THE BINARY CONNECTION

IT'S POSSIBLE TO SUBSTITUTE THE DIGITS 0 AND 1 FOR THE OFF AND ON STATES OF A SWITCH. THE TRUTH TABLES FOR THE GATES ON THE PREVIOUS PAGE THEN BECOME:

"AND" GATE

A	B	OUT
0	0	0
0	1	0
1	0	0
1	1	1

"OR" GATE

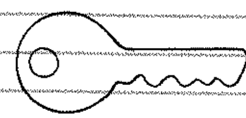
A	B	OUT
0	0	0
0	1	1
1	0	1
1	1	1

"NOT" GATE

IN	OUT
0	1
1	0

THE 0 AND 1 INPUT (A & B) COMBINATIONS FORM NUMBERS IN THE TWO DIGIT (OR BIT) BINARY NUMBER SYSTEM. IN DIGITAL ELECTRONICS, BINARY NUMBERS SERVE AS CODES THAT REPRESENT DECIMAL NUMBERS, LETTERS OF THE ALPHABET, VOLTAGES AND MANY OTHER KINDS OF INFORMATION.

DECIMAL	BINARY	BINARY-CODED DECIMAL (BCD)
0	0	0000 0000
1	1	0000 0001
2	10	0000 0010
3	11	0000 0011
4	100	0000 0100
5	101	0000 0101
6	110	0000 0110
7	111	0000 0111
8	1000	0000 1000
9	1001	0000 1001
10	1010	0001 0000
11	1011	0001 0001
12	1100	0001 0010
13	1101	0001 0011
14	1110	0001 0100
15	1111	0001 0101

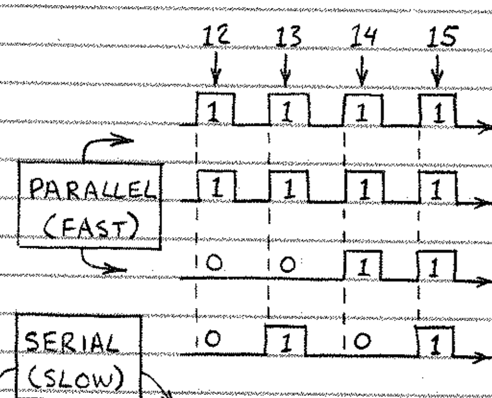


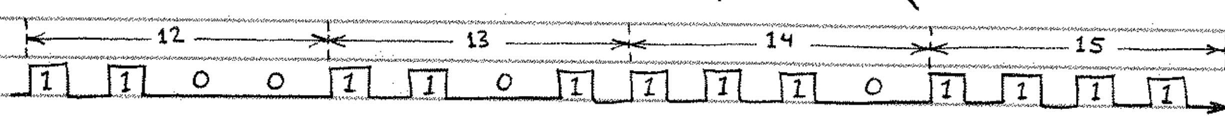
BINARY FACTS

A BINARY 0 OR 1 IS A BIT.
A PATTERN OF 4 BITS IS A NIBBLE.
A PATTERN OF 8 BITS IS A BYTE.

BCD— EACH DECIMAL DIGIT IS ASSIGNED ITS BINARY EQUIVALENT. NOTE THAT LEADING ZEROS ARE SHOWN. IN DIGITAL ELECTRONICS ALL BIT LOCATIONS ARE OCCUPIED.

BINARY NUMBERS CAN BE SENT THROUGH WIRES (BUSES) ALL AT ONCE (PARALLEL) OR A BIT AT A TIME (SERIAL). SHOWN HERE ARE SERIAL AND PARALLEL TRANSMISSION OF 15... 14... 13... 12.

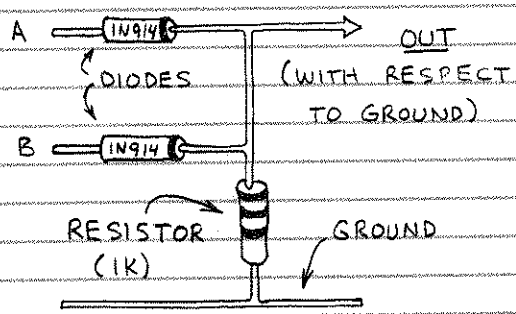




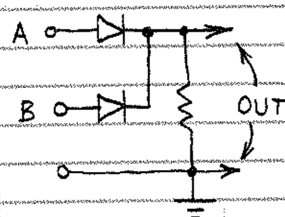
DIODE GATES

OFTEN IT'S DESIRABLE TO CONTROL A GATE ELECTRICALLY RATHER THAN MECHANICALLY. THE SIMPLEST ELECTRICALLY CONTROLLED GATE USES PN JUNCTION DIODES THAT ARE SWITCHED ON (FORWARD BIAS) OR OFF (REVERSE BIAS) BY AN INPUT SIGNAL OF SEVERAL VOLTS (BINARY 1 OR HIGH) OR AN INPUT NEAR OR AT GROUND (BINARY 0 OR LOW).

☐ DIODE "OR" GATE



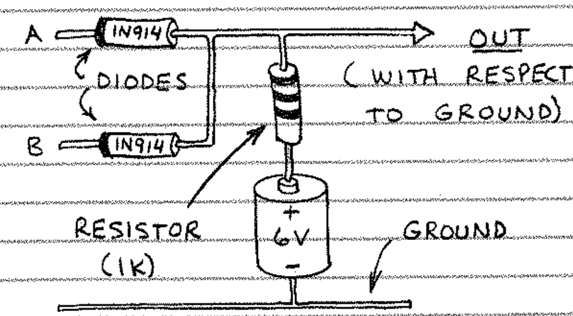
WHEN THE INPUT VOLTAGE AT A OR B IS MORE POSITIVE THAN GROUND, IT PASSES THROUGH THE FORWARD BIASED DIODE(S) AND APPEARS AT THE OUTPUT. OTHERWISE THE OUTPUT IS AT OR NEAR GROUND. THE TRUTH TABLE IS VALID FOR INPUTS OF 0 VOLT (0 OR LOW) AND +6 VOLTS (1 OR HIGH).



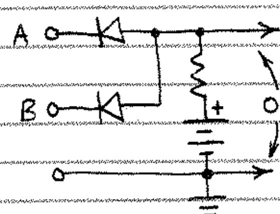
A	B	OUT
0V	0V	0V
0V	6V	5.4V
6V	0V	5.4V
6V	6V	5.4V

THE OUTPUT DOES NOT REACH A FULL 6 VOLTS WHEN HIGH BECAUSE THE DIODES REQUIRE A FORWARD VOLTAGE OF 0.6 VOLT. THIS VOLTAGE IS SUBTRACTED FROM THE OUTPUT VOLTAGE. (IN ELECTRONICS JARGON A SILICON DIODE CAUSES A "VOLTAGE DROP" OF 0.6 VOLT.)

☐ DIODE "AND" GATE



WHEN THE INPUT VOLTAGE AT A AND B IS MORE POSITIVE THAN GROUND, CURRENT FLOWS FROM THE BATTERY THROUGH THE RESISTOR TO THE OUTPUT. IF EITHER A OR B IS AT OR NEAR GROUND, ONE OR BOTH DIODES BECOME FORWARD BIASED AND CURRENT FLOWS AWAY FROM THE OUTPUT.



A	B	OUT
0V	0V	0V
0V	6V	.5V
6V	0V	.5V
6V	6V	5.4V

AS CIRCUITS BECOME MORE COMPLICATED, PICTORIAL VIEWS ARE NOT PRACTICAL. THAT'S WHY THIS PAGE INTRODUCES CIRCUIT DIAGRAMS FOR EACH OF THE TWO PICTORIALS SHOWN ABOVE. WE'LL FIND OUT MORE ABOUT CIRCUIT DIAGRAMS LATER. IN THE MEANTIME, THE NEXT PAGE SHOWS MORE OF THEM...

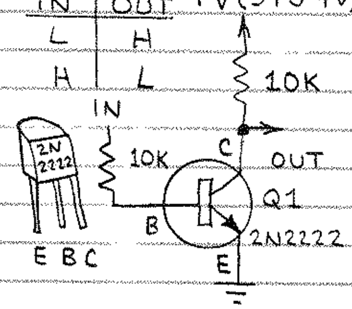
TRANSISTOR GATES

THE VOLTAGE DROP OF DIODE GATES MEANS AMPLIFICATION IS REQUIRED IN ORDER TO CONNECT TOGETHER A SERIES OF GATES. WHILE TRANSISTORS CAN PROVIDE THE NECESSARY AMPLIFICATION, TRANSISTORS CAN FUNCTION AS GATES! BOTH BIPOLAR AND FIELD-EFFECT TRANSISTORS CAN BE USED. ON THIS PAGE ARE SHOWN CIRCUIT DIAGRAMS FOR SOME OF THE SIMPLEST BIPOLAR TRANSISTOR GATES. TOGETHER THEY FORM THE RESISTOR-TRANSISTOR DIGITAL LOGIC FAMILY. YOU CAN ACTUALLY MAKE THESE GATES. BUT THE MAIN REASON THEY'RE HERE IS TO GIVE YOU AN APPRECIATION FOR THE INTEGRATED CIRCUIT GATES WE'LL BE LOOKING AT SHORTLY...

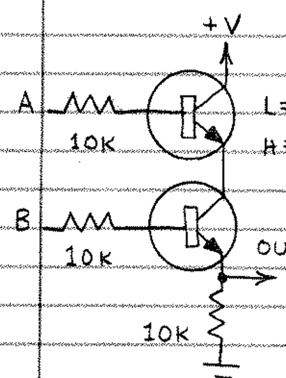
☐ "NOT" GATE (INVERTER)

WHEN IN IS AT +V (BINARY 1 OR HIGH), TRANSISTOR Q1 SWITCHES ON AND CONNECTS OUT DIRECTLY TO GROUND (BINARY 0 OR LOW). WHEN IN IS LOW, Q1 SWITCHES OFF AND OUT BECOMES (THROUGH R1) +V. "NOT" GATES LIKE THIS MAKE POSSIBLE IMPORTANT NEW LOGIC GATES.

IN	OUT
L	H
H	L



☐ "AND" GATE

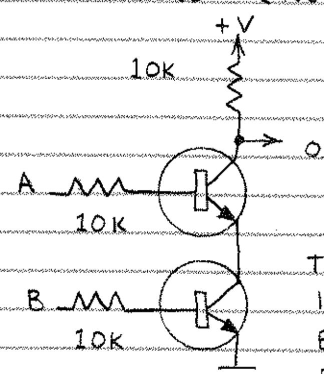


L = LOW
H = HIGH

A	B	OUT
L	L	L
L	H	L
H	L	L
H	H	H

USE 2N2222 OR ANY COMMON NPN TRANSISTOR FOR ALL THESE GATES.

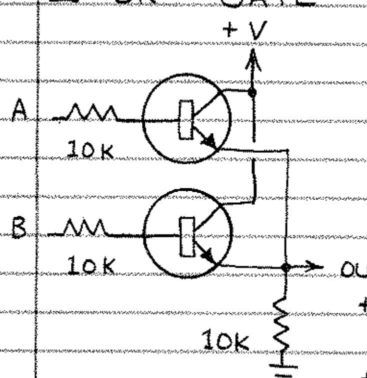
☐ "NAND" (NOT-AND) GATE



A	B	OUT
L	L	H
L	H	H
H	L	H
H	H	L

THE "NOT" FUNCTION IS "BUILT-IN" (NO EXTRA TRANSISTOR REQUIRED).

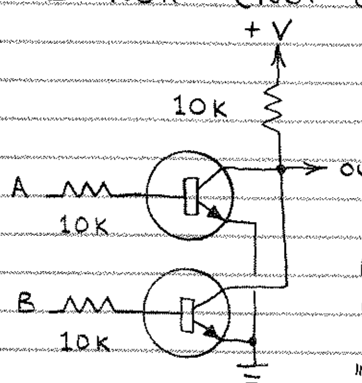
☐ "OR" GATE



A	B	OUT
L	L	L
L	H	H
H	L	H
H	H	H

+V FOR ALL THESE GATES CAN BE +3 TO +9 VOLTS.

☐ "NOR" (NOT-OR) GATE



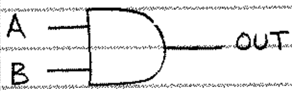
A	B	OUT
L	L	H
L	H	L
H	L	L
H	H	L

LIKE THE "NAND" GATE, THE "NOT" FUNCTION IS "BUILT-IN."

GATE SYMBOLS

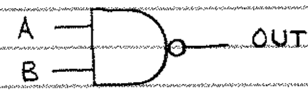
BEFORE MOVING ON TO DIGITAL INTEGRATED CIRCUITS, LET'S LOOK AT THE SYMBOLS FOR THE VARIOUS KINDS OF GATES. THIS IS ALSO A GOOD PLACE TO INTRODUCE SEVERAL GATES WE'VE NOT YET ENCOUNTERED.

☐ "AND" GATE



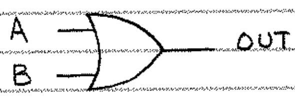
A	B	OUT
L	L	L
L	H	L
H	L	L
H	H	H

☐ "NAND" GATE



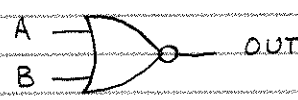
A	B	OUT
L	L	H
L	H	H
H	L	H
H	H	L

☐ "OR" GATE



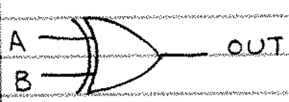
A	B	OUT
L	L	L
L	H	H
H	L	H
H	H	H

☐ "NOR" GATE



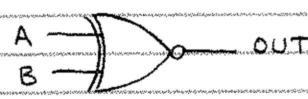
A	B	OUT
L	L	H
L	H	L
H	L	L
H	H	L

☐ "EXCLUSIVE-OR" GATE



A	B	OUT
L	L	L
L	H	H
H	L	H
H	H	L

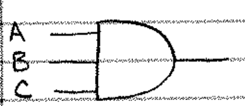
☐ "EXCLUSIVE-NOR" GATE



A	B	OUT
L	L	H
L	H	L
H	L	L
H	H	H

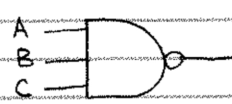
☐ LOGIC GATES WITH MORE THAN TWO INPUTS — THE GATES SHOWN ABOVE ARE CALLED LOGIC CIRCUITS BECAUSE THEY MAKE LOGICAL DECISIONS. LOGIC GATES OFTEN HAVE MORE THAN TWO INPUTS. ADDITIONAL INPUTS INCREASE THE DECISION MAKING POWER OF A GATE. THEY ALSO INCREASE THE NUMBER OF WAYS GATES CAN BE CONNECTED TO ONE ANOTHER TO FORM ADVANCED DIGITAL LOGIC CIRCUITS. HERE ARE TWO EXAMPLES:

3-INPUT "AND" GATE



A	B	C	OUT
L	L	L	L
L	L	H	L
L	H	L	L
L	H	H	L
H	L	L	L
H	L	H	L
H	H	L	L
H	H	H	H

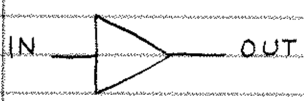
3-INPUT "NAND" GATE



A	B	C	OUT
L	L	L	H
L	L	H	H
L	H	L	H
L	H	H	H
H	L	L	H
H	L	H	H
H	H	L	H
H	H	H	L

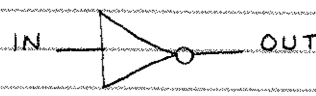
☐ SINGLE-INPUT GATES — THE "NOT" GATE OR INVERTER IS VERY IMPORTANT SINCE IT CAN INVERT (REVERSE) THE OUTPUT FROM ANOTHER GATE. STRICTLY SPEAKING, HOWEVER, THE INVERTER IS NOT A DECISION MAKING CIRCUIT (LIKE GATES WITH TWO OR MORE INPUTS). A CLOSE RELATIVE OF THE INVERTER IS THE BUFFER, A NON-INVERTING CIRCUIT THAT ISOLATES GATES FROM OTHER CIRCUITS OR ALLOWS THEM TO DRIVE HIGHER THAN NORMAL LOADS. THREE-STATE INVERTERS AND BUFFERS HAVE AN OUTPUT THAT CAN BE ELECTRONICALLY DISCONNECTED FROM THE REMAINDER OF THE CIRCUIT. THE OUTPUT IS THEN NEITHER HIGH NOR LOW. INSTEAD IT "FLOATS" AND APPEARS AS A VERY HIGH RESISTANCE.

☐ BUFFER



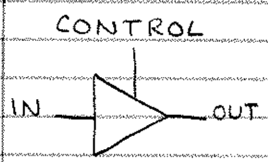
IN	OUT
L	L
H	H

☐ INVERTER ("NOT" GATE)



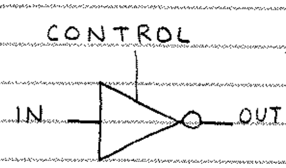
IN	OUT
L	H
H	L

☐ 3-STATE BUFFER



CONTROL	IN	OUT
L	L	L
L	H	H
H	X	HI-Z

☐ 3-STATE INVERTER



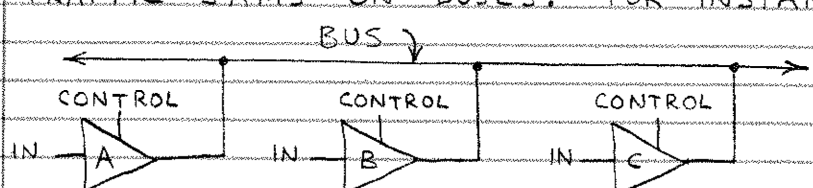
CONTROL	IN	OUT
L	L	H
L	H	L
H	X	HI-Z

"X" MEANS "DOESN'T MATTER." HI-Z MEANS HIGH OUTPUT RESISTANCE.

DATA "HIGHWAYS"

OFTEN CIRCUITS MADE FROM GATES EXCHANGE INFORMATION (BINARY 0'S AND 1'S ENCODED AS LOW AND HIGH VOLTAGE LEVELS). THE INFORMATION IS USUALLY SENT OVER WIRES CALLED BUSES. A BUS IS LIKE A DATA HIGHWAY. IT MAY BE ONE WIRE THROUGH WHICH INFORMATION IS SENT SERIALLY (BIT BY BIT). OR IT MAY BE UP TO EIGHT (OR MORE) WIRES THROUGH WHICH INFORMATION IS SENT IN PARALLEL (A BYTE OR MORE AT A TIME). IN BOTH CASES, OF COURSE, A GROUND IS REQUIRED TO COMPLETE THE CIRCUIT.

☐ 3-STATE TRAFFIC COPS — 3-STATE GATES CAN STOP "TRAFFIC JAMS" ON BUSES. FOR INSTANCE:



ONLY DATA ENTERING THE SELECTED BUFFER (CONTROL = L) GETS ON THE BUS.

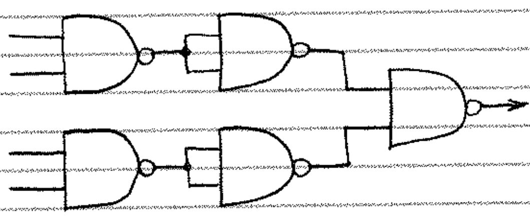
HOW GATES ARE USED

GATES CAN BE USED INDIVIDUALLY OR CONNECTED TOGETHER TO FORM A "NETWORK" OF GATES CALLED A LOGIC CIRCUIT. ALMOST ALL LOGIC CIRCUITS CAN BE PLACED IN ONE OF TWO CATEGORIES: COMBINATIONAL OR SEQUENTIAL.

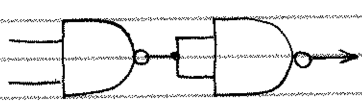
COMBINATIONAL LOGIC CIRCUITS

COMBINATIONAL LOGIC CIRCUITS RESPOND TO INCOMING DATA (0's AND 1's) ALMOST IMMEDIATELY AND WITHOUT REGARD TO EARLIER EVENTS. (THIS WILL MAKE MORE SENSE WHEN YOU READ ABOUT SEQUENTIAL CIRCUITS...) COMBINATIONAL LOGIC CIRCUITS CAN BE VERY SIMPLE OR IMMENSELY COMPLICATED. VIRTUALLY ANY COMBINATIONAL CIRCUIT CAN BE IMPLEMENTED WITH ONLY "NAND" OR "NOR" GATES. LIKE THESE "NAND" GATE CIRCUITS...

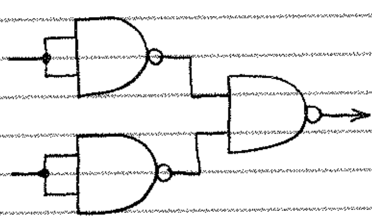
4-INPUT "NAND" GATE



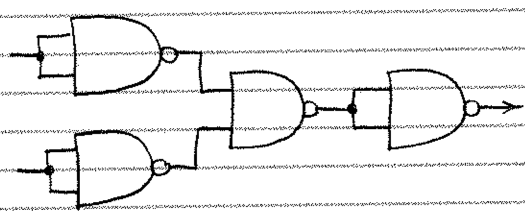
"AND" GATE



"OR" GATE

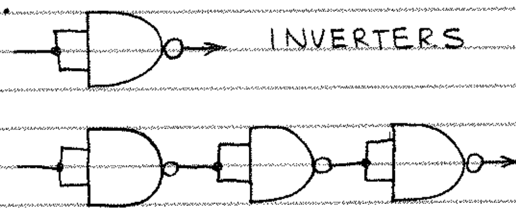


"NOR" GATE

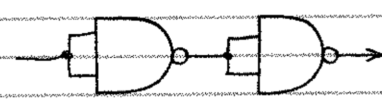


NOTE: THESE CIRCUITS DO NOT SHOW THE GROUND CONNECTION THAT MUST BE PRESENT. USUALLY THE GROUND IS COMMON TO THE INPUT AND OUTPUT.

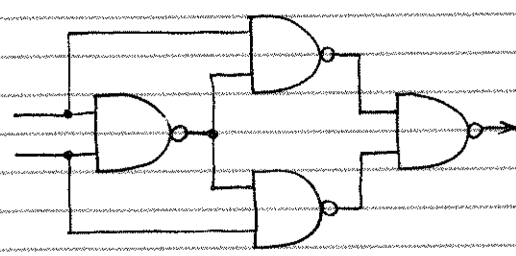
INVERTERS



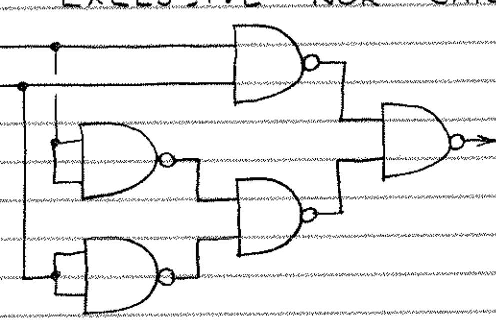
BUFFER



"EXCLUSIVE-OR" GATE

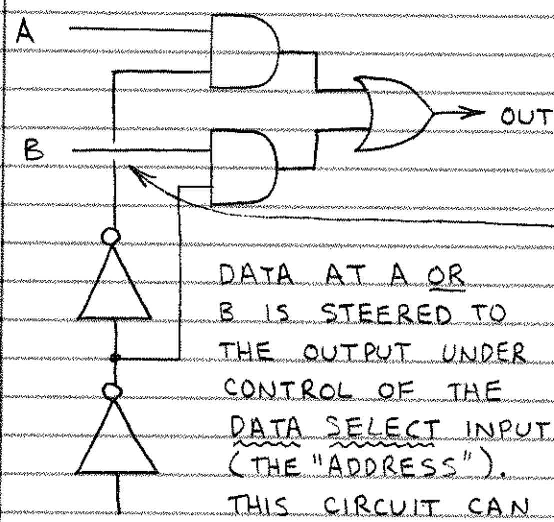


"EXCLUSIVE-NOR" GATE



☐ COMBINING DIFFERENT GATES — HERE ARE TWO EXAMPLES OF COMBINATIONAL NETWORKS THAT USE MORE THAN ONE KIND OF GATE. (REMEMBER, BOTH THESE CIRCUITS CAN ALSO BE MADE ENTIRELY FROM "NAND" GATES!)

DATA SELECTOR

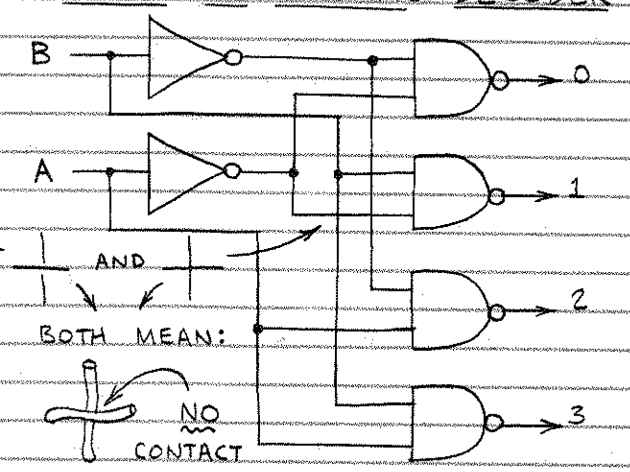


DATA AT A OR B IS STEERED TO THE OUTPUT UNDER CONTROL OF THE DATA SELECT INPUT (THE "ADDRESS").

THIS CIRCUIT CAN BE EXPANDED TO INCLUDE MANY MORE INPUTS AND ADDRESSES.

DATA SELECT:
L SELECTS A
H SELECTS B

BINARY TO DECIMAL DECODER

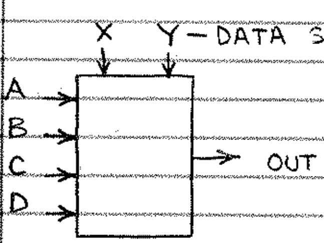


THIS CONVERTS A TWO-BIT BINARY NUMBER TO ITS DECIMAL EQUIVALENT.

A	B	0	1	2	3
L	L	L	H	H	H
L	H	H	L	H	H
H	L	H	H	L	H
H	H	H	H	H	L

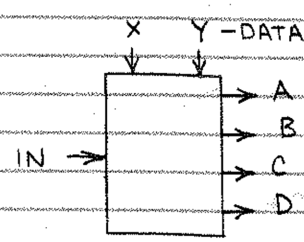
☐ ADVANCED COMBINATIONAL NETWORKS — HERE ARE SOME SIMPLE EXAMPLES FROM FOUR MAJOR FAMILIES OF COMBINATIONAL NETWORKS. THESE AND MANY OTHER NETWORK FAMILIES ARE AVAILABLE AS INTEGRATED CIRCUITS. BOXES LIKE THOSE SHOWN ARE LOGIC CIRCUIT SYMBOLS THAT REPRESENT COMPLICATED NETWORKS OF GATES.

MULTIPLEXER (DATA SELECTOR)



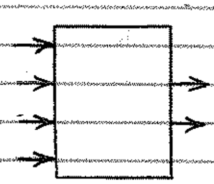
X	Y	OUT
L	L	A
L	H	B
H	L	C
H	H	D

DEMULTIPLEXER



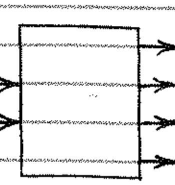
X	Y	IN TO...
L	L	A
L	H	B
H	L	C
H	H	D

ENCODER



CONVERTS DECIMAL AND OTHER DATA TO BINARY. USES "OR" GATES.

DECODER



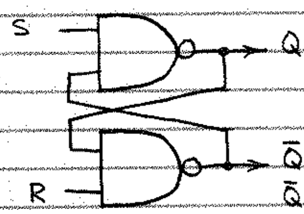
CONVERTS BINARY TO DECIMAL AND BCD TO DECIMAL DIGITS ON DIGITAL READOUTS.

SEQUENTIAL LOGIC CIRCUITS

THE OUTPUT STATE OF A SEQUENTIAL LOGIC CIRCUIT IS DETERMINED BY THE PREVIOUS STATE OF THE INPUT. IN OTHER WORDS, BITS OF DATA MOVE THROUGH SEQUENTIAL CIRCUITS STEP-BY-STEP. OFTEN THE DATA ADVANCES ONE STEP WHEN A PULSE IS RECEIVED FROM A "CLOCK" (A CIRCUIT THAT EMITS A STEADY STREAM OF PULSES). THE SEQUENTIAL LOGIC BUILDING BLOCK IS THE FLIP-FLOP. HERE'S A QUICK FLIP-FLOP REVIEW:

☐ THE BASIC "RS" (RESET-SET) FLIP-FLOP

ALSO CALLED A LATCH. THE OUTPUTS (Q AND $\bar{Q}$) ARE ALWAYS IN OPPOSITE STATES. ($\bar{Q}$ MEANS "NOT Q".)

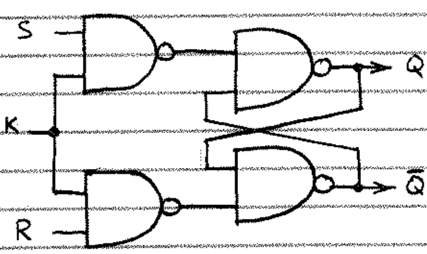


S	R	Q	$\bar{Q}$
L	L	(DISALLOWED)	
L	H	H	L
H	L	L	H
H	H	NO CHANGE	

$\bar{Q}$ = NOT Q (IF Q = 0, $\bar{Q}$ = 1).

☐ CLOCKED "RS" FLIP-FLOP

THIS LATCH IGNORES DATA AT S AND R UNTIL A "CLOCK" (OR ENABLE) PULSE ARRIVES. THEN IT CHANGES STATES.

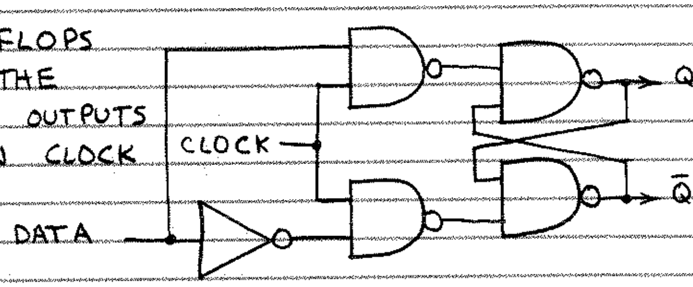


S	R	Q	$\bar{Q}$
L	L	NO CHANGE	
L	H	L	H
H	L	H	L
H	H	(DISALLOWED)	

VALID AFTER CLOCK PULSE ARRIVES.

☐ "D" (DATA OR DELAY) FLIP-FLOP

D FLIP-FLOPS STORE THE CURRENT OUTPUTS BETWEEN CLOCK PULSES.

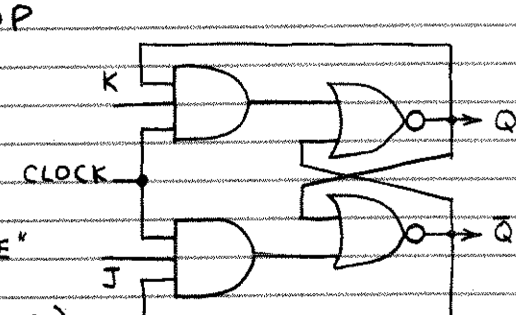


D	Q	$\bar{Q}$
L	L	H
H	H	L
	(OR)	
0	0	1
1	1	0

VALID AFTER CLOCK PULSE ARRIVES.

☐ "JK" FLIP-FLOP

THE "JK" FLIP-FLOP ALLOWS BOTH INPUTS TO BE H. (IN WHICH CASE ITS OUTPUTS "TOGGLE" OR SWITCH STATES AT EACH CLOCK PULSE.)

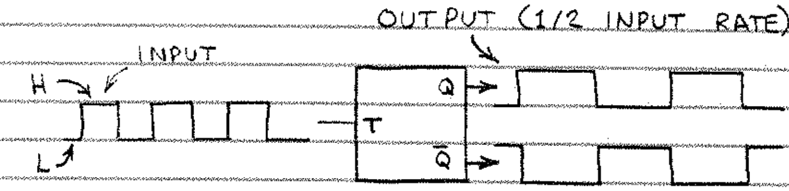


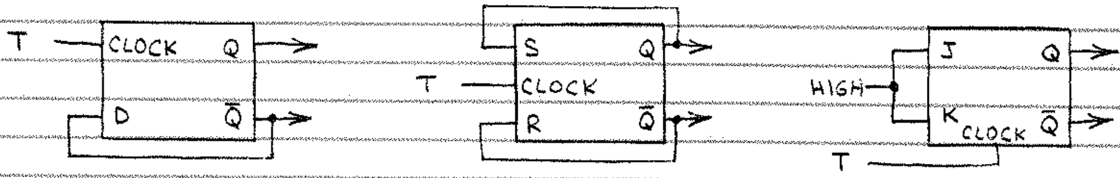
J	K	Q	$\bar{Q}$
L	L	NO CHANGE	
L	H	L	H
H	L	H	L
H	H	"TOGGLE"	

VALID AFTER CLOCK PULSE ARRIVES.

☐ "T" (TOGGLE) FLIP-FLOP

THE Q (OR $\bar{Q}$) OUTPUT IS L (OR H) FOR EVERY OTHER INPUT PULSE. THEREFORE THE INPUT PULSES ARE DIVIDED BY TWO. HERE ARE SEVERAL WAYS TO MAKE A "T" FLIP-FLOP:

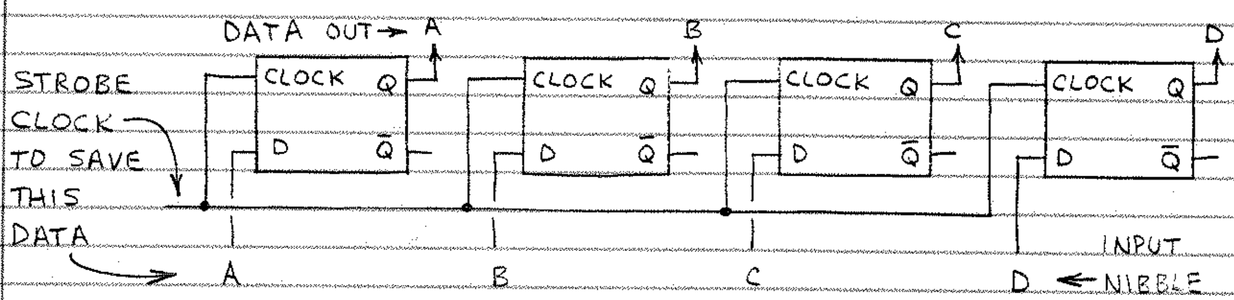




"D" FLIP-FLOP CLOCKED "RS" FLIP-FLOP JK FLIP-FLOP

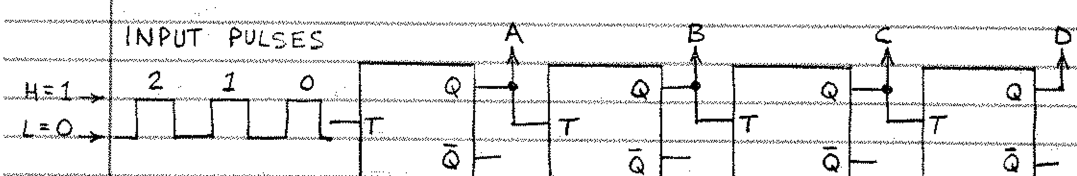
☐ "D" FLIP-FLOP DATA STORAGE REGISTER

HERE'S HOW FOUR "D" FLIP-FLOPS FORM A STORAGE REGISTER OR MEMORY THAT "LOADS" (SAVES) THE 4-BIT BINARY NIBBLE AT INPUTS A-D WHEN THE "CLOCK" INPUT IS "STROBED" (PULSED). MANY TYPES OF IC REGISTERS ARE AVAILABLE.



☐ "T" FLIP-FLOP COUNTER

HERE'S HOW FOUR "T" FLIP-FLOPS FORM A 4-BIT BINARY COUNTER:



COUNT	D C B A
0	0 0 0 0
1	0 0 0 1
2	0 0 1 0
3	0 0 1 1
4	0 1 0 0
5	0 1 0 1
6	0 1 1 0
7	0 1 1 1
8	1 0 0 0
9	1 0 0 1
10	1 0 1 0
11	1 0 1 1
12	1 1 0 0
13	1 1 0 1
14	1 1 1 0
15	1 1 1 1

EACH "T" FLIP-FLOP DIVIDES INCOMING PULSES BY TWO. AS THE BINARY TRUTH TABLE REVEALS, THE RESULT IS A 0000 → 1111 BINARY COUNT. (THE COUNT RECYCLES TO 0000 AFTER THE 16TH INCOMING PULSE.) THERE ARE MANY TYPES OF IC COUNTERS, MOST OF WHICH INCLUDE SPECIAL FEATURES (COUNT UP OR DOWN, RESET, ETC.).

A COMBINATIONAL – SEQUENTIAL LOGIC SYSTEM

HERE'S HOW COMBINATIONAL AND SEQUENTIAL LOGIC IC'S CAN FORM A DECIMAL COUNTING CIRCUIT, A VERY SIMPLE DIGITAL LOGIC SYSTEM.

1. THE BLOCK DIAGRAM

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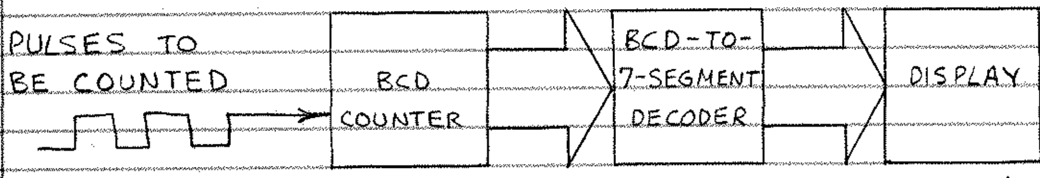
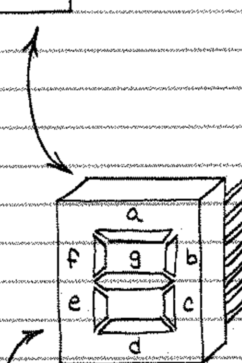
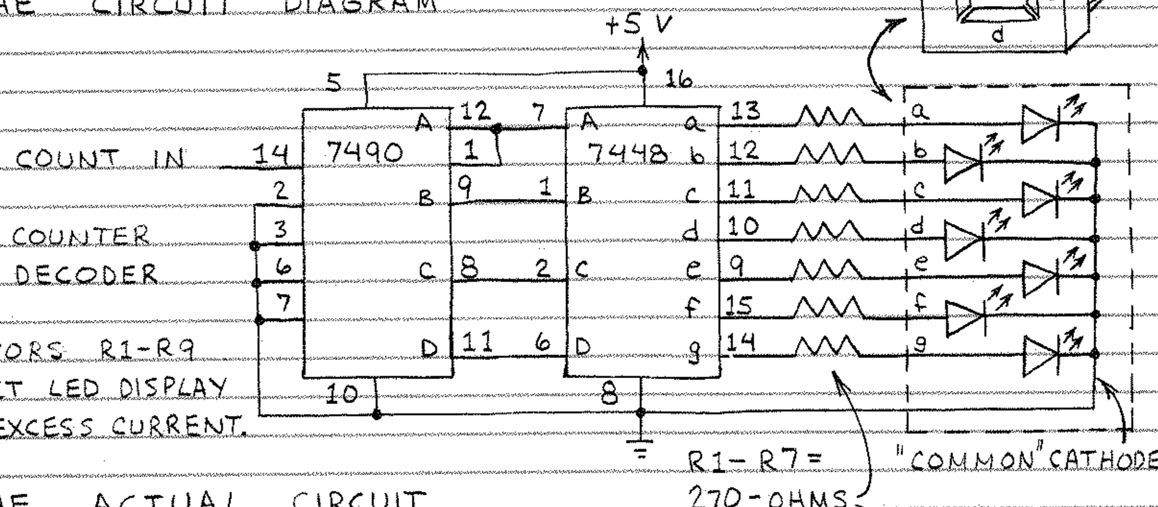


THE BCD COUNTER ADVANCES ONE COUNT FOR EACH INCOMING PULSE. WHEN THE COUNT REACHES 1001 (DECIMAL 9), THE COUNTER RECYCLES TO 0000. THE DECODER ACTIVATES THE APPROPRIATE SEGMENTS OF AN LED DISPLAY.



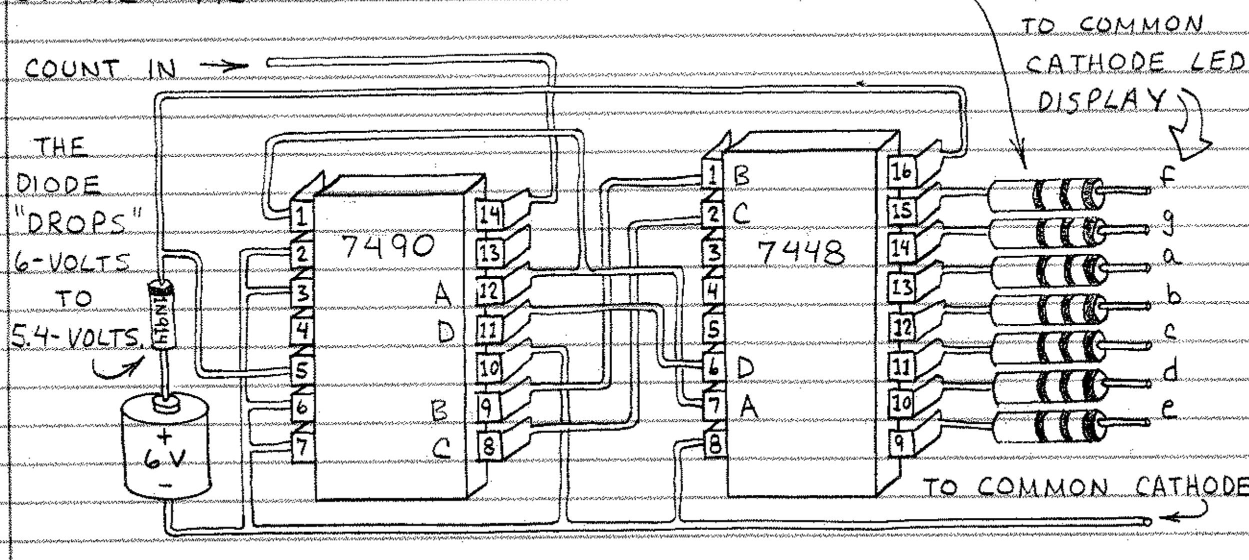
2. THE CIRCUIT DIAGRAM



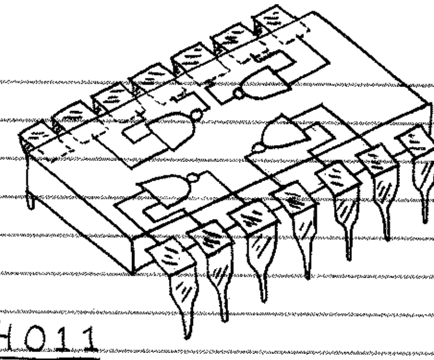
7490 = COUNTER
7448 = DECODER

RESISTORS R1-R9 PROTECT LED DISPLAY FROM EXCESS CURRENT.

3. THE ACTUAL CIRCUIT



DIGITAL IC FAMILIES



4011

A "QUAD" (FOUR) OF 2-INPUT CMOS "NAND" GATES

THERE ARE MORE THAN A DOZEN MAJOR FAMILIES OF BIPOLAR AND MOS INTEGRATED CIRCUITS. EACH IC (OR "CHIP") CONTAINS A SPECIFIC LOGIC NETWORK OR ASSORTMENT OF VARIOUS LOGIC FUNCTIONS. HERE ARE SOME OF THE MAJOR DIGITAL IC FAMILIES:

☐ BIPOLAR DIGITAL IC's

1. TRANSISTOR-TRANSISTOR LOGIC (TTL OR T^2L). THE LARGEST AND FORMERLY MOST POPULAR DIGITAL IC FAMILY. CAN CHANGE STATES MORE THAN 20,000,000 TIMES PER SECOND. VERY INEXPENSIVE. DRAWBACKS: MUST BE POWERED BY 5-VOLT SUPPLY. USES LOTS OF POWER. (INDIVIDUAL GATES REQUIRE 3 OR 4 MILLIAMPERES.) MOST WIDELY USED IS THE 7400 SERIES. THE 7404, FOR EXAMPLE, CONTAINS FOUR INVERTERS.

2. LOW-POWER SCHOTTKY TTL (LS). A NEWER KIND OF TTL THAT CONSUMES ONLY 20% AS MUCH POWER. DRAWBACK: MORE EXPENSIVE THAN STANDARD TTL. MOST WIDELY USED IS THE 74LS00 SERIES.

☐ MOSFET DIGITAL IC's

1. P- AND N-CHANNEL MOS (PMOS AND NMOS). CONTAIN MORE GATES PER CHIP THAN TTL. MANY SPECIAL PURPOSE CHIPS (MICROPROCESSORS, MEMORIES, ETC.). DRAWBACKS: FEW COUNTERPARTS TO POPULAR TTL CHIPS. SLOWER THAN TTL. MAY REQUIRE TWO OR MORE SUPPLY VOLTAGES. MAY BE DAMAGED BY STATIC ELECTRICAL DISCHARGE.

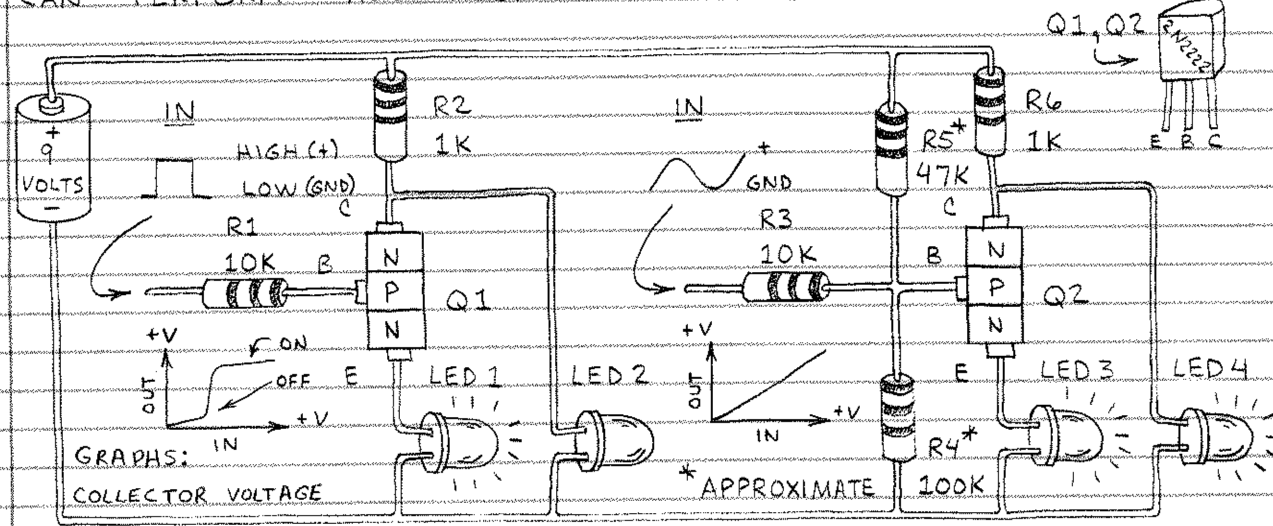
2. COMPLEMENTARY MOS (CMOS). FASTEST GROWING AND MOST VERSATILE DIGITAL IC FAMILY. THERE ARE CMOS VERSIONS OF MOST POPULAR TTL CHIPS. ONE SERIES USES THE SAME DESIGNATION NUMBERS. THE 74C04, FOR EXAMPLE, IS THE CMOS EQUIVALENT OF THE TTL 7404. NEW HIGH-SPEED CMOS JUST AS FAST AS TTL. MOST CMOS HAS A WIDE SUPPLY VOLTAGE RANGE (TYPICALLY +3 TO +18 VOLTS). USES LESS POWER THAN ANY OTHER DIGITAL IC FAMILY. (INDIVIDUAL GATES REQUIRE 0.1 MILLIAMPERE.) DRAWBACK: MAY BE DAMAGED BY STATIC ELECTRICAL DISCHARGE. MOST WIDELY USED ARE 74C00 AND 4000 SERIES.

7. LINEAR INTEGRATED CIRCUITS

THE INPUT AND OUTPUT VOLTAGE LEVELS OF LINEAR INTEGRATED CIRCUITS CAN VARY OVER A WIDE RANGE. OFTEN THE OUTPUT VOLTAGE IS PROPORTIONAL TO THE INPUT VOLTAGE. THEREFORE, A GRAPH OF INPUT VERSUS OUTPUT IS A STRAIGHT (LINEAR) LINE. THERE ARE MANY TYPES OF LINEAR IC'S. ONLY THE MAJOR TYPES ARE COVERED HERE. FIRST LET'S COMPARE THE BASIC DIGITAL AND LINEAR CIRCUITS:

THE BASIC LINEAR CIRCUIT

A SINGLE BIPOLAR OR FIELD-EFFECT TRANSISTOR CAN FUNCTION AS A DIGITAL OR LINEAR CIRCUIT. IN BOTH CASES, THE TRANSISTOR CAN INVERT THE SIGNAL AT ITS INPUT. HERE'S HOW AN NPN BIPOLAR TRANSISTOR CAN PERFORM ALL FOUR FUNCTIONS:



DIGITAL:

LINEAR:

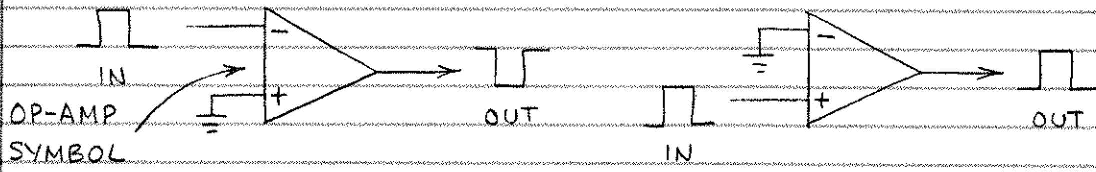
HERE TRANSISTOR Q1 IS USED AS A SWITCH. WHEN THE INPUT IS NEAR +V (OR HIGH), Q1 TURNS ON AND LED 1 IS ILLUMINATED. WHEN THE INPUT IS NEAR GROUND (OR LOW), Q1 TURNS OFF. THIS TURNS LED 1 OFF AND ALLOWS LED 2 TO GLOW. (R2 CONTROLS THE CURRENT THROUGH BOTH LEDs.) THIS CIRCUIT IS THEN A COMBINED DIGITAL BUFFER AND INVERTER.

HERE Q2 IS AN AMPLIFIER THAT OPERATES OVER THE ENTIRE RANGE FROM FULL OFF TO FULL ON. R4 AND R5 FORM A VOLTAGE DIVIDER THAT APPLIES A SMALL VOLTAGE TO Q2'S BASE TO KEEP Q2 SLIGHTLY ON EVEN WHEN NO INPUT IS PRESENT. THIS ALLOWS Q2 TO OPERATE IN A LINEAR MODE. AS THE INPUT VOLTAGE RISES, LED 3 BRIGHTENS AND LED 4 DIMS.

OPERATIONAL AMPLIFIERS

OPERATIONAL AMPLIFIERS (OR "OP-AMPS") ARE BY FAR THE MOST VERSATILE OF LINEAR IC'S. THEY'RE CALLED "OPERATIONAL" AMPLIFIERS SINCE THEY WERE ORIGINALLY DESIGNED TO DO MATHEMATICAL OPERATIONS. OP-AMPS AMPLIFY THE DIFFERENCE BETWEEN VOLTAGES OR SIGNALS (AC OR DC) APPLIED TO THEIR TWO INPUTS. THE VOLTAGE APPLIED TO ONLY ONE INPUT WILL BE AMPLIFIED IF THE SECOND INPUT IS GROUNDED OR MAINTAINED AT SOME VOLTAGE LEVEL.

☐ OP-AMP OPERATION — THE OP-AMP HAS AN INVERTING AND NON-INVERTING INPUT. THE POLARITY OF A VOLTAGE APPLIED TO THE INVERTING INPUT IS REVERSED AT THE OUTPUT. (INVERTING INPUT IS − ; NON-INVERTING INPUT IS +.)



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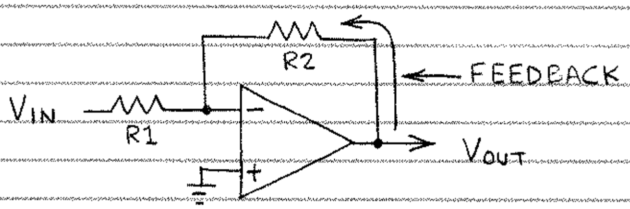
INVERTING MODE NON-INVERTING MODE

☐ OP-AMP "FEEDBACK" — THE CIRCUITS SHOWN ABOVE ALLOW THE OP-AMP TO OPERATE AT ITS MAXIMUM AMPLIFICATION LEVEL (OR GAIN). USUALLY THE GAIN IS REDUCED TO A MORE PRACTICAL LEVEL BY FEEDING SOME OF THE OUTPUT BACK TO THE INVERTING (−) INPUT. FOR EXAMPLE:



INVERTING AMPLIFIER

GAIN = R2 / R1

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$V_{OUT} = -V_{IN}(R2/R1)$

☐ OP-AMP COMPARATOR — WHEN OPERATED WITHOUT A FEEDBACK RESISTOR (R2 ABOVE), THE OUTPUT VOLTAGE WILL SWING FROM FULL ON TO FULL OFF (OR VICE VERSA) WHEN THE VOLTAGES APPLIED TO THE INPUTS DIFFER BY ONLY ABOUT 0.001 VOLT! THIS DIGITAL-LIKE MODE MAKES POSSIBLE MANY USEFUL APPLICATIONS.

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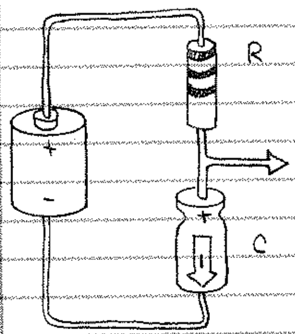
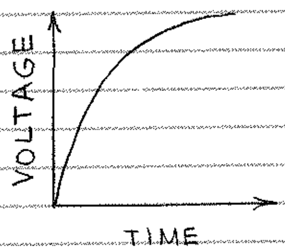
☐ TYPES OF OP-AMPS — BOTH BIPOLAR AND MOSFET IC OP-AMPS ARE AVAILABLE. SOME BIPOLAR OP-AMPS HAVE FET OR MOSFET INPUTS TO PROVIDE VERY HIGH INPUT RESISTANCE. MANY DIFFERENT OP-AMPS ARE MADE. A SINGLE IC MAY INCLUDE UP TO FOUR INDIVIDUAL OP-AMPS.

TIMERS

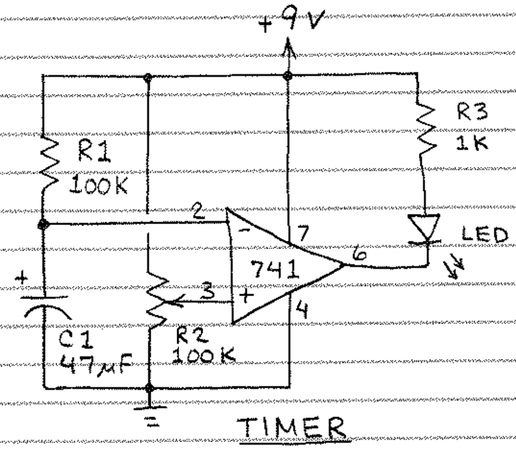
WHEN OPERATED AS A COMPARATOR, THE OP-AMP CAN BE USED AS A TIMER. ALL THAT'S REQUIRED IS AN RC (RESISTOR-CAPACITOR) CIRCUIT LIKE THIS:



RC CIRCUIT



RC CHARGING GRAPH



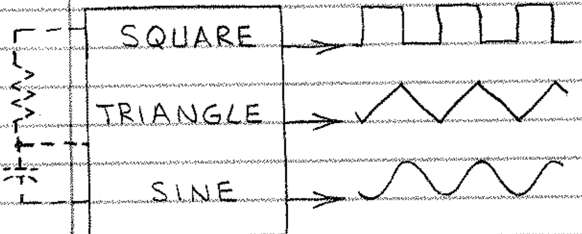
TIMER

IN THE CIRCUIT DIAGRAM (ABOVE RIGHT), R1 AND C1 FORM AN RC CIRCUIT. C1 GRADUALLY CHARGES TO +9 VOLTS THROUGH R1. WHEN THE VOLTAGE ON C1 EXCEEDS THE REFERENCE VOLTAGE SUPPLIED TO THE NON-INVERTING INPUT OF THE OP-AMP, ITS OUTPUT SWINGS FROM HIGH TO LOW AND THE LED GLOWS. THE TIME DELAY CAN BE CHANGED BY ALTERING THE VALUES OF R1 AND C1 OR THE SETTING OF R2. DISCHARGE C1 (USE PUSHBUTTON SWITCH) FOR NEW CYCLE.

☐ IC TIMERS — THE SIMPLE CIRCUIT ABOVE IS THE KEY INGREDIENT OF MOST IC TIMERS. MOST INCLUDE AN OUTPUT FLIP-FLOP TO GIVE DEFINITE HIGH OR LOW OUTPUT. SOME INCLUDE A BINARY COUNTER THAT ADVANCES ONE COUNT PER DELAY PERIOD (OR CYCLE). THE TIMER IS RECYCLED EACH TIME THE COUNT ADVANCES. A DECODER AT THE COUNTER OUTPUT ALLOWS TOTAL DELAYS OF FROM DAYS TO A YEAR OR MORE TO BE SELECTED. BOTH BIPOLAR AND CMOS TIMERS ARE AVAILABLE. P.126 ⇒

FAMOUS FACT: ANALOG COMPUTERS USE OP-AMPS TO SOLVE COMPLEX EQUATIONS!

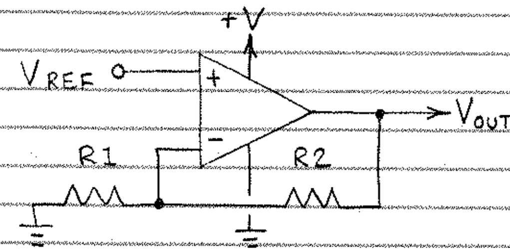
FUNCTION GENERATORS



THESE IC's GENERATE VARIOUS KINDS OF OUTPUT WAVES SUCH AS THOSE SHOWN HERE. THE FREQUENCY OF THE WAVES CAN BE CONTROLLED BY AN EXTERNAL RC CIRCUIT.

VOLTAGE REGULATORS

VOLTAGE REGULATORS CONVERT A VOLTAGE APPLIED TO THEIR INPUT INTO A FIXED OR VARIABLE (BUT USUALLY LOWER) VOLTAGE. IN MOST A SMALL, FIXED REFERENCE VOLTAGE (USUALLY A VOLT OR SO) IS APPLIED TO THE NON-INVERTING INPUT OF AN OP-AMP. THE RERERENCE VOLTAGE (OR V_{REF}) IS THEN AMPLIFIED BY THE RATIO OF THE FEEDBACK AND INPUT RESISTORS (THE GAIN). IF ONE OF THE RESISTORS IS A POTENTIOMETER, THE OUTPUT VOLTAGE (V_{out}) CAN BE VARIED FROM V_{REF} TO +V (THE CHIP SUPPLY VOLTAGE). ACTUAL IC REGULATORS INCLUDE EXTRA TRANSISTORS TO PROVIDE V_{REF} AND TO ALLOW THE CHIP TO DRIVE LOADS THAT REQUIRE MORE POWER THAN AN OP-AMP ALONE CAN DELIVER.



BASIC VOLTAGE REGULATOR

☐ IC REGULATORS — MANY TYPES OF FIXED AND VARIABLE OUTPUT IC REGULATORS ARE AVAILABLE. MOST ARE INSTALLED IN PACKAGES MADE OF METAL OR HAVING METAL TABS TO HELP RADIATE EXCESSIVE HEAT INTO THE SURROUNDING AIR. CAUTION: MANUFACTURER'S OPERATING INSTRUCTIONS AND STANDARD SAFETY PRECAUTIONS MUST BE FOLLOWED FOR BEST RESULTS. P. 125

OTHER LINEAR IC's

THERE ARE NUMEROUS SPECIAL FUNCTION LINEAR IC's, MANY OF WHICH INCORPORATE OP-AMPS. FOR EXAMPLE:

☐ AUDIO AMPLIFIERS — MANY KINDS AVAILABLE. SOME INCLUDE TWO AMPLIFIERS ON ONE CHIP (FOR STEREO).

☐ PHASE-LOCKED LOOPS — BASED ON AN OLD BUT CLEVER IDEA IN WHICH AN ON-CHIP OSCILLATOR DUPLICATES (OR TRACKS) THE FREQUENCY OF AN INCOMING SIGNAL. USED TO DETECT THE PRESENCE OF CERTAIN FREQUENCIES (LIKE TOUCH-TONE® TONES) AND TO DEMODULATE FM RADIO SIGNALS.

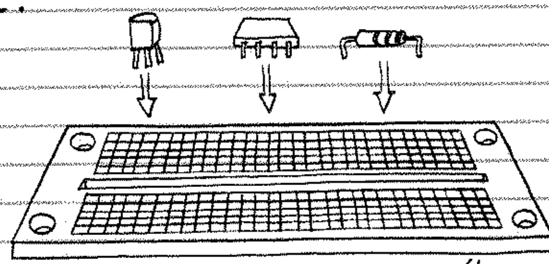
☐ OTHER LINEAR IC's — INCLUDED ARE MANY KINDS OF CHIPS FOR TELEPHONE, RADIO, TELEVISION AND COMPUTER COMMUNICATIONS. ALSO, MANY KINDS OF IC's THAT DETECT TEMPERATURE, LIGHT AND PRESSURE.

8. CIRCUIT ASSEMBLY TIPS

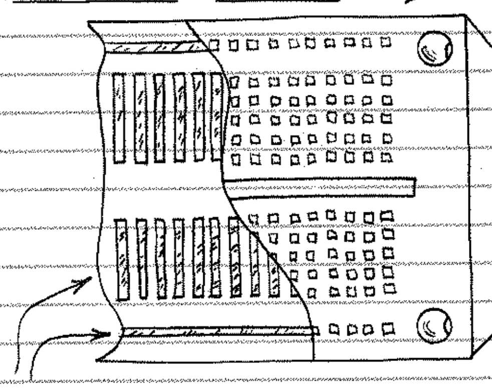
THERE ARE SEVERAL WAYS TO MAKE EITHER TEMPORARY OR PERMANENT VERSIONS OF ELECTRONIC CIRCUITS. IN THIS CHAPTER WE'LL LOOK AT SOME CIRCUIT ASSEMBLY TIPS YOU MAY FIND HELPFUL.

TEMPORARY CIRCUITS

IT'S ALWAYS WISE TO BUILD A TEMPORARY VERSION OF A CIRCUIT BEFORE ASSEMBLING IT IN PERMANENT FORM. YOU CAN THEN MAKE CHANGES AND FIND OUT HOW WELL THE CIRCUIT WORKS. BY FAR THE MOST IMPORTANT TOOL FOR TEMPORARY CIRCUIT ASSEMBLY IS THE PLASTIC SOLDERLESS MODULAR BREADBOARD SOCKET. IT'S A GOOD IDEA TO KEEP SEVERAL ON YOUR WORKBENCH. THEY WILL LET YOU BUILD ENTIRE CIRCUITS IN MINUTES. USE "JUMPER" WIRES TO INTERCONNECT PARTS WHOSE LEADS ARE NOT INSERTED IN THE SAME ROW OF TERMINALS. TO AVOID BENDING THEIR PINS (AND PRICKING YOUR FINGERS), INSTALL AND REMOVE IC'S CAREFULLY.



MODULAR SOCKET



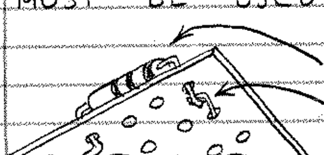
CUTAWAY SHOWING COMMON TERMINAL CONNECTIONS.

HINT: INSTALL SOCKET ON BASE AND ADD POTENTIOMETERS, BATTERY, LEDs, SWITCHES, ETC.

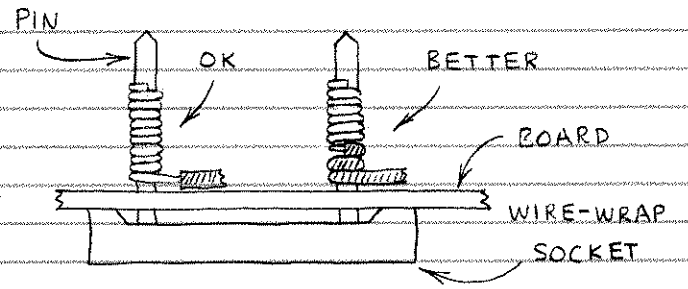
PERMANENT CIRCUITS

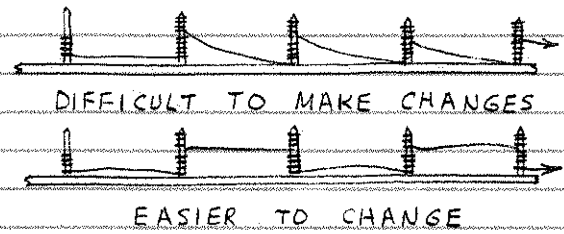
WITH THE EXCEPTION OF SOME VERY SIMPLE CIRCUITS, MOST PERMANENT CIRCUITS ARE ASSEMBLED ON SOME FORM OF CIRCUIT BOARD.

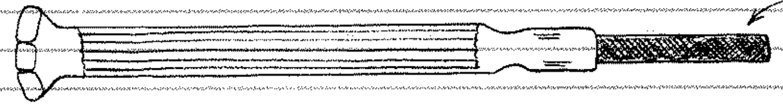
☐ PERFORATED BOARD CONSTRUCTION — COMPONENT LEADS ARE INSERTED THROUGH PERFORATIONS IN A PHENOLIC OR SIMILAR BOARD AND SOLDERED TOGETHER ON THE BACK SIDE OF THE BOARD. OFTEN INSULATED CONNECTION WIRES MUST BE USED. ONCE ASSEMBLED, "PERFBOARD" CIRCUITS ARE DIFFICULT TO REPAIR SINCE COMPONENT LEADS ARE OFTEN TWISTED AND SOLDERED.



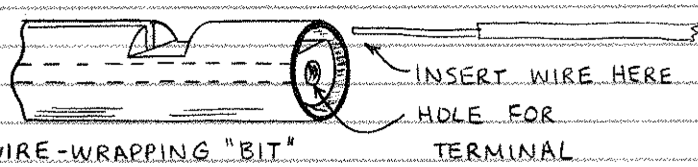
☐ WIRE-WRAP — FASTEST WAY TO ASSEMBLE CIRCUITS THAT USE MORE THAN A FEW IC'S. USE WIRE-WRAP IC SOCKETS (WITH SQUARE CONNECTION PINS). BOTH HAND AND MOTOR POWERED WRAPPING TOOLS ARE AVAILABLE. IF YOU USE THE KIND THAT REQUIRES SOME OF THE WIRE'S INSULATION BE REMOVED, WRAP A FEW TURNS OF INSULATED WIRE AROUND THE CONNECTION PIN TO STRENGTHEN THE CONNECTION.



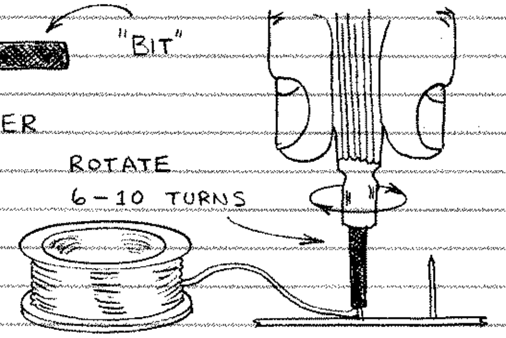




TYPICAL HAND-POWERED WIRE-WRAPPER



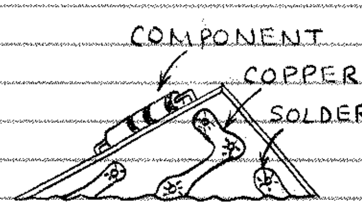
WIRE-WRAPPING "BIT"



☐ PRINTED CIRCUIT (PC) — PROVIDES THE NEATEST AND MOST PROFESSIONAL APPEARING COMPLETED CIRCUIT. SOCKETS NOT REQUIRED, BUT COMPONENT LEADS MUST BE SOLDERED TO THE COPPER PATTERNS ON THE BOARD. THERE ARE MANY TYPES OF PC BOARDS. TWO TYPES USED BY EXPERIMENTERS ARE:

1. PRE-ETCHED PERFORATED GRID BOARDS HAVE A ROUND, COPPER FOIL SOLDER PAD AT EACH HOLE. ON MANY BOARDS ROWS OF HOLES ARE CONNECTED BY COMMON COPPER FOIL STRIPS (LIKE A SOLDERLESS BREADBOARD). IT'S USUALLY NECESSARY TO JOIN SOME OF THE CONTACTS ON THE BOARD WITH "JUMPERS" (SHORT LENGTHS OF INSULATED HOOKUP OR WRAPPING WIRE).

2. CUSTOM PC BOARDS ARE MADE BY APPLYING A TAPE OR CHEMICAL COATING (THE "RESIST") TO THE CLEAN COPPER FOIL OF A PC BOARD. THE UNCOATED COPPER IS THEN CHEMICALLY ETCHED AWAY, LEAVING BEHIND A FOIL WIRING PATTERN. HOLES ARE DRILLED FOR COMPONENT LEADS. TAKES LOTS OF TIME, BUT PRODUCES NEAT CIRCUITS.



HOW TO SOLDER

GOOD SOLDERING PRACTICES ARE ESSENTIAL FOR RELIABLE OPERATION OF A CIRCUIT WITH SOLDERED CONNECTIONS. HERE ARE SIX STEPS FOR SUCCESSFUL SOLDERING:

1. ALWAYS USE A LOW-WATTAGE SOLDERING IRON (25 TO 40 WATTS). BE SURE TO TIN THE TIP ACCORDING TO THE MANUFACTURER'S INSTRUCTIONS.

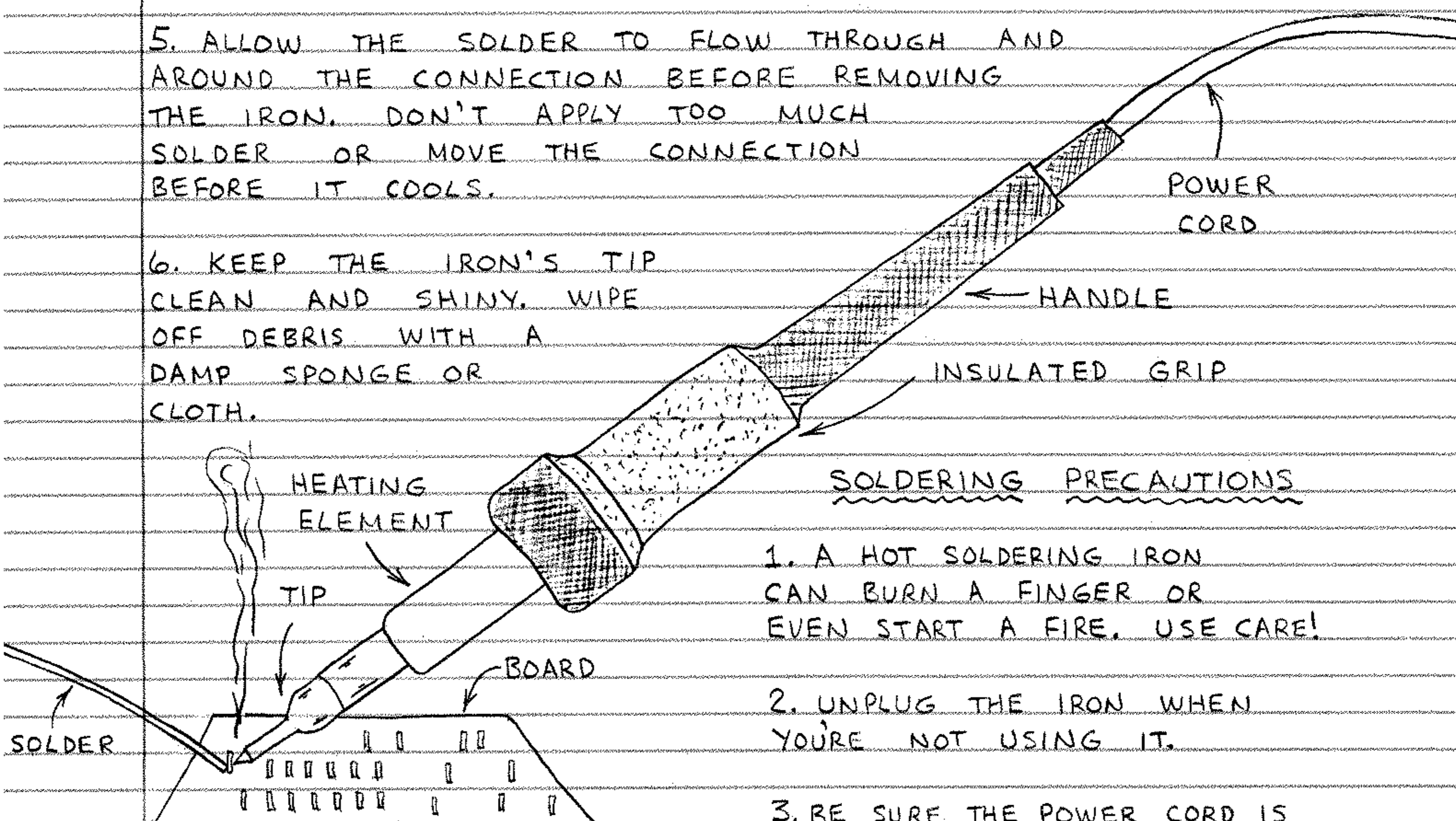
2. ALWAYS USE ROSIN CORE SOLDER WHEN SOLDERING ELECTRONIC COMPONENTS. NEVER USE ACID CORE SOLDER SINCE IT WILL CORRODE THE SOLDERED LEAD.

3. SOLDER DOES NOT ADHERE TO PAINT, GREASE, OIL, WAX OR MELTED INSULATION. REMOVE ALL SUCH FOREIGN MATTER WITH A SOLVENT, STEEL WOOL OR FINE SANDPAPER. ALWAYS BUFF THE COPPER FOIL OF A PC BOARD WITH STEEL WOOL BEFORE SOLDERING. (THE COPPER SHOULD BE SHINY.)

4. TO SOLDER, FIRST HEAT THE CONNECTION (NOT THE SOLDER!) FOR A FEW SECONDS WITH THE HOT TIP OF THE IRON. THEN LEAVE THE IRON IN PLACE AND APPLY SOLDER.

5. ALLOW THE SOLDER TO FLOW THROUGH AND AROUND THE CONNECTION BEFORE REMOVING THE IRON. DON'T APPLY TOO MUCH SOLDER OR MOVE THE CONNECTION BEFORE IT COOLS.

6. KEEP THE IRON'S TIP CLEAN AND SHINY. WIPE OFF DEBRIS WITH A DAMP SPONGE OR CLOTH.



(HOLD PARTS IN PLACE WITH TAPE)

SOLDERING PRECAUTIONS

1. A HOT SOLDERING IRON CAN BURN A FINGER OR EVEN START A FIRE. USE CARE!

2. UNPLUG THE IRON WHEN YOU'RE NOT USING IT.

3. BE SURE THE POWER CORD IS NOT WHERE YOU CAN TRIP OVER IT.

POWERING ELECTRONIC CIRCUITS

☐ BATTERY POWER — MANY CIRCUITS USE SO LITTLE POWER THEY CAN BE POWERED BY BATTERIES. THIS KEEPS THE COMPLETED CIRCUIT COMPACT AND ALLOWS IT TO BE OPERATED ANYWHERE.

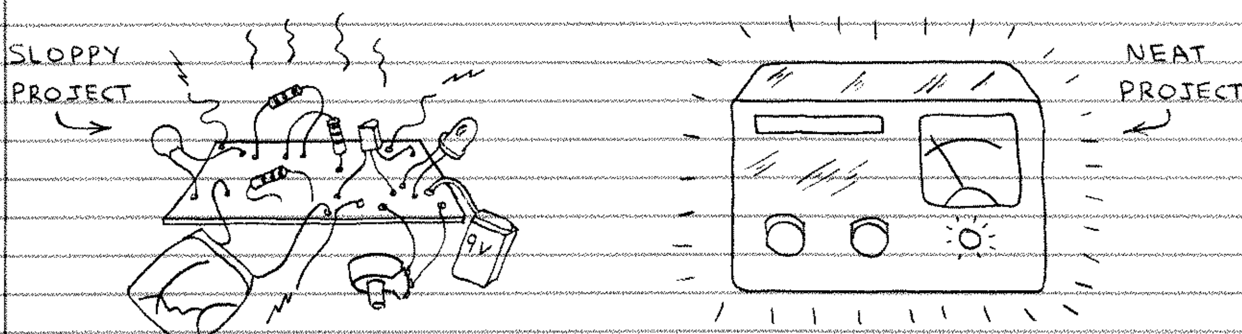
☐ SOLAR POWER — SOLAR CELLS CAN POWER YOUR CIRCUITS DIRECTLY. OR YOU CAN USE AN ARRAY OF SOLAR CELLS TO CHARGE A RECHARGEABLE BATTERY.

☐ LINE POWER — THE SIMPLEST LINE POWERED SUPPLY IS THE SO-CALLED AC ADAPTER. THESE MODULAR UNITS ARE COMPACT AND EASY TO USE. UNITS HAVING VARIOUS OUTPUT VOLTAGES AND CURRENTS ARE AVAILABLE. YOU CAN MAKE YOUR OWN LINE POWERED SUPPLY USING AN IC VOLTAGE REGULATOR.

☐ CAUTION — SAFETY SHOULD BE YOUR FIRST CONCERN WHEN BUILDING YOUR OWN LINE POWERED SUPPLY. THE POWER CORD MUST BE PROTECTED FROM THE SHARP EDGES OF A HOLE DRILLED IN A METAL CABINET. (USE A PLASTIC STRAIN RELIEF.) ALL CONNECTIONS TO THE AC LINE MUST BE INSIDE A FULLY ENCLOSED HOUSING! LEAVING SUCH CONNECTIONS EXPOSED IS A POTENTIAL SHOCK HAZARD. MAKE SURE ALL COMPONENTS THAT ARE CONNECTED TO THE AC LINE (SWITCHES, FUSES, TRANSFORMERS, ETC.) MEET OR EXCEED THE POWER REQUIREMENT OF YOUR CIRCUIT.

SUMMING UP CIRCUIT ASSEMBLY

THE REMAINDER OF THIS BOOK INCLUDES MANY CIRCUITS YOU CAN QUICKLY ASSEMBLE ON A SOLDERLESS BREADBOARD. CHANCES ARE YOU'LL WANT TO MAKE PERMANENT VERSIONS OF SOME. FOR BEST RESULTS, PLAN THE PROJECT CAREFULLY. A NEATLY ASSEMBLED PROJECT WILL BE MORE RELIABLE THAN ONE HASTILY ASSEMBLED.



9. 100 ELECTRONIC CIRCUITS

HERE'S A COLLECTION OF 100 ELECTRONIC CIRCUITS. I'VE ASSEMBLED EACH CIRCUIT TO MAKE SURE ALL OF THEM WORK.

☐ SELECTING AND SUBSTITUTING COMPONENTS— YOU CAN FIND MOST OF THE COMPONENTS AT RADIO SHACK STORES. SAVE TIME AND MAKE A LIST OF WHAT YOU NEED BEFORE YOU VISIT RADIO SHACK. (YOU CAN FIND CURRENT CATALOG NUMBERS IN THE LATEST RADIO SHACK CATALOG.) IF A COMPONENT IS UNAVAILABLE, TRY ELSEWHERE. SOMETIMES YOU CAN SUBSTITUTE COMPONENTS. FOR EXAMPLE, IT'S OFTEN OK TO SUBSTITUTE NPN SWITCHING TRANSISTORS FOR ONE ANOTHER (2N3904 FOR 2N2222, ETC.). NEARBY VALUES OF RESISTORS AND CAPACITORS CAN OFTEN BE USED (1.2K FOR 1K RESISTOR, 0.33 μF FOR 0.47 μF CAPACITOR, ETC.). ALWAYS FOLLOW APPROPRIATE VOLTAGE AND POWER RATINGS!

☐ WHEN A CIRCUIT DOESN'T WORK— MAKE SURE THE CIRCUIT IS RECEIVING ADEQUATE POWER. IF IT IS <u>OR</u> IF YOU SMELL OR FEEL A HOT COMPONENT, <u>IMMEDIATELY</u> DISCONNECT THE POWER AND FOLLOW THESE STEPS: 1 RECHECK <u>ALL</u> CONNECTIONS. (IS A WIRE MISSING? IS AN IC PIN BENT? IS A SOLDER CONNECTION BAD? IS A WIRE "SHORTED"? IS A DIODE BACKWARDS?) 2 IS A COMPONENT DEFECTIVE? 3 SOMETIMES, ESPECIALLY WHEN POWER SUPPLY LEADS ARE MORE THAN SIX INCHES LONG, IC CIRCUITS WILL WORK IMPROPERLY OR NOT AT ALL UNLESS YOU CONNECT A 0.1 μF CAPACITOR ACROSS THE POWER SUPPLY PINS OF EACH CHIP. IT MAY ALSO BE NECESSARY TO CONNECT A 1 TO 10 μF CAPACITOR ACROSS THE POWER LEADS WHERE THEY ENTER THE BOARD. 4 DOES THE PUBLISHED CIRCUIT CONTAIN AN ERROR?

☐ SAFETY FIRST— BE SURE TO FOLLOW APPROPRIATE PRECAUTIONS WHEN WORKING WITH AC LINE POWERED CIRCUITS. BE CAREFUL WHEN SOLDERING. CIRCUITS WITH SPEAKERS CAN PRODUCE <u>VERY</u> LOUD SOUNDS. KEEP YOUR DISTANCE, AND DON'T USE HEADPHONES.

☐ GOING FURTHER— TRY EXPERIMENTING WITH THE VALUES OF COMPONENTS IN RC CIRCUITS (P. 37). TRY SUBSTITUTING OTHER OUTPUT DEVICES IN CIRCUITS THAT DRIVE A RELAY, PIEZO BUZZER, ETC. (BE SURE TO FOLLOW VOLTAGE AND CURRENT RATINGS. USE OHM'S LAW AND, IF NECESSARY, ADD A SERIES RESISTOR TO REDUCE CURRENT.) BEFORE BUILDING A PERMANENT VERSION OF A CIRCUIT, <u>ALWAYS</u> ASSEMBLE AND TEST A BREADBOARD VERSION. FINALLY, BE SURE TO BUY RADIO SHACK'S CURRENT "SEMICONDUCTOR REFERENCE GUIDE" AND "ENGINEER'S NOTEBOOK." FOR MORE ADVANCED CIRCUITS AND INFORMATION ABOUT NEW DEVELOPMENTS, READ MY COLUMN ("THE ELECTRONICS SCIENTIST") IN <u>COMPUTERS & ELECTRONICS</u>.