A Brief, Selective, and Incomplete Introduction to Practical Electronics, for Physicists.

This is a substantial chunk of practical electronics, in ~ 3 hours, assuming some theoretical knowledge of the physics. It should be sufficient to proceed alone thereafter, aided by Wikipedia/YouTube etc. for elucidation. Images are from various online sources. Written by Richard Neill, 2013-20, for his IA Nat-Sci Students at Magdalene Cambridge.

Contents: Voltages and Currents • Multimeters • Breadboard • Resistors • Diodes • LEDs • Capacitors • Inductors • Transistors • MOSFETs • Logic Gates • Beepers and sound transducers • Op-Amps • 555 Timer • Computer interfacing • Arduino • Sensors • PCB Construction techniques • Electrical safety • Circuit ideas • Component pinouts and data.

Books and Resources

"**Getting Started in Electronics**" - Forrest M. Mims III	- Informal notebook style, starting with the physics.
"A Level Electronics Explained" - M. W. Brimicombe	- More detailed course, aimed at A-level.
"The Art of Electronics" (3rd ed, 2015) - Horowitz and Hill	- Extremely detailed, 1200 pages, beginner to professional.
learn.sparkfun.com and learn.adafruit.com	- Online tutorials, and creative projects.
www.ibiblio.org/kuphaldt/electricCircuits/index.htm	- A comprehensive, free textbook.
www.allaboutcircuits.com	- Online course: textbook and lots of projects / tutorials
https://www.electronics-notes.com/articles/basic_concepts/	- Another online resource, with a focus on radio.
www.alldatasheet.com	- Datasheets for almost all ICs/transistors/semiconductors.

Voltages and Currents

Voltages are measured *across* a component; current flows *through* it. 1 Volt = 1 Joule/Coulomb.
The voltage "**at**" a point means "potential difference between that point and ground". ← Ground/Earth is a convenient zero-point.

We always use "conventional current" i.e. flow from positive-to-negative. $e = -1.602 \times 10^{-19}$ C.
Electric *fields* (i.e. voltages) move at ~ 0.7*c* in copper. Electron *drift-velocity* is typically ~ 0.1 mm/s: $\mathbf{I = n A v q}$

Kirchoff's Laws:

(i) The algebraic sum of currents in a network of conductors meeting at a point is zero.
(ii) The sum of the EMFs in any closed loop is equivalent to the sum of the potential drops in that loop.

An "ideal voltage source" provides a constant voltage, irrespective of the current drawn; a constant current source/sink regulates the same current, irrespective of the voltage across it (insofar as it can, given other constraints).

Ohm's Law: $\mathbf{V = I R}$ ← This also works if **I** is in mA and **R** is in kΩ.
Power: $\mathbf{P = I V = I^2 R = V^2 / R}$

USB ports provide 5 ± 0.1 V at up to 500 mA. ← Computer USB ports *"should"* be internally protected against short-circuits, but caution!

"10% Rule": calculations within 10% suffice (because of component tolerances). E.g. $\pi \approx 3 \approx \sqrt{10}$.

Using a Digital Multimeter

Using a Multimeter (DMM): the **red** probe is positive; **black** is negative (but reverse-polarity won't harm the meter).

Set the full-scale range correctly: *over-range* is usually shown as "1" in the *leftmost* digit followed by blanks, like: "**1**   ".

In DC Voltage-mode, the DMM usually has a high impedance (usually > 20 MΩ), and doesn't affect the circuit it measures.

The AC voltage range corrects for RMS (root mean square), measuring the average, which is (the peak / √2). This is chosen so that $\mathbf{P = V^2 / R}$ calculations work the same as they would for DC. e.g. "240 V mains" is a 339 V amplitude sine-wave. [*Never* use AC-mode to read DC voltages: meters vary; depending on type, 10 V DC can mis-read as 14.1, 20, or **0** VAC !]

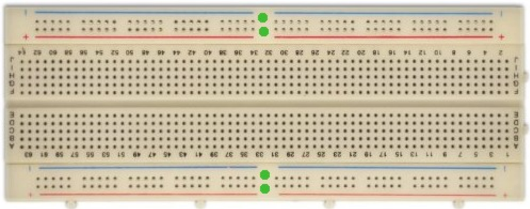
In current-mode, you must usually *move* the positive probe to the alternate socket; move it back afterwards. (this safety feature, prevents accidentally measuring a voltage using an ammeter, which would result in "*spitzensparken und blowenfusen"*.).

In resistance mode, select the appropriate range (Ω, kΩ, MΩ). If the resistance is too high for the range, it shows over-range.

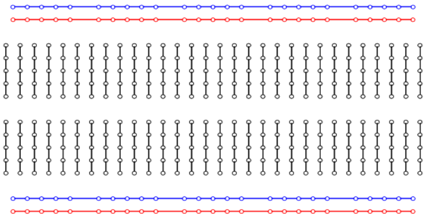
Multimeters often have other functions, e.g. modes for continuity testing (beeps when the resistance is low), diode testing (polarity and forward-voltage-drop), transistor testing (current gain, h_{FE}, of NPN/PNP, or can light an LED), capacitance and inductance measurement, frequency counters, temperature sensing, and battery testing (voltage under load).

Wiring up Circuits: Solderless Breadboard

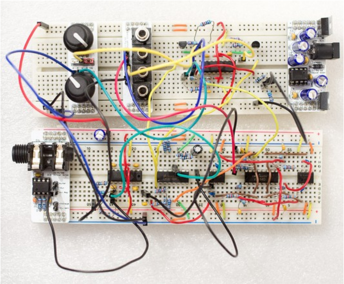
This is a typical solderless **breadboard** (also called protoboard). The internal connections are made with springy metal clips, in rows and columns as shown by the lines. Components simply plug in across the gaps, which are on the standard 0.1 *inch* pitch. **Note the connection pattern carefully**; otherwise you'll get shorted out components.



Solderless breadboard. Components plug in: each hole has a spring clip. Power-rails are at the top and bottom. The gap in the middle is for integrated circuits. Green dots denote breaks.



The pattern of connections, in rows and columns. Power-rails are continuous, while the vertical connections are in groups of 5.



The sort of thing you can create.

Some breadboards have *2 pairs* of power rails (as here). ***Ignore*** the upper-blue and lower-red rail ← used when several boards are clipped together, or for complex circuits which need more than one power-supply voltage. If you do utilise them, be very careful which is which. This Breadboards for Beginners video may help: www.youtube.com/watch?v=W6mixXsn-Vc

Some breadboards have horizontal bus-strips which are *split* mid-way, and have a break in the centre. If so, remember to bridge this gap !! ← one such board is shown in the left photograph, marked with green dots where the connections "should" be. This is a very common **gotcha!**

You can choose your own **topology** of which components you want to place where. Bend the legs as needed, but not too much.

- Keep the positive rail at the top and the negative rail at the bottom.
- Work logically from left-to-right (i.e. signal flow from the inputs at the left to the outputs on the right).
- Be *careful* not to short-circuit a component, e.g. by placing *both* legs of an LED in the same column. ← **gotcha!!**
- Be *careful* not to miss a connection, e.g. by placing two wires accidentally *offset* by one. ← **gotcha!!**
- Pay attention to *orientation* of polarised components (e.g. LEDs, transistors, ICs).
- Some components are fragile: insert the pins straight down, or gently use pliers.
- ICs also have *sharp* legs: be careful when removing them! (lift from both ends, don't lever them up at 45º)
- Use solid-core wire, or tin the end of stranded wire.

Use the colour-code: **Red** = Positive; **Black** (or **Blue**) = negative. **Green** is used for earth in dual-supply-voltage circuits.

Supply **5V power** to the breadboard, from a USB-cable, with stripped, tinned wire ends, or a small micro-usb adapter board. Wire this on the left side, with red ("VCC") to the top, black ("GND") to the bottom; draw power from a *charger*, not a valuable laptop in case you short it!

Tip: **crocodile clip** a short piece of solid-core wire onto each of the multimeter probes, so that they can be connected to the breadboard, leaving your hands free.

Almost all modern components can be used with breadboards, and they are invaluable for prototyping and experimenting. The *Wikipedia* article on "Electronic Component" is a very useful aid to part-identification, and further information. Some very small devices won't fit, but are usually available in the form of "breakout boards", or SOIC (small outline IC) adapters. For high-frequency circuits (> 10 MHz), the capacitance between strips can matter.

Historical note: circuits such as radios were often literally constructed on actual wooden bread-boards! These were ideal as a strong mechanical base for bulky components, such as valves (vacuum tubes), tuning capacitors, and large coils, which often needed to be screwed down. Also wood is electrically insulating, and non-magnetic – especially important for high voltages and radio circuits.

Experiments

The experiments below are (mostly) intended to take no more than 1-2 minutes each. The aim is to gain an intuition for what electronics does, and how you might continue on your own, *not* to make very precise measurements. Make brief **notes** on this printout as you go. Given time-constraints, the most important experiments to perform are **underlined**; work fast as the fun stuff comes at the end! A list of components, their pinouts, and some key data is on *last* page.
If time is short, then entirely *omit* the sections on inductors and MOSFETs; then choose *either* op-amps or logic-gates. The most interesting material is later.

Experiment #1: Use the DMM [continuity beeper] to verify that the connection pattern of the breadboard is what you think that it is. If the meter probes won't fit into the board, use crocodile clips and a short length of wire.
This experiment is important, since most mistakes arise from unintentionally shorted or isolated connections. (If not completely certain, see the YouTube tutorial "Introduction to Breadboard (Protoboards)".)

Resistors

Resistors impede the flow of current, dissipating energy as heat. Measured in Ohms (symbol **Ω**, sometimes typed as "**R**").

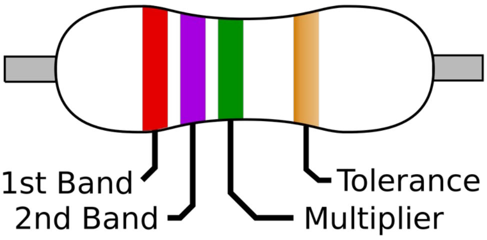
Ohm's Law: $\mathbf{V = I\,R}$ ← Voltage across the resistor is proportional to the current through it.
Resistors in Series: $\mathbf{R_{total} = R_1 + R_2 + R_3 \ldots}$
Resistors in Parallel: $\mathbf{1/R_{total} = 1/R_1 + 1/R_2 + 1/R_3 \ldots}$

Voltage divider: $\mathbf{V_{out} = V_{in} \times R_2 \,/\, (R_1 + R_2)}$ ← Output = Input × R_2's share of total resistance (diagram below).
Use the linear interpolation (fair share of voltage) rule, provided that no significant current is drawn from the output.

Resistors are identified by the resistor colour code. The colour code is: ← remember this as: black, brown, rainbow, grey, white.
0=Black, **1=Brown**, **2=Red**, **3=Orange**, **4=Yellow**, **5=Green**, **6=Blue**, **7=Purple**, **8=Grey**, **9=White**.

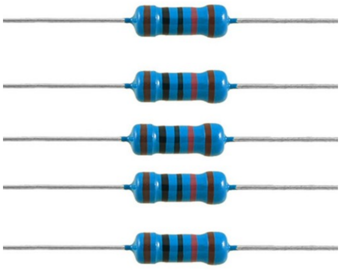
There are *usually* **3 main stripes** (+ tolerance) interpreted as: **Digit**, **Digit**, then **N more zeros** (± **tolerance** %).
The *final* band is the tolerance: usually 5% (**Gold**) or 1% (**Brown**). ← There is *usually* a slight gap before this band, for orientation.
E.g. a yellow-**purple**-**red** resistor is 4, 7, 00 = 4.7 kΩ ← Abbreviations: "4k7" means 4.7 kΩ, "100R" means 100 Ω.

Standard resistors come in the **E12** resistor logarithmic-series, covering all values within ±10 %. After calculating a resistance, select the *nearest* match, e.g. 500 Ω → 470 Ω. E12 series: *10-, 12-, 15-, 18-, 22-, 27-, 33-, 39-, 47-, 56-, 68-, 82-, [100]*.
NB: higher-precision resistors use **4** stripe codes for higher accuracy: $\mathbf{D\,D\,D \times 10^N \pm T\ \%}$. Sometimes their orientation is unclear.



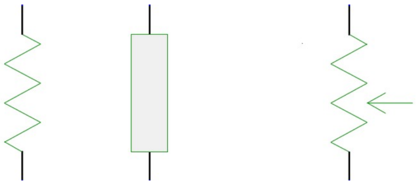
How to read a 3-digit resistor. Note the slightly larger gap before the tolerance band. This one is 2.7 MΩ, 5% tolerance. Common shorthand omits "Ω" thus "2.7M" or "2M7".

5% carbon ¼ W resistors.
3 bands (+ tol.), so easier to *read*.
Brown-Black-Red = 1 kΩ.

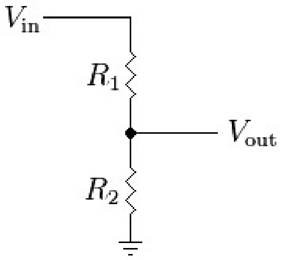


1% metal-film 0.6 W resistors.
4 bands (+ tol.). Better *specification*.
Brown-Black-Black-Orange = 100 kΩ.

Variable resistors, "potentiometers", "pots", or "presets" (single/multi-turn screw adjustable).
3 pins, unless ganged (stereo) or switched.
Usually linear, sometimes logarithmic for audio.



Left: two fixed resistor symbols, used interchangeably.
Right: variable resistor: the middle contact is the adjustable wiper, while the ends are often labelled CW, CCW.
Symbols are from Gschem. Also see: xkcd.com/730 .



The voltage-divider circuit.
$\mathbf{V_{out} = V_{in} \times R_2 \,/\, (R_1 + R_2)}$
The formula generalises for Z_1, Z_2.

Experiment #1: For a voltage divider, with a 5 V supply, and R_1 = 10 kΩ and R_2 = 47 kΩ, calculate V_{out}.
Now wire up the circuit on breadboard, and measure the result: how close is it to the calculation?

Experiment #2: Find the input impedance (Z_{in}) of your digital multimeter: Measure the supply voltage directly, then repeat but with a 1 MΩ resistor in series with the meter (i.e. R_1 = 1 MΩ; the DMM itself acts as R_2). What is Z_{in} ?
[Note: DMMs typically have input-impedance > 20 MΩ, but, the *DT-838/XL830L* meters are "low-cost".]

Experiment #3: Measure your own resistance (gently touch the meter probes; then repeat with a firm grip).
[This is how "lie-detectors" work. Humans (and electrolytes) don't exactly obey Ohm's law.]

Experiment #4: Measure the resistance of the light-dependent resistor (LDR) in the dark, and in bright light.

Experiment #5: A 10 kΩ potentiometer has 3 pins. Twiddle it, while measuring the resistance across each pair.

Physics note: resistors generate noise (thermodynamics): see *Wikipedia* article on "Johnson-Nyquist noise". [E.g. 1 kΩ @ 10 kHz bandwidth ~ 400 nV]
Thevenin's theorem: for any circuit of multiple supply-rails and resistors, there is an equivalent circuit with one supply-voltage and one series-resistor.

Diodes

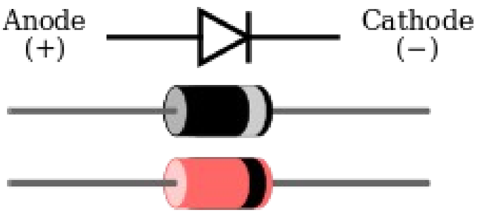
Diodes allow [conventional] current to flow only one way, from anode (a) to cathode (k). Real-world silicon diodes such as the 1N4148 are nearly perfect insulators (< 10^{-9} A) in the reverse direction and withstand up to 100V before destruction. In the forward-direction, little current flows until the threshold voltage (~ 0.6 V) is reached; thereafter, current climbs exponentially, but is limited by the internal resistance. A **signal diode** (e.g. `1N4148`) can take about 100 mA before overheating.
Rectifier diodes (e.g. `1N4004`) can cope with > 1 A, sometimes hundreds of amps.
Overloaded diodes tend to melt and often become *short-circuits.* ← unlike fuses/resistors, which fail open-circuit.

The forward voltage-drop of a **Silicon** (Si) diode is quite reliably 0.6 V, though it decreases slightly with increasing temperature (*useful* for measurement; *annoying* for transistor amplifier thermal-runaway). **Germanium** (Ge) diodes, used in A.M. radios, and **Schottky** diodes, used for motor-suppression, have a lower V_F (0.3 V, 0.25 V respectively). The detailed and fascinating physics of diodes is explained in the *Wikipedia* article on "Diode modelling".

Zener diodes (e.g. `BZX55C3V3`) have a specific, selectable, intentional reverse-breakdown voltage, such as 3.3 V. They are used for voltage-regulation, wired up "backwards", with a series resistor. The symbol has a *jagged* bar for the cathode line.

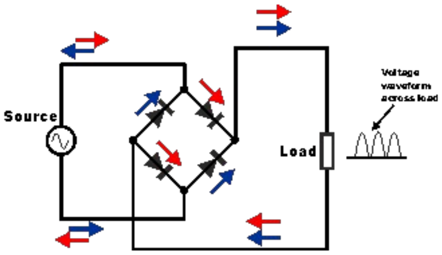
A **Bridge-Rectifier** is an arrangement of 4 diodes to convert AC to DC on both phases.

Photo-diodes respond to light; unlike LDRs, they are fast (~ 1 ns response), but the signal is very small (~ 1 µA).

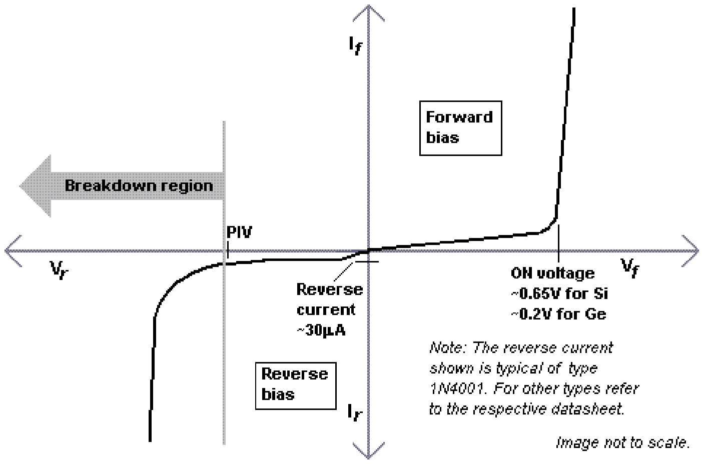


Identification of the Cathode is by the stripe on one end.
Diode part numbers are printed (in tiny fonts) on the body.

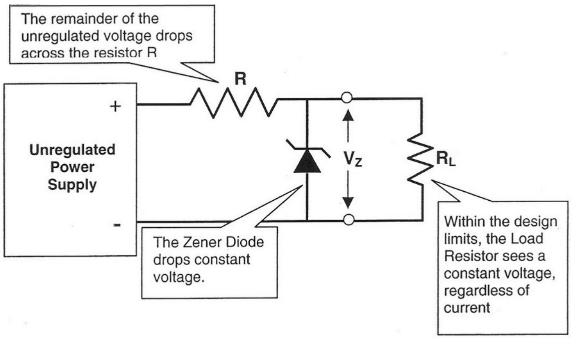
1N4148 diode (3mm long)
Typical Si signal diode.



Bridge Rectifier: 4 diodes combined, so that opposite pairs conduct on each half-cycle.



A typical diode I-V curve, showing forward and reverse bias.



Zener diode: cathode more positive, so that reverse-breakdown occurs.
Useful in voltage-regulator circuits; the Zener is wired "backwards".

Experiment #1: Test a diode with the DMM's diode mode: it can tell you the polarity, and the forward-voltage-drop (in mV).
[Use a signal diode (marked "`1N4148`" or "`1N4004`"), not the similar-looking (but fatter) Zener diode.]

Experiment #2: Connect a diode in series with a resistor (1 kΩ, then 100 kΩ), and use a 5V power-supply.
Measure the forward-voltage across the diode. Does the voltage change significantly with current?

Experiment #3: Now reverse-bias the diode, (still use 1 kΩ in series for protection), and measure the current flowing.
[Also, try the reversed-diode, in series with 1 MΩ, measure the voltage across the resistor, calculate current.]

Experiment #4: Connect the 3.3 V Zener diode (marked "`BZX55C3V3`") in series with 1 kΩ (use a 5 V supply, with the *cathode* more positive), and measure the voltage-drop across it. How much current can your "regulated" 3.3 V supply now provide before the output voltage drops too far?
[Note that Zeners aren't particularly precise, nor constant, especially as temperature changes].

LEDs (Light Emitting Diodes)

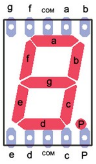
LEDs are **diodes** which emit visible light. The *anode lead is longer* (until you cut it!). The cathode has a *flat on the body*. Typically, LEDs operate at 1 mA to 20 mA (though clear LEDs can be perceived at 1 μA, and bright ones can be 100 Watts). Different colours have different forward voltages, typically 1.8 V for Red and 2.2 V for Green (the forward voltage also varies slightly depending on the current and temperature).

LEDs always need a **series resistor** to limit the current. E.g. a red LED (specified: $V_f = 1.8$ V with $I_f = 10$ mA), operated from a 5 V supply. The resistor must drop (5V – 1.8V) = 3.2 V, while passing 10 mA: this gives 320 Ω, so choose a 330 Ω resistor, via the 10% rule. LEDs in series can share a resistor; when in parallel, use one resistor each, or the lower-voltage LED will be "greedy" and consume all the current. LEDs are less tolerant of large reverse voltages than diodes: 12V reverse, or > 50 mA forward will usually let out the "magic smoke", and it smells terrible! ← Don't try: it's really *nasty*, worse than burned plastic.

Some LEDs have multiple colours in the same package, or a built-in flasher IC. 7-Segment or Starburst displays are used as indicators. LEDs are "fast": they can flash at > 100 MHz, useful for data-transmission (e.g. fibre optic data links). Laser diodes are specially constructed LEDs with interferometric ends; they are electronically fragile, and sometimes dangerously bright.


Standard 5mm LEDs.


RGB LED.

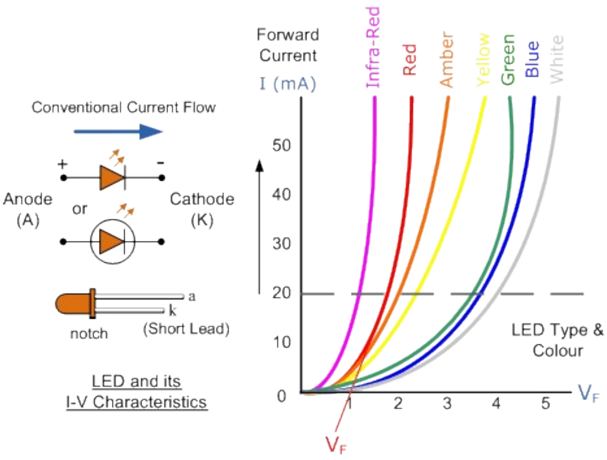


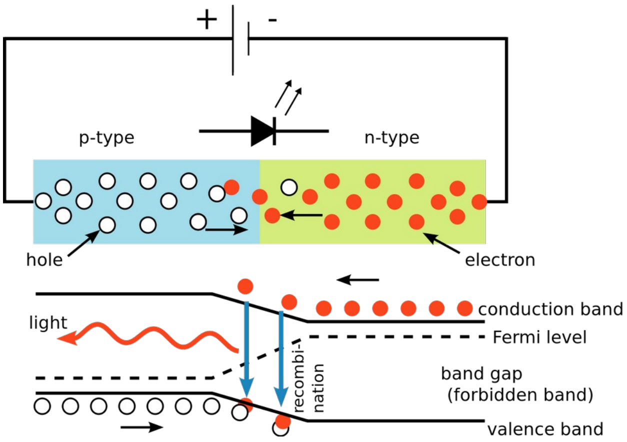
7 segment.


Starburst display.


SMD LEDs (1 x 2 mm)


Laser diode module.





LED physics is fascinating: direct- and indirect- band-gaps, photons vs. phonons, light-extraction, ITO transparent contacts, colour-change with temperature (including in liquid nitrogen), high power LEDS, photo-diodes, and the material-science of crystals and strained lattices: GaAs, InGaN, AlInGaP...

Experiment #1: Light a green LED from the 5 V supply, using a series resistor to set a current of 10 mA. To choose the right resistor, see datasheet for V_f. How many volts to drop across the resistor? Then use Ohm's Law.

Experiment #2: Wire up a red, green and blue LED to operate at the same current (10 mA). Which appears brighter? Use the RGB (3 in 1) LED, for colour-mixing. Common anode; pins are: flat:{K_R, A, K_G, K_B}.

Experiment #3: Using a clear-lensed red/green LED, set the current to a low value where it just perceptibly glows, then measure the voltage. (Use R ~ 1 MΩ). If every electron crossing the band-gap emits a photon, calculate a value for Planck's constant. Is this correct? Hint: how many electron-volts are there in a Joule?
Formulae: $E = h f$ $c = f \lambda$ $e = 1.602 \times 10^{-19}$ C $h = 6.63 \times 10^{-34}$ m^2 kg s^{-1}.

Experiment #4: An LED can also act like an inefficient solar-cell. Connect it directly to a multimeter, and measure the output voltage. (Tip: shine a bright light directly into the LED, end-on; later try an op-amp follower).

Red LEDs have a single, sharp spectral line. **Orange**/**Yellow**/**Green** are a bit wider. **Blue** LED spectra are not well-defined. **White** LEDs actually contain a blue emitter and a yellow phosphor: this is why white-LED illumination often has such a poor quality (bad colour-rendering index, or CRI) compared to tungsten filament lamps, though phosphors are improving. Unusual LEDs include IR, UV, **turquoise**, and **purple** (which also uses a phosphor: there is no such thing as *purple light*: purple = red + blue ≠ violet; it's better thought of as "white without the green").

In physics, it makes sense to consider the (absolute) *radiometric* quantities, measured in W, or W/m², or W/sr (the steradian is the unit of solid angle, 1 sr = sphere / 4 π), however LEDs are usually specified in (perceptual) *photometric* quantities, such as the Candela or Lumen. The Candela (cd) is a ridiculous choice for an SI base-unit: it assumes that the light-source has a black-body spectrum (it invariably doesn't), and it is weighted by the (standardised) *colour-response of the human eye*! The human-eye has a logarithmic response to light. For more details, see the *Wikipedia* articles on "Photometry (optics)" and "Luminous Efficacy": the word "brightness" has at least 6 incompatible meanings!

Capacitors

Capacitors store charge. Measured in Farads, though the microfarad (*µF*, often written *uF*) is more convenient, or the pico-farad (pF) or nano-farad (nF) is used for small values. [pico = $\times 10^{-12}$.] For a parallel plate capacitor, $\mathbf{C = \varepsilon_0 A / d}$.

Small (**ceramic**) capacitors are un-polarised; printed values are 3 digits in *pF*, e.g. **154** means 1,5,0000 pF = 0.15 uF.
Larger (**electrolytic**) capacitors are *polarised*: the body is marked with **-** signs, and the positive lead is longer.
Super-capacitors (> 100F) can store ~ 10% of the energy of a similar-sized battery, but with ~ 1 kA peak currents.
Tuning capacitors (used in radios) are mechanically variable, rotations adjust the plate overlap, typically 50-500 pF.

Electrolytic capacitors have wide (20%) tolerances, so usually only the 10-, 22-, 47- values are common. Small electrolytics have low maximum voltages; typically 6.3 V or 16 V: *never* exceed this, especially with **tantalum** capacitors which like to catch fire at even slight (5%) overloads! Note that physically larger capacitors can be rated for much higher voltages and store *lots* of energy to be released rapidly: supercapacitors can discharge at very high current, while camera-flash capacitors are high voltage (e.g. 470 µF @ 400 V).

← Electrician's Commandment #1: "*Beware of Lightning That Lurketh In The Undischarged Capacitor*"

Charge, Q (in Coulombs): $\mathbf{Q = C\ V}$ Energy $= \frac{1}{2}\ \mathbf{C\ V^2}$
Current: $\mathbf{I = C\ dV / dt}$ $\mathbf{Q = \int I\ dt}$

Capacitors in Series: $\mathbf{1/C_{total} = 1/C_1 + 1/C_2 + 1/C_3\ ...}$
Capacitors in Parallel: $\mathbf{C_{total} = C_1 + C_2 + C_3\ ...}$

When a capacitor discharges through a resistor, there is *exponential* decay of the voltage over time.
Time constant: $\boldsymbol{\tau = R\ C}$

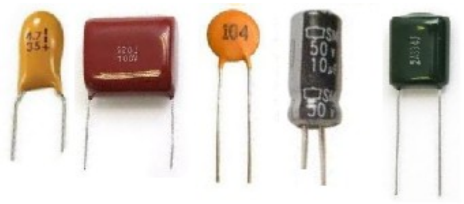
← This formula also works if R is in kΩ, C is in µF, and τ is in ms.

In an AC circuit, the *reactance* (the "effective resistance") of a capacitor is $\mathbf{X = 1 / \omega C}$
This approximation for voltage-dividers only works if there are no inductors, since it ignores phase and resonance. The correct formulae use complex impedances, **Z**, where $\mathbf{Z = 1 / i\omega C}$.

← Derivation: $Z = V / I$ $I = C\ dV / dt$ $V = A\ e^{i\omega t}$

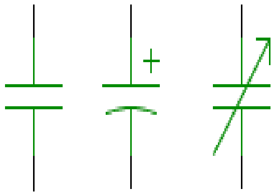
The leakage current (parasitic parallel resistor) determines how fast a capacitor self-discharges, usually ~ hours.
The **ESR** (equivalent series resistance) limits how fast we can get energy out (and for radios, the **Q** of an LC resonant circuit).

In circuits, **coupling** capacitors are used between sections of a circuit, to allow the AC-component of a signal to pass, while blocking the DC-component: this is useful in amplifiers where the DC-bias of each stage should not be amplified by the subsequent stage. **Decoupling** capacitors go across power-lines to reduce unwanted interference between different parts of a circuit.

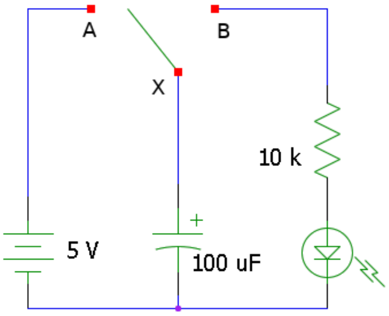


Capacitors: various types. From left → right:
- * Tantalum electrolytic: 4.7 µF (3.5V max, polarised).
- * Polypropylene film: 22 µF.
- * Ceramic disc (marked "104"): 0.1 µF.
- * Aluminium electrolytic: 10 µF (50V max, polarised).
- * Polyester film (marked "334"): 330 nF.

[1000 µF ESR is typically ~ 0.1 Ω]



Schematic symbols for capacitors: unpolarised, polarised, variable. Unpolarised capacitors are usually in the range 1 pF → 1 µF. Polarised capacitors are typically 0.1 µF → 0.01 F. Variable capacitors are usually very small values, typically 500 pF.



Experiment to observe RC time constant: With the (green) wire to the left (X↔A), charge the capacitor from the power supply. Then *move* the wire to the right (X↔B), to discharge it via the resistor and LED.

Experiment #1: Charge a 100 µF capacitor (connect it briefly to to 5 V), then discharge it through a 10 kΩ resistor through an LED. How long do you expect the LED to light for? (Try changing R to 330 Ω, or C to 1000 µF). [Hint: $\tau = R.C$, where the units are normally s, Ω, F but this also works in ms, kΩ, µF]

Experiment #2: Charge a 1000 µF electrolytic to a high voltage (max *within* the marked rating e.g. 16 V) and, carefully, (away from your eyes), touch the leads to some Aluminium foil. Enjoy the sparks... but stop if the capacitor gets warm, lest it leak corrosive electrolytic goo, or go pop!

Physicists may also enjoy the *Wikipedia* articles on "Leyden Jar", "Types of capacitor", "Dielectric absorption", and "Capacitor plague". Capacitors are also useful as cryogenic temperature sensors within superconducting magnets. An air-gapped capacitor has dielectric constant ε_0, whereas solid-cored capacitors (containing insulating, polarisable dielectric materials) use $\varepsilon_0.\varepsilon_r$ instead. Very thin dielectrics are great for compactness, but experience very high electric-fields, which can cause breakdown or leakage. All capacitors have some (ideally negligible) series/parallel resistance and inductance.

Inductors, Transformers and Relays

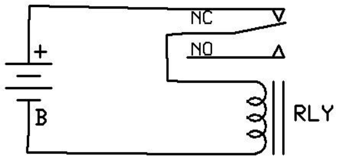
Inductors are much less commonly used than capacitors. Measured in Henries (or μH). The maths is symmetrical with capacitors, but swapping V ↔ I. Inductors "store" current in their magnetic field. For a solenoid: $L = \mu_0 N^2 A / l$.
The phase lead/lag mnemonic is "CIVIL" i.e. **C**: I leads V; V leads I for **L**. ← φ is phase lead: think phi-lead-elphia cheese.

Induced voltage by a changing current: $\mathbf{V = L\ dI / dt}$ Energy stored = $\mathbf{\tfrac{1}{2}\ L\ I^2}$

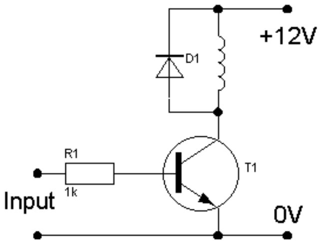
A **transformer** is a pair of inductors, wound on the same iron core, for linked magnetic flux. They are used for changing voltages, isolation, and matching impedances: $\mathbf{N_{secondary} / N_{primary} = V_{out} / V_{in} = I_{in} / I_{out} = \sqrt{(Z_{out} / Z_{in})}}$.

A **relay** is a mechanical switch from the days of the telegraph (~ 1840): current in the coil attracts a spring-loaded change-over (SPDT) switch contact. Relays allow low-power circuits to control high-current loads (e.g. computer control of lighting). ← solid-state alternatives are MOSFETs, TRIACs.

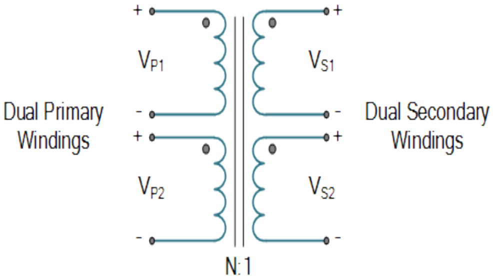
Note: large inductors "hate" it when they are suddenly switched *off*: as the magnetic field collapses, the energy in the field has to go somewhere. The current tries to keep flowing, and creates a **back-EMF** in the coil, which can destroy the control-circuit. Always use a protection diode (also called a "freewheeling" or "snubber" diode), wired "the *wrong* way" across the relay-coil.



Relay: spark-oscillator. As the relay turns on, it disconnects its own power, thus turning off. It buzzes, arcing and emitting radio waves. A capacitor across the contacts can change the frequency. NC/NO = Normally closed/open.



The diode protects the transistor (see below), by dissipating the current flowing at the moment that the transistor turns *off*. The current continues to flow clockwise through the coil and diode, so that there is no sharp back-EMF voltage spike.



A typical mains-transformer configuration. The two primaries are each rated for 120 V, while the two secondary coils are each 6 V. This allows for various serial/parallel options. The dots in the symbol denote coil orientations.

Experiment #1: Wire a relay coil in parallel with a neon-bulb. Connect it to a *battery* [i.e. not a computer's USB port], then disconnect. Observe the neon lamp flash on disconnection. [If your fingers *were* in the wrong place, you'd feel a slight shock; this is how electric-shock "toys" and electric fences work; it's not advisable, particularly across both hands]. Now add the protection diode across the relay coil (pointing the "wrong" way), and repeat: the energy is dissipated. [Don't use a computer's USB port for this experiment; it could be damaged!]

Experiment #2: Measure the inductance of the primary and secondary coils of a mains transformer. If the coil has a center-tap, compare the inductance of one half with that of the entire coil. [Data below.]

Experiment #3: Use the 20 H + 150 Ω, series-wired primary coils from #2 to light an LED from 5 V. How long does it take for the LED to come on? Reverse one of the coils: what happens, and why?

Experiment #4: Wire up the relay up such that it interrupts its own power (i.e. put the normally-closed contacts in series with the coil). It will buzz angrily. This is an old-fashioned spark-gap transmitter, and can be received on a nearby A.M. radio when it is tuned to the gap between stations. [Again, don't use PC USB here, in case of damage.] [Do not connect a large aerial to the relay: transmitting radio-interference is unpopular / illegal with Ofcom.]

For Experiment #2, here's some data measured earlier with an L-C-R meter, for a small toroidal mains step-down transformer, whose secondary is specified as 6V–0–6V, at 15 W. (Farnell part #953-0231). How much quiescent power is wasted when the primary is connected to the mains, (secondary not connected)?

One primary coil:	5.1 H	← yes, really, it's huge.
Both primary coils, in *parallel*:	5.2 H	← as expected: just changes the wire thickness.
Both primary coils, in *series*:	20.2 H	← proportional to N-squared, not L1 + L2.
Both primary coils, in *reverse-series*:	154 Ω, resistive.	← Inductances cancel out – why?
One secondary coil:	25 mH	← $L_S / L_P \neq (N_S / N_P)^2$, since the areas are unequal.

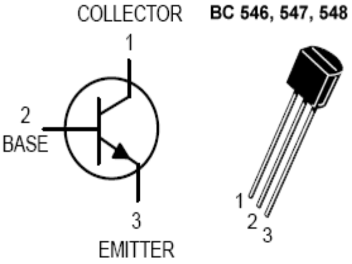
Transformer physics: AC *voltage* across the primary causes a primary *current*, which creates an oscillating magnetic field; this induces a *voltage* in the secondary coil and an *opposing voltage* [Lenz' law] in the primary. The *self-inductance* of the primary minimises primary-current, *unless* the secondary's load draws current: the secondary's field withdraws energy from the primary field. *mutual inductance* makes the transformer *act* like a voltage-transfer device.
Transformer design: mutual-inductance dominates self-inductance. Self-inductance dominates series-resistance. Eddy-currents are minimised.
[See also: auto-transformers (variacs), current-transformers, resonant transformers (Tesla coils). LC resonant circuits: youtube.com/watch?v=hFJeIt_JcEc]

Neon bulbs typically *strike* at ~ 90 V and *extinguish* at ~ 60 V. Ne bulbs usually require a series resistor, as they exhibit negative resistance (i.e. dV/dI < 0). The physics is "glow discharge"; for DC, only the cathode illuminates. Observe the photoelectric effect: shine an LED on a neon which isn't quite at striking voltage: bright red does nothing; faint blue will trigger it. Also: www.tiffe.de/roehren/neon.pdf and wwwhome.cs.utwente.nl/~ptdeboer/ham/neonclock

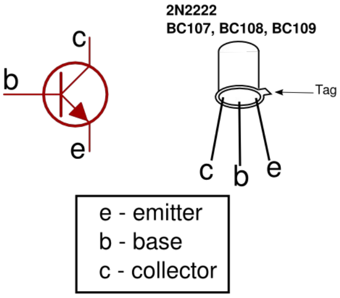
Transistors (Bipolar)

Transistors are active components, used to *switch*, *amplify* or *oscillate*. Transistor is short for “transfer-resistor”. Transistors are constructed from very pure silicon (< 10^{-12} parts impurities) with ~ 10^{-9} parts of added dopant atoms added in precise layers: **n**-type silicon uses phosphorus (group V, donor, adds electrons); **p**-type silicon uses boron (group III, acceptor, adds holes).

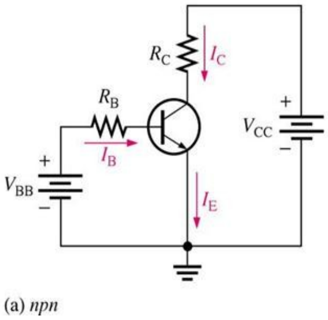
Bipolar transistors (i.e. ordinary transistors) are *linear*, **current-controlled** devices. The 3 terminals are named *base*, *emitter*, and *collector*. There are 2 symmetrically opposite types: **NPN** and **PNP**, we'll use NPN here. ← emitter/collector were named by analogy with thermionic valves (cathode/anode); base is the physical substrate. NPN and PNP denote the layers of n- or p-doped silicon used for C-B-E.



`BC549` NPN transistor, in a plastic TO-92 case. (All BC5*xx* pins are ordered as: C-B-E). Much cheaper than metal-bodied (3p vs. 30p), but less able to dissipate heat.



`BC108` NPN transistor in a metal TO-18 case. TO-18 is standardised (emitter: tag, base: middle, collector: can), so easy to identify, but also easy to short-circuit on breadboard. Heatsinkable.



Typical transistor circuit, showing the base and collector currents and voltages. A tiny I_b controls a much larger I_c, this is the gain, h_{FE}.

Rule 1: The base-emitter junction is exactly like a silicon diode, (except that the forward-voltage is 0.7 V rather than 0.6 V). If V_{BE} is below 0.7 V, very little current flows in it and the transistor is *off.* If the base voltage is raised, it clamps at about 0.7V, and a current flows, whose size depends on the (external) base-resistor (R_B). ← don't short the base to +V, or it will melt.

Rule 2: The collector-emitter current is *controlled* by the base-current: provided that the external circuit can supply it, the collector current will always be a fixed multiple (the **gain**, typically ~ 400) of the base-current. The collector-emitter voltage adjusts to satisfy the current requirement (as much as the circuit-context allows). So V_{CE} can be anywhere from the power-supply voltage (when the transistor is off) to the saturation voltage (about 0.2V) when the transistor is fully on.

Thus: $\mathbf{I_E = I_B + I_C}$ and $\mathbf{I_C = h_{FE} \times I_B}$ where **h_{FE}** is the **current-gain** of the transistor.

Rule 3: Ohm’s Law does the rest: the base-current is determined by (input voltage – 0.7V) / R_B, while the collector voltage is determined by (supply voltage – ($R_C \times I_C$)). ← can also usually approximate: $I_E \approx I_C$

The transistor DC **current-gain** (symbol: **h_{FE}**) *varies* from one transistor type to another, typically 50 – 800. Even “identical” transistors from the same batch can have gains that vary by 25%. Many multimeters have a transistor-mode (labelled “h_{FE}”): try it out now. Typically, a `BC549C` might have 10 mA in the collector-circuit, controlled by 20 µA in the base-circuit.

For **PNP** transistors, the *polarities* are swapped, and the schematic symbol has the emitter-arrow *reversed* (it points E → B).

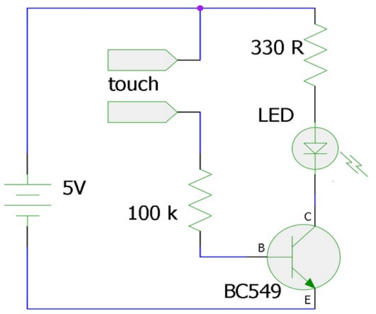
Parts: `BC547`... `BC550` are all similar NPNs; `BC557`... `BC560` are PNP. ← suffix (e.g. BC549**C**) denotes gain group: C > B > A.

Use in circuits:

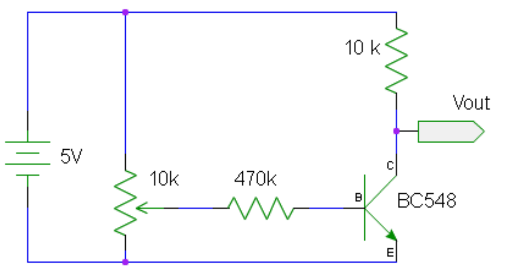
- When transistors are used as **switches**, they *prefer* to be completely-on or completely-off. At the midpoint, I_C is substantial, and so is V_{CE} which makes the power dissipation large and the transistor gets hot. A `BC549` can dissipate 100 mW safely, whereas a much larger `2N3055` (with a *heatsink*) can cope with 115 W. (Maximum power theorem).

- When used as **amplifiers**, both voltage- and current- gain can be large (but unpredictable without knowing **h_{FE}**). The basic transistor amplifier inverts the signal (as the base-voltage rises, more current flows, so the collector voltage falls). To allow the greatest voltage-swing, the transistor should be *biased* at an *operating-point* with the collector-voltage at half the supply-voltage. [If we don't know the gain, R_C must be adjustable, or we need an advanced technique such as emitter-degeneration]. To remove the DC offset, a *coupling capacitor* is used between stages.

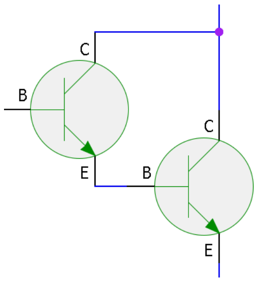
Techniques include the *emitter-follower, collector-feedback biasing,* the *emitter-degenerated amplifier*, *Darlington pair*, *Sziklai pair*, and *push-pull amplifier*. Common circuits include the astable (oscillator) and bistable (flip-flop), class A and B amplifiers, logic gates, long-tailed pairs and current mirrors (in op-amps), mixers, radio-transmitters/receivers, etc... See also: Wikipedia articles: “Bipolar Junction Transistor” , “Bipolar Transistor Biasing”, hackaday.com/2018/05/04/biasing-that-transistor-part-1-the-common-emitter-amplifier (typical self-bias: 1k Rc and 330k Rb) and talkingelectronics.com/projects/TheTransistorAmplifier/TheTransistorAmplifier-P1.html



The transistor switch, controlling an LED.
The 330 Ω resistor limits LED current.
The 100 kΩ resistor protects the transistor;
do not short the base directly to +5 V.



Transistor bias: vary the base voltage, and observe the change in collector voltage. Voltage Gain = (dV_{out} / dV_{in}).
The 470 kΩ resistor protects the base.
[Any of `BC547`, `BC548`, `BC549` or `BC108` are suitable.]



A Darlington Pair: use this instead of a single transistor to square the gain (at the cost of increased V_{BE}).
See also the Sziklai NPN/PNP pair.

Experiment #1: The transistor as a switch. Build the 1st circuit. (Use the BC549 transistor). Touch your finger across the two test-points. A small current through your fingertip lights the LED. How much current is needed?

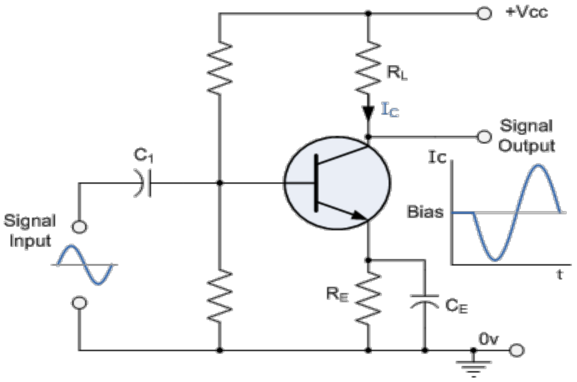
Experiment #2: Repeat #1, exchanging the NPN (`BC549`) for a PNP transistor (`BC557`): reverse all the polarities.
Repeat #1, with the NPN transistor, but swapping E ↔ C. [This "*reverse-active*" mode has much lower gain.]

Experiment #3: Now, swap the single transistor for a two-transistor version (called a *Darlington pair*). This has a combined gain of about 10^5 (product of the individual gains) and lights the LED very brightly from the merest touch. [If it lights up on its own (RF interference/mains hum); add a 1 MΩ pull-down resistor to the base.]

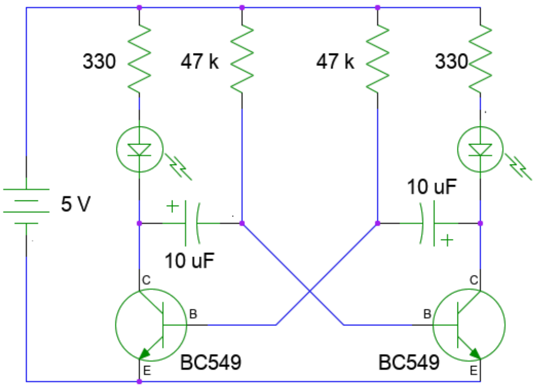
Experiment #4: Simple transistor bias. Build the 2nd circuit. Twiddle the potentiometer, and observe the base-voltage, base-current, and collector-voltage. What is happening? What is the voltage-gain of *your* transistor-circuit?

A more complex circuit is the inverting amplifier with 10x gain. The principle is that the emitter voltage always tries to follow the base (to maintain $V_{BE} = 0.7$ V), and since $I_C = I_E$, (neglecting the small base-current) the gain is given by the ratio of the collector-resistor / emitter-resistor (independent of h_{FE}). This is "emitter-degeneration". The rest is just bias-calculations.

The two-transistor oscillator (**astable**) is the standard blinking-LED circuit, very widely used.



Inverting amplifier, with gain set to -10. Omit the emitter-capacitor, C_E initially.
1. The ratio R_L / R_E sets the gain: choose R_E = 1 kΩ, R_L = 10 kΩ for gain = 10.
2. The operating-point of collector should be ½ supply-voltage (i.e. 2.5V), so the emitter's quiescent voltage = 0.25 V (same current in R_E and R_L).
3. So the base bias-voltage must be 0.25 V + 0.7 V = 1.05 V.
4. Select a potential divider allowing enough base-current, but not too low a Z_{in}: e.g. top resistor = 400 kΩ, bottom resistor = 100 kΩ.
5. C_1 is chosen by setting RC > 10 ms (low-frequency limit), thus ~ 100 nF.



The two-transistor oscillator, or "astable multivibrator".
Probably the most famous circuit in the world! The two transistors each take it in turns to turn the *other* one off, but are only able to do so for as long as it takes for the respective capacitor to charge.
Vary the capacitors and inner resistors to change frequency, but always keep the base-resistors above 470 Ω to protect the transistors.
Time-constant ~ RC, variable from minutes to MHz.
[The capacitor ↔ base wires just cross over, but do ***not*** connect.]
Ring Oscillator: https://www.youtube.com/watch?v=OXnS1NefDQ8

Experiment #5: Inverting amplifier with fixed gain. Inject a 10 mV, 1 kHz sine wave from a signal-generator, view the output on an oscilloscope. Is the gain actually -10? What is the frequency-range over which the amplifier works (with constant gain and not too much distortion)? Vary the ratio of R_L/R_E (set R_L = 1 kΩ).
Try re-adding the emitter-capacitor (100 µF, polarised), to see the AC gain increase.

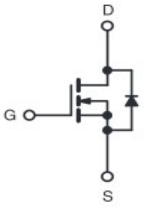
Experiment #6: Build the two-transistor astable. (Assemble the two "halves of the circuit (like #1), *without* the capacitors, check both LEDs light, *then* connect the capacitors).Vary the frequency by changing the capacitors and 47 k resistors: try asymmetry (e.g. 10 µF, 100 µF), or increase frequency to 1 kHz to drive a beeper (below). Always keep the base resistors > 470 Ω, and the correct polarity of the capacitors. How does it work?

Field-Effect Transistors (MOSFETs)

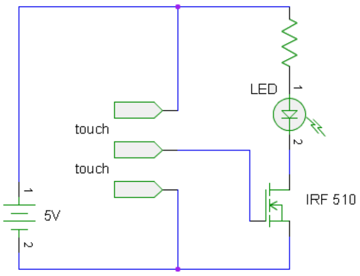
FETs (field-effect transistors) are *non-linear*, **voltage-controlled** devices. Their equivalent terminals are *gate*, *source*, and *drain* (the electrons flow from source to drain, controlled by the gate). The symmetric types are **N-**, and **P-channel**. FETs come in two variants, the **MOSFET** (Metal-Oxide-Semiconductor FET), used here and the **JFET** (Junction-gate FET), which are completely *different* in operation from each other. FETs are non-linear (useful or problematic depending on context).

- **JFET**s are initially conducting, and you apply a *negative* voltage to turn them *off* (like stepping on a hose-pipe), and they are very non-linear. Useful in radios (no load on the tuned-circuit), or frequency-mixers. ← (we won't mention JFETs again).

- **MOSFET**s are used for high-power switching, so their non-linearity doesn't matter, ← (amplifiers use negative-feedback anyway). and, when paired with their symmetric opposites, for logic-gates. ← CMOS = "Complementary Metal Oxide Semiconductor [FET]"



N-Channel MOSFET



The `IRF510 (or IRFZ44)` N-Channel Power MOSFET (enhancement-mode), in a TO-220 case. The symbol shows that the gate is insulated, that the device is N-channel (arrow points towards the gate), and that there is an internal parasitic (side-effect) body-diode. Usually, an N-MOSFET circuit is operated with the drain always more positive than the source. However, if $V_D < V_S$, the body diode will conduct once the reverse voltage exceeds ~ 0.7 V.

Rule 1: The Gate-input is internally *insulated* by an oxide layer. An electric *field* from the gate controls the FET, but no current flows into the gate. The input resistance is ~ 1 GΩ; the gate acts like a ~ 100 pF capacitor. ← The high input resistance means that FETs (and CMOS logic gates) are susceptible to damage by static discharge, even from a fingertip. The gate capacitance also limits the maximum switching speed.

Rule 2: The gate-source voltage, V_{GS}, can safely be anywhere within ± 20 V.

- When $V_{GS} \ll V_{GS(TH)}$ (the threshold-voltage, typically ~ 3 V), the MOSFET is off. ← assuming $V_D > V_S$
- When $V_{GS} \gg V_{GS(TH)}$ (typically ~ 5 V), the MOSFET is on. ← even when $V_S > V_D$
- When $V_{GS} \sim V_{GS(TH)}$ the FET is in the "linear" region. ← not actually very linear!

Rule 3: When the MOSFET is off, the drain-source resistance, $R_{DS(OFF)}$ is very high, at least 1 MΩ, and the MOSFET can withstand at least 50 V without breakdown. ← if the MOSFET is backwards, i.e. $V_S > V_D + 0.7\text{V}$, then the body-diode still conducts.

Rule 4: When the MOSFET is on, $R_{DS(ON)}$ is very low, sometimes as little as 10 mΩ, and the MOSFET can handle ~ 5 A, sometimes much more. ← usually, electrons flow from the source to the drain for N-channel; vice-versa for P-channel.

Rule 5: In the "linear" region, the MOSFET carries substantial current, yet it still has a significant voltage across it. It can get hot if it remains in that state for more than a few ms: MOSFETS like to be switched *decisively.* ← maximum power theorem.

Rule 6: When the MOSFET is reversed ($V_S > V_D$), current can flow through *either* the body-diode (off) *or* R_{DS} (on).

E.g. `IRF510` (or `IRFZ44`) Power MOSFET: switch 6 A; $R_{DS(ON)} < 0.5\ \Omega$; $V_{GS(TH)} = [2, 4]$ V, varying slightly with temperature and V_{DS}. The inexpensive `2N7000` "Fetlington" has $V_{GS(TH)} \sim 2.1$ V. The `4066` IC has 4x bi-directional analog switches.

Experiment #1: Connect the MOSFET in the same way as the transistor switch, as in the circuit diagram above. Touch either of the connector-pairs, and the LED will stay in its state for some time, due to the stored charge on the gate. How sensitive is the gate to a nearby electric field? Could this circuit be used as a magician's prop?

Experiment #2: Exchange the LED/resistor for a filament lamp (6 V, 100 mA); observe that a tiny gate current can control a large drain-current. (Then try swapping Source ↔ Drain, to experiment with the body-diode).

Experiment #3: Connect a variable-voltage to the gate: a 10 kΩ pot, across the power rails. Twiddle it: what happens? How wide is the part-on, part-off region? Does the FET get warm? [As before, use the 6 V bulb as the load].

Calculation #4: Fermi estimation: how many *moles* of transistors are there now in the World? [Hint: flash-memory, used in SD cards and SSDs, probably makes the dominant contribution to this sum.]

Physics note: the semiconductor physics of [mosfet] transistors are explained lucidly here: YouTube: "Veritasium, How does a Transistor Work?"
The History of the Transistor is described here: wwwyoutube.com/watch?v=OuFlISa73Sw

Logic Gates

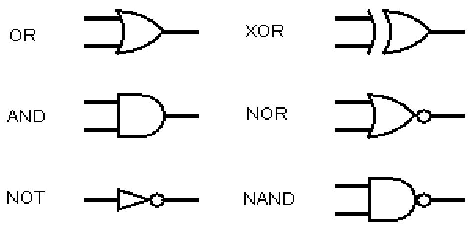
A **Logic gate** performs **logical operations**. For example, *the output of an AND gate is on, if and only-if both inputs are on*. The set of permutations is given by a *truth table;* the mathematical method is called Boolean-algebra.

Common logic gates are: 1 input: **NOT** 2 or more inputs: **AND**, **NAND**, **OR**, **NOR**, **XOR**, **XNOR.**

["NAND" is short for "Not-And". "OR" means "*inclusive* or", whereas "XOR" means "*exclusive* or".]

Equivalents: **1**, **high**, **on**, **true**, **+5V** *vs.* **0**, **low**, **off**, **false**, **0V**.

Logic gate symbols:



← note that the power-lines are ***implicit***, and often omitted from circuit schematic diagrams. The abbreviations V_{CC} or V_{DD} mean the positive supply voltage, usually + 5V, while V_{SS} or GND mean the zero-volt (ground) supply.

← the little circle on the end of the inverting gate-symbols denotes the "not". An inverted output is denoted with an overline: e.g. $\overline{X}$, read as "X-bar", though for typography, a prefixed "n" or apostrophe are sometimes used, eg: nX and X'.

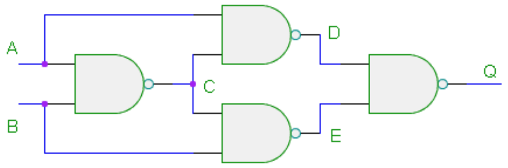
Truth tables (**A** and **B** are inputs, the output for that gate is in **green**):

A	**B**	**AND**	**NAND**	**OR**	**NOR**	**XOR**	**XNOR**
0	0	0	1	0	1	0	1
0	1	0	1	1	0	1	0
1	0	0	1	1	0	1	0
1	1	1	0	1	0	0	1

A	**NOT**
0	1
1	0

Boolean algebra uses the following notation:

$\overline{A}$	means "*not*-A", and is pronounced "A-bar". Complementary outputs are often labelled Q and $\overline{Q}$.
A **.** B	means "A *and* B". The **.** operator acts like normal multiplication, e.g. A**.**(B+C) == A**.**B + A**.**C .
A + B	means "A *or* B" (inclusive). The + operator acts like normal addition, but is constrained to [0,1].
A ⊕ B	means "A *xor* B" (exclusive). For example, A ⊕ A == 0, A ⊕ $\overline{A}$ == 1, A ⊕ 0 == A .



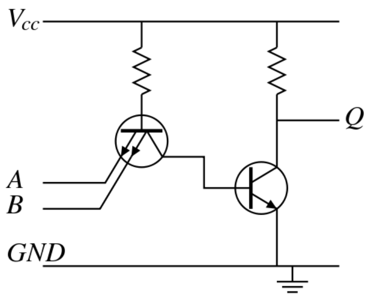
A compound XOR gate, formed out of 4 NAND gates.
[NANDs are versatile: *any* logic can be made entirely out of NAND (or NOR) gates.
e.g. *NAND (NOT(a), NOT(b)) === OR (a, b)* ← De-Morgan's theorem.]

Calculation #1: Draw a truth table for the 4 permutations of inputs (A,B), the midpoints (C,D,E) and the output (Q). What gate results?

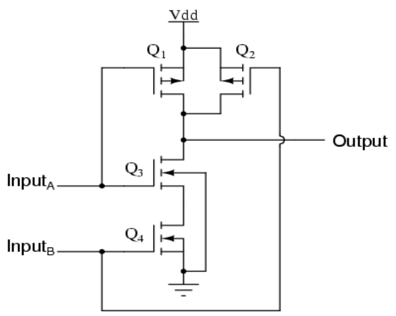
Logic gate hardware: there are various *families* of logic gates, including 4000-series CMOS (40*xx*), 5V-TTL (74*xx*), 3.3V-TTL (74LV*xx*), and High-Speed CMOS (74HC*xx*). Usually, select the **74HC family**, using a power-supply of 2-6 V.

74HC CMOS logic requires ~ 0.1 µA input, and can drive up to 20 mA output; the current-consumption of the IC is nearly zero, except when the inputs are changing at high-frequency; the logic level transition threshold is about half the supply-voltage. Don't leave unused inputs "floating": connect them to ground or +5 V. Max frequency ~ 50 MHz.

Logic gates are actually just convenient packages of transistors: the basic transistor switch is also a NOT-gate. Advanced logic circuits include: adders, memory, flip-flops, latches, counters, multiplexers, microcontrollers, CPUs, ...



TTL (transistor-transistor-logic) NAND gate (simplified). Multiple-emitter transistor on left.



CMOS (Complementary MOSFET) NAND
Note P- and N- type MOSFETS.

Logic gates can be made from individual transistors (bipolar, TTL gate on left) or from MOSFETs (CMOS gate on right).

TTL logic threshold is ~ 1 V. Unconnected inputs float high. Each gate uses a few mW.

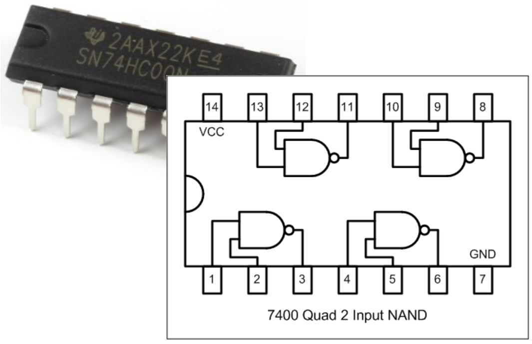
CMOS logic threshold = supply-voltage / 2. Unconnected inputs float "randomly", so use pullup/pulldown resistors. CMOS logic consumes almost zero quiescent currennt.

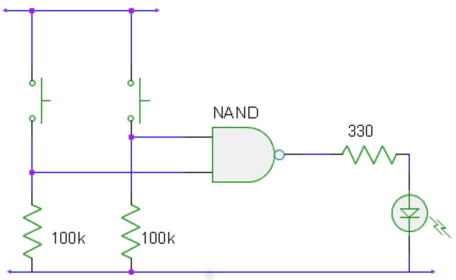
Recommended family: **74HC**-series logic.
74HC00 = NAND, 74HC02 = NOR, etc.
See Wikipedia: "7400 Series".

Integrated circuits are usually supplied in **DIL** [dual inline] chip packages. The *indent on the left denotes pin 1*. Plug into breadboard across the centre gap (squeeze the pins gently together if needed).

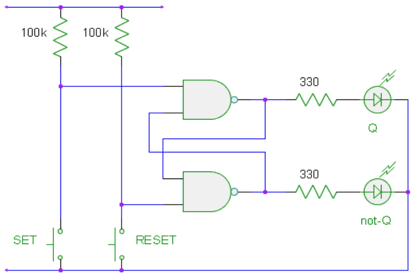
This is a `74HC00` chip, containing **4 x NAND gates in one IC.**
All 4 gates are identical, you can use the ones which are most convenient.

Remember to power-up the chip: the (shared) power connections are:
+5V on V_{CC} (pin 14) and GND on pin 7. ← Optionally, decouple with 0.1 uF.





The NAND gate. Use 2 push-button switches and resistors as simple logic-inputs, and an LED to view the output state. Use `74HC00` or `4011` Gates. There are 4 gates in each IC: it doesn't matter which you use. Note that the ***power-lines*** are not shown, but you must connect them up.

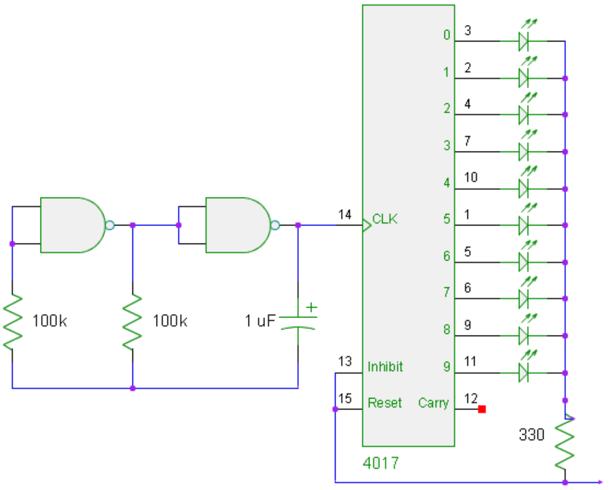


The Set-Reset latch, (a.k.a. the S-R or R-S latch, strictly known as the $\overline{S}$-$\overline{R}$ latch). When Set is low, Q is high. When Reset is low, $\overline{Q}$ is high. When both Set and Reset are high, the output is latched in the previous state. This is a 1-bit memory. [A more complex version of this is in the 7474 IC.]

Experiment #2: NAND gate. Wire up the first circuit, using a `74HC00` logic gate (see pinout above), or a 4011. Remember to power-up the chip using pins 7 and 14 (Power supply lines are usually implicit). Does it do what you expect?

Experiment #3: Now swap it for a NOR gate (`74HC02` or `4001`). Finally, create a compound-AND gate, by using a NAND in series with a NOT; you can make the NOT from another NAND with both inputs connected together.

Experiment #4: Set-Reset **latch**: a 1-bit memory element, which can be *set* or *reset*. Draw the truth table, and build it. [This exists as a dedicated IC, the `74HC74` $\overline{S}$ / $\overline{R}$ flip-flop. Other flip-flops include the D- and J-K types.]



A more advanced circuit. A pair of NANDs form an oscillator, running at ~ 3 Hz. This supplies the clock-input to a 10-way counter, the `74HC4017`, which decodes the output onto one of 10 sequential LEDs.

Since only one LED is lit at a time, they can share a series resistor.
Note: the `4017` has **green** numbers representing the output sequence number, and **black** numbers representing the DIL package pin number.

The reset input isn't used here. Carry-out could be used for cascading counters.

The power lines for both chips are not shown: don't forget to wire them up.

Counters (*sequential* logic) operate internally in binary. The output can be converted, using a *decoder* or *demultiplexer* (*combinatorial* logic) into individual outputs (as here), or a 7-segment display, or a pattern such as spots on a die.

One binary digit is a *bit,* 4 bits are a *nibble*, 8 bits make a *byte*. A nibble is conveniently represented in hexadecimal by one digit from 0-F; a byte is 2 digits. *BCD* is binary-coded-decimal, i.e. 0-9 rather than 0-F. Negative numbers are represented in *two's complement*.

Experiment #5: Build the left-hand half of the circuit (just the oscillator: 2 NANDs, 2 Rs and a C), and check it can flash an LED. Then connect this into the 4017 counter, and make an LED sequencer. Now make it only count up to 5 (i.e. reset the counter on the 6th pulse; remember we start at 0). If you used a push-button switch at pin 14 as the clock-source, what would "switch bounce" do to it?

Experiment #6: Build the electronic cat (circuit diagram shown in the "beeper" section below).

Experiment #7: *Experiment* with the other ICs. You also have: a `74HC02` quad **NOR**, `74HC74` dual **D-Flip-Flop**, a `74HC595` **Shift-Register**, and `74HC4543` **BCD-to-7-Segment Display-Driver**. Read their **datasheets**...

Calculation #8: Bit sequences are often written in Hexadecimal for brevity. What is 0xE9 in binary? 01111011 in hex?

Physics note: www.anandtech.com/print/8223/an-introduction-to-semiconductor-physics-technology-and-industry

Piezo Beeper, and other Sound-related Devices and Signals

These **beep** when a voltage is applied, usually a 1-20 V square wave of about 1 kHz. There is a resonant peak for each type of sounder, and they are much louder when rigidly mounted. The polarity doesn't matter much (the signal is AC anyway). Current draw is low (~ 1 mA): they can even be directly driven by logic-gates.

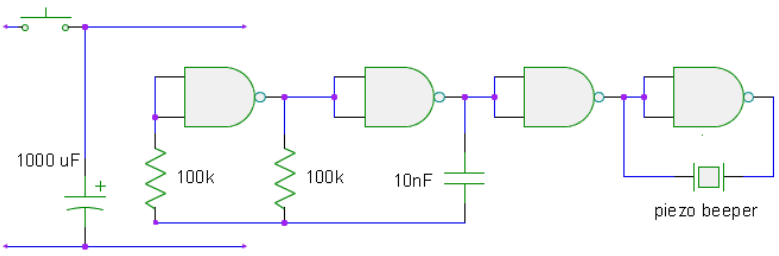
Piezo elements may be un-cased (a thin brass disc, very fragile), or may be within small plastic case (which also helps the acoustic resonance). The sounders usually require an AC signal, (though *some* devices have an inbuilt oscillator, and just require 5 V DC). Square waves sound louder than sine-waves. You can make the beeper 4× louder by driving both sides with anti-phase square-waves, typically using a NOT gate.

It's also possible to use these piezo elements as knock-sensors, or crude microphones. The effect is called "Piezoelectricity".

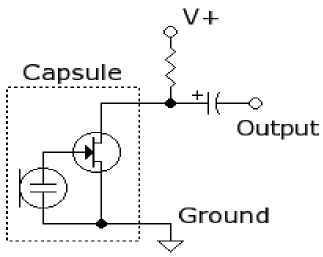
Experiment #1: Connect the beeper to a signal generator. Vary the frequency and find the loudest one.

Experiment #2: *After* learning about logic gates above, build a 1 kHz oscillator from 2 NAND gates. Buffer the output with a 3rd gate (to avoid damping the oscillator), and use a 4th gate to make an anti-phase signal. Then drive the beeper from the 3rd and 4th outputs for maximum volume.

Experiment #3: Place a 1000 µF (electrolytic, polarised) capacitor across the IC's power rails, then arrange a push switch to interrupt the upstream power. Enjoy the pleasant *meowing* of your new electronic pet cat as the voltage falls. [This device is called a voltage-controlled oscillator; the complete circuit is below.]



Oscillator + buffer + antiphase-driver. (Use `74HC00` or `4011` logic gates).
The final gate doubles the voltage change across the beeper, quadrupling the power.
Try doubling the frequency: change 10 nF to 4.7 nF (or use 2x 10nF in series).
Q: What did the engineer name his pet cat? A: Five.



Electret condenser microphone.
Typical DC Bias: 1.5-3 V via 1 kΩ, and
AC coupling of the output via 10 µF.

Other sound transducers: ← a transducer is device which converts signals between forms of energy.

- **Loudspeakers** typically have a low impedance: 4 - 8 Ω. To drive them, you usually need a *step-down transformer*: remember that the impedance-ratio is the square of the turns-ratio.
- **Headphones** are usually ~ 32 - 64 Ω (each side). You can drive them at "line-level" (~ 1 V) with an op-amp.
- **Crystal earpieces** are very sensitive, and *high*-impedance (usually ~ 20 MΩ). They can be driven directly from a crystal-radio (using only the received radio-energy), or even used as simple detectors for mains-hum. (Try it).
- The most common **microphone** is the "Electret", which has an internal FET buffer. Therefore, it needs to be powered in the right way: usually 1.5-3 V via 1 kΩ and 10 µF. ← electrets are dielectric materials with a permanent electric dipole. Other microphones are moving-coil, or carbon granule (simple, resistive, in early telephones). "Mic-level" signals are ~ 1 mV peak-peak; "Line-level" are ~ 1 V. ← audio amplifiers usually distinguish between these.

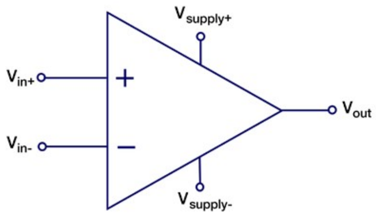
Standard (unbalanced) Audio cables use a ¼-inch or 3.5 mm (TRS) jack plug/socket, or phono (RCA) connectors:
White = Left = *Tip*, Red = Right = *Ring*, **Ground** = *Sleeve*. ← mono uses the left channel; the absent "ring" shorts to the sleeve.

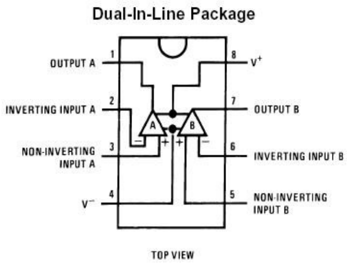
Long cables (100 m) use *balanced* audio to cancel-out interference/crosstalk/mains-hum, combined with twisted-pair or starquad layout to reject EM-coupling. The signal and an inverted copy are transmitted, and subtracted by the receiver, thereby cancelling out common-mode noise. ← use XLR connectors: pin 1 = **X**[sh]ield (ground), pin 2 = **L**ine (hot, +), pin 3 = **R**eturn (cold, -).

[Power] Gain = 10 $\log_{10}(P_{out}/P_{in})$ **dB**. Sound is measured in **dB(A)**: decibels, A-weighted, for the standardised response of the human ear. Human hearing is from 20 Hz – 20 kHz, peaking at ~ 1 kHz; we perceive loudness logarithmically.

See also: **Ground-loops** (a source of noise/interference) and **Star-grounding** (a technique to minimise unwanted feedback).

Operational Amplifiers (Op-Amps)





Op-amps are high-precision linear components, so-named because they were originally used for performing mathematical operations/computations in analog computers. We use the `MCP602` which contains two op-amps in a single 8-pin package, runs from between 2 – 7 V, and is a "rail-to-rail" op-amp, with near "perfect" specifications. ← The DIL version costs 45 pence.

The op-amp has 2 inputs, **non-inverting** (+) and **inverting** (-), and one output. Power-lines are usually not shown, for clarity. Zero current flows into the inputs (in reality ~ a few pA); the output can supply ~ 20 mA. ← MCP602's Zin = $10^{13}\Omega$ || 6pF.

V_{out} = Gain × (V_+ - V_-) Gain ~ 10^5 to 10^{11} (approximation: infinite), V_{out} is constrained by the supply rails.

Rule 1: If there is no negative feedback, then the op-amp acts as a comparator, i.e. the output is always saturated, i.e. at one or other supply rail. ← Standard, non rail-rail op-amps, e.g. the `741` and `358` can't quite reach the supply rails by 1-2 V.

Rule 2: If there is *negative feedback* (any path from output to the inverting input), then approximate the gain as *infinite*. Provided that the output hasn't saturated, the op-amp adjusts to make the inverting and non-inverting inputs equal.

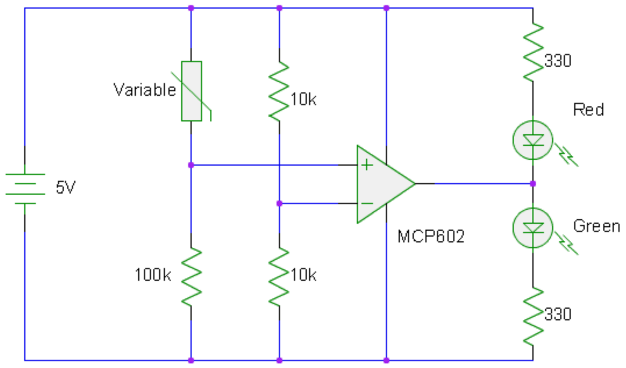
Rule 3: we usually reduce the gain using sets of resistors and negative feedback. So the circuit's gain is always highly predictable, regardless of the underlying gain of the chip itself. ← see also: slew-rate, and gain-bandwidth product.

Op-amps in audio-circuits are usually operated from *symmetrical* split supplies (± 5 – 15 V). This allows signals to be referred to ground, without being near to the saturation point of the op-amp. However, it is often possible to cheat (as we are doing): we use a rail-to-rail amplifier, and, where necessary, a voltage-divider to obtain the mid-point: i.e. consider our single 5 V supply as if it were ± 2.5 V. ← the voltage-divider must be lightly loaded: draw negligible current, ensure "ground" voltage is constant.

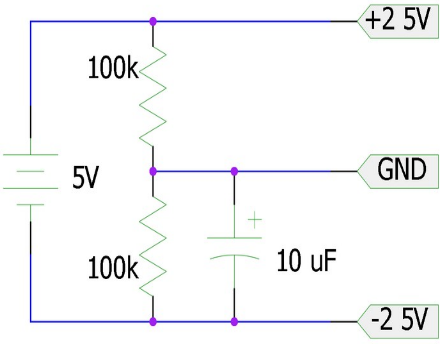
The op-amp power-supply lines are often *omitted* from circuit diagrams for clarity (though shown in the first diagram below).

Very high-precision op-amps, (with high stability and low DC-offset/drift) are called *instrumentation amplifiers* (e.g. `LT1014`) or *auto-zero* amplifiers (e.g. `OPA335`). ← op-amp selection: lowest-noise, vs. lowest-power, vs. bandwidth vs. cost.

Op-amps are useful for buffering signals (e.g. sensors), and for audio-amplification. Circuits include: comparators, buffers, inverting/non-inverting amplifiers, schmitt-triggers, integrators, differentiators, high and low-pass filters, summing amplifiers, difference amplifiers, oscillators, square, sine and triangle-wave generators, gyrators, servo controls, analog computers, ...

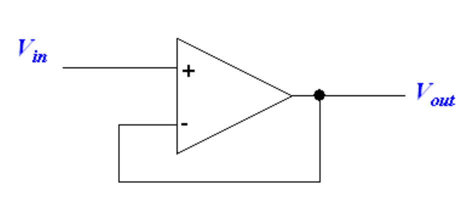


An op-amp **comparator**. Adjust the variable resistor: when $V_+ > V_-$, the comparator's output will swing fully positive (lighting the green LED); otherwise it will go fully negative (lighting the red LED). The output attempts to reach 10^6 × the difference in input-voltage, but is constrained by the power supply.

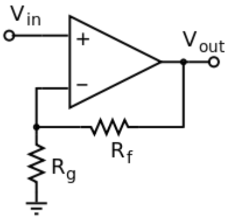


Circuit to "fake" a symmetrical split supply rail, converting a single 5V source into +2.5 V and –2.5 V. If GND is merely a reference point, with negligible current (e.g. inverting amplifier below), this works well. Otherwise, reduce R as needed, or avoid this technique.

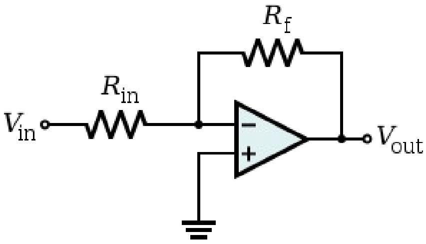
Experiment #1: Build the Op-amp comparator. Try exchanging the variable resistor for an LDR, to make a light-activated switch. What if some light from one or other LED falls on the sensor? Try adding positive feedback: a 1 MΩ resistor from the output to the + input: this makes it more "decisive" at the midpoint, a.k.a. "hysteresis".



The op-amp follower (or unity-gain buffer).



Non-inverting amplifier: Gain = $(R_F + R_G) / R_G$

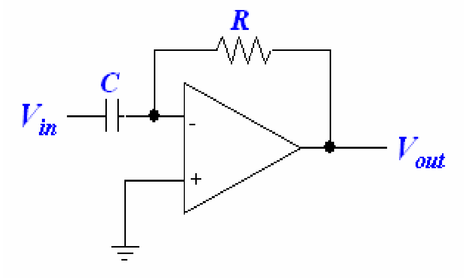


Inverting amplifier: Gain = $- R_F / R_{IN}$.

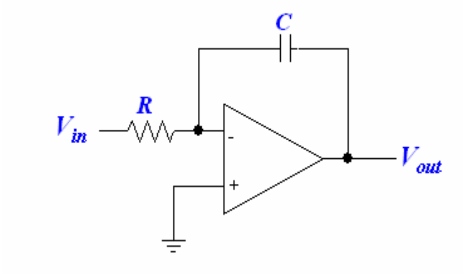
Experiment #2: Op-amp follower. The circuit is very simple. Use it to buffer the output from a high-impedance source to drive a low-impedance device. Can you now measure the *output* voltage of an LED more accurately than by directly using a voltmeter? [`MCP602` datasheet: Zin > $10^{12}\,\Omega$ (yes, it *really* is that good).]

Experiment #3: Non-inverting amplifier. Only a fraction of the output is fed-back, so the output must move more than the input in order to keep V_+ equal to V_-. Use $R_F = R_G = 100$ kΩ, for a gain of +2.
NB: the non-inverting (+) input should be connected to earth *in the context of a split supply voltage.* Fake it, with a stiff-source mid-point at 2.5 V, from a pair of 1 kΩ resistors in series across the 5 V supply. Test it with an oscilloscope and signal-generator.

Experiment #4: Inverting amplifier. Choose input, feedback resistors to obtain a gain of -50, and test. Note that the inverting (-) input is always at the same voltage as the non-inverting (+) input: it is a "*virtual earth*", since no current flows into it. [Now, the 2.5 V midpoint potential-divider can use 100 kΩ resistors.]



Inverting differentiator. $I = C\, dV_{in} / dt = -V_{out} / R$



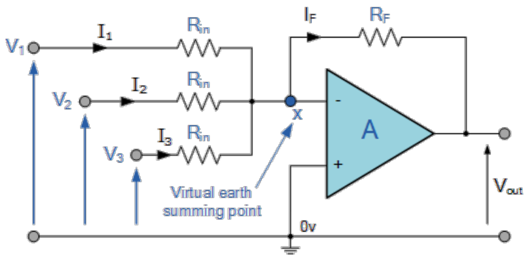
Inverting integrator (NB: the "plus a constant" from the offset/drift).

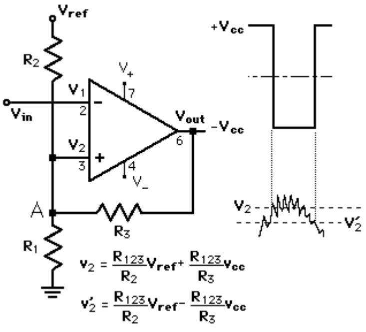
Experiment #5: Inverting differentiator. Swap #4's R_{in} for a capacitor. (Try 0.1 μF and 1 kΩ, giving τ = 0.1 ms). What does it do if the input is a 10 kHz sine-wave? Square-wave? Vary the frequency, R, or C?

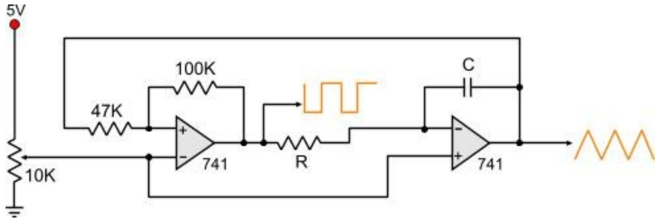
Experiment #6: Inverting integrator. Why won't this circuit actually work in the real world? What's the best you could do?

Experiment #7: Design/build an audio amplifier, using the electret mic and the earpiece, with inverting gain = -100. [Hints: 3 V for mic via voltage-divider, 2.5 V virtual-earth, coupling capacitors, 100 μF across DC supply.]

… and a few more, just for fun. The inverting summing amplifier makes use of the fact that zero current flows into a virtual earth to create a weighted sum of the inputs. The Schmitt-trigger uses some positive-feedback to add hysteresis: the switching thresholds vary depending on the current state of the output. Finally, a triangle-wave generator, which uses two op-amps (to understand the cycle, start with the left-op-amp's output being low, and C uncharged).





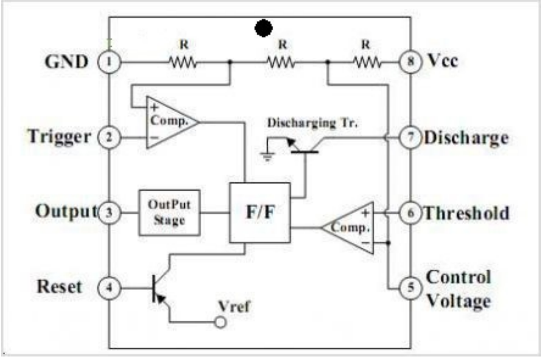


Top-left: inverting summing amplifier.
Top-right: inverting Schmitt-trigger.
Bottom-left: square and triangle-wave oscillator.

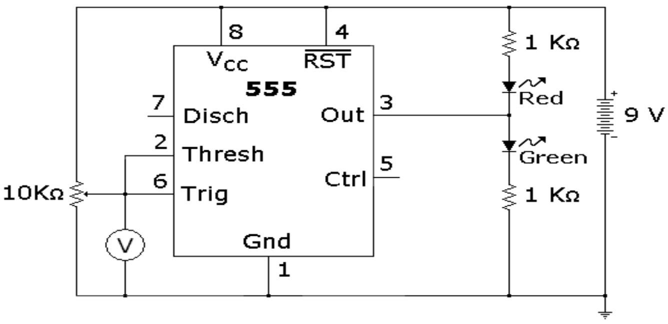
The 555 Timer IC

This is an *exceptionally* useful and *versatile* device. It can be used as a buffer (connecting a sensor input to a higher-power load), a Schmitt-trigger, an astable (oscillator), a monostable (single triggered pulse), and about 1000 other things (search for "*555* application note"). It contains a voltage divider network, two comparators, a flip-flop, a discharge-transistor, and a power-output stage.

We use the original (bipolar transistor based) `NE555` chip (supply-voltage: 4.5 – 16 V) since it has higher output-current capability (200 mA), and is more robust, and very low cost. However, for most applications, use the improved (CMOS) `7555` variant, with a wider supply-voltage (2 – 18 V), and much lower input current (20 pA). Search: "555 datasheet" or "7555 datasheet". See also the *Wikipedia* article "555 timer IC". ← 555s are inexpensive (8 pence each)

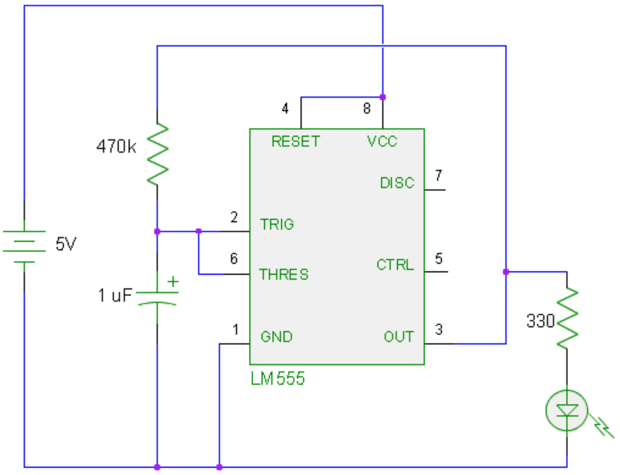


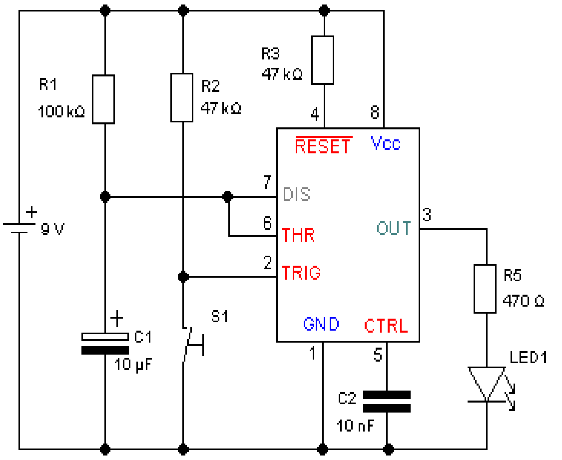
The `555` (`NE555`) pinout: 8 pin DIL, **indent at pin 1**. This also shows some aspect of how the device works. Among other advantages, the time-constant is designed to be easy to calculate, and nearly independent of supply-voltage: it always triggers at 1/3 and 2/3 of the supply.



The `555` NOT gate. Pins 2,6 are the input, and Pin 3 is the output. As the input voltage varies, the output switches state at 1/3 and 2/3 of the supply voltage. This inverting hysteresis can be used to make a "Schmitt-Trigger".

Experiment #1: The `555` Schmitt NOT-gate. Observe the hysteresis (different input thresholds depending on output state). The input current is small (< 1 µA), yet the output can supply 200 mA, for a small bulb, or loudspeaker. Make a dark-activated light (use an LDR, 100 kΩ voltage-divider on input, light bulb on output). [Note that pin 4 is the "Reset" input: whenever taken low, it always forces the output low.]





Astable: the circuit constantly oscillates. (a.k.a. "relaxation oscillator"). When output (pin 3) is high, the capacitor charges through the resistor. Once the voltage reaches 2/3 of supply voltage, threshold input (pin 6) makes the output low. The capacitor now discharges, until it reaches 1/3 of supply voltage, when the trigger input (pin 2) makes the output high again. Frequency ~ 1/(2RC) .

Monostable: one stable state, and one temporary unstable state. A low-going pulse on pin 2 triggers it, and the monostable makes the output (pin 3) briefly high, during the time it takes C1 to charge through R1. After the output pulse, discharge (pin7) prepares the capacitor for the next cycle. Take reset (pin4) low to stop the pulse.

Experiment #2: Relaxation oscillator: the simplest possible oscillator, using feedback. $\tau = RC$. Look at the outputs on pins 2 and 3 on an oscilloscope. Change R,C and drive the beeper at 1 kHz. [A better `555` oscillator circuit uses pin 7, and a pair of resistors for mark/space-ratio adjustment.]

Experiment #3: The monostable (timer). A short pulse low on pin 2 causes pin 3 to go high for a time of ~ RC. What happens if pin 2 is held low for longer than RC?

Experiment #4: Play with the other `555` pins, e.g. change the voltage on pin 5, and observe the signals on a 'scope.

The `555` internally contains 24 transistors, some diodes and resistors: the circuit diagram is available online.
The `555` can be misused in some truly *creative* ways, as described here: www.evilmadscientist.com/2011/some-gems-from-the-555-contest

Computer-Interfacing

To interface circuits and experiments to a computer, consider using one of the following:

USB interfaces, such as the `DLP-IOR4` USB relay board or `USB-245M` 8-bit I/O module, see: dlpdesign.com .

The **Arduino** (or Arduino Nano): an microcontroller that can be programmed in C, which also has an IDE (integrated development environment). Typically 12 digital outputs, 5 analog inputs, standardised peripherals, and a USB-serial port. [Variants: Arduino **Mega** (more I/O ports); **Teensyduino** (faster); **Digispark** (tiny); **ESP8266** or **ESP32** has Wi-Fi].

A **Raspberry Pi**: a tiny Linux computer which has onboard GPIO and other features such as I2C, programmable in C or Python. Recommended: **Model 3B** (with heatsink). The Pi Zero is now available for tiny projects. See www.raspberrypi.org and www.cl.cam.ac.uk/projects/raspberrypi . A complete IOT project is at: richardneill.org/src/dinnerdog .

For further inspiration, look at www.sparkfun.com and www.adafruit.com . See also Node-RED.

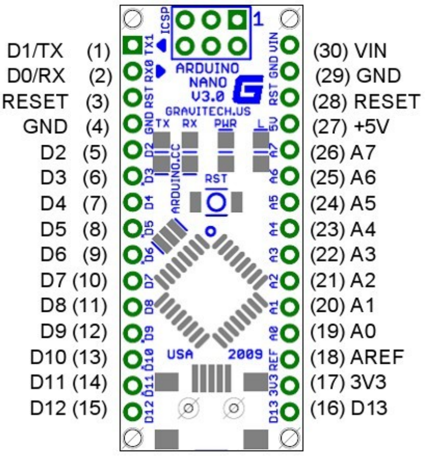
Arduino Nano

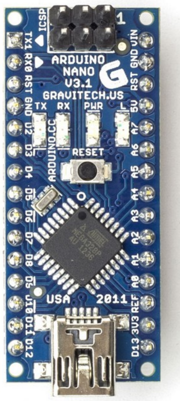
The **Arduino** is a simple, yet versatile, **microcontroller** combined with a cross-platform integrated development environment (IDE). Once programmed, the Arduino can run stand-alone, or it can be used as an interface between your computer and the electronic circuit, or experiment of your choice.

← An Arduino Nano 3.0 (clone) now only costs £2.89 !

arduino.cc/en/Main/ArduinoBoardNano	- Specifications and Hardware description of this device.
arduino.cc/en/Reference/HomePage	- Programming language (basically C, with useful functions).
arduino.cc/en/Main/Software	- Download the **environment** (Linux/Mac/Windows).

The microcontroller is an Atmel **`ATmega328`**, with 32 kB of ROM, 2 kB of RAM, and a 16 MHz clock. This is remarkably capable. It includes a USB-serial port, 14 digital pins and 8 analog inputs, as well as PWM, timers, SPI, I2C and several other useful functions. It runs at 5 V (the on-board **voltage regulator** accepts 6-20 V), and can control ~ 40 mA. For further expansion, use Arduino "shields", or bigger boards like the Mega. Really tiny circuit boards also exist. The Arduino environment is widely used and capable, but it's really just C / Assembler. The pinout and a photo are shown below: this is in the footprint of a large DIL IC (be careful not to force it too hard into the breadboard).





Arduino Nano v. 3.0 or 3.1 (45mm x 18mm).
This includes a USB serial port, 6-20 V voltage-regulator, ATmega328 8-bit CPU, and digital/analog I/O.

A microcontroller (µC) is a microprocessor, complete with all the useful extras (memory, ADC, power-control, etc. in a single low-power IC costing about £1.
The USB-serial port adapter is already onboard the PCB.

The Arduino is an open-source design and environment, which supports different models of board, CPU, and has standard "shields" which plug in to add functionality.
It's deigned for education (which makes it really easy to get started), but is powerful enough to run all sorts of interesting devices (e.g. to control a 3D printer).

Experiment #1: To get started, simply download the (free) IDE, connect the Nano via USB (no other circuit is needed), open the first "sketch" [File → Examples → 01.Basics → Blink], select your model of Arduino [Tools → Board → Nano, ATmega 328], and USB Serial port [Tools → Serial Port → /dev/ttyUSB0], then Compile and Upload to the µC. You have now deployed 1 *million* transistors to make a flashing LED! Try changing delay = 100 (lines #21 and #23).

Experiment #2: Read analog sensor data (LDR, microphone, reed-switch) and vary the colour and brightness of an RGB LED (by pulse-width-modulation (PWM). Extension: try controlling a string of 100 "Neopixel" (WS2812B) digital LEDs.

For a real-world experimental-physics example, take a look at: richardneill.org/src/arduino_delay/

For an excellent detailed **tutorial**, including the **C programming language**, read the "Arduino Starter Kit Manual", by Earthshine Design. You already have most of the parts required for this e.g. `74HC595`. The Nano is compatible with the "Duemilanove" (just look at the pin names). The manual is at: math.hws.edu/vaughn/cpsc/226/docs/askmanual.pdf

Note that the *Apollo Guidance Computer* (the one that took humanity to the Moon aboard the Saturn V rocket) has a very similar spec, but ran at only 2 MHz.

Reference: Sensors (a brief list)

Light:	LDR (light-dependent resistor, usually CdS), photodiode, phototransistor, solar-cell, colour detector.
Sound:	microphone (moving coil, piezo, electret, digital). Loudspeaker (used as a sensor).
Heat:	thermistor, thermocouple, change in diode-bandgap, `LM35` temperature IC (easiest to use).
Magnetism:	reed switch (SPST or SPDT), Hall-effect IC.
Position:	tilt-switch, various kinds of gyro and accelerometer IC (see e.g. Sparkfun), rotary-encoders, strain-gauge.
Force:	various switches, microswitches, quantum-tunneling composite, resistive-touchscreen.
Misc:	flammable gas-sensors, liquid level (conductivity or capacitance), proximity sensors (optical or ultrasound), Geiger-Müller tube, humidity, pressure, CCD camera.

Reference: Permanent Construction

To make a circuit permanent, it's usually wired on a Printed Circuit Board, and then **soldered**. Soldering is quite easy: heat both parts simultaneously, *then* flow in the solder. Don't use the iron to transfer the solder onto the job. A proper job will be "wetted" completely, and looks shiny once cooled. The physics of "Eutectic melting" and "Tin Whiskers" is interesting.

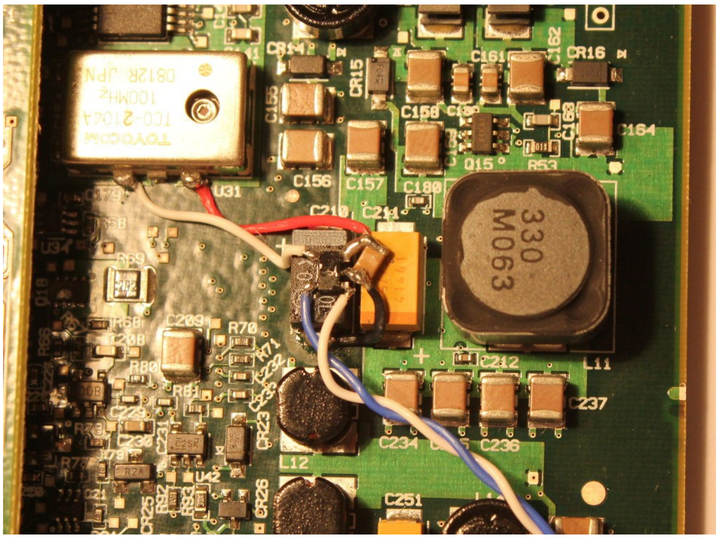
Take care not to burn your fingers, nor to heat up semiconductors for more than 3 seconds. Practice first. Insulated wire tends to melt: work quickly, or use Kynar or PTFE-coated wire whose insulation does not shrink back. A basic 25-watt iron is sufficient, though temperature-controlled soldering-irons are nicer to use. You will find a solder-sucker, and desoldering-braid to be useful. Tin-Lead (Sn-Pb) solder is still available for non-commercial use, and it works better (lower melting point) than the lead-free type (186 ºC vs. 217 ºC): but wash your hands afterwards, also don't breathe the fumes. Take care to avoid solder splashes, or wear goggles. Most components are still available as "through-hole" (with wires), but increasingly, are "surface-mount" (SMD) which are very, very small! (SMD how-to on YouTube: "Gavan Fantom: Hobby electronics like a pro").

PCBs are expensive though, so for one-offs, you may also consider:

- Stripboard (veroboard): easy, cheap, fast, but very ugly. Use a veroboard spot-cutter tool to break the lines.
- Perma-proto: a different layout, just like a protoboard breadboard (this product is made by Adafruit).
- Solder to tagboard: point-to-point construction for larger circuits (may use an actual wooden bread board).
- "Dead-bug" construction, for simple circuits: bend the legs, crop unused pins, solder, (and maybe heat-shrink tube).
- Super-glue components to a base, bend the wires into a 3-D structure and solder (this works surprisingly well).
- "Manhattan style": copper board for base/ground-plane; cut out and glue small pillars for non-grounded points.
- Actually make a PCB: not too costly if you can accept 2-week lead-times. 1-layer boards are easy to DIY.

Schematic, PCB software, manufacturing: gpleda.org pcb.geda-project.org fritzing.org pcbtrain.co.uk
(Many of the circuit diagrams in this document were drawn in *Gschem*, part of *Geda*.)

Recommended component suppliers in the UK: *Rapid Electronics*, *Farnell*, *Proto-PIC, Pimoroni.*
With care, you can buy unusual components at low cost in bulk on *eBay/Amazon/BangGood* – but be careful of quality.



This shows a variety of techniques. The circuit is built on a multi-layer (4+) laminated fibreglass and copper printed-circuit board (PCB). The top layer has solder-resist and silk-screen; tracks on different vertical layers are connected by using vias. Most of the components are surface-mount; except for the large crystal-oscillator module, (top-left) which is through-hole.

The `NI4462` device has been modified to export a clock signal, by adding a `FIN1001` transmitter IC and power-decoupling capacitor, these were glued on, and soldered with short-lengths of PTFE-coated 0.7mm diameter wire.

Actual width: 5.3 cm: some of the SMD (surface-mount device) resistors, such as R70 are really really small! TQFP chips can be just-about be hand-soldered (under a microscope), but soldering BGA (ball-grid-array) devices requires robotic placement and a reflow oven.

Note: circuits that run at > 10 MHz, or use signals < 100 µV require a level of "**magic**". Parasitic capacitances and inductances dominate, while every component acts as a radio transmitting/receiving aerial. Even simple PCB traces have non-negligible capacitance, resistance, and inductance. Resistors and transistors are a source of noise. Circuits that work in practice do not necessarily work in theory – and vice versa! At high-frequency, oscilloscope probes *affect* what they measure!!

Reference: Electrical Safety !!

Electronics of this type (as long as it remains low-voltage) is generally safe. However, bear in mind:

- Don't wire up 240 V mains circuits. Seriously *just don't do it.* Not until you have a lot of experience, and then some more. Electric shocks are not much fun, especially if the path is across the chest. If you are unlucky, you may be unable to release your grip; if lucky, your own muscle contraction could throw you across the room! 1 mA is quite enough to hurt you, and > 50 V is always dangerous. Wet skin, sharp wires, or arcs increase the risk.

- Even low-voltage circuits can be dangerous if the current is high enough. Ultracapacitors and Lithium Batteries can inadvertently summon Vulcan. Shorting USB ports should do no permanent harm (they are supposed to be "over-current protected"), but will likely crash your computer, and may damage the port. If you measure your power-supply voltage with a DMM set to current-mode, you'll need a new fuse, and will learn not to do it again ;-).

- When unplugging DIL ICs from breadboard, especially if they are stiff, take care. They have surprisingly nasty *sharp* legs, and it is really easy to jab yourself in the thumb. Even worse, you might bend the legs on the IC.

- Static discharges (ESD) probably won't hurt *you,* but they can silently destroy susceptible devices (especially CMOS ICs and FETs, and PC internals). Anti-static precautions are wise, but at least, don't wear nylon/fluffy clothes, and touch a grounded terminal periodically (and try not to scuff your shoes on the carpet).

- Don't eat the parts (especially button cells and neodymium magnets). Likewise, be careful after handling lead-based solder (wash hands, don't breathe flux fumes). Obviously, soldering irons are *hot*. If you knock it off the bench, do not reflexively attempt to catch it as it falls!

- RF emissions are bad for your wealth if you emit enough interference to make Ofcom track you down...

- Attempting to hand-solder smaller SMD devices (such as 0402 or TQFP) will drive you crazy and cross-eyed.

- High voltages (~ MV) can jump several meters, even through air. High-voltage (kV) arcs emit UV and X-rays.

- Tesla Coils and Lasers (even cheap eBay pointers) are "safe" toys... in the same way that crocodiles are good pets.

Computing

All scientists need to know how to control a computer. You will need to learn programming at some point. It is far more likely that you will be productive if you are familiar with *Linux* than if you try to proceed with a consumer-only system such as OSX or MS Windows. Recommendation: download and install *Ubuntu*, (probably in the XFCE or MATE flavour, for 64-bit systems): it is *free* from ubuntu-mate.org or xubuntu.org , and you can try it out from a USB key. You should then gain some familiarity with (Bash) *shell-scripting.* For scientists, GNU *Octave* (compatible with Matlab) and *Numerical Python* are recommended. Also, pick one of *PHP*, *Perl*, *Python*. Recommendation: don't begin with: C, C++, Fortran, or Java. Never, ever, use spreadsheets for serious work.

And Finally, Just for Fun

You may find that a few of these search terms yield fascinating and entertaining results...

- HackADay • Instructables • EEVblog
- The Electrician's Ten Commandments • XKCD Circuit Diagram
- YouTube: Mr Carlson's Lab • BigCliveDotCom • ElectroBoom • GreatScott! • Andreas Spiess • Technology Connections • PhotonicInduction
- Zeusaphone • Tesla Coil • Jacob's Ladder • Cockcroft-Walton multiplier • Hand making Vacuum Tubes
- Das Blinkenlights • Mercury delay line • The Story of Mel • Apollo Guidance Computer
- LED in Liquid Nitrogen • Unwise Microwave Oven Experiments • Plasma physics
- Mike's Electric Stuff • Vacuum tubes • Geissler tube
- PowerLabs • Rail gun • Capacitor bank • Ultracapacitors
- CentennialBulb • Alexanderson alternator • Coherer • History of Radio (and Radio Astronomy)

~ The End ~

To do: explain more on amplifiers (especially sources of noise, shielding, ground-loops, balanced cables), high-frequency parasitics and "magic", physics of radio aerials, AM radio circuits, how valves/vacuum tubes work, ADC, sampling and the Nyquist theorem. Use of Oscilloscopes (Android/iPhone apps).

Appendix: Some Circuit Ideas

Here are some ideas you may wish to try out, as sources of inspiration:

1. Use of Android application as a Signal Generator and Oscilloscope. There are many suitable apps which connect in via the headphone/mic port; use a series resistor of at least 100 Ohms to protect your phone, and keep the voltage below 5V. Or you can buy a cheap ‘scope (the £25 basic ones are surprisingly decent, within their limits).

2. Sense the environment. Scuff your socks on a carpet, then hold one of the wires of a neon bulb, and touch the other to a metal object; it will flash. Or, touch one terminal of the crystal earpiece and ground the other; your body acts as an antenna and you will clearly hear the mains hum. (The screws on a wall-mounted light-switch are always grounded).

3. Build a simple AM radio receiver. You’ll need a ferrite rod antenna and variable capacitor, and maybe a germanium diode. It might be possible to use the included inductor, and a capacitor of approximately 60 pF (N.B. stray capacitances) to receive BBC Radio 4 on 198 kHz longwave.

4. Build an Electronic Candle. Use an LDR and Op-amp comparator so that the light from a torch falling on an LDR makes the op-amp’s output go from low to high. Drive the filament lamp from this, via the MOSFET. Arrange for some of the lamp’s light to fall on the LDR (positive feedback). In a darkened room, you can “light” the candle with a match, and “blow it out” by covering the LDR as you pretend to blow on the bulb. Reverse the comparator to make a night-light.

5. Electronic Candle v2: added flicker. Use a chain of 74HC595 shift-registers and an XOR gate to build a linear-feedback shift-register, which generates a “pseudo-random” pattern of repeating bits. Use this to make your candle flicker.

6. Theremin. Build a theremin, with a voltage-controlled oscillator. A small speaker will make this more impressive. Either control it with the LDR, with the 2N7000 to detect electric field, or “properly” with a heterodyne oscillator.

7. Build an audio amplifier. Use the Op-amp to drive a push-pull output stage (NPN + PNP transistors) with negative feedback for linearity. Connect it to the microphone, or one of the above circuits. Then output to headphones. If the gain is sufficiently high, you can use the microphone to pick up your own breathing or your pulse (avoid screaming feedback).

8. Electronic “Piano”. Use a carefully calibrated resistor chain to get different oscillation frequencies from a 555. The “Concert A” pitch is 440 Hz, while successive notes increase in frequency by a factor of 2 ^ (1/12). You’ll need resistors in series / parallel, or try drawing on A4 paper with a graphite pencil. There are tuning applications for phones that will help calibrate it. Or you could use the Arduino. Try shaping the waveform with multiple oscillators, filters, or a DAC.

9. Pulse detector. Use the piezo element as a knock-sensor. Connect it via a latch (S-R flip-flop) to an LED. Or trigger a 555 monostable. This kind of pulse-detector is useful for counting particles.

10. Electronic Die. Use a fast oscillator, counter, and logic decoder circuit to show the numbers 1-6 as a set of spots on 7 suitably-arranged LEDs. There are many ways to do this, varying from the 555 + 4017 + 7400 approach, to using the microcontroller. Some approaches use diodes to form the logic-decoder.

11. Build a lie-detector. Measure skin-resistance. Use an op-amp comparator, or an op-amp oscillator and listen to the frequency.

12. Bargraph display. Use both op-amps to give a 3-level display. Note that CMOS logic gates switch quite accurately at the supply-voltage midpoint, so you can nake extra comparators that way.

13. Measure something in physics. Use the piezo sensor as a pulse detector, and tape it to a table. Make it flash an LED every time a ball bounces. Now use the Arduino to time the successive pulse intervals. Does it fit the model? The Arduino can capture analog signals too. (Light-gates are useful, but you’ll need a phototransistor: the LDR’s response time is too slow).

14. Build a stroboscope. Use the white (or high-intensity narrow-beam) LEDs, and the 555 to produce short pulses of variable frequency. A 1% duty-cycle (mark-space ratio) at 50-500 Hz is a good place to start. Observe falling droplets of water and see if you can make them appear stationary, or move slowly upwards in reverse. The perceptually brightest LED is the Green high-intensity, which can support an *average* current of 30 mA. But the limit here is thermal, so at a 1% duty cycle, you can increase the current: peak currents of 300 mA are OK, *provided* that the duty-cycle is low and that the frequency exceeds 10 Hz. Ensure your circuit can never stop oscillating, before reducing the LED series-resistors.

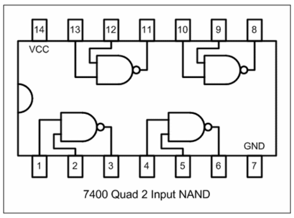
15. Use the Arduino to control a chain of individually addressable WS2812B “Neopixel” LEDs for exciting festive lights.

16. The sky is the limit... what are you inspired to create?

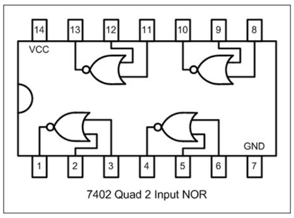
Appendix: Components, Pinouts and Data (see also datasheets)

Resistors:	1/4W carbon: 100R, 1k, 10k, 100k, 1M, 10M, 220R, 2k2, 22k, 220k, 330R, 470R, 4k7, 47k, 470k. [x10 each, x20 of 1k,10k,100k] Variable: 1k, 10k, 100k single turn preset potentiometer with shaft. 10% tolerance. [x1 each] Thermistor: 5mm disc type. NTC (negative temperature coefficient). 10 kΩ @ 25 ºC, 670Ω @ 100 ºC. (Farnell part: *118-7031*) LDR: (light-dependent resistor): > 10 MΩ (dark), 10 kΩ (indoors), 450 Ω (torch beam). Freq ~ 1 Hz. 80 mW max.
Capacitors:	Ceramic: 100p,1n,10n,100n,1u,4.7n,47n,470n [x4 ea.]; Electrolytic: 1u,10u,100u [x2 ea.]; 2u2,22u,220u, 4u7,47u,470u, 1000u [x1 ea.]
Inductor:	10,000 uH (40Ω series resistance) [x1]
Diodes:	(Cathode, negative connection, k, has a stripe. Zeners are used “backwards” in reverse-breakdown mode.)
`1N4148:`	Signal diode. V_f = 0.6 V (falls as temperature rises). I < 100 mA. $V_{reverse}$ < 100 V [x5]
`BZX55C33:`	Zener diode. V_{rev} = 3.1 – 3.5V. Power dissipation < 500mW (The zener diode is larger than the signal diode) [x3]
LEDs:	(Anode leg (+) is longer, cathode has a flat on the side of the package.)
5mm diffused:	Red (V_f = 1.9 V), Yellow (V_f = 2.0 V), Green (V_f = 2.0 V), Blue (V_f = 2.8 V), White (V_f = 2.8 V). I < 20 mA. [x2 each]
5mm clear:	RGB (4pins, common anode, anode = longest leg, flat:{K_R, A, K_G, K_B}). I < 20 mA. [x2]
High-Brightness:	Red (V_f = 2.1 V, 40 mA, 624 nm), Green (V_f = 3.0 V, 30 mA, 527 nm). Both 35000 mcd, 15°. [x1 each]
7-segment:	Red (V_f = 1.9 V), 10 mA/segment. Pinout: 10 pins, common anode = center-top *and* center-bottom. [x1]
Transistors:	NPN: `BC549C` [x7]; PNP: `BC557C` [x2]. N-MOSFET: `2N7000` [x1], `IRF510` [x1]
`BC557C`, `BC549C`:	Gain ~ 550. V_{CE} < 45V. I_c < 100 mA. Power < 500 mW. TO-92 case: orient to read the label, left:{C,B,E}:right.
`2N7000:`	V_{DS} < 30V. I < 75 mA. $R_{DS(ON)}$ < 5Ω. $V_{GS(Th)}$ = 1 - 3V. T0-92 case: orient to read label, left:{Source,Gate,Drain}:right.
`IRF510/IRFZ44:`	V_{DS} < 100V. I < 5.6 A. $R_{DS(ON)}$ < 0.5Ω. $V_{GS(Th)}$ = 2 - 4V. T0-220AB case: orient to read label, left:{Gate,Drain,Source}:right.
Integrated Circuits:	(DIL ICs, pinouts below. Notch/dimple always on left, then pins are numbered anti-clockwise from bottom-left corner).
`MCP602:`	Dual Op-Amp. Supply: 2.7 – 6 V, 250 µA. I_{in} ~ 20 pA, I_{out} < 20 mA. Freq < 2.8 MHz. DC Gain 115 dB (10^{11}). CMRR 90dB. $Z_{in} = 10^{13}$ Ω, 6 pF. Rail-rail input (includes 0.3V below ground) and rail-to-rail output (within 50 mV of supply each side). [x1]
`NE555:`	Timer. Bipolar version. Supply: 4.5 – 16 V. I_{in} < 0.1uA, I_{out} < 200 mA. Frequency < 1 MHz. [x2]
`74HCxx:`	74HC Logic. Supply 2-6 V. I_{in} < 0.1 µA, I_{out} < 20 mA. Freq < 50 MHz. Corner pins are GND and V_{CC} (positive). [x1 each] `'00` = NAND gates; `'02` = NOR gates; `'74` = D-flip-flop; `'4017` = decade counter; `'595` = shift-register; ~~`'4543` = BCD/7-segment.~~
Lamps:	Neon bulb (strike voltage: 95V); MES filament bulb + holder: 6 V, 100 mA, 0.6 W. [x1 each]
Switches:	SPST tactile 2-pin push switch 5x5 mm [x4]; Reed switch (SPST) + magnet (Nd) [x1]
Relay:	Coil: 5 V, 75 Ω, 54 mH. Contact: 7 A , SPDT (changeover). Pinout: CW from above, top_left{NO,coil,C,coil,NC}:bottom_left. [x1]
Arduino:	Arduino Nano v. 3.1 (clone) + mini-USB cable. ATmega328; 32 kB ROM, 2 kB of RAM, 16 MHz, PWM, ADC, I2C. 6-20 V. [x1]
Sound:	Beeper (resonant ~ 2.4 kHz). Piezo element. Electret mic (3 V, 1 kΩ via 10 µF; Case = Gnd). Crystal Earpiece (> 20 MΩ). [x1 each] TRS socket (stereo, 3.5 mm jack). Pinout: clockwise from above: {Sleeve, Tip [socket hole] Tip, Ring} = Gnd,Left Left,Right.
Misc:	Solderless breadboard: (830 holes: 63x10 + 4x50 in 2 pairs split supply rails) [x1]. Solid-core wire [2m x11]. 0.9l Box [x1] Side-cutters [x1]. USB power-cable (tinned ends, or micro-USB PCB) [x1]. Crocodile-clip leads [x2]. PP3-9V battery clip [x1]
Meter:	XL830L Digital Multimeter. Features: DC-voltage, AC-voltage, DC-current, Resistance (up to 2 MΩ), Continuity beeper, Diode (+LED) test, NPN/PNP Transistor gain. Uses 9V battery. [DC Voltage mode: input-impedance (Z_{in}) ~ 1 MΩ.] [x1]

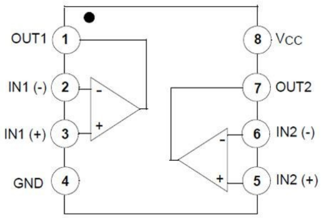
74HC00 NAND gate
Quad, 2-input:



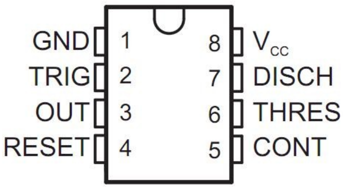
74HC02 NOR gate
Quad, 2-input:



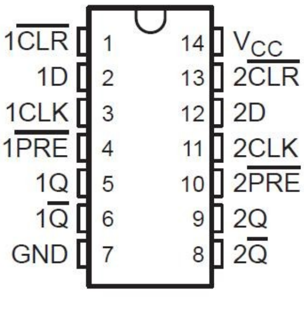
MCP602 Op-Amp
Dual Rail-Rail:



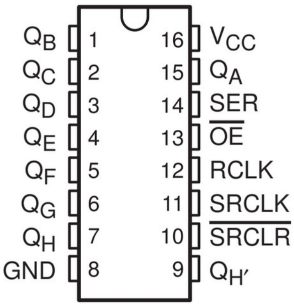
555 Timer IC
(The 7555 is similar):



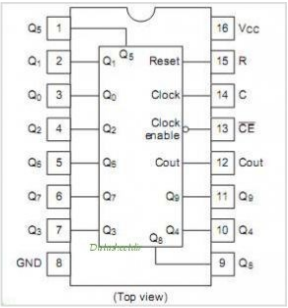
74HC74 D-Flip-Flop
Dual. (Pre/Clr = Set/Reset):



74HC595 Shift-Register
Serial-in, Parallel out :



74HC4017 Decade Counter with decoder:



~~**74HC4543 BCD to 7-segment** decoder/driver.~~ (Alt: 74HC4511)