ECE 115

Introduction to Electrical and Computer Engineering

Laboratory Experiment #1

Using the MATLAB Desktop and Command Window

In this experiment you will learn: how to start and quit MATLAB, about the organization of the MATLAB desktop and command window, how to enter instructions for immediate execution, some MATLAB syntax, how to define the complex number and matrix data type, how to do complex arithmetic, compute with vectors, use MATLAB plotting functions, and how to use the help facility.

A Brief History of Computer Technology

A complete history of computing would include a multitude of diverse devices such as the ancient Chinese abacus, the Jacquard loom (1805) and Charles Babbage's ``analytical engine'' (1834). It would also include discussion of mechanical, analog and digital computing architectures. As late as the 1960s, mechanical devices, such as the Marchant calculator, still found widespread application in science and engineering. During the early days of electronic computing devices, there was much discussion about the relative merits of analog vs. digital computers. In fact, as late as the 1960s, analog computers were routinely used to solve systems of finite difference equations arising in oil reservoir modeling. In the end, digital computing devices proved to have the power, economics and scalability necessary to deal with large scale computations. Digital computers now dominate the computing world in all areas ranging from the hand calculator to the supercomputer and are pervasive throughout society.

The evolution of digital computing is often divided into *generations*. Each generation is characterized by dramatic improvements over the previous generation in the technology used to build computers, the internal organization of computer systems, and the programming languages.

The Mechanical Era (1623-1945)

The idea of using machines to solve mathematical problems can be traced at least as far back as the early 17th century. The first multi-purpose, i.e., *programmable*, computing device was probably Charles Babbage's Difference Engine, which was built beginning in 1823, but was never completed. A more ambitious machine was the Analytical Engine. It was designed in 1842, but unfortunately it also was only partially completed by Babbage. Babbage was truly a man ahead of his time: many historians think the major reason he was unable to complete these projects was the fact that the technology of the day was not reliable enough. A machine inspired by Babbage's design was arguably the first to be used in computational science. George Scheutz read of the difference engine in 1833, and along with his son Edvard Scheutz began work on a smaller version. By 1853 they had constructed a machine that could process 15-digit numbers and calculate fourth-order differences. Their machine won a gold medal at the Exhibition of Paris in 1855, and later they sold it to the Dudley Observatory in Albany, New York, which used it to calculate the orbit of Mars. One of the first commercial uses of mechanical computers was by the US Census Bureau, which used punch-card equipment designed by Herman Hollerith to tabulate data for the 1890 census. In 1911 Hollerith's company merged with a competitor to found the corporation which in 1924 became International Business Machines.

First Generation Electronic Computers (1937-1953)

Three machines have been promoted at various times as the first electronic computers. These machines used electronic switches, in the form of vacuum tubes, instead of electromechanical relays. Electronic components had one major benefit-they could ``open'' and ``close'' about 1,000 times faster than mechanical switches.

The earliest attempt to build an electronic computer was by J. V. Atanasoff, a professor of physics and mathematics at Iowa State, in 1937. Atanasoff set out to build a machine that would help his graduate students solve systems of partial differential equations. By 1941 he and graduate student Clifford Berry had succeeded in building a machine that could solve 29 simultaneous equations with 29 unknowns. However, the machine was not programmable, and was more of an electronic calculator.

A second early electronic machine was Colossus, designed by Alan Turing for the British military in 1943. This machine played an important role in breaking codes used by the German army in World War II. Turing's main contribution to the field of computer science was the idea of the Turing machine, a mathematical formalism widely used in the study of computable functions. The existence of Colossus was kept secret until long after the war ended, and the credit due to Turing and his colleagues for designing one of the first working electronic computers was slow in coming.

The first general purpose programmable electronic computer was the Electronic Numerical Integrator and Computer (ENIAC), built by J. Presper Eckert and John V. Mauchly at the University of Pennsylvania. Work began in 1943, funded by the Army Ordnance Department, which needed a way to compute ballistics during World War II. The machine wasn't completed until 1945, but then it was used extensively for calculations during the design of the hydrogen bomb.

Software technology during this period was very primitive. The first programs were written in machine code, i.e., programmers directly wrote down the binary numbers that corresponded to the instructions they wanted to store in memory. By the 1950s programmers were using a symbolic notation, known as assembly language, then hand-translated the symbolic notation into machine code. Later programs known as assemblers performed the translation task.

Second Generation (1954-1962)

The second generation saw several important developments at all levels of computer system design, from the technology used to build the basic circuits to the programming languages used to write scientific applications.

Electronic switches in this era were based on discrete diode and transistor technology with a switching time of approximately 0.3 microseconds. The first machines to be built with this technology include TRADIC at Bell Laboratories in 1954 and TX-0 at MIT's Lincoln Laboratory.

During this second generation, many high level programming languages were introduced, including FORTRAN (1956), ALGOL (1958), and COBOL (1959). The second generation also saw the first two supercomputers designed specifically for numeric processing in scientific applications.

Third Generation (1963-1972)

The third generation brought huge gains in computational power. Innovations in this era include the use of integrated circuits, or ICs (semiconductor devices with several transistors built into one physical component), semiconductor memories started to be used instead of magnetic cores, and the introduction of operating systems.

The first ICs were based on small-scale integration (SSI) circuits, which had around 10 basic logic devices per circuit (or ``chip''), and evolved to the use of medium-scale integrated (MSI) circuits, which had up to 100 basic logic devices per chip.

Fourth Generation (1972-1984)

The next generation of computer systems saw the use of large scale integration (LSI - 1000 devices per chip) and very large scale integration (VLSI - 100,000 devices per chip) in the construction of computing elements. Semiconductor memories replaced core memories as the main memory in most systems.

Two important events marked the early part of the fourth generation: the development of the C programming language and the UNIX operating system, both at Bell Labs. In 1972, Dennis Ritchie developed the C language. C was then used to write a version of UNIX. This C-based UNIX was soon ported to many different computers, relieving users from having to learn a new operating system each time they change computer hardware. UNIX or a derivative of UNIX is now a de facto standard on virtually every computer system.

Fifth Generation (1984-1990)

The fifth generation saw the introduction of machines with hundreds of processors that could all be working on different parts of a single program. The scale of integration in semiconductors continued at an incredible pace - by 1990 it was possible to build chips with a million components - and semiconductor memories became standard on all computers.

Other new developments were the widespread use of computer networks and the increasing use of single-user workstations. This period also saw a marked increase in both the quality and quantity of scientific visualization.

Sixth Generation (1990 -)

This generation began with many gains in parallel computing, both in the hardware area and in improved understanding of how to develop algorithms to exploit diverse, massively parallel computer architectures.

One of the most dramatic changes in the sixth generation has been the explosive growth of wide area networking. Network bandwidth has expanded tremendously in the last few years and will continue to improve for the next several years.

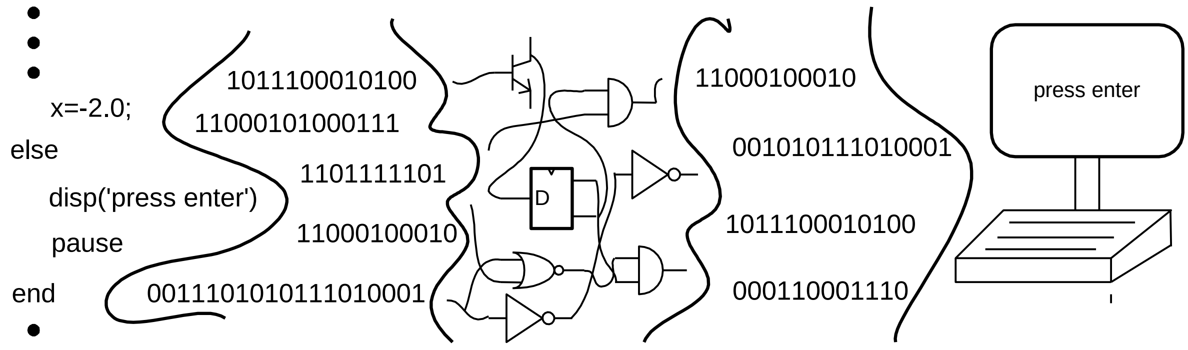

Illustration of the computing process

Before you come to the laboratory, read the chapter, *MATLAB Environment*, that was put on the blackboard.

For this experiment, you will be using MATLAB that is installed in the computers located in the lab.

1) Click on the MATLAB icon to launch MATLAB. The window shown is the MATLAB desktop window. Within the tool bar at the top of the desktop there are the file, edit, view, etc. tools, and on the bar below the tool bar there is a little window that shows the current directory where MATLAB will retrieve and store files. This directory can be changed by clicking on the button to the right of the current directory window. If it is not already open, click on the view tool button, and open and activate the command window.

a) Type into the command window: "2+ 3.5 (do not type the quotation marks.), and press enter. ***Explain what happened?*** You can also assign a value to a variable. Type into the command window: "$x = 2 + 3.5$", and press enter. ***Explain what happened.*** To prevent an immediate display of a calculation result, end the input with a semi-colon. Type: "$y = 3\wedge 2 + \log(pi/2)*\sin(x);$ " , and press enter. ***What value did MATLAB use for x?*** To see the result, type: "y" , and ***explain what happened***.

b) MATLAB has an enormous number of built in functions. Type: "$theta = a\sin(-0.5)$", ***and explain what happened.*** Click on the HELP tool in the tool bar at the top of the command window, and select Product Help. When the help window opens, click on the Search Results tab at the left. Type in: “tan”, and select it. On the right of the help window MATLAB will show how to use the built in tangent function. In the command window, type in an expression to obtain the tangent of: $\pi/3$. ***Give the MATLAB expression, and explain what happened.***

c) MATLAB can output results in different formats. Type in: “format short e”. Then type: “pi”, which is a word reserved by MATLAB to mean 3.14159…….. ***What happened?*** Now type: “format long”, and then type: “pi”. ***What happened? Repeat the above for: ”format long e”***. ***What happened?*** Then, return the format to: “format short”.

d) ***Use MATLAB to obtain the results for:***

$$2^4/(2^4-1);\quad sqrt(7);\quad \ln(e^2);\quad \log_{10}(10^4);\quad y=\cosh^2(4.2\pi)$$

Use the help facility of MATLAB to find out how to use the built-in functions given here. ***Give your MATLAB statements and results.***

e) MATLAB can work with complex numbers. It uses the letters, "j" and "i" to mean $\sqrt{-1}$. To assign the complex number: -3-j4 to the variable x, write the MATLAB statement: "x=-3-j*4" . Type in: "z = -3+j*4 ". ***What happened? Repeat for:*** "a = cos(3*pi/2)-j*sin(3*pi/2)". ***Explain why the result has a real part that is zero.***

f) Use MATLAB to compute: (-3.5-j5))/(1.7-j4). ***Give the MATLAB statement and result.***

2) MATLAB is ideally suited to work with vectors and matrices. A matrix is an array of elements, such as:

$$a=\begin{bmatrix} 3 & 5 & -1 \\ 3.5 & -6 & 7 \end{bmatrix}$$

Here, the matrix, a, has 2 rows and 3 columns, and the element in the first row and second column is $a_{12}=5$. With subscripts we can refer to any element in the array (matrix). Generally, we write: $X_{n\,m}$ to refer to the element in the nth row and mth column. Of course, we could write instead: $X_{k\,l}$ to refer to an element in the matrix X. The dimension of a matrix gives the size of the matrix, and here the dimension is the number of rows and columns in the matrix. For the matrix a, the dimension is a 2x3 matrix. An Nx1 matrix is an N element column vector, and a 1xM matrix is an M element row vector. A matrix can have more than two dimensions. A three dimensional matrix would have a size given by, for example, N x M x K, for some integers N, M and K.

a) Type in: "$x=[-2\quad 3\quad 4]$". ***What happened?*** To assign a row vector to a variable, we can put a blank between each element in the assignment statement. Type in: "$y=[3;\quad -1;\quad 6;]$". ***What happened? What is the dimension of y?*** A semi-colon terminates a row definition, and starts a new row.

b) ***Write a MATLAB statement to assign to z a row vector with elements:*** $z_{11}=-3$***,*** $z_{12}=5$***, and*** $z_{13}=-1.5$. ***What happens when you type: "a=x+z"? What corresponding elements of x and z were summed? What happens when you type: "b=x+y", and explain? Give the result for: b=2*a, and explain.***

c) MATLAB has many convenient functions to define a matrix. Type in: "x=linspace(0, 9, 4)". ***What happened?*** Use the MATLAB help facility to look up the function, linspace. ***Give an explanation for what this function does.***

d) Type in: "z=sqrt(x)", where x was defined in part (c). ***Explain the result. What does each element of z mean? Repeat this for:*** $\sqrt{-x}$***, and explain the result.***

e) MATLAB is very useful for matrix algebra. To multiply two vectors, let us use for example, $x=[2\;\; 4\;\; -3]$, and $a=[-2\quad 5\quad -4]$. Type them into MATLAB. Now, compute y=(a)(x transpose), by typing: "y=a*x' ", where the prime takes the transpose of x, making x' a column vector. ***Explain the result.*** Here, we have computed the inner product of two vectors**.**

e) To multiply the corresponding elements of two matrices, use the operation ".*" . Type in: "y=x.*a". ***Explain the result.***
f) Type in: "y=a'*x", which multiplies the column vector a' times the row vector x. ***Explain the result.*** Here, we have computed the outer product of two vectors.
g) ***Write MATLAB statements to find y for each element in x, where an element, x_n, of x is given by:*** $x_n = n/2, \ \ n = 0, 1, ..., 10$***, and*** $y = -1.5x + 6.25$***. Give the result.***

3) MATLAB has many built-in functions for plotting. Type in the following statements. Note, in place of names, enter your names.

```
clear all
clc
f=50;
T0=1/f;
w=2*pi*f;
N=200;
time=linspace(0, 4.0*T0, N+1);
x=cos(w*time);
plot(time,x)
xlabel('time - seconds')
ylabel('volts')
title('Sinusoidal Function, Names')
```

a) ***Explain each line. Type in the variable names: T0, f, w, and N and give their values.***
b) Type in grid on. ***Explain what happened.***
c) ***In the figure window, use the file pull down menu to print the figure and include it in your lab report.***
d) ***How many cycles of the sinusoidal function does your figure show?***
e) In milli seconds, give the time in which the sinusoidal function goes through one cycle.
f) ***If you heard a sound that could be caused by this sinusoidal function, would you say that the sound is a low or a high frequency sound? Give an example of a musical instrument in a band that mainly produces sounds having the frequencies like this sinusoidal function.***

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Introduction to Electrical and Computer Engineering

Laboratory Experiment #2

Matrices, Vectors, Complex Numbers and Programs

In this experiment you will learn about several MATLAB built-in functions, matrix and vector operations and the complex number data type. Shown below are several MATLAB programs. You will learn how each program works and how to modify it as specified.

Before you come to lab, read Sections 1 and 2 of Chapter 2, titled, "Programs and Functions".

Experiment

In all of the following programs use MATLAB help to find out about the kind of operation and built-in function.

```
% Your experiment report must provide a print of the program and the results.
% Make a separate program, m-file, for each problem.
% Name the files PROB1.m, PROB2.m, and so on.
%
% Problem 1
clear all;
f=2.0;
w=2.0*pi*f;
time=[0.0:0.01:2.0]; %line 9
amp=5.0;
phase=pi/4.0;
x=amp*cos(w*time+phase); %line 12
plot(time,x);
grid on;
title('Cosine Function'); %line 15
disp('press enter to continue'); pause; %this appears in the Command Window
%
% a) Explain what line 9 does. Add a statement that uses the MATLAB, size,
%    function to find out how many entries the matrix, time, has. Do this
%    again, but use the MATLAB function, length.
% b) Explain what line 12 does.
% c) Add statements after line 15 to put axis labels on the plot.
% Use volts for the vertical axis, and use seconds for the horizontal axis.
%
% Problem 2
clear all;
a=-3.0;
b=6.5;
```

```
c1=a+i*b; %line 27
real_c1=real(c1);
imag_c1=imag(c1);
mag_c1=abs(c1); %line 30
angle_c1=angle(c1);
%
c2=3.0*exp(i*pi/4); %line 33
%
% a) Explain what line 27 does, and give the value of c1.
%    Add a MATLAB statement to find c2=the complex conjugate of c1.
%    Use the MATLAB help facility to find out about the MATLAB
%    function to obtain the complex conjugate of a complex number.
% b) Explain what line 30 does.
% c) Explain what line 33 does.
%
N=10; T=0.01;
time=[-N*T:T:N*T]; % line 40
w=pi/4.0;
z=2.0*exp(i*w*time); x=real(z); %line 42
plot (time,x);
grid on; %line 44
disp('press enter to continue'); pause;
%
% d) Explain what line 40 does.
% e) Explain what line 42 does.  Is z a real or complex vector?  What
%    is the dimension of z?
% f) Add title and axes statements after line 44, and run the program.
%    Provide program and result print out.
% g) Add statements to find and plot the imaginary part of z, and run
%    the program.  Provide program and result print out.
%
% Problem 3
clear all;
p1=[1.0 1.0 -2.0]; %line 52
r_p1=roots(p1); disp(r_p1); %line 53
disp('press enter to continue'); pause; % Use HELP to find out about pause.
p2=[3.0 4.5 -1.5 20.0];
r_p2=roots(p2); disp(r_p2);
disp('press enter to continue'); pause;
p3=poly(r_p2); %line 58
%
% a) Explain what line 52 does.
% b) Explain what line 53 does. Look up the roots function.
% c) Explain line 58, and explain results. Add a statement to display p3.
% d) Add statements to find roots of:  x^3 + 2.0*x^2 + 2.0*x^1 + 1.0 = 0.0.
% e) Add statements to verify your results of part (d), i.e., use a MATLAB
%    function to find a polynomial given its roots.
%
% Problem 4
clear all;
a=[1.0 1.0; 1.5 2.0]; %line 68
d=a'; %line 69
b=inv(a); %line 70
c=a*b; %line 71
disp(c);
disp('press enter to continue'); pause;
%
```

```
% a) Explain what line 68 does.
% b) Explain what line 69 does.
% c) Explain what line 70 does.  Manually find the inverse of A, and
%    check program results.
% d) Explain what line 71 does, and explain the results.
% d) Add statements to solve equation: a*x=y, for x, where y=[1.0 3.0]'.
%
% Problem 5
clear all;
% A=[1 2 3; 4 5 6; 7 8 9]
% The above line defines a 3x3 matrix.  We can use MATLAB continuation and
write
A=[1 2 3; ...
   4 5 6; ...
   7 8 9]; % The three dots cause a line to be continued
b=A(2,3) %line 88, get an element
C=A(2:3, 1:3) % line 89, get rows 2 and 3 from columns 1 to 3
D=A(1:2, :) % line 90, get rows 1 and 2 from all columns
D(:, 2)=[] % line 91, delete column 2 in all rows by nulling column 2
v=[10 11 12];
E=[A v'] % line 93, augment A with a column
F=[A; v] % line 94, augment A with a row
[m, n]=size(E) % line 95
G=zeros(m,n) % line 96
%
% a) Explain what line 88 does.
% b) Explain what line 89 does.
% c) Explain what line 90 does.
% d) Explain what line 91 does.
% e) Explain what line 92 does.
% f) Explain what line 93 does.
% g) Explain what line 94 does.
% h) Explain what line 95 does.
% i) Explain what line 96 does.
%
% Problem 6
% We see that MATLAB has numerous methods to manipulate vectors and matrices
% Use MATLAB help to describe the following operations (built-in functions):
%
% a)   eye(m,n)
% b)   ones(m,n)
% c)   rand(m,n)
% d)   diag(v)
% e)   fliplr
% f)   flipud
%
% g) and give a program that illustrates the use of each of these operations.
%
% Problem 7
% In MATLAB vectors can be created in many ways.
clear all;
v_begin=-1.0;
v_end=12.0;
v=linspace(v_begin, v_end, 14) % line 126
u=zeros(1, 100) % line 127
w=ones(1, 10) % line 128
x=-1.0:2:20 % line 129
```

```
theta=0:pi/16:2*pi; k=size(theta) % line 130
%
% a) Explain what line 126 does.
% b) Explain what line 127 does.
% c) Explain what line 128 does.
% d) Explain what line 129 does.
% e) Explain what line 130 does.
%
% Problem 8
clear all;
a=[10 2 3 4 5; ...
   6 7 8 9 10; ...
   0 -1 -2 -3 -4; ...
   -5 -6 -7 -8 9; ...
   1 2 3 2 1];
b=[-1 -3 4 5 2; ...
   3 7 5 9 5; ...
   -1 -2 -3 -4 0; ...
   5 -2 -1 2 0; ...
   3 2 -1 0 1];
c=a/b % line 150
d=det(a)
e=det(b) % line 152
f=det(c); g=d/e;
f
g
%
% a) Explain what line 150 does.
% b) Explain what line 152 does.
% c) Why are f and g equal, explain?
```

Problem 9

Look up the arc-tangent (atan) function, and write a program to plot it: y=atan(x), with 501 points over the range: x = -100.0 to +100.0. Provide a program listing and a plot.

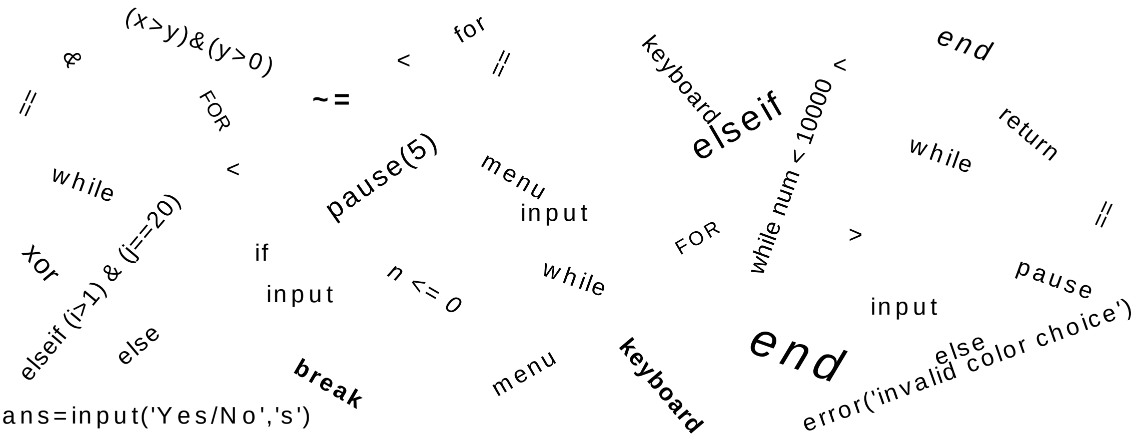
ECE 115

Introduction to Electrical and Computer Engineering

Laboratory Experiment #3

Loops, Branches and Program Flow Control

Objective: To learn about and how to use MATLAB program flow control commands.



Before you come to the Lab, read Sections 1-5 of Chapter 4, titled, "Program Flow Control", which is posted on the blackboard.

For processing certain operations and commands repeatedly, MATLAB has **for loop** and **while loop** commands. With the **if-elseif-else** structure a program can test conditions and execute alternative program segments. With the **break, error,** and **return** commands program execution can be controlled. Interactive input is facilitated with the **input, keyboard, menu** and **pause** commands. These commands are often used in association with relational and logical operations, which produce a logical result. In this experiment you will learn about each of these commands and to use relational and logical operations.

The relational operations are:

<	less than
<=	less than or equal to
>	greater than

```
>=      greater than or equal to
==      equal to
~=      not equal to
```

and the logical operations are:

```
&       and
|       or
~       not
xor     exclusive or function
```

A relational operation produces either 1, meaning the relation is true, or 0, meaning the relation is false. For example, consider the following MATLAB program segment:

```
x = 2.0;
y = -5.0;
z1 = x < y;
z2 = x == y;
z3 = x ~= y;
```

The result is: z1=0, since it is not true (false) that x is less than y, z2=0, since it is false that x equals y, and z3=1, since it is true that x is not equal to y. Relational operations and logical operations can be compounded. For example, the following MATLAB program segment:

```
w = 9.0; x = 2.0; y = -5.0;
z1 = (x>y) & (x<w);
```

produces z1=1, since it is true that x is greater than y, and it is true that x is less than w. If the expression is instead: z1=(x<y) & ~(x<w), then z1=0, since (x<w) is true, and ~(x<w) is false.

EXPERIMENT

For each of the following problems, your report should include a listing of your program.

Problem 1

a) Type in the following **for loop**.

```
sum=0.0;
for m=0:2:8
        sum = sum + 1/(2^m);
end
sum
```

What is the value of m and sum after the loop has executed?

b) Type in the following program.

```
for n=10:-2:-10, k=1/exp(n), end
```

Describe how n changes through each loop. What is the purpose of the commas? What happens if commas are replaced by semi-colons?

Problem 2

a) Type in the following program.

```
% find all powers of two below N
clear all
N=500;
v=1; num=1; i=1;
while num < N
    num = 2^i;
    v = [v; num];  % explain this line
    i = i +1;
end
v   % display v
```

What is the dimension of **v** ***after this program has executed?***

b) Modify the program of part (a) so that a user of the modified program is instructed to enter a value for N. Execute the program only if an N greater than two is entered. If N is not greater than two inform the user that the program will be terminated. Use a while loop around the present while loop. For example, you could start with:

```
N = input('Enter a value for N:  ')
go = N > 1;
while go
    y =1;
    .
    .
    .
```

Test your program for N greater than and less than 2, and describe results. Look up the **input** ***command in MATLAB help, and discuss what the input command does when 's' is also included in the*** **input** ***statement.***

For example, consider the following MATLAB program segment.

```
clear all
x = input('enter Y/N:  ','s')
ans = (x == 'Y') | (x == 'y')
```

Explain what this program segment does, and specifically, explain what is being compared with the == operations.

Problem 3

a) Type in the following program.

```
clear all;
a = 2; j = 21;
if a > 5
        k = a;
elseif (a > 1) & (j == 20)
        k= 5 * a  + j;
else
        k = 1;
end
```

Here, in the **if** command, MATLAB checks whether or not, a>5, is true, and if it is true, then k=a is executed, and then execution continues after the **end** statement. However, if a>5 is false, then in the next **elseif** command, (a > 1) & (j == 20), is checked, and if it is true then the next statement, k= 5 * a + j, is executed and execution continues after the **end** command, and if it is false, then the statement, k=1, after the **else** command, is executed. Any number of additional **elseif** sections can be added. ***Add another elseif section to the program that executes,* k = j, *if* a < 1. *Then, for what assignment to* a *can it occur that* k=1 results?**

b) The command **break** inside a **for** or a **while** loop unconditionally terminates the execution of the loop. Just before the statement, i=i+1, in the program of part (2a) add the statements:

```
if length(v) > 8
        break
end
```

Use MATLAB help to find out what the* length *command does, and explain what happens in the program due to the addition of the above statements.

c) ***Write a small program that uses a* while *loop that includes within it an* if-end *structure like the one given above to break out of the* while *loop. Explain program operation.***

Problem 4

The command **error('message')** terminates function or program execution and returns control to the keyboard. The **return** command returns control from a function back to the invoking program or function. The **keyboard** command inside a function or program returns control to the keyboard at the point where the **keyboard** command occurs. Within the command window the prompt becomes k>> to show that the keyboard command has executed. Any valid MATLAB command can then be executed from within the command window. Program or function execution can be made to continue just after the place where the **keyboard** command occurs by entering the **return** command from within the command window.

Write a program to use the following function, and describe what happened when your program executes a statement like b=SquareRoot(a) for a=2, a=0 and a= -1.

```
function y = SquareRoot(x);
y=0;
if x < 0
   error('the function argument cannot be negative')
end
if x == 0
   return
else
   y = x^0.5;
end
```

Problem 5

a) The following program illustrates use of the **menu** command.

```
clear all
theta = linspace(0, 2.0*pi, 101);
x = sin(theta);
plot_type = menu('plot type menu','stem plot','line plot'); % display plot selection menu
if plot_type == 1
        stem(theta, x);
else
        plot(theta,x);
end
grid on
disp('press enter to continue'); pause; % pause to view plot
```

Type in the program given above, and execute it. Describe the appearance of the menu. Select each menu item and describe what the program does. What does the **pause** ***command do?***

b) ***Add another type of plot choice to the*** **menu** ***command, and expand the if-end structure with an*** **elseif** ***segment to include the new plot type in the possible output plots.***

ECE 115

Introduction to Electrical and Computer Engineering

Laboratory Experiment #4

Use of Some Analog Instrumentation

The purpose of this experiment is to become acquainted with the operation and utility of some of the conventional instrumentation used to investigate the operation of electronic circuits and devices. You will learn how to use an oscilloscope, a signal (function) generator, a multimeter, a power supply, and a facility for conveniently putting together small circuits.

Oscilloscope

The oscilloscope, like the one shown below, is probably the most widely used instrument to investigate the operation of an electronic circuit. The oscilloscope provides a visual display of the voltage between two points in an electronic circuit, as this voltage varies with time.

This oscilloscope can display simultaneously two voltages, one voltage that is an input to its channel 1 input and another voltage that is an input to its channel 2 input. The user can elect to view either channel 1 or channel 2, or both. Basically, the way an oscilloscope (scope) works is very simple. Electronic circuitry within the scope controls the horizontal position of a lighted point on the display screen. This lighted point is made to repeatedly sweep across the display screen from left to right, giving the appearance of a horizontal line to the observer. The voltage that is applied at an input to a channel causes the lighted point to be deflected up, if the input voltage is positive, or down, if the input voltage is negative. Therefore, as the lighted point sweeps across the display screen, the viewer will observe a lighted wave shape that corresponds to how the channel input voltage varies with time.

There are many attributes of how the observed wave shape should appear on the display, and that is why there are many controls on the front panel of a scope. Some of these controls are set according to user preferences, such as: the horizontal width of the displayed image, the vertical position of the displayed wave shape, the intensity (brightness) of the display, and others. Some of these controls are set according to what the voltage to be displayed is like.

For example, if the input voltage varies very slowly with time and the lighted point sweeps across the display very quickly, then the image looks more-or-less like a horizontal line, and we do not see very well how the input voltage varies with time. In this case we would adjust a front panel control to decrease the horizontal sweep rate, and then as the lighted point sweeps across the display it would also move up and down sufficiently so that you can see how the input voltage varies with time. If the sweep rate is set to make the lighted point move from the left side to the right side of the display in one millisecond, then we would see how the input voltage varies over a one millisecond time interval. Therefore, if the input voltage is a sinusoidal voltage having a frequency of: 1000 cycles/sec = 1K Hz, then the display would show one cycle of the sinusoidal input voltage. If the input frequency is increased to 2K Hz, then with the same scope settings you would see two cycles of the sinusoidal voltage.

If the input voltage varies very rapidly with time and the lighted point sweeps across the display very slowly, then the image looks more-or-less like a solid mass, and we do not see very well how the input voltage varies with time. In this case we would increase the horizontal sweep rate, and then as the lighted point sweeps across the display it would also move up and down sufficiently so that we will see how the input voltage varies with time. Therefore, if we want to see a few cycles of a 1K Hz sinusoidal input voltage, then we set the horizontal sweep rate, for example, to 0.1 millisec/division, and if the input frequency is instead 1M Hz, then the sweep rate must be increased to 0.1 microsec/division.

How rapidly the input voltage varies with time is one attribute of the input that the scope user must accommodate with appropriate scope settings. Another input voltage attribute is the minimum value to maximum value range over which the input voltage varies. Of interest is to use enough of the vertical display to clearly see how the input voltage varies. The vertical distance over which the lighted point can move can be controlled by the user. For example, if the input voltage varies within the range -5 millivolts to +5 millivolts (an input range of 10 millivolts) and we want the vertical display to range over 2 divisions of vertical displacement, then we should set the vertical sensitivity to 5 millivolts/division. If for some reason the input voltage range increased from 10 millivolts to 50 millivolts, then, with the same sensitivity setting, the vertical image size will increase to 10 divisions, and to keep the image size the same as before we must decrease the vertical sensitivity to 25 millivolts/division. The user can also control the vertical position of the display. This is useful to provide space for displaying the inputs from two channels or more channels on other multi-channel scopes.

There are numerous other controls on the scope front panel depending on other functions that a scope can perform. For example, some scopes can be set to start a sweep only when the input voltage exceeds a user set threshold (trigger). A very important characteristic of an oscilloscope is its ability to respond to a voltage input as it increases and decreases, and this depends on how rapidly the input voltage varies. It is significantly more costly to design and build an oscilloscope that can display input voltages that may vary sinusoidally with frequencies up 1 GHz, than to display input voltages that may vary sinusoidally with frequencies up to 1 MHz. The highest frequency of a sinusoidally varying voltage input that an oscilloscope can adequately display is called the bandwidth (BW) of the oscilloscope. Therefore, a scope with a BW = 20 MHz would not be able to display a voltage signal having frequencies above 20 MHz. On the other hand, if a scope is to be used exclusively for displaying audio signals (BW < 20 KHz), then there is no need to acquire an oscilloscope more expensive than a scope having a BW of about 20 MHz, a common instrument.

Function Generator

The function (or signal) generator is an instrument that produces voltages having certain standard wave shapes. Some standard wave shapes are: sinusoidal, triangular and square. Its purpose is to provide a controlled voltage signal that can be inputted into an electronic circuit to investigate how the circuit will respond to inputs, when the input properties are known and can be controlled. The signal generator output voltage properties that the user can set are amplitude and frequency for sinusoidal, triangular and square (a rectangular wave with a 50% duty cycle) waves, and some signal generators can: add a user controlled constant voltage (offset) to the output, allow the user to control the duty cycle of the rectangular wave output, modulate (change) the frequency of the output at some user set frequency, which produces an FM (frequency modulated) wave, and more. Like an oscilloscope, the cost of a function generator increases as the range of frequencies over which it can operate increases. A function generator that can produce test signals having frequencies upwards of 30 GHz can be very expensive, while a function generator having a frequency range over the audio frequency range (0 – 20 KHz) is relatively inexpensive.

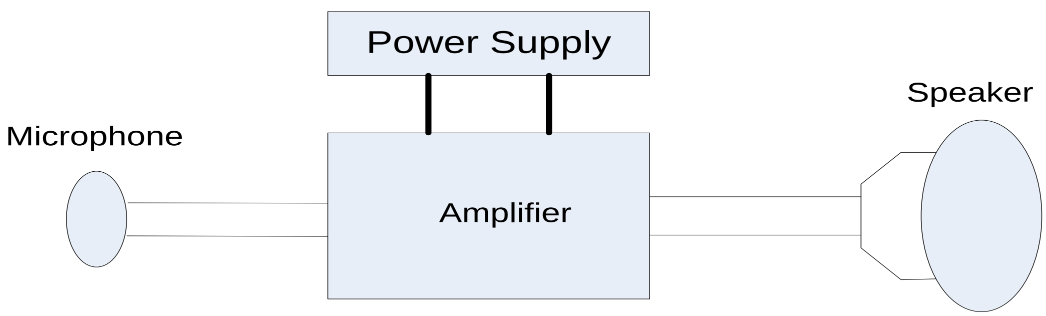
Multimeter

A multimeter is used to measure several distinctly different kinds of electrical quantities. It is several different meters in one package. The different electrical quantities that it can measure are: DC voltage, which is a voltage that does not vary with time, AC voltage, which is a voltage known to vary with time, typically a 60 Hz sinusoidally varying voltage, DC current, which is a current that does not vary with time, and the resistance of a resistor, a circuit component that impedes the movement of charge through it depending on its resistance value, given in units of Ohms. Ideally, a conductor (short circuit) has a resistance value of zero Ohms, while an open circuit (no conductor) has a resistance value of infinity Ohms. The sensitivity range of the multimeter must be selected by the user to accommodate the range of the quantity to be measured. A multimeter is an inexpensive device to measure the voltage across two points in a circuit. An oscilloscope can also be used to do this.

Power Supply

Generally, for an electronic system, circuit, or device to operate the way it does, it must be supplied with electrical energy. Mostly, the form of this required energy is a constant voltage (DC voltage) and a constant current (DC current) depending on the power requirements of the system or device that receives the electrical energy.

For example, consider the electronic system shown below. At its output, the microphone produces a time varying voltage having a very small amplitude range, and the microphone output is a low power signal. The speaker requires a high power input signal to produce a sound having sufficient energy (volume). The electronic circuitry of the amplifier uses the energy from the power supply to amplify the power of the signal coming from the microphone to produce an output signal that is a voltage signal that varies proportionally to the input voltage and has a much higher power than the input signal.



A battery is a DC voltage source, which is available at numerous different voltage levels and power ratings. However, a battery cannot supply electrical energy indefinitely. A 12 volt car battery, for example, can only supply power at: P = (12 volts) (100 amperes) = 1200 Watts = 1200 Joules/second to a starter motor for a minute, depending on its condition.

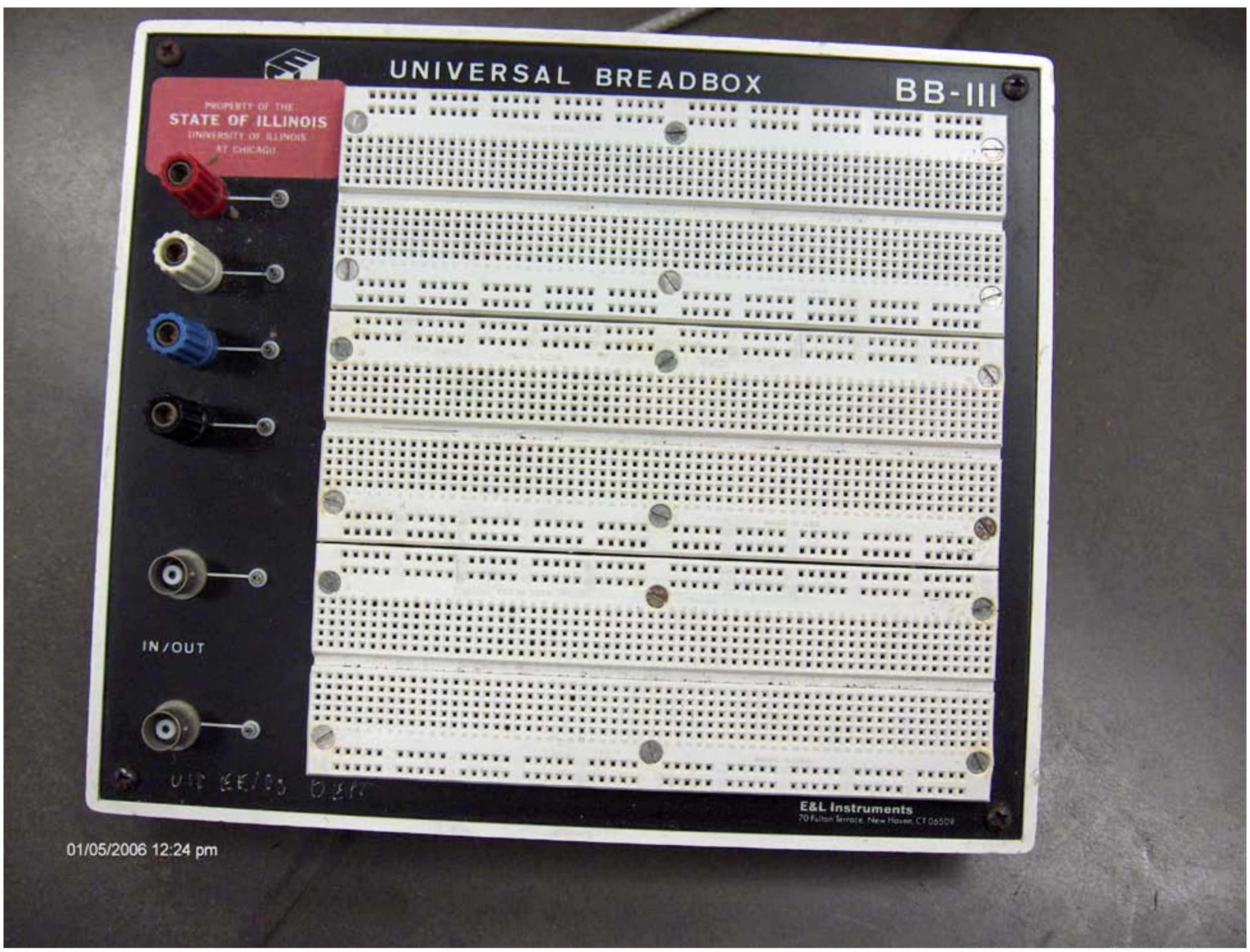
Generally, at the wall outlet, electrical energy is available in the form of an AC (60 Hz sinusoidal) voltage with a zero-to-peak amplitude of: $(110)\sqrt{2} = 155.56$ volts, where 110 volts is its RMS (root mean square) value. The purpose of a power supply is to convert the available AC power to DC power that electronic systems and devices require to operate.

A device that does the opposite of a power supply (power converter) is a power inverter. A power inverter receives its input electrical energy from a battery, and it converts the DC power from the battery to AC power, which can be used to temporarily supply AC power to devices. For example, in the event of an AC power loss to a computer, an inverter can be used .

Commercially available power supplies vary considerably in the number of independent supply voltages available within a single package, the maximum current that they can provide and how well these outputs are controlled. Since the power supply converts an AC voltage to a DC voltage, an important operating characteristic of a power supply output is the extent to which it is free of AC noise.

BreadBox

BreadBox is a term used to refer to a means to conveniently and quickly build a circuit for the purpose of testing a design. Usually only small circuits (those with few components) are built this way. The breadbox shown below has on it three superstrips, as they are called, for wiring together components of a circuit. Along the center of each superstrip are columns of five holes each, and within the superstrip these five holes are wired together.



Therefore, to connect wires from two circuit components together, push each of the wires into one of the holes in a five hole column. Parallel to each edge of each superstrip are two rows of holes grouped in groupings of five holes for total of ten groups along each such row. Within a row, five groups of five holes are all connected within the superstrip. The rows along the edges are commonly used to distribute the positive and negative terminals of the power supply to the components connected into the column holes.

Experiment

At the beginning of this experiment all instruments should be turned off.

1) Power up the function generator and the oscilloscope, and use a cable to connect the output of the function generator to the channel 1 input of the oscilloscope. Set the generator to produce a sinusoidal voltage having a 10K Hz frequency. The front panel of the oscilloscope has knobs, grey keys and white keys. The knobs are used most often. The grey keys bring up softkey menus. The white keys are instant action keys. Press the channel 1 select key to select channel 1 for display.

The oscilloscope has an autoscale feature that automatically sets up the oscilloscope to best display the input. (a) Press the Autoscale button, and ***give the resulting sweep rate*****.** ***What happens on the scope display as you increase and decrease the output amplitude from the signal generator*****?** ***Give the vertical sensitivity.*** Then, undo the autoscale feature by pressing Setup and then pressing the Undo Autoscale softkey. (b) ***Repeat the above steps for a 100 Hz triangular wave****.*

2) ***List and describe each item on the display while the scope is showing a waveform.***

3) Through the softkey below the display, the scope can perform many operations. Let's exercise just one of them, which is the feature to have the scope determine the frequency of a sinusoidal wave form. Set the function generator to produce a sinusoidal wave form, and display it on the scope. (a) ***Knowing the sweep rate and the number of divisions required to display one cycle, find the period in seconds of the wave form and then invert this to find its frequency. How does this compare to the dial setting of the function generator?*** Then, press the Time key below the scope display. A menu should appear with six softkey options. Toggle the source softkey to select a channel 1 for the frequency measurement. Press the Freq softkey, and the scope will measure the frequency and display it on line near the bottom of the display. (b) ***Give the result.***

The oscilloscope has many other features which you may investigate. See the oscilloscope documentation at your lab station.

4) Remove the function generator cable from the channel 1 scope input, and connect instead a cable from one voltage source within the power supply. The negative (black) wire from the power supply output should go the ground input of the scope, and the

positive (red) wire from the power supply output should be the input to channel 1 of the scope. Also, set the multimeter to measure DC voltage, and connect the multimeter leads to the power supply voltage outputs. Connect the negative lead of the multimeter to the negative terminal of the power supply. Turn on the multimeter and the power supply. Adjust the voltage control of the power supply to produce approximately 5 volts. Use the scope and the multimeter to measure the voltage. ***Discuss what happened. Give the meter reading, scope vertical sensitivity, and number of display divisions from zero volts to the voltage to which you set the power supply output.***

5) Your station is supplied with seven ¼ W resistors and some wire that is suitable for interconnecting components on the breadbox. Starting at one end, each resistor has at least three colored bands around it. The band closest to the end and the next band are color codes for digits as follows:

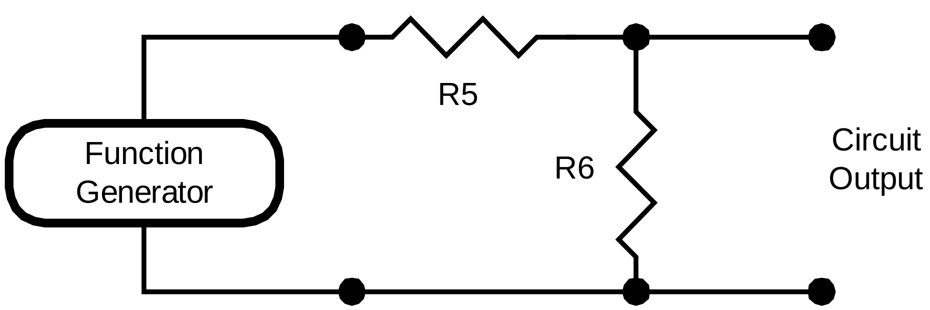
black	brown	red	orange	yellow	green	blue	violet	gray	white
0	1	2	3	4	5	6	7	8	9

The third band is also a color code for a digit, but this digit is used as a power of ten. Therefore, if the first three bands have the color codes given by: **red, violet, and orange**, then the resistor has a resistance value close to: 27K Ohms. Additional color bands on a resistor give the precision to which the actual resistance value matches the claimed color coded value.

For convenience, let us refer to the given resistors as R1, R2, …, R7, where
R1 = R2: brown, black, red
R3: red, red, red
R4: orange, orange, red
R5 = R6: brown, black, orange
R7: red, red, orange

Using the multimeter to measure, give the resistance of each resistor.

6) On the breadbox, wire the circuit shown below.



The circuit consists of the connection of R5 and R6. The function generator is connected to a part of the circuit called the circuit input, and the voltage across the resistor R6 is considered to be the circuit output. Connect channel 1 of the oscilloscope to the circuit input, and connect channel 2 of the oscilloscope to the circuit output. Then, we will be able to see simultaneously the circuit input and the circuit output. Set up the function generator to produce a 1K Hz sinusoidal voltage, having an amplitude of 5 volts. This wave form should be positioned to appear in the top half of the scope display. The bottom half of the scope display should show the output waveform. (a) ***What is the amplitude of the output sinusoidal signal?*** The output amplitude is proportional to the input amplitude, and a circuit analysis will give that

$$v_{output}(t) = \frac{R5}{R5+R6} v_{input}(t)$$

(b) ***Use the values of R5 and R6 to compare the result of this formula with experimental results.***

(c) ***Repeat part (b) using a triangular wave.***

(d) ***Repeat part (b) using R3 and R4 instead of R5 and R6, respectively.***

ECE 115

Introduction to Electrical and Computer Engineering

Laboratory Experiment #5

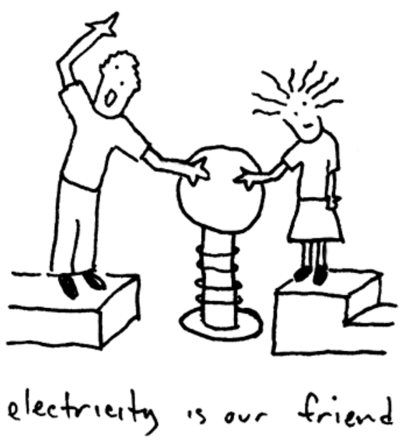
How Does Electric Energy Get Distributed?

Purpose:

The purpose of this experiment is to learn about the fundamentals of power transfer by studying a simple transformer and a diode.

Pre-lab:

Read Sections 3.2.4 and 3.2.5 on inductors in your *Essentials of Electrical and Computer Engineering* text.



History:

1830 - Inductance

In 1830, Joseph Henry (1797-1878), discovered that a change in magnetism can make charge flow, but he failed to publish this. In 1832 he described self-inductance - the basic property of an inductor. In recognition of his work, inductance is measured in henries. The stage was then set for the encompassing electromagnetic theory of James Clerk Maxwell. The range of variation of currents is enormous. A modern electrometer can detect currents as low as 1/100,000,000,000,000,000 amp, which is a mere 63 electrons per second. The current in a nerve impulse is approximately 1/100,000 amp; a 100-watt light bulb carries 1 amp; a lightning bolt peaks at about 20,000 amps; and a 1,200-megawatt nuclear power plant can deliver 10,000,000 amps at 115 V.

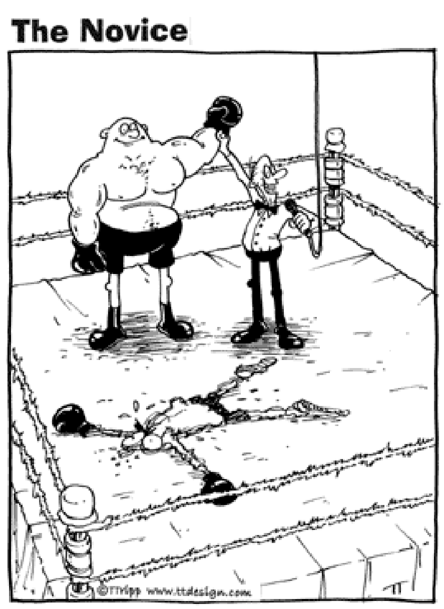
1855 - Electromagnetic Induction

Michael Faraday (1791-1867) an Englishman, made one of the most significant discoveries in the history of electricity: Electromagnetic induction. His pioneering work dealt with how electric currents work. Many inventions would come from his experiments, but they would come fifty to one hundred years later. Failures never discouraged Faraday. He would say; "the failures are just as important as the successes." **He felt that failures also teach.** The farad, the *unit of capacitance* is named in the honor of Michael Faraday.

Faraday was greatly interested in the invention of the electromagnet, but his brilliant mind took earlier experiments still further. *If electricity could produce magnetism, why couldn't magnetism produce electricity*. In 1831, Faraday found the solution. Electricity could be produced through magnetism by motion. He discovered that when a magnet was moved inside a coil of copper wire, a tiny electric current flows through the wire. H.C. Oersted, in 1820, demonstrated that electric currents produce a magnetic field. Faraday noted this and in 1821, he experimented on the theory that, if electric currents in a wire can produce magnetic fields, then magnetic fields should cause electric currents. By 1831, he was able to prove this and through his experiment, was able to explain, that these magnetic fields were lines of force. These lines of force would cause a current to flow in a coil of wire, when the coil is rotated between the poles of a magnet. This action then shows that the coils of wire being cut by lines of magnetic force, in some strange way, causes charge to move (electric current). These experiments, convincingly demonstrated the discovery of electromagnetic induction in the production of electric current, by a change in magnetic intensity.

AC vs. DC

Tesla vs. Edison



1879 - DC Generation, Incandescent Light

Thomas Alva Edison, (1847-1931) was one of the most well known inventors of all time with 1093 patents. Self-educated, Edison was interested in chemistry and electronics. During the whole of his life, Edison received only three months of formal schooling, and was dismissed from school as being retarded, though in fact a childhood attack of scarlet fever had left him partially deaf.

Nearly 40 years went by before a really practical DC (Direct Current) generator was built by Thomas Edison. Edison's many inventions included the phonograph and an improved printing telegraph. In 1878 Joseph Swan, a British scientist, invented the incandescent filament lamp and within twelve months Edison made a similar discovery in America. Swan and Edison later set up a joint company to produce the first practical filament lamp. Prior to this, electric lighting had been made with crude arc lamps.

Edison used his DC generator to provide electricity to light his laboratory and later to illuminate the first New York city street that was lit by electric lamps, in September 1882. Edison's successes were not without controversy, however. Although he was convinced of the merits of DC for generating electricity, other scientists in Europe and America recognized that DC brought major disadvantages.

Back at the very beginning, transmission was a matter of intense debate. On one side were proponents of direct current (DC), in which electrons flow in only one direction. On the other were those who favored alternating current (AC), in which electrons oscillate back and forth. The most prominent advocate of direct current was none other than Thomas Edison. If Benjamin Franklin was the father of electricity, Edison was widely held to be his worthy heir. Edison's inventions, from the light bulb to the electric fan, were almost single-handedly driving the country's—and the world's—hunger for electricity.

However, Edison's devices ran on DC, and as it happened, research into AC had shown that it was much better for transmitting electricity over long distances. Championed in the last two decades of the 19th century by inventors and theoreticians such as Nikola Tesla and Charles Steinmetz and the entrepreneur George Westinghouse, AC won out as the dominant power supply medium. Although Edison's DC devices weren't made obsolete—AC power could be readily converted to run DC appliances—the advantages AC power offered made the outcome virtually inevitable.

1883 - The Alternating Current System

Nikola Tesla was born of Serbian parents July 10, 1856 and died a broke and lonely man in New York City on January 7, 1943. He envisioned a world without poles and power lines. Referred to as the greatest inventive genius of all time. Tesla's system triumphed to make possible the first large-scale harnessing of Niagara Falls with the first hydroelectric plant in the United States in 1886. With the DC generator being in operation by 1882, it was not long before the first direct-current central power station built in the United States, in New York, was in operation in 1882. Around this period however, the scientists were still experimenting, as they realized that with DC current, they could not transmit electric power over long distances. Nikola Tesla was experimenting with generators, and he discovered a way to rotate a magnetic field in 1883, which is the principle for generating alternating current. This rotating magnetic field changed in opposite directions fifty time a second, and making its frequency 50 Hertz. The alternating current generator has a rotating magnetic field, and it produces current referred to as A.C. current. He then developed plans for an induction motor, which would become his first step towards the successful utilization of alternating current.

George Westinghouse was awarded the contract to build the first generators at Niagara Falls. He used his money to buy up patents in the electric energy field. One of the inventions he bought was the transformer from William Stanley. Westinghouse invented the air brake system to stop trains, the first of more than one hundred patents he would receive in this area alone. He soon founded the Westinghouse Air Brake Company in 1869.Westinghouse was a famous American inventor and industrialist who purchased and developed Nikola Tesla's patented motor for generating alternating current. The work of Westinghouse, Tesla and others gradually persuaded American society that the future lay with AC rather than DC (Adoption of AC generation enabled the transmission of large amounts of electrical power using higher voltages via transformers, which would have been impossible otherwise). Today the unit of measurement for magnetic fields, the Tesla, commemorates Tesla's name.

1885 - AC Generation

In 1885, George Westinghouse, head of the Westinghouse Electric Company, bought the patent rights to Tesla's polyphase system of alternating current generation. In America, in 1886 the first alternating current power station was placed in operation, but as no AC motor was available, the output of this station was limited to lighting. Although Telsa developed the polyphase AC induction motor in 1883, it was not put into operation until 1888 and from then on, this AC motor became the most commonly used motor for supplying large amounts of mechanical power. An electric motor converts electric energy to mechanical energy.

Below is shown a very large transformer used in electric energy distribution systems.

Faraday's, discovery of electromagnetic induction, was used to create the transformer. The transformer is a simple device, mainly consisting of two separate coils of wire. When a current is applied to the first coil, a current is "induced" in the second coil. By this induction, the magnitude of the voltage in the second coil depends on the number of turns in the coil. If the number of turns in the second coil is greater than the first coil, the voltage is increased and vice versa. The first transformer was announced by L. Caulard and J. D. Gibbs in 1883, and so this device revolutionized the systems of power transmission. By generating at a low voltage, the transformer steps it up to a high voltage for transmission and then to a lower voltage where required.

Probably the first generating station in the world to serve private consumers was the Holborn Viaduct in London, which started up in 1882, supplying about 60 kilowatts of power. Also in 1882, Brighton in England had its first public supply, and in that year the Crystal Palace in London, had its first demonstration of electric light. The Pearl Street Central Power Station in New York, was the first station of record in America in 1882. One of the first transmission lines, was between Miesbach to Munich in Germany in 1882.

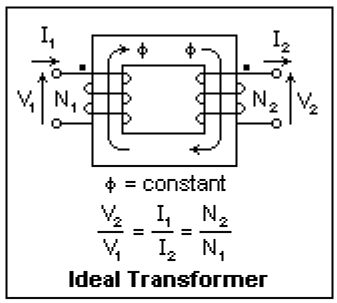
Theory:

Based on the history above, you should now have some idea of magnetic and electric fields. The Right-Hand-Rule, is a useful way of visualizing the magnetic field caused by an electric current: Pointing your thumb in the direction of the current, fingers will wrap around the wire in the direction of the circular magnetic field (lines), created by that current.

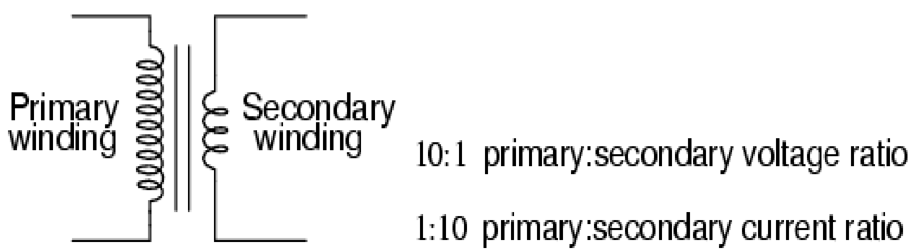
As a magnet is moved toward a turn of wire in the coil, the induced current produces a magnetic force that pushes against the entering magnet. The opposite of this occurs when the magnet is moved away from the wire. As the magnet is moving through the coil, each end of the magnet feels a force resisting its movement. Since the change in the magnetic field is being resisted, we must spend energy (do work) to push or pull the magnet through the coil of wire.

A *transformer* is a device in which two circuits are coupled by a magnetic field that is linked to both. There is no conductive connection between the circuits, which may be at arbitrary constant currents. Only *changes* in current one circuit affect the other. The circuits often carry at least approximately sinusoidal currents, and the effect of the transformer is to change the voltages level, while transferring power with little loss.

The figure below shows how a transformer is made. The magnetic field lines, indicated by the lines of flux, ϕ, are concentrated in the iron core, a square donut, of the transformer. The primary coil, which is insulated from the iron core, is wound around one part of the iron core, and the secondary coil, which is electrically insulated from the primary coil and also insulated from the iron core, is also wound around the iron core. Many different core and winding configurations are used.



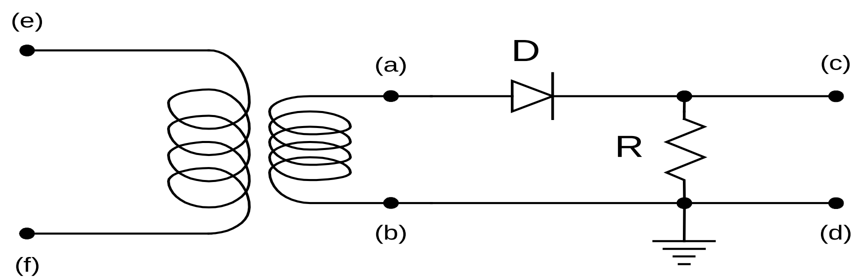
Below is a schematic symbol for a transformer. An efficient (ideal) transformer is one where the output power equals the input power, so that there is no power loss through the transformer. Therefore, we have that: $V_1\ I_1 = V_2\ I_2$, and the primary coil to secondary coil turns ratio then determines either the primary to secondary voltage ratio or the primary to secondary current ratio. If we step up the voltage, then we step down the current, but the power into the transformer equals the power out of the transformer.



A transformer is used to change the AC voltage level in one circuit to another AC voltage level in another circuit. Since there is no conducting path between the primary and secondary windings of a transformer, a transformer also isolates the circuit on its primary side from the circuit on its secondary side.

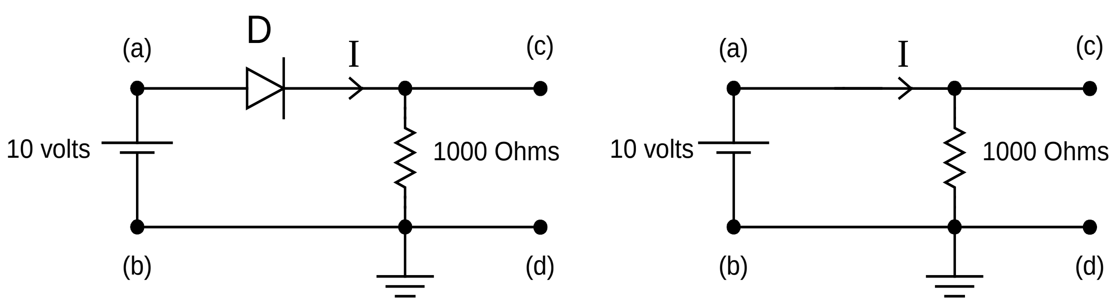
Compared to DC voltages and DC currents, it is more efficient to use AC voltages and AC currents to distribute electrical energy. However, the devices we use, such as desktop computers and televisions use electrical energy in DC voltage and DC current form to work the way they do. Therefore, these devices each include a power supply, which is a circuit that converts the electrical energy available in AC form to electrical energy in DC form.

Consider the circuit shown below, which uses a transformer like the transformer that was described earlier in this experiment. An AC voltage is applied to the primary winding at terminals (e)-(f). This transformer has a primary to secondary winding turns ratio such that the AC voltage that is produced out of the secondary winding has a smaller amplitude than the amplitude of the AC voltage applied at the primary winding.



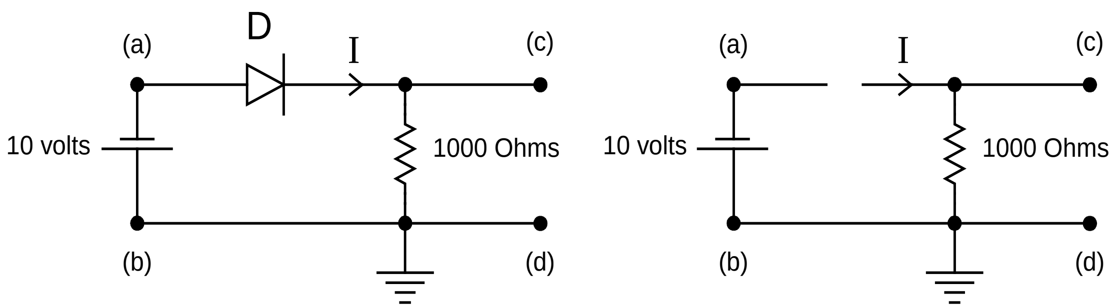
The transformer output is connected to the series connection of a diode, the component labeled D, and a resistor, the component labeled R. The diode is a device that permits current through it in only one direction, from the side called the anode, the left side in the schematic, to the side called the cathode, the right side in the schematic.

To more easily understand the operation of a diode, consider the circuit shown on the left below, which consists of a battery, diode and resistor connected in series.



Here, the voltage drop from (a) to (b) is **plus** 10 volts, which equals the voltage drop from (a) to (c) plus the voltage drop from (c) to (d). The voltage on the anode side (point (a)) of the diode is higher than the voltage on the cathode side (point (c)) of the diode. We say the diode is forward biased, in which case the diode acts substantially like a short circuit. The current, I, for the circuit on the left is essentially the same as the current, I, for the circuit on the right, where the diode has been replaced by a conductor, a short circuit. The voltage drop from the diode anode side to the diode cathode side is very small, and the current I is almost: $I = 10$ volts/1000 Ohms $= 1.0 \times 10^{-2}$ Amps = 10 mA.

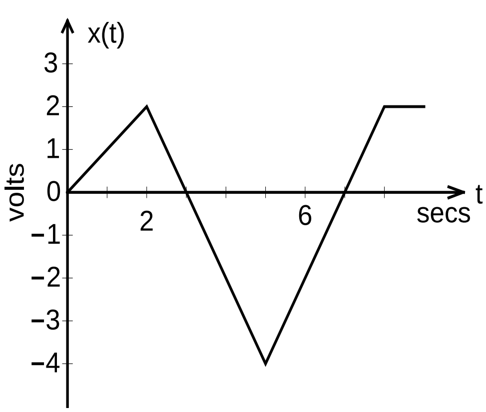
Now, suppose the polarity of the battery is reversed, resulting in the circuit shown on the left below.

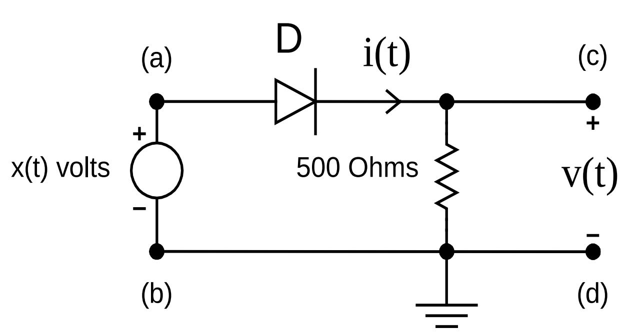


Here, the voltage drop from (a) to (b) is **minus** 10 volts, which causes the voltage on the cathode side (point (c)) of the diode to be higher than the voltage on the anode side (point(a)) of the diode. Now, we say that the diode is reversed biased, in which case the current through the diode becomes zero, and the diode acts substantially like an open circuit. The current, I, for the circuit on the left is essentially the same as the current, I, for the circuit on the right, where the diode has been replaced by an open circuit. Since the current, I, through the resistor has become zero, the voltage drop from point (c) to point (d) is zero, and the voltage drop from the cathode side of the diode to the anode side of the diode is **plus** 10 volts.

Generally, when the voltage drop, V_d, from the anode side of a diode to the cathode side of the diode is positive (forward bias), then the diode is almost an ideal short circuit, and when V_d is negative (reverse bias), then the diode is almost an ideal open circuit.

(1) ***To check your understanding of the operation of a diode, give plots for the current i(t) and voltage v(t) for the circuit shown below. You must show your plots to the lab TA before continuing with the experiment.***





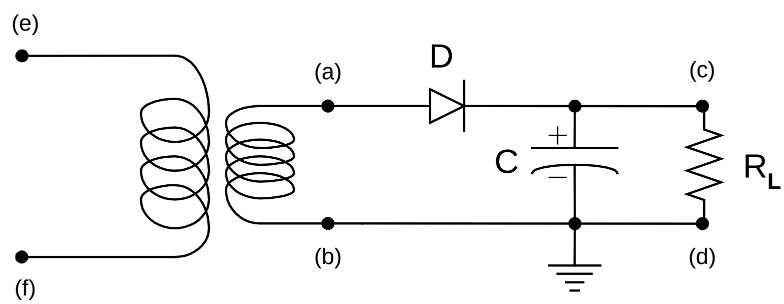
Now, we return to the circuit with the transformer. With the transformer disconnected from the AC voltage source, build this circuit on the breadbox. Use R = 1 K Ohm, and the diode provided in the lab. The diode comes in a cylindrical package, with a band at one end. This band indicates the cathode side of the diode.

When you have completed wiring the circuit, supply AC power to the AC wall transformer. We know that the AC outlet provides an AC voltage with an amplitude equal to $(110)\,(\sqrt{2}) = 155.56$ volts, where 110 volts is the RMS (root mean square) value of the voltage. (2) Use the oscilloscope, channel 1, to see the AC voltage at the secondary (across terminals (a) and (b)) of the transformer, and ***provide a sketch of it. This is a bipolar (both positive and negative) voltage . What is the frequency and amplitude of the secondary AC voltage? What is the RMS value of the secondary voltage? Given the above primary voltage amplitude, what is the transformer primary to secondary turns ratio?***

(3) Use channel 2 of the scope to see the voltage across terminals (c) and (d). Notice that terminals (b) and (d) are the ground terminals as indicated by the ground symbol, the symbol with short parallel lines that change (decrease) length to make a triangle. ***What is the frequency and amplitude of this voltage? How is it different from the voltage at the transformer secondary winding? Is this a bipolar or unipolar voltage?*** From the way the diode changes the voltage across (a)-(b) to the voltage across (c)-(d), the diode is also called a rectifier.

(4) The purpose of a power supply is to convert AC to DC, and we do not yet have a DC voltage. **Turn off the AC power supply.** Wire the circuit shown below. For the capacitor, use a C = 10 uF capacitor, and be sure to connect the negative side of the capacitor to the ground side of the circuit. For capacitors with a large capacitance, the insulating material between the plates of the capacitor is designed to only prevent the motion of charge from plate to plate in one direction. Therefore, large valued-capacitors have a polarity associated with their use. Use R_L = 1K Ohm., and connect channel 1 of the scope to terminals (a)-(b) and channel 2 of the scope to terminals (c)-(d). Apply AC power. ***Give sketches of the voltages across (a)-(b) and (c)-(d). What is the voltage value across the resistor? How much power is being delivered to the resistor?***

(5) ***Repeat step (4) with C = 100 uF. Discuss any difference in the voltage across (c)-(d). Set channel 2 of the scope for AC coupling to only see the AC part of a voltage, and increase the vertical sensitivity. Is the voltage across the resistor nearly a constant voltage?***



The above circuit is a very simple power supply that converts AC to DC. The DC voltage level depends on the turns ratio of the transformer. As the value of R_L becomes smaller, a small voltage oscillation will appear across it, which can be diminished by increasing the value of C. There are power supplies with much better performance than this circuit. For example, we would like the voltage across R_L to remain a constant voltage regardless of the value of R_L .

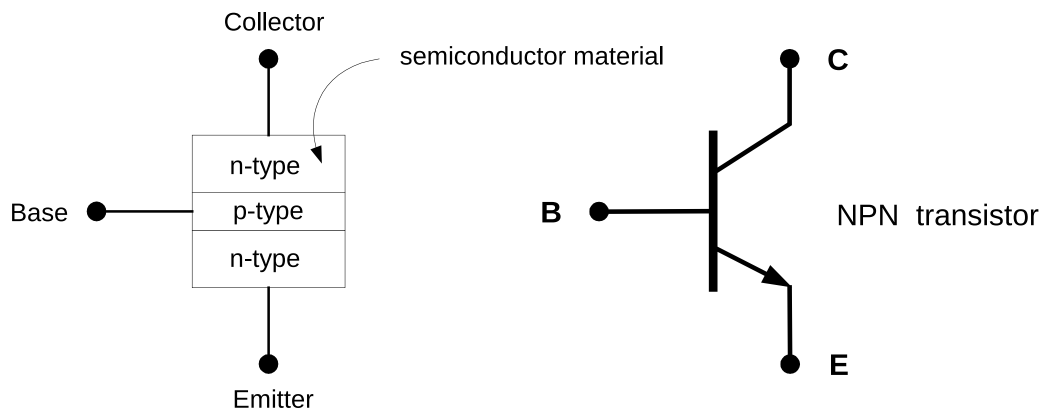
ECE 115

Introduction to Electrical and Computer Engineering

Laboratory Experiment #6

Transistor

The transistor is one of the most important inventions of the 20th century.



In this experiment you will investigate the operation of the transistor to learn that it can behave like a switch, and with a very small input current you can control a much larger current through some other device. To provide a visual indication of this activity, an LED, a light emitting diode, will be used.

YEAR	Timeline of Events in Electronic Technology Development
1898	Thomson discovers the electron
1899	Wireless telephone invented
1900	Max Planck describes quantum effect
1901	Marconi transmits radio signal across the Atlantic
1902	Carrier invents air conditioning
1905	Einstein described his special theory of relativity
1906	De Forest invents radio amplifier, voice & music radio broadcast in US
1909	AT&T announces coast to coast phone system plan, GE markets electric toaster
1912	De Forest invents telephone amplifier
1915	Coast to coast phone system operational
1916	Condenser microphone
1918	Mass spectroscope invented

1919	Proton discovered
1923	De Forest shows first sound-on-film motion picture
1930	Quantum Mechanics meets semiconductors
1932	Quantum theory of solids developed
1939	Electron microscope invented, television debuts at NY World's Fair
1940	Russell Ohl discovers the P-N junction
1941	Regular TV broadcasting begins
1945	Shockley & Morgan assemble solid state research teams
1946	ENIAC, the pioneering electronic digital computer, uses 18,000 vacuum tubes
1947	Invention of point-contact transistor
1948	Shockley invents junction transistor
1949	First Germanium transistors sold
1950	Transistors developed at Bell Labs
1951	Junction transistor developed, J Bardeen leaves Bell Labs and joins the University of Illinois
1952	Bell shares the technology
1953	First product to use transistor sold: hearing aid
1954	First transistor radio, first fully transistorized computer, Texas Instruments makes silicon transistor
1956	Shockley leaves Bell Labs; Nobel Prize Awarded to Shockley, Brattain & Bardeen
1957	Fairchild Semiconductor Co. established by Shockley, superconductivity theory described by Bardeen et al
1958	J Kilby invents integrated circuit
1959	R Noyce invents better integrated circuit
1960	First "Mini" Computer
1961	Fairchild & Texas Instruments sell integrated circuits
1965	"Moore's Law" predicts the rate of growth of IC components
1967	First hand held calculators
1968	G Moore & R Noyce leave Fairchild to form Intel Corp
1970	ARPA develops computer network
1971	T Hoff invents the microprocessor (with 2300 transistors)
1972	J Bardeen wins 2nd Nobel Prize for work in superconductivity
1975	W. Gates and P. Allen start Microsoft Corp
1976	VHS videotape developed
1977	Apple II personal computer

1981	IBM PC
1983	Nintendo entertainment system is introduced in the US
1989	World Wide Web
1990	Hubble space telescope, human genome project
1997	Intel Pentium microprocessor produced with 7.5 million transistors

Bell Laboratories, one of the world's largest industrial laboratories, was the research arm of the giant telephone company American Telephone and Telegraph (AT&T). In 1945, Bell Labs was beginning to look for a solution to a long-standing problem.

1907 - The Problem

AT&T brought its former president, Theodore Vail, out of retirement to help it fight off competition erupting from the expiration of Alexander Graham Bell's telephone patents. Vail's solution: transcontinental telephone service.

In 1906, the eccentric American inventor Lee De Forest developed a triode in a vacuum tube. It was a device that could amplify signals, including, it was hoped, signals on telephone lines as they were transferred across the country from one switch box to another. AT&T bought De Forest's patent and vastly improved the tube. It allowed the signal to be amplified regularly along the line, meaning that a telephone conversation could go on across any distance as long as there were amplifiers along the way.

But the vacuum tubes that made that amplification possible were extremely unreliable, used too much power and produced too much heat. In the 1930s, Bell Lab's director of research, Mervin Kelly, recognized that a better device was needed for the telephone business to continue to grow. He felt that the answer might lie in a strange class of materials called semiconductors.

1945 - The Solution

After the end of World War II, Kelly put together a team of scientists to develop a solid-state semiconductor switch to replace the problematic vacuum tube. The team would use some of the advances in semiconductor research during the war that had made radar possible. A young, brilliant theoretician, Bill Shockley, was selected as the team leader.

Shockley drafted Bell Lab's Walter Brattain, an experimental physicist who could build or fix just about anything, and hired theoretical physicist John Bardeen from the University of Minnesota. Shockley filled out his team with an eclectic mix of physicists, chemists and engineers. The group was diverse, yet close knit

In the spring of 1945, Shockley designed what he hoped would be the first semiconductor amplifier, relying on something called the "field effect." His device was a small cylinder coated thinly with silicon, mounted close to a small, metal plate. It was, as University of Illinois Electrical Engineer Nick Holonyak said, a crazy idea. Indeed, the device didn't work, and Shockley assigned Bardeen and Brattain to find out why. According to author Joel Shurkin, the two largely worked unsupervised; Shockley spent most of his time working alone at home.

Ensconced in Bell Labs' Murray Hill facilities, Bardeen and Brattain began a great partnership. Bardeen, the theoretician, suggested experiments and interpreted the results, while Brattain built and ran the experiments. Technician Phil Foy recalls that as time went on with little success, tensions began to build within the lab group.

In the fall of 1947, author Lillian Hoddeson says, Brattain decided to try dunking the entire apparatus into a tub of water. Surprisingly, it worked... a little bit. Brattain began to experiment with gold on germanium, eliminating the liquid layer on the theory that it was slowing down the device. It didn't work, but the team kept experimenting using that design as a starting point.

Shortly before Christmas, Bardeen had an historic insight. Everyone thought they knew how electrons behaved in crystals, but Bardeen discovered they were wrong. His breakthrough was what they needed. Without telling Shockley about the changes they were making to the investigation, Bardeen and Brattain worked on. On December 16, 1947, they built the point-contact transistor, made from strips of gold foil on a plastic triangle, pushed down into contact with a slab of germanium.

When Bardeen and Brattain called Shockley to tell him of the invention, Shockley was both pleased at the group's results and furious that he had not been directly involved. He decided that to preserve his standing, he would have to do Bardeen and Brattain one better. His device, the junction (sandwich) transistor, was developed in a burst of creativity and anger, mostly in a hotel room in Chicago. It took him a total of four weeks of working pen on paper, although it took another two years before he could actually build one. His device was more rugged and more practical than Bardeen and Brattain's point-contact transistor, and much easier to manufacture. It became the central artifact of the electronic age. Author Michael Riordan says Bardeen and Brattain got "pushed aside." That insult broke the team apart, turning a once cooperative environment into one that was highly competitive. The problems of whose names should be on the patent for the device, and who should be featured in publicity photographs, sent tensions higher still.

Bell Labs decided to unveil the invention on June 30, 1948. With the help of engineer John Pierce, who wrote science fiction in his spare time, Bell Labs settled on the name "transistor"--combining the ideas of "trans-resistance" with the names of other devices like thermistors.

The invention got little attention at the time, either in the popular press or in industry. But Shockley saw its potential. He left Bell Labs to found Shockley Semiconductor in Palo Alto, California. He hired superb engineers and physicists, but, according to physical chemist Harry Sello, Shockley's personality drove out eight of his best and brightest. Those "traitorous eight" founded a new company called Fairchild Semiconductor. Bob Noyce and Gordon Moore, two of the eight, went on to form Intel Corporation. They (and others at Texas Instruments) co-invented the integrated circuit. Today, Intel produces billions of transistors daily on its integrated circuits, yet Bardeen, Brattain, and Shockley earned very little money from their research. Nonetheless, Shockley's company was the beginning of Silicon Valley.

Bardeen left Bell Labs for the University of Illinois, where he won a second Nobel Prize. Brattain stayed on for several years, and then left to teach. Shockley lost his company and taught at Stanford for a while.

In the 1950s and 1960s, most U.S. companies chose to focus their attentions on the military market in producing transistor products. That left the door wide open for Japanese engineers like Masaru Ibuka and Akio Morita, who founded a new company named Sony Electronics that mass-produced tiny transistorized radios. Bell Labs' President Emeritus Ian Ross said that part of their success lay in developing the ability to quickly mass-produce transistors. The transistorized radio changed the world, opening up the information age. Information could quickly be scattered to the ends of the Earth.

The original three met several times after their breakup: once in Stockholm, Sweden, to receive the 1956 Nobel Prize for their contributions to physics, and once again at Bell Labs in 1972 to commemorate the 25th anniversary of their inventions. They were celebrating something that they could not know when they first began working on the transistor -- that they were going to change the world.

The Future of Transistors

The first announcement of the invention of the transistor met with almost no fanfare. The integrated circuit was originally thought to be useful only in military applications. The microprocessor's investors pulled out before it was built, thinking it was a waste of money. The transistor and its offspring have consistently been undervalued -- yet turned out to do more than anyone predicted.

Today's predictions also say that there is a limit to just how much the transistor can do. This time around, the predictions are that transistors can't get substantially smaller than they currently are. Then again, in 1961, scientists predicted that no transistor on a chip could ever be smaller than 10 millionths of a meter (1 micron = 1 millionth of a meter.), and on a modern Intel I5 chip they are about 100 times smaller.

With hindsight, such predictions seem ridiculous, and it's easy to think that current predictions will sound just as silly thirty years from now. But modern predictions of the size limit are based on some very fundamental physics -- the size of the atom and the electron. Since transistors run on electric current, they must always, no matter what, be at least big enough to allow electrons through.

On the other hand, all that's really needed is a single electron at a time. A transistor small enough to operate with only one electron would be phenomenally small, yet it is theoretically possible. The transistors of the future could make modern chips seem as big and bulky as vacuum tubes seem to us today. The problem is that once devices become that tiny, everything moves according to the laws of quantum mechanics -- and quantum mechanics allows electrons to do some weird things. In a transistor that small, the electron would act more like a wave than a single particle. As a wave it would smear out in space, and could even tunnel its way through the transistor without truly acting on it.

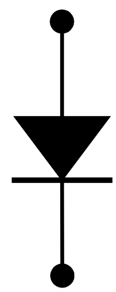
Researchers are nevertheless currently working on innovative ways to build such tiny devices -- abandoning silicon, abandoning all of today's manufacturing methods. Such transistors are known, not surprisingly, as single electron transistors, and they'd be considered "on" or "off" depending on whether they were holding an electron. (Transistors at this level would be solely used as switches for binary coding, not as amplifiers.) In fact, such a tiny device might make use of the quantum weirdness of the ultra-small. The electron could be coded to have three positions -- instead of simply "on" or "off" it could also have "somewhere between on and off." This would open up doors for entirely new kinds of computers. At the moment, however, there are no effective single electron transistors.

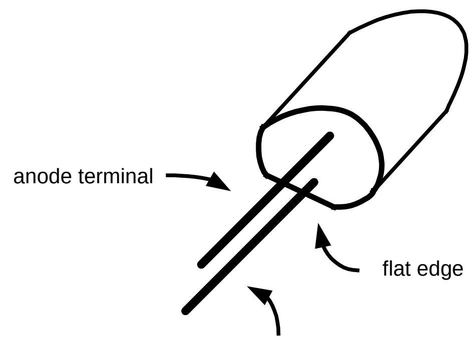
Even without new technologies, there's room for miniaturization. By improving on current building techniques, it's likely that present transistors will be at least twice as small by 2015. With well over a billion transistors on Intel's latest processor that would mean four times as many transistors on a chip are theoretically possible. Chips like this would allow computers to be much "smarter" than they currently are.

Light Emitting Diode

An LED, light emitting diode, works like a conventional diode, it allows for the movement of charge through it in only one direction, and in addition to this, when it does conduct a current, it also emits photons. The emitted light can have different colors, such as the conventional red, yellow, green, blue, and white colors.

The anode and cathode terminals of an LED are identified by the flattened edge of the package, as shown below. When the voltage from the anode to the cathode is positive, the diode is said to be forward biased and it conducts current, acting almost like a conventional conductor, a wire. When the voltage from the anode to the cathode is negative, the diode is said to be reversed biased, and it does not conduct current, acting like an open circuit.



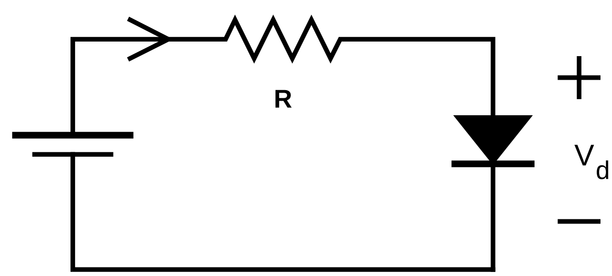


Experiment

The circuits below show a forward and a reversed biased diode. When a diode is forward biased, it has very little resistance, and there is a small voltage drop, V_d, across it that is approximately **1.4 volts**, regardless of the current. Because the diode resistance is very small, there must be a resistor in series with the diode to limit the current. With R too small the current can become large and burn out the diode. With $R = 330\ \Omega$, the current is given by

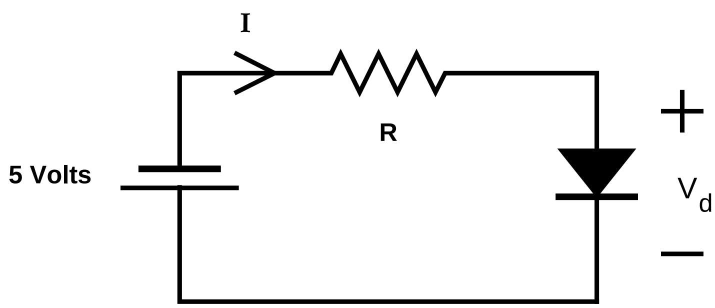
$$I = \frac{5.0 - V_d}{330} = \frac{5.0 - 1.4}{330} = 10.9\ \ ma$$

which is a typical amount of current for a bright light output of this low-power LED.



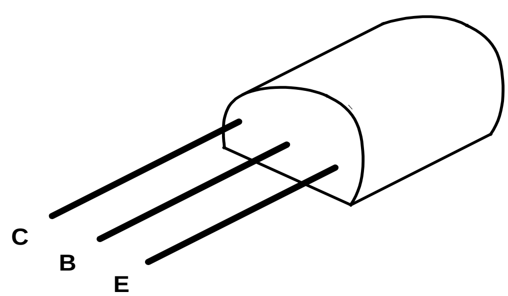
1) Wire this circuit on the breadboard. Before you connect the power supply voltage to the breadboard and your circuit, measure and check the power supply voltage with the multimeter. (a) ***Measure the voltage across the resistor, and give the result. Using the measured voltage, use Ohms law to find the current through***

the resistor? Replace the $330\,\Omega$ resistor with a larger resistor (try 1K Ω), and measure the voltage across this resistor. Calculate the current I? Discuss how the LED brightness varies as you increase or decrease the LED current.
(b) Reverse the voltage polarity as shown below. Use $R = 330\,\Omega$. ***Measure the voltage across the resistor, and give the result. What is the current I? Measure the voltage across the diode, and give the result. Label the resistor voltage V_R, and give the KVL equation for this one-loop circuit. Are the measured voltages in agreement with the KVL equation?***



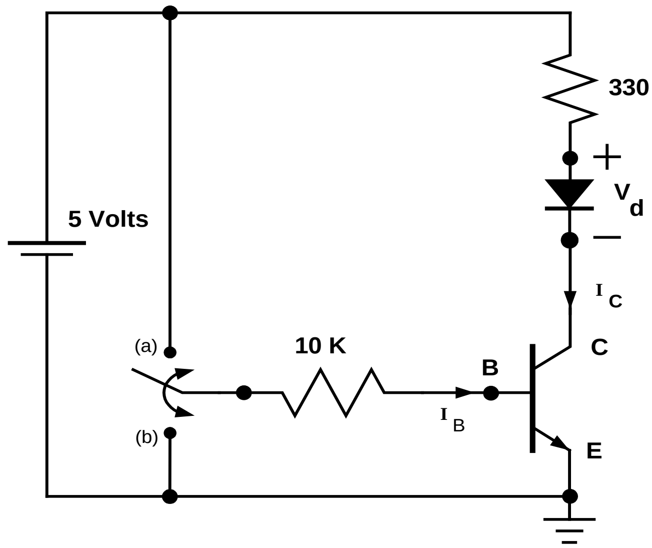
Transistor

You will work with an npn junction transistor. Generally, transistors are three terminal devices, and there are many different kinds of transistors that are available in a variety of packages, which depends on the needs of the application that the transistor is designed to meet. The transistor you will use comes in the package shown below.



With respect to the flattened edge you can identify the collector, base and emitter terminals. The current into the base terminal controls the current into the collector terminal, and both currents exit through the emitter terminal.

2) The circuit below is suitable to see how the base current controls the collector current. Wire this circuit, and connect the ground terminal of the oscilloscope to the ground terminal of this circuit. Connect channel 1 of the scope to the base terminal of the transistor, and connect channel 2 of the scope to the collector terminal of the transistor. Set the scope channels to DC coupling. Then, on the oscilloscope you can see the Base-Emitter voltage, V_{BE}, and the Collector-Emitter voltage, V_{CE}, on channels 1 and 2, respectively.



(a) When the 10K Ohm resistor is connected to position (a), which connects it to the plus side of the power supply (the 5 volt source), there will be a small positive base current I_B into the base of the transistor, the voltage V_{BE} will be approximately **0.6 volts**, the voltage V_{CE} will be approximately **0.2 volts** and the collector to emitter resistance will be very small, making the transistor look like a closed switch from the collector to the emitter. Therefore, the cathode side of the LED will be near zero volts, forward biasing the LED. The 330 Ohm resistor is there to **limit the diode and collector current.** ***Is the LED on or off?***

For connection to position (a), you can write two KVL equations, which are

$$\begin{aligned} -5 + 10*10\wedge 3 * I_B + V_{BE} &= 0 \\ -5 + 330 * I_C + V_d + V_{CE} &= 0 \end{aligned}$$

The collector current is approximately given by

$$I_C = \frac{5.0 - V_d - V_{CE}}{330} = \frac{5.0 - 1.4 - 0.2}{330} = 10.3\ ma$$

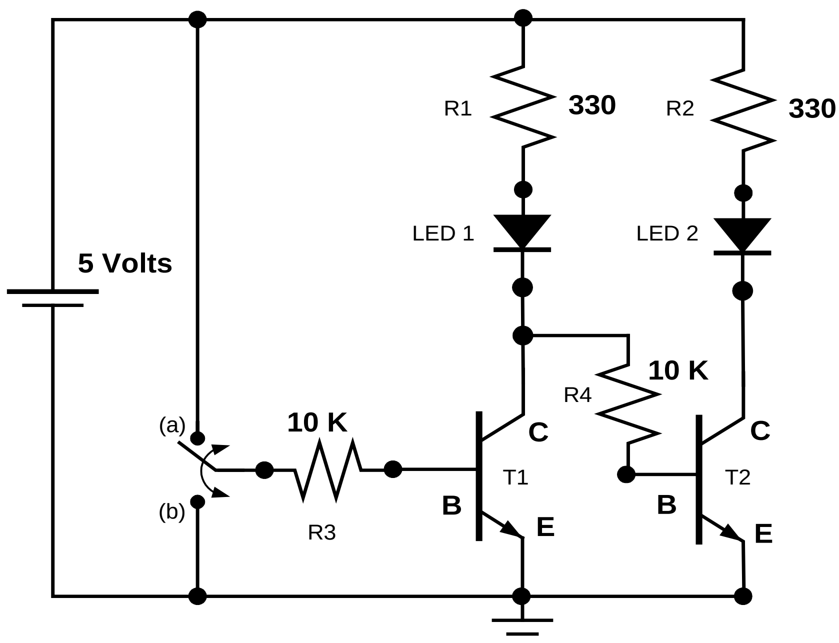
With the multimeter, measure the voltages across the 10 K and 330 Ohm resistors and then calculate the current through these resistors, which are called I_B and I_C, respectively.

Give the measured voltages V_{BE} and V_{CE}. Are these voltages close to the expected values mentioned (0.6 and 0.2) above? Check the KVL equations. Give the ratio of the collector current to the base current. This ratio, denoted by h_{fe}, is the current gain factor of the transistor.

(b) ***Now change the 10 K Ohm connection to position (b), and give the voltages V_{BE} and V_{CE}. Use the multimeter to measure the voltage across the two resistors. What are these voltages, and therefore, calculate the base and collector currents? In this situation, since the collector current is essentially zero, the transistor acts like an open circuit from the collector to the emitter, and therefore the transistor has switched the LED off.***

(c) ***Now replace the 10K Ohm resistor by a 100K Ohm resistor, and discuss how well the transistor works as a switch to turn on and off the LED. Is the LED current large enough for the LED on state to be visible?***

(d) ***Wire the circuit shown below, and explain which LED is on when the connection is at point (a) and when the connection is at point (b). Give the collector to emitter voltage, V_{CE}, and the base to emitter voltage, V_{BE}, for each transistor for each switch connection option. Provide an organized table that describes the operation of this circuit.***



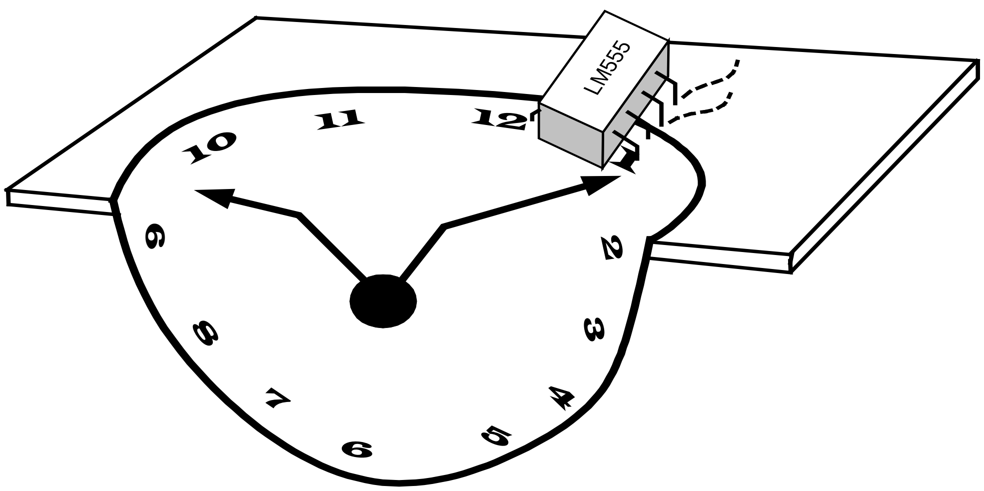
ECE 115

Introduction to Electrical and Computer Engineering

Laboratory Experiment #7

Pulse Trains, Timers and Clocks

Objective: The objective of this experiment is to learn what a clock is, and how to design a clock circuit with the LM555 timer integrated circuit (IC). The LM555 timer is one of the most useful electronic devices in the market. The LM555 integrated circuit was manufactured first by Signetics Corp, and today it is available from almost every integrated circuit manufacturer. For this reason it is very inexpensive and widely applied. With an LM555 timer, you will design and build a circuit that produces a 1K Hz rectangular wave with a 75% duty cycle.



Background

We use a clock to keep track of the amount of real time that has elapsed from some start or reference time point. For example, when your wristwatch indicates that the time is 8:00 AM, it is stating that 8 hours and zero minutes have elapsed since midnight. We also use a clock to know when other events must start and end.

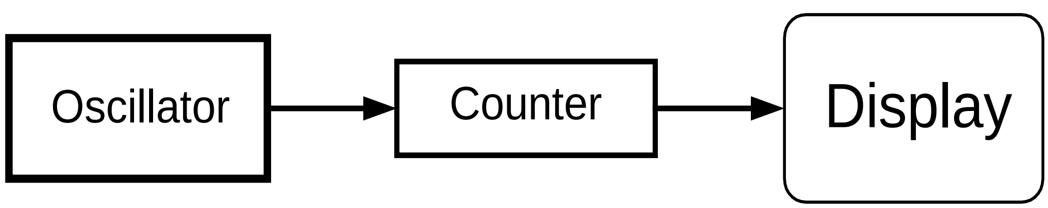
The resolution of a clock depends on the number of time segments into which we divide a particular time range. For example, if the pendulum (or balance wheel) of a mechanical clock swings to one side and back every second, and we count the number of such full swings to one side and back, then the clock resolution is one second, i.e., we can know the amount of time that has elapsed over some time interval to within one second. The counting is actually done by the gears that position the second, minute and hour hands of the clock to point to numbers that we read. Of course, we are assuming that each swing to one side and back takes exactly one second, which, in fact, can change with time for a variety of reasons, such as wear and changing friction. Thus, while the resolution is one second, the clock may be inaccurate. It would not be inappropriate to call the pendulum a mechanical oscillator, and call each swing of the pendulum to one side and back a clock cycle. Therefore, the clock rate is one cycle/second.

If we divide a second into one billion time segments, and count the number of one billionth of a second segments, then our clock resolution, which now is one billionth of a second, is much higher. Like before, we are still concerned that each segment takes from the start of a segment to the end of a segment exactly one billionth of a second to occur, so that by counting these segments we can obtain accurate elapsed time measurements. Now, the clock rate is 10^9 cycles/second, or 1 GHz. The precision of a clock (both the resolution and accuracy) depends on the clock rate and how well this rate is kept constant over time.

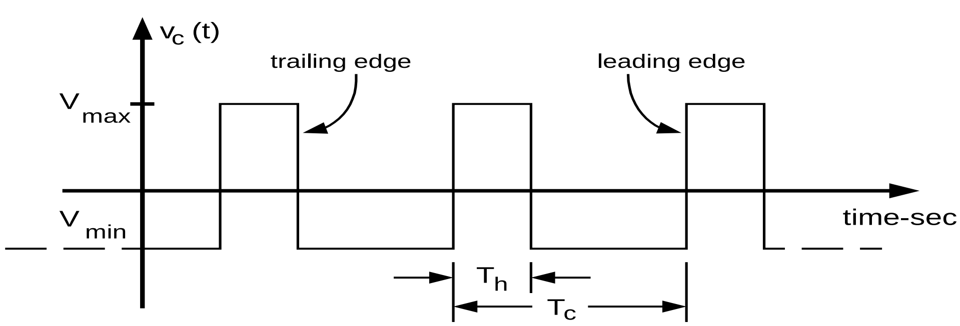
Generally, a clock is used for two purposes:

1) pace the occurrence of events, even certain activities over every clock cycle,
2) measure elapsed time.

A clock could be represented by the block diagram shown below.



An electronic circuit that outputs (produces) an oscillating voltage can be used for a clock. Such a circuit usually produces a voltage that is a rectangular wave like the voltage shown in the following figure. Here, the voltage oscillates between

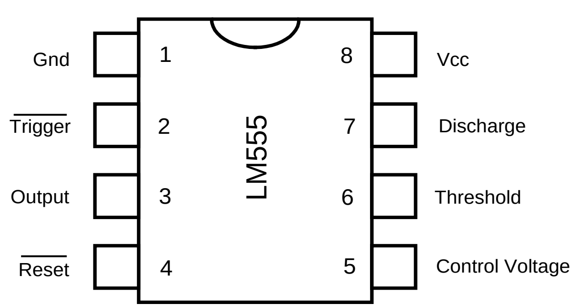


two voltages, V_{max} and V_{min}, which commonly are: V_{max} = +5.0 volts and V_{min} = 0.0 volts or V_{max} = +12 volts and V_{min} = -12 volts, or some other two different voltages. It is common to refer to the oscillator alone as the clock.

When the voltage is at V_{max} volts, we say it is hi (an abbreviation of high), and when it is at V_{min} volts, we say it is lo (an abbreviation of low). In addition to the parameters V_{max} and V_{min}, a clock oscillator is characterized by the parameters T_h and T_c. T_c is the time of one cycle of oscillation, and the oscillation frequency f_c is given by $f_c = 1/ T_c$. The parameter T_h is given indirectly through the duty cycle d, which is determined with $d = 100 \; (T_h / T_c) \; \%$. Therefore, if, for example, the duty cycle is 25%, then the clock (rectangular wave) is hi for ¼ of its cycle time. The part of the rectangular wave where the voltage changes from lo to hi is called a leading edge, and the part where the voltage changes from hi to lo is called a trailing edge. One cycle of the clock is a single pulse, and the entire rectangular wave is also called a pulse train.

LM555 Timer

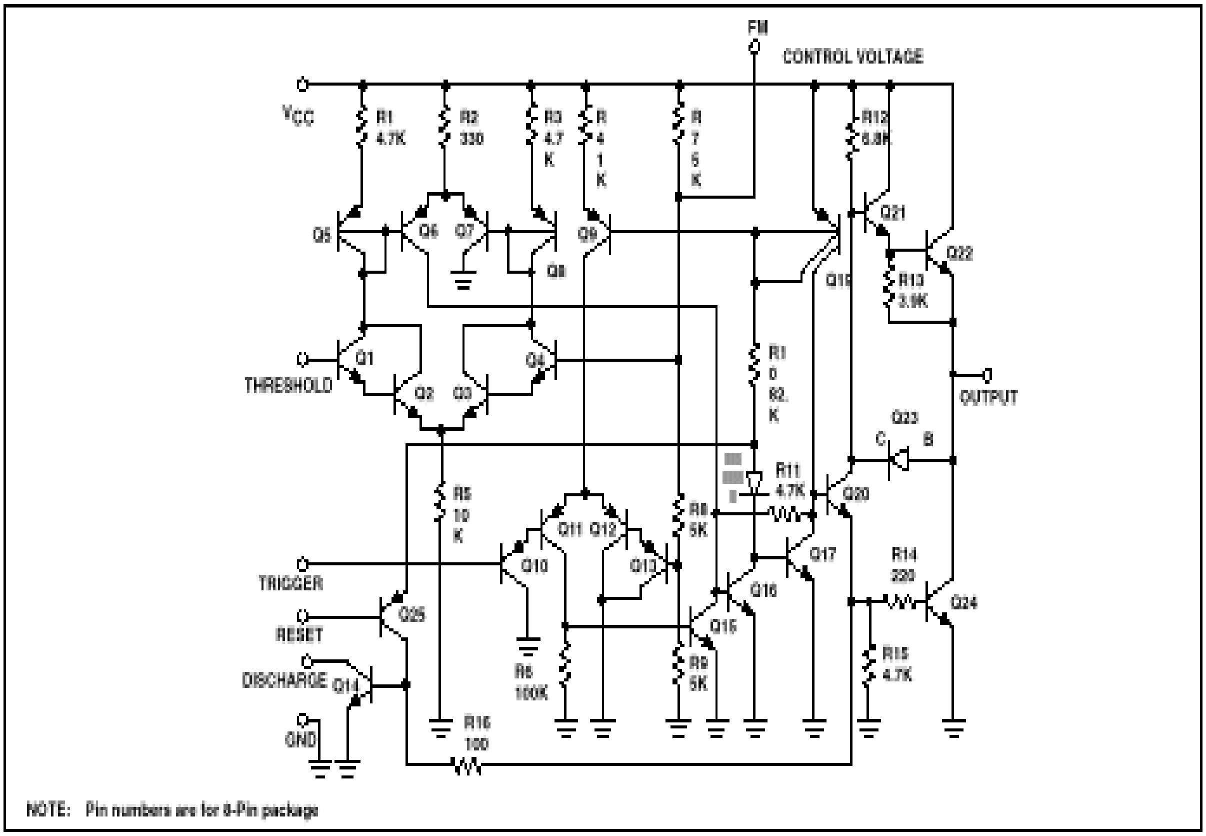
An integrated circuit that was specifically designed to produce a pulse or a rectangular wave is the LM555 timer circuit. This circuit comes in a rectangular package having 4 pins on each side as shown below. Because the pins of the package are arranged into two rows, one on each side of the package, it is called a dual in-line package (DIP). This is an 8 pin DIP. Looking from the top, the indentation at one end of the package identifies pin 1 of the package.



top view

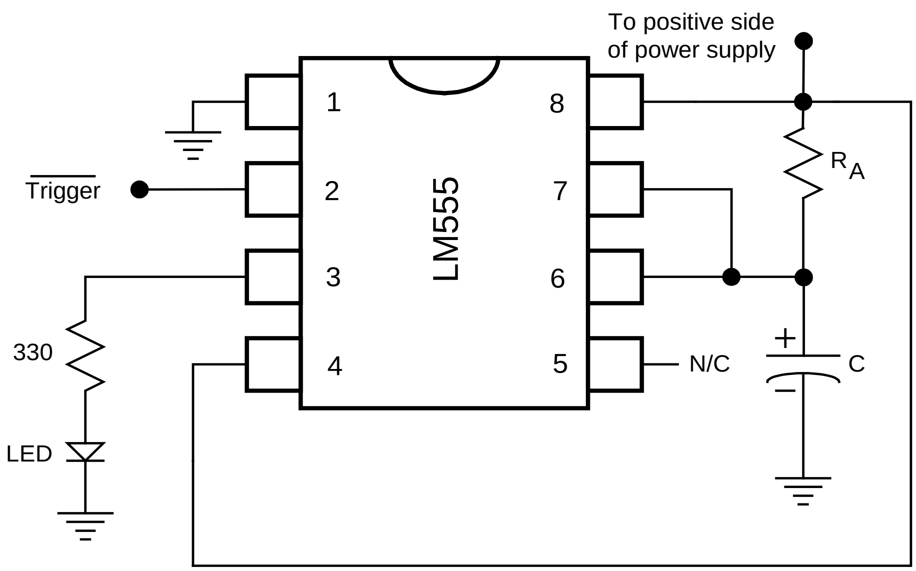
This integrated circuit is a complex circuit made mostly with transistors, as shown below. To achieve an understanding of the operation of this circuit is beyond the scope of this experiment. However, we will see that it is easy to design a rectangular waveform generator (clock) with this device.

EQUIVALENT SCHEMATIC



To pin 8, called Vcc, we connect the positive terminal of a power supply, and to pin 1, which is called the ground (Gnd) pin, we connect the negative side of the power supply. Vcc can range from 3 to 15 Volts, without harming the LM555 device. The output of the LM555 at pin 3 is either a voltage near Vcc or a voltage near Gnd, depending on the on or off state of transistors Q22 and Q24. If Q24 is on, like a short circuit, and Q22 is off, like an open circuit, then the output voltage will be near Gnd, and if Q24 is off and Q22 is on, then the output voltage will be near Vcc. When the output voltage is near Vcc, then the current through a device connected to pin 3 of the LM555 is the collector current of Q22.

1) The circuit below is a simple circuit that uses the LM555 to produce a single output pulse whenever almost any kind of a low level spurious voltage is applied to pin 2. An LED will be used to see the pulse. Wire this circuit, and do not connect the power supply until the circuit is completely wired. In the circuit schematic, **N/C means no connection**. Connect channel 1 of the oscilloscope to pin 3 and connect channel 2 to pin 6. Use R_A = 10K Ω and C = 220 uF. Be careful to connect the negative side of the capacitor to ground. (a) ***Connect pin 2 to pin 8 (Vcc).*** Set the power supply to 5 volts and connect it to the circuit. ***Upon turning the power supply on, describe what happens to the LED. What is the purpose of the 330 Ω resistor? Provide sketches of the oscilloscope display channels 1 and 2. Describe how the voltage across the capacitor changes with time.***



(b) Disconnect pin 2 from pin 8, but leave a wire going to pin 2. ***What happens when you touch the wire going to pin 2? Using the oscilloscope, determine the amount of time that the LED is on. This is the width of the pulse at the pin 3 output.*** (c) ***Replace the 10K resistor with a 100K resistor, and repeat part (b).*** Notice that if we use a variable resistor, then we can very precisely control the width of the output pulse. (d) The pulse width can also be controlled by the capacitor value, as the width of the pulse is given by: 0.69 R_A C. ***Show that the unit of the product of R and C is seconds. Then, check to see if the results of parts (b) and (c) agree with this formula.***

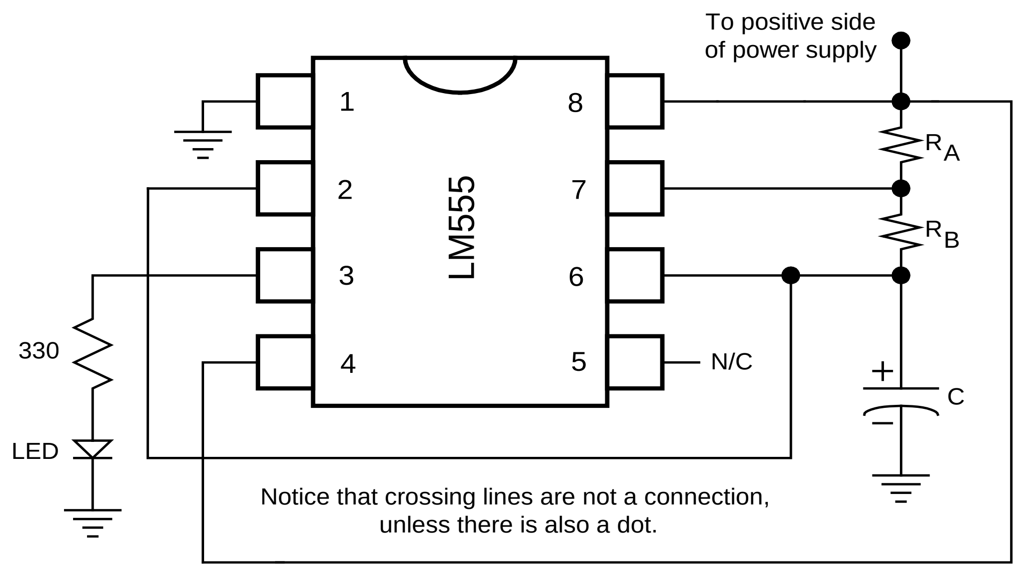
2) The circuit of part(1) is said to be a monostable circuit, because a zero output voltage is the stable output level, and a high output voltage occurs only for a short while, making this output level the unstable output level. The circuit shown below is an astable circuit, which means that each output level can only last for a short while, i.e., each output level is unstable, and therefore this circuit produces a pulse train.

(a) Using C = 220 uF, R_A = 10 K Ω and R_B = 2.2K Ω, wire this circuit. Connect the oscilloscope channels 1 and 2 to pins 3 and 6, respectively. Connect the power supply, and turn it on. ***Provide a sketch of the oscilloscope display. Using the oscilloscope, determine the frequency and duty cycle of the rectangular wave. What is the hi voltage? What is the lo voltage?*** (b) The oscillation (clock) frequency is given by

$$f_c = 1.44/((R_A + 2R_B)C)$$

and the time that the output is hi is given by

$$t_h = 0.69(R_A + R_B)C$$



Give a formula for the time that the output is low. For the circuit of part (a) compare the results with the results of using these formulas.

(3) ***Design and build a circuit that will produce a 1K Hz rectangular wave with a 75% duty cyle. Use a 0.1 uF capacitor. There may not be resistors in the lab that have values exactly as your design requires. Use resistor values that are close to your design requirements. You might consider connecting resistors in series to obtain an equivalent resistor with a value close to a design requirement. Provide sketches of the voltages at pins 3 and 6. Confirm that the measured frequency and duty cycle agree (come close to) with your design goals.***

(4) Go to the internet, and type into Google the search phrase, "555 timer". Find a website that shows many other kinds of circuits using the LM555. ***Give the schematic for some circuit and describe what it is supposed to do according to the website.***

(5) Clock circuits are used to pace the activity of many systems, where at the leading and trailing edge of every clock cycle some activity is caused to occur. Consider for example, a Pentium microprocessor, having a clock speed of 3 GHz. This means that within the integrated circuit of the Pentium microprocessor there is a pulse train generator with a 0.333×10^{-9} second cycle time. Therefore, within the time span of 1/3 of a nano-second the microprocessor executes some activity. However, an LM555 cannot produce a clock signal at this high a frequency, and therefore the clock generator within a Pentium microprocessor is made with other electronic devices that can switch at such high speeds.

Give an example of another device or system, which you use regularly, that has within it an electronic clock that makes the device work the way it does. For your example, explain the purpose of the electronic clock.

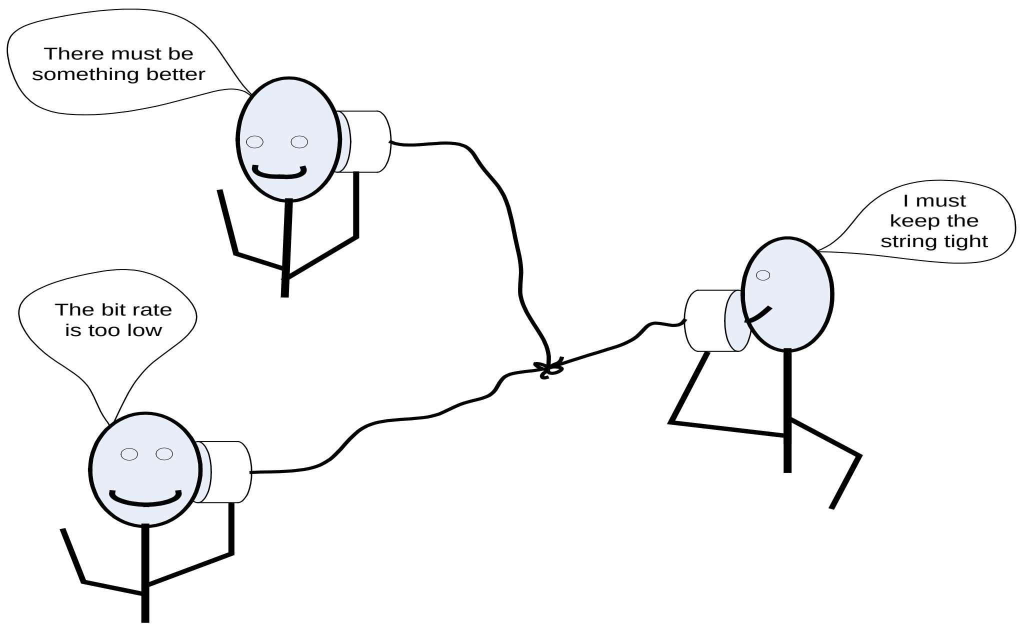
ECE 115

Introduction to Electrical and Computer Engineering

Laboratory Experiment #8

Wireless Network

Objective: The objective of this experiment is to communicate data over a wireless network.



Background

A radio transmitter is an electronic circuit that transforms electric power from a battery or power supply into an alternating current in a conductor, which reverses direction millions to billions of times per second. The energy in such a rapidly changing current can radiate away from a conductor (the antenna) as electromagnetic waves. The transmitter also modulates the current in a way that depends on audio, video or data information, which modulates the electromagnetic wave that is radiated by the antenna. When the electromagnetic wave strikes the antenna of a receiver, the wave causes a similar (but less powerful) current in it. The receiver extracts the information from the received electromagnetic wave. A practical radio transmitter usually consists of these parts:

1) A power supply

2) An electronic oscillator circuit to generate a high frequency signal $c(t) = A\cos(\omega_c t + \theta)$, called the carrier wave, where the frequency ω_c is precisely controlled.

3) A circuit to embed information in the carrier wave. This is done by varying some aspect of the carrier wave. The information provided to the transmitter can be an audio signal, a video signal, or data in the form of a binary signal. In an AM (amplitude modulation) transmitter the amplitude (strength) of the carrier wave is varied in proportion to the information signal. In an FM (frequency modulation) transmitter the frequency of the carrier is varied by the information signal. In an FSK (frequency-shift keying) transmitter, which transmits digital data, the frequency of the carrier is shifted between two frequencies which represent the two binary digits, 0 and 1. Many other types of modulation methods are also used.

4) A power amplifier to increase the power of the modulated carrier wave.

5) An antenna and associated electronic circuitry to transfer power efficiently to the antenna.

Transmitter/Receiver Modules

The transmitter and receiver modules that will be used in the experiment are shown in Figure 1. Note that the pin names are on the side opposite from the components side of the module.

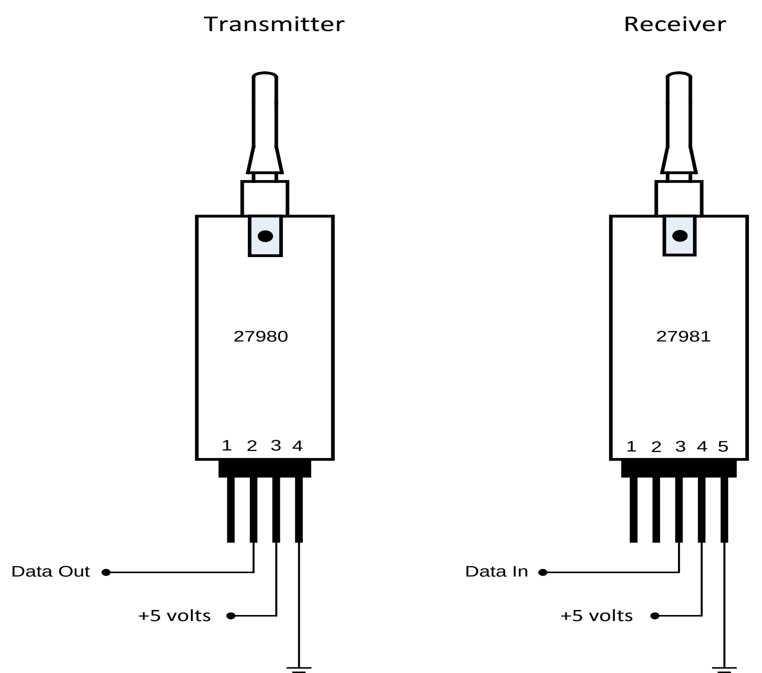


Figure 1. Transmitter and receiver modules with pin assignments.

The Parallax 433.92 MHz RF Transmitter allows users to easily send serial data, robot control, or other information wirelessly. When paired with the matched RF Receiver, reliable wireless communication is as effortless as sending serial data. The power-down (PDN) pin may be used to place the module into a low power state (active low), or left floating (it is tied high internally).

Features

- High-speed data transfer rates (1200 ~ 19.2k Baud depending on controller used)
- SIP header allows for ease of use with breadboards
- Compatible with most microcontrollers
- As easy to use as simple SEROUT/SERIN instructions
- Power-down mode for conservative energy usage (longer battery life)
- Line-of-sight range of 500 feet (or greater depending on conditions)

Application Ideas

- Remote controlled robot
- Wireless data acquisition
- Remote sensors and triggers

Theory of Operation

Short for Radio Frequency, RF refers to the frequencies that fall within the electromagnetic spectrum associated with radio wave propagation. When applied to an antenna, RF current creates electromagnetic fields that propagate the applied signal through space. Any RF field has a wavelength that is inversely proportional to the frequency. This means that the frequency of an RF signal is inversely proportional to the wavelength of the field. The Parallax RF modules utilize a frequency of 433.92 MHz, this works out to be a wavelength of approximately 0.69 meters (2.26 feet, or 7.3e-17 lightyears). 433.92 MHz falls into the Ultra High Frequency (UHF) designation, which is defined as the frequencies from 300 MHz ~ 3 GHz. UHF has free-space wavelengths of 1 m ~ 100 mm (3.28 ~ 0.33 feet or 1.05e-16 ~ 1.05e-17 lightyears).

Pin Definitions and Ratings

Transmitter (#27980)
Pin Name Function
1 PDN Power Down - active low, pulled high internally so may be left floating
2 DATA Data Out (data to be transmitted)
3 5v Power – connect to +5v DC (such as Vdd)
4 GND Ground → 0 v (such as Vss)
Transmitter Supply Current:
At Logic High Input: 5.1 mA
At Logic Low Input: 1.8 mA
Low Power mode (PDN): 5 µA

Receiver (#27981)
Pin Name Function
1 RSSI Received Signal Strength Indicator
2 PDN Power Down - active low, pulled high internally so may be left floating
3 DATA Data In (data received)

4 5v Power – connect to +5v DC (such as Vdd)
5 GND Ground → 0 v (such as Vss)
Receiver Supply Current:
During Operation (High or Low): 5.2 mA
Low Power mode (PDN): 28 µA

PDN
Pulling the power down (PDN) line low will place the transmitter/receiver into a low-current state. The module will not be able to transmit/receive a signal in this state.
RSSI *(receiver only)*
Received Signal Strength Indicator. This line will supply an analog voltage that is proportional to the strength of the received signal.

IT IS VERY IMPORTANT TO NOT REVERSE VOLTAGE POLARITY OR EXCEED THE 5 VOLT RATING OF THE TRANSMITTER AND RECEIVER MODULES.

Experiment

The pin definitions of each module are given on the side of the printed circuit board that is opposite of the components side. In Figure 1, the pins are numbered 1 through 4 from left to right of the transmitter module (pin 4 is labeled GND) and 1 through 5 from left to right of the receiver module (pin 5 is labeled GND). Without connecting any power supply to the breadboard, plug the transmitter and receiver modules into the breadboard, as shown in Figure 2.

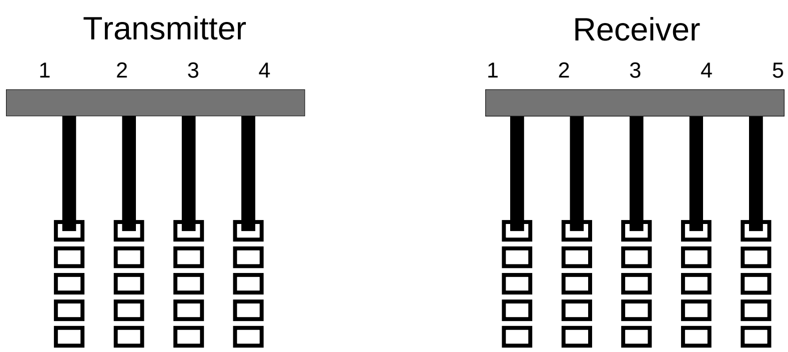


Figure 2. Connection of modules to the breadboard.

Connect the signal generator output to channel #1 of the oscilloscope (scope). Turn the signal generator and scope on, and adjust the signal generator to produce a square wave that oscillates between 0 volts and 5 volts at 1K Hz. Adjust the scope horizontal sweep rate to show several cycles of the square wave across the scope screen. Adjust the vertical sensitivity and position of the scope to use the top half of the scope screen for the output of the signal generator. This signal will be transmitted by the transmitter module, but it should not yet be connected to the transmitter module.

Use the multimeter to measure and adjust the output voltage of the power supply, and set it to produce +5 volts at its output.

To eventually see the signal received by the receiver module, connect pin 3 (data in pin) of the receiver module to channel #2 of the scope. Be sure to connect a common ground line between the power supply, signal generator, scope, receiver module and transmitter module. **Do not yet connect +5 volt power to the receiver and transmitters modules.**

To check that the transmitter module at each lab station is working, only one transmitter module can be allowed to transmit at a time. Now, most of the connections have been made. The connections that have not yet been made are the +5 volt connections to the transmitter and receiver modules and the connection of the signal generator output to the transmitter module pin 2 (data out pin).

At this time the TA will come to each station to: (1) check that the transmitter and receiver modules are correctly plugged into the breadboard, (2) that the power supply is set to produce +5 volts, (3) that the scope shows that the signal generator is producing a square wave ranging from 0 volts to +5 volts at 1K Hz, (4) that the +5 power supply pins of the transmitter and receiver modules have been correctly identified, and (5) that the data out and data in pins of the transmitter and receiver modules, respectively, have been correctly identified. These precautions are taken, because the transmitter and receiver modules are costly to replace.

After the TA has checked the set up at all lab stations, with the power supply turned off, connect the +5 volts line to the receiver module pin 4 at all stations and turn on the power supply.

Read all steps (a) through (d) before you start.

Starting with station #1, only one station at a time, as prompted by the TA, can be transmitting.

(a) **To start**, station #1, connect power to pin 3 and the signal generator output to pin 2 of the transmitter module. All stations 1 through 14 should now be receiving a square wave, as seen on the scope, channel #2. Adjust the scope as necessary. If not, ask the TA to help.

After all stations, including station #1, have received the transmission from station #1, at station #1, disconnect from the transmitter pin 2 the signal generator output. Leave the power connected to pin 3.

(b) Repeat step (a) for each station 2 through 14. Wait for the TA to prompt you to proceed. However, station #2 must transmit a 2K Hz signal, station #3 must transmit a 3K Hz signal, and so on until station #14 has transmitted a 14K Hz signal. See step (c).

(c) ***As the signal frequency increases, how does the received signal change? Give a sketch or scope screen print out of the received transmission from a low numbered (maybe #1) station, a middle numbered (maybe #7) station and a high numbered (maybe #14) station.***

(d) ***In your report, give a schematic (drawing) of your experimental set up.***

(e) ***Explain the purpose of pin 1 of the transmitter module.***

(f) ***According to the specifications, what is the highest signal frequency that the transmitter and receiver pair is expected to communicate well. What is the meaning of 1 Baud?***

(g) ***When powered down, how much current does the receiver module use, and how much power does it use?***

ECE 115

Introduction to Electrical and Computer Engineering

Laboratory Experiment #9

Boolean Algebra and Fundamental Logic Gates

Objective: The purpose of this experiment is to introduce you to Boolean algebra. You will learn about the operation of basic logic gates.

Digital logic is a rational process for making simple "true" or "false" decisions based on the rules of Boolean algebra. It is a natural match to the binary number system, in which each binary digit (bit) has a value of either 1 or 0 (or TRUE or FALSE) and to physical devices that have two stable states, which can be used to represent 1 or 0, plus or minus, up or down, open or closed, yes or no, and other two condition situations. By using several binary digits, multiple conditions can be represented. Typically, digital logic circuits use a high voltage (for example 5 volts or 3 volts) to represent the bit value 1 and a low voltage (for example, 0 volts) to represent the bit value 0. There are other standards where, for example, –12 volts represents logic 1, while +12 volts represents logic 0. In the binary number system, digital logic circuits can be used to perform calculations such as addition, subtraction, multiplication, and division.

A Brief History of Boolean Algebra

Binary logic was first proposed by 19th-century British logician and mathematician, George Boole, who, in 1847, invented a two-valued system of algebra that represents logical relationships and operations. In the 1930s, this system of algebra, called Boolean algebra, was used by the German engineer Konrad Zuse to build the Z1 calculating machine.

In the late 1930s American physicist John Atanasoff and his graduate student Clifford Berry used Boolean algebra in the design of the first digital computer. During 1944 and 1945 Hungarian-born American mathematician John von Neumann suggested using the binary arithmetic system for storing programs in computers. In the 1930s and 1940s British mathematician Alan Turing and American mathematician Claude Shannon also recognized how binary logic was well suited to the development of digital computing systems.

The instructions that control the circuit-level operations of a computer are known as **machine code,** and these instructions are written as sequences of groups of bits. These bits switch **logic gates** on and off, and the outputs of these gates constitute binary code for a great variety of kinds of information such as arithmetic results of computation, characters to be printed or displayed, signals to control other devices, sounds, images, etc.

Digital Logic Gates

Digital logic gate circuits are manufactured as integrated circuits: all the constituent transistors, diodes and resistors are fabricated on a single piece of semiconductor material. Such semiconductor devices are available in a variety of packages. A common package is a DIP (**Dual Inline Package**). DIP-enclosed integrated circuits are available with even numbers of pins, located at 0.100 inch intervals from each other for standard circuit board layout compatibility. Pin counts of 8, 14, 16, 18, and 24 are common for DIP "chips."

The part numbers given to these DIP packages specify the type of gates that are contained within the package. These part numbers are industry standards, meaning that, for example, a "74LS02", which is a quad 2-input TTL NOR gate, manufactured by National Semiconductor will be identical in function to a "74LS02" manufactured by Advanced Micro Devices or by any other manufacturer. Leading letter codes to the part number are unique to the manufacturer, and they are not industry-standard codes. For instance, an SN74LS02 is a quad 2-input TTL NOR gate manufactured by Motorola, while a DM74LS02 is the exact same circuit manufactured by Fairchild.

Logic circuit part numbers beginning with "74" are commercial-grade TTL circuits, where TTL stands for transistor/transistor logic. If the part number begins with the number "54", the chip is a military-grade unit: having a wider temperature operating range, and typically more robust with respect to allowable power supply and signal voltage levels. The letters "LS" immediately following the 74/54 prefix indicates "Low-power Schottky" circuitry, using Schottky-barrier diodes and transistors throughout, to decrease power consumption. Non-Schottky gate circuits consume more power, but are able to operate at higher frequencies due to their faster switching times. There are a great variety of processes used to manufacture integrated circuits that perform as digital logic gates, depending on switching speeds, power consumption, operating voltage levels, tolerance to background electrical noise, component density, heat dissipation, operating temperature ranges, and other factors. Depending on circuit complexity and printed circuit board attachment methods, these devices come in a variety of packages having anywhere from a few package pins (electrical connections) to several hundred pins.

A few of the more common TTL "DIP" circuit packages are shown at the end of this lab experiment for reference.

Logic 0 or Logic 1

You can manually provide a logic signal with the resistor and switch circuit shown in Fig. 9.1. The logic signal, v(t), is the input to some logic circuit. Generally, logic circuits are

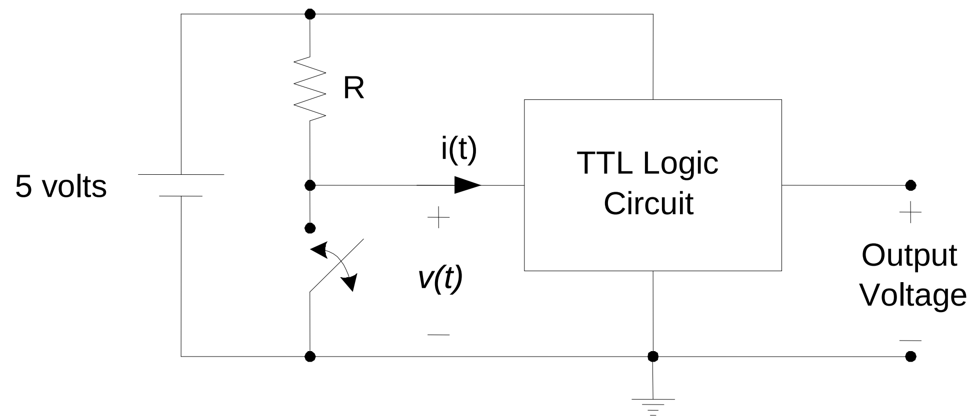


Fig. 9.1. Circuit that illustrates how to manually input a logic signal into a logic circuit.

fabricated to have a very high resistance as seen by any voltage source connected to the logic circuit's input terminals. Therefore, the current, i(t), into the logic circuit is very small. The TTL logic circuit is powered by the 5 volt constant voltage source.

When the switch is closed, the input voltage, v(t) is v(t)=0, which means that the input to the logic circuit is logic 0, and, depending on the kinds of gates used within the logic circuit and their interconnections, the logic circuit will output a voltage that is either 5 volts, which means logic 1 or 0 volts, which means logic 0. The value of the resistor, R, is typically 10K Ω, so that the current through it is given by: 5 / 10K = 0.5 mA.

When the switch is open, the current through the resistor is near zero, because we assume that logic circuits are fabricated such that the current, i(t), into the logic circuit is near zero, and therefore the voltage across the resistor will be zero. Therefore, the voltage, v(t) becomes v(t)=5 volts, which means that the input to the logic circuit is logic 1, and the output of the logic circuit will change according the design of the logic circuit.

With the switch you control the voltage input to the logic circuit. Because the voltage increases from 0 volts to 5 volts when the switch is opened, the resistor, R, is called a **pull-up resistor**. Therefore, with a switch and resistor circuit, as shown in Fig. 9.1, you can manually control the logic input to a logic circuit.

Gate Operation

NOT Gate or Inverter

One of the basic logic gates is the NOT gate. Basically, a NOT gate performs the operation of the circuit shown in Fig. 9.2.

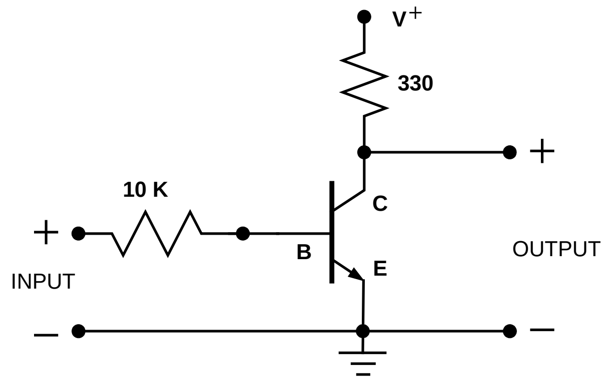


Fig. 9.2. A transistor circuit that performs the operation of a NOT gate.

Recall from an earlier experiment that when the input voltage is high, then the transistor acts like a short circuit, so that the output voltage is very low. And, when the input voltage is low, say near zero volts, then the transistor acts like an open circuit, so that the output voltage is a high voltage. Here, the 330 Ω resistor performs like a pull-up resistor.

The output of a **NOT gate**, also called an **inverter**, is called the complement of the input. The logic operation of an inverter is given is Table 9.1, which shows the output of an inverter for the two possible inputs. The ANSI (American National Standards Institute) symbol for a NOT gate is shown in Fig. 9.3.

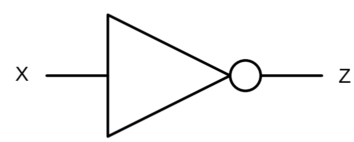


Fig. 9.3. Standard symbol for a NOT gate.

The symbolic representation does not include the fact that the NOT gate circuit must be connected to a power supply. This is assumed. Also, the symbolic representation does not show that the input and output are voltages with respect to a reference terminal. This is also assumed. The symbols for the input and output are thought to be logical variables, which are either logic 0 or logic 1. In the actual circuit, the input and output are voltages at one value or the other value. The circuit used to make a NOT gate is more complicated than the circuit given in Fig. 9.2, to achieve the property that the current into the NOT (and all other logic gates) gate is very small.

From a logic symbol viewpoint, the operation of a NOT gate can be described by the **truth table**, as it is called, given in Table 9.1.

Table 9. 1. Truth table of a NOT gate.

Input	Output

x	z
1	0
0	1

In Boolean algebra, the NOT function is usually indicated by a bar over the variable or a following prime. For example,

$$Z = \overline{X} = X'$$

AND Gate

The **AND gate** is another basic gate that has at least two inputs. The AND gate provides a true output (logic 1 or high voltage) only when all inputs are true (logic 1 or high voltage). The ANSI symbol for an AND gate is shown in Fig. 9.4.

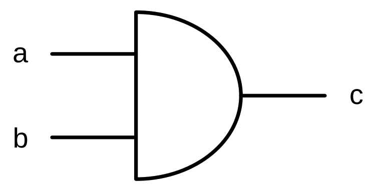


Fig. 9.4. Standard symbol for the AND gate.

This AND gate has two logic inputs. The number of inputs depends on the number of logic variables that we want to check to know when they are all true (logic 1) at the same time.

The operation of an AND gate is defined by Table 9.2. In this and the following truth tables, true is represented by a logic 1, and false is represented by a logic 0. This truth table shows the output c of a two-input AND gate for each possible combination of the inputs a and b.

Table 9.2. Truth table of a two-input AND gate.

a	b	c
0	0	0
0	1	0
1	0	0
1	1	1

In Boolean algebra, the AND function is usually indicated by a dot between the inputs (logical multiplication). For example

$$c = a \text{ AND } b = a \bullet b = ab$$

OR Gate

The **OR gate** is the third of the three basic logic gates. The OR gate provides a true output when any one or more of its inputs are true. The ANSI symbol for the OR gate is shown in Fig. 9.5.

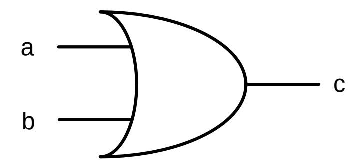


Fig. 9.5. Standard symbol for the OR gate.

The operation of an OR gate is defined in Table 9.3. This truth table shows the output z of a two-input OR gate for each possible combination of the inputs.

Table 9.3. Truth table of a two-input OR gate.

a	b	c
0	0	0
0	1	1
1	0	1
1	1	1

Notice that the output is logic 1 whenever at least one of the inputs is logic 1. Or, we can say that the output is logic 0 only when all of the inputs are logic 0. In Boolean algebra, the OR function is usually indicated by a plus between the inputs (logical addition). For example

$$c = a \text{ OR } b = a + b$$

NAND Gate

Other gates can be made from combinations of the basic gates. The output of the **NAND gate** is simply the complement of the output of the AND gate. It can be made with an AND followed by a NOT gate. Thus the NAND gate provides a false output only when all inputs are true. The ANSI symbol for the NAND gate is shown in Fig. 9.6.

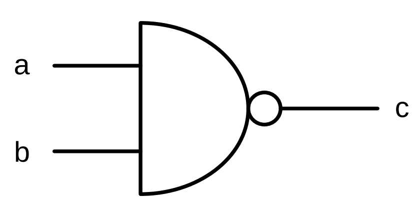


Fig.9.6. Standard symbol for a NAND gate.

The operation of the NAND gate is given in Table 9.4. This truth table shows the output c of the NAND gate for all possible combinations of the inputs.

Table 1.4. Truth table of a two-input NAND gate.

a	b	c
0	0	1
0	1	1
1	0	1
1	1	0

In Boolean algebra we write

$$c = (a \text{ AND } b)' = \overline{a\,b}$$

NOR Gate

The output of the **NOR gate** is the complement of the output of the OR gate. The ANSI symbol for the NOR gate is shown Fig. 9.7.

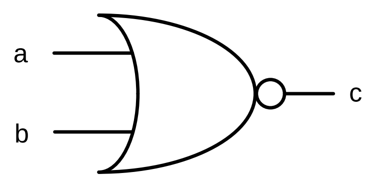


Fig. 9.7. Standard symbol for a two-input NOR gate.

The operation of the NOR gate is defined in Table 9.5. This truth table shows the output c of a two-input NOR gate for all possible combinations of the inputs.

Table 9.5. Truth table for a tw0-input NOR gate.

a	b	c
0	0	1
0	1	0
1	0	0
1	1	0

In Boolean algebra, the NOR function is not a primitive operator, but is a combination of the OR and invert functions. A NOR operation is simply the OR function with its output inverted: NOT (OR). This can be written in Boolean algebra as

$$c = (a + b)' = \overline{a + b}$$

Logic Probe

When working with logic circuits it is useful to have a visual indication of the high or low state of a logic signal. A device used to do this is called a **logic probe**. You can make a circuit that works like a logic probe, as shown in Fig. 9.8.

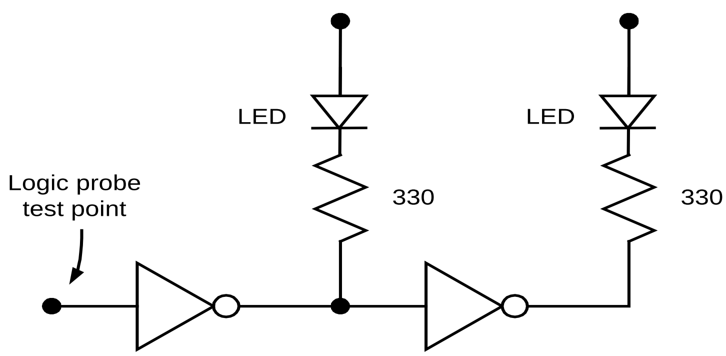


Fig. 9.8. A two-LED circuit to indicate if the test point is at logic 1 or logic 0.

Caution !

When building logic circuits follow the precautions given below.

1) Always start with the power OFF and disconnected from the breadboard.
2) Insert the required chips into the breadboard. (Make sure the chips are oriented correctly.) Use the package indentation to identify pin 1.
3) Connect all power (V_{cc}) and ground (GND) to +5v and ground, respectively. Measure the power supply voltage before you connect it to the logic circuit.
4) Connect wires between pins, switches, LEDs, and so on, as labeled on your logic diagram.
5) Visually inspect your circuit and correct any mistakes.
6) Turn on the power and test the circuit.

Parts List:

1) Quad AND gate (7408)
2) Quad OR gate (7432)
3) Hex Inverter (7404)
4) Quad NAND gate (7400)

5) Quad NOR gate (7402)
6) LED, two
7) Wire
8) Resistor (10K, two)
9) Resistor (330 ohm, two)
10) Breadboard with power supply (5 V_{DC})
11) 8 position DIP switch

Experiment

1) Toward one end of the breadboard build the circuit shown in Fig. 9.8. Look up the TTL part number for the hex NOT gate IC at the end of this lab experiment. This will show you the purpose of each pin of the DIP. Note which pin should be connected to +5 volts and which pin should be connected to ground. Insert the IC into the breadboard, and wire in the LEDs and resistors. **What are the LED states when the test point is connected to ground? What are the LED states when the test point is connected to +5 volts? Like in Fig. 9.8, provide a drawing of your circuit in your report. Label the LEDs as LED0 and LED1 to signify which LED is on when the test point is 0 volts (logic 0).**

2) Wire two resistor and switch circuits like the one shown in Fig. 9.1. Then, with switches, you will have the ability to manually control two logic signals. Test each resistor switch circuit with the logic probe you wired in part (1). **What does the logic probe indicate when a switch is closed? What does the logic probe indicate when a switch is open? Provide a drawing of your circuit in your report.**

3) Look up the TTL part number for the quad two input AND gate IC at the end of this lab experiment. This will show the purpose of each pin of the DIP. Insert the IC into the breadboard, connect the power and ground pins to the +5 volt and ground line of the power supply, and connect the inputs of one of the AND gates to the resistor switch circuits to provide a manual means for specifying the two inputs to an AND gate. **Verify the proper operation of the AND gate for all input combinations by using the input switches.** Use the logic probe to test the AND gate inputs and output. **Record the TTL part number, provide a schematic (circuit drawing) and produce a truth table based on your results.**

4) OR gate operation. (Repeat part (3) for a two input OR gate.)
5) NAND gate operation. (Repeat (3) for a two input NAND gate.)
6) NOR gate operation. (Repeat (3) for a two input NOR gate.)

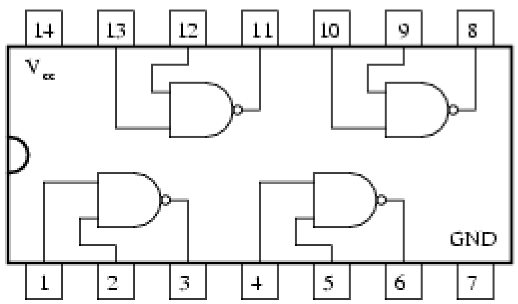
Questions

7) What level does an unconnected input appear to be (high or low)? (**Hint: Repeat one of the previous operations with one input left unconnected.**) What reasoning did you use to determine your answer?
8) What does a NOR gate become when the two inputs are connected together?
9) What is the importance of using a resistor in series with an LED?
10) What does a NAND gate become when the two inputs are connected together?

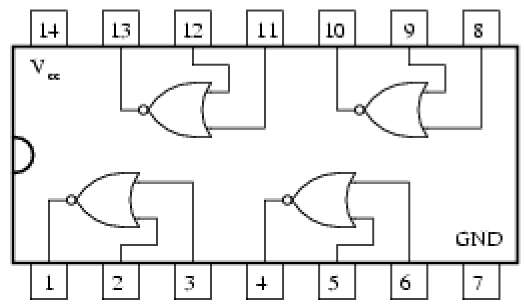
11) Suppose a switch S1 closes and opens when a car door opens and closes, respectively, a switch S2 opens and closes when the driver seat belt is not connected and connected, respectively, and a switch S3 opens and closes when there is no one in the driver's seat and there is some one in the driver's seat. We want a logic circuit that gives an indication (a logic signal) that the driver's side car door is closed, that the seat belt is buckled, and that there is some one in the driver's seat to allow turning the ignition switch to start the car. Give a schematic using resistors and basic gates that will test this condition.

12) Describe what an XOR gate does. Give its symbol. Give a truth table.

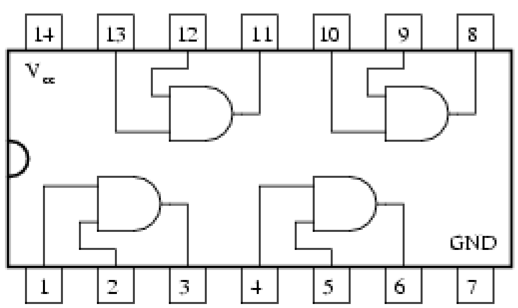
5400/7400
Quad NAND gate



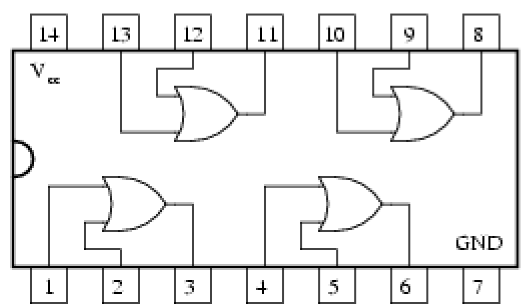
5402/7402
Quad NOR gate



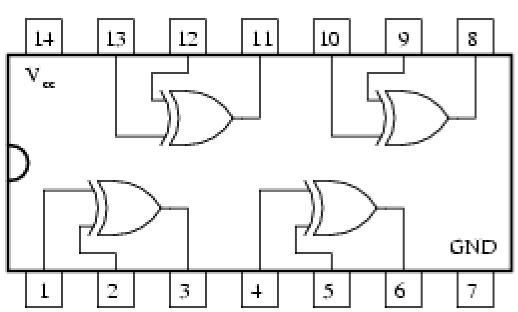
5408/7408
Quad AND gate



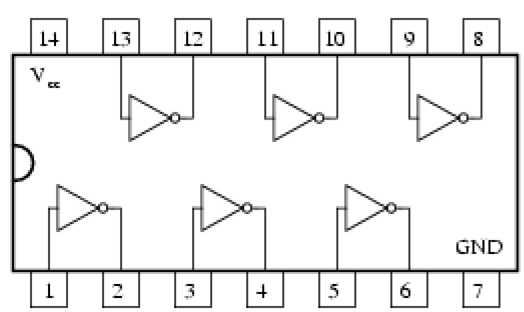
5432/7432
Quad OR gate



5486/7486
Quad XOR gate



5404/7404
Hex inverter



ECE 115

Introduction to Electrical and Computer Engineering

Laboratory Experiment #10

Digital Adder

Objective: Within the central processing unit (CPU) of a computer there is a digital logic circuit module dedicated to output the sum of two N-bit binary number inputs, where N may be 4, 8, 16, 32, or 64, depending on the computing speed and precision. In this experiment you will learn how to describe binary addition with Boolean functions, and you will design and build an N=2 bit full adder.

The First Computer

In the 1830s, Charles Babbage envisioned a massive brass, steam-powered, general-purpose, mechanical computer, which he called the analytical engine. It anticipated almost every aspect of the modern computer. In Fig.10.1 is shown a part of this machine that could do arithmetic.

The analytical engine was intended to use loops of Jacquard's punched cards to control an automatic calculator, which could make decisions based on the results of previous computations. This machine was also intended to employ several features subsequently used in modern computers, including sequential control, branching, and looping.

The analytical engine was to be powered by a steam engine and would have been over 30 meters long and 10 meters wide. The input (programs and data) was to be provided to the machine on punch cards, a method being used at the time to direct mechanical looms. For output, the machine would have a printer, a curve plotter and a bell. The machine would also be able to punch numbers onto cards to be read in later. It employed ordinary base-10 fixed-point arithmetic. There was a store (i.e., a memory) capable of holding 1,000 numbers of 50 digits each. An arithmetical unit (the "mill") would be able to perform all four arithmetical operations.

The programming language to be employed was akin to modern day assembly languages. Loops and conditional branching were possible and so the language as conceived would have been Turing-complete. Three different types of punch cards were used: one for arithmetical operations, one for numerical constants, and one for load and store operations, transferring numbers from the store to the arithmetical unit or back. There were three separate readers for the three types of cards.

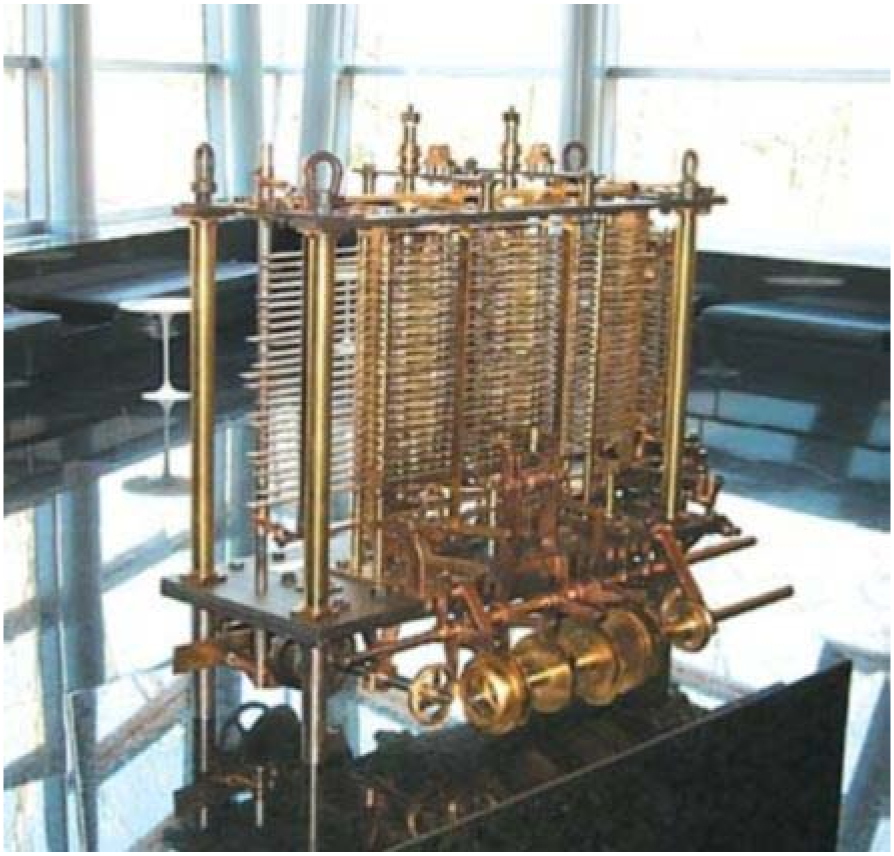


Fig. 10.1. The Babagge difference engine.

How Computers Store Numbers

Modern computer systems are constructed of digital electronic circuits. This means that the electronic circuits receive as input signals voltages that are at one of only two voltage levels and produce output signals that are at one of only two voltage levels. Two commonly used voltage levels are +5 Volts, which is designated logic 1, and 0 Volts, which is designated logic 0. It is said that a logic signal is either at a high state (logic 1 or ON state) or a low state (logic 0 or OFF state). These electronic circuits can have: (1) one input and one output, and perform the operation of a NOT gate, (2) two or more inputs and one output, and perform the operation of an AND gate, and (3) two or more inputs and one output, and perform the operation of an OR gate. These three gates are the fundamental building blocks of digital systems.

With the three fundamental building blocks other basic gates can be made (See Experiment 9.). For example, the NAND, NOR, XOR, and EQ gates are also commonly used building blocks to make more complex gates and digital system building blocks.

The two states of digital electronic circuits make them compatible with the binary number system, where the digits (or bits) are either 1 or 0. Because of their digital (or binary) nature, a CPU's electronic circuitry can manipulate numbers represented in binary by treating 1 as "on" and 0 as "off." A computer's CPU has circuits that can add, subtract, multiply, and divide numbers represented in binary, and do many other kinds of operations..

The Binary Number System

To understand the binary (or base -2) number system it is useful to first review the base-10 (decimal) number system. The decimal number system uses ten digits, 0 through 9, to represent a count. When we write a number, say A=365, we give a base-10 code for a count, which is here denoted by A, where the digits count different powers of ten. The digit, 6, counts the number of tens (10^1), the digit, 3, counts the number of hundreds (10^2) and likewise, 5 counts the number of ones (10^0). Thus, 365 is a code for the count, which is given by

$$A = 3 \times 10^2 + 6 \times 10^1 + 5 \times 10^0$$

Generally, the code for a base-10 number is written as

$$A = \ldots\ldots A_4\ A_3\ A_2\ A_1\ A_0$$

where each A_i is a digit, while the count is given by

$$A = \ldots\ldots + A_4 \times 10^4 + A_3 \times 10^3 + A_2 \times 10^2 + A_1 \times 10^1 + A_0 \times 10^0$$

Each digit, A_i , has a value, 0, 1, 2, …., 9, and it is a count of a power of ten, 10^i.

Similarly, in the binary (base -2) number system there are two digits (or bits), 0 and 1, and using the binary number system, the count of a number, given its binary code, is given by

$$A = \ldots\ldots + A_4 \times 2^4 + A_3 \times 2^3 + A_2 \times 2^2 + A_1 \times 2^1 + A_0 \times 2^0$$

where the binary code is: $A = \ldots\ldots A_4A_3A_2A_1A_0$. For example, if in binary we have A = 11011, then the count in base ten is: A = 27, since the binary code means that there is a sixteen (A_4=1), an eight (A_3=1), no four (A_2=0), a two (A_1=1) and a one (A_0=1) in the count. As we move to the left, from one bit position to the next, the value of each bit is doubled, and the column values are: 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, and so on. Notice that 2^{10} equals 1024, which, in computer engineering, is commonly denoted by 1K. A grouping of eight bits is called a byte, and with a byte we have the 8-bit binary numbers from 0 to 255 in base ten and from 00000000 in binary to 11111111 in binary, respectively.

Binary Addition

Consider the addition of decimal numbers:

$$\begin{array}{r} 23 \\ +\ 48 \\ \hline \end{array}$$

We begin by adding 3+8=11. Since 11 is greater than 9, a one is put into the 10's column (carried), and a 1 is recorded in the one's column of the sum. Next, add {(2+4) +1} (the one is from the carry) = 7, which is put in the 10's column of the sum. Thus, the answer is 71.

Binary addition works on the same principle, but the numerals are different. Let us begin our study of binary addition with one-bit binary addition. All possible combinations are shown below.

$$\begin{array}{r} 0 \\ +\ 0 \\ \hline 0 \end{array} \quad \begin{array}{r} 0 \\ +\ 1 \\ \hline 1 \end{array} \quad \begin{array}{r} 1 \\ +\ 0 \\ \hline 1 \end{array} \quad \begin{array}{r} 1 \\ +\ 1 \\ \hline 10 \end{array}$$

The addition on the right indicates that we have to account for two output bits when we add two input bits: the sum and a possible carry. The addition, 1+1, causes a carry bit. In decimal form, 1+1=2. The decimal number, "2", is written in binary notation as: "10", $(1 \times 2^1)+(0 \times 2^0)$. Record the 0 in the ones column, and carry the 1 to the twos column to get an answer of "10." In our vertical notation, we have

$$\begin{array}{r} 1 \\ +1 \\ \hline 10 \end{array}$$

The process is the same for multiple-bit binary number addition.

Binary ADDER Logic Circuit

To design a logic circuit that can add numbers written in binary code, let us consider what happens in the i^{th} column of adding two numbers in binary as shown below.

$$\begin{array}{rr} & A_i \\ & +\ B_i \\ \cline{2-2} C_{i+1} & S_i \end{array}$$

We can describe the desired result with a truth table, where we consider every possibility for A and B as we add two bits to produce the sum bit S and the carry bit C into the column to the left of the i^{th} column.

Table 10.1. Truth table for addition in a column, not using a carry bit from the right.

A	B	S	C
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

From the truth table we can write the Boolean function for the sum bit and the carry bit, given by

$$S = A'B + AB' = A \oplus B$$
$$C = AB$$

A logic circuit that performs the addition of two binary digits like this is called a half adder. A half adder (HA gate) can only add two binary digits. It cannot handle the addition of any two arbitrary numbers because it does not allow the input of a carry bit from the addition of two binary digits to the right. If we want a long binary number added to another long binary number, we must use circuits called "full adders", each of which handles one bit of each number.

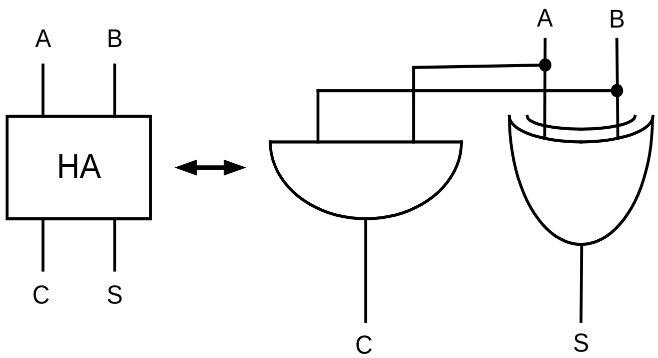


Fig. 10.2. Logic diagram of a binary half adder.

For full column addition, we must take into account a carry bit from the right, which we will denote by C_{IN} , and we must produce a carry bit for the column to the left, which we will denote by C_{OUT}. To construct a full adder logic circuit, we will describe with a truth table how we want the circuit to operate. Table 10.2 shows the truth table for full addition in a column.

Table 10.2. Truth table for a full adder.

INPUTS			OUTPUTS	
A	B	C_{IN}	C_{OUT}	S
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

Here, addition in a column consists of adding C_{IN} + A + B, to produce the column sum bit S and the column carry bit C_{OUT}. From the truth table we can write a Boolean function for the sum bit S given by

$$S = A'B'C_{IN} + A'BC_{IN}' + AB'C_{IN}' + ABC_{IN}$$

Grouping the first and fourth terms, and the second and third terms gives

$$S = (A'B' + AB)C_{IN} + (A'B + AB')C_{IN}' = (A'B + AB')'\,C_{IN} + (A'B + AB')C_{IN}'$$

If we let X= A'B + AB' and Y= C_{IN}, then we can write

$$S = X'Y + XY'$$

The Boolean function for the carry out bit C_{OUT} is given by

$$C_{OUT} = A'BC_{IN} + AB'C_{IN} + ABC_{IN}' + ABC_{IN}$$

The third and fourth terms can be combined to become

$$ABC_{IN}' + ABC_{IN} = AB(C_{IN}' + C_{IN}) = AB$$

which means that we can write

$$C_{OUT} = (A'B + AB')C_{IN} + AB = XC_{IN} + AB$$

Notice that if A and B are the inputs to an HA, then X and AB are its outputs. With another HA we can obtain $S = X'Y + XY'$ and $XY = XC_{IN}$. Therefore, full addition can be obtained with two HAs and an OR gate as shown in Fig. 10.3.

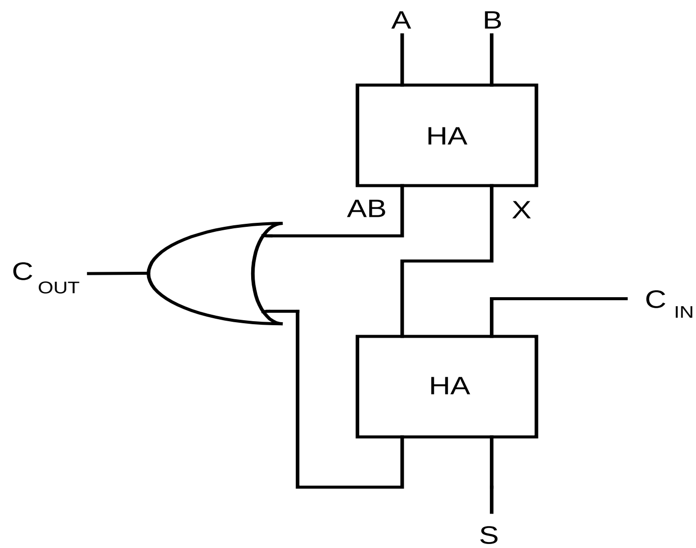


Fig. 10.3. Logic circuit for a full adder.

To add multi-bit binary numbers we use full adders as shown in Fig. 10.4 for the addition of 2-bit binary numbers.

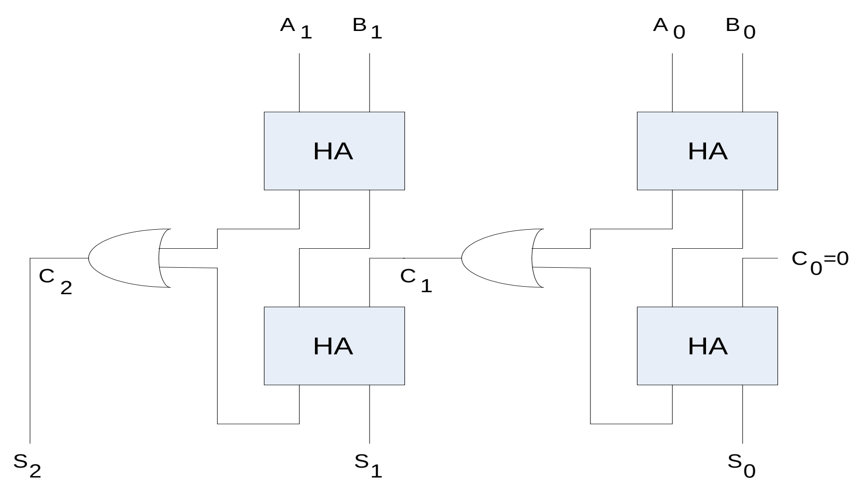


Fig. 10.4. Logic circuit for a two-bit full adder, $S_2S_1S_0=A_1A_0+B_1B_0$.

Experiment

Parts List

1) Switches (8 switch DIP)
2) Resistor (330 Ohm, 3)
3) Resistor(10K, 4)

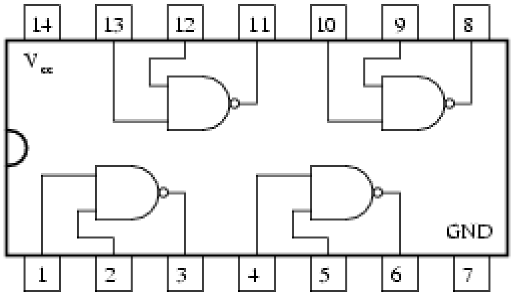
4) LED (3)
5) Quad OR (7432, 2)
6) Quad AND (7408, 4)
7) Hex inverter (7404, 4)
8) Quad XOR (7486, 4)

1) Use an AND gate and an XOR gate to build an HA. ***Test the HA by using switch and pull-up resistor circuits to manually set the inputs, and by using two NOT gates, two LEDs in series with resistors to observe the outputs. Give the truth table for the results, and a complete schematic.***

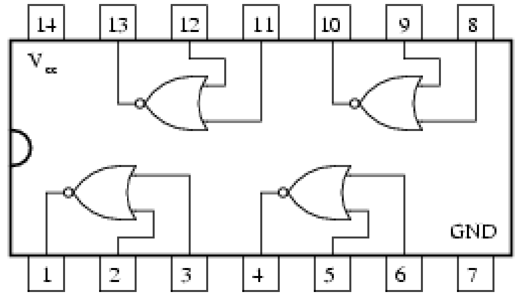
2) Build another HA and use an additional OR gate to make a full-adder, as shown in Fig.10.3. Use another switch and pull-up resistor circuit to manually provide the carry in bit. ***Provide a complete schematic. Test the full-adder, and give a truth table for the results.***

3) Build another full-adder, and connect the two full-adders to achieve 2-bit binary addition. ***What is the carry in bit for the LSB (least significant bit) column? Provide a complete schematic. Give a truth table of results for every combination of binary addition of two 2-bit numbers. Demonstrate to your TA that your circuit works.***

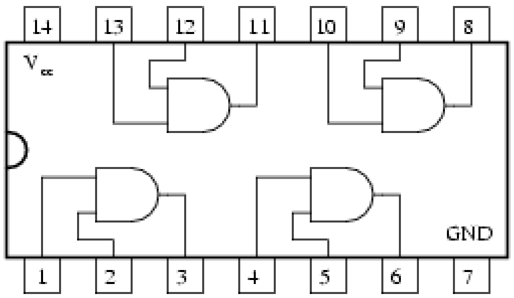
5400/7400
Quad NAND gate



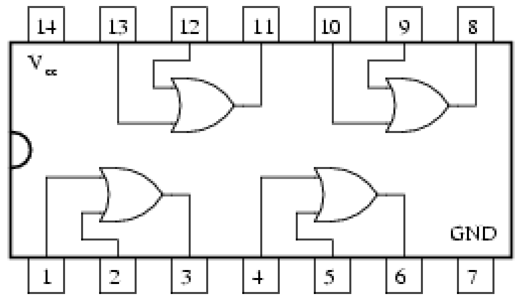
5402/7402
Quad NOR gate



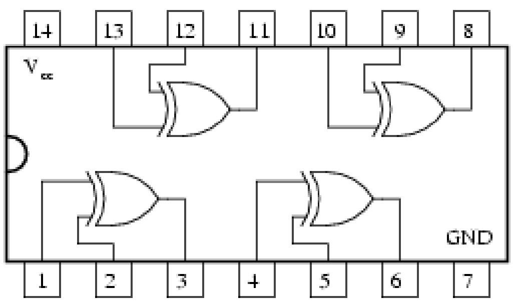
5408/7408
Quad AND gate



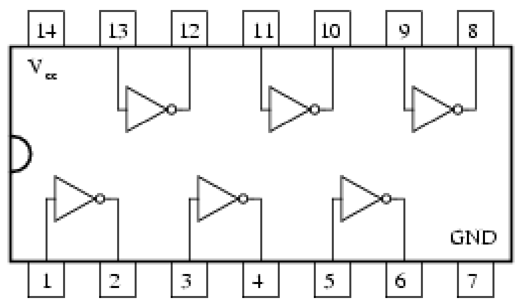
5432/7432
Quad OR gate



5486/7486
Quad XOR gate



5404/7404
Hex inverter



ECE 115

Introduction to Electrical and Computer Engineering

Laboratory Experiment #11

Memory

Objective: In this experiment you will learn how computer memory works. The kind of memory that will be investigated is called RAM, random access memory. The basic building block of RAM is the flip-flop, (FF). You will learn how to design memory with the FF.

Memories Are Made of These

Computer systems use memory generally for two purposes: to store data and to hold programs. The data may be predetermined and input to a program or may be generated by an executing program to be outputted or used later by the program. For these different kinds of data, different kinds of memory are used. RAM (random access memory) is the kind of memory to which data can be written and from which we can read data in any sequence. RAM keeps its data content as long as power is supplied to the RAM circuitry, and all data content is lost when power to the circuitry is turned off.

ROM (read only memory) is the type of memory into which data and programs can be placed, and the content of this memory is retained even when power to the circuitry is turned off. However, once placed into ROM, this data can then no longer be changed. Virtually all computer systems have ROM memory to hold data and programs that execute when power is first applied to the computer. Also, all computer systems have RAM memory that contains copies of the programs that will be executed and the data that is the result of computing.

The physical devices that are used to make RAM and ROM vary considerably. For one kind of memory, called DRAM (dynamic random access memory) the main storage element is a capacitor. When the capacitor is charged, we say it holds logic 1, and when the capacitor is uncharged, we say it holds logic 0. A major problem with such a storage device is that the charge tends to dissipate, and in a few milliseconds after writing data to this kind of memory the content of memory is lost. Charged capacitors will tend to discharge and uncharged capacitors will tend to charge. However, such a memory element can be manufactured in very high density. The problem of memory retention can be overcome, and therefore this type of memory is the main memory of most computer systems. RAM, also called static RAM (SRAM) is made of FFs, and data that has been written to this memory is retained indefinitely, as long as power is supplied to its circuitry.

The logic circuitry of computer systems (digital systems) can generally be classified into to major groups: combinational (or combinatorial) circuits and sequential circuits. The output of a combinational circuit is a function solely of its inputs, like the logic circuit that performs the activity of a full adder. These circuits can be described by Boolean functions. On the other hand, the output of a sequential circuit is a function not only of the inputs but also of the current and past outputs. It is said that there is feedback from the outputs to the inputs. Sequential circuits have both combinational logic components and memory. Since the output of a combinational circuit depends solely upon the inputs, the implication is that combinational circuits have no memory.

For a device to serve as memory, it must have three characteristics:

- the device must have two stable states
- there must be a way to read the state of the device
- there must be a way to set (write) the state at least once.

R-S Latch (Flip Flop)

The R-S latch is one of the most basic RAM building blocks. With this basic circuit, which is also called a flip-flop (FF), memory registers, cache memory, and complex sequential circuits are constructed.

Consider the circuit shown in Figure 11.1. The output of a NOR gate is true (logic 1 or high) only when both inputs are false (logic 0 or low). The output of each NOR gate is fed back to the input of the other NOR gate. This means that if the output of one NOR gate is true, then the output of the other NOR gate must be false.

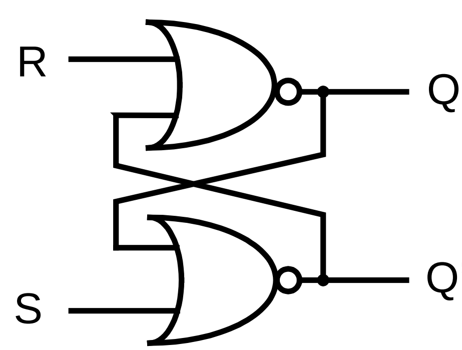


Figure 11.1. RS latch using NOR gates.

Suppose the S input is high, and the R input is low. Then, the output of the upper NOR gate, called Q, is forced to be high. Even if S is set low, Q will remain high, and the output of the other NOR gate, called not Q (Q'), will remain low. The circuit will remain in this stable state indefinitely.

Suppose the S input is low, and the R input is high. Then Q is forced to be low. Even if R is set low, Q will remain low, and Q' will remain high. The circuit will remain in this stable state indefinitely. The circuit has two stable states.

Notice that the Q and Q' outputs are complements of each other. The S input stands for set the flip-flop (FF) to make Q = 1 ($Q' = 0$), and the R input stands for reset the FF to make Q = 0 ($Q' = 1$). Once the FF is set, then setting it again will not change it, and once the FF is reset, then resetting it again will not change it. However, at any time we can set it, and it will retain the set state indefinitely, and we can reset it, and it will retain the reset state indefinitely.

The activity of the R-S flip-flop (also called a latch) is described in Table 11.1.

Table 11.1. Characteristic table of a NOR gate R-S latch

R	S	FF Activity
0	0	Q remains unchanged
0	1	Q = 1
1	0	Q = 0
1	1	Input not used

The output of the circuit is stable in either state when the inputs are low. The output will only change when complementary inputs are applied. Such a circuit is said to be bistable, because it has two stable output states.

For convenience we use the symbol shown in Fig. 11.2 for an RS-FF.

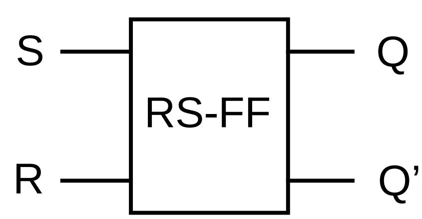


Figure 11.2. Symbol for the FF in Fig. 11.1.

Binary Cell

A computer system may have millions of flip-flops for RAM memory, not all of which are read or written at the same time. We must be able to specify

a) that we want to read from a flip flop
b) that we want to write to a flip flop

c) which FF of many is the memory we want to access (read or write)
d) and when a read or write operation should happen.

Therefore, we add steering logic to the basic FF given in Fig. 11.2. This is shown in Fig. 11.3. In the figure is shown a circuit called a binary cell. The small circles at AND gate inputs are called bubbles, and they perform the logic NOT function, like a NOT gate. The line over S (meaning SELECT) and W (meaning write) means that to perform the action this signal must be low. It is said that $\overline{S}$ is an active low control input and that R/$\overline{W}$ is an active low write control input and an active high read control input.

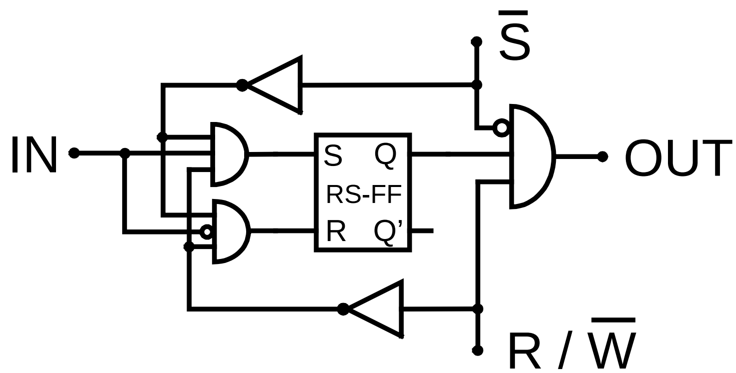


Figure 11.3. A one-bit memory circuit called a binary cell.

When we want to read the content of a binary cell (BC), the R/$\overline{W}$ input is set high and the $\overline{S}$ input is set low, and then the output OUT will give OUT = Q. To deselect the BC, set the $\overline{S}$ input back to high. Notice that when the $\overline{S}$ input is high, then the R and S inputs to the FF are both low, and the Q output cannot be altered. When we want to write a particular bit to the BC (FF), then we must first apply the bit (high or low) to the input, IN. Then, we set the R/$\overline{W}$ input low, signifying that we want to write to the BC. When the $\overline{S}$ input is taken low, then the Q output of the FF will become the same logic value as the input, IN, but the output, OUT will not respond. Again, to deselect the BC, set the $\overline{S}$ input back to high, which prevents further alteration of Q.

This BC can be one of many binary cells in a computer system. Let us use Fig. 11.4 as a symbol for a BC.

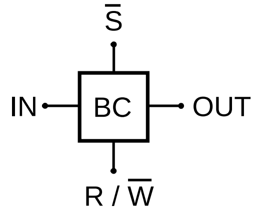


Figure 11.4. Symbol for a binary cell.

With a binary cell we can make a RAM memory register that can hold a byte of data or program code, as shown in Fig. 11.5.

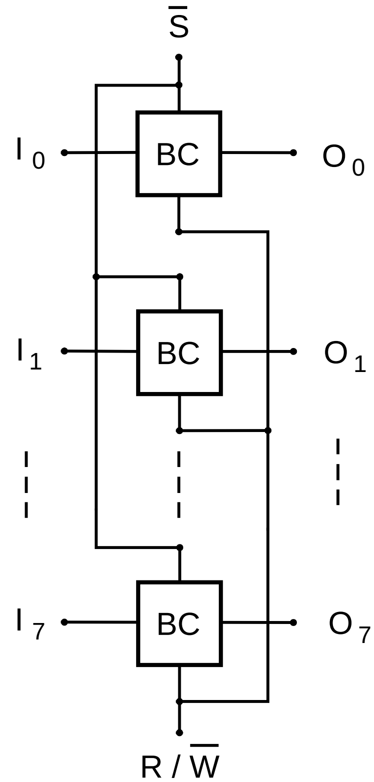


Figure 11.5. Eight binary cells connected in parallel to form an 8-bit register.

In Fig. 11.5, the R/$\overline{W}$ and $\overline{S}$ inputs of all BCs are connected together to simultaneously read and write a byte (8 bits) of data from and to the 8 binary cells. A grouping of BCs is called a register. Here, we have an 8-bit register. This register is redrawn more conveniently in Fig. 11.6. In the right drawing, the notation accounts for 8 lines with a single line.

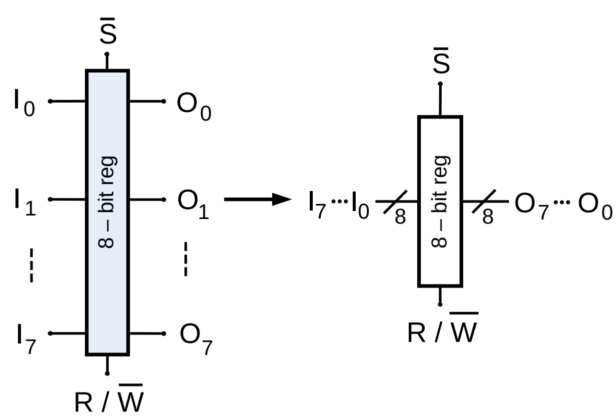


Figure 11.6. Block notation for a register.

Experiment

1) Build the circuit shown in Fig. 11.1. Use switch and pull-up resistor circuits to manually apply the R and S inputs, and use NOT gate, LED and resistor circuits to show the outputs Q and Q'. ***Give the characteristic table for the circuit. What happens to Q when both inputs are set to logic 1 and then to logic 0? Try this several times. Are the results always the same?***

2) Build the BC of Fig. 11.4, which is detailed in Figs. 11.1 and 11.3. ***For every one of the eight possible combinations of the three inputs, IN, R/$\overline{W}$, and $\overline{S}$, give the resulting output OUT.*** Use switch and pull-up resistor circuits to manually apply the three inputs, and use a NOT gate, LED and resistor circuit to show the output, OUT. ***Provide a table showing your results. Describe what you must do to read the BC. Describe what you must do to write a bit into the BC, where you must write logic 0 and then logic 1 and check each write operation by reading the BC to find if each write operation worked.***

Demonstrate to your TA that your binary cell works as intended.

3) ***Leaving the $\overline{S}$ input high, the IN input low and the R/$\overline{W}$ input high, turn power off and on. Then read (set the $\overline{S}$ input low) the BC, and give results. Do this three times. Are the results always the same?***

4) In your report, give a drawing of a 32-bit register by connecting four 8-bit registers in parallel. Denote the inputs to the four registers with:

$$I_{31}\, I_{30} \cdots I_{24} \quad I_{23}\, I_{22} \cdots I_{16} \quad I_{15}\, I_{14} \cdots I_{8} \quad I_{7}\, I_{6} \cdots I_{0}$$

and similarly for the outputs.

Parts List:

1) quad NOR gate (1, 7402)
2) quad AND gate (1, 7408)
3) hex NOT gate (2, 7404)
4) LED (2)
5) Resistor (2, 330 Ohms)
6) Resistor (3, 10K Ohms)
7) 8 switch DIP (1)

ECE 115

Introduction to Electrical and Computer Engineering

Laboratory Experiment #12

The Operational Amplifier

Objective: In this experiment you will learn about the operational amplifier, one of the most widely used integrated circuits. As a building block, the operational amplifier, also called op-amp, is very easy to use, has only a few important properties, and is widely applied. You will learn to use the op-amp to make an inverting amplifier, a non-inverting amplifier, and a low-pass filter.

Brief History

The operational amplifier was designed to perform mathematical operations, such as: addition, subtraction, integration, differentiation, and much more. Using vacuum tubes, op-amps were originally developed in the 1940s, to be used in analog computers to solve differential equations.

The first integrated circuit (IC) op-amp became available in the 1960s, and it was the analog IC numbered “741”. Although op-amps that have a great variety of chatacteriestics are in use today, the 741 op-amp is still widely used. Many manufacturers produce a version of the 741 op-amp.

Ideal Op-Amp

The circuit symbol for an op-amp is shown in Fig. 12.1. The op-amp has an "inverting" or (-)

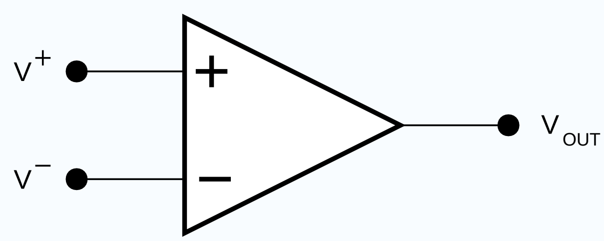


Figure 12.1. Op-amp symbol.

input and a "noninverting" or (+) input and a single output. The circuit of an op-amp can be very complex, typically consisting of more than twenty transistors. The op-amp is usually powered by a two polarity power supply +Vcc in the range of +5 to +15 volts and –Vcc in the range –5 to –15 volts for the positive and negative power supplies, respectively. A dual polarity power supply is shown in the Fig. 12.2. The two 9 volt power supplies could be two 9 volt batteries for portable applications. The inputs V_a and V_b can be positive or negative signals, as long as V_{OUT} is within the range –Vcc to +Vcc.

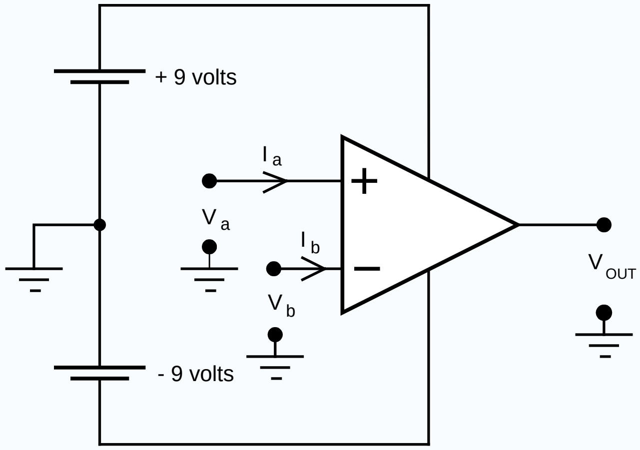


Figure 12.2. Op-amp circuit connections of inputs, power supplies and output.

Basically, the circuit of the op-amp is designed to achieve the gain equation given by

$$V_{OUT} = A\,(V_a - V_b)$$

where A is very large. Table 12.1 gives ideal and realistic values for some important parameters of an op-amp. The resistance looking into the electronic circuitry of the op-amp between an input terminal and ground, called the input resisitance, is very large, making I_a and I_b essentially zero. The resistance looking back into the electronic circuitry of the op-amp between the output terminal and ground, called the output resistance, is very small, making the output behave like a voltage source.

Table 12.1. Ideal and realistic op-amp properties.

Parameter Synbol	Ideal Value	Realistic Value
A, gain	∞	$10^5 - 10^9$
R_{in} , input resistance	∞	$10^6 - 10^{12}$ Ohms
R_o , output resistance	0	$50 - 1000$ Ohms

Inverting Amplifier

A simple circuit that illustrates the utility of the op-amp is shown in Fig. 12.3. The schematic does not show the power supply connection, which is given in Fig. 12.2. The op-amp plus input is connected to ground.

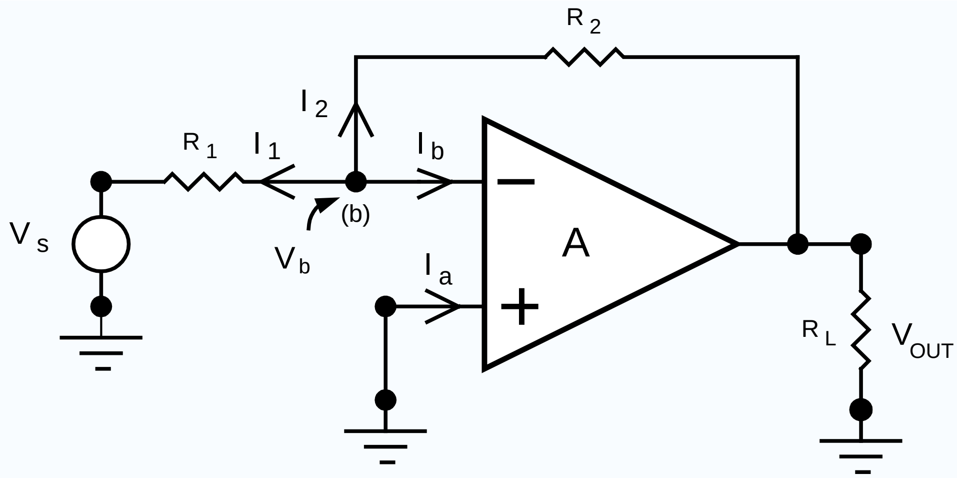


Figure 12.3. Inverting amplifier circuit using an op-amp.

To see what this circuit can do, let us apply Kirchhoff's current law (KCL) to the node labeled (b), where the voltage from this terminal to ground is V_b . The current I_1 leaving node (b) through R_1 is given by

$$I_1 = (V_b - V_s)/R_1$$

and the current leaving node (b) through R_2 is given by

$$I_2 = (V_b - V_{OUT})/R_2$$

By the op-amp gain equation we have

$$V_{OUT} = A(0 - V_b) = -AV_b$$

so that

$$V_b = -\frac{1}{A}V_{OUT}$$

By KCL we have

$$\frac{V_b - V_s}{R_1} + \frac{V_b - V_{OUT}}{R_2} + I_b = 0$$

$$V_b\left(\frac{1}{R_1} + \frac{1}{R_2}\right) - \frac{V_s}{R_1} - \frac{V_{OUT}}{R_2} + 0 = 0$$

$$-\frac{V_{OUT}}{A}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) - \frac{V_s}{R_1} - \frac{V_{OUT}}{R_2} = 0$$

Since the gain A is very large, the first term in the above equation is negligible compared to the second and third terms. Therefore, this equation reduces to

$$-\frac{V_s}{R_1} - \frac{V_{OUT}}{R_2} = 0$$

which gives

$$V_{OUT} = -\frac{R_2}{R_1} V_s$$

Therefore, the circuit inverts and multiplies the input signal V_s by a constant given by the resistor ratio, R_2 / R_1 .

The circuit is an inverting amplifier, regardless of the value of R_L. However, R_L cannot be too small, because the electronic circuitry of the op-amp cannot sustain a large current out of the output terminal. With the 741 op-amp, R_L must be large enough to limit the current through it to about 10 mA or less.

This circuit is commonly used to amplify low voltage level signals, such as the speech signal coming from the output of a microphone in a cell phone.

Non-Inverting Amplifier

Depending on the kinds of components and how they are connected to an op-amp, a great variety of signal processing activities can be achieved. Many different configurations are possible, making the op-amp one of the most versatile of all electronic building blocks.

Fig. 12.4 shows the circuit for a non-inverting amplifier. Here we have

$$V_{OUT} = A(V_{IN} - V_b)$$

By setting the sum of the currents I_b, V_b/R_1 and $(V_b - V_{OUT})/R_2$ leaving node (b) to zero and using the fact that A is very large, we find that

$$V_{OUT} = (1 + \frac{R_2}{R_1})\, V_{IN}$$

which means that this circuit multiplies the input voltage by a positive constant.

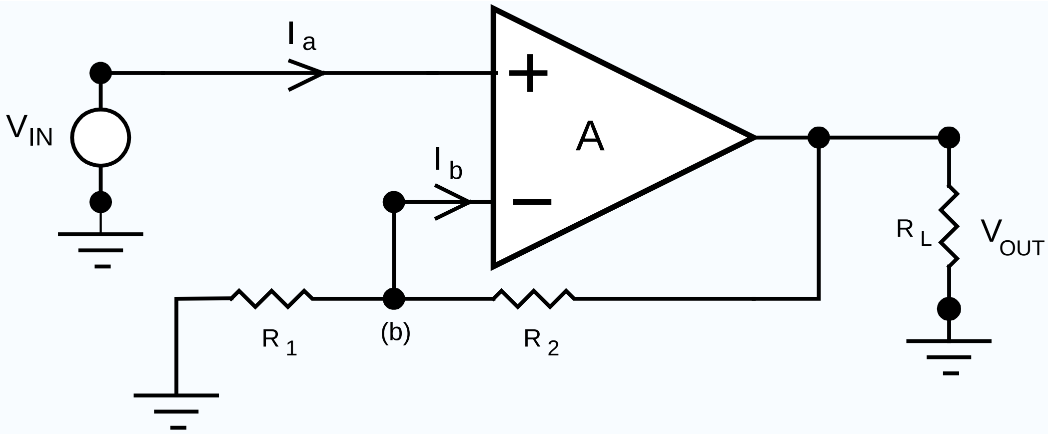


Figure 12.4. Op-amp circuit configuration for a noninverting amplifier.

Regardless of the vlaue of R_L, the gain is determined by the resistance ratio R_2/R_1. The same limitations apply to R_L, as they do for the circuit in Fig. 12.3.

Active Low-Pass Filter

In analog signal processing, such as processing audio signals, a low-pass filter is a circuit whose output amplitude can vary depending on the frequency of the input. A circuit that behaves like a low-pass filter is given in Fig. 12.5.

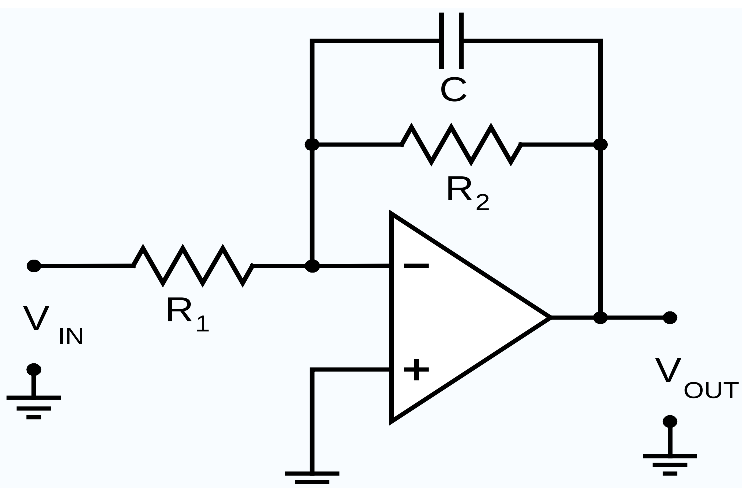


Fig. 12.5. An active RC low-pass filter.

Suppose the input voltage signal varies sinusoidally, so that

$$V_{IN}(t) = K\cos(\omega t + \theta)$$

where K is the input amplitude, $\omega = 2\pi f$ rad/sec (f, the frequency in Hz) and θ is the phase angle. The output signal will also be a sinusoidally varying voltage given by

$$V_{OUT}(t) = B\cos(\omega t + \phi)$$

where B is the amplitude of the output and ϕ is the phase angle of the output. The change in amplitude and phase angle from the input to the output depends on the frequency of the input. For this circuit, if the input frequency f is low then we get

$$B = -K (R_2/R_1)$$

as if the capacitor is like an open circuit and the circuit behaves like an inverting amplifier as in Fig. 12.3.

When the frequency of the input is increased, the amplitude of the output decreases to becoming substantially zero if the frequency of the input is large enough. This is useful for applications where the input is a combination of sinusoidal signals having parts with low frequencies and other parts with high frequencies. Suppose the input is

$$V_{IN}(t) = K_1\cos(\omega_1 t + \theta_1) + K_2\cos(\omega_2 t + \theta_2)$$

where $f_1 = \omega_1 / 2\pi$ is a low frequency, and $f_2 = \omega_2 / 2\pi$ is a high frequency. The output will be

$$V_{OUT}(t) \simeq B_1\cos(\omega_1 t + \phi_1)$$

and the circuit has eliminated (filtered out) the high frequency part of the input signal and reproduced (passed) the low frequency part of the input signal, as the name of this circuit, low-pass filter, suggests.

The frequency f_c at which the output amplitude starts to decrease substantially is given by

$$f_c = \frac{1}{2\pi R_2 C}$$

and for low frequency inputs, the output to input amplitude ratio is given by: $G = -R_2 / R_1$, where G denotes the gain of the amplifier. Thus, we can design a low-pass filter to perform trebble control in an audio amplifier system.

With op-amps, resistors and capacitors (active RC circuits) it is possible to design a great variety of filter types that are commonly used in audio signal processing, video signal processing, and communication systems.

LM741 Operational Amplifier

The 741 op-amp is available in a variety of packages. One of these packages is an 8 pin DIP (dual in-line package) shown in Fig. 12.6.

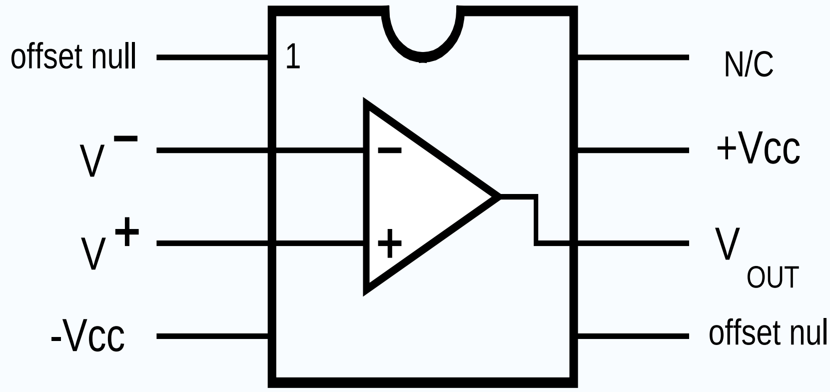


Fig. 12.6. Pin assignment for the LM741 op-amp in an 8-pin DIP.

Experiment

1) Using the LM741 op-amp, build the circuit shown in Fig. 12.3. You do not have to connect anything to pins 1, 5 and 8. Set R_2 to 20K Ohms (two 10K Ohm resistors connected in series will work), and set R_1 to 10K Ohms. Use +Vcc = 9 volts and –Vcc = -9 volts, and connect the power supplies as shown in Fig. 12.2, Be sure to measure the power supply voltages before connecting the power supply to your circuit. Also, leave the power supply unconnected to the circuit while you are building the circuit. For R_L , use 10K Ohm.

Use the oscilloscope to set the output of the signal generator to a 1 volt amplitude sinusoidal voltage signal having a frequency of 100 Hz. Connect the signal generator to channel 1 of the oscilloscope and also to the input of the op-amp circuit. Observe the output of the circuit with channel 2 of the oscilloscope**.**

a) ***Provide a drawing (Use the package outline and pin numbers in Fig. 12.6.) of your circuit that also shows the power supply and oscilloscope connections. Provide sketches of the oscilloscope display showing the input and output signals. What is the amplitude of the output sinusoidal signal? Be sure to know the oscilloscope vertical sensitivity volts/div setting. Is there a sign reversal from input to output?***

b) ***What happens if you momentarily remove the resistor R_L. Can it be permanently removed without affecting the operation of the circuit?***

c) ***What happens as you increase the input signal frequency to 10K Hz? Provide oscilloscope display sketches.***

d) ***Now connect a 10K Ohm resistor in parallel with R_1. What has the effective resistance of R_1 become? Provide an oscilloscope display sketch. What is the gain from input to output of the circuit? In terms of resistor values, what is the gain of the amplifier?***

e) ***If R_2 is made a variable resistor, can we then manually control the amplification factor of this circuit? Explain.***

2) ***Repat all of the steps in part (1) for the circuit shown in Fig. 12.4.***

3) Wire the circuit shown in Fig. 12.5. Use +Vcc = +9 volts and –Vcc= -9 volts. Use $R_1 = R_2 = R_L$ = 10K Ohms, and C = 0.1 uF. Connect the signal generator to channel 1 of the oscilloscope, and adjust the amplitude and frequency of a sinusoidal signal to 1 volt and 100 Hz, respectively. Also, connect the signal generator output to the circuit input, and connect channel 2 of the oscilloscope to the circuit output to see the voltage across R_L.

a) ***Provide a sketch of the oscilloscope display. From the oscilloscope display, what is the input to output amplitude ratio? Is there a sign reversal from input to output amplitude?***

b) ***For the component values used, use the given formula to find fc. What is this value? Is it substantially above 100 Hz?***

c) ***Now increase the input frequency to f_c, and provide a sketch of the oscilloscope display. What is the input amplitude, and what is the output amplitude?***

d) ***Now increase the input frequency further until the output amplitude is 1/5 of the input amplitude. At what frequency does this occur? Provide oscilloscope sketches. Does the circuit behave as a low-pass filter? What is the very low frequency gain? What happens as the frequency of the input is increased?***

e) ***What would happen to the value of f_c, if the value of C is changed by connecting another 0.1 uF capacitor in parallel with the capacitor used so far? What is the new value of f_c?***

4) ***Like the derivation for the gain of the inverting amplifier, give a derivation for the gain of the non-inverting amplifier.***

Parts list:

1) Op-amp (LM741 8-pin DIP, 1)
2) Resistor (10K Ohm, 5)
3) Capacitor (0.1 uF, 2)