

Hardware Hacking



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Contents

Part I: Starting

Introduction -- 4

Chapter 1: Getting Started -- 7

Tools and materials needed.

Chapter 2: The Seven Basic Rules of Hacking -- 9

General advice.

Part II: Listening

Chapter 3: Circuit Sniffing -- 12

Using radios and coils to eavesdrop on hidden electromagnetic music.

Chapter 4: In/Out -- 15

Speaker as microphone, microphone as speaker – the symmetry of it all.

Chapter 5: The Celebrated Jumping Speaker of Bowers County -- 17

Twitching loudspeakers with batteries.

Chapter 6: How to Solder -- 19

An essential skill.

Chapter 7: How to Make a Contact Mike -- 21

Using Piezo disks to pick up tiny sounds.

Chapter 8: Turn You Tiny Wall Into a Speaker -- 27

Resonating objects with Piezo disks, transformers and motors.

Chapter 9: Tape Heads -- 30

Playing credit cards with hand-held tape heads.

Chapter 10: A Simple Air Mike -- 33

Cheap condenser mike elements make great microphones.

Part III: Touching

Chapter 11: Laying of Hands -- 38

Transforming a portable radio into a synthesizer by making your flesh part of the circuit.

Chapter 12: Tickle the Clock -- 41

Finding the clock circuit in toys.

Chapter 13: Hack the Clock -- 44

Changing the clock speed for cool new noises.

Chapter 14: Ohm's Law for Dummies -- 48

How to understand resistors.

Chapter 15: Beyond the Pot -- 50

Photocells, pressure pads, and other ways to control and play your toy.

Chapter 16: Switches -- 55

How to understand different switches, and even make your own.

Chapter 17: Jack, Batt & Pack -- 58

Finishing touches: powering and packaging your hacked toy.

Part IV: Building

Chapter 18: World's Simplest Oscillator -- 64

Six oscillators on a 20 cent chip, guaranteed to work.

Chapter 19: From Breadboard to Circuit Board -- 72

How to solder up your first homemade circuit.

Chapter 20: More Oscillators -- 75

Oscillators that modulate each other.

Chapter 21: Even More Oscillators -- 79

Dividers, feedback loops and instability; using oscillators as clocks for toys.

Chapter 22: On/Off -- 83

Gating, ducking, tremolo and panning -- and extracting sounds from remote controls.

Chapter 23: Amplification and Distortion -- 91

A simple circuit that goes from clean preamp to total distortion.

Chapter 24: Analog to Digital Conversion, Sort of -- 94

Modulating other audio sources with your oscillators.

.

Part V: Looking

Chapter 25: Video Music/Music Video -- 98

Translating video signals into sound, and hacking cheap camera circuits.

Chapter 26: LCD Art -- 100

Making animated modern daguerreotypes.

Part VI: Finishing

Chapter 27: Mixers, Matrices and Processing -- 104

Very simple, very cheap, very clean mixers, and ways of configuring lots of circuits.

Chapter 28: A Little Power Amplifier -- 108

Cheap & simple amplifier.

Chapter 29: Power Supplies -- 110

If you must, here's how to plug into the wall with minimal risk.

Appendices

Appendix 1: Resources -- 116

Where to find information and materials.

Appendix 2: Inventory -- 118

What you need to do the projects in this book.

Appendix 3: The Rules of Hacking -- 122

A recapitulation.

Part I: Starting

Introduction

This book teaches you how to tickle electronics. It is a guide to the creative transformation of consumer electronic technology for alternative use. We live in a cut and paste world: Control-X and Control-V give us the freedom to rearrange words, pictures, video and sound to transform any old thing into our new thing with tremendous ease and power. But, by and large, this is also an “off-line” world, whose digital tools, as powerful as they might be, are more suitable to preparing texts, photo albums, movies and CDs in private, rather than on stage. These days most “live electronic music” seems to be hibernating, its tranquil countenance only disturbed from time to time by the occasional, discrete click of a mouse.

My generation of composers came of age before the personal computer, at a time when electronic instruments were far too expensive for anyone but rock stars or universities, but whose building blocks (integrated circuits) were pretty cheap and almost understandable. A small, merry, if masochistic, band, we presumed to Do-It-Ourselves. We delved into the arcane argot of engineering magazines, scratched our heads, swapped schematics, drank another beer, and cobbled together home-made circuits -- most of them eccentric and sloppy enough to give a “real” engineer dyspepsia. These folk electronic instruments became the calling cards of a loose coalition of composers that emerged in the mid-1970s, after John Cage, David Tudor, and David Behrman, and before Oval, Moby, and Matmos. By the end of the 1970s the microcomputers that would eventually evolve into Apples and PCs had emerged from the primordial ooze of Silicon Valley, and most of us hung up our soldering irons and started coding, but the odd circuit popped up from time to time, adding spice to the increasingly digital musical mix.

Computers are wonderful, don't get me wrong, but the usual interface -- an ASCII keyboard and a mouse -- is awkward, and makes the act of performing a pretty indirect activity -- like trying to hug a baby in an incubator. “Alternative controllers” (such as those made by STEIM and Buchla) are a step in the right direction, but sometimes it's nice to reach out and touch a sound. This book lifts the baby out of the basinet and drops her, naked and gurgling, into your waiting arms, begging to be tickled.

The focus is on sound -- making performable instruments, aids to recording, and unusual noisemakers -- though some projects have a strong visual component as well. No previous electronic experience is assumed, and the aim is to get you making things as quickly as possible, and keep you alive from start to finish.

After learning basic soldering skills, you will make a variety of listening devices: acoustic microphones, contact mikes, coils for picking up stray electromagnetic fields, tape heads. Then you will lay hands upon, and modify, cheap electronic toys and other found circuitry -- the heart and soul of hacking. You'll build some circuits from scratch: simple, robust oscillators that can be controlled through a

variety of means (light, touch, knobs, switches), and combined to create rich electronic textures at minimum cost and difficulty. With the confidence instilled by such a delicious din you can proceed with circuits to amplify, distort and otherwise mangle sound. You can move on to some designs for linking sound with visual material, and some convenient “glue” circuits, useful for putting disparate parts together for performance or recording. Finally, there are several appendices to direct the reader to sources of supplies and further resources for information.

In selecting the specific projects to include in this book I was guided by a handful of fundamental assumptions and goals:

- 1) To keep you alive. All the projects in this book are battery powered; none plug into the potentially lethal voltage running through your walls. This makes the early stages of unsupervised electronic play activity considerably safer, and less daunting for the beginner.
- 2) To keep things simple. We work with a small number of very simple "axiomatic" circuits and concepts that can be combined with great permutational richness as you proceed and gain experience, but are easy to understand and quick to get running at the beginning. The point is to make cool sounds as quickly as possible.
- 3) To keep things cheap. By limiting ourselves to a few core designs we minimize the quantity and cost of supplies needed to complete this book. You don't need a full electronics lab, just a soldering iron, a few hand tools, and about \$50- worth of parts which you can easily obtain on-line. By focusing on toys and other simple consumer electronics we also minimize the threat of "catastrophic loss" in the early, unpredictable days of freestyle hacking: a Microjammer sets you back considerably less than a vintage Bass Balls.
- 4) To keep it stupid. You will find here an absolute minimum of theory. We learn to design by ear, not by eye, gazing at sophisticated test instruments or engineering texts. Ignorance is bliss, so enjoy it.
- 5) To forgive and forget. There's no "right way" to hack. I will try to steer you away from meltdowns, but have included designs that are robust, forgiving of wiring errors, and accept a wide range of component substitutions if you don't have the preferred part. Most of these circuits are starting points from which you can design many variations with no further help from me -- if you love a hack, let it run free.

As a result of these koans, this is a distinctly non-standard introduction to electronic engineering. Many of the typical subjects of a basic electronics course, such as the worryingly vague transistor and the admittedly useful little thing called an op-amp, are left unmentioned. After turning over the last page, you will emerge smarter, if weirder, than when you first opened the book. You will have acquired some rare skills, and ones that are exceedingly useful in the pursuit of unusual sounds. You will have significant gaps in your knowledge,

but these gaps can be filled by a less structured stroll through resources easily available in books and on-line (as described in Appendix 1.) And everything electronic you choose to do after this book will be easy, I promise. Why? Because you will be fearless. You will have the confidence to survey those presumptuous “No user serviceable parts inside!” labels and laugh. You will be a hacker.

Chapter 1: Getting Started

You'll need the following tools and materials to get started, and for most of the projects in the book

Tools:

- Soldering iron, finest point possible, 25-60 w. Not a soldering gun -- that's for VoTech classes. Don't get a cheap iron -- it makes it very frustrating to learn soldering. Weller makes good ones that are reasonably priced and have replaceable, interchangeable tips.
- Solder -- fine, rosin core -- not "acid-core" solder, that's for plumbers.
- Diagonal cutters, small, for cutting wire and components down by the circuit board.
- Wire strippers (unless you have the perfect gap between your front teeth) -- simple, adjustable manual kind for light-gauge wire.
- A set of jeweler's screwdrivers (flat & philips) -- for opening toys with tiny screws.
- A pair of scissors.
- A Swiss Army Knife.
- A small saw, utility knife, file, and drill will be useful when you start to hack toys and make cases for your circuits.
- A cheap digital multimeter -- test meter capable of reading resistance, voltage and current.
- Plastic electrical tape.
- Battery powered mini-amplifier with speaker. The cheapest one I've found is from Radio Shack (#277-1008, \$11.99). You can also find wee bitty guitar amps by Fender, Marshall, Dan Electro, etc. -- they look like little lunchboxes or the guitarist's equivalent of shrunken heads. They cost more than the Radio Shack amp, but some have the advantages of a bigger speaker, a tone control and overdrive/distortion. It's nice to have a lot of gain available, so stay away from those small powered speakers they sell for computers or Diskmen.
- Mini jumper cables with small alligator clips at each end, about 20 of them.
- A "Sharpie"-style fine-tipped permanent marker.
- Some small spring clamps or clothespins.

Materials

- Lightweight insulated hookup wire, 18-22 gauge, 1 roll stranded, 1 roll solid..
- Lightweight shielded audio hookup cable, single conductor plus shield.
- Assortment of standard value resistors, 1/8 or 1/4 watt. Sets are easily and inexpensively available from Radio Shack or mail order/web retailers.

- Assortment of capacitors, in the range of .001 - .1 uf monolithic ceramic or metal film, and 1uf to 100uf electrolytic. These can be bought in assortments, or you can purchase a handful of each of a few different values from across the full range, then replaced or supplemented as needed as you go.
- 9 volt battery clips -- the things that snap onto the nipples at the end of a 9 volt battery and terminate in lengths of wire. Get five or more.
- Assorted audio jacks and plugs to mate with other devices, i.e., your amplifier, jacks on toys, etc.
- Batteries for your amplifier, toys and circuits. Be a friend of the environment and invest in some rechargeable batteries.

Other tools and materials will be introduced as needed. Basic shop tools -- such as a small saw for metal and plastic, files, and an electric drill -- are useful when you start to work on packaging. A complete inventory of parts needed for all the projects is included in Appendix 2.

Your work space should be well-lit and ventilated. It should have a lot of table space; the table surface may be damaged by soldering, drilling and filing, so no Chippendale please. You'll need electrical power at the table for you soldering iron.

Chapter 2: The Seven Basic Rules of Hacking

Rule #1: Never get into a conversation with anyone at Radio Shack.

Rule #2: Don't take apart anything that plugs directly into the wall.

We will work almost exclusively with battery-powered circuitry. AC-powered things can kill you. AC adapters ("wall warts") may be used only after you have displayed proper understanding of the difference between insulation and electrocution.

Rule #3: It is easier to take something apart than put it back together.

Objects taken apart are unlikely to function normally after they are put back together, no matter how careful you are. Consider replacement cost before you open.

Rule #4: Make notes of what you are doing as you go along, not after.

Most wires look pretty much alike. As you take things apart make notes on which color wire goes to where on the circuit board, or to what jack, etc. Especially important are the wires that go to the battery. Likewise, note what you add as you add it, what you change as you change it.

Rule #5: Avoid connecting the battery backwards.

This can destroy many circuits.

Rule #6: Many hacks are like butterflies: beautiful but short lived.

Many hacks you perform, especially early in your career, may destroy the circuit eventually. Accept this. If it sounds great, record it as soon as possible, and make note of what you've done to the circuit so you can try to recreate it later (see Rule #4.)

Rule #7: In general try to avoid short circuits.

Try to avoid making random connections between locations on a circuit board using plain wire or a screwdriver blade. This can destroy a circuit -- not always, but inevitably at the most inconvenient time.

Additional rules will emerge from time to time throughout the book, and are recapitulated in Appendix 3.

Part II: Listening

Chapter 3: Circuit Sniffing

You will need:

- A battery-powered AM radio.
- A battery-powered amp/speaker.
- An inductive telephone pickup coil or a loose electric guitar pickup.
- Optionally: a hundred feet of light-gauge insulated wire, an audio plug and 2 long pieces of wood.

Radios

Radios make the inaudible audible. Unlike microphones and amplifiers, which merely make very quiet acoustic sounds much louder, radios pick up electromagnetic waves that have no acoustic presence whatsoever and translate them into signals that can be heard through a loudspeaker. Radios are manufactured for listening to intentionally transmitted electromagnetic waves, i.e., those sent from radio stations. But they can also be used to sniff out other types of waves, such as those emitted by lightning, sun spots, Aurora Borealis, meteorites, camera flash units, computers, etc. Generally speaking AM radios (the cheaper the better) do a better job of picking up these “spurious” noises than FM radios.

Put batteries in the radio and turn it on; if it has a band switch set it initially to AM. Try moving it around various electrical appliances: fluorescent lights, electric motors, computers, portable CD players, cell phones, MP3 players (iPod) and remote controllers for RC planes and cars are especially noisy. Fire off a camera flash next to it. Experiment with tuning the radio to different stations, between them and to the dead bands at either end of the dial.

As the FCC often warns you, certain electrical appliances can cause “radio interference.” What this means is that, as a byproduct of whatever useful thing they are doing, they emit lots spurious electromagnetic radiation in the same frequency region as radio and TV broadcasts -- they whistle while they work. As you tune the radio it picks up different frequencies (mostly very high) of electromagnetic waves, shifts them down into the range of our hearing and amplifies them. Compared to radio stations these appliances put out very weak signals -- the noise from a computer drops off rapidly as you move the radio a few feet away (hence the FCC advice on what to do.)

If your radio has a FM band, try it as well. The technique of FM radio transmission and reception is designed to minimize interference, but strong periodic signals (like the clock frequency of a computer) can sometimes be tuned in.

Coils

An alternate approach to picking up electromagnetic signals is to use a simple coil of wire and an amplifier. A telephone pickup consists of yards of thin copper wire wrapped around an iron slug. Plugged into an amp this coil acts like a radio antenna for low frequencies. Stuck on a telephone receiver (or held against any other loudspeaker) it picks up the electromagnetic field generated by the voice coil of the speaker, allowing you to record your landlord making unsavory threats.

Plug the tap coil into the portable amp and repeat the same experiments we did with the radio. Sometimes you will hear different types of sounds from the same appliance. The coil is small enough that you can move it close in and to precise locations, like a stethoscope. Open up a computer and pass it slowly over the motherboard, or over a laptop, and note the change in sound as you move from the CPU area to the RAM to the disk drive to the CDROM. Listen to small motors in fan, vibrators and toys; notice the change in pitch as you change the motor speed. Take a ride on the subway and listen to the motors and doors as you come in and out of stations. Cozy up to a neon sign.

Jérôme Noetinger, Andy Keep, Nathan Davis and others have made beautiful use of this secret magnetic music.

The stethoscope-like accuracy of the coil moving over a circuit board makes it a useful, non-destructive device for pinpointing the location of interesting sounds that we can later tap off directly with a wires soldered to the board.

If you move the coil near the speaker of your amplifier it will begin to feed back with the coil that moves the speaker cone (see next chapter.) As with feedback between a microphone and speaker, the pitch is affected by the distance separating the two parts, but here the pitch changes smoothly and linearly, without the odd jumps caused by the vagaries of acoustics, giving you a Theremin-like instrument. Try this with a full-size guitar amplifier for greater range.

Speaking of guitars, you can use a guitar pickup in place of a telephone tap – a guitar pickup is just a coil of wire, wrapped around a magnet, inside an expensive package. You can repeat the above experiments with a whole guitar in your hands, but a loose pickup is handier. At repair shops you can sometimes buy cheap the low-end pickups removed when better ones are installed. Jump ahead to Chapter 6 if you need advice on wiring the pickup to a cord and plug. As most guitarists know, “single coil” pickups are better at picking up hum and weird electromagnetic noise, while “humbuckers” are so called because they tend to be less sensitive to exactly the kind of garbage we want to hear here.

Cults

The length of wire used in the coil affects its sensitivity to different frequencies (like the tuning dial on a radio.) Joe Banks (Disinformation) and other fans of what is know as VLF (Very Low Frequency) radio make big coils by wrapping yards of wire around big wooden crosses and then camp out on remote hilltops like hermit Klansmen. Get far enough from civilization's ubiquitous 60/50 hz hum and you may be lucky enough to pick up the Aurora Borealis, "whistlers" induced by meteorites self-immolating as they enter the earth's atmosphere, the pipping of GPS satellites, or top-secret submarine radio communication.

If you want to experiment, take a hundred feet of ordinary insulated wire and wrap it around a wooden armature (nail 2 5' piece of 2x2 together and notch the ends to keep the wire from slipping off.) Solder one end of the wire to the tip of a plug that fits into your amp or tape recorder, and solder the other end to the sleeve. Plug in, turn on, drop out.

Chapter 4: In/Out (the Eighth Rule of Hacking)

You will need:

- A battery-powered mini amplifier.
- A pair of headphones or a small speaker.
- A pair of jumper leads and a jack to fit the input jack of your amplifier.

Electromagnetism

There is a beautiful symmetry to the principles of electricity that are most commonly used to translate acoustic sound into an electrical signal and then back into sound again. Inside every dynamic microphone (such as a typical PA mike) is a lightweight plastic membrane affixed to a coil of fine wire encircling a cylindrical magnet. Madonna sings, and her sound waves jiggle the membrane which moves the coil in the field of the magnet, generating a very small electrical current. This current is amplified, equalized, flanged, reverberated, compressed and finally amplified even more before being sent back out to a bigger coil wrapped around an even bigger magnet. Now this shimmering electromagnetic field pushes and pulls against the big magnet (think of the two magnetic Scotty dogs, forever trying to align themselves nose to tail), moving a paper cone back and forth, producing sound waves of....a louder, possibly improved, Madonna.

A record player cartridge is just a microphone with a needle where the diaphragm should be; and record cutting heads are just beefy backwards phonograph cartridges. Headphones are just tiny speakers. The telephone tap coils we used earlier are just electromagnets with no moving parts, receiving and emitting electromagnetic waves rather than sound waves.

Not only is the same electromagnetic force used for both input and output devices (microphones and speakers), but sometimes the gizmos themselves are interchangeable. Try plugging a Walkman headphone into the input jack on your amp or cassette recorder; speak into it and listen -- more than one band's demo tape was recorded this way. Plug any small speaker into the input of the amp. According to legend, Motown engineers recorded kick drum with a large speaker placed in front of the drumhead -- a sort of a sub-woofer mike. These alternative microphones don't sound as generically "good" as a \$5000- Neumann tube mike, but (as Motown's sales have shown) for special applications they can be very useful.

Likewise any dynamic (i.e., coil & magnet) microphone can be used as a very quiet speaker or headphone, but microphones have very delicate coil windings and can be easily blown out, so BE CAREFUL. Also, condenser mikes (like the "plug-n-power" mikes for cassette recorders, or expensive studio mikes) use a different, not-so-easily reversible principle of translation, so: IF THE MIKE USES A BATTERY OR PHANTOM POWER OR IS REALLY, REALLY EXPENSIVE, DON'T USE IT BACKWARDS.

Rule #8: In electronics some things are reversible with interesting results, but some things are reversible only with irreversible results.

Some of you may recognize that the 8th Rule of Hacking is a pragmatic offshoot of the First Law of the Avant Garde:

Do it backwards.

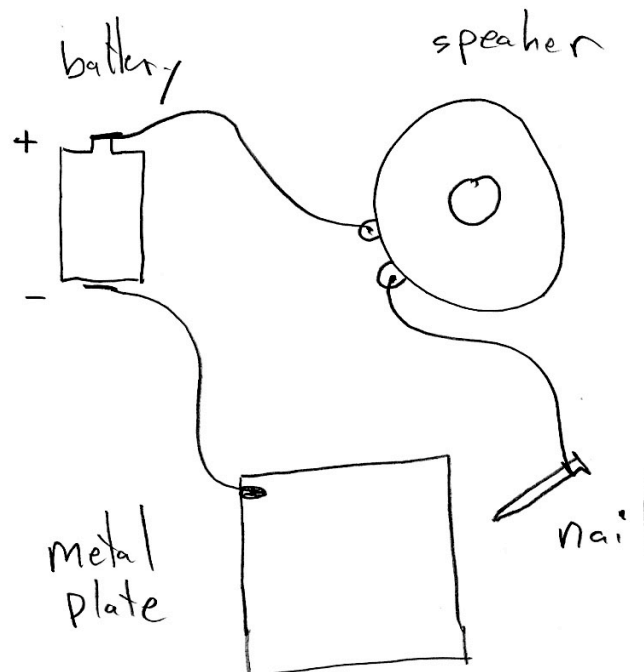
Chapter 5: The Celebrated Jumping Speaker of Bowers County

You will need:

- A dispensable raw loudspeaker (3-8" diameter.)
- 1 or 2 "C" or "D" cell batteries.
- Some jumper leads.
- Some hookup wire.
- Some electrical tape or gaffing tape.
- A medium size nail.
- A sheet of copper, steel or iron, or a chunk of some conductive metal.

Creative mistreatment of loudspeakers goes beyond Motown, and even precedes amplification itself. British computer scientist and musician John Bowers has developed a beautiful electric instrument, evoking the spirit of 19th Century electrical experimentation (think twitching frogs legs and early telephones) out of nothing more than a speaker, some batteries, a few nails and some scrap metal.

Hook up the "circuit" shown below:



Use electrical tape or gaffing tape to attach wire (strip the ends first) to either end of a "C" or "D" cell battery (1.5volts.) Connect the other end of one of the wires (it doesn't matter which) to one terminal of the speaker -- you can solder it on or

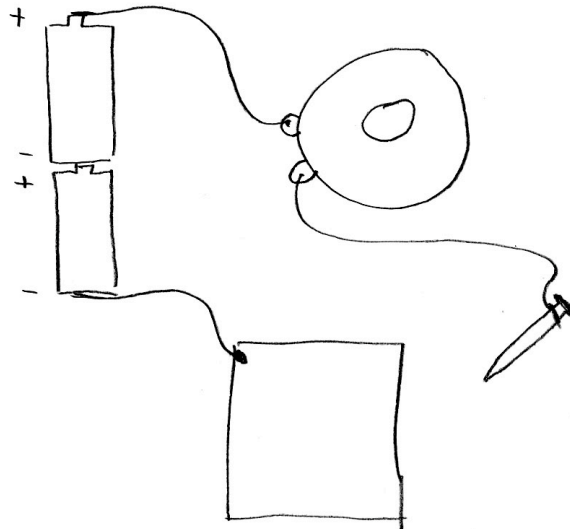
use a jumper lead to make a connection between the bare wire and terminal. Connect the free end of the other battery wire to a plate or chunk of some conductive metal: a pie tin, scrap copper flashing, an anvil, a piece of girder, a brake drum, a frying pan, a file, etc. -- the rougher the metal surface the better. You'll probably have to make this connection with a clip or clamp. Clip one end of a jumper lead to the other terminal of the speaker and the other end to a nail.

Tap the nail on the plate. When it touches the metal the nail completes the circuit and sends 1.5 volts to the speaker coil, making the cone jump. By scraping the nail across the metal you can produce pleasing, if scratchy, percussive sounds. You can use your hands, bowls or toilet plungers to mute and resonate the sound further. Put gravel, loose change or dried lentils inside the cone for additional rhythmic accents.

Avoid holding the nail on the metal for an extended period of time -- loudspeakers get hot and bothered when presented with a steady DC voltage, so it's better to send them shorter pulses.

Instead of nails on the plate, you can clip the leads to two paperclips, washers, or loops of copper wire that you place inside the speaker cone. The cone jumps when contact is made, breaking the contact for a moment, then the metal bits fall against each other and the process starts all over -- a mechanical oscillator.

You can put more batteries in series if you want a louder sound, but at some point you may blow out the speaker with excessive voltage, so be warned: don't try this with your roommate's Bang & Olufsen, and don't plug a speaker directly into the wall. A 9 volt battery has a small current capacity, so will go flat pretty fast if used in this circuit -- stacked "C" or "D" cells will last longer.



Chapter 6: How to Solder

You will need:

- A soldering iron with a fine tip.
- A small damp sponge (or folded paper towel in a pinch.)
- Rosin-core solder.
- Diagonal wire cutters.
- Wire strippers.
- Some light gauge insulated wire.

Soldering is one of the fundamental skills of hardware hacking. It is almost impossible to hack hardware without knowing how to solder. As a skill it commands a lower hourly wage than Java, but your friends and parents will be very impressed at your acquisition of such arcane knowledge (as if you had learned fire eating or Linear B.)

Successful soldering, like fundamentalist Christian comedy performed in mid-winter by an L-Dopa patient, depends on cleanliness, heat, steady hands and.....timing!

Soldering is not a question of dropping melted solder onto a joint. Rather, one must first melt a thin layer of solder onto each surface. Then let them cuddle up to one another while you heat both surfaces to re-melt the solder until it commingles to form a strong bond. The process is similar to gluing wood: the strongest bond comes from permeating the surfaces of both pieces of wood with a layer of glue before assembly, rather than just squeezing a blob of glue between them.

We will begin by practicing soldering wires together -- high temperature knitting.

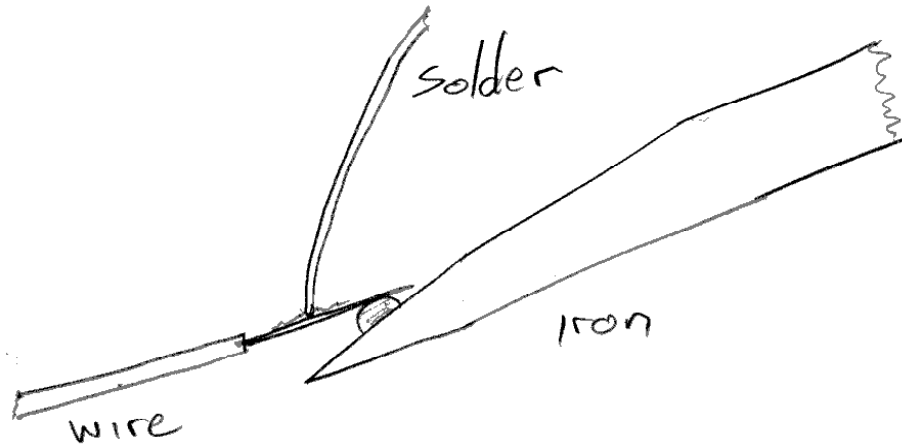
1) Plug in the iron and place it somewhere where the tip will not make contact with flammable/meltable/scorchable surfaces or the power cord (they make cute little wire rests for this purpose.) Wait a long time for it to warm up. The iron is hot enough to use when solder touched to the tip melts.

The tip of the iron must be smooth and clean enough that the solder flows evenly, leaving a shiny silver coating. If blobs of solder fall off and the tip remains grey & crust, unplug the iron and, after it has cooled down, polish the tip with steel wool, fine sandpaper or a file. If the tip of the iron is seriously pitted you will need to replace the tip (or, if it is a cheap iron with non-replaceable tip, the whole iron.)

2) Strip the about 1/2" of insulation from the ends of two pieces of wire. Use the adjustments on the strippers (or a fine sense of touch) to avoid nicking the wire. If the wire is stranded, twist the strands to eliminate frazzling. Hold the wires in something so that the tips are up in the air but don't wiggle. You can use a fancy

“third hand” gizmo, or a vise, or just weight the coil of wire down under a book or something.

3) “Tin” the wires. Melt a small blob of solder on the tip of the iron. Hold this blob against one of the wires. Hold the tip of the solder roll against the wire, not the iron, After a 2-5 seconds the wire should be hot enough that the solder will melt, flowing around the wire to coat it evenly in a smooth layer; if not, apply a tiny bit more solder to the tip of the iron and try again.



Remove the iron from the wire. The solder should cool to a smooth, shiny silver; if it is rough and grey you did not get the wire hot enough -- try again.

4) Twist the wires around one another like strands in rope. Once again apply a small blob to the iron and use the blob to conduct heat to the bundled wires. After a few seconds the tinned solder should re-melt and flow together; you may apply a bit more solder to strengthen the joint, but only as much as can flow and distribute itself smoothly. Wait several seconds without wiggling for the joint to cool and harden.

Blobs of solder on the wire or dull grey solder are signs of a “cold solder joint”, which is neither electrically nor mechanically strong. Do it again.

5) When tinning and soldering only apply heat for the minimum amount of time needed to get the solder to flow, otherwise you may damage the components you are soldering (for example, melting the insulation off the wire.)

6) Repeat this process until you get it right and feel comfortable with the “touch” of soldering: how much heat and solder to apply for how long, etc. It’s small step from here to cracking safes.

Chapter 7: How to Make a Contact Mike

You will need:

- A battery-powered mini amplifier.
- A Piezo-electric disk (see text below.)
- 8' lightweight shielded cable.
- Some plugs to match the jacks on the amp.
- Plastic insulating electrical tape.
- A can of "Plasti-Dip" (sold in hardware stores for dipping tool handles.)
- Small spring clamps.
- Molex-style terminal block.
- Hand tools, soldering iron and electrical tape.
- Optional: sparklers, small blowtorch, guitar strings, metal scrap, Slinky, springs, condoms.

The Piezo-electric Effect

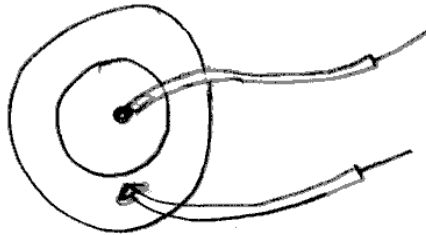
Another common principle of reversible sound translation is the "Piezo-electric effect," which depends on the electrical properties of crystals, rather than electromagnetism: bang a crystal with a hammer and it will generate a pretty sizeable electrical signal (enough to light a flashlight bulb); send an electrical current into a crystal and it will twitch. Piezo-electric disks, made by bonding a thin layer of crystal to thin, flexible sheet of brass, are everywhere today, inside almost everything that beeps: appliances, phones, toys, computers, etc. Because they are manufactured in huge quantities they are incredibly cheap, and they happen to make even better contact microphones than they make speakers. Drum trigger and commercial contact mikes are often made from Piezo disks and sold at absurdly marked-up prices.

How to make a Piezo-disk contact mike

- 1) Try to find a Piezo-disk that already has wires attached, since soldering directly to the disc's surface is infuriatingly difficult. Better yet, get a few disks in case you break them. You can salvage them from all sorts of trashed electronic devices, from toys and alarm clocks to cell phones and computers, or buy them from Radio Shack or any number of web-based "electronic surplus" outlets.
- 2) The disk may be encased in a kind of plastic lollipop. If so, carefully pry open the case and remove the disk. Try not impale yourself, but **DO NOT BEND OR SCRATCH THE DISK!**
- 3) The disk may have a tiny circuit board attached, Snip off the connecting wires close to the circuit board, so that the wires attached to the disk are as long as possible. Remove the board.

4) Once removed, the disk should appear as a circle of gold or silver-colored metal, with a smaller circle of whitish "crystal" within. Depending on the design, there will be 2 or 3 wires connected to the disk. One will always be connected to the metal portion, somewhere near the edge; this we will call the "ground" connection. One will connect to the main part of the inner circle; this we will call the "hot" connection. In some cases there will be a narrow, tongue-like shape differentiated within the crystal, to which the third wire connects; this we will call the "curious but unnecessary" (CBU) connection.

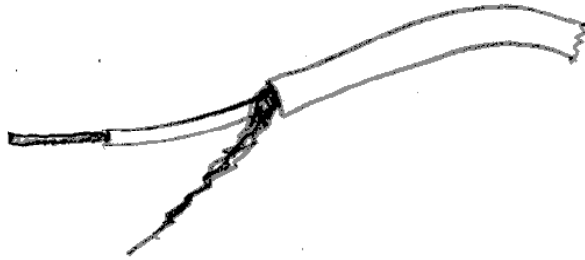
4) Cut the connecting wires so that they protrude about 2" from the disc. Strip about 1/2" of insulation from the ends of the ground and hot wires; do not strip the CBU wire. Tin the stripped ends.



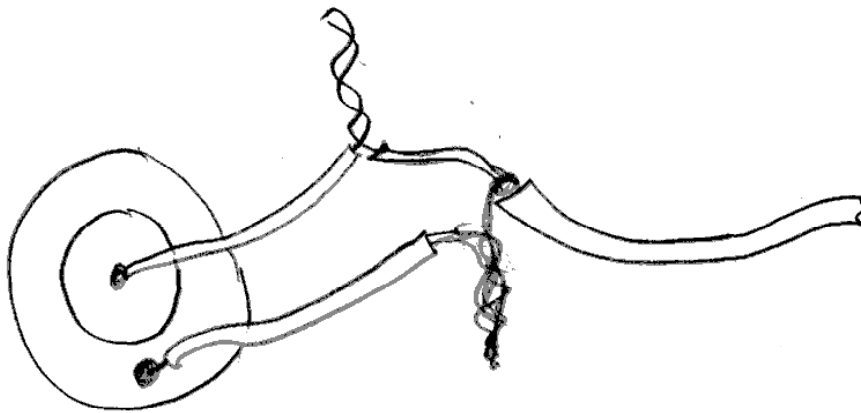
5) Shielded cable consists of stranded wire inside insulation, which is then wrapped inside a layer of braided or twisted wire, which is in turn covered by another layer of insulation. A cross-section looks like tree rings or a target. Shielded wire is used to protect audio signal from hum and other electromagnetic interference. Shielded cable comes with any number of internal conductor wires, but for audio purposes most cable has one or two internal conductors plus the shield. Unless otherwise specified we will use cable with a single internal conductor plus shield.

Rule #9: Use shielded cable to make all audio connections longer than 8", unless they go between an amplifier and a speaker.

Cut a 5' section of shielded cable, the thinner and more flexible the better. Strip back 1" of the outside insulation. Unbraid the shielding and twist into a single thick strand. Now strip back 1/2" of the inner insulation, and twist the center conductor into a neat strand. Keep the two strands separate. Tin both strands, being careful not to melt back the insulation.



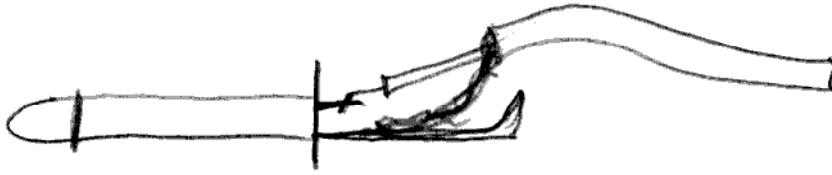
6) Twist together the hot wire from the Piezo Disk and the inner wire from the shielded cable. Solder them together. Twist together the ground wire from the Piezo disk and the shield from the shielded cable. Solder them together. Wrap both joints separately with a bit of electrical tape so that they cannot short against each other.



7) Strip the free end of the shield cable as in step #5: 1" outer insulation, twist shield, 1/2" inner insulation, twist conductor, tin the wires.

8) Unscrew the plug you are using to connect the contact mike to your amplifier/recorder. Pass the barrel back over the shielded wire toward the disk so that the threaded portion faces the freshly tinned end. Unscrewing the barrel of the plug should have revealed two connector tabs: the shorter one connects to the "tip" of the plug and the longer one connects to the "sleeve."

Solder the inner conductor of the shielded wire to the tip of the plug and the shield to the sleeve. Sometimes there are small holes in the connector tabs that you can hook your wire onto, to hold it in place before soldering. Otherwise you will have to tin the tabs and hold each wire against its respective tab while soldering -- a job for three hands, a vise or a steady buddy.



Now is as good a time as any to introduce the 10th Rule of Hacking, if it is not obvious already:

Rule #10: Every audio connection consists of two parts: the signal and a ground reference.

In the case of a contact mike the signal comes from the white part of the Piezo disk, while the ground is the brassy bit; on the plug the tip carries the signal and the sleeve is the ground. In future chapters I may get a bit sloppy and only refer to the signal when describing connections -- always assume that a ground connection must accompany every signal.

9) Plug into your amp and check that your new contact mike works -- tapping the mike should make a solid thumping sound. If there is no sound check the joints at both ends of the cable -- make sure they are good and there are no shorts. If there is hum you may have connected the hot and ground wires to the wrong conductor of the cable -- de-solder and reverse them. If it works, screw the barrel down onto the plug and test again -- sometimes squeezing the barrel down over a marginal solder joint will break or short it. A small piece of electrical tape can be used to isolate the connections if excess wire tends to short when the barrel is screwed down.

Whoops! Did you forget to slide the barrel onto the wire before you soldered? If so, desolder the plug, go back to step 8, but don't feel too stupid -- everybody makes this mistake.

Rule #11: Don't drink and solder.

10) When you are sure you have an electrically functional contact mike, cover the ceramic side with a piece of electrical tape -- you can trim it around the circumference with scissors or a knife, or you can wrap the edges over to the other side of the disk.

11) Open up and stir your can of Plasti-Dip. As per the instructions on the label, slowly dip the contact mike end of your cable into the goop until you have covered the wire past the electrical tape. Slowly withdraw it and hang it up to dry. Take a break and go away -- this stuff is stinky. You can dip a second layer after the first one dries thoroughly, which can take up to several hours. More than two layers tends to muffle the sound.

The tape & Plastic-Dip treatment serves several functions:

- It strengthens the connections between the wires and the Piezo-disk.
- It insulates the disk from electrical shorts, and prevents hum when you touch it.
- It waterproofs the contact mike, so you can use it to record underwater sounds, freeze it in ice-cubes, dangle it in a drink, etc.
- It deadens slightly the pronounced high-frequency resonance of the disk (similar to the effect of gaffing tape on the head of an unruly snare drum.)
- It looks really cool and is a fun treat after all that soldering.

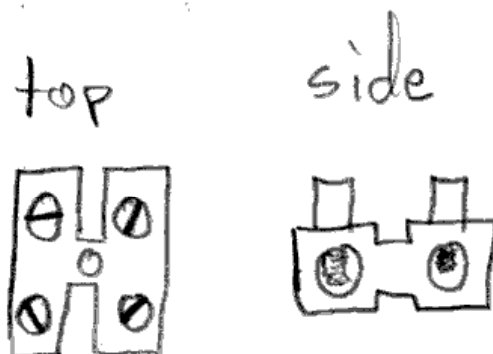
What to try with your contact mike

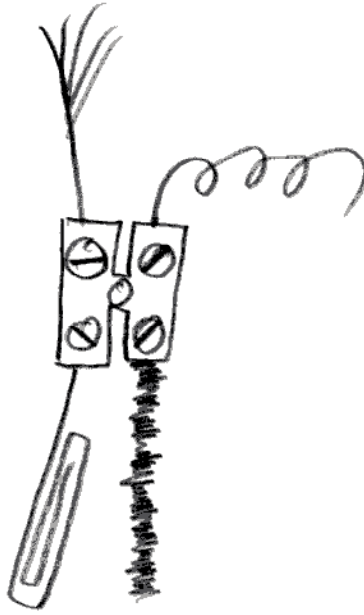
Contact mikes are great for greatly amplifying hidden sounds in everyday objects. The trick is making positive physical contact with the vibrating object.

Use double-stick tape or Blu-tak to attach the mike to the surface of vibrating objects. Try: guitars, violins, drums, pots & pans, wrists & knees, foreheads, pinball machines.

Use small spring clamps to hold things to the contact mike. Try: strips of metal, gaffing tape, rulers, popsicle sticks.

“Terminal strips” are used to make electrical connections in lamps and other appliances. They can be salvaged from discarded appliances or bought from any number of sources, including Radio Shack, DIY shops like Home Depot, and on-line electronic surplus retailers. Cut terminal strip into small section and clamp onto the mike with a spring clamp. Insert thin objects into the terminal openings and hold in place by tightening the screws. Try: Slinkies, springs, loose guitar strings, toothpicks, satay sticks, broom straws, porcupine quills, cactus needles.





This is an excellent way to replicate the old-fashioned phonograph cartridges used by John Cage in his visionary work of live electronic music, "Cartridge Music."

Many metals make unusual sounds as they heat and cool. Clamp a sparkler in the terminal block, light & listen. Or clamp steel wire and heat with a torch. Richard Lerman has made beautiful miniature instruments consisting of short pieces of wire affixed to piezo disks and "bowed" with small blowtorches.

Amplify the contact mike into a raw speaker. Place the speaker on its back, like a candy dish. Rest the contact mike inside the cone and turn up the gain. The contact mike should jump up and down as it feeds back with the speaker (a slightly higher-tech variation on the jumping speaker in Chapter 5.)

Once waterproofed with the electrical tape and Plasti-Dip the contact mikes will also serve as affordable hydrophones and submersible mikes.

- Fill a plastic yogurt container with water, drop in the contact mike and pop it in the freezer. Listen as it freezes. Once frozen, remove from the ice block from the container, float it in a bowl of hot water, and listen to it melt.
- Drop it in the water next time you go fishing and check if they're really laughing at you.
- Eat the mike, but please observe safe sex practices: put an extra layer of protection between you and electricity by encasing the contact mike in a condom or balloon.

Chapter 8: Turn Your Tiny Wall Into a Speaker (or How to Make a Piezo Driver)

You will need:

- A battery-powered mini amplifier with output jack for external speaker.
- You contact mike from the previous chapter.
- Another Piezo-electric disk.
- 2 plugs to match the amp output connector.
- A female jack to match the plugs you are using.
- One small audio output coupling transformer (Radio Shack 273-1380 or equiv.)
- A few feet of lightweight speaker cable or stranded hookup wire.
- Electrical tape.
- A can of “Plasti-Dip.”
- Small spring clamps or clothespins.
- A sound source, such as a CD player, and cable to connect it to the amp input.

Piezo disks are used to make beeps because they do so very efficiently -- which is to say that they require very little current, and therefore are well-suited to battery-operated devices. As loudspeakers they display a rather uneven, non-“hi-fi” response, but they can nonetheless be very useful when coupled to other objects to make “speaker objects.”

To get the most vibration out of a Piezo disk it is necessary to feed it a very high voltage signal, albeit at a minuscule (and therefore harmless) current. A transformer is a kind of audio-lever that allows one to jack up the voltage of an electrical signal very easily. For this experiment we will wire up an “output transformer” backwards (see Rule #8) to step up the output voltage of a small amplifier from around 6 volts to over 200 volts.

1) The transformer will have a “primary” and “secondary” side. The primary will be designated as having an impedance of around 1000 ohms (1kOhm), and may have two or three wires. We will use the outer two wires -- the center wire, as indicated in the drawing or coming out of the package, can be ignored. The “secondary” will usually have just two wires, and an impedance of 8 Ohms. In the case of the Radio Shack part, the outer primary leads are blue and green and the secondaries are red and white.

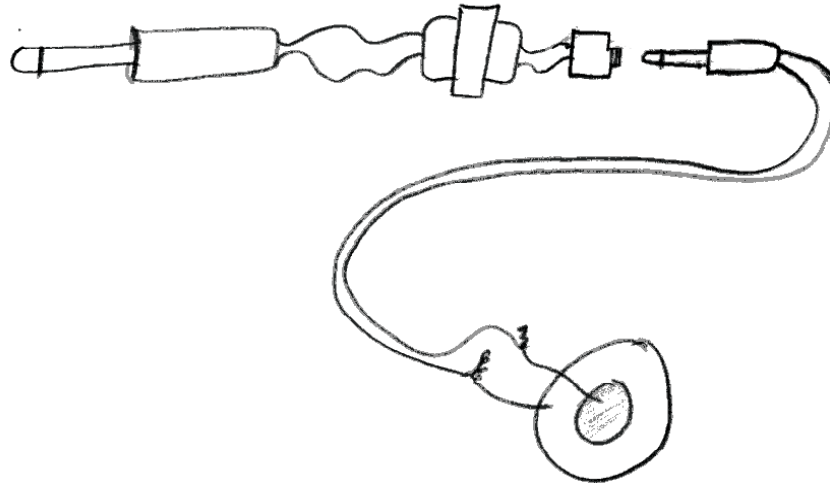
Strip 1/2” of insulation off the ends of the primary and secondary wires and tin the ends.

2) Solder one of the secondary wires to the tip of a plug that mates with the output jack of your amplifier. Solder the other secondary wire to the sleeve of the plug. Polarity is irrelevant here – it does not matter which of the two

secondary leads goes to the tip and which to the sleeve. If possible, slip the plug's barrel over the wires before you solder them up (as we did with the contact mike;) there may not be sufficient wire length to allow this, in which case you can wrap some electrical tape around the connections later (after you have proven that the gizmo works, and being very careful not to squeeze the connections together to make a short.

3) Solder one of the primary wires to the tip connection of a female jack that mates with the plug you used on your contact mike (previous chapter.) Solder the other primary wire to the sleeve connection of the jack. Once again, polarity is irrelevant here – it does not matter which of the two primary leads goes to which connection.

4) Plug the plug-end of the transformer assembly into the output jack of the amplifier. Plug your contact mike (made in the previous chapter) into the jack-end of the transformer assembly.



5) Plug a sound source into the amplifier input: a microphone, cassette recorder, CD player, radio, etc. Slowly raise the amp gain. The disk should start to radiate sound. If not, check your connections.

Use plastic spring clamps, clothespins or tape to clamp the disk to different objects and resonate them with various sounds. Thin materials work better than thick ones: pie tins, etching plates, paper cups, tin cans and balloons, rather than bricks, anchors and baseball bats.

A quaint reverb unit can be made by sending signals into a spring or plate of metal using a Piezo driver and picking them up with a Piezo contact mike (you'll have to solder up a few more Piezo disks.) This is similar to the technique used in early plate reverb units common in recording studios before digital reverb, and also the principle behind David Tudor's famous "Rainforest" installation, which used sculptural objects to transform sound material. You can patch the

Amp/Driver/Contact Mike assembly into your mixer just as you would a reverb or effect processor: connect a send bus output to your driver-amplifier input, and bring the contact mike back to any console input to amplify and mix in the “reverb” with the dry signal. Often flexing or dampening the object can affect the character of its filtering of the original sound. Try this process with loose guitar strings, Slinkies, balloons, plastic bags, vinyl records, drumheads, oil drums, buckets of water, bowls of jello. Whether as a reverb substitute in a mixdown situation or as part of a live performance setup, this is a cheap, easy, fun route to unusual signal processing.

With all due respect to the First Law of the Avant Garde, this transformer assembly does not do a very effective job of increasing the gain of a Piezo disk used as a contact mike – its use is effectively limited to boosting the efficiency of a Piezo driver. But don’t take my word -- try it for yourself.

You can create feedback by plugging a contact mike into the amp input and a Piezo driver into the output, and attaching the two to the same object. Flexing or dampening the object can affect the feedback pitch, and turn a piece of garbage (such as the plastic bubbly packaging from toys) into a playable instrument -- an electronic musical saw. You can configure several channels of amps, drivers and contact mikes to send audio signals through a series of objects for multi-stage processing; using Y-cords you can branch off and mix after each resonator-object. Get together with your buddies and form a Piezo Band. (See Chapter 27 for more information on matrix processing.)

Whereas size does not greatly affect the loudness of a contact mike made from a Piezo disk, it makes a big difference when you are making a driver. If you have a choice, get the largest possible disk and you get a bigger sound out of whatever you are driving.

By the way, if you place your finger across an un-Dipped, bare Piezo disk while it is being run as a driver you may experience a mild, not entirely unpleasant electric shock. This demonstrates how high the voltage gets when jacked-up by the transformer. To reduce distracting stimulation and protect the driver from damage or shorting you should Dip it as you did the contact mike.

Another Kind of Driver

In addition to Piezo disks, small motors can be adapted as drivers. They are most effective for lower frequencies, and can complement the rather tinny quality of the Piezo. Connect the two wires of any small DC motor (one that runs off batteries) directly to the output of your mini-amplifier. It should twitch in response to your sound source. Sometimes coupling the body of the motor directly to an object will be sufficient to transmit the vibration; sometimes you’ll need to get clever with a cam on the motor shaft. Some motors work better than others (vibrators from pagers and cell phones tend to be good) -- experiment.

Chapter 9: Tape Heads

You will need:

- A tape head (see text.)
- Some magnetic media: cassettes, transit cards, credit cards, hard disks, etc.
- A battery powered mini-amplifier with considerable gain.
- An additional sound source, such as a CD or tape player.
- Optionally, a surplus credit card reader (see text.)

Even in the age of CDs there's a lot of data sitting around in magnetic particles: music and phone messages on cassette tapes, personal data on your credit card, files on hard drives and Zip disks, virtual money on transit cards. Whereas a cassette tape player is a pretty common device and we're all familiar with the sounds of cassettes, it's not often we get to hear the information on other magnetic storage media. But all it takes is a tape head and an amplifier.

A tape recorder works by translating audio signals into a fluctuating electromagnetic field -- essentially flipping the north-south orientation of a magnet in response to the audio signal's wobbling between its plus and minus voltage extremes. This flipping magnet is the "tape head," the small metal blob you can see inside a cassette player or answering machine. The tape head's undulating magnetism in turn aligns little tiny magnetic domains in the iron-like powder covering one surface of the recording tape, as if they were tiny compass needles. When the tape is played back the whole process reverses: the varying magnetic orientation held by the mini-magnets on the tape now induce current flow in the tape head which, when amplified, should resemble pretty closely what went into the tape recorder earlier. It's not so different from translating sound vibrations into grooves cut into a record's surface, later followed by a needle whose wiggling is re-translated back into sound waves -- only with tape it's magnetic fluctuations instead of shimmying grooves. Digital tape recordings, such as floppy disks or credit card stripes, are like cassette tape only simpler: the magnetic domains just flop back and forth between two states, 0 and 1, instead of tracing the nuanced contour of an analog waveform.

Preparation

The easiest place to get a tape head is from inside a broken or otherwise unwanted answering machine or cassette player. Many web-based electronic surplus stores sell individual tape heads or credit card data readers at reasonable prices. The advantage of Aztecking a tape head (i.e., ripping it out of a still warm body) is that an audio wiring is attached, usually in the form of some shielded cable; in this case just cut the cable so as to leave as long a section as possible attached to the tape head, and solder a connector to the free end -- make sure you solder the shield to the sleeve of the jack and the inner conductor to the

tip, or much hum will ensue. The answering machine will yield a simple mono tape head, while the Walkman will probably be stereo, but for the purposes of this experiment stereo is not very important, and you can get away with wiring up just one channel if you're feeling cheap or lazy.

If the tape head arrives unwired you will have to try various permutations of connecting pins on the head to the shield and tip of the jack. Always use shielded cable to minimize hum, but bear in mind that tape heads are very hummy things and some noise is inevitable.

Playback

Plug the head into a high gain amplifier. Now rub it over some recorded media: transit cards and credit cards, eviscerated cassette tapes, computer disks. With cassette tape it helps to stretch the audiotape across a tabletop or other flat surface and fasten it down with the sticky kind of tape. You will notice that one side (emulsion) will be MUCH louder than the other (backing.) Digital data (credit cards, transit cards) tends to make a much louder sound than audio tape.

If the signal is weak you may need to boost ("preamplify") it, by connecting it to the low-level (microphone) input of a mixer, or a guitar amplifier. (In Chapter 23 we will make a preamplifier of our own.)

Recording

You can try recording with hand-held tape heads as well as well. Stretch cassette or reel-to-reel tape over a tabletop as above. Plug a CD or cassette player into the input of a mini-amplifier; plug the tape head into its external speaker output. While playing the CD/cassette move the tape head over the tape surface (keep the head in close contact with the tape.) After a while stop recording and try playing back the tape -- either by amplifying the head while moving it by hand across the surface or reloading the tape into a cassette or reel and play back on a tape recorder. Sometimes this works better than others, so don't be disappointed if you don't get good results

If you have a working boom box or cassette recorder you're willing to sacrifice on the altar of the weird, you could carefully remove the record head and extend it with a few feet of shielded cable; press "record" and wiggle the head across some scrap tape.

John Cage once made a nice gallery piece by covering a table-top with tape, inviting the public to scribble across it with tape-heads attached to pencils,. At the end of the evening he wound the tape onto a reel and played it back on an ordinary reel-to-reel tape recorder.

Feedback

As with the coils we used in Chapter 4, sometimes you can get nice feedback between a tape head and a speaker, or between two tape heads, or the left and right channels of a stereo head. Plug the tape head the input of an amplifier, move it near the speaker and listen for the squeal. Split the output of one head with a y-cord and send it into two amplifier inputs; plug another tape head into the output of one of the amplifiers. Raise the amplifier gains and listen as the head coils feed back and interact.

Card Readers

Surplus outlets often sell “card readers” from ATM machines, public telephones, etc. The reader consists of a tape head inside a housing that guides the card smoothly past it, along with circuitry needed to decode the digital data. Stealing credit card data is advanced hacking (ask Mark Trayle, whose piece “Capital Magnetics” makes music out of credit data), but for our immediate purposes you can discard the circuitry, wire the head up as above, plug into an amp, and end up with a very nice instrument for “scratching” cards.

Chapter 10: A Simple Air Mike

You will need:

- An electret microphone element (see text below.)
- 8' lightweight shielded cable.
- Some plugs to match the jacks on your amp , recorder or mixer.
- 9 volt battery and battery hook-up clip.
- An amplifier or mixer.
- Assorted resistors and capacitors.
- Packaging supplies as needed.
- Hand tools, soldering iron and electrical tape.

We've saved the most normal form of microphone for last: after coils, contact mikes, and tape heads we finally get around to your basic hear-my-song mike. From any number of sources (Radio Shack, web retailers, electronic surplus outlets) one can buy, quite cheaply, high quality "electret condenser microphone" elements. You can also scrounge them from telephone answering machines and even some toys. These are the basic building blocks of recording microphones that can sell for several hundred dollars. All that stands between your US\$2.00 purchase and a pretty good mike is a handful of cheap components and a soldering iron.

If you have any choice of models when you go to buy an element, look for the highest signal-to-noise ratio and a flat, extended frequency response. If you have a choice between "cardioid" (directional) and "omnidirectional" pickup pattern bear in mind that the omnidirectional models usually have a flatter response curve -- the quality of the sound tends to make up for its lack of directionality.

Figure 1 shows the basic wiring. A 9 volt battery powers the mike through a resistor. A capacitor blocks this voltage from entering your amplifier or mixer. A switch turns the battery on and off -- the microphone drains very little current, but the switch will help your battery last for months. It's best to turn on or off the mike when it is not connected to your recorder or amp, to avoid big thunks. Solder on whatever plug matches your recorder/mixer -- I've included in Figure 2 the rather odd connections needed if you use an XLR connector (used on the microphone inputs of more professional audio gear.)

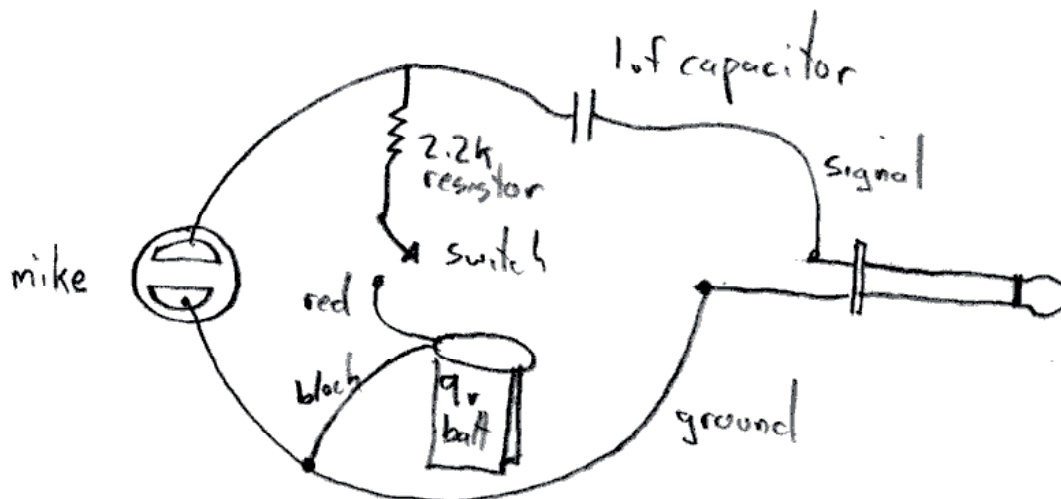


Figure 1

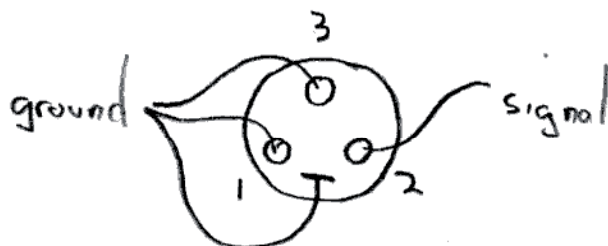


Figure 2

Occasionally one finds condenser microphone elements with three wires instead of two. This makes the job even easier. Instead of combing signal and battery power on a single wire, one wire will be designated as the signal, and will connect directly to the tip of the plug or pin 2 of the xlr; another will be labeled "power" and connects to the "+" of the battery; the third (invariably the shield) connects to both the connector ground and the battery's "-" terminal.

The mechanical packaging is trickier than the electronic wiring. The tiny electret element can be glued into a plastic drinking straw or encased in heat-shrink tubing, and the cable run down to a small box containing the battery, resistor, capacitor, switch and jack. Or you can drill a hole in a small box, insert a plastic grommet into which the mike fits, build-in the remaining components, and run a

cable out of the box to a plug. The challenges of this part of the design process may make you less critical of Neumann's mark-up, but it's worth it.

Two of these tiny mikes attached to a pair of headphones make a great binaural recording set-up. Mount one at the focus of a parabolic reflector (a satellite dish or kid's snow-saucer) for a hyper-directional mike for wildlife sound recording. These mikes are cheap enough to embed in musical instruments -- they're great inside accordions and melodicas and in mutes for trumpets and trombones.

Even the least expensive of electret microphone elements has a surprisingly extended bass response -- often extending down to 20Hz or so. They are very susceptible to wind noise and breath pops, and you may need to roll off the bass to avoid overloading your recorder input under certain circumstances. But this also makes them excellent for picking up subsonic pressure waves, such as those produced by opening and closing doors, wind gusts and some weather changes - - in this case roll off everything above 50Hz and the remainder is your weather.

Part III: Touching

Chapter 11: Laying of Hands I (St. Vitus' Dance)

You will need:

- A battery-powered AM radio.
- Batteries for the radio.
- A small screwdriver, flat and/or Phillips, as required to disassemble the radio.
- Plastic electrical tape and some stranded hook-up wire may be needed.
- Optionally: cigar box, double-stick foam tape.

How to choose a radio

It should be cheap enough that you won't be too angry if it never works again. The AM band is more important than FM, but it doesn't matter if the radio picks up both. It should have analog tuning (ie, a dial) rather than digital presets or scan buttons. Older radios are usually better than newer ones. Larger radios are easier to work with than tiny ones, and often produce a wider range of sounds. Small boom-boxes are great, and you can use the tape head for other experiments (as shown in Chapter #9.) It's better if it has a built-in speaker, not just a headphone jack, but a headphone jack in addition to a speaker is useful. And most importantly: **IT MUST BE BATTERY POWERED!** Beware: an alarm clock radio with a built-in "backup battery" is not suitable, since it requires AC power to function as a radio.

Laying of hands

Install the batteries, confirming that the radio works prior to disassembly; if not functional, return it to the store. If it works, remove the batteries.

Remove screws holding radio together. Put them somewhere safe (like a cup, not loose on top of the workbench,) taking care to make a note of location if they are of different sizes. Some screws may be hidden beneath stickers or under the batteries. Gently separate the halves of the radio. If plastic wedge-fasteners are used you may need to twist a thin flat screwdriver or clam shucker along the seams. Don't force it -- check for hidden screws if it resists. Avoid tearing wires. Once open, make note of any wires connecting the two halves of the radio or the circuitry to the speaker, battery, antenna, etc., in case they get torn later (see Rule #4.)

Locate and remove any screws holding circuit board to the radio housing. Remove any screws holding knobs or switches. Carefully remove the circuit board from the chassis. Sometimes adhesive may be used as well as screws. Knobs and switches may intrude into slots in the case and require bending the plastic to release the board. **CIRCUIT BOARDS, ESPECIALLY CHEAP ONES, CAN BE VERY BRITTLE, SO DON'T BEND THEM!**

The side of the board with most of the little bumpy colorful things (resistors, capacitors, chips) is called the “component side;” the side that consists mostly of little wiggly lines (usually silver or copper colored, sometimes with a translucent green wash) is the “solder side.” Turn the board so that the solder side is accessible. Replace the batteries; depending on the construction of the case you may have to hold the batteries in place using plastic electrical tape, or extend the battery leads with extra wire. If it has a telescoping antenna this may need to be disconnected in order to expose the circuit board – you probably won’t need to reconnect it. Remove the volume and tuning knobs if they are large enough to cover over parts of the circuit board

Turn on the radio and tune it to a “dead spot” between stations or at the end of the dial. Touch the circuit board lightly in different places with your finger until you find a location that affects the radio’s sound. Search for touch points that cause the radio to start to whistle, squeal or motorboat. Tune the radio across the band, and continue to experiment with finger placement. Try several fingers at once. Try licking your fingertips before placing them on the circuit -- moisture increases conductivity. I suggest you do not try licking the circuit board directly -- even low voltage electricity is an acquired taste. And, observing Seventh Rule of Hacking, avoid “shorting” points on the circuit board with screwdriver tips, bare wire, or full immersion in drool.

Don’t worry if you don’t get new sounds immediately -- it’s a bit like trying to make your first sound on a trumpet or flute. Sometimes you have to work a while before you find a sweet spot, but then you’ll lock in and quickly form a tight feedback relationship with the instrument, and the sounds should pour forth. It can take up to an hour to make your first squeal. If you can’t get anything after an hour, try another day or another radio.

What is happening? As Ol’ Sparky has demonstrated on too many occasions, flesh is an excellent conductor of electricity. By bridging different locations on the board with your finger you are effectively -- if haphazardly -- adding resistors and capacitors to the existing circuit. Your body becomes part of the circuit. Varying the pressure (or dampness) of your finger changes the values of these components. Depending on the location and pressure, you may end up merely re-tuning the radio, or affecting its loudness, but you may change the radio into very different kind of circuit, like an oscillator. This happens when the output of an output stage (like the amplifier) flows back through your skin into an input -- voilà, feedback, the musician’s friend!

You may not know exactly what you are doing, but you should soon acquire a sense of touch: what points work best, how does pressing harder affect the sound, etc. This is a very direct, interactive sense of control is similar to that which a “real” instrumentalist, such as a violinist, uses to articulate and intonate notes.

Later we will modify circuits by replacing your flesh with specific “knowable” components -- the effect may be more predictable and stable, but the sense of

touch will be diminished. In the future if things start to sound too controlled, remember you can always add your body to the circuit. And if your eviscerated radio becomes too predictable, try a friend's or hack another.

Older-style radios sometimes have tuning coils whose colorful slotted tops are just asking for the twist of a screwdriver. Doing so may diminish or disable the radio's ability to pick up stations, but can add whooshy noise and rhythmic motorboating sounds to your instrument's palette.

When you are through experimenting you may want to re-assemble the radio -- this is the safest way to carry it around, and to insure its future functionality as a radio. But if you are so enamored of your electronic Ouija board that you cannot bear to seal it up again, welcome to the most hardware part of hacking: finding a box. Cigar boxes work great: using double-stick tape, you can stick down the circuit board (solder side up,) speaker and related parts. Close the lid to transport, open it to play. Don't do this with metal boxes, as they may short out the circuit, but wood or plastic are fine.

If your radio has a headphone jack you can connect it to a battery-powered amplifier -- if the amp has a larger speaker than the radio it should give you a louder, fuller range signal. Alternatively, place a telephone tap, guitar pickup or contact mike on the speaker and plug it into an amplifier. Coils pick up lower frequencies than you'll ever hear out of a small speaker, while contact mikes bounce around, adding a percussive edge to the feedback squeal -- like the bottle caps around the calabash of an mbira.

NOTE: DON'T EVEN THINK ABOUT "LAYING HANDS" ON ANYTHING THAT PLUGS INTO THE WALL!! AND NEVER PLUG YOUR RADIO'S HEADPHONE JACK INTO AN AC-POWERED MIXER OR AMPLIFIER UNLESS YOU ARE 101% CERTAIN THAT THERE IS NO POSSIBILITY OF A GROUND FAULT (I.E., NEVER!)

Chapter 12: Tickle the Clock (Laying of Hands II)

You will need:

- An electronic toy.
- Small screwdrivers.
- A Sharpie-style fine-tip permanent marker.

Hacking is a like hot-rodding your car: you don't need to be able to build a car from scratch to swap in a 4-barrel carburetor, but it helps to know what a carburetor looks like before you get too creative with the wrench. We'll use a simple but very useful hack as a way to learn how to identify basic electronic components and introduce some electronic axioms.

How to choose a toy

As with the radio, select a toy that is expendable, not too tiny, and has a built-in speaker. A toy that makes sound is preferable to a mute one, and sampled sounds (like voices, animal sounds or instruments) are more useful than simple beeps. The more buttons and switches the better, generally speaking. Keyboards are a gamble: some cheap Yamahas hack magnificently, while others have curiously limited potential for interesting modification. Cheaper is usually better -- the more expensive toys often use crystal clocks, which are more difficult to hack. And, of course: **THE TOY MUST BE BATTERY POWERED!**

Clocks

The majority of electronic toys manufactured since the early 1980s are essentially simple computers dedicated to running one program. In most a crude clock circuit determines the pitch of the sounds and the speed of its blinking lights, graphics and/or program sequence. This is true for many analog toy circuits as well. If you can find the clock circuit and substitute one component, you can transform a monotonous bauble into an economical source of surprisingly malleable sound material

What's Under the Hood?

Open up the toy, carefully noting wire connections in case one breaks. Study the circuit board and try to identify the following types of components:

- Resistors: little cylinders encircled by colorful 1960s retro stripes.
- Capacitors, in two basic forms:
 - Small discs of dull earth tones, or colorful squares;
 - Cylinders, upright or on their side, fatter than resistors, with one stripe at most.

- Transistors: three wire legs supporting a small plastic blob or metal can.
- Diodes: cylinders smaller and less colorful than resistors, sometime one stripe, glass or plastic.
- Integrated Circuits (“ICs”): usually black or grey, sometime like square bugs with legs on one, two or four sides; sometimes a malignant looking black circular blob oozing up from the board.
- LEDs (Light Emitting Diodes): colorful sources of light.
- Other things you’ll learn about later.

More and more toys are being made these days with “surface mount devices” (SMDs) – insanely tiny rectangular versions of the above building blocks. Until you gain some hands-on experience with them you can despair of distinguishing the various different types of components, and decoding and hacking these toys will be a doubly foggy experience.

We’re looking for resistors, especially those lying near an IC, flanked by a disc or square capacitor.

Laying of Hands, Again

As with the radio hack we did earlier, your fingers are usually the most direct form of circuit manipulation and testing. Get the circuit making sound. Position it so that you can touch the solder-side of the circuit board, if possible while looking at the component side. Lick a fingertip and place it across various connections, in particular try to connect across points at either end of a resistor, so that your finger parallels the resistor’s connection. When your finger bridges a resistor that is part of the clock circuit you should hear the pitch slide up a bit, or the tempo speed up. If the circuit has lots of connections, and you are having trouble finding the spot, concentrate on those resistors lying close by small capacitors. If the circuit is too small for your fingers, clip a test lead to each end of a 2kOhm resistor and touch the free ends of the leads to the ends of various resistors on the circuit board until you hear the pitch go up.

When you think you’ve found a hot spot, mark in on the PC board with a Sharpie.

If the circuit incorporates the above-mentioned SMDs, most of the components and connections will be on the same side of the board, and it may be difficult to distinguish the capacitors from resistors. Go after the blips with two shiny solder blobs at either end, rather than three or more, and you’re more likely to hit one of the timing components.

So what’s happening?

Electric current flows through wire like water through a fat pipe. Resistors are like skinny pipes, or the rust-laden risers of NYC loft buildings: the higher the

resistance (measured in chantworthy Ohms), the less current flows. Capacitors also resist the flow of electric current, but resist it more at some frequencies than others, in a manner that defies liquid analogies. Capacitance is measured in soukable Farads, usually in small enough amounts to be called “microfarads” or “picofarads.” (Yes, the vocabulary of hardware is much cuter than that of software.)

When a resistor and a capacitor are combined in the feedback loop of an amplifier, they resonate at a frequency that can be adjusted by changing the value of either of the two components; with enough gain the circuit starts to oscillate. Make either of them smaller and the frequency goes up; make either larger and the frequency goes down. When the frequency gets too high to hear it enters the range of a useful clock rate for a computer or digital toy.

When you place one resistor in parallel with another you lower the net resistance (think of it as adding an additional pipe for the current to flow through.) Your skin is a resistor -- when you press your finger across the circuit board contacts you effectively decrease the size of the resistor on the other side of the board. More current flows and the pitch goes up.

Chapter 13: Hack the Clock (Learn a New Alphabet)

You will need:

- The electronic toy from the previous experiment.
- Some hookup wire.
- Test leads with alligator clips.
- A few resistors of different values.
- A potentiometer, 1megOhm or greater in value.
- Soldering iron, solder & hand tools.

Fingers are fine for making the clock go faster. But we all know that the Second Law of the Avant Garde is:

Slow it down, a lot.

To slow it down we need to make the resistance larger instead of smaller. Which means removing the clock resistor (once you are sure which one it really is) and replacing it with a larger one.

- 1) Locate the clock resistor you identified in the previous experiment. Wedge a small flat-bladed screwdriver under the clock resistor. Melt the solder on the underside of the circuit board at one end of the resistor, and lever the screwdriver to lift that end free from the solder connection. Now grip the resistor with a pair of pliers and pull it free of the board as you melt the other solder joint. Put it somewhere safe and DON'T LOSE IT!

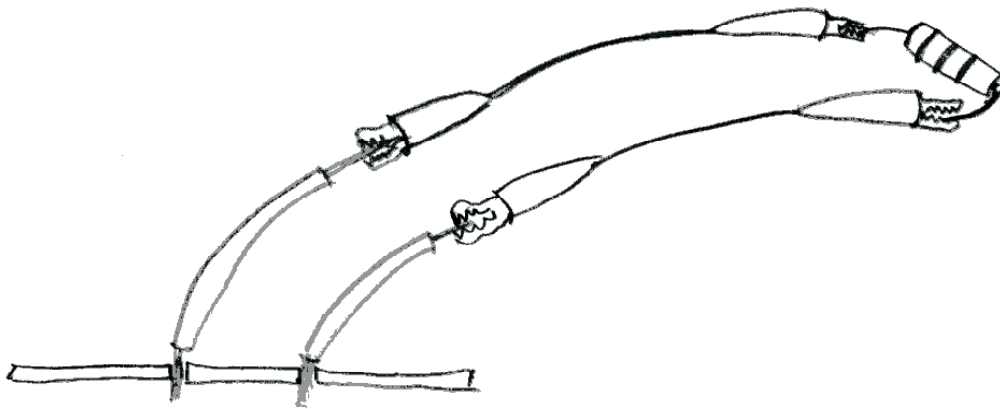


- 2) Strip and tin the ends of two pieces of hookup wire (c. 6" long). Press the end of one into one of the holes left after removing the resistor, from the component-side of the circuit board. Melt the solder on the solder-side of the board as you press the end of the wire through the hole. Touch up the solder joint with a bit of fresh solder to make sure it is solid. Repeat with the second wire into the other

hole. Your circuit board should now have two colorful whiskers sprouting from amongst the vertically challenged components.

Sometimes the circuit will work if you pinch the leads between your fingers, but if you try this be careful not to let the wires touch each other and make a short circuit.

3) Attach a clip lead to the free end of each of the wires. Clip the resistor you removed between the other ends of the clip leads, effectively re-inserting it to the circuit. If you didn't damage anything in desoldering, the circuit should behave as it did before the operation.



4) Those colorful stripes around the resistor indicate its value. Look at the decoder chart below:

Resistor Color Codes:

Color	Value	Multiplier
black	0	1
brown	1	10
red	2	100
orange	3	1,000
yellow	4	10,000
green	5	100,000
blue	6	1,000,000
violet	7	10,000,000
gray	8	100,000,000
white	9	1,000,000,000

Color	Tolerance	(for end band only)
no color	+/- 20%	
silver	+/- 10%	
gold	+/- 5%	

Now study your resistor. The first two stripes represent number values, the third is a multiplier, and a final gold or silver band the tolerance. So if the bands go: brown, black, yellow, silver:

brown=1

black=0

yellow=multiply by 10,000

silver= $\pm 10\%$ tolerance

So we get: $10 \times 10,000 = 100,00$ Ohms (or 100kOhms) $\pm 10\%$

Another example: orange (3) orange (3) red ($\times 100$) gold = 3300 $\pm 5\%$. Get it?

5) What are the color bands of the resistor you removed:

What is its value: _____

6) Go to your resistor assortment and find a resistor at least twice as big, and one about $1/2$ the value. Clip the larger one into the circuit and the pitch should go down. Replace it with the smaller one and the pitch should go up. If either one does not work it may be so extreme a value that the circuit shuts down, so replace it with one whose value is somewhere between the original resistor and the non-functional one. In the event of such a crash observe the 12th Rule of Hacking:

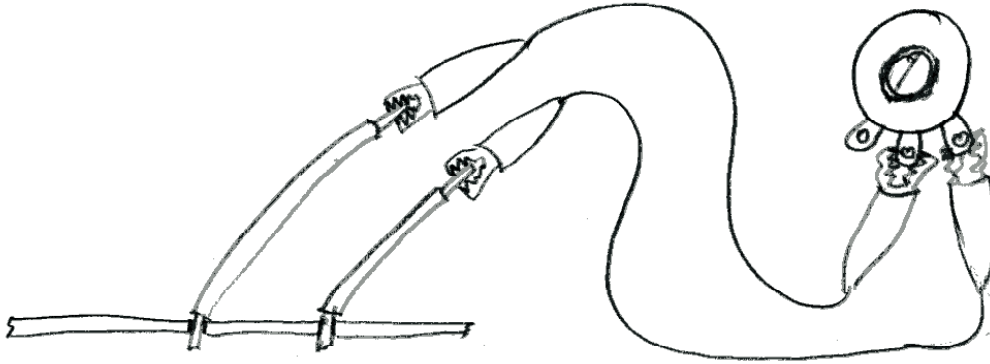
Rule #12: After a hacked circuit crashes you may need to disconnect and reconnect the batteries before it will run again.

7) Substituting resistors should give you a good idea of what values produce what kind of sound, but you may wish to vary the pitch/speed without interruption. A potentiometer ("pot") is a continuously variable resistor. In order to extend the pitch downward you need a pot whose maximum value is greater than the resistor you removed. Since most clock circuits use rather large resistors ($>100\text{k}\Omega$) you will probably need a pot whose maximum value is 1megOhm (1,000,000 Ohms) or greater.

Pots have three terminals. The resistance between the outer two is fixed at the designated value of the pot, which is its maximum resistance (ie, 1megOhm.) As you turn the shaft of the pot, the resistance between the center terminal and one of the outer ones goes up from 0 Ohms to the maximum value, while the resistance between the center terminal and the other end terminal goes down from the maximum to 0 -- like a seesaw.

Clip one test lead to the center terminal and the other to one of the end terminals. Rotate the pot and listen. The circuit will probably crash if you raise the pitch

past a certain point (see Rule #10, above.) If there is no appreciable change in pitch or tempo you may have picked the wrong resistor as the clock timing component – solder it back into the board and use your finger to search again for the hot spot (as we did in the previous chapter.)



Note: one can also change the clock frequency by varying the capacitor in the clock circuit, rather than the resistor, but this is very difficult to make continuously variable.

Chapter 14: Ohm's Law for Dummies

You will need:

- The electronic toy from the previous experiment.
- Some hookup wire.
- Test leads with alligator clips.
- An assortment of resistors.
- A potentiometer (1 MegOhm or greater in value.)
- A multimeter.
- Soldering iron, solder & hand tools.

Now it's time for a smidgin of theory – sorry.

Measuring Resistance

A Multimeter is a device for measuring various electronic properties, such as testing the voltage of a battery to see if it's dead or alive, or checking the value of a resistor. Meters come with analog readouts (a wiggling needle) or digital displays -- simple digital meters are cheap these days and generally more useful. Most meters have a multi-position rotary switch for selecting different measurement modes (DC voltage, AC voltage, current, resistance, etc.) and the range of values measured and displayed.

Grab a meter, turn it on, and select the Ohm setting (Ω) and measure some resistors to confirm your prediction of value from the color code, and to acquaint yourself with this new tool. Most meters have a few ranges for resistance -- experiment & see how changing the range affects the readout. Measure between the different tabs of a pot as you turn the shaft and observe the see-saw like changes in resistance.

Series and Parallel (Ohm's Law)

You may recall that a finger pressed on a circuit puts your flesh in parallel to the existing components, lowering the net resistance and increasing the speed of the clock and raising the pitch of the toy. In order to lower the pitch you had to remove the on board resistor and insert a pot of larger value. This demonstrates an aspect of "Ohm's Law" so essential to hacking that we will appropriate it:

Rule #13 (Ohm's Law for Dummies): The net value of two resistors connected in parallel is always a little bit less than the smaller of the two resistors; the net value of two resistors connected in series is the sum of the two resistors.

To make a clock slower than it already is you must add a pot in series with the resistor on the board: desolder one end of the resistor and connect the pot between this loose end of the resistor and the hole out of which it came (Figure 1.) To make it go faster you connect the pot in parallel: leave the resistor in the

board and solder wires from the two tabs to the two ends of the resistor (Figure 2.) To make the clock go slower and faster you remove the resistor entirely and connect a pot of larger value than the removed resistor in its place (Figure 3.)

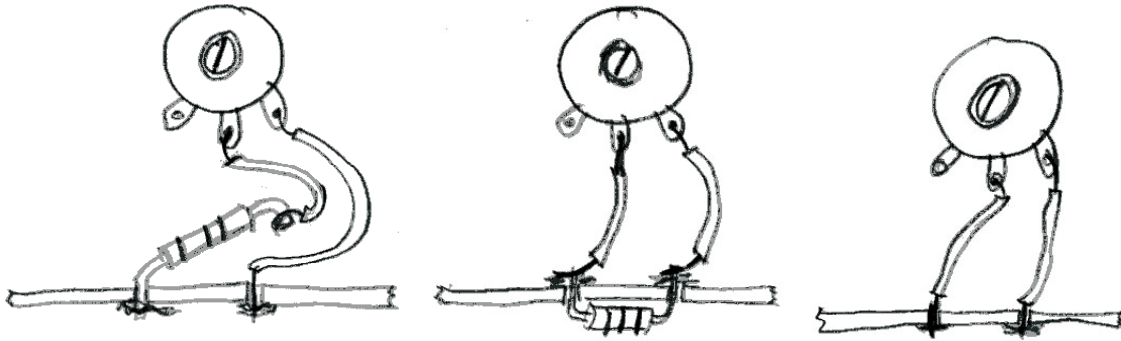


Figure 1

Figure 2

Figure 3

If this doesn't make sense in the abstract, check it out. Use the meter to measure some series and parallel combinations of fixed resistors. Then try some modifications to a toy clock circuit.

Theory class is over. Back to work.

Chapter 15: Beyond the Pot

You will need:

- The electronic toy and radio from the previous experiments.
- Some hookup wire.
- Test leads with alligator clips.
- An assortment of resistors.
- A few different photocells (photoresistors.)
- A flashlight.
- Some loose change.
- Anti-static foam from packaging integrated circuits.
- Some fruit and or/vegetables.
- A multimeter.
- Soldering iron, solder & hand tools.

You've opened a toy, tickled the clock, replaced its timing resistor with a potentiometer, learned a bit of theory to help swapping resistors -- what's left in the way of basic hacks?

Photocells

A photocell (or photoresistor, as it is properly called) is a resistor whose value changes in response to light level: the resistance gets smaller when it is exposed to a bright light, and gets larger in the dark. The lowest resistance in bright light is anywhere from 100 to 2000 Ohms, depending on the kind of photocell; the "dark resistance" is very large, typically around 10 megOhms. Because this is higher than most pots, and because most clock circuits use pretty large resistors, photocells are a convenient variable resistor for slowing down toys a lot.

Photocells are pretty cheap. Sometimes they come with data on the range of resistance, sometimes not. In addition to different "light" (minimum) and "dark"(maximum) resistances, different photocells will respond at different speeds to changes in light level -- some are more sluggish than others. All these factors affect how they perform in a musical circuit. You can test them with a multimeter, but ultimately your ear is the best guide to picking the best photocell for your circuit. Don't be disappointed if it takes a while to find the perfect one.

Select a photocell. It is a small disk with two wire leads; one side of the disk has a fine network of thin lines, the other is blank. The side with lines is light-sensitive. Remove the pot from the clock circuit of your toy and, using clip leads, attach the two leads of the photocell where the pot tabs were connected. Listen to how the circuit behaves when you pass your hand over the cell or shine a flashlight on it. If you have more than one type of cell listen to how different ones affect the circuit.

You can put the cell at one end of an opaque tube (such as a drinking straw painted black) to make it very directional in its light sensitivity: it will only respond to light aimed directly down the tube. This is the core technology of certain carnival shooting galleries.

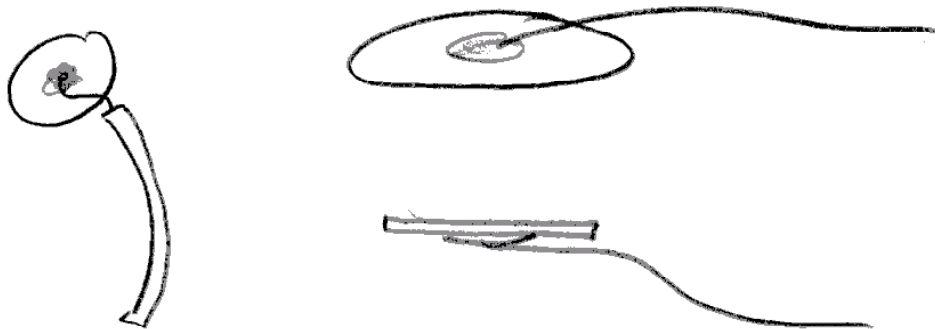
You can place the photocell in your mouth and make a very expressive controller that responds to both the change in light level as you open and close your mouth and the conductivity of your saliva-laden tongue (a naughty extension of the licked-finger-on-circuit-board effect.) Once again: **DON'T EVER THINK OF TRYING THIS WITH ANY CIRCUIT THAT IS EVEN BATTING ITS EYELASHES AT A WALL OUTLET!!!**

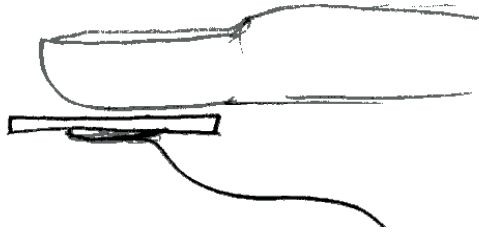
Try placing a fan between a light source (such as flashlight/torch) and the photocell, or reflecting light off a record turntable – you may hear a vibrato effect or other wobbly modulation. If the toy has blinking lights or LEDs you can tape the photocell to one of the lights and the toy will “self-modulate” itself to produce interesting patterns.

A photocell can be a good compromise between the fluid, if somewhat unpredictable (and occasionally dangerous,) effect of the finger on the circuit board and the more controllable but less expressive potentiometer. You can use it as a very responsive performance interface, to interpret hand shadows or flashlight movement, or as an installation sensor, reacting to ambient light and the shadows cast by visitors. We'll look at more photocell applications in Chapters 18 and 22.

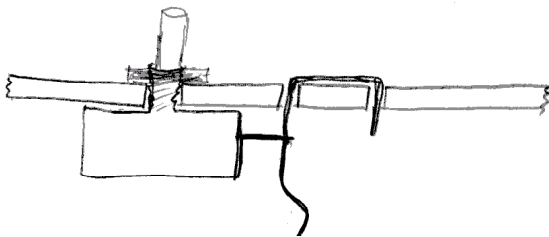
Electrodes

If you want to use your fingers to connect points on the board that are widely separated, or you just want a more formal playing surface, dimes or other silver-plated coins make excellent electrodes. Strip 1/4" of insulation off both ends of a few 5" pieces of wire. Solder one end of each wire to one of the “sensitive points” you've found on the circuit board, and solder the other end to a dime. Arrange the dimes in a pattern that lets you bridge them easily with your fingers (but avoid direct shorts.)

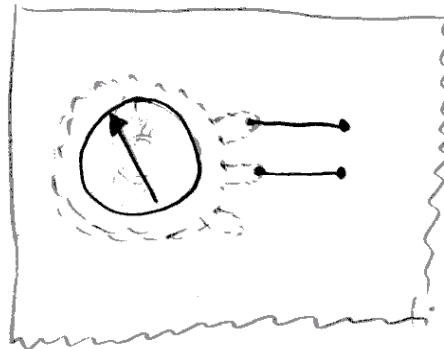




A nice way to combine the control certainty of a potentiometer with the gestural expression of finger-on-circuitry is to parallel the pot and a pair of electrodes. When you solder your hook-up wires to the lugs of the pot leave an extra inch of bare wire sticking up through the solder hole. When you go to mount the pot in the box that will hold the circuit (see Chapter 17), drill small holes to line up with the wire ends and two more about 1/2" away. Dress the wires up through the panel at the pot and then down again, so that they form two parallel strips. You will have convenient electrode contacts immediately adjacent to the knob so you can slip your finger back and forth between precision adjustment and touchy-feely playing.



side view



top view

Cheap Pressure Sensors

The squashy black "antistatic foam" in which Integrated Circuits are sometimes packaged has interesting electrical properties. Put a piece between two coin electrodes and measure the resistance as you squeeze them together -- it gets smaller as you apply more pressure. This home-made pressure sensor can be used in place of a pot or photocell to make a pressure-sensitive controller for performance of installation (under chair legs to measure weight, for example.)



Vegetable and fruit also have resistive value, which changes as they dry out or are squished. You can try substituting small slices of produce for the antistatic foam in the above experiment, or poke bare wire directly into carrots or apples. Paul Demarinis made some beautiful “circuits with a natural lifetime” this way. As some of you may remember from childhood science experiments, it is also possible to make a battery out of fruit or vegetable, but this will wait for another chapter.

Almost a Short Circuit

Another very useful modification is using a resistor to make a new connection between two locations on a circuit board. Start with a resistor of about 1000 Ohms (1kOhms). While listening to the toy, press one end of the resistor to a solder point on the solder side of the board; then touch the other end to various other points -- if the circuit board is large you may need to use a clip lead to reach all over. You may or may not get some interesting sounding circuit malfunctions.

Disconnect immediately any connection that seems to cause heat, smoke or flame.

Try different value resistors, but avoid shorting out the board with straight wire (see the 7th Rule of Hacking.) If you find that the best sounds happen with the smallest value resistor you can try a straight wire, but do so gingerly and be prepared to remove the wire as soon as you feel or smell trouble. You can also try using capacitors instead of resistors. You can go back to your radio and experiment with using resistors to jump between the hot spots you bridged with your damp finger.

Once you find a useful connection you can solder the resistor permanently into place, or add a switch to connect and disconnect it (see next chapter for switch information.)

This technique is the heart of Reed Ghazala’s wonderful “Circuit Bending” philosophy of hardware hacking (see Appendix 1,) and is a very powerful and creative tool for extracting unusual sounds from almost any found circuits.

Interconnecting Toys

Once you've opened and hacked a few toys don't be afraid to experiment with interconnecting them. First connect a clip lead between the grounds ("-") end of the batteries) of both toys. Then use the clip lead and resistor technique to make random connections between any point on one toy and any on the other. In particular try jumpering between the clocks and you may get the toys to cross modulate each other; if you jumper clock points and remove the resistor from one circuit you can sometimes drive both in sync from one clock.

The blinking lights of one toy can be used to modulate its own photocell-controlled clock, or the clock of another. You can cross-link two toys by using each one's lights to modulate the other's clock. The more toys, the greater your chances of creating artificial life.

Chapter 16: Switches

You will need:

- The electronic toy from the previous experiments.
- Some hookup wire.
- A Single-Pole Double-Throw switch (SPDT,) momentary or toggle.
- Soldering iron, solder & hand tools.

Switches are useful for turning power on and off to a circuit to save battery life, for turning on and off specific sounds or functions, and for resetting a circuit if it freezes up. They are often described in catalogs, on websites or in packaging by arcane abbreviations. Here are the main distinguishing features:

- Mechanical style

A switch can be momentary pushbutton, like a door bell, that changes state (turns something on) when you press it, and returns to its default state (off) when you release it; or it can be a push-on/push-off switch that alternates but holds states. It can be a toggle switch with a handle, like a traditional light switch, that stays where you put it until you switch it back. There is also the rotary switch, such as the cycle selector on a clothes washer, with which you select between several positions, rather than just on and off. Slide switches, like the rotary switch, can select between two or more positions. There are a few other oddball switches we'll discuss if they become relevant.

- Number of "throws"

A switch is also described by the number of mutually exclusive connections it makes when moved or "thrown". A simple pushbutton that either turn something on or does nothing is called a "Single Throw" or "ST" switch. If the switch alternates between two possible connections it is a "Double Throw" or "DT" switch. Rotary switches that can make several different connections are classified by the number of connections – i.e., a 5 position switch would be abbreviated as "5T".



Single Throw (ST)



Double Throw (DT)



5-Throw (5T)

- Number of “poles”

Sometimes a single handle or button can switch two or more separate circuits simultaneously (think of the huge double-bladed switches in “Frankenstein.”) Most pushbutton and toggle switches are either “Single Pole” (“SP”), meaning that they switch only one circuit, or “Double Pole” (“DP”), which switch two circuits.



Single Pole (SP)



Double Pole (DP)

- Terminal Designations

In a Double Throw (DT) switch the solder terminal that is normally off or unconnected is called “Normally Open” and abbreviated “NO.” The one that is normally on or closed is the “Normally Closed” (“NC”.) The terminal that is moved by the button or toggle to swing between the NO and NC terminals is the “Common” (“C”.)



Reset Switch

You may have noticed that your toy occasionally freezes up, usually when the clock is run too high or too low, or you short out some part of the circuit. As per the 10th Rule of Hacking, momentarily removing the batteries will usually fix the problem. But this gets tiresome. We can add a kind of reset switch that lets you press a button or throw a toggle to disconnect the batteries temporarily, without the bother of actually removing them. You’ll need a SPDT (Single Pole Double Throw) or DPDT (Double Pole Double Throw) switch. It can be a momentary switch, assuming the toy already has a built-in power on/off switch; if you want

to use the reset switch as a power switch as well, then select a toggle switch instead.

Cut one of the wires connecting the batteries to the circuit board. Solder one end of the cut wire to the switch's Common terminal (C); solder the other end to the Normally Closed (NC) terminal. If the battery wire is very short you may want to extend one or both sections with some additional hookup wire. If the switch has more than three connectors, or they are unmarked, you should use a Multimeter to figure out the switch logic.

The switch is normally closed, so the battery voltage flows into the C terminal and out through the NC terminal to the circuit; when you press the switch the C flips its connection to the NO terminal, severing the connection to the NC terminal and disconnecting the batteries from your circuit. Next time your circuit crashes, return the pot to a middle setting (and remove any suspect jumpers,) press the switch for a moment, and (hopefully) the circuit will "re-boot" when you release it.

If you use a toggle switch the circuit will stay in the off state when switched, instead of bouncing back when released, so it will function as a power on/off switch as well.

Other uses for switches

Toggle or momentary switches can also be used to switch on and off the resistive jumpers you made in the previous chapter, or to switch between a fixed clock and a variable one.

Chapter 17: Jack, Batt & Pack

You will need:

- The electronic toy or radio from the previous experiments.
- A battery-powered mini amplifier.
- Some hookup wire.
- One or more jacks for external audio connection.
- A large ball bearing, some short brads and a small piece of wood.
- A battery holder (if appropriate -- see text.)
- A box of some kind to house your circuit.
- Soldering iron, solder & hand tools.

It's time to "close" your first hack, as they say in the O.R., but let's look at a few final modifications before Frank rises from the slab.

Jacks

Beyond retuning the clock and finding some musically-viable almost-shorts, the most significant change you can make to a toy is replacing the little speaker with a big one -- confirming the Third law of the Avant Garde (and the First Law of Pop), which you may already have discerned from our earlier work with coils and contact mikes:

Make it louder, a lot.

By adding a jack to connect the circuit to an external amp and decent-size loudspeaker you not only make the sound much louder, which lets you hear more detail, but you will also hear low frequency components that aren't audible through the tiny, parent friendly speakers inside most toys. It's easy to do:

- 1) Find the wires leading from the circuit board to the speaker.
- 2) Desolder them from the speaker terminals or cut them as near to the speaker as possible.
- 3) Solder the two wires to a female jack of your choice; usually it doesn't matter which wire goes to which terminal, but you must always have one wire going to the shield/sleeve connector and one to the hot/tip connector.
- 4) Plug it into a decent sound system and listen. Start at a low volume setting, since the output of a toy can be surprisingly loud. If there's lots of hum, reverse the hot and ground connection at the jack. If there's no sound at all, check your soldering. You may find that the raw sound is too much -- too noisy or abrasive, too much extreme high or low -- but that's where the equalization on a mixer,

amp or “stomp box” can help you carve the sound you want out of the toy’s raw material.

As long as you’re adding one jack, why don’t you see if there are any other interesting signals running around the circuit board unheard?

- 1) Solder a wire from the shield / ground connection on a jack to the place on the circuit board where the “-” terminal of the battery pack connects, or to the shield / ground terminal on the main output jack, if you’ve added one already.
- 2) Solder another wire to the hot tip of the jack and strip & tin the other end.
- 3) Solder a 1kOhm resistor to the tinned end of the wire.
- 4) Plug a cord between the jack and an amplifier, preferably battery powered..
- 5) Turn the volume up just a little bit. Poke the free end of the resistor around the circuit board and listen to the different sounds. Adjust the volume as needed. Sometimes you can find very odd noises that seem completely unrelated to the basic sound of the toy.
- 6) When you find a place you like, solder down the free end of the resistor. Wrap the bare wire and resistor lead in electrical tape to prevent shorts (you can shorten the resistor leads prior to soldering to minimize the amount of bare wire running around your circuit.
- 7) If you wish, add another jack and repeat the process. Or add a multi--position switch (like a rotary switch) to select among different circuit points to connect to a single jack.

If you get sound when one or the other of your two jacks are connected to the same amplifier / mixer, but not with both, you have probably unintentionally crossed your grounds. Desolder one of the two incompatible jacks from its wires (the speaker jack, if used, is the first choice) and switch the “hot” and “ground” connections.

VERY IMPORTANT: Be very careful connecting a hacked circuit to a mixer or amplifier that gets its power from the wall, especially if you touch the circuit directly when playing it. It’s best to test for any possible electrocution hazard by gingerly tapping the circuit board, jacks and pots with a dry finger and feeling for any buzz or tingle before you apply any saliva. Alternatively, let a squirrel run across the board. And always remember the 12th Rule of Hacking:

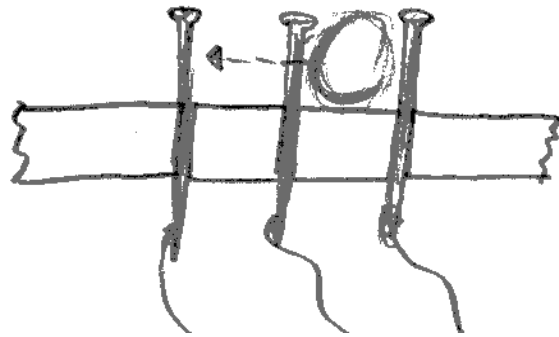
Rule #12: Kick me off if I stick (Zummo’s rule.)

Always have a buddy nearby when there is a risk of electrocution, and chant this mantra before you power up.

An excellent insurance against electrocution is to insert what is know as an “audio isolation transformer” between your circuit and the AC-powered world, but if you are unsure of your power grid, **JUST STAY AWAY FROM IT!**

Home-made switches

You can make a very nice multi-position tilt switch by hammering a ring of brads into a piece of wood, soldering a wire between teach nail and a point on the circuit board that needs switching. You can use this switch to select different circuit hot-points to connect to an output jack (see above) or jumper the almost-shorts you found in Chapter 15. Variations on this design can be made with loops of wire, strips of copper, or even blobs of mercury (once a common switch element, now banished behind the sign of a skull and crossbones.)



Battery Substitution

Almost all toys use batteries that put out either 9 volts or 1.5 volt. Most 9 volt batteries basically look the same: bricks with 2 connectors that resemble android navels. 1.5 volt batteries come in all sorts of packages: cylindrical ones, like D cells (the biggest kind, in the flashlights that Southern sheriffs beat people with,) C cells (smaller,) AA cells (“penlight flashlight batteries”,) and AAA cells (even thinner & a bit shorter, like some metric mismatch of an AA battery;) and “button cells”, that are infernally small, come in a zillion different sizes and shapes, and are way too expensive and hard to find.

9 volt batteries are usually used singly, but 1.5 volt are often combined to add up voltage to power a circuit -- commonly one will find them in sets of 2, 3 or 4. The larger (and heavier) the battery the more current it provides, which means it lasts longer and can power a larger circuit, so:

Rule #15: You can always substitute a larger 1.5 volt battery for a smaller one, just make sure you use the same number of batteries, in the same configuration.

This means you can replace those little button battery cells with the same number of AA cells and run the circuit much longer much cheaper, and afterwards you can find replacement batteries anywhere. All you need to do is:

- 1) Disconnect the existing battery holder, noting which wire connects to the "+" end of the battery stack, and which connects to the "-" end.
- 2) Get a battery holder for larger batteries of your choice.
- 3) Connect it to the circuit, observing the proper polarity.

Some low-current 6-volt circuits (i.e., using four AA or AAA or button cell batteries) will run on a 9-volt battery, and even reflect the additional juice with extra perkiness, but others will succumb to cardiac arrest. Unfortunately there's really no way to know until you try it, so proceed with caution (and a duplicate circuit, if at all possible,) and stop if you see or smell smoke.

How big a battery to upgrade to has as much to do with fitting them inside the toy as any electrical consideration, which brings us to:

Packaging

As your first toy hack nears completion you have to decide how to package it. You have a few basic style choices:

Stealth: keep the original packaging, with added knobs, switches & jacks, as needed.

Camp: go for another recycled housing, like a cigar box, a BandAid tin or a human skull (David Tudor favored plastic soap boxes.)

Sandwich: two slabs of plexiglass or thin wood with a circuit board in between (David Behrman plexi-sandwiched his first Kim 1 computer.)

Traditional: one of those plastic or metal boxes from Radio Shack or elsewhere, that make your toy look "professional."

The decision is partly topological (how do I fit in the new jacks, pots & switches?), partly practical (what's the easiest material to drill?), but largely aesthetic (what looks coolest?). Remember that a bare circuit board will short out if placed in a metal box unless it is isolated from the metal with standoffs of some kind, or you cover the metal or circuit board with electrical tape or a sheet of cardboard. Cigar boxes are great because you can open them easily to change batteries or play the circuit, but the wood is too thick for some jacks and pots to mount directly -- you may need to countersink the mounting holes in order to secure the nuts that screw down.

Part IV: Building

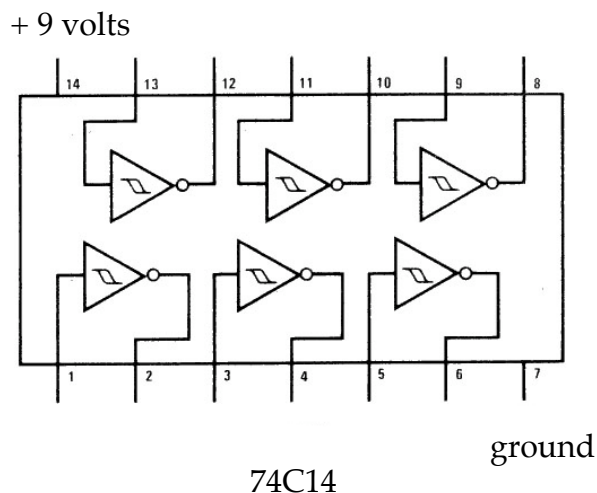
Chapter 18: The World's Simplest Oscillator

You will need:

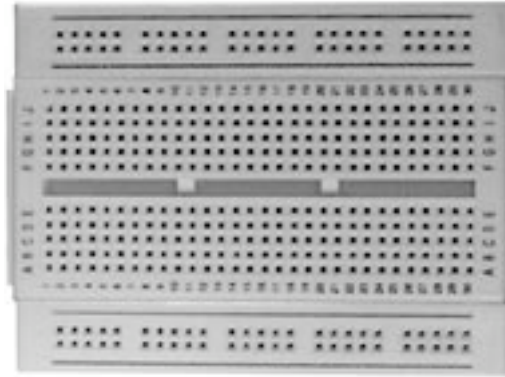
- A plastic prototyping board ("breadboard".)
- 1 CMOS Hex Schmitt Trigger Integrated Circuit (4584, 40106, or 74C14) (see text below.)
- Assorted resistors, capacitors, pots and photocells.
- Some small signal diodes, such as 1N914.
- Some solid hookup wire.
- A plug to match your amp.
- A 9 volt battery and connector.
- An amplifier – preferably battery powered.
- Hand tools.

In the contrarian spirit of hacking, the first circuit we build from scratch is based on the misuse of an Integrated Circuit (IC) never intended for making sound. The "Hex Schmitt Trigger" is a CMOS digital logic building block consisting of 6 identical "inverters." An inverter takes a logical input, 1 or 0, and puts out its opposite (so 1 becomes 0, 0 becomes 1.) This particular version of the inverter is useful to us because it runs for a long time on a 9 volt battery, it is very cheap, and it contains a circuit known as a "Schmitt Trigger", whose fine points you don't need to understand at this point but, trust me, transforms the chip from a simple digital no-man (as opposed to a "yes man") into a versatile sound generator.

The Hex Schmitt Trigger may be labeled with the numbers 4584, 40106, or 74C14. There may be prefixes, suffixes or additional number strings that you can ignore, but chips with a different "innerfix" may not work: if labeled 74HC14 or 74AC14 they will not run on a 9 volt battery and so are less suitable for this project. Here are the internal configuration and connections:



We will build our circuit on a breadboard. The breadboard is a system for interconnecting electronic components without solder. On it you can prototype and rearrange circuit designs quickly, without damaging components. It consists of a plastic block with lots of little holes, beneath which are strips of wire arranged in a matrix. These strips, called “buses,” run in one or two long horizontal strips along the top and bottom edges of the block, and in numerous shorter vertical strips that extend above and below a central groove.



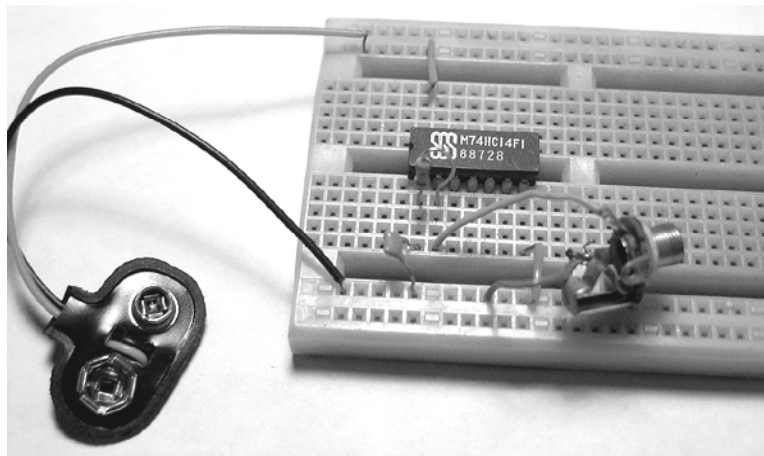
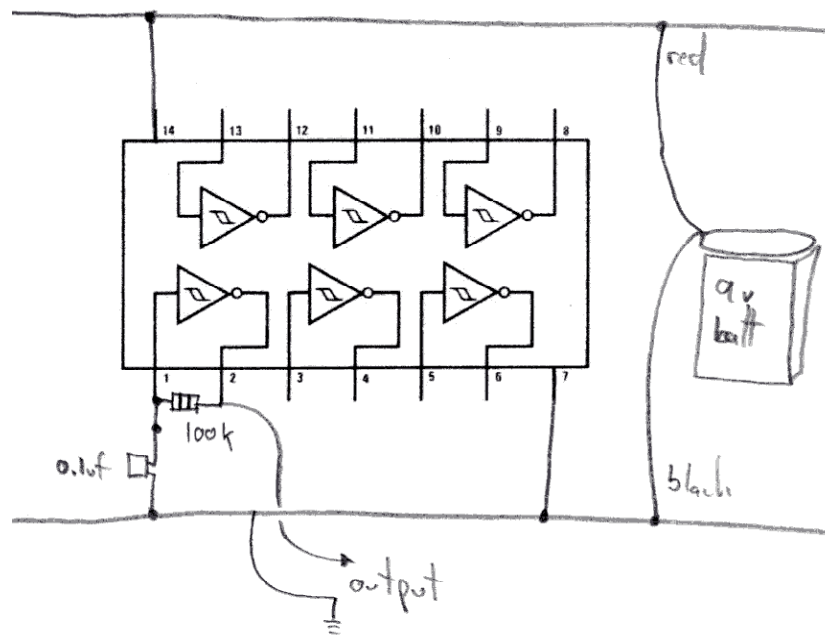
The holes are the right diameter for the leads of most electronic components (resistors, capacitors, integrated circuits, etc.) and hookup wire. Circuits are built up by inserting components into the holes on the board and connecting them by linking rows and columns of the matrix with short strips of wire.

1) Place the breadboard on the table so the trough-like central groove runs horizontally, from left to right. Strip, twist & tin carefully 1/2" from the ends of each lead of a 9v battery hookup clip. Insert the end of the red wire in one end of the bus on the upper edge of the breadboard and the black wire in a bus along the lower edge. Anything inserted in the upper bus will now be connected to +9 volts, while anything inserted into the lower one will be connected to ground (0 volts.)

2) Press a Hex Schmitt Trigger IC into the breadboard, taking care not to bend over any pins. Observe the orientation of the notch and/or small dot as shown in the schematic. Use a jumper to connect pin 14 to the +9 volt bus and pin 7 to the ground (0 volt) bus.

Connect a 0.1 uf capacitor between pin 1 and the ground bus. Connect a resistor of about 100kOhm between pin 1 and pin 2. Use clip leads and a short pieces of wire to connect the tip of a jack to pin 2 and the sleeve of the jack to any point along the ground bus. Connect the battery to its hookup clip. Turn on the amplifier and listen (watch the volume -- this circuit is loud.) You should hear a strident steady pitch, a square wave -- if not, check your connections.

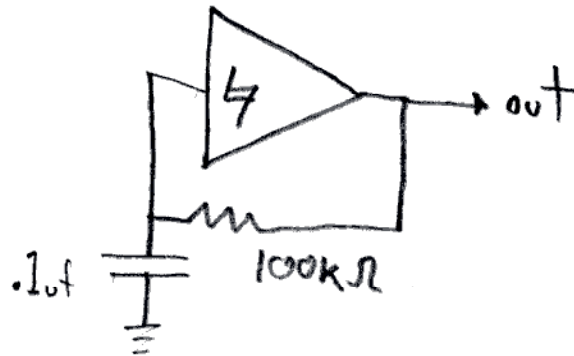
Here's what your circuit should look like if you use the first section of the chip, and make your connections to pins 1 & 2:



If the circuit doesn't seem to make any sound, make sure the component values are correct – too small a capacitor or resistor will cause the circuit to oscillate at a frequency too high to hear; larger values produce sub-audio frequencies, the slow tick tock of a metronome. If the circuit oscillates, but erratically, and is sensitive to placing fingers on chip pins and component leads, then you may have forgotten to connect the + and – power to the chip, or connected them to the wrong pins, or left one leg of the capacitor or resistor unconnected (this chip will

sometimes work even without power hooked up.) When in doubt, triple check all connections.

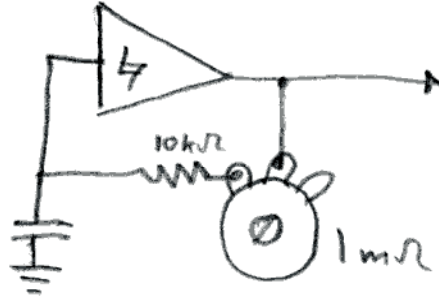
You could use any of the six sections interchangeably, so this is as good a time as any to get familiar with schematic representation, which conveys a circuit design independently of the physical arrangement of its components of a board:



The translation from this symbolic schematic to the mess of wires and components on the board may not seem obvious at first, but once you get more familiar with the language of electronics you'll see that the schematic is an useful way to represent the way a circuit functions, rather than just the way it goes together.

3) Substitute different resistors and capacitors and listen to the effect. Take a pot or photocell and substitute it for the fixed value resistor – the wiggly resistor symbol in the schematic above can be taken to mean any form of resistor, including variable ones such as pots or photocells. The capacitor determines the range through which the variable resistor will sweep the pitch. Too small a capacitor (less than 0.001uf) and the circuit will make sounds that only dogs & bats can hear. Larger values (greater than 5.0uf) lowers the pitch range to that of rhythm -- you'll hear the oscillation as a tick-tock instead of a buzz. A photocell turns this simple oscillator circuit into a wonderful, Theremin-style instrument controlled by light and shadow.

When you use a pot you will notice that at one extreme of the rotation the pitch will go too high to be heard. It will also drain much more current at this ultrasonic pitch, and shorten battery life. Therefore you may want to put a modest resistor (try around 10kOhm) in series with one leg of the pot to set a maximum pitch that is within the range of hearing, as we demonstrated in Chapter 14.



Similarly, if you wire a pot in series with a photocell, you can use the pot to set the upper pitch limit of a light-control instrument, combining the best of two worlds: the accurate control of the pot and gestural freedom and expressiveness of the photocell.

4) You can also use bare wires (with or without dimes soldered to the ends) to make a “laying of hands” oscillator, like our radio and toy experiments, or the infamous STEIM “Kracklebox.” Substitute the electrodes for the resistor or pot by connecting one to the inverter’s input and one to its output; if you connect the electrodes in parallel to a pot (as discussed in Chapter 15) you can use both elements to control the pitch. Experiment with alternate types of resistors.

Why? (If you care.)

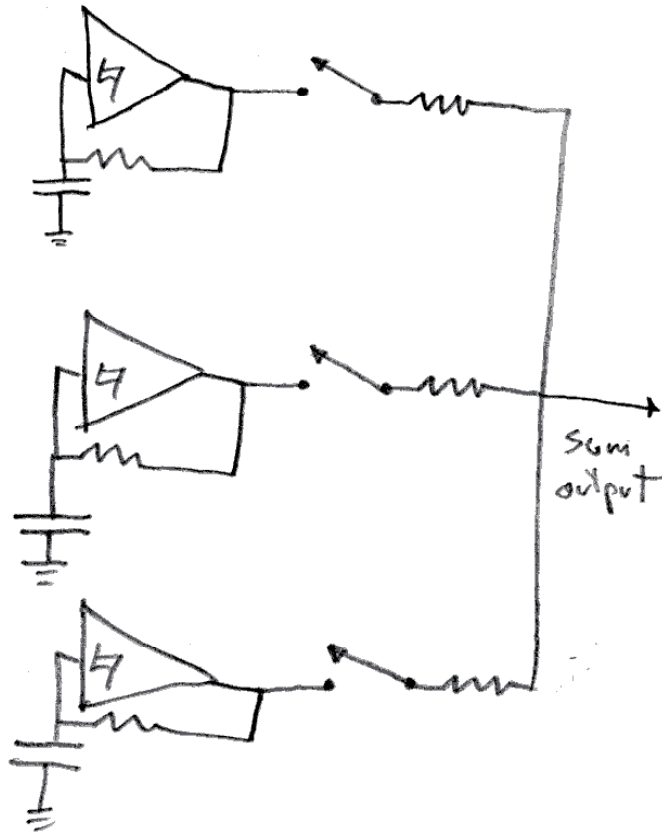
In case you wonder, this circuit oscillates because of the principle of argumentation. Each inverter stage, represented by the small triangle in the schematic, puts out the opposite of whatever signal appears at the input: if a binary “1”, represented by 9 volts, is applied to the input, then a “0” (0 volts) is sent to the output. That 0 flows through the resistor back to the input. When the 0 appears at the input the output goes to 1, which flows back to the input and the whole process begins again, causing the circuit to flip back and forth between two states, generating a square wave. The speed of the flip-flopping (the pitch we hear) depends on the values of the resistor and capacitor -- just like in our earlier clock experiments, the smaller the values the higher the pitch. It’s like the Monty Python argument sketch: I disagree with everything you say, so our output keeps flipping between yes and no according to how fast each of us can reply. The resistor and capacitor act like booze – the more you add the slower the argument goes, ergo the lower the pitch.

Polyphony

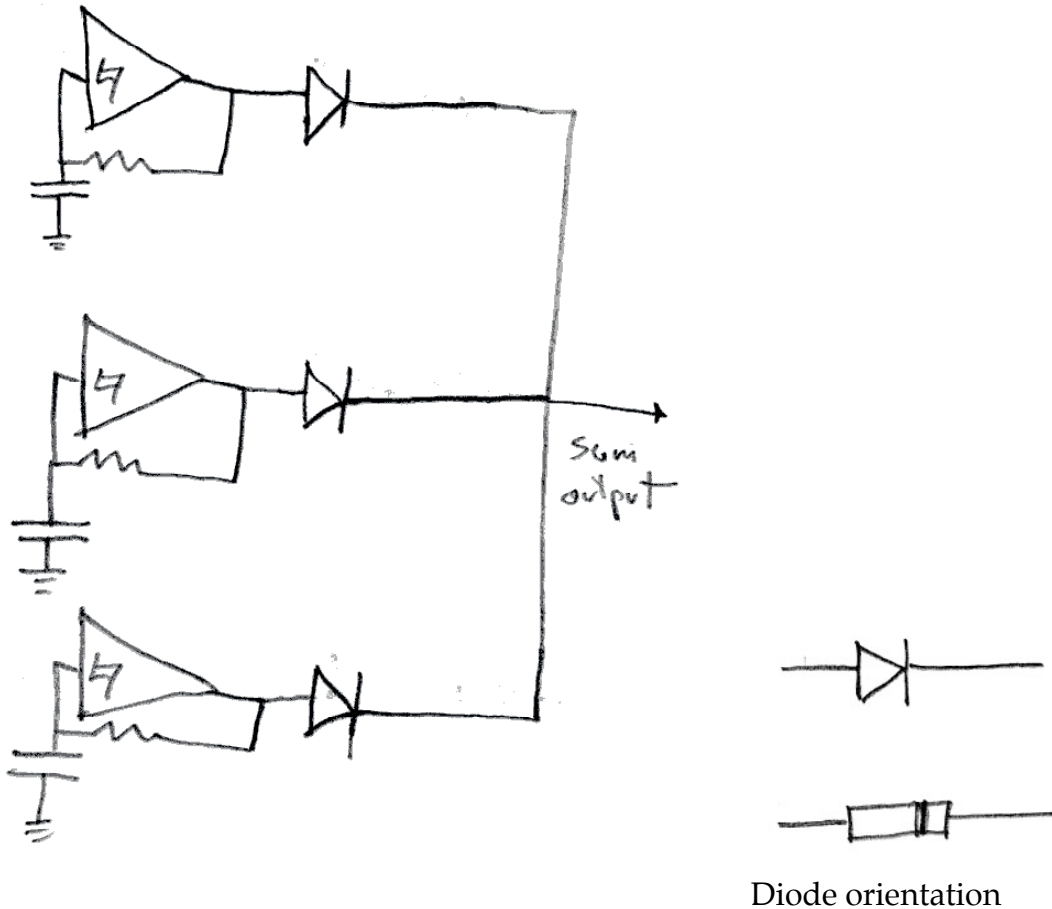
As you might be able to tell from the schematic, the Hex Inverter has six identical sections. You can make an oscillator circuit with any stage -- just duplicate the connections we made for our first oscillator with another set of components, attached to another set of pins: capacitor between any input and ground; resistor, pot, or photocell between that input and its appropriate output; connect the

output via a jack to the amplifier. Remember when working on the “top” side of the chip (pins 8-14) that the capacitor leg must go between the chip and ground, not to the + supply that shadows the ground bus on the upper side of the board. And remember that every oscillator output signal needs a ground connection to the jack as well.

You can use different size capacitors for each oscillator, so each of the 6 covers a different range, from low BPM to ultrasonic pitches. You can also add a switch that selects different capacitors for each oscillator. To mix more than one oscillator to a single jack, connect each output to the jack through a resistor of about 10kOhm -- don't jumper them together with plain hookup wire, since that causes the dreaded short circuit and can damage the chip. Or you can use the home-made tilt switch from Chapter 17 to select different oscillator outputs as you wobble the circuit.



If you substitute a component called a “diode” for the resistors to do the mixing you’ll find that the individual oscillators interact and distort, producing a “ring modulation” type sound.



Diodes are odd little devices that only allow signals to pass in one direction -- I'm not really sure why they make such a cool sounding mixer for these circuits so I won't try to explain it. Which brings us neatly to Rule #16:

Rule #16: If it sounds good and doesn't smoke, don't worry if you don't understand it.

Six square-wave oscillators make a wonderful din. With six photocells or electrode pairs control is somewhat unpredictable but very "playable." Try it.

Caveat

There is a corollary of sorts to Rule #16 that is worth bearing in mind:

Rule #17: Start simple and confirm that the circuit still works after every addition you make.

Don't assume after you get one oscillator buzzing that you can smote the remaining five in one blow. When you find yourself gazing down at a rat's nest

of wires that makes neither sound nor sense, strip your board back to one oscillator and start over, one voice at a time, listening as you go.

Chapter 19: From Breadboard to Circuit Board

You will need:

- Your breadboarded circuit from the previous experiment.
- A full duplicate set of parts used in the circuit.
- Circuit board (see text.)
- 14 pin IC socket.
- Solid and stranded hookup wire.
- Hand tools & soldering iron.

The breadboard is great for prototyping -- mistakes are easily undone -- but not very stable if you want to take your music on the road. At some point you may wish to solidify the circuit. This means soldering the components down on one of a number of circuit boards that are made for this purpose. These boards have buses and interconnected rows similar to the breadboard (Radio Shack part #276-170 mimics a breadboard exactly -- Figure1) or patterns of individual copper pads that can be linked together with bits of wire any way you wish (Figure 2.) (There's a third kind of board, with long, parallel strips of conductor on one side, but assembling a circuit on one of these involves a fair amount of pre-planning and trace cutting, and I don't recommend it for your first project.)

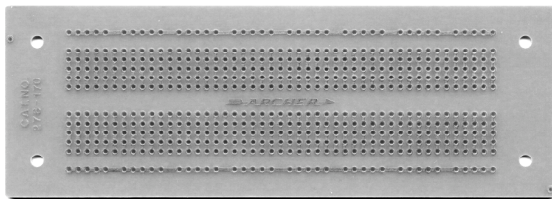


Figure 1

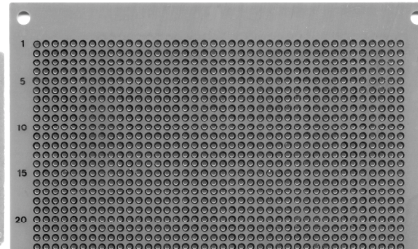
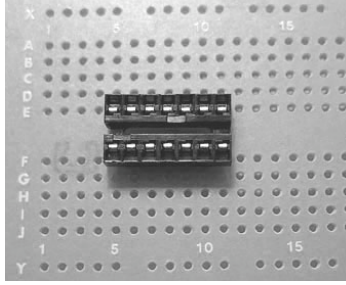
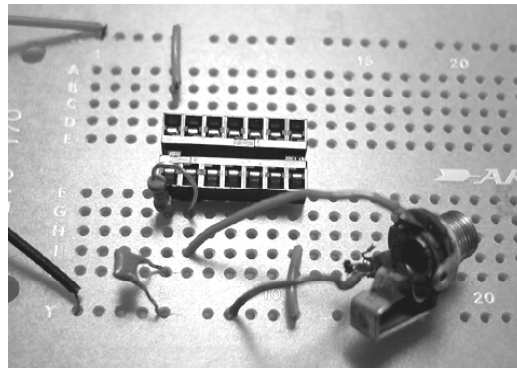


Figure 2

Once you've got a circuit board, start by placing a 14-pin IC socket on the side of the board that does not have the copper paths and pads (this is the "component side" -- the other side is the "solder side.") Push the pins gently through the holes, insuring that, if there is a matrix of rows and columns like on the breadboard, the socket is similarly positioned, with a rows fanning out from each pin, not shorting them all together. Make sure all the pins go though fully, and none are bent over on top of the board. Solder the socket pins carefully, and avoid letting blobs of solder short together adjacent pins or copper traces. The IC is inserted into this socket when you have finished all your soldering, which protects the chip from damage by the heat of the iron and makes it easier to replace the chip if it blows out later.



Now solder an identical set of resistors, capacitors and other components onto the component side of the board, following their placement on the breadboard. Use thin, insulated wire (solid or stranded) to make interconnections on the board -- strip insulation off the ends, as you did to make the jumpers for the breadboard; link points by running the wire along the component side of the board, passing it through holes where appropriate, and solder to the pads. Make sure the uninsulated ends of wire do not short against each other or adjacent solder pads. Use stranded, rather than solid, wire for the pots, jacks and photocells, so the wire can flex easily without breaking when you mount the circuit in a case. Don't forget that every jack needs signal connection and a ground wire (Rule #10.)



If you use an exact clone of a breadboard (such as the Radio Shack board) it will have ground and +9 volt buses you can wire to just like on the breadboard; if you are working with another design you may have to create your own "virtual buses" by linking the ground ends of all the capacitors and the chip ground together with wire, for example. Solder the black wire of a 9 volt battery clip to the ground bus on the circuit board. Solder the "NO" terminal of a toggle switch to the +9 volt line (red wire) so you can turn the circuit on and off without having to remove the battery, then solder a wire from the "C" terminal of the switch to the board. Put the chip in the socket after all soldering is finished, and check to make sure its orientation is correct (i.e., pin 14 goes to +9 volts, pin 7 to ground, not backwards.)

Rule # 18: Always leave your original breadboard design intact and functional until you can prove that the soldered-up version works.

This makes it much easier to debug any mistakes, by comparing the working version on the breadboard with the miscreant on the circuit board.

Be careful not to make unintentional “solder bridges” between traces when soldering. (After transferring your first design to a circuit board you will see how important it is to have a good soldering iron with a very fine tip.) Compare your connections against the breadboard one more time before connecting the battery and turning on the circuit. If the battery or chip get hot when the circuit is on, shut it off immediately and check again for mistakes.

If the circuit makes sound, but is quieter than the breadboarded version or just acts weirder than it should, check to make sure you remembered to hook up the battery’s + and - connections to pins 14 and 7 of the chip -- sometimes the circuit almost works without a direct power hookup, by sucking voltage through other connections you have made (spooky!). Another tip for keeping this (and all other) circuits running cleanly is to solder a 0.1uF capacitor between the + pin (14) and the - pin (7), keeping it as close to the pins as possible (not at the other end of the board and linked by wires.)

A circuit board that mirrors your breadboard exactly makes the transfer process much easier. If you can’t obtain such a board you must make adaptations carefully, checking your connections as you go. Once you have transferred a few designs, and get comfortable with the “topology of circuitry,” you can choose various sizes and patterns of circuit board that give you the freedom to rearrange your design between prototype and final version. Larger boards can be cut into smaller sections for simple one-chip circuits like our first oscillator.

When your circuits start to get complicated you may find that regular hookup wire gets thick and messy on the board. If you want to lighten up, and move from spaghetti to capellini, buy yourself a roll of what is called “wire wrapping wire.” At 30 awg gauge, it’s real thin, stays in place when snaked around the board, and comes in nice bright colors.

Once you’ve confirmed that everything works you can move on to finding a box and drilling a mess of holes (see Chapter 17.) Have fun!

Chapter 20: More Oscillators

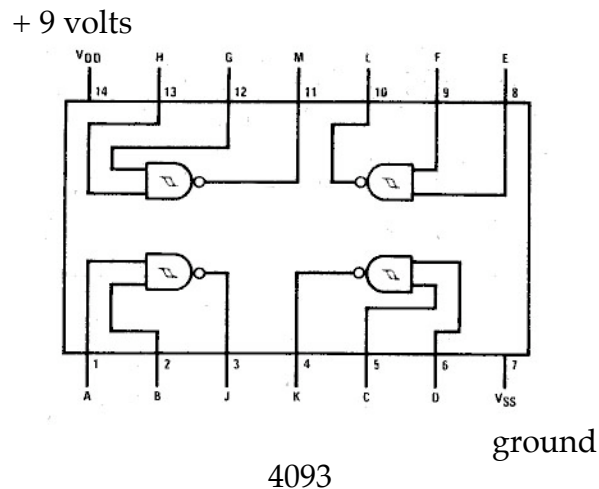
You will need:

- A breadboard.
- 1 CMOS Quad NAND Gate Schmitt Trigger Integrated Circuit (#4093)
- Assorted resistors, capacitors, pots & photocells.
- Some solid hookup wire.
- A jack to match your amp.
- A 9 volt battery and connector.
- An amplifier.
- Hand tools.

Here are some variations on our basic oscillator design.

Gated Oscillator

The Schmitt Trigger circuit that turns each Inverter in the 74C14 into a potential oscillator is also found in other CMOS digital circuits. Most useful is the 4093 “Quad NAND Gate.”



This chip consists of 4 identical NAND gates. Note that this chip has the same power connections as the 74C14 Hex Inverter chip we used in the previous two chapters: + voltage to pin 14, ground to pin 7. There are two NAND gates on each side of the chip, but unlike the 74C14, there is mirror symmetry on each side: the outputs of each gate face each other, rather than the same direction.

A NAND gate is a variant of the basic binary function of an AND gate, which for two inputs generates the following outputs:

INPUT A	INPUT B	OUTPUT
0	0	0
1	0	0
0	1	0
1	1	1

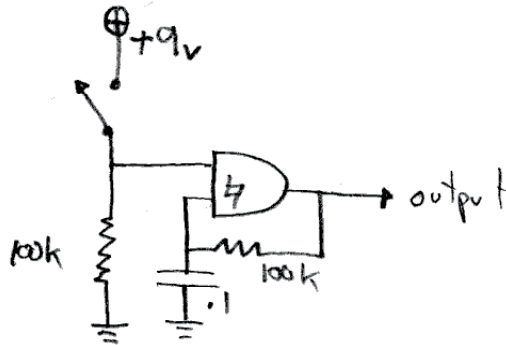
You see that the output only goes “true” when both inputs are true.

A NAND gate adds an inverter stage after the AND logic to flip the output like this:

INPUT A	INPUT B	OUTPUT
0	0	1
1	0	1
0	1	1
1	1	0

The inverter introduces the principle of Pythonesque denial (discussed in the Chapter 18) that transforms this logic circuit into a “gateable oscillator.”

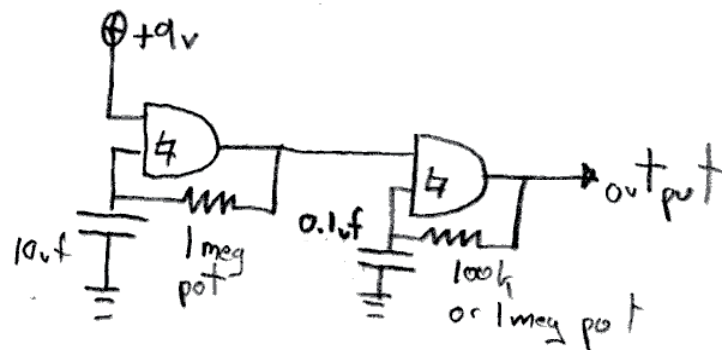
Look at the circuit below. Note that the basic design is similar to our earlier oscillator: a capacitor between an input and ground; a feedback resistor from the output back to the input. But where each stage in the Hex Inverter package had just one input, each NAND gate has two inputs. Because of the combinatorial logic of the NAND gate, the second input of the gate can be used as a control input to turn the oscillator on and off: the output of the circuit can only change state (i.e., oscillate) when the control input is held “high” (+9 volts), otherwise the output always stays in its “1” state (+9 volts.)



Try it. Remember to hook up power to the chip as you did with the 74C14: +9 volts to pin 14, ground (battery -) to pin 7. For the “switch” indicated in the schematic, you can just plug a bit of wire into the socket near the gate input and connect and disconnect the other end from the +9 volt bus to make the contact. The two inputs to each gate are identical -- it doesn’t matter which you use for the “control input” (the one with the switch) and which for the “feedback input”

(the one with the capacitor and feedback resistor), as long as you don't mix up the two and connect the capacitor and switch to one and the feedback resistor to the other, for example. And you can use any of the four NAND gates on the chip – they function identically. The oscillator oscillates when the control input is connected to the +9v bus; it turns off when the input is disconnected from +9 volts (the resistor between the control input and ground insures that the input is pulled to 0 when not connected to +9 volts.) Big deal, you say, we can do this by simply connecting and disconnecting the battery. But we can turn each of four oscillators on & off independently: by adding a momentary switch to each control input to make a simple keyboard, with each oscillator individually tuneable and gateable.

More significantly, because the oscillator's output consists of a square wave swinging between "true" / +9v and "false" / ground, we can also use the output of one oscillator to gate another on and off. Breadboard the circuit shown below Use a large capacitor (4-10uf) and pot for Oscillator 1, and a 0.1uf capacitor and 100k resistor or pot for Oscillator 2.

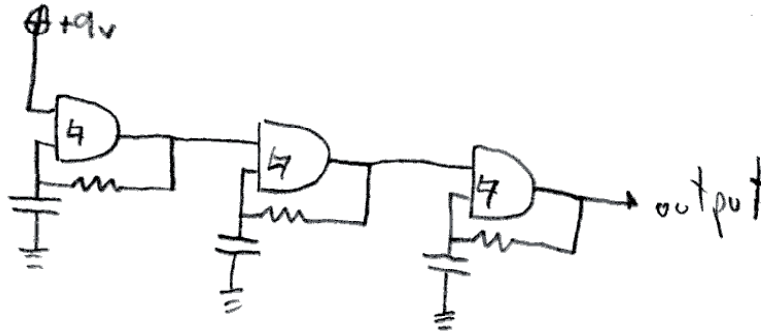


Oscillator 1

Oscillator 2

The control input on Oscillator 1 is tied directly to +9 volts, so it runs all the time (like the basic 74C14 oscillator we built in Chapter 17.) But the control input of Oscillator 2 is connected to the output of Oscillator 1, which gates it on and off. If the Control Oscillator (#1) has a large capacitor and runs slowly (like a metronome,) you can hear Oscillator #2 switch on and off at a regular tempo. As we tune Oscillator #1 higher and higher the obvious on/off function transforms into a kind of frequency modulation that is heard as a change in the tone color rather than tempo.

You can cascade more than 2 oscillators, as shown below, to create rhythmic patterns or (if the oscillators are running at audio frequencies) tone clusters.



Experiment with different value capacitors and pots for the different stages. You can substitute photocells or electrodes for the resistors/pots in any of these circuits.

Note that even though the control input might be connected to + 9 volts we still need to connect + 9 volts to pin 14 and ground (- voltage) to pin 7. These voltages are used for two distinct purposes in our circuit: through pins 14 and 7 they provide power to the chip, needed to run its internal operations – this is the “gas.” But + and – voltage also have arithmetic value, and are evaluated as part of the (admittedly simple) mathematical calculations that the circuit performs in order to oscillate. As with our previous circuit with the 74C14, sometimes this chip will make sound without proper power connections, but it will be “coasting”, and probably will not perform reliably (or go up hills.)

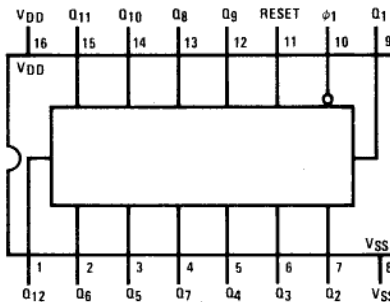
Chapter 21: Even More Oscillators

You will need:

- A breadboard.
- 1 CMOS Hex Schmitt Trigger Integrated Circuit (74C14) or CMOS Quad NAND Gate Schmitt Trigger Integrated Circuit (#4093)
- 1 CMOS Binary Counter/Divider (#4040)
- Assorted resistors, capacitors, pots & photocells.
- Some solid hookup wire.
- A jack to match your amp.
- A 9 volt battery and connector.
- A Piezo disk
- An amplifier.
- Hand tools.

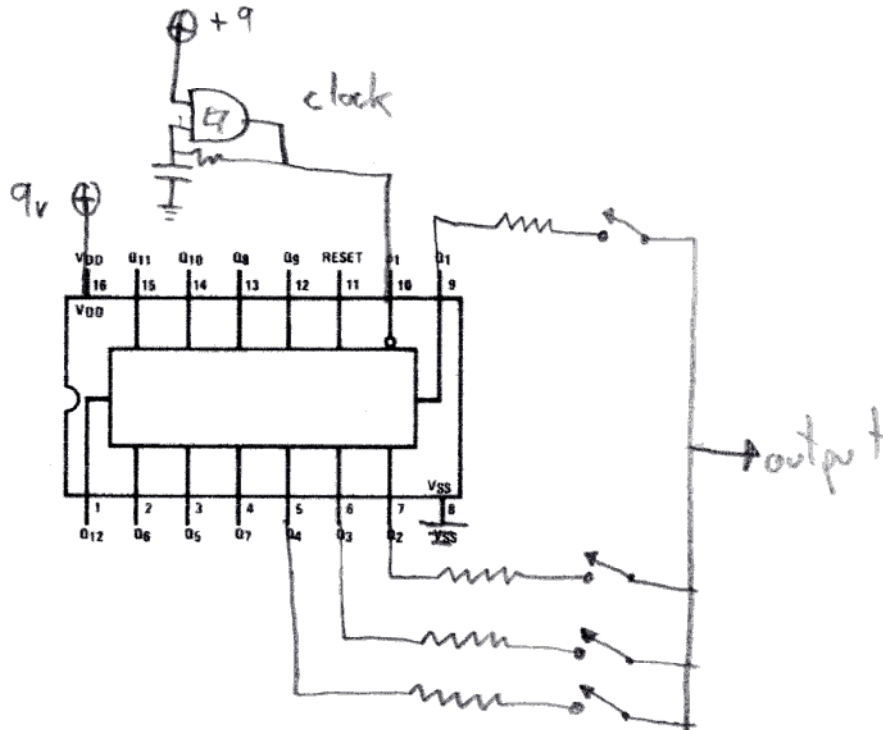
Dividers

The musical applications of digital logic circuits go well beyond simple oscillators. For example, a chip that performs the arithmetic function of dividing a number can be used to generate several harmonically related pitches from a single master oscillator.



4040

Breadboard the circuit shown below. Ground (battery -) connects to pin 8, +9 volts to pin 16. The master oscillator is connected to pin 10, the clock input of the divider circuit (#4040). The chip has 12 cascaded stages, each of which divides its input frequency by 2 (ie, outputs are provided for the input signal divided by 2, 4, 8, 16, etc, all the way to 4096.)



Listen to the output of the oscillator (“master output”) and tune it to a high frequency audio pitch. Now listen to Output Q1 and note that it sounds an octave lower. Output Q2 sounds an octave below that, Output Q3 an octave below that, etc. Using switches as shown, you can mix these “subharmonics” in any combination to build up a rich waveform (this is very nice with a tilt-switch system, like that described in Chapter 16). Because the thick texture and low frequencies of this circuit you may want to listen to it over a larger loudspeaker than that of the tiny test-amplifier.

The switches show in the figure can be anything: momentary push-buttons, toggle switches, our home-made tilt switch from Chapter 17, or just some wire jumpers on the breadboard.

Slow the master oscillator down to the rate of a tempo, rather than a pitch, and the various outputs become subdivisions of the beat -- good for setting up nested rhythmic patterns.

Random Acts of Kindness

Disconnect the oscillator circuit from the clock input (pin 10) and connect a short piece of solid wire. Sometimes your body carries enough of an electrical charge that if you touch the end of the wire the noise of your flesh will trigger the divider – listen to the different divisor outputs as you experiment with brushing

and squeezing the wire. Sometimes it helps to connect a large resistor (100kOhm – 1mOhm) between the clock input pin (pin 10) and ground or + 9 volts to stabilize the circuit when you are not touching it.

Some applications for oscillators

The oscillator circuits we've made have a number of applications beyond just plugging into an amplifier and droning away

Clocks for toys

Sometimes you can use the output of a high frequency oscillator as a substitute for the clock circuit in a toy. Breadboard an oscillator that runs too high to hear – use a capacitor around 100 pf and a pot to adjust the speed. Connect the ground of the toy (- battery point) to the ground on your oscillator (- battery bus.) Disconnect the timing resistor of the toy and solder a jumper to each of the pads at either end of the resistor. Plug one wire into the output point of the oscillator. Does the toy run? You may need to disconnect and reconnect the batteries, and adjust the oscillator speed with the pot. If it doesn't work, try the lead from the other resistor pad. If neither works try another toy or give up. But if it does work you can proceed with applying all of our oscillator variations (gated, divided, etc.) to modifying the toy's performance.

Crickets

Although a CMOS oscillator does not put out enough current to power an ordinary loudspeaker (even a small one) directly, it will make beautiful cricket-like sounds when wired to a Piezo disk. Connect the oscillator's output to the hot wire of a disk (center), and connect the ground to the circuit's ground bus (don't use the Chapter 8 transformer in this configuration.) Low frequency pulses should yield a pleasing clicking sound, while audio pitch should buzz like a sultry August (in the Northern Hemisphere) afternoon. If they're too quiet for your taste, clamp the Piezo to a cookie sheet, or place it on a wooden matchbox with a stone on top, or glue it to the wing of a balsa glider. Many of Felix Hess' beautiful insect-like installations have been based on low-power circuitry pinging Piezos.

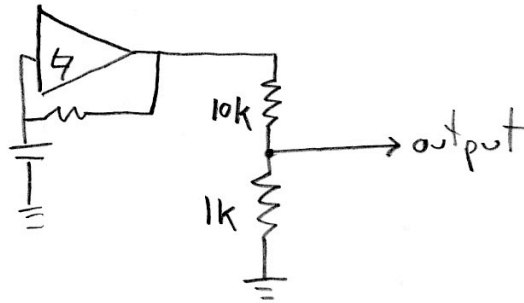
More Randomness

Once you get the hang of these basic oscillator circuits and the way they are supposed to work, don't be afraid to experiment with alternate configurations, even if you have no idea what you're doing (see Rule 16) – these chips are hard to blow up. The 74C14 and 4093 IC packages contain several identical oscillator building blocks. Create multiple feedback paths by linking the outputs of some oscillators to the inputs of others. Add multiple electrode touch contacts. You

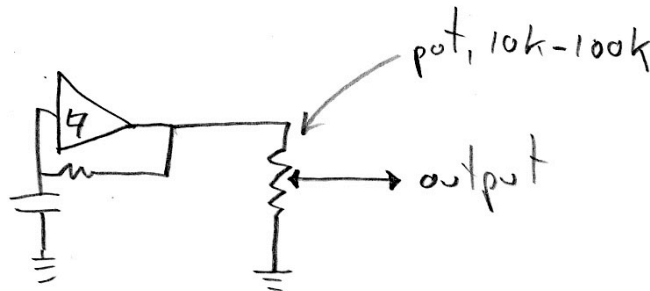
may need to add pull-up resistors to the inputs of the circuits to start them oscillating: connect a resistor in the 100kOhm – 1mOhm range between the input pin and +9 volts of the various stages of your circuit. Arranged in matrices, sometimes the oscillators produce unstable, complicated patterns of pitch and rhythm not displeasing to the ear (or brain.)

Volume Control

These oscillator circuits are really loud: they put out 9 volts peak-to-peak, versus about 0.7 volts peak-to-peak for the output of a typical piece of consumer audio gear, such as a CD player. They may overload the input to your amplifier or mixer, causing distortion (not always a bad thing) and limiting the useful range of your faders. If you want to drop the level down to a more reasonable volume, try adding this circuit to the output of each oscillator or the mix of several oscillators:



Alternatively, if you want fade the volume up and down, rather than just drop it, you can add a volume control at the output of the oscillator, as shown below. Any pot whose value is 10kOhm or greater will do. If you can find a pot designated as having an “audio taper” it will make the fade sound smoother (see Chapter 27 for a discussion of pot characteristics.)



Chapter 22: On/Off (more fun with photocells)

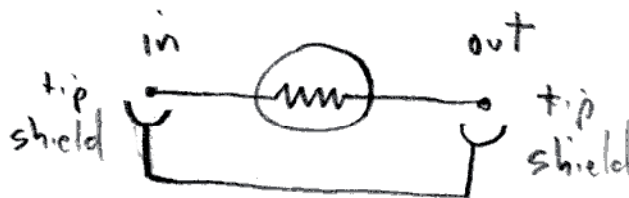
You will need:

- Two things to turn on & off, such as a radio, cassette or CD player with an audio output jack.
- Some photocells.
- A flashlight (torch.)
- A basic oscillator circuit from one of the previous chapters, on a breadboard.
- Some LEDs (Light Emitting Diodes.)
- A phototransistor.
- Some heat shrink tubing (optional.)
- Assorted resistors, capacitors.
- Some solid hookup wire.
- Some plugs and jacks.
- Clip leads and Y-cords.
- A 9 volt battery and connector.
- An amplifier or two.
- Hand tools.
- An infra-red remote control from a TV or other appliance.

As we have seen in our earlier experiments with toy clocks and simple oscillators, the photocell changes resistance in response to changes in light level; this change in resistance in turn affects the speed of a clock or pitch of an oscillator. A photocell can also be used as a kind of gate to pass or block any audio source.

Flashlights

Breadboard or clip together the simple circuit shown below:

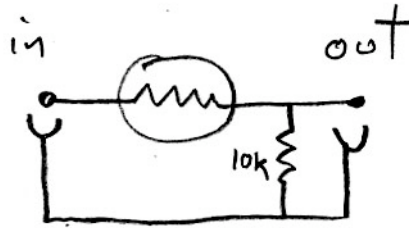


photocell

Connect the “hot” of any audio signal (such as the output of a portable cassette or CD player) to the input of the circuit; connect the output of the circuit to the “hot” of your amplifier input. Connect the shield/ground of the audio source to the shield/ground of the amplifier input (Rule 10.) Turn on the amp, play the

cassette/CD, and confirm that audio passes through. Take the whole rat's nest into a dark place. The sound should get much quieter. Turn on the flashlight and pass the beam across the photocell -- the sound should get louder when the cell is lit, quieter when the cell is dark. This circuit won't shut off the sound completely, but you should hear a significant volume difference between light and dark. The back side of a photocell is usually translucent, so total darkness can only be achieved if you fully enclose the cell – in your hand for example, or you can cover the back with black electrical tape. Make sure you don't let the leads short out (you should spread them apart before applying the tape.)

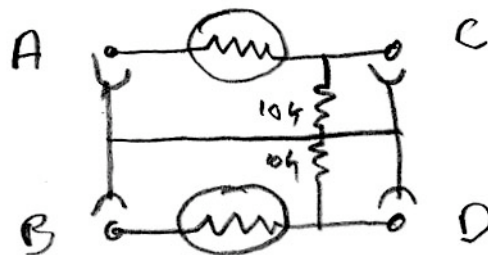
You can increase the dynamic range of this circuit (the difference in loudness between "on" and "off") by adding a resistor of about 10kOhm between the output signal and ground, as shown below. Without getting into unnecessary technical detail, the resistor "clamps" the output to ground when the circuit is "off", minimizing bleed-through of the input signal, and increasing the depth of the muting.



Our second photocell circuit, shown below, can be used in two ways:

1) Connect one audio source to points "A" and "B" (use clip leads); connect "C" to the input of one amplifier, and "D" to the input of another. When you pass a flashlight across the two photocells, the sound should pan from one speaker to the other.

2) Connect one audio source (ie, a CD) to jack "A," and a different one (cassette) to jack "B;" jumper "C" and "D" together to the input of one amplifier. When you pass a flashlight across the two photocells you should be able to mix between the two sources (like cutting between turntables.)



Remember to connect all shields/grounds together as we did for our first photocell circuit. If you choose to solder up this circuit you can use switches or y-cords to tie A and B or C and D together, according to your application, or you can hardwire one of these configurations if you're sure you will only be using it either as a panner or a mixer.

Flashlight controlled circuits like these gates, panners and mixers and our earlier photocell-controlled oscillators occupied a distinguished place in the history of live electronic music: similar circuits could be heard in early work of David Behrman ("Runthrough"), Larry Austin and David Tudor, as well as in Voice Crack's wonderful performances throughout the 1980s and 90s.

Blinkies

An LED (Light Emitting Diode) is a small cheap source of light that can be controlled electronically. The LED has one shorter leg, and if you look closely you will notice that one side of the lower rim of the LED is slightly flattened -- the short leg and flat side indicate the - connection of the LED, the other leg is + (Figure 1). Breadboard the circuit shown in Figure 2.

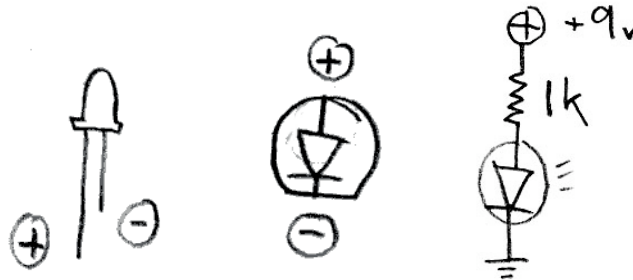


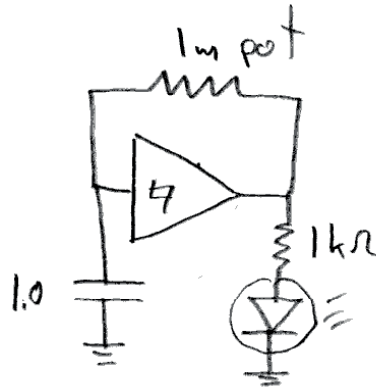
Figure 1: LED connections

Figure 2: simple LED circuit

Swap the polarity of the LED and observe that it only lights in one configuration. Substitute different values for the resistor and note the change in brightness: the smaller the resistor, the brighter the light, but only to a point, after which the LED will burn out. Don't use a straight wire -- with a 9 volt battery supply 1kOhm is a good value to start with.

Rule #19: Always use a resistor when powering an LED, otherwise the circuit and/or LED might blow out.

Breadboard the circuit shown below. This is the simple oscillator from Chapter 18 (you could also use the 4093-based design in Chapter 20,) but now we are connecting it to an LED instead of an amplifier; it blinks the light instead of clicking the speaker. We want it to blink at an observable rate, so we use a reasonably large capacitor.



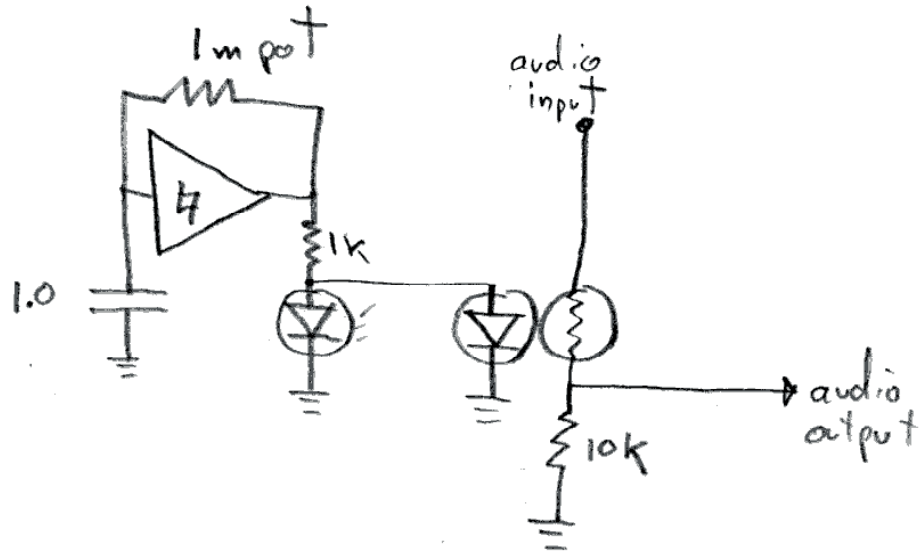
Vary the speed and watch the effect. Fun enough just to look at, but wait -- it gets better!

Now take the LED and hold it against the photocell as shown below. Spread the leads of the photocell and LED apart so they do not touch each other, then wrap the photocell and LED in electrical tape so that they are sealed from outside light. Be very careful not to let any of the wires touch each other or the circuit will not work -- you can wrap each of the four wires separately if this helps.

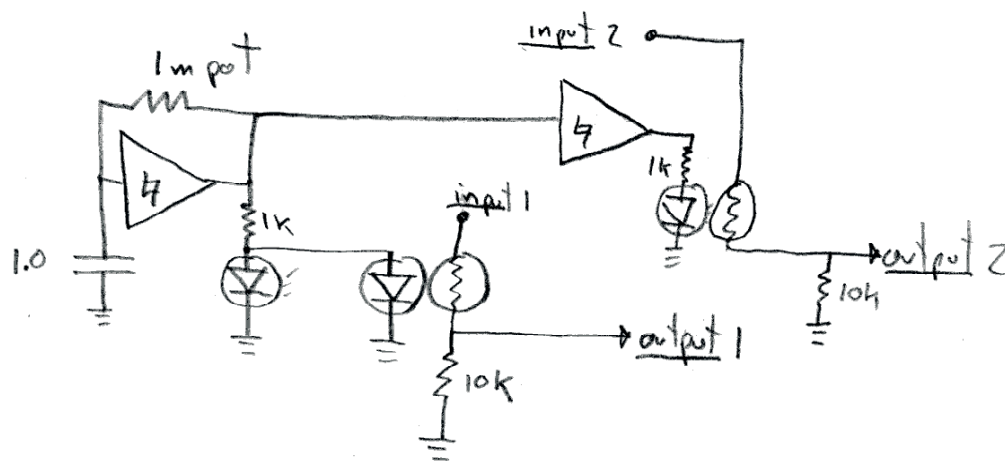


Now run audio through the photocell while you vary the speed of the oscillator - - you should hear the cassette/CD get chopped on and off as the LED blinks. As you speed up the oscillator into the audio range the on/off rhythm is replaced by a kind of a distorted, buzzing, sound. Experiment with different size capacitors until you find a good range of speeds.

If you want to see what's happening as well as hear it you can add a second LED as an indicator light (and we all love blinking lights,) as shown below



We can use a slight extension of this basic oscillator/LED/photocell design to create a variation on our flashlight-controlled panner/mixer. The circuit shown below uses one stage of the Hex Schmitt Trigger to make an low-frequency oscillator; a second stage simply inverts the clock signal from the first, so the two blinking lights are always out of phase -- note that one LED is always off when the other is on. Use a Y-cord or clip leads to connect a CD player to both circuit inputs and connect the two circuit outputs to two amplifiers; adjusting the oscillator frequency changes the panning speed -- Psycho-Pan-Scan! Hook up two different audio sources to the two circuit inputs, mix both circuit outputs to one amplifier input (Y-cords or clip leads), and the adjust the oscillator to cut between the two signals at different speeds -- Super Crab!



The basic concept of the blinking LED chopping audio can be extended from simple oscillators to more complicated control circuits. You can connect the various outputs of the Divider circuit shown in Chapter 21 to multiple LED/photocell gates to chop multiple sound sources in rhythmic patterns -- Hacking Dub! Or drive the LED with the output of the cascaded gated oscillators we made in Chapter 20 -- crazy rhythms! Just don't forget to include a resistor between each divider output and its LED.

As with the flashlight-in-the-closet experiment, these circuits do not produce a total mute when off -- some of your audio signal will continue to bleed through even when the LED is off. The amount of bleed will depend largely on the choice of photocell and how effectively they are shielded from outside light. The photocell should have as large a difference as possible between "on" and "off" resistance, but is best picked by ear, by substituting different choices into the circuit.

If the masses of electrical tape offend your sensibilities, you can put the photocell and LED inside an opaque soda straw, or the plastic sleeve of a mini plug or guitar plug -- you may want to put some BluTak or opaque silicon sealant into the ends of the tubes to prevent light leakage -- once again, be careful to avoid shorting the leads against one another. "Heat shrink tubing" is another tidy solution to light isolation: slide narrow pieces around the legs of the LED and photocell to insulate them from shorting against one another; slide a wider piece over the LED and cell; nuzzle the two components tightly together; apply heat from a hair-dryer to shrink the tubing tight around them. Voilá! A microelectronic "Bruit Secret."

This type of optical gating is much prized by audiophiles for its sonic purity. Only a few small, if confusing, additions stand between these simple circuits and some very expensive studio noise gates, compressors and limiters.

Other uses for Photocells

As you should grasp by now, the photocell is resistor like any other, but for its Nosferatu-like response to light (it shrinks from it.) You can substitute a photocell for most resistors and pots, and then modulate that resistance with a light -- either performed (flashlights, shadows, etc.) or automated (the blinking LEDs.) If you already have a toy or oscillator whose pitch is controlled by a photocell, press a blinking LED against the cell and hear what happens (similar to the toy cross-modulations we tried at the end of Chapter 15) -- controlling the pitch of an audio frequency oscillator with a blinking LED of a slower oscillator running at a suitable B.P.M yields a pleasingly Disco-tinged "syn-drum" swoop.

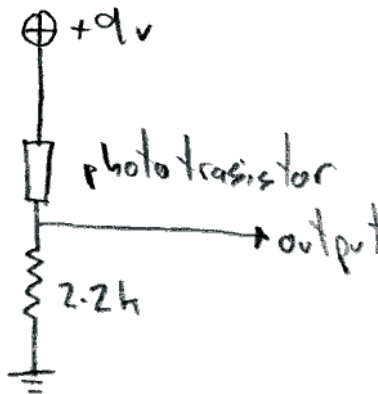
Sometimes, if its "on" resistance is low enough, a photocell can be substituted for a low-current switch. If your toy has switches to trigger sounds or enable functions, try paralleling a switch with the photocell: connect the two photocell legs to the points on the toy's circuit board that are joined when the switch is closed. Run the LED at a slow tempo and see if the chosen event is triggered

when the LED is on -- if so, you've got a simple solution to automating some of the toy's functions; if not, try another switch or another toy. Don't use the photocell as a substitute for the on/off switch of a circuit or between the circuit and its speaker, since it can't pass enough current.

Channel Surfing Music

In Chapter 3 we used coils to pick up the electromagnetic signals given off by various appliances and electronic devices. We can also eavesdrop on light signals of various kinds by using a specialized type of photocell. The "phototransistor" is the heart of any infra-red remote control receiver circuit, such as that in your TV. It detects the pulses of infra-red light sent by your remote control and converts them into a stream of on/offs, that are in turn translated into digital data by the microprocessor in the TV.

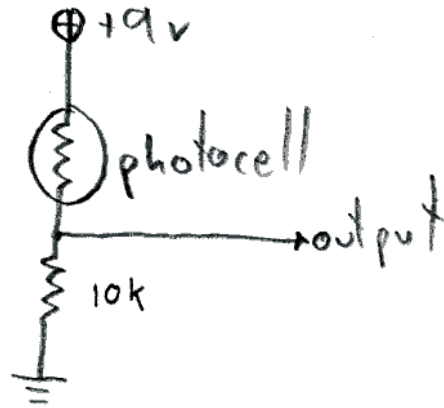
Aim a remote control at the simple circuit below (keep it close) and you should hear pulse trains as you press the buttons (remember to connect the shield of your jack to the circuit ground.) If not, reverse which leg of the phototransistor connects to +9 volts and which connects to the load resistor. The differences between one button and another may sound pretty subtle, even though the encoded data is different. Try different remotes -- the fundamental frequency and basic timbre may differ from one to another, but it's a minor difference, since they're all sending similar pulse trains.



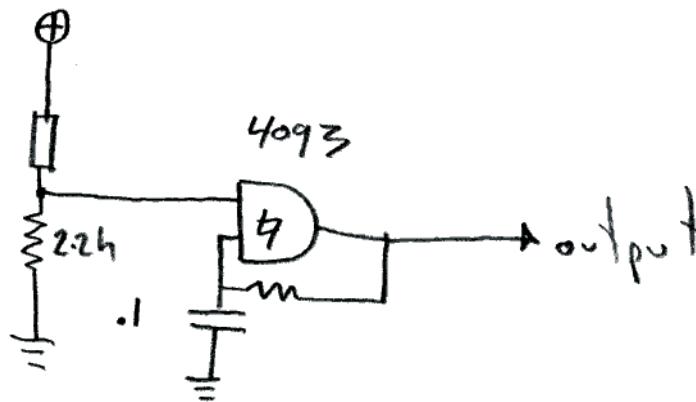
Since the lights on many electronic circuits look steady but are in fact "scanned" by the central processor unit, you can use this circuit to extract sound from almost any device with LEDs. Try it on bicycle flashers, toys with blinking lights, the front panels of studio gear, TV screens, computer monitors.

You can substitute an ordinary photocell for the phototransistor; you may need to increase the size of the load resistor from 2.2kOhm to 10kOhm or larger. Because photocells are sensitive to light across the spectrum (not just infra-red) you will get much more interference from the power grid AC frequency present in incandescent and fluorescent lighting (60hz in America, 50hz in Europe,) but

you may find this interesting rather than irritating, so try it. Stephen Vitiello has made beautiful recordings by placing this photocell circuit on the eyepiece of a telescope trained on traffic and pedestrians from his studio high atop the old World Trade Center in New York City – the flickering light/dark contrast translated movement into ominous yet poignant thunks.



If these pulsey or hummy sounds get too dull, try using the phototransistor or photocell circuit as the control input to the basic 4093 gateable oscillator circuit from the Chapter 20. If you also put a photocell in place for the oscillator frequency control resistor (i.e., instead of a pot) you get a pretty weird “multi-phase” light-to-sound converter.

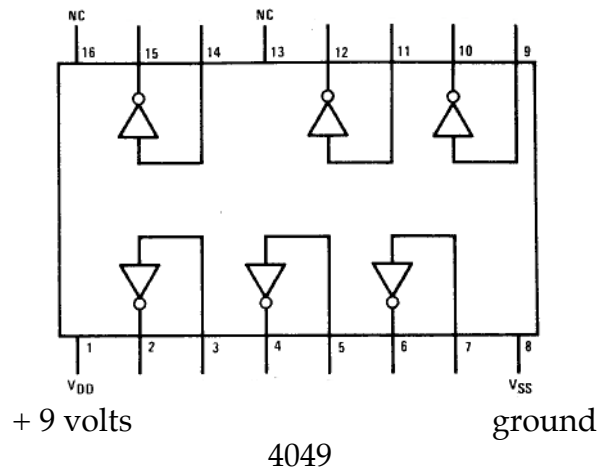


Chapter 23: Amplification & Distortion

You will need:

- Something to amplify: a guitar, a cassette or CD player, etc.
- A breadboard.
- 4049 CMOS Hex Inverter.
- Assorted resistors, capacitors & pots.
- Some solid hookup wire.
- Assorted jacks and plugs.
- A 9 volt battery and connector.
- An amplifier.
- Hand tools.

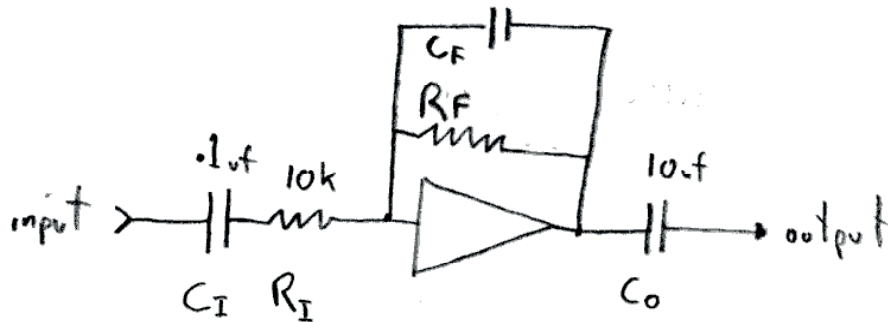
In addition to turning sounds on and off, there are many occasions on which we just want to make something louder (see Rule #3 of the Avant Garde.) Loudness comes in different flavors, and a little experimenting with the 4049 Hex Inverter demonstrates several of them. This is another example of a digital logic chip being “mis-used” for analog purposes. Its internal configuration and pinout are shown below. Note that the 4049 is a rare exception to the general rule of corner pins for power hookup in CMOS chips (as in the Hex Schmitt Trigger, the NAND Gate and the Divider circuit we used in previous chapters) If you are a practicing dyslexic, now is the time to hold onto your hat: +9 volts connects to pin 1 (marked “V_{DD}” on the schematic,) while the ground connects to pin 8 as expected (“V_{SS}”). The “NC” by pins 13 and 16 indicates “no connection.” IMPORTANT: do not substitute the 74C14 Hex Schmitt Trigger for the 4049 -- it is an inverter, but has a different internal circuit design that won’t work properly in these configurations.



Preamplifier

Hook up the circuit shown below. This general purpose amplifier circuit has six basic components:

- 1) The CMOS Inverter amplification stage. As with our oscillator circuits, the six sections of the 4049 chip are interchangeable.
- 2) The input resistor, R_I , generally around 10kOhms.
- 3) The feedback resistor, R_F , larger than R_I , can be a pot for variable gain.
- 4) The input capacitor, C_I , generally around 0.1uf.
- 5) The feedback capacitor, C_F , usually omitted or very small (10-100pF.)
- 6) The output capacitor, C_O , always around 10uF.



4049

The gain -- how much the circuit amplifies the incoming signal -- is determined by the ratio of R_F/R_I . So if $R_I=10\text{k}\Omega$ and $R_F=100\text{k}\Omega$, the gain is 10, which means that any signal you plug into the circuit comes out 10 times louder. If $R_I=10\text{k}\Omega$ and $R_F=10\text{m}\Omega$ the gain is 1,000, which makes it much MUCH louder.

The input and output capacitors (C_I & C_O) block the DC voltage present in the circuit from the reaching whatever you're plugging into. They usually don't affect the sound much (see "Tone Control" below) but are necessary for protection. Likewise, the feedback capacitor (C_F) is usually omitted unless one needs tone control or, when amplifying a lot ($> 100\times$) a small capacitor (c. 10-100PF) prevents the circuit from oscillating or getting very noisy.

By substituting different values for R_F , or using a pot instead of a fixed resistor, you can make a convenient preamplifier for a contact microphone, coil. electric guitar, acoustic microphone, etc. To hear the subtler effects of component substitutions you may need to listen through larger speakers than the mini amplifier.

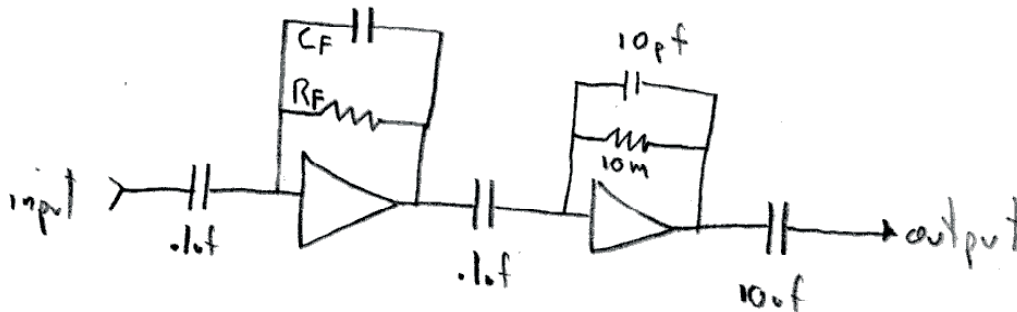
Tone Control

The frequency response of this circuit is determined by the feedback capacitor (C_F) and input capacitor (C_I). If C_F is not used, the circuit is pretty much flat in frequency response. If a small capacitor is used, say 100pF, you will notice a slight rolloff of high frequencies. If you make C_F large, around .01uf, you will

cut a lot of highs and the sound will be very bassy. In contrast, a large value of C_I (0.1 μ F) has almost no effect on the tone, but a very small one (100pF or so) will cause much of the bass to disappear and the sound will be very tinny. This simple equalizer is affected by its gain as well as the values of the capacitors -- for simple tone control purposes, it is best to have unity gain, i.e., use the same value for R_I and R_F . At unity gain ($R_I=R_F=100k$), with a moderate capacitor in C_F (0.01 μ F), this circuit can roll off the high edge of a square wave oscillator (like those we've built), making it sound smoother, more like a triangle wave.

Distortion

Amplifier sections can also be cascaded to produce greater gain, i.e., 2 sections of a gain of 10 = gain of 100.. But this simple circuit is not "perfect" and by adding a lot of gain in series we introduce distortion, the guitarist's friend. The circuit below, based on a venerable design by Craig Anderton (the godfather of musical hacking,) is simple, versatile and good sounding. By varying the gain (via R_F) and substituting different capacitors for C_F one can produce a wide range of distortion timbres. For R_F try a 100k resistor in series with a 5 meg pot for variable distortion



As Robert Poss says:

Rule #20: Distortion is Truth. (Poss's law)

But truth nonetheless comes in many flavors -- if you are interested in distortion you should spend some time substituting different values of resistors and capacitors in this circuit until you find perfection.

Unlike more sophisticated equalizers and tone controls, the frequency response in both the preamplifier and distortion circuits can only be varied in steps, by substituting capacitor values, and not with a continuous turn of a pot. But if you want more control you can incorporate a multi-position switch for this purpose (switching different capacitors in and out of the circuit) when you go to solder up.

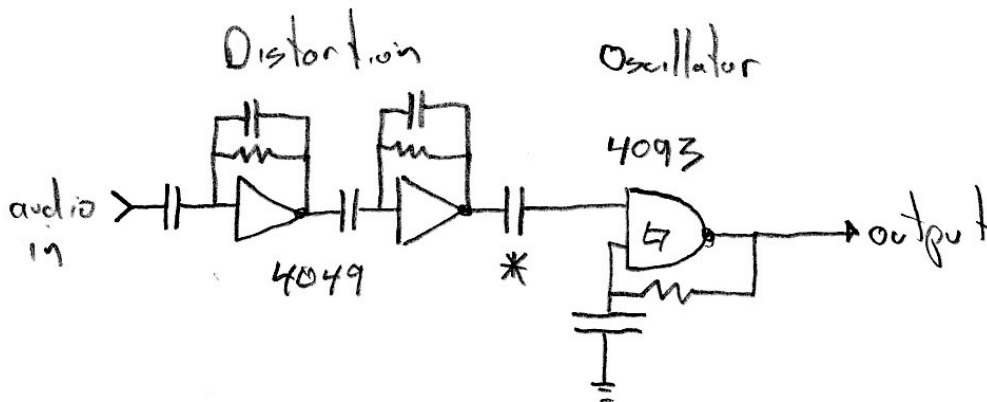
Chapter 24: Analog to Digital Conversion, Sort of

You will need:

- Something to amplify: a guitar, a cassette or CD player, etc.
- A breadboard.
- Gain & distortion circuits from the previous chapter.
- Quad NAND Gate Schmitt Trigger (#4093).
- Binary Counter/Divider (#4040).
- Assorted resistors, capacitors & pots.
- Some solid hookup wire.
- Assorted jacks and plugs.
- A 9 volt battery and connector.
- An amplifier.
- Hand tools.

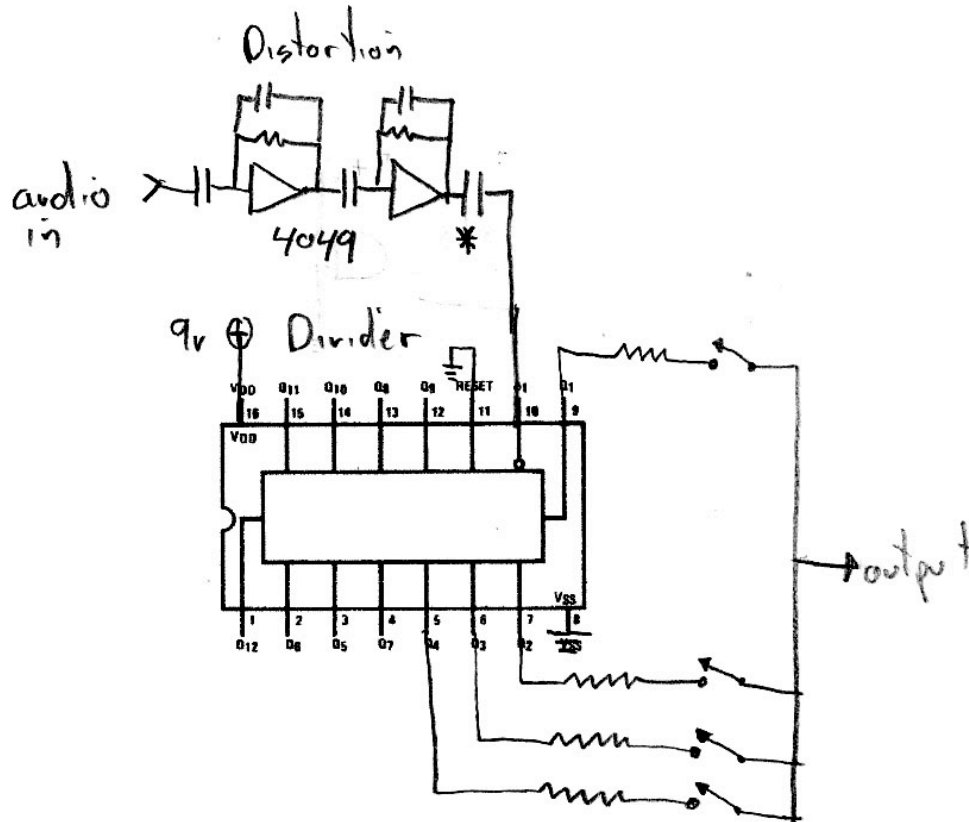
The gain and distortion circuits in the previous chapter are useful on their own -- to boost a low level signal or make an electric guitar sound legitimate -- but also in conjunction with other circuits. With enough gain and distortion, any analog audio signal starts to look like a digital square wave (like that put out by our oscillators) and can be easily interfaced to certain digital circuitry.

The circuit shown below is a variation on the gated oscillator in Chapter 20. When the oscillator runs at low speeds (1uF timing capacitor) it effectively "chops" the output of the distortion circuit on and off; at higher speeds (0.01 - 0.1uF capacitor) it interacts with the distorted signal to create a "ring-modulator"-type effect.



"The Fuzzy Dicer"

Substitute the output of the distortion circuit for the clock/oscillator in the divider circuit we used in Chapter 21, and the divisor outputs become subharmonics of whatever you play into it -- a "rocktave box," to use the industry parlance:



"The Low Rider"

You can use switches to select different subharmonics or make a fixed mix.

With these designs we are getting into a very wooly area of circuit conglomeration. If you have trouble getting these circuits to work consistently, try any of these possible fixes:

- 1) Omit the distortion output capacitor (marked with the asterisk.)
- 2) Connect a resistor in the range of 10kOhm-100kOhm between the oscillator control input (Fuzzy Dicer) or divider clock input (Low Rider) and either the +9 volt supply or the ground bus. Experiment with different values for the resistor, and whether it connects to + or ground. This can help keep the circuit quiet in the absence of an input signal to modulate (i.e., when you're not playing the guitar.)

3) Put a Schmitt Trigger Inverter stage (from a 74C14 or 4093) between the distortion output and the digital circuit input. This can clean up the input signal so the circuit will track the fundamental better, rather than the noisy higher overtones. If you use a NAND gate from a 4093 as a buffer, connect the output of the distortion circuit to one input of the gate and tie the other one to + 9 volts, or connect the output of the distortion circuit to both NAND inputs.

4) If the circuits still seem very noisy and tend to oscillate on their own, put larger capacitors in the feedback loops of the distortion circuit (Cf). This will roll off the higher frequencies and send the subsequent circuits a signal that emphasizes the fundamental.

Having previously extolled the virtues of random circuit variation, I encourage you to pursue free-style interconnection of “real world” audio signals with your circuits – only please observe our “no-AC power” safety practice.

Part V: Looking

Chapter 25: Video Music/Music Video

You will need:

- A video camera or camcorder.
- A video monitor.
- Photocell controllable oscillators.
- A cheap, hackable CCD video camera circuit board (see text.)
- An audio amplifier.

Various ingenious software tools exist for translating pictorial data into sound: Soundhack's "Open Anything" turns any digital file into a sound file (i.e., a spreadsheet to-hit-record converter), STEIM's "Big Eye" and Max's "Jitter" track moving objects in a video image and extract MIDI or audio information. But here are two simple hardware approaches to the same task that bypass the computer.

"Cloud Music" Revisited

In the 1970s David Behrman and Bob Watts collaborated on "Cloud Music," a video music project that translated live images of clouds drifting across the sky into electronic sound. Photocells glued to the screen of the video monitor controlled the pitch of oscillators in response to the fluctuations in light level that occurred as clouds passed in front of the camera. In 1999 I saw two young Czech artists do a cheap and noisy variation on this piece with a camera pointed out the window at a country road. Yasunao Tone taped photocells to a screen and projected film for his "Molecular Music."

Try it. Wire up a few photocell-controlled oscillators (Chapter 18.) Place the sensitive side of a photocell against the screen of a video monitor and use a thin strip of tape across the back to hold it in place; repeat for each photocell, distributing them across the screen. Hook up a camera or play back a tape. Action! Instant soundtrack! You can do this on a projection screen as well.

You can also use the photocell gating/panning/mixing circuits from Chapter 22 to adjust the loudness of oscillators or other audio signals (CD, tape, microphone, etc.) in response to fluctuations in the image.

Frame Rate Music

Connect the analog video output of a camera to an amplifier and speaker -- that's right, video output to audio input. Pan the camera around the room as you listen. You should hear a steady drone whose overtones fluctuate in response to the image content and brightness. The fundamental pitch is a function of the video frame rate (NTSC or PAL specific,) while the overtone balance directly represents the image data, line by line. Nice if you like drones. Try aiming the

camera through a rotating fan; vary the fan speed and you should be able to hear interference patterns between the frame rate and the fan speed. Focus on a white card off-center on a black turntable mat, and switch between 33 and 45. Aim an IR remote at the camera (most video cameras detect infrared light and show it as hot white.)

The frame rate is fixed, and normally doesn't budge until you move between NTSC and PAL. But if you invest in a cheap black and white CCD camera circuit board (available from most electronic surplus mail-order places for less than US\$25-) you can experiment with varying the clock frequency by a laying of hands or replacing the clock crystal with a variable oscillator (as discussed in Chapter 21.) Split the camera output between a video monitor and amplifier, so you can see as well as hear the affect of your hack. Sometimes lifting one leg of the camera's crystal time base makes it just unstable enough to produce a coherent image when left alone, but jitter like crazy when touched. You may be able to make an oscillator whose pitch is controlled by a pot, photocell, etc., and whose timbre is a function of what it sees.

USE A BATTERY POWERED VIDEO MONITOR AND AMPLIFIER IF AT ALL POSSIBLE, TO MINIMIZE THE RISK OF ELECTROCUTION. APPROACH THIS EXPERIMENT WITH EXTREME CAUTION IF THIS IS NOT POSSIBLE.

The hacked camera will not generate a stable sync signal when tickled. Most video monitors will continue to display scratchy video in the absence of a stable sync, but many video projectors are too "smart": they will interpret intermittent sync as a sign that there is no video signal at all, and will display that irritating blue screen with the legend "no video input." Providing a proper sync under scratch video is beyond the scope of this book, sorry -- use an old TV instead.

Chapter 26: LCD Art

You will need:

- A toy with an LCD screen.
- Some test leads.
- 9 volt battery and battery hook-up clip.
- Hookup wire.
- A basic oscillator circuit from Chapter 18 or 20.
- Hand tools, soldering iron and electrical tape.

A lot of handheld toys and games incorporate small LCD screens. Find the contact points between the circuit board and the screen and try listening to them -- sometime they produce very nice, rich chords. But here are a couple of purely visual hacks, natural bi-products of your toy experiments.

In many cases the LCD only contributes “foreground action” to the game; often a simple printed cardboard sheet provides the backdrop. If you feel creative with a pen and paper you can often transform the game with an alternative background of your own wicked imagination -- what would Mr. Potato-Head’s nose look like on a.....

Moreover, when the screen is removed from the circuit its visual elements can sometimes be turned on and off with simple connections of voltages, either directly from a battery or from an oscillator. Start by tinning the tips of the red and black power lines from a 9 volt battery clip, so they have a stiff, sharp points -- you can also solder sewing pins to the wires for stronger, sharper contacts. Locate the connections to the LCD -- usually these are tiny points embedded in a rubber-like strip at either end of the glass. Press the + lead against one connection and the ground wire to another. Keep trying different pairs of points while watching the screen -- at some point an LCD element should become visible. Make a note of the location of the contacts and keep exploring. If you find a set of images that you like you can find a way to make the connections permanent -- usually by wedging and taping wires or pins against the contact strips.

You can animate the images by using the outputs of oscillators, instead of battery leads, to drive the LCD elements. Take one lead from the ground of an oscillator’s circuit running at a low speed (tick-tock range) and one from the oscillators output. Find good connections as you did above, but now you can adjust the oscillator speed to cause the LCD elements to turn on and off, creating your own animation.

The small LCD screens bear a certain resemblance to old Daguerreotypes, and have a certain charm as modern miniatures. The screens can be combined with new backdrops (as above) or left in their rather ghostly, mostly transparent state as tiny digital stained glass windows.

The current consumption of the LCD device and a low frequency oscillator is so small that you can leave the object running on a 9 volt battery for weeks before it runs down. You could even power the whole thing with a small solar panel. If you go shopping for the latter, look for one that puts out anywhere from 3 to 12 volts, with a current capacity of 5 milliamps or so. Some circuit can even be powered by a potato battery (dust off those childhood science fair notes.....)

Part VI: Finishing

Chapter 27: Mixers, Matrices and Processing

You will need:

- An assortment of sound-making circuits, found or made.
- A few pots of the same value (c. 10kOhm - 100kOhm).
- Assorted resistors.
- Some solid and stranded hookup wire.
- Assorted jacks and plugs.
- An amplifier or two.
- Soldering iron, solder and hand tools.

Mixers

Now that your collection of noisemakers is growing, a simple mixer might prove useful. Here is a completely passive circuit -- it uses no batteries, needs no on/off switch or circuit board. Even if you already have a "real" mixer, this is a very convenient way to expand the number of inputs.

The basic schematic is shown in Figure 1. The signal (i.e., tip) of each input jack is connected directly to one ear of a pot. The center tap on the pot (nose?) is soldered to a 10kOhm "summing" resistor. The non-pot ends of all the summing resistors are tied together and connected to the signal/tip of the output jack. The ground/shields of all the jacks are connected together and soldered to the other ear of all the pots -- this common bus is indicated by the ground sign. Figure 2 shows which ear to use for input and which for ground if you want a traditional mixer feel (ie, turning the knob clockwise raises the level.) You can expand this circuit for any number of inputs by simply adding another jack, pot and resistor for each additional signal.

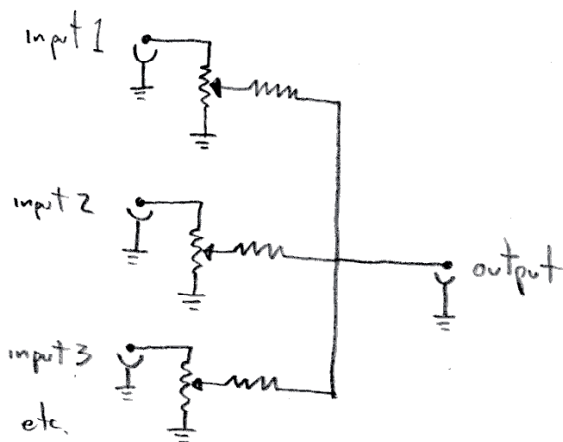


Figure 1

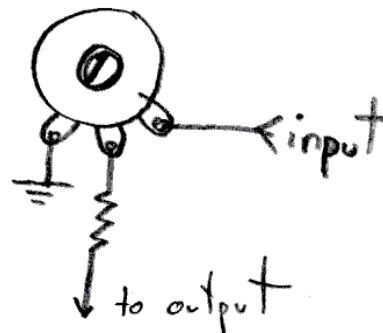


Figure 2

By adding some switches and another output jack you can make a stereo version of the same circuit (Figure 3.) Each summing resistor is connected to the switch's C; NO is connected to one output jack, NC to the other; throwing the switch swaps the signal between the left to right outputs.

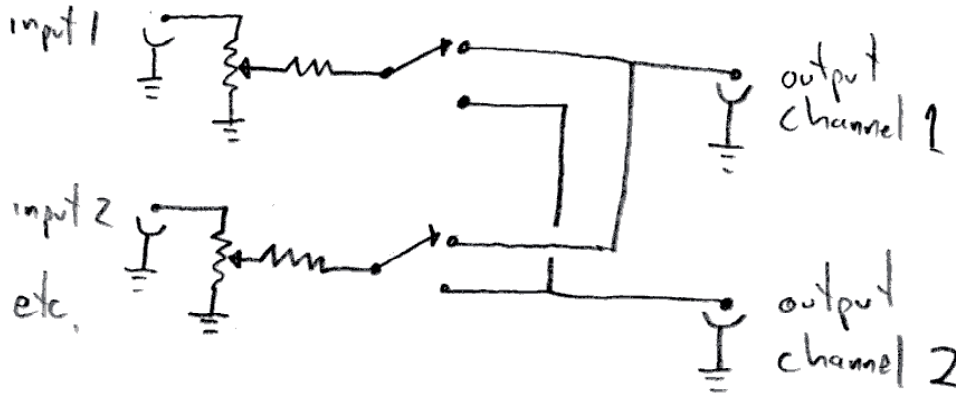


Figure 3

Because this circuit is completely passive it is also bi-directional -- like the photocell circuits in Chapter 22. If you plug a CD player into the output jack of the circuit in Figure 1 you can use the pots to send it to any number of the "input" jacks, which in this case become the outputs -- useful for distributing a signal to a number of different amplifiers or signal processors. Sound confusing? Just try it.

The pots can be of any value between 10-100kOhm. It's best if all the pots are the same. Pots are specified as "linear taper" (what we've been using so far) and "audio taper", which are optimized for adjusting audio level. You may find that the curve of volume change sounds smoother with an audio taper pot. If you find yourself mixing a lot of stereo signals (like the outputs of CD players) you may want to use stereo pots, which let you trim two signals together from a single knob. You can use ordinary rotary pots for these circuits, or slide pots (easy to find through on-line sources), which make your circuit look more like a "real" mixer, but be warned:

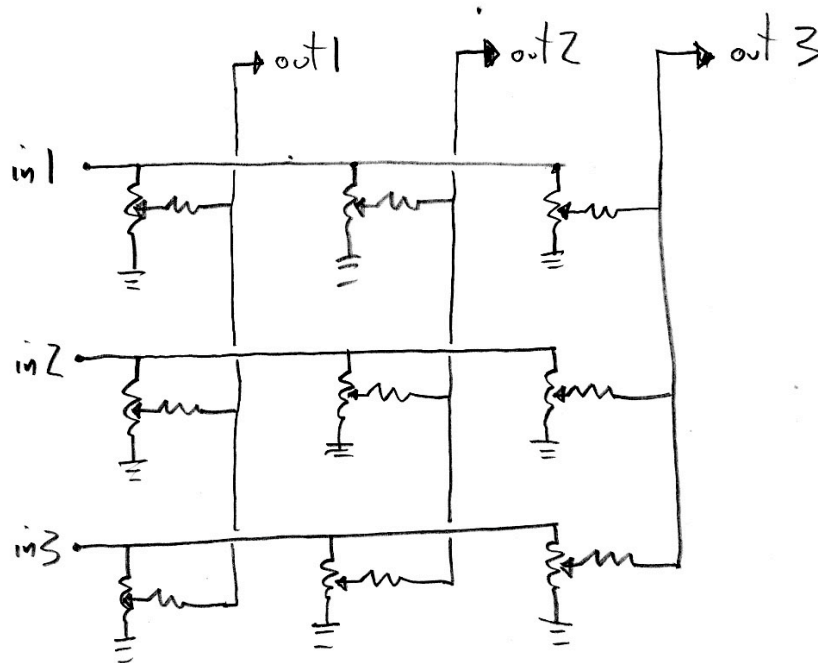
Rule #21: It is easier to drill round holes than slots.

Because it contains no amplifiers or other gain circuits, this circuit is best for mixing signals of more or less similar levels (ie, CD and tape players, oscillators), and is not so useful with low-level signals like microphones. What it lacks in gain it makes up for in versatility and audio quality, but you can incorporate preamplifier circuits such as those in Chapter 23 if you get ambitious -- insert them between the input jack and the pot.

Matrices

David Tudor, one of the pioneers in the field of live electronic music, used matrices of relatively simple or common circuits to produce sound of great richness and variation. Instead of simply mixing a handful of sound sources down to a stereo signal, Tudor built up arrays of modules with multiple feedback paths and output channels. The recent rise of the “no input mixing” school of internal machine feedback has exposed a new generation of musicians and listeners to the possibilities of matrix feedback.

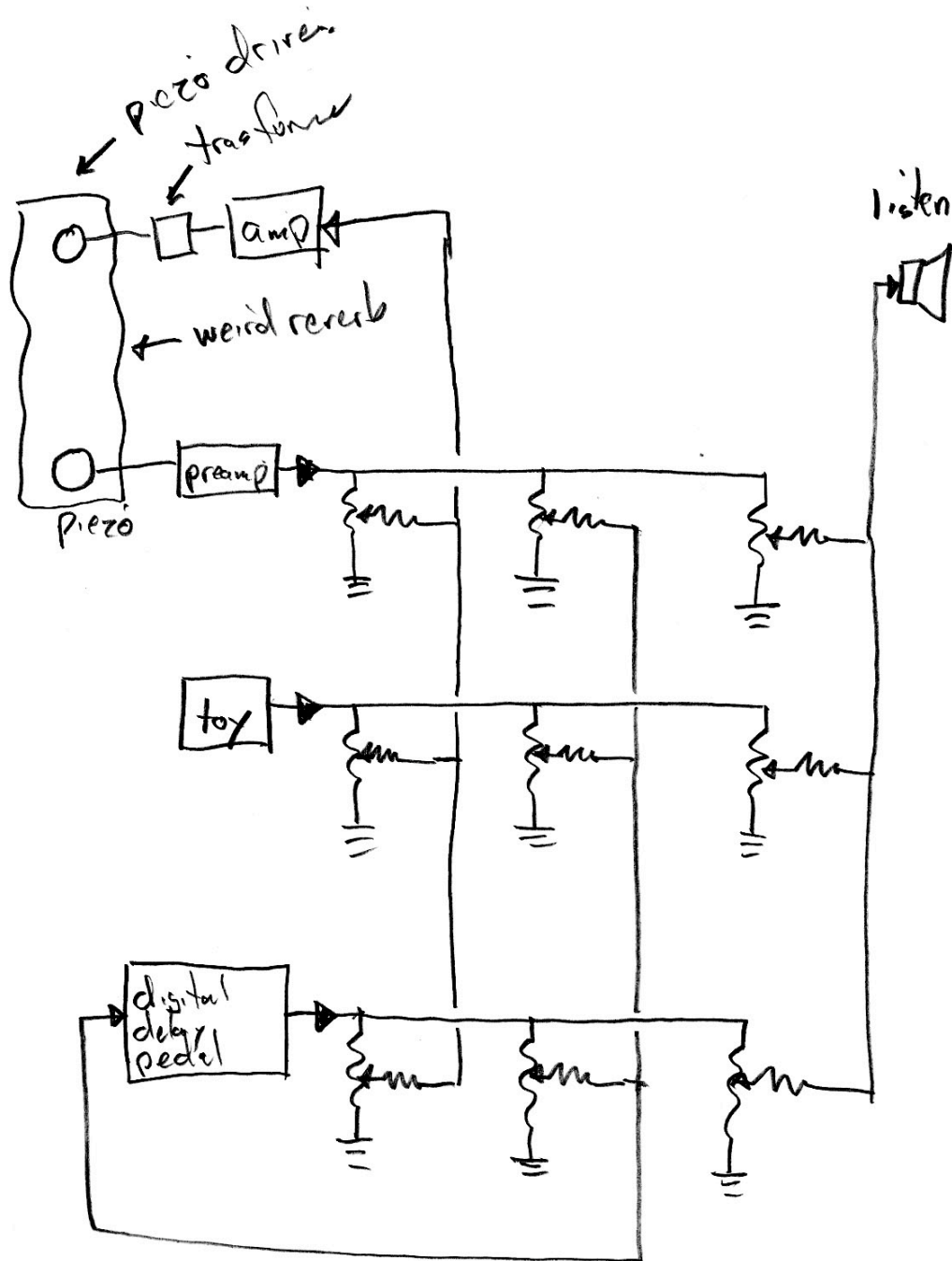
You can set-up matrices with nothing more than patchcords and clip leads, but the 3 x 3 matrix mixer shown below lets you adjust levels more easily.



You can expand this circuit with as many pots as you can afford.

Connect a few circuits, including both sound generating circuits, such as your oscillators or toys, and some processing circuits, such as a photocell panner, a fuzztone or an echo pedal. Send one output of the matrix to an amplifier for listening, and the others can be sent to the inputs of your circuits. By adjusting the levels of the various pots you can create a pretty straightforward signal path (toy through fuzz to speaker) or a more devious one (toy through fuzz to speaker, fuzz also to delay which goes both to speaker and back into its own input.)

The Piezo-driver pseudo-reverbs we discussed in Chapter 8 work very well in these configurations. Some of the most unassuming rock pedals reveal astonishing musicality when placed in feedback loops. Incorporated into matrices, time based effects (such as delays and flangers) can contribute a wonderful instability that transforms a table of electronics into a richly challenging performance instrument.

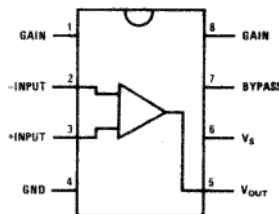


Chapter 28: A Little Power Amplifier

You will need:

- Something to amplify: a guitar, a cassette or CD player, etc.
- A breadboard.
- Audio Power Amplifier chip, LM386.
- Assorted resistors, capacitors & pots.
- Assorted jacks and plugs.
- A small speaker.
- Some solid hookup wire.
- A 9 volt battery and connector.
- Hand tools.

Whether in pursuit of a self-contained electronic instrument or some form of sound sculpture, one day you will tire of choosing between the putty-colored Radio Shack mini-amplifier and a bulkier, more expensive (and potentially more dangerous) external amplifier and speaker. If you wish to drive a speaker directly with the output of one of your circuits, consider the lowly LM386. At less than US\$1.00 retail, this chip, combined with a few other components in a very simple configuration, makes a cheap but decent low-power audio amplifier. It is the heart of the aforementioned mini-amp, and -- once soldered up -- can be substituted accordingly.



LM386

The basic configuration (Figure 2) gives a gain of 20. By adding a 10 μ F capacitor between pins 1 and 8 the gain rises to 200 (Figure 3.) The 0.05 μ F capacitor and 10 Ohm resistor shown at pin 5, and the .1 μ F "bypass" capacitor at pin 7 are optional parts, to be added if the circuit oscillates and whines by itself. When you go to solder up this circuit you may have to rearrange the components a few times to avoid oscillation -- this amplifier is more stable than many, but audio power amps are tricky sometime. Both circuit below include a pot for input volume control. You'll want to add a power switch as well, or disconnect the battery from its clip when not in use.

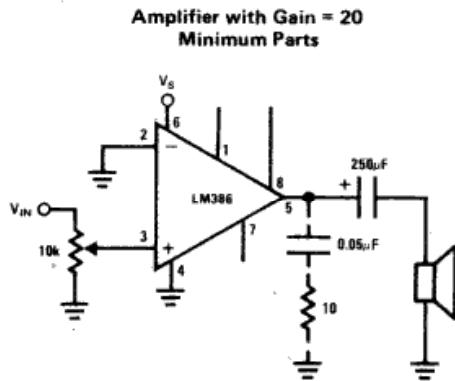


Figure 2

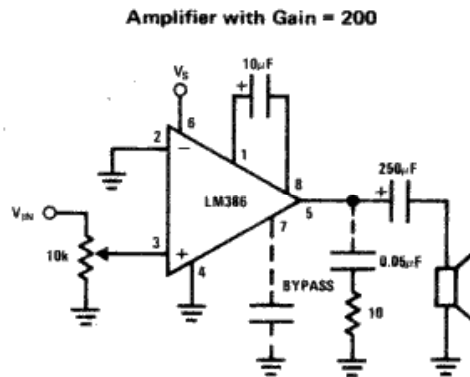


Figure 3

This circuit puts out about 1/4 watt of audio power, and can be used to drive small speakers or headphones. It runs nicely off a 9 volt battery or a set of 4 AA batteries. Via the backwards transformer arrangement shown in Chapter 8 it can also drive a Piezo disk at very high sound levels. This amplifier can drive a small motor (such as the vibrating motors from cell phones and pagers, also discussed in Chapter 8) or a low-power solenoid, instead of a speaker, to make a driver that, with a more extended low frequency range, is a kind of subwoofer complement to the Piezo.

There are numerous similar amplifier chips on the market, some capable of putting out many Watts of power, but most require a substantial “plug into the wall” power supply. The LM386 is a good “starter amp.”

Chapter 29: Power Supplies

You will need:

- A DC “Wall Wart” plug in power supply.
- A diode, 1N4004 or equivalent.
- Some capacitors, 0.1 and 100uf or so.
- A 9 volt regulator (7809.)
- Hand tools, test meter, soldering iron.

Oh dear, I feel like a father enrolling his son in a driver education class or explaining safe sex: I wish we could stop here, but one day you will leave home and must be prepared for the big world. This is truly the last chapter of this book.

Although the Second Rule of Hacking barred you from touching an AC power cord, the time will come when batteries will not suffice. You will tire of the cost of replacing them, and the accompanying environmental guilt (although these concerns can be minimized by rechargeable batteries), or you will build a circuit that draws so much current that it drains the battery flat before you can say “Union Carbide.” As a stop-gap solution to exposing your hands (and heart) to lethal voltages, you can advance to the ubiquitous “wall-wart” power supply that power so many domestic appliances these days.

The power grid in America delivers to your outlet a sine wave that fluctuates between 0 and 120 volts 60 times per second (in Europe, 240 volts at 50 cycles per second.) If you plugged a very strong speaker directly into the wall (not recommended, by the way) you would hear a loud, low pitch around 2 octaves below middle C. The wall-wart consists of a transformer encased in plastic and wired directly to an AC plug. The transformer takes the 120 volts of alternating current (AC) and steps it down to the non-lethal range suitable for powering electronic circuitry. The advantage of the wall wart supply is that the lethal voltages remain within the plastic lump, and the ends of the wires present a mild, safe, very battery-like voltage. The traditional power supply found inside your TV or guitar amplifier, on the other hand, brings the wall voltage right into the chassis, where it can easily be touched (ouch!) as you tinker. So if you must use a power supply, let the wall-wart be your condom.

There are two kinds of wall-wart. An AC wall-wart consists solely of this step-down transformer; it puts out a low voltage 60 or 50hz signal, which must be further conditioned to make it useful for circuitry. A DC wall-wart contains the additional circuitry (a few diodes and a big capacitor, to be specific) required to smooth out the fluctuating signal into a DC voltage that more closely resembles the output of a battery.

The wall-wart should be marked with the following information:

- The primary voltage, i.e., 120 (US) or 240 (Europe) volts AC (or VAC.) We need a 120 volt primary voltage.
- The secondary voltage, i.e., something in the range of 3-24 volts. We need a secondary voltage in the range of 12-18 volts.
- Whether it has an AC or DC output. We need DC.
- The amount of power the transformer can provide, usually measured in watts (W), amps (A or MA) or volt-amps (VA). We want a transformer that puts out a minimum of 100 milliamps (ma), which may be indicated as 0.1 amps or 5-10 watts.

For example, a wall-wart might say “120vac input, 12vdc output, 200 ma). “ You can find wall-warts everywhere, with a zillion slightly different types of connectors, often very cheaply. Some offer switchable output voltages and/or interchangeable connectors.

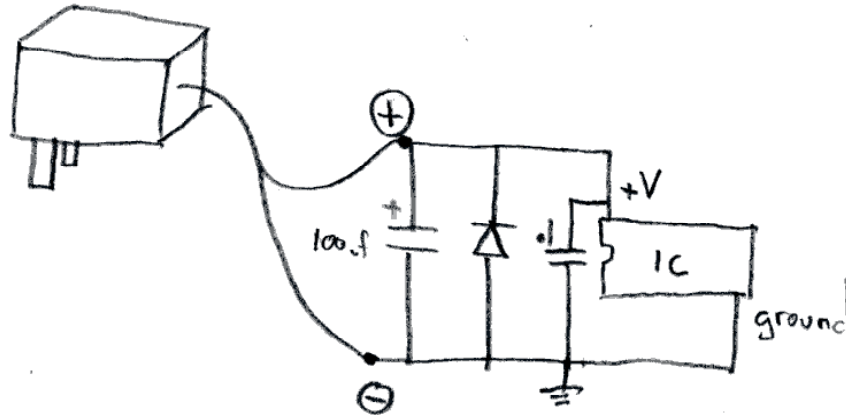
When adapting a battery-powered circuit to a wall-wart you must observe two critical factors:

- The voltage must be within two limits (i.e., greater than 12 volts but less than 18 volts), but the current can be anything higher than the minimum need to power the circuit (i.e., a circuit requiring 20 ma can be powered by a supply producing 20 ma, 100 ma or 1000 ma.)
- Note the proper polarity when connecting the wall-wart to the circuit board – i.e., the + to where the battery’s + was, - to the -.

Sometimes the wall-wart will indicate which wire or which part of the connector is + and which is -, but it is always safer to test using a multi-meter. Set the meter to measure “DC Voltage.” One probe plugs into the meter’s “ground” or “-” input, while the other connects to something probably marked “voltage” in red. Touch one probe to the end of one of the power supply’s wires or one part of the connector, and the other to the other. If the meter reads out a voltage with no prefix (i.e., “13.6”), then the wire/connector touching the ground probe is the - output, and the other is the +. But if the meter puts a “-” before the number (“-13.6”) you know that the connections are reversed, that the wire touching the minus probe of the meter is actually the + output and the other is -. Confused? Try this test on a battery.

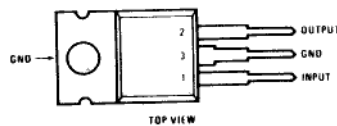
Once you figure out which wire is which, mark them carefully!

To hook up the wall-wart to your circuit you can either find a matching connector to whatever is attached to the wall-wart’s cord, or you can cut off the connector and solder the wires directly to the board. Double check the polarity before you plug it in! As a safety precaution against frying your circuit with a backwards power supply you can connect a diode across the power supply as shown:



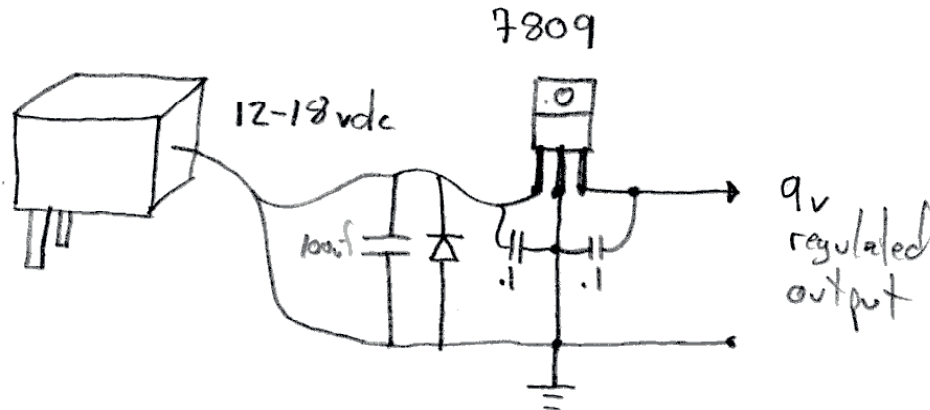
Note that cheap wall-warts will always have some AC ripple in their voltage output. And that a circuit powered from such a supply may “hum” slightly. Until you get good at designing or finding better power supplies a battery will usually sound cleaner. One easy fix that sometimes helps is to add a big capacitor, say between 100-100µF, between + and - supply on your circuit board (Figure 1.) Big capacitors, called electrolytic capacitors, have polarity, just like a battery, which is marked on the body. Make sure you connect - to -, + to +. Placing an additional 0.1µF capacitor between the + and ground supply pins of a chip also helps lower noise and reduce “crosstalk” between different parts of your circuit.

Finally, you should add a “Regulator” chip, as shown below:



7809 Regulator

This chip filters out the last of the ripple and sets the voltage to a precise level, which you specify when you select the chip. A “7809” will put out 9 volts, just like the battery we’ve been using for our circuits. It needs an input voltage of at least 3 volts more than it puts out (i.e., 12 volts), so measure the output of your wall wart with your meter to make sure it is high enough. You can get regulators for a wide range of voltages, should you need them for future projects, but these basic design principles remain the same. Bolt the regulator tab to a piece of metal to help keep it cool.



The regulator chip not only keeps the supply voltage free of spurious hum and noise, but it lets you be very sure of the exact voltage being used to power your circuit. A simple measurement with a voltmeter will show that even though a wall-wart might be marked "12 volts DC" in bright white letters, it might put out anything from 10 to 20 volts. The CMOS chips used in most of our circuits were chosen in part for their forgiving nature, but they have limits --- upper limits: they can run on power supplies from 3 volts to about 18 volts, but above 18 volts they can explode quite dramatically. The 9 volt battery we've been using sits comfortably between these two extremes, and a 9 volt regulator substitutes admirably for that battery. But if you choose to use a wall wart-based supply that is merely filtered ((by capacitors) and not regulated, always measure the real output voltage before connecting your circuit.

Rule #22: Never trust the writing on the wall-wart.

Appendices

Appendix 1: Resources

A few years ago I walked into the office of a technically-minded colleague at my school to ask for a reference manual in which I could look up the pinout and schematic of an unfamiliar chip. Clamping a large, Chicago-style hand to my shoulder, Ed replied, “Nic, I could loan you the book, but let me ask you this: give a man a fish and he’s fed for one day, teach him how to fish and he.....?” “...wastes all his time fishing when he should be helping out around the house?” I continued. “No,” sighed a disappointed Ed. “Type the part number into Google and you will find the data sheet in the first hit,” he muttered as he closed the door. The point I missed in his parable: it’s never been easier to hack.

In the early days of home-made electronic music, schematics and suggestions were passed from hand to hand like samizdat books in the Soviet Union, or cures for colicky babies. Then a few dumbed-down circuits crawled out of engineering journals into music magazines, and one or two books appeared, written in something like English rather than Technese. Finally Tim Berners-Lee birthed the web and a hundred fuzztones burst into flower. Anything you want to know is out there; all you need to do is find it and understand it. Finding it is easy, even though understanding it may take some work -- you may have to teach yourself a bit more of the vocabulary of electronics than was demanded in this book. As Ed suggested, type part number or name of a component will usually direct a search engine to a manufacturer’s data sheet -- the information you’ll need to work with it. Enter a descriptive phrase, such as “Phase Shifter’+schematic”, and you’ll be directed to any of a number of wacky websites hosted by people who seem to have nothing better to do than compile vast collections of circuit diagrams and links to like-minded fanatics.

I would be remiss if I did not mention here the fabulous Reed Ghazala, the founding father of “Circuit Bending.” A hacker since childhood, Reed estimates that he has taught millions of students through his articles for Bart Hopkins’ “Experimental Music Instruments” journal and, since 2000, his web site: www.anti-theory.com. Go there right now!

PDF data sheets can be downloaded as you need them, but thick data books are still available from the major chip manufacturers -- they’re expensive, but worth it if you get in deep. There are a few books that can help fill in theoretical gaps between the one you are reading now and the more engineer-oriented data you will find on the web. Walter Jung’s [OpAmp Cookbook](#) and Don Lancaster’s [CMOS Cookbook](#) are excellent, understandable references. Craig Anderton, the grandfather of electronic hacking for musicians, published [Electronic Projects for Musicians](#) back in 1980s and it’s still an excellent guide to basic musical circuitry and general principles of design and construction.

What holds true for information also goes for material resources. Although Canal Street no longer teems with the warrens of weird electronic and

mechanical surplus shops that enthralled me from childhood, the web has become the medina of the misplaced and unwanted. Add “+price” to the search field after anything you desire -- plugs, Piezo disks, tape heads, tilt-switches -- and you’ll soon find a place to buy it. Since you’re not mass-manufacturing missiles or airbags, you’ll need to find a source that will sell to the common man (or woman.) For ICs, resistors, capacitors, and other small components a straightforward electronic retailer is probably the best bet -- as of the time of writing these are a few good sources that stock a wide range of parts:

Digikey: www.digikey.com

Jameco: www.jameco.com

But for hackable gizmos, used equipment, pots, jacks, boxes and inspiration you should try the “surplus” outlets. Here are a few reputable sources that have been around for a while selling cool stuff:

All Electronics: www.allelectronics.com

Marlin P. Jones: www.mpja.com

Electronic Goldmine: www.goldmine-elec.com

Paia is a longstanding manufacturer of kits for building everything from modular synthesizers to an electronic wind-chimes: www.paia.com

Velman and a few other companies (mostly European) make kits for a wide range of circuits, from amplifiers to zappers-of-bugs. A convenient source in North America is Quality Kits in Kingston, Ontario: www.qkits.com. Another useful kit outlet is www.Ramseykits.com.

The web knows no national boundaries, but the Post Office does. The above US sources will charge a premium for shipping abroad. In England Maplin (www.maplin.co.uk) carries a wide range of components. In Germany Conrad is a good bet (and they have retail shops in Berlin, and a few other cities): www.conrad.de. RS Components delivers across Europe: <http://rswwww.com>.

For impulse shopping in Yourtown, USA there’s always Radio Shack (www.radioshack.com), but always remember the First Rule of Hacking, lest its meaning become too self-evident.

Appendix 2: Tools and materials needed for this book

This is a list of the basic supplies needed for the workshop. Most can be obtained from a variety of sources -- I have listed web outlets that stocked the parts at reasonable prices as of December 2003. Most of the designs are forgiving of a wide range of component variation and substitution; those few items that are critical and should not be substituted without due care and attention have been marked with an asterisk. You should be able to pick up all the needed parts for under US\$50.00; tools might set you back another \$50.00.

Tools

A good soldering iron, with as fine a tip as possible. 15-60Watts.

A roll of "rosin-core" electrical solder (not "acid core" solder for plumbing and metalwork.

Battery-powered amplifier

RS: 277-1008, \$11.99

Assorted patchcords to connect to amplifier from various jacks.

Prototyping breadboard

AE: PB-400, \$3.00

Inexpensive digital multimeter (voltage, resistance, current.)

Small diagonal wire cutters, suitable for light gauge wire.

Simple wire strippers, suitable for light gauge wire.

Set of small screwdrivers (sometimes called "jeweler's screwdrivers"), flat and phillips tips, suitable for opening electronic toys, portable radios, etc..

A "Sharpie" style fine-tipped permanent marker.

A roll of insulating electrical tape.

4 batteries, 9 volt.

A portable radio (see below.)

An electronic toy (see below.)

Flashlight.

Small saw for plastic and metal.

Double-stick tape.

Small saw for plastic and metal.

Files.

Electric drill & bits.

Small spring clamps or clothespins (non-conductive: plastic or wood, not metal.)

Scissors.

Utility knife.

A Swiss Army knife is always useful.

Parts

= number of pieces needed

\$ = cost each in US\$: 1-10pcs / 10-100pcs

Sources indicated:

AE=www.allelectronics.com

J=www.jameco.com

RS=www.radioshack.com
Within Europe, some UK sources:
RSUK: <http://rswww.com>
CPC: <http://www.cpc.co.uk>

Insulated wire, 22 gauge, stranded, c. 20'
RSUK 177-1107

Insulated wire, 22 gauge, solid, c. 20'
CPC CBBR0251

Shielded audio cable, 1 conductor + shield, lightweight (as thin as possible), c. 20'
Can of "Plasti-Dip" tool handle insulation paint
c. \$13.00

Plastic terminal barrier strip, 1 piece
AE: TB-20, \$2.10
RSUK: 725-061

Sheet of antistatic foam (used for packaging Integrated Circuits)
J: 13864, \$7.95 (1pc 24"x12"x1/4")

5: 1/8" (3.5mm) male plugs
AE: PMP, \$0.35/.30
RSUK 449-994

5: 1/8" (3.5mm) female jacks
AE: MJW-8, \$0.30/.20
RSUK: 454-249

2: small Piezo disks (.6"/15mm)
AE: PE-45, \$0.65/.50

2: large Piezo disks (1.36")
AE: PE-35, \$0.75/.50

4: 9 volt battery connector clips
AE: BST-3, \$0.25/.15
RSUK: 489-021

10: test leads with alligator clips at each end
AE: MTL-10, \$2.50/10 PCs.

1: telephone tap coil
AE: TPX-1, \$1.50

1: audio output transformer
RS: 273-1380, \$2.99

6: 1.0 megOhm linear taper potentiometers
AE: NLTP-1M, \$0.50/.40

4: audio taper potentiometers
10kOhm: AE: ATP-10K, \$0.50
or 20kOhm: AE: AP-20K, \$0.50

6: photocells
J: 120310, \$1.20/1.09

Resistor Assortment, 100 pieces common values
RS: 271-308, \$5.99

Capacitor assortment (all Jameco part numbers and prices, and some RSUK.)
(Most values are not critical – any general purpose capacitor assortment that covers this range will do):
monolithic ceramic caps

10: 10pf, 15333, \$0.07 / .06
10: 100pf, 15341, \$0.05 / .035
10: 0.001uf, 81517, \$0.09 / .07
10: 0.01uf, 25507, \$0.09 / .06, RSUK: 829-586
10: 0.1uf, 25523, \$0.07 / .06, RSUK: 829-615

electrolytic caps

10: 1.0uf, 29832, \$0.057 / .048, RSUK :324-5543
10: 2.2uf, 93729, \$0.038 / .033, RSUK: 324-5559
10: 4.7uf, 31000, \$0.038 / .033, RSUK: 324-5515
10: 10.0uf, 198838, \$0.045 / .03, RSUK: 324-5593
10: 22.0 uf, 198846, \$0.045 / .04, RSUK: 324-5470
10: 47uf, 31114, \$0.06 / .05, RSUK: 324-5492

6: LEDs

J: 152864EF, \$0.24 / .19

6: small signal diodes (1N914 or equiv.)

1: phototransistor

J: 112168, \$0.30 / .24

3: 74C14 Hex Schmitt Trigger Integrated Circuit

THESE MUST NOT BE 74AC14 OR HC14, ONLY 74C14!

J: 44257, \$0.35 / .31

3: CD4093 Quad NAND Schmitt Trigger Integrated Circuit

J: 13400, \$0.25 / .19

RSUK: 345-5728

2: CD4040 Binary Divider Integrated Circuit

J: 12950, \$0.29 / .19

RSUK: 345-5475

2: CD4049 Hex Inverter Integrated Circuit

J: 13055, \$0.24 / .21

1: LM386N-3 Power Amplifier Integrated Circuit

J: 24133, \$0.59 / .49

RSUK: 414-6318

1: 8 pin DIP IC socket

J: 51570, \$0.07 / .06

4: 14 pin DIP IC socket

J: 112213EF, \$0.10 / .075

RSUK: 402-765

2: 16 pin DIP IC socket

J: 112221EF, \$0.13 / .115

RSUK: 402-771

1: PC board

R: 276-0170, \$2.99

HOW TO CHOOSE A RADIO

It should be cheap enough that you won't be too angry if it never works again. The AM band is more important than FM, but it doesn't matter if the radio picks up both. It should have analog tuning (ie, a dial) rather than digital presets or scan buttons. Larger radios are easier to work with than tiny ones. It's better if it

has a built-in speaker, not just a headphone jack, but a headphone jack in addition to a speaker is useful. And most importantly: **IT MUST BE BATTERY POWERED!** Beware: an alarm clock radio with a built-in “backup battery” is not suitable, since it requires AC power to function as a radio.

HOW TO CHOOSE A TOY

As with the radio, select a toy that is expendable, not too tiny, and has a built-in speaker. A toy that makes sound is preferable to a mute one, and sampled sounds (like voices, animal sounds or instruments) are more useful than simple beeps. The more buttons and switches the better, generally speaking, although musical keyboards often have limited potential for interesting modification. And, of course: **IT MUST BE BATTERY POWERED!**

Appendix 3: The Rules of Hacking

Rule #1: Never get into a conversation with anyone at Radio Shack.

Rule #2: Don't take apart anything that plugs directly into the wall.

Rule #3: It is easier to take something apart than put it back together.

Rule #4: Make notes of what you are doing as you go along, not after.

Rule #5: Avoid connecting the battery backwards.

Rule #6: Many hacks are like butterflies: beautiful but short lived.

Rule #7: In general try to avoid short circuits.

Rule #8: In electronics some things are reversible with interesting results, but some things are reversible only with irreversible results.

Rule #9: Use shielded cable to make all audio connections longer than 8", unless they go between an amplifier and a speaker.

Rule #10: Every audio connection consists of two parts: the signal and a ground reference.

Rule #11: Don't drink and solder.

Rule #12: After a hacked circuit crashes you may need to disconnect and reconnect the batteries before it will run again.

Rule #13: The net value of two resistors connected in parallel is always a little bit less than the smaller of the two resistors; the net value of two resistors connected in series is the sum of the two resistors. (Ohm's Law for Dummies)

Rule #14: Kick me off if I stick. (Zummo's rule)

Rule #15: You can always substitute a larger 1.5 volt battery for a smaller one, just make sure you use the same number of batteries, in the same configuration.

Rule #16: If it sounds good and doesn't smoke, don't worry if you don't understand it.

Rule #17: Start simple and confirm that the circuit still works after every addition you make.

Rule #18: Always leave you original breadboard design intact and functional until you can prove that the soldered-up version works.

Rule #19: Always use a resistor when powering an LED, otherwise the circuit and/or LED might blow out.

Rule #20: Distortion is Truth. (Poss's law)

Rule #21: It is easier to drill round holes than slots.

Rule #22: Never trust the writing on the wall-wart.

Appendix 2: The Laws of the Avant Garde

Rule #1: Do it backwards.

Rule #2: Slow it down, a lot.

Rule #3: Make it louder, a lot.

