Foundations of Practical Electronics
An Intuition-Driven Guide to Circuits and Systems

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Preface

Written as a personal technical reference and learning companion. Designed to allow rapid re-entry into circuit design after time away, and to serve as an intuitive introduction for motivated beginners.

This document does not at this time attempt to cover RF design, high-speed PCB layout, or integrated circuit design. These topics are intentionally excluded in favor of foundational circuit-level understanding. This document describes digital electronics concepts, unless analog behavior is specifically noted.

Familiarity with basic algebra is assumed. Calculus is not required. Prior exposure to Ohm's law, discrete mathematics, or basic logic gates may be beneficial, but all required concepts are introduced as needed.

Emphasis is placed on physical intuition, failure modes, and mental models rather than formal derivations. Mathematical rigor is introduced as optional material only where it directly supports understanding.

All circuits are assumed to operate at low voltages. Readers are responsible for safe practices when working with electricity.

This is an early, evolving technical manuscript.

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Thinking Discretely

We will begin by clarifying a common misconception. Discrete is defined as being separate, distinct, or individual, while discreet implies prudence and being careful.

Binary

In practical digital electronics work, electrical states are treated as discrete values. That is to say, its behavior is abstracted into separate states. Once a signal crosses a defined threshold the circuit is interpreted as being on, or off. Although voltages are continuous, Intermediate values are ignored, this abstraction is the basis of digital electronics. Operating on continuous values would describe analog behavior which is beyond the scope of this document.

As a simplified example, assume a threshold of 0v. All voltages above this level are considered to be logic high, while any voltage below zero is interpreted as logic low.

These HI/LO states are also represented as 1's and 0's. This forms the foundation of binary code, and describes the action of a digital signal.

Logic Gates

Logic gates operate on logical states, HI/LO, 1/0, not on voltages.

Each logic gate performs a specific Boolean operation which deterministically maps input states to an output state.

Output states are determined only by the current input state, past input values have no impact on output.

The output of one logic gate may be connected to the input of another, allowing for complex functions to be constructed.

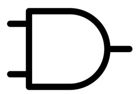
Every input must be satisfied, undefined inputs (not connected to anything) do not represent valid logical states.

Below, the three simplest logic gates and their behavior are listed.

AND

AND, also referred to as conjunction, is a logical operator which accepts at least two inputs, and outputs TRUE only when both inputs are TRUE.

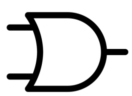
It can be represented graphically as follows.



OR

OR, also referred to as disjunction, is a logical operator which accepts at least two inputs, and outputs TRUE when at least one input is TRUE.

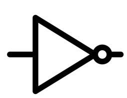
It can be represented graphically as follows.



NOT

NOT, also referred to as negation, is a logical operator which accepts at least one input, and outputs the opposite of the input.

It can be represented graphically as follows.



Truth Tables

The behavior of any given logic gate is defined by its truth table. Truth tables are logical tools which list every possible combination of input variables, and are used to determine their outputs. Truth tables value lay in their ability to determine the logical validity of a given logical argument.

The Truth tables for AND, OR, and NOT gates are given below

<table>
<tr><th colspan="10">AND OR NOT
INPUT |OUTPUT INPUT |OUTPUT INPUT|OUTPUT</th></tr>
<tr><td>0</td><td>0</td><td>0</td><td></td><td>0</td><td>0</td><td>0</td><td></td><td>0</td><td>1</td></tr>
<tr><td>0</td><td>1</td><td>0</td><td></td><td>0</td><td>1</td><td>1</td><td></td><td>1</td><td>0</td></tr>
<tr><td>1</td><td>0</td><td>0</td><td></td><td>1</td><td>0</td><td>1</td><td></td><td></td><td></td></tr>
<tr><td>1</td><td>1</td><td>1</td><td></td><td>1</td><td>1</td><td>1</td><td></td><td></td><td></td></tr>
</table>

Boolean Algebra

Boolean Algebra is a branch of mathematics and the fundamental logical operators, AND, OR, and NOT can be written symbolically as $\wedge$, $\vee$, and, ¬ (or alternatively, ~)

These are used to create logical expressions which can be manipulated, and simplified by applying various laws, just as in traditional algebra.

Boolean expressions provide a symbolic, mathematical description of logical behavior.

This section will be expanded on in later versions of this document.

Reading and Thinking in Schematics

Electronic circuits are rarely simple enough to construct directly by placing components on perfboard without prior planning. As a result, circuits are often first modeled at higher levels of abstraction based on their intended logical behavior.

An important conceptual link to establish is that Boolean expressions describe the mathematical behavior of a given circuit, while schematics provide a graphical depiction of that same behavior.

In decreasing levels of abstraction, these diagram types are as follows.

Logic Diagrams (Abstract)

This section will be expanded on in later versions of this document.

Electronic Schematics (Physical reality)

This section will be expanded on in later versions of this document.

The Non-Negotiable Laws of Circuits

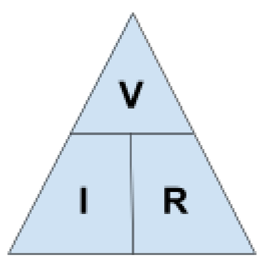
Ohm's Law

Ohm's law consists of three simple formulas which describe the fundamental relationships between voltage (V), current (I), and resistance (R) in a circuit.

$$V = I \times R$$

$$I = V \div R$$

$$R = V \div I$$



The relationship between these three characteristics of electricity is somewhat analogous to water in a pipe. Voltage can be thought of as the water pressure, current as the flow rate, and resistance as the diameter of the pipe (resistance to flow).

Kirchhoff's Current Law (Nodes)

KCL, also known as the Junction Rule, states that the total current entering a junction, also called a node, must equal the total current leaving it. The key takeaway is that charge must be conserved, current is not simply lost at a connection point, it splits or combines.

Kirchhoff's Voltage Law (Loops)

KVL states that if you start at a point in a circuit, travel around a closed loop and return to the starting point, the total change in voltage must be zero. By the time the entire circuit is traced there must be the same amount of energy. Energy can not appear nor disappear arbitrarily. Any rise or fall in voltage must be accounted for by an energy source or sink somewhere in the circuit.

Kirchhoff's laws essentially affirm conservation of energy.

Fundamental Components

Resistors

These are perhaps the most common and fundamental electronic components. Their primary function is to oppose the flow of current within a circuit. This opposition is characterized by a property known as resistance, measured in ohms (Ω). Higher resistance values result in lower current flow for a given voltage.

Beyond simple current limitation, the resistive behavior of resistors can be exploited in several practical ways, the most common of which are outlined below.

Resistors are non-polarized, and as such can be placed in a circuit without regard for orientation.

Current Limiting:

Resistors are commonly used to limit current to a desired level. This is especially important when driving current sensitive components such as LED's or transistor bases, where excess current may cause damage.

Voltage Division:

When placed in series resistors will reduce voltage by a fraction determined by the ratio of resistances. The output at any given node may be calculated with the following formula.

$$Vout = Vin \times \left(\frac{R2}{R1 + R2}\right)$$

Timing:

When used in conjunction with capacitors, a resistor controls the timing behavior of a circuit. The resistance value influences how quickly a capacitor charges or discharges, forming the basis of RC timing circuits used for delays, filtering, and signal shaping.

Measurement:

By measuring voltage drop across a resistor with a known value, current may be inferred through application of Ohm's law. This circumvents more invasive measurement techniques, which can disturb normal circuit operation.

Failure Modes:

When overloaded by high current load, a resistor may result in an open circuit. Alternatively in the case of extreme voltages, internal arcing may occur leading to short circuit behavior. It is worth noting that resistors experience resistance drift as they age, resulting in higher or lower resistance values. This effect is exacerbated by humidity and heat.

Capacitors

Another ubiquitous component is the capacitor. This component is unique in its ability to retain and release an electrical charge rapidly for short durations. This behavior differs from a battery in that electrical charge is stored electrostatically, as opposed to chemically. This results in a component which can provide fast bursts of energy, but is limited in duration.

The ability of a capacitor to store charge is referred to as its capacitance. This property is measured in Farads, most practical capacitors are rated in the microfarad range (μF).

It is important to note the differences in behavior during different phases of its operating cycle. During charging and discharging, current can flow freely through the capacitor. Once the voltage across it stabilizes, current flow effectively ceases.

Capacitors vary in their construction. Consideration must be given to polarity in certain variants. The most common polarized and non-polarized types are listed below.

Polarized:

Electrolytic capacitors contain two plates coated with aluminum oxide acting as dielectric, separated by a liquid electrolyte material which facilitates charge transport. These are general purpose capacitors which excel in bulk storage at low cost. Liquid electrolyte dries over time, resulting in reduced capacitance and increased resistance, limiting lifespan.

Tantalum capacitors utilize rare manganese dioxide solid metal electrolyte, and tantalum pentoxide dielectric, offering high stability, longer expected service life, smaller form factor, and excellent stability. Higher cost and high sensitivity to exceeding voltage limits their applications to designs where stability and space constraints are a priority.

Failure modes:

Care must be taken to ensure correct orientation. Inadvertently reversing the polarity of a polarized capacitor leads to rapid degradation of the dielectric layer, creating heat, and potentially resulting in energetic failure. Reversed polarity failure modes include smoking, venting, and especially in the case of tantalum, explosion.

Non-Polarized:

Ceramic Capacitors

Thin ceramic sheets form the dielectric material, and printed metal electrodes are stacked on either side. A key benefit of ceramic capacitors is their relatively high nominal capacitance relative to their small package size, making them particularly well suited for space-constrained applications.

Paper Capacitor

Thin paper film, often oil-impregnated or waxed, make up the dielectric layers. Layers of aluminum foil conductors are interleaved and securely rolled into protective packaging. Paper capacitors offer long service life, and excellent stability. Reliability results from a self-healing property wherein damaged sections are vaporized, producing an insulating void preventing further degradation.

Plastic Film Capacitors

Similar in construction to paper capacitors, substituting plastic film as the dielectric layer. This allows for much higher voltage ratings, higher stability when exposed to temperature changes, and more robust construction in a package smaller than paper, though larger than ceramic. The same self-healing property is retained, but cost and limited maximum capacitance values limit their use cases.

Certain capacitor types primarily used in RF and precision frequency control applications are intentionally omitted, as they fall outside the scope of this work.

Failure Modes:

Non-polarized capacitors can fail open, short, or experience drift as a result of dielectric breakdown due to exceeding voltage ratings.

Common practical implementations are outlined below.

Energy Storage(Bulk and Local)

Decoupling and Bypassing

Diodes

Transistors

MOSFETs

Power Distribution

This section will be expanded on in later versions of this document.

Signals, Time, and Noise

In practical circuits, signals are shaped not only by logic and topology, but by the time and frequency dependent behavior of components. The following sections describe common signal behaviors and how they are controlled in practice.

Signal Conditioning

Smoothing

Fluctuations in DC voltage can be smoothed out by utilizing a capacitor placed in parallel with a pulsing voltage source. The capacitor stores electrical potential during signal peaks, and releases it during dips opposing rapid changes in voltage, effectively smoothing the ripple, providing a more stable voltage signal.

DC Blocking

A property of capacitors is their ability to block DC signals while permitting AC to pass. When DC voltage is applied, a capacitor charges toward the supplied voltage level at an exponential rate while allowing current to flow. Once voltage has stabilized, it acts as an open circuit until such time as it discharges.

Filtering

Unwanted signals can be filtered out by exploiting the frequency-dependent behavior of capacitors. When combined with resistive paths this behavior can be controlled by varying resistive and capacitive values to form low-pass and high-pass filters which preferentially allow low or high frequencies to pass, respectively.

Timing

Resistor-Capacitor circuits are formed by placing a capacitor and resistor together to control charge/discharge rates. The capacitor's charge and discharge current must flow through a resistive path. Varying resistance and capacitance values permits setting of specific timing characteristics. This is referred to as RC behavior and is covered later on as a practical example circuit.

Measurement and Debugging

This section will be expanded on in later versions of this document.

Common Failure Modes and Lessons Learned

Resistors most commonly fail as open circuits often due to excessive power dissipation. When a resistor is required to dissipate more power than it is rated for, excess electrical energy is converted to thermal energy. In extreme cases, this can lead to visible damage or combustion.

A common cause of resistor failure is the misuse of simple resistive voltage dividers in applications with significant current draw. Resistors are intended for signal-level voltages, not for power loads. When a load draws a significant current, their safe operating limits can be quickly exceeded and lead to failure.

Lesson learned: Voltage dividers should be used for setting signal voltages, not for supplying power to large loads.

This section will be expanded on in later versions of this document.

Appendix

Glossary

Image Attributions

AND Gate Symbol - Logic gates icon by *joalfa,*Flaticon

OR Gate Symbol - Logic gates icon by *joalfa,*Flaticon

NOT Gate Symbol - Logic gates icon by *joalfa,*Flaticon

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