Electronic Music Techniques Used to Enhance Introductory Circuit Analysis

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ABSTRACT

To provide not only an interesting challenge but also experience in teamwork and communication skills, honors students in my introductory circuit analysis course are assigned a project involving electronic music synthesis devices. The students are teamed up into pairs, with each pair having responsibility for one of several modules which together compose a working voltage-controlled sound synthesis system. In addition to their individual tasks, each pair of students must collaborate throughout the semester with the others to resolve system integration issues.
A typical set of modules built by the students includes voltage-controlled amplifiers, power supplies, envelope (or transient) generators, and simple low frequency oscillators. Basic circuit designs are provided which the students must analyze, construct, integrate into a functional synthesizer, and explain to the class during their final oral report and demonstration. Taken together, these modules demonstrate practical applications of most of the major concepts and components covered in the standard introductory circuits course. They also introduce several more advanced ideas and devices. An audio amplifier and speakers as well as the more complex functions (voltage-controlled oscillators and filters) necessary for a fully functional system are usually provided for the project due to the complexity of these circuits for students at this level.

INTRODUCTION

When I was assigned to teach the introductory circuit analysis course (ECE 202), I was informed that I would have to provide an “honors component” for those students taking it as an honors course, ECE H202. (There is insufficient demand to offer a stand-alone honors course, so ECE H202 is taught as an “add-on” course, with the honors students attending a standard section.) I decided to adapt the work I was involved with during the late 1970’s in electronic music synthesis as a project for ECE H202.

HISTORY

In the mid-1960’s, Robert Moog began marketing the first commercially successful voltage-controlled electronic music synthesis equipment. Following the release of Walter Carlos’ ground-breaking album *Switched On Bach*, sales of Moog’s synthesizers soared. Several competing companies jumped on the bandwagon, and by the mid-seventies, most popular music groups used such equipment in addition to many avant garde and classically oriented musicians. With the personal computer revolution of the eighties, sound synthesis moved inexorably toward the digital domain. As microprocessors and memory became faster and cheaper, real-time digital synthesis became feasible. By 1990, analog voltage-controlled music synthesis was essentially obsolete. With its dozens (or hundreds) of potentiometers and patch-cords for “programming” the sounds, the voltage-controlled devices simply could not compete in terms of cost and ease of use.

THE BASICS

Voltage-controlled music synthesis equipment is by its very nature modular. The general idea is that every parameter of all sound generation and processing devices should be controllable by a voltage, and that the output of every device should be a voltage, thus (theoretically) any module can control the operation of any other module. In reality, of course, there are some types of interconnections which are never used. The interconnections traditionally were accomplished by means of patch cords (the usual type used 1/4” phone plugs). As an example, if vibrato (a slight periodic (a few hertz) variation of the frequency of a sound) is desired, the sinusoidal output of a low-frequency oscillator (LFO) would be connected to the frequency control input of a voltage-controlled oscillator (VCO). The output of the VCO would then vary in frequency sinusoidally at the rate set by the LFO.

Although there are many of types of modules that can be constructed to generate and modify sounds (or rather audio frequency electrical signals) there are only a few which are used to implement most sounds. Out of this group, some are beyond the scope of an introductory circuits course, so the problem was to determine a subset of modules which would be sufficient to illustrate the basic principles of voltage controlled music synthesis without going into too much depth with more advanced concepts such as electronics or control theory.

A connection of modules for a very simple sound is shown in Figure 1. The VCO generates an audio waveform (sine, pulse, sawtooth, etc.) with the frequency being determined by a voltage from a user interface device, usually a standard organ keyboard. The output of the VCO goes to the signal input of a voltage-controlled filter (VCF) which modifies the harmonic content (the timbre) of the sound. Note that the cutoff frequency of the VCF is also controlled by the keyboard to maintain a constant timbre. The output of the VCF goes to the signal input of a VCA and from there to an audio amplifier and speakers. To create individual notes, the keyboard must in some way control the VCA, turning it on when a key on the keyboard is depressed, and setting the gain to zero when the key is released. If the VCA is turned on or off suddenly, a distinct pop will be heard (this follows from basic Fourier analysis), so somehow the gain of the VCA must be increased and decreased gradually (over a few milliseconds or more). The device usually used for this purpose is called either a transient generator or an envelope generator. Although most envelope generators are a bit more complex, in the simplest case it will accept a Gate signal (a binary signal indicating whether or not a key is depressed). When the gate goes high (key depressed) the envelope generator will gradually increase its output voltage from zero to some maximum (typically 5V) at a rate set by the user. The output remains high until the gate goes low (key released), at which point the output of the envelope generator gradually decreases back to zero, also at a rate set by the user and usually different from the rate of increase. Connecting the output of the envelope generator to the control input of the VCA then allows the amplitude of the sound to increase from zero up to a maximum without the pop, then die away gradually when the key is released.

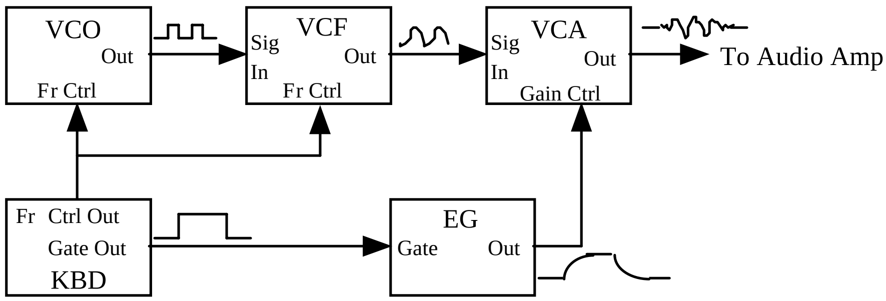

Figure 1 - Generating a Simple Sound

Although not shown in Figure 1, vibrato could be added by taking a low frequency sinusoid from an LFO and connecting it to another frequency control input of the VCO. (Most VCOs have multiple control inputs for this reason.) With this as a starting point, I considered the options. The VCO and VCF are really too complex for an introductory course. The VCF is not absolutely necessary, so I sometimes omit it. The VCO is too fundamental, being the source of the audio signal itself, so I provide this for the students. As an alternative, many function generators in standard college labs have a voltage-controlled frequency input which could be used for this purpose. After one iteration of the course, I also decided that the keyboard interface was too difficult and dropped it. This still leaves enough options to have an exciting honors project.

THE MODULES

The typical output levels of commercial equipment are typically +/- 5 volts, and this was chosen for the H202 project. These signal are large enough to avoid excessive noise problems and yet low enough that standard garden-variety op-amps do not run into slew-rate problems at audio frequencies. The modules that make up the core of the project are described below. In the discussion of each module, I have given a brief explanation of its function as well as indicating both the course concepts demonstrated by the module and other ideas which are necessary to understand the circuit although not part of the standard course. If only a few students are involved, the power supply could be replaced with a bench supply. If more modules are desired, different students could implement the basic functions by alternate methods, or other less common yet relatively simple devices could be added to the list. See the bibliography for many ideas.

Although each student or pair of students is assigned responsibility for one specific module, and their oral report covers that module, I meet with the entire group of honors students and go through an explanation, appropriate for introductory students, on the operation of all of the devices being constructed. Many of the basic concepts of the course are thus reinforced as well as having many new ideas introduced. The students also gain additional practical experience beyond the required lab course.

Power Supplies

A bipolar supply is needed for most of the circuits (to power the op-amps). I chose a +/-15 volt supply, although this could vary somewhat. In addition, there are a few cases where +5 volts is needed, so a separate five volt supply is built. For all three supplies, I use standard three-terminal regulators connected to a full-wave rectifier and filter capacitor. This type of circuit is so standard that it will not be shown here.

Reinforcing the course material is the idea of the capacitor used to filter the output of the full-wave rectifier. I discuss the consequences of varying the capacitance and varying the current drawn from the circuit by the regulator. Also, the practical matter of the tiny tantalum capacitor in parallel with the huge electrolytic capacitor is covered. I begin this discussion by pointing out that the capacitance of the electrolytic is probably only guaranteed to be within 20% of the stated value, and that the capacitance of the tantalum is much less than this 20% variation. If capacitances in parallel really add, this seems a bit silly. This of course leads to a discussion of the non-ideal characteristics of components we usually treat as ideal in an introductory course. The tantalum capacitor is necessary to control high-frequency instabilities in the regulator since electrolytics have poor high-frequency characteristics. The practical issue of component placement is also covered; the tantalum won't do much good if it is located several inches from the regulator, even though topologically the circuit is correct.

New concepts covered include the transformer (not introduced until our second circuits course), diodes used as rectifiers and the full-wave bridge configuration (I even give a simplified explanation of what is happening at the P-N junction), and the three terminal regulator (which I furiously wave my hands about since the internal operation is a bit complex for introductory students.

Low Frequency Oscillator (Figure 2)

The LFO chosen uses a simple integrator-Schmitt trigger design. The output of an inverting integrator is connected to the input of a comparator with hysteresis (+/- 5 volt switching points). When the input to the comparator goes below -5 volts, the output goes low; when the input goes above +5 volts, the output goes high. The comparator's output is fed back to the input of the inverting integrator. The result is a triangular waveform at the output of the integrator (close enough to a sine for useful vibrato and tremolo) and a square wave from the comparator. Although this is not a voltage controlled device, it is quite useful in music synthesis.

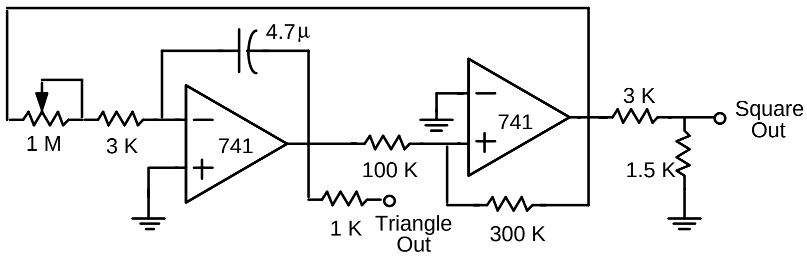

Figure 2 - Low Frequency Oscillator

The basic integrator is covered in class and this provides an example of a practical circuit, as well as more practice in analyzing the integrator. The low frequency of the oscillator points out another practical problem with capacitors. To obtain frequencies of one hertz or less with a reasonable potentiometer value (perhaps 1 megohm) a capacitor of over 1 microfarad is needed. Since the voltage across the capacitor routinely reverses polarity, a non-polarized type is needed. The students find that there are few such capacitors available with the desired capacitance, and the ones that can be found are rather large and expensive. A practical use of voltage division is shown in the reduction of the +/- 15 volt square wave to the desired +/- 5 volt level.

Although the basic comparator is covered in class, hysteresis is not, but is fundamental to the operation of the oscillator. In addition to explaining how the circuit accomplishes this, I also talk about other reasons hysteresis is used (e.g. avoiding false switching with noisy and/or slowly changing signals). In addition, I bring in an old mechanical home thermostat with a mercury switch mounted on a bimetallic coil. Not only does this introduce the ideas of the mercury switch and the bimetallic element, but gives them an example of mechanical hysteresis which is perhaps a little easier to grasp. This understanding can then be applied to the more abstract idea of hysteresis in general.

The Voltage Controlled Amplifier (Figure 3)
There are numerous VCA circuits, many of which use an operational tranconductance amplifier (OTA). Most such circuits for electronic music synthesis are designed with a maximum of unity gain, thus they are actually used to reduce the signal level, not increase it. The circuit I normally use is not the simplest to understand, but this actually turns out to have a pedagogical advantage.

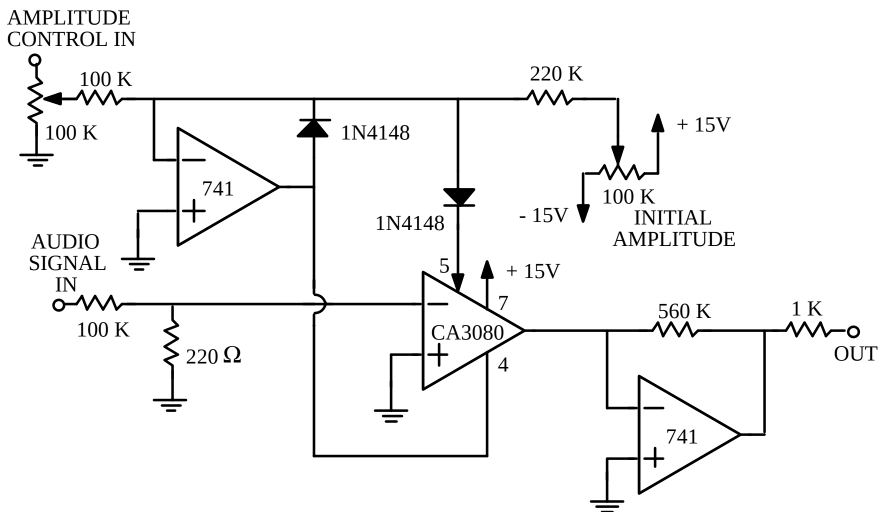

Figure 3 - Voltage Controlled Amplifier

The basic op-amp adder is covered in class, and is represented in this circuit. The amplitude control inputs to the VCA must be added together, thus illustrating op-amp summation circuit. The signal input to be amplified must be scaled down since the OTA expects input signal levels in the millivolt range and the other modules all use signals with a five volt amplitude. This is another illustration of a practical use for voltage division.

Since the output of the OTA is a current, this must be converted to voltage with an amplitude of five volts when the VCA gain is maximum (assuming a five volt input signal). This is a fairly straightforward modification of the standard inverting amplifier with which the students are already familiar. The complexity of this circuit lies in the fact that the feedback loop from the output of the control signal summer to its inverting input goes through the negative power supply of the OTA! This required some thought to successfully explain to beginning students, but it illustrates the important point that there are many non-standard ways of using off the shelf components to make them do tricks you might not expect. For the CA3080 OTA used, the gain control input pin floats one diode drop above the negative supply, and the typical means of supplying current to this pin is simply to connect it to a voltage through a resistor. In this circuit, the resistor is connected to the summing node (virtual ground) of the op-amp which adds the control signals. Since the op-amp will do what it can to maintain a virtual ground at the summing node, this means adjusting the negative supply voltage of the OTA (thus the voltage at the OTA's control input) so that the current into the gain control input (from virtual ground to the gain control pin through the resistor - Ohm's Law) is the same as the currents added at the summing node.

The Envelope Generator (Figure 5)
This is perhaps my personal favorite for illustrating basic circuit principles, although its use in music synthesis is perhaps a bit difficult to fully comprehend at first. There are many circuits which could be used for the envelope generator, and I have in fact used several different variations, only one of which will be discussed here. For alternate circuits, refer to the bibliography.

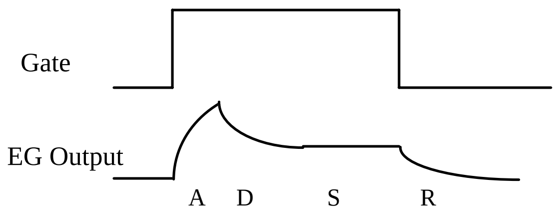

Figure 4 - Relationship between Gate and Envelope Generator Output

The basic envelope generator is a sequentially switched RC circuit with three stages. The envelope generator accepts as input a gate signal (a pulse rising from ground to five volts, then returning to ground) and generates the following output (Figure 4). The output of the circuit is simply a reflection via a voltage follower of the voltage on a capacitor that is being charged and discharged. When the gate goes high (usually representing a key depressed), the output begins rising toward six volts at a rate set by a potentiometer. This is called the attack phase. When the output reaches five volts, a comparator switches the circuit (note that the six volt goal is never reached) and the capacitor begins discharging through a different potentiometer (the decay phase) to a level set by another potentiometer. This sustain level is between ground and five volts. As long as the gate remains high, the output will remain at the sustain level, assuming it reaches that point before the gate turns off. When the gate goes low again (key no longer depressed), the capacitor discharges to ground through yet another potentiometer, the final release phase. Since there are four controls, attack speed, decay speed, sustain level, and release speed, these devices are often called ADSR transient generators.

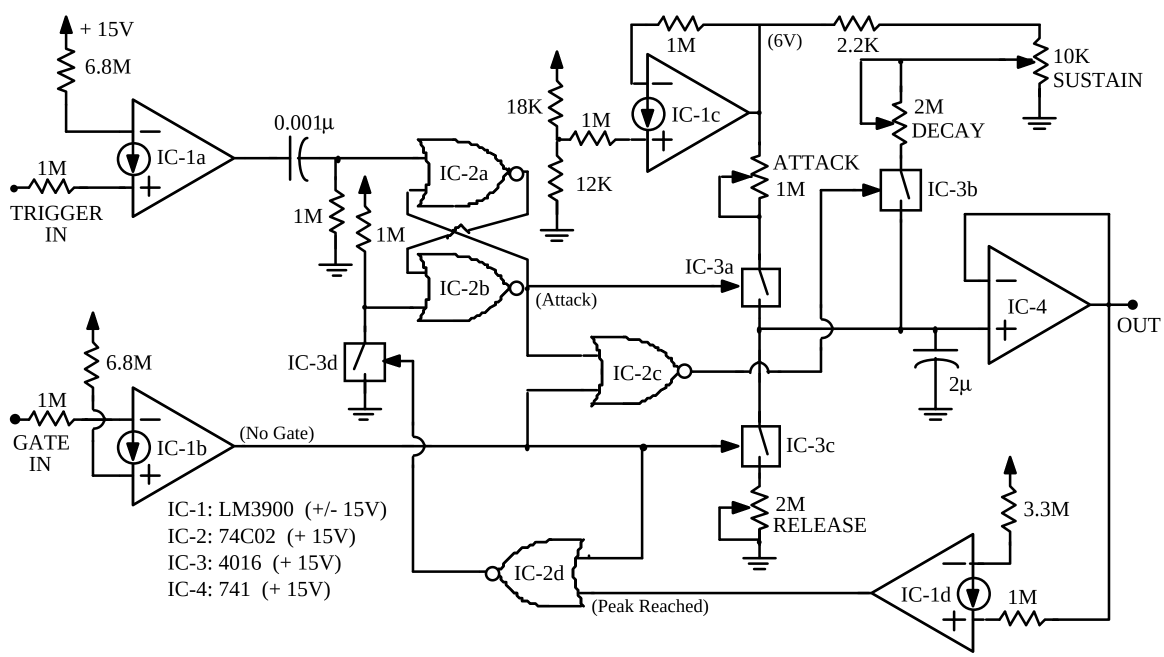

Figure 5 - ADSR Envelope Generator (From Reference 1, Chapter 5e)

In the circuit shown there is also a “trigger” input which is a brief five volt pulse. In terms of music synthesis its purpose is to indicate that the key depressed has changed even if the gate did not go low. For the purposes of the project, the trigger is derived from the gate by inverting and differentiating the gate and using the resulting negative pulse to trigger a monostable which generates a well defined pulse. The circuit shown in Figure 6 accomplishes this task.

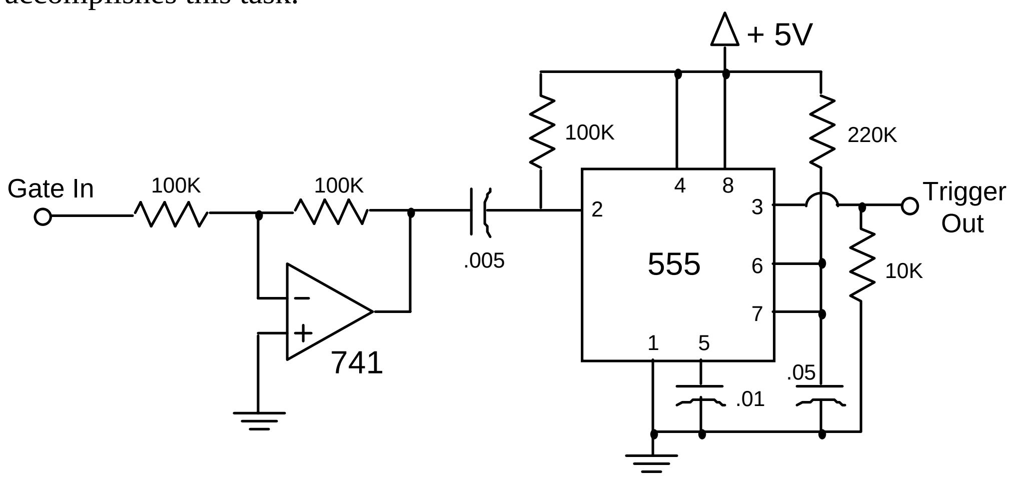

Figure 6 - Trigger Generator

In the introductory circuits course, most students seem to think sequential circuits exist only to appease the sadistic impulses of the textbook author and the professor. This gives them a practical example of the use of a switched RC circuit. Also covered is the op-amp voltage follower to buffer the capacitor voltage and use of a capacitor to differentiate a signal.

Most electrical and computer engineering students at Clemson take the introductory digital logic course during the same semester they are enrolled in the introductory circuits course. The ADSR transient generator gives a practical example of a hybrid circuit, having both analog and digital components. Along the way, the analog switch (itself a hybrid) is introduced. Also introduced is the current-differencing amplifier (CDA). Use of the CDA as both an amplifier and a comparator are represented in this circuit. The trigger generator also introduces the 555 timer.

CONSTRUCTION

Most of the circuits are constructed using standard prototyping boards (holes on 0.1 inch centers for standard DIP ICs). I prefer boards with four bus strips, two on each side, for ground, the bipolar supply, and the five volt supply where needed. The power supply is usually built on perfboard, but there are other options. I supply a panel with potentiometers and 1/4” phone jacks already mounted to which the students can connect their circuits. This simplifies the interconnections between modules and makes demonstrations much easier to conduct. I also supply several patch cords with 1/4” phone plugs for the interconnections between modules.

DEMONSTRATIONS

With these few modules, many demonstrations can be performed, and the students are always fascinated by the sounds they are able to make. Of course, if more devices were constructed, more elaborate demonstrations could be conducted. I will give a few simple examples here, but the range of sounds is limited mainly by one's imagination. (Walter Carlos synthesized an incredibly realistic thunderstorm on one of his albums, for instance, but he also had a tremendous amount of hardware.) In all cases, initial frequencies and levels of control signals must be set to achieve the desired effect. This takes only moments after a little practice. Typically most signal and control inputs of the various modules will include a potentiometer to attenuate the signals to the desired levels, so this is not a problem. (These pots are not shown on the VCA circuit diagram, however.)

Sirens (Figure 7)
The "European" alternating pitch siren is easily implemented by controlling the VCO frequency with a square wave of about one hertz. An electronic warbling siren similar to those commonly heard from emergency vehicles can be implemented by controlling the VCO frequency with a triangle wave of a few hertz.

Listening to a capacitor charge and discharge (Figure 8)
The ADSR transient generator can be used to control the frequency of the VCO (not often done in music synthesis) to actually hear the effect of a capacitor charging and discharging. The Attack and Release controls are set for a long time constant (two or three seconds), and the Sustain potentiometer is set to maximum (five volts). When the gate goes high, the pitch of the sound can be heard to rise, quickly at first, then more slowly until the maximum (five volts) is reached. When the gate goes low, the pitch drops rapidly at first, then more slowly until it sort of fades into the minimum frequency.

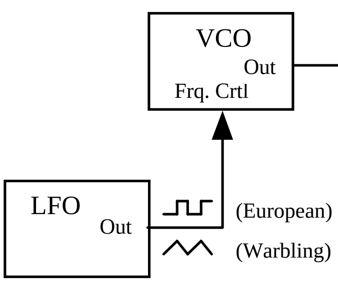

Figure 7 - Sirens

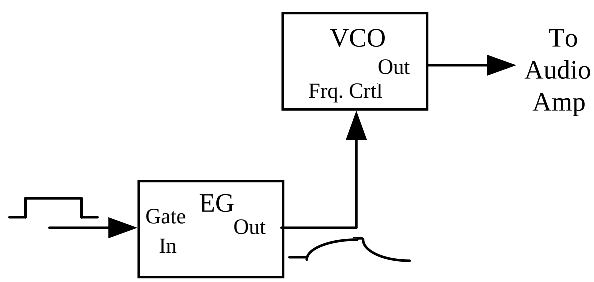

Figure 8 - Capacitor Charging and Discharging

Tremolo (Figure 9)
Tremolo (repetitive change in amplitude) is implemented by controlling the gain of the VCA with the low frequency triangle wave. The output of the VCO goes to the signal input of the VCA, and its amplitude is thus modulated.

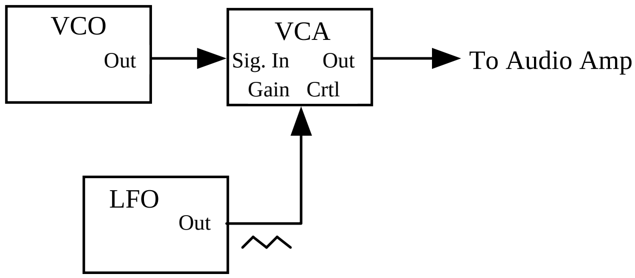

Figure 9 - Tremolo

Imitating real instruments (Figure 10)
With an envelope generator controlling the amplitude of an audio signal from a VCO by means of a VCA, synthesis of recognizable instruments is possible. (Admittedly, extremely realistic reproductions require substantially more hardware.)

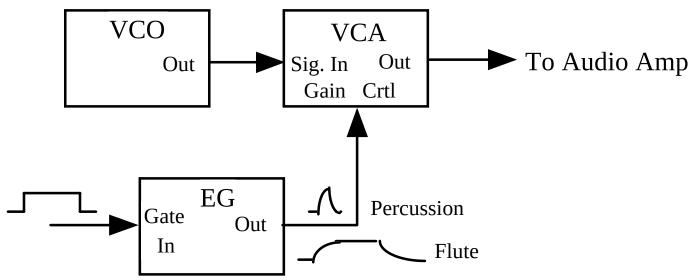

Figure 10 - Simple Instrument Simulations

For percussion sounds (drums, wood blocks, etc.) various waveforms from the VCO can be used, but the primary factor is the setting of the envelope generator. The sustain level should be set to zero, and both attack and decay times should be relatively fast. Since most percussion instruments get loud very quickly but also diminish to inaudibility almost immediately, this is exactly what is imitated electronically. On the other hand, to synthesize a flute, the sustain level is set near its maximum, with intermediate speeds for attack and final release. For the flute, it is also important to use a sinusoid or possible a triangle waveform as the sound source from the VCO. A small amount of vibrato (not shown) also enhances the flute simulation.

A couple of other interesting sounds (Figures 11 and 12)
The following diagrams illustrate a couple of other interesting possibilities, but there are many others. Figure 11 shows a variation on the warbling siren with the frequency of the warble itself changing repetitively. Figure 12 illustrates a circuit with an automatically increasing and decreasing tremolo level.

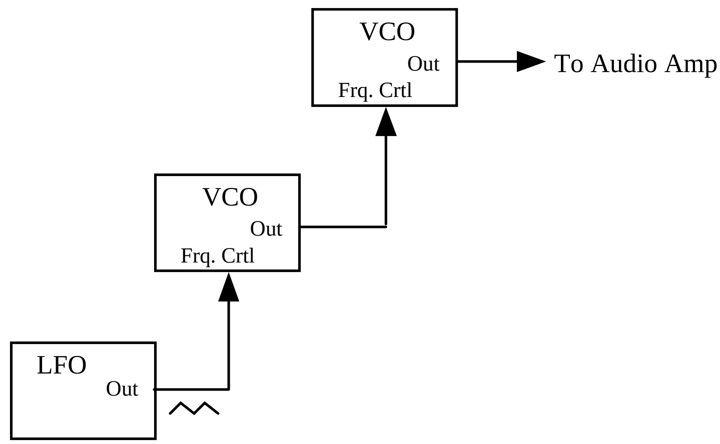

Figure 11 - Siren with varying warble

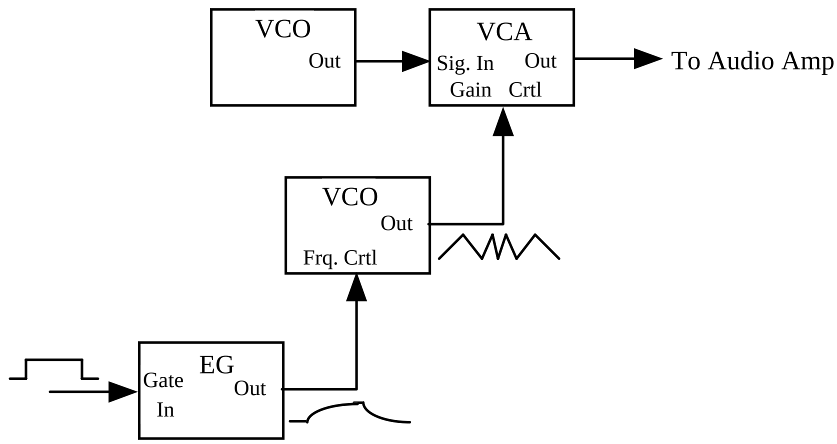

Figure 12 - Varying tremolo

CONCLUSIONS

This project is somewhat different every time I conduct it, and the discussion above is meant only as a starting point. These devices not only illustrate many of the concepts covered in the course, but introduce more advanced concepts. During the oral reports to the class, the other students get a glimpse of some of the practical applications of the theory covered in the course as well. The honors students become quite involved in the project. They are always fascinated the first time we hook together a couple of modules and make strange sounds. My course evaluations bear out the popularity of the project, with almost all honors students giving the course the highest possible ranking on our standard course evaluation forms.

BIBLIOGRAPHY

All of the references listed here have practical circuitry with varying degrees of technical explanation. The publications by Electronotes are especially helpful but are unfortunately a bit difficult to locate.

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