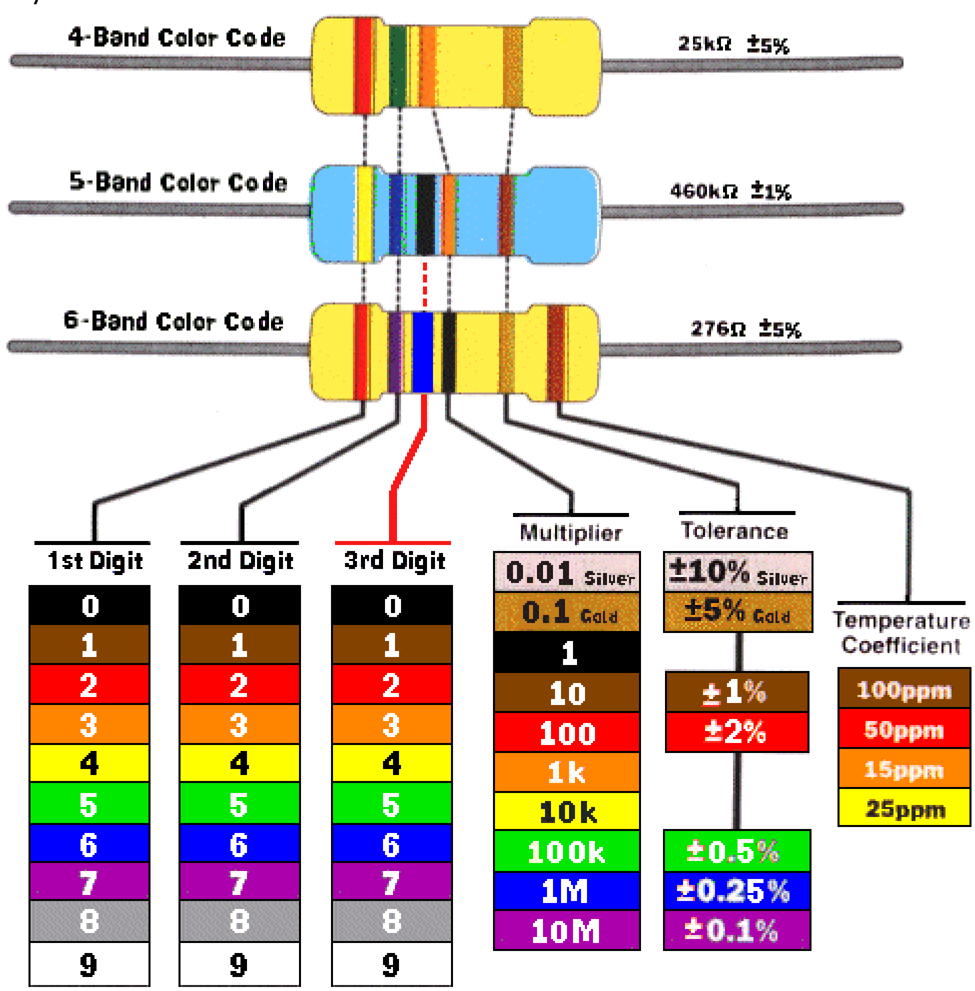
Capacitor Value Codes Fig. 2

3rd Digit	Multiplier	Letter	Tolerance
0	1	D	0.5 pF
1	10	F	1 %
2	100	G	2 %
3	1,000	H	3 %
4	10,000	J	5 %
5	100,000	K	10 %
6,7	Not Used	M	20 %
8	.01	P	+100, -0 %
9	.1	Z	+80, -20 %

Current and Resistivity

Current flows through conductive objects (metals and semi conductors---also dielectrics beyond their breakdown point), and not all of those objects pass electric charge equally. Materials have an inherent opposition to current, called resistance, which is measured in ohms.

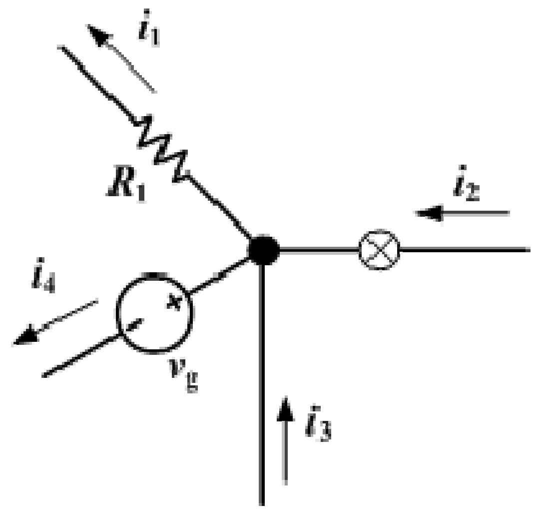
Electronic components called resistors are designed specifically to oppose the current flow. Their value in ohms is indicated by a series of color bands:



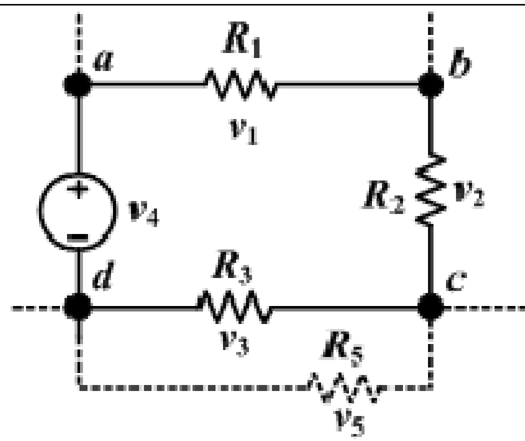
Laws:

Here are a few useful and ubiquitous laws when dealing with electronics. We won't be using them today but they're good to have at hand and to be familiar with for the future.

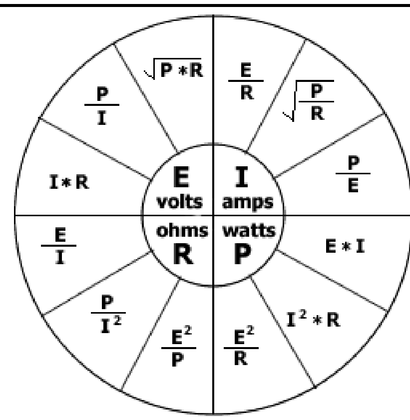
Kirchhoff's current law: The sum of all currents entering a node is equal to the sum of all currents leaving the node.



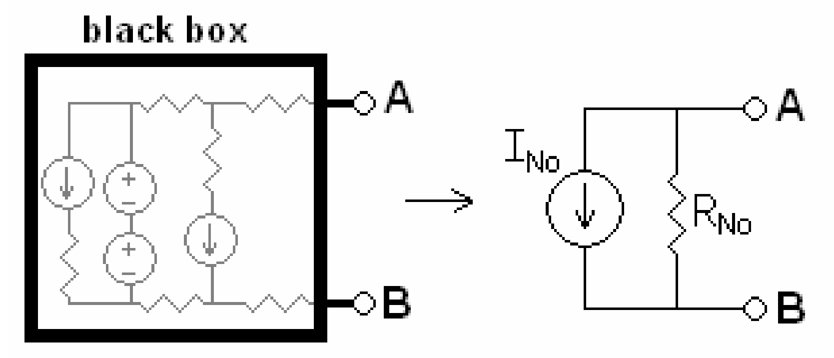
Kirchhoff's voltage law: The directed sum of the electrical potential differences around a loop must be zero.



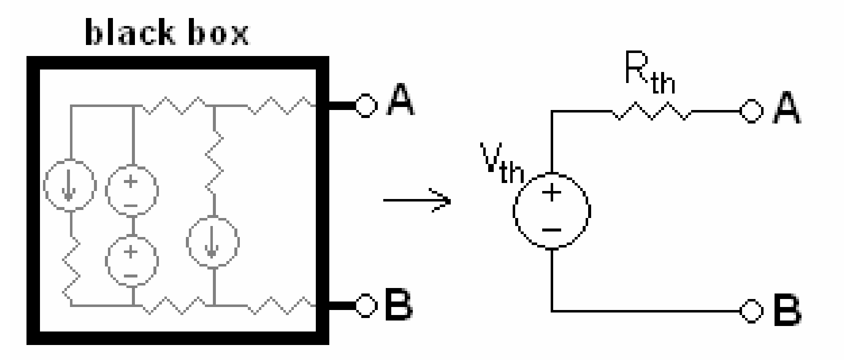
Ohm's law: The voltage across a resistor is equal to the product of the resistance and the current flowing through it (at constant temperature).



[Norton's theorem](): Any network of voltage and/or current sources and resistors is electrically equivalent to an ideal current source in parallel with a single resistor.



[Thévenin's theorem](): Any network of voltage and/or current sources and resistors is electrically equivalent to a single voltage source in series with a single resistor.



Digital Systems

These represent signals and information in a discrete numeric form rather than continuous voltages as in analog systems. In our situation, we are dealing with two-state, or binary digital systems, where the states of "high" and "low" are represented by differing voltage levels, typically zero volts and some voltage above zero. Positive logic recognizes the "high" state as one being a voltage some measure above the ground reference, which is recognized as "low". Logical 1 or "yes" is the "high" state, and logical 0 or "no" is the "low" state.

A digital circuit is often constructed from small electronic circuits called logic gates. Each logic gate represents a function of boolean logic. A logic gate is an arrangement of electrically controlled switches, typically relays or transistors. There are several different types of logic gates, which perform a boolean logic operation on a given number of inputs. Logic gates typically have a number of inputs and give a single output.

Most common of the logic gates that we'll deal with in this workshop and beyond are the NOT, OR, NOR, AND, NAND, XOR, and XNOR gates.

The NOT gate has one input and one output. If we present a logical 1 at the input, the gate returns a logical zero, and visa versa. It inverts the signal presented at its input, and for that reason we call NOT gates inverters. Two NOT gates in series creates a non-inverting buffer and can be used to prevent interactions between different parts of your circuit.

The OR gate has 2 or more inputs and a single output. The output of the OR gate will remain logical 0 until a logical 1 is present at ANY of its inputs. A NOR gate can be made from placing a NOT gate after the OR gate. The resulting behavior is inverted. That is, any logical 1 on ANY input will cause the output of the NOR gate to return a logical 0.

the AND gate has 2 or more inputs and a single output. The output will return a logical 1 if and only if ALL of its inputs are at logical 1. For all other conditions, the AND gate remains at logical 0. A NAND is formed by placing a NOT gate in series after the AND output, thus inverting the behavior of the AND gate.

The XOR (exclusive or) has 2 or more inputs and a single output. When all of the inputs of the XOR gate are either logical 1 or logical 0, the output will return a logical 0. For all other conditions, if one but not all or none of the inputs are positive, then the XOR returns a logical 1. An XNOR is formed by placing a NOT gate in series with the output of an XOR gate, thus inverting its behavior.

CMOS 4000 Series Logic

These chips operate on a wide range of voltages from 3-15 volts. Without getting into the physics of it, CMOS chips are capable of analog signal transmission and a hand full of chips are specifically designed to pass analog. The family can be broken down in terms of function. The two primary groups are asynchronous and synchronous (clocked) logic. Asynchronus provides an immediate output in response to changes at the inputs. Synchronous logic performs its operation on a timed clock pulse. Synchronous logic is the foundation for simple memory based operations such as adding and storing. Between both groups of logic there are logic gates, buffers, shift-registers, counters, flip-flops, phase-locked loops, line drivers, multiplexers, switches, and more. The types chips we'll be focusing on include counters, multiplexers, and buffers. Specifically we will cover the 40106 (inverting buffer), 4040 (12 bit binary counter), and the 4051 (8 to 1 multiplexer demultiplexer).

40106 (see appendix A)

Also known as the hex-schmitt-trigger inverting buffer, this IC is the heart of our little digital system. On this chip alone there are six inverters. Put a logical 1 on the input and you get an logical 0 on the output. Feed the input to the output and you have an oscillator. To control the frequency of oscillation, we places a resistor in the feedback path and create a place for charge to slowly build up and discharge through a capacitor connecting the input of the gate to ground. This type of oscillator is an RC relaxation oscillator and it works with the 40106 because there are two thresholds in operation when determining whether or not the buffer's output changes state. The threshold for the output of the buffer to go low is higher than that required to send it high. This phenomenon is called hysteresis and is employed intentionally to create clean on/off transition points, eliminating some error due to noise.

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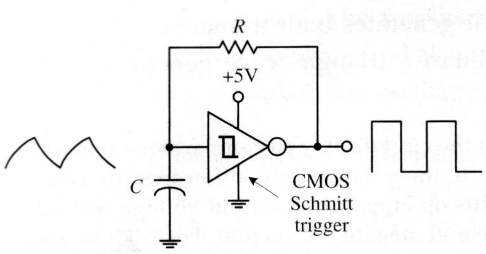
Digital oscillator
(using a Schmitt trigger inverter)

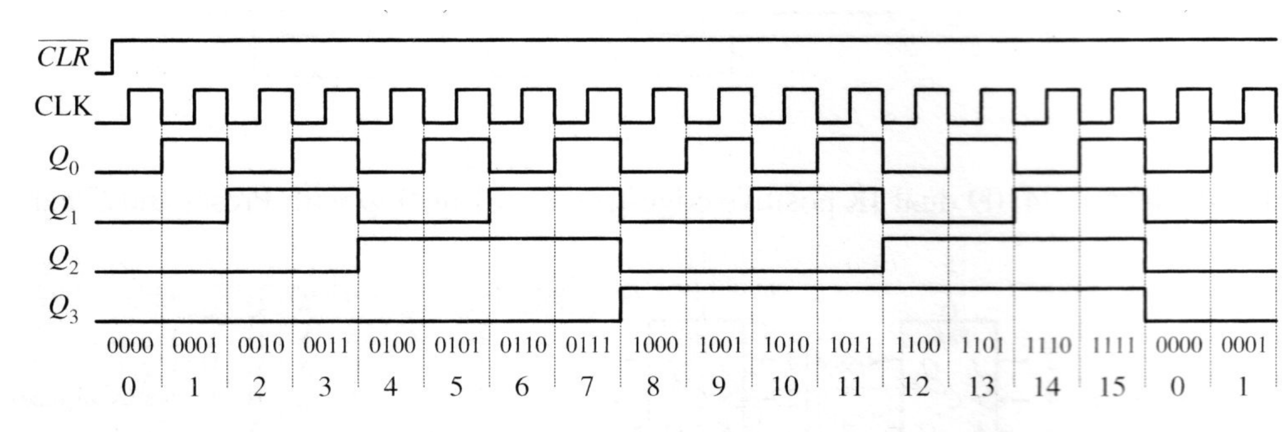


Digital oscillator (using inverters)

Here a simple relaxation oscillator is built from a Schmitt trigger inverter IC and an *RC* network. (Schmitt triggers are used to transform slowly changing input waveforms into sharply defined, jitter-free output waveforms (see Chap. 12). When power is first applied to the circuit, the voltage across *C* is zero, and the output of the inverter is high (+5 V). The capacitor starts charging up toward the output voltage via *R*. When the capacitor voltage reaches the positive-going threshold of the inverter (e.g., 1.7 V), the output of the inverter goes low (~0 V). With the output low, *C* discharges toward 0V. When the capacitor voltage drops below the negative-going threshold voltage of the inverter (e.g., 0.9V), the output of the inverter goes high. The cycle repeats. The on/off times are determined by the positive- and negative-going threshold voltages and the *RC* time constant.

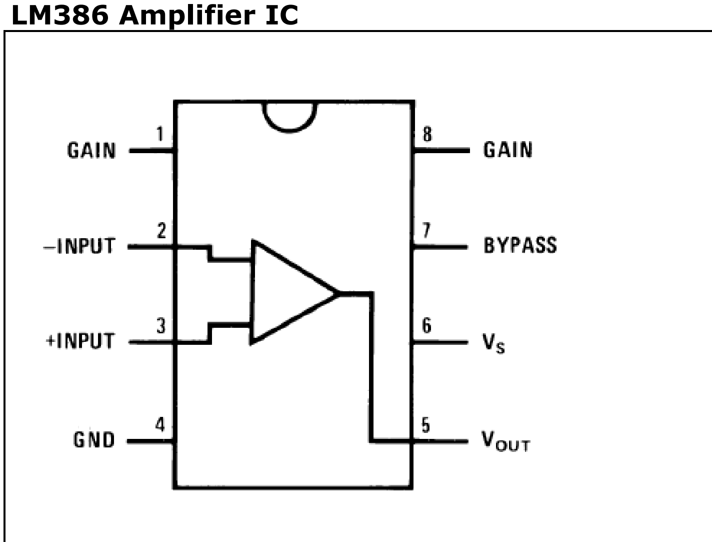
4051 (see appendix B)
It functions like a 8 position single pole rotary switch, however each position corresponds to a different 3-bit binary number, which can be addressed non linearly, meaning the selector switch can jump from one position without going through the others. In our circuit we use a counter IC to divide the oscillator created from the 40106 into different octaves. Each of those octaves is connected to on of the 8 inputs on the 4051. We then use another 4040 (which receives its clock from the first 4040) to provide the 3-bit control signal to tell the 4051 which octave to play.

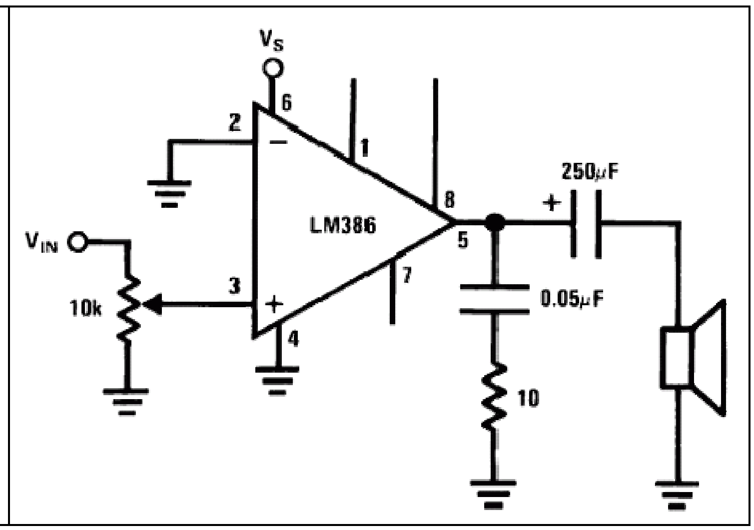
4040 (see appendix C)
This is the binary counter IC. In our circuit we use it to divided out oscillator's pitch into sub-octaves and to control the 4051. A binary counter is an example of a synchronous logic component. On the rising edge of a clock pulse, the counter is advanced, presenting its current count along its 12 output pins. This count holds until the rising edge of the next clock pulse. The first output changes its state a 1/2 the frequency of the input, the second changes at 1/4 the frequency of the clock, the third at 1/8th and so on. Each output is, in musical terms, is a sub-octave of the initial clock frequency.



Our oscillator from the 40106 functions as the clock in the above diagram. Q0 is one octave below the clock frequency. Q1 is two octaves below the clock frequency; Q2 is three octaves lower in pitch, etc.

LM386 Amplifier IC



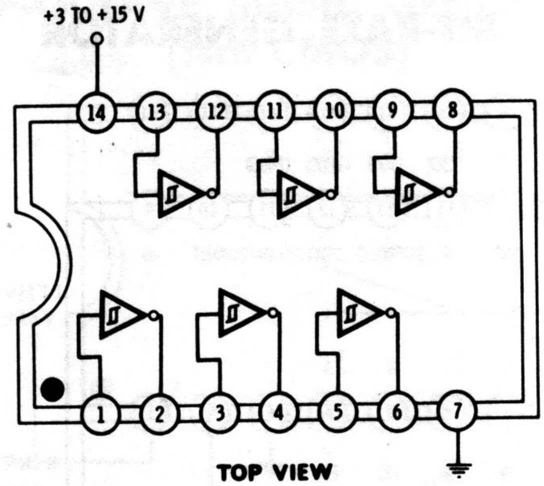


This little bug of a chip converts our 1 bit chirps into the kind of power we need to drive a little 8ohm speaker from a battery. This chip is designed with an internal gain programmable from 20 to 200, meaning it will multiply the voltage on its input by up to 200 times (given that it doesn't exceed the power supply)! We have a few extra parts added to our design to prevent the CMOS voltages from blowing up our speaker. The capacitors on the output provide some high gain stability, preventing the chip from self oscillating when it drives the speaker with a loud sound, and to prevent DC offset voltage from conduction through the speaker, thus preventing it from heating up and burning out.

And with that, I'm about burned out. This workshop was meant to be a sort of survey and intensive plunge into making music with CMOS chips. It's a load less complicated than programming your own MCUs, involves a lot less CPU power, but you can see that the complexity of the circuits needed to pre-compose material on the level that Tristan Perich is doing is a bit prohibitive. So far I've had success implementing these ideas in interactive installations, sound and light sculptures, and the knowledge ports over nicely into electronic music performance. Remember, this workshop is only the tip on the iceberg in terms of possibilities. There are myriad ways of creating sequencers and tones. We will go deeper in future workshops. Be on the look out for them!

4584

HEX SCHMITT TRIGGER



TOP VIEW

All six inverters may be used independently. While this package can be used as ordinary inverters, internal hysteresis on the inputs makes this device ideal for noisy or slowly changing input levels. It is also well suited to debouncing, contact conditioning, and astable and monostable circuits.

If an input is *low*, the output will be *high*, and vice versa.

On a positive-going waveform, the output will change at 2.9 volts with a 5-volt supply and at 5.9 volts with a 10-volt supply.

On a negative-going input waveform, the output will change at 2.3 volts with a 5-volt supply and at 3.9 volts with a 10-volt supply. Thus, the hysteresis, dead band, or noise immunity is 0.6 volt with a 5-volt supply and 2 volts with a 10-volt supply.

Propagation delay is 200 nanoseconds at 5 volts and 90 nanoseconds at 10 volts. Total package current is 0.3 milliampere at 5 volts and 0.6 milliampere at 10 volts for a 1-megahertz clocking rate.

Device is functionally equivalent to the TTL 7414, and the CMOS 40106 and 74C14 devices.

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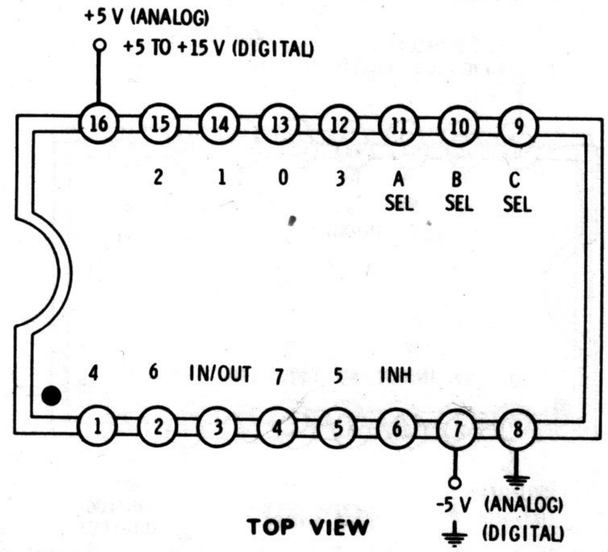
4051

1-OF-8 SWITCH



TOP VIEW

This package may be used as a 1-of-8 analog data multiplexer or demultiplexer, or as a 1-of-8 digital selector or distributor.

In the analog mode, —5 volts is applied to pin 7, and digital-control signals of low = ground and high = +5 are applied to the A, B, C, and INH inputs. If INH is high, no channel is selected. If INH is low, the channel selected is determined by the binary word input to A = 1, B = 2, and C = 4. Analog signals may be any value between +5 and —5 volts.

In the digital mode, pin 7 is grounded, and digital-control signals of low = ground and high = pin-16 voltage are applied to the A, B, C, and INH inputs. If INH is high, no channel is selected. If INH is low, the channel selected is determined by the binary word input to the A = 1, B = 2, and C = 4 inputs. Digital signals controlled may be any value between the pin-16 voltage and ground.

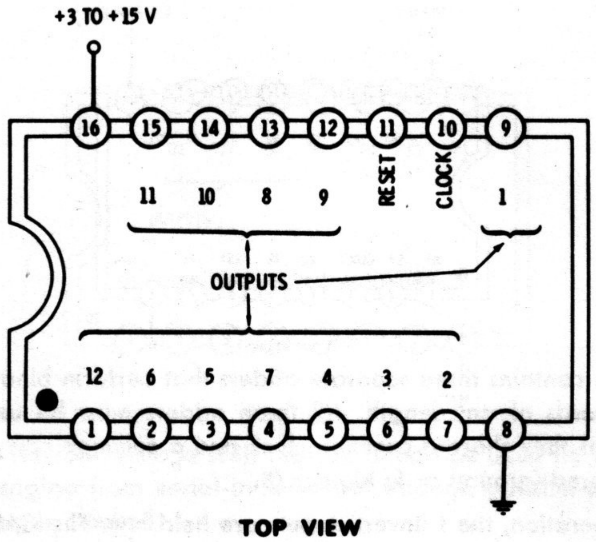
In either mode, the OFF state is an open circuit and the ON state is a 120-ohm resistor. Pin 3 may be used as an input or an output, depending on whether information is to be gathered from eight possible sources or distributed to eight possible locations. For digital signals only, device is functionally equivalent to the 74151 (TTL) and the 74C151 (CMOS) devices.

The minimum permissible load resistance is 100 ohms, and not more than 25 milliamperes can be routed through the circuit.

Total package current at a 1-megahertz clock rate is 0.5 milliampere at 5 volts and 1 milliampere at 10 volts, open circuited. Propagation delay is 200 nanoseconds for the supply connections shown. See Chapter 7 for more information.

4040

12-STAGE (÷4096) BINARY RIPPLE COUNTER



This is a binary ripple counter that counts in the up direction using positive logic.

The reset input is normally held at ground. Every time the clock changes from positive to ground, the counter advances one count. The 1 output divides the input clock by $2^1 = 2$. The 2 output divides the input clock by $2^2 = 4$. The 3 output divides the input clock by $2^3 = 8$, up to the 12 output which divides by $2^{12} = 4096$.

Making the reset input positive forces all outputs to ground and holds them there until the reset returns to ground.

The clock input must be conditioned to be noiseless and fall only once per desired count. Clock rise and fall times should be faster than 5 microseconds.

Since this is a ripple counter, the outputs change in sequential order and incorrect counts will briefly result during the settling time. Device is functionally and pin-for-pin equivalent to 74HC4040 for LS TTL levels.

Maximum input frequency is 6 megahertz at 10 volts and 2 megahertz at 5 volts. Total package current at a 1-megahertz clock rate is 0.4 milliampere at 5 volts and 0.8-milliampere at 10 volts. Consult the manufacturer's data sheet for propagation times.

Resources:

Books –

Practical Electronics for Inventors - Paul Scherz
The Art of Electronics – Horowitz and Hill
The CMOS Cookbook – Don Lancaster (check out his whole cookbook series)
Getting Started in Electronics - Forrest M. Mims III (check out his project series)

Places for Parts –

Mouser.com
Jameco.com
Goldmine-elec.com
Allelectronics.com
Digikey.com

My Website-

art-rash.com/pixelform
pixelform@art-rash.com