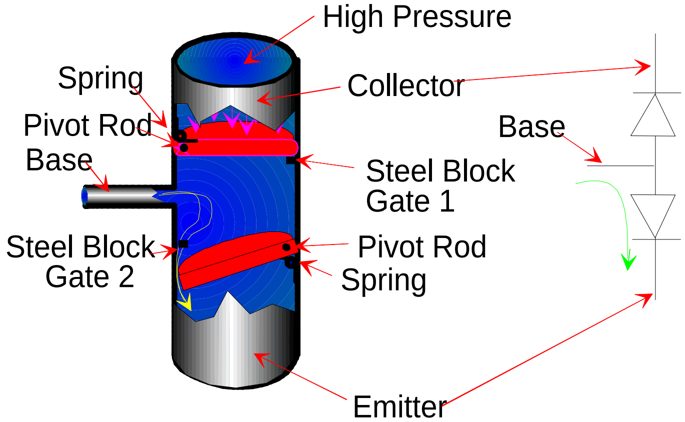
# THE TRANSISTOR

## The First Transistor

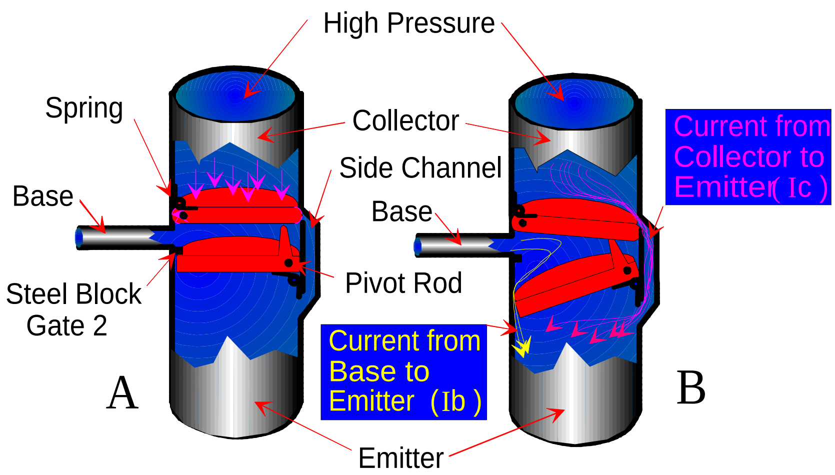
**This is it! The biggest thing to hit electronics since the electron itself. The "Transfer Resistor" or what most people call it, the Transistor. The transistor was developed at Bell Telephone Laboratories by the American physicists Walter Houser Brattain, John Bardeen, and William Bradford Shockley. For this achievement, the three shared the 1956 Nobel Prize in physics. Shockley is noted as the initiator and director of the research program in semiconducting materials that led to the discovery of this group of devices; his associates, Brattain and Bardeen, are credited with the invention of an important type of transistor.**

**In the course on Diodes, you were asked if current could flow through two diodes connected together but polarized for opposite current flow. Let's look at those water pipes again to see what would happen. The drawing below shows two diodes (check valves) connected back to back.**




**Let's call the top cathode the collector and the bottom cathode the emitter. The junction of the two Anodes will be called the Base. Notice how the pressure on the collector in Figure 17A forces gate 1 against the Steel Block and no current can flow. We can still force current into the base and out the emitter through gate 2, but it has no affect on gate 1. Because these two gates are far apart they do not interact and current cannot flow from collector to emitter, even if base to emitter current is flowing. This is also true in electronics. If you put two diodes together as shown in the schematic above, the flow of current through one diode will have no affect on the current flowing in the other diode.**

**Now let's move the gates closer to each other and modify them slightly as shown here.**




**In drawing A above you can see how the steel block for gate 1 has been replaced with a bump on gate 2 just above the pivot rod for gate 2. We have also added a side channel from the emitter to the back edge of gate 1. The pressure on gate 1 forces the gate against the bump on gate 2. The pivot rod under the bump on gate 2 prevents the bump from moving downward and gate 1 remains fixed as shown in drawing A.**
**Look what happens if a current (Ib) is forced into the base in drawing B. Opening gate 2 allows a larger current (Ic) to flow from collector to emitter through the side channel. The bump above the gate 2 pivot rod moves down enough to allow gate 1 to drop and this opens a passage to the side channel. The higher pressure on the collector forces more than 100 times the base current to flow from collector to emitter through the side channel.**
**To watch a water pipe transistor working, click on the animated gif file called "The_NPN_Transistor" on emailschool's course page.**
**The exact same thing happens in the electronic device called the transistor. When the two diodes are made atomically close to each other, a small amount of base current will electronically open a channel from collector to emitter that allows a large current to flow. You might say the "resistance" from collector to emitter is "transferred" from a high value of resistance to a low value when base current flows. The name was shortened from transfer-resistor to "Transistor" and a whole new world in electronics was launched.**

## The NPN Transistor Switch

**A single NPN transistor can be switched from "ON" to "OFF" by simply raising the base voltage high enough with respect to the emitter to produce base current. When the collector is tied to B+ through a fairly high resistance the voltage on the collector will fall to zero when the transistor is "ON" and rise to B+ when the transistor is "OFF".**
**Digital logic is a rational process for making simple "true" or "false" decisions based on the rules of Boolean algebra. If "True" is represented**

**by a 1 or high voltage and "false" by a 0 or low voltage, then numerals appear as signals of two different levels. Logic circuits are used to make specific true-false decisions based on the presence of multiple true-false signals at the inputs. The signals may be generated by mechanical switches or by solid-state semiconductor devices such as an NPN transistor.**

## Saturation Voltage for NPN Transistors

**Even after a transistor has been switched "ON" it has resistance due to the "side channel" size. Some transistors are made to handle large currents and others are made for speed and high frequency. A measure of the amount of current a transistor can handle is the Saturation Resistance ($R_{SAT}$) of that transistor. When the transistor is switched on the voltage across the transistor from collector to emitter divided by the collector current is a measure of the "Saturation Resistance" ($R_{SAT}$) at that current level.**

## Collector to Base Breakdown

**The manufacturers of semiconductors publish a specification for each transistor they make. Although there are small differences the critical specifications for common part numbers such as the 2N3904 will be the same for every manufacturer. The Breakdown voltage from Collector to Emitter with the base Open ($V_{CEO}$) is rated at 40 volts minimum on the specification sheet. The Breakdown voltage from Collector to Base with the emitter Open ($V_{CBO}$) is rated at 60 volts minimum on the specification sheet. The Breakdown voltage from Emitter to Base with the collector Open ($V_{EBO}$) is rated at 6 volts minimum on the specification sheet.**
**These ratings are all minimums because a larger breakdown voltage will not affect a circuit designed to work with the lower value of breakdown. In other words, it is important that the circuit designer does not design a circuit with more than 40 volts on the collector and zero on the emitter for a 2N3904 transistor. Also the base of the 2N3904 should never go more than 6 volts below the emitter voltage. These specifications are listed in data manuals published by the manufacturers of transistors. Or you can visit certain web sites that show the transistors specifications. The site** http://www.fairchildsemi.com/pf/2N/2N3904.html#Datasheet **for example offers downloads for many semiconductor products. If you are connected to the Internet, try visiting this site and looking at the 17 pages of specifications for the 2N3904 transistor. The following is a listing from a Motorola site of only a portion of the data on the first page of the specification.**

1 Motorola Small–Signal Transistors, FETs and Diodes Device Data

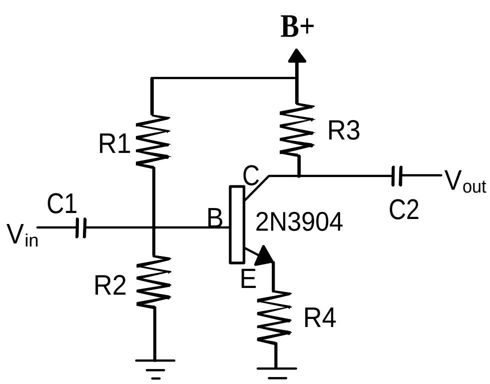
**NPN Silicon** **MAXIMUM RATINGS**

**Rating Symbol Value Unit**
Collector–Emitter Voltage V CEO 40 Vdc
Collector–Base Voltage V CBO 60 Vdc
Emitter–Base Voltage V EBO 6.0 Vdc

Collector Current — Continuous I C 200 mAdc   Derate above 25°C  P D 625mW   5.0mW/°C   Total Device Dissipation @ T C = 25°C   Derate above 25°C
Thermal Resistance, Junction to Case R _JC 83.3 °C/W
**ELECTRICAL CHARACTERISTICS** (T A = 25°C unless otherwise noted)
**Characteristic Symbol Min Max Unit**
**OFF CHARACTERISTICS**
Collector–Emitter Breakdown Voltage (2)
(I C = 1.0 mAdc, I B = 0)
V (BR)CEO 40 — Vdc
Collector–Base Breakdown Voltage
(I C = 10 _Adc, I E = 0)
V (BR)CBO 60 — Vdc
Emitter–Base Breakdown Voltage
(I E = 10 _Adc, I C = 0)
V (BR)EBO 6.0 — Vdc
Base Cutoff Current
(V CE = 30 Vdc, V EB = 3.0 Vdc)
I BL — 50 nAdc
Collector Cutoff Current
(V CE = 30 Vdc, V EB = 3.0 Vdc)
I CEX — 50 nAdc
***Motorola Preferred Device**
**CASE 29–04, STYLE 1**
**TO–92 (TO–226AA)**

## Class A Biasing for an NPN Transistor Amplifier

**As described earlier, the transistor can amplify current. Any circuit that increases the amplitude, or power, of an electric signal can be called an Amplifier. Amplifying the weak electric current drawn from the antenna of a radio receiver to drive a detector and eventually a loudspeaker is just one example. Proper DC biasing of a transistor is required to set the electrical current to the correct level and ensure the proper operation of the circuit. First consider the voltage on the collector of the npn transistor amplifier circuit shown here.**




**If the collector voltage is close to ½ the B+ voltage, the transistor can pull that voltage down toward ground (more current) or let the voltage move towards B+ (less current). You may have already figured out that the emitter current is equal to the collector current plus the base current. Since the base current is very small compared to the collector current, lets assume the current coming into the collector is very close to the current going out of the emitter. If R3 is 4.7K and .5 ma (milliamp) flows through it the drop across it will be 2.35 volts. Use the ohms law calculator to verify this. Since R4 has approximately the same current you can calculate the**

**voltage drop across it also. Let R4 equal 1K and calculate the drop across this resistor using the Ohms Law Calculator. Your answer should be .5 volts. The base emitter diode is forward biased so a small amount of current flows through this diode. The voltage drop on a forward biased silicon diode is approximately .7 volts. Since the emitter is at .5 volts and the drop on the base-emitter junction is .7 volts, the base must be at 1.2 volts.**

**Since the base is at 1.2 volts, then R2 has a voltage drop across it of 1.2 volts. If you make R2 a 15K resistor the current through it can be calculated. If this current also passes through R1 and the voltage drop on R1 is 5 volts minus 1.2volts (3.8 volts) then the value of R1 can be calculated using the Ohms Law Calculator. This is one method for determining the values for the two biasing resistors, the collector load, and the emitter resistor. If you used the calculator correctly the value for R1 should be 47,500 ohms. Next use the resistor calculator to find the closest 5% value. Hint, 5% values will only have 2 significant digits i.e. 45000, 44000, 46000 etc.**

## A Single Stage NPN "Class A" Amplifier

**The Class "A" amplifier varies the current to the load by increasing and decreasing its value around some nominal zero signal current. The circuit shown in the previous discussion is a "Class A" amplifier.**

**The Class "A" amplifier shown above uses the 47K (R1) and 15K (R2) resistors to set the base voltage. The 4.7K (R3) Resistor is called the "Load Resistor". The 1K (R4) Resistor or emitter resistor, is used to stabilize the current over a wide temperature range. If the 2N3904 transistor current started increasing due to heat the voltage drop on the 1K would increase, making the voltage from base to emitter smaller and thus turning the transistor current down. The 10uf capacitor connected to the base of the transistor is used to allow AC signals to pass to the base of the transistor while it blocks any DC voltage that could change the biasing voltage set for the base. The 10uf capacitor on the collector is used to block the DC on the output while it passes the amplified AC to the next circuit.**

## Measuring DC Bias Voltages with the Digital Meter

**To check the DC biasing of the Class "A" amplifier described previously, place a multimeter in the DC voltage mode and on the 20 volt range. Put the common lead on the ground run. All DC voltages will be measured with respect to ground. Measure and record the voltages $V_B$, $V_E$, $V_C$, and $B^+$ by moving the red voltage probe to the appropriate points.**

**Since the emitter resistor is a 1000 ohm resistor, the voltage across it equals the current through it in milliamps. In other words $V_E = I_E$ in ma. $I_E$ will be used later to calculate the AC & DC gain of the amplifier. The DC base voltage ($V_B$) should be approximately .7 volts higher than the emitter voltage (same as the little spring in the check valve analogy that holds the**

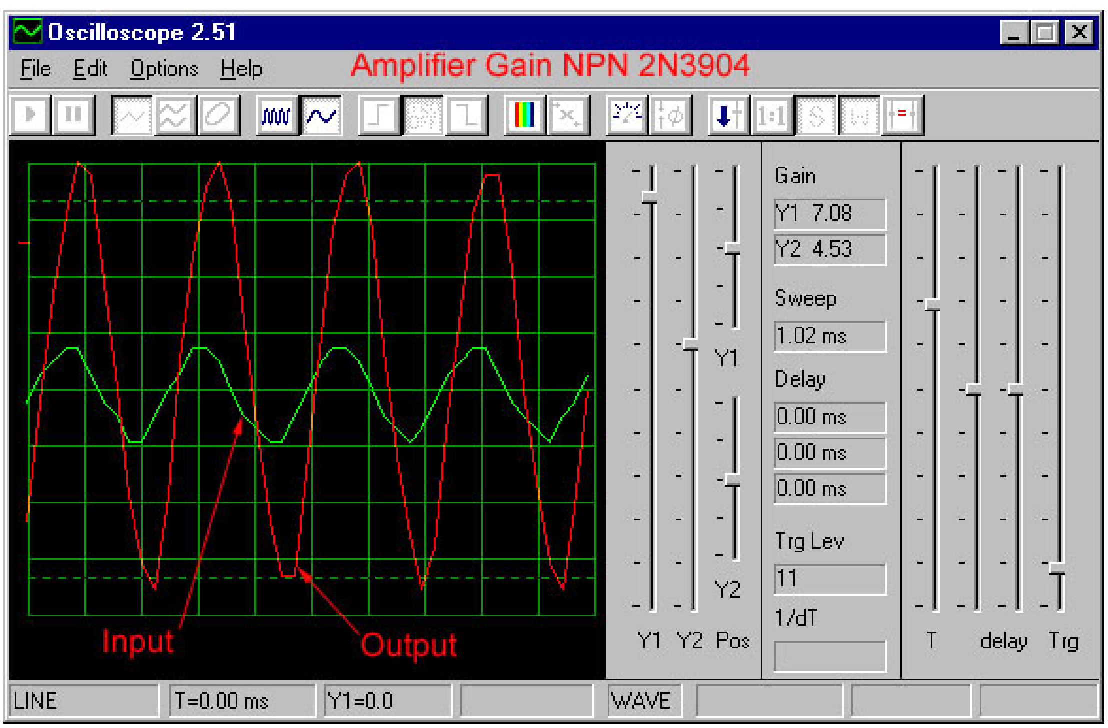
gate shut and takes .7 lbs. to push it open). A .7 volt drop is always a good approximation for a silicon diode junction that has current flowing through it. $V_C$ or collector voltage should be close to ½ the B+ reading. This allows maximum possible change in both positive and negative directions before clipping occurs.

## Measuring AC Voltage Gain with the Digital Meter

Using the circuit shown above, place an AC 1000 Hz generator on the capacitor going to the base of the transistor. Use a multimeter in the AC voltage mode on the lowest range. Adjust the generator output control to the minimum output position. Or find some way to reduce the generator output voltage to a very small signal. Measure the AC voltage ($V_{out}$) at the collector with the voltmeter on the 2 volt AC scale. Increase the generator output until the $V_{out}$ Equals 1 volt rms. Next measure the AC voltage on the base of the transistor without changing the generator control. Record this as $V_{IN}$. Divide the $V_{out}$ by $V_{IN}$ to get the AC gain of the amplifier. Some digital voltmeters are very inaccurate when reading low levels of AC voltages which can make this method less accurate.

## Measuring AC Voltage Gain with Oscilloscope.

Using the same circuit described above, a computer oscilloscope was connected to the input signal and that signal was stored with a green trace. The oscilloscope was then connected to the output signal and that signal was stored in red. The results are shown here.



**If you measure the peak to peak divisions for each signal and compare them you will find $V_{out}$ = 7.6 and $V_{in}$ = 1.8. In the above example the gain is calculated as $V_{out}$ / $V_{in}$ or 7.6/1.8 = 4.22. A quick rule of thumb for voltage gain ($V_{gain}$) of a class "A" stage similar to above is $V_{gain} = R_L / (R_E + R_e)$. Where;**

**$R_L$ = 4700 ohms**
**$R_E$ = 1000 ohms**
**And $R_e$ = 63 ohms**

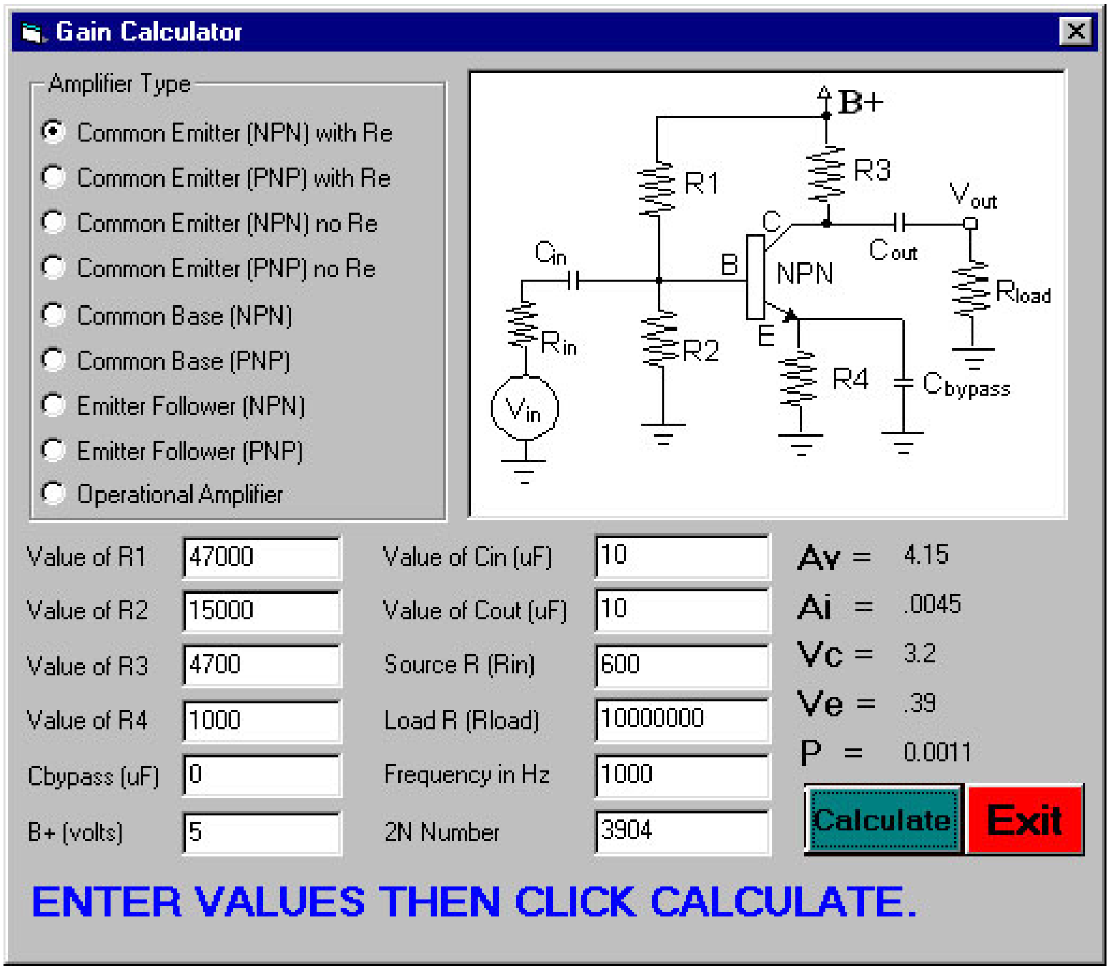
**Re is calculated as { 30 / (number of milliamps in base emitter diode) } + 3 ohms bulk resistance or 30 / .5 + 3 = 60 + 3 = 63 ohms.**
**This makes the calculated gain $V_{gain}$ = 4700 / 1063 = 4.42. The small difference between the calculated gain and the measured gain is due to the loading of the measuring equipment, and the accuracy of the measuring equipment and resistor values. The actual percent error is .2 / 4.42 or 4.5%.**

## Measuring DC Voltage Gain.

**A multimeter in the DC voltage mode was used to measure the DC at both base and collector of the transistor $V_{B1}$ & $V_{C1}$ and recorded. Then the 15K base biasing resistor was changed to a 16K resistor by adding 1K in series with it. The DC at both base and collector of the transistor was measured again and recorded as $V_{B2}$ & $V_{C2}$. The decrease in the DC voltage at the base of the transistor due to the addition of the 1K resistor is equal to $V_{B1}$ - $V_{B2}$ or $V_{IN}$. Notice the decrease in base voltage caused an increase in collector voltage. This type of amplifier causes a phase shift in the amplified signal of 180 degrees. In other words, if the input voltage goes toward ground (decreases), the output voltage goes toward B+ (increases). The DC change at the collector due to the decrease in base voltage is equal to $V_{C1}$ - $V_{C2}$ or $V_{OUT}$. The DC voltage gain equals $V_{OUT}$ divided by $V_{IN}$.**
**The AC voltage gain was found to be very close to the DC voltage gain for this amplifier.**

## Amplifier Gain Calculator

**A program called AmpGain.exe is available on the emailschool website under courses. Using this program you may calculate the gain for 9 different amplifier configurations. Make sure the resistor values, capacitor values, and transistor are the same as in each example and click the calculate button. Below is an example of what the calculator would show for a common emitter NPN amplifier with an emitter resistor.**

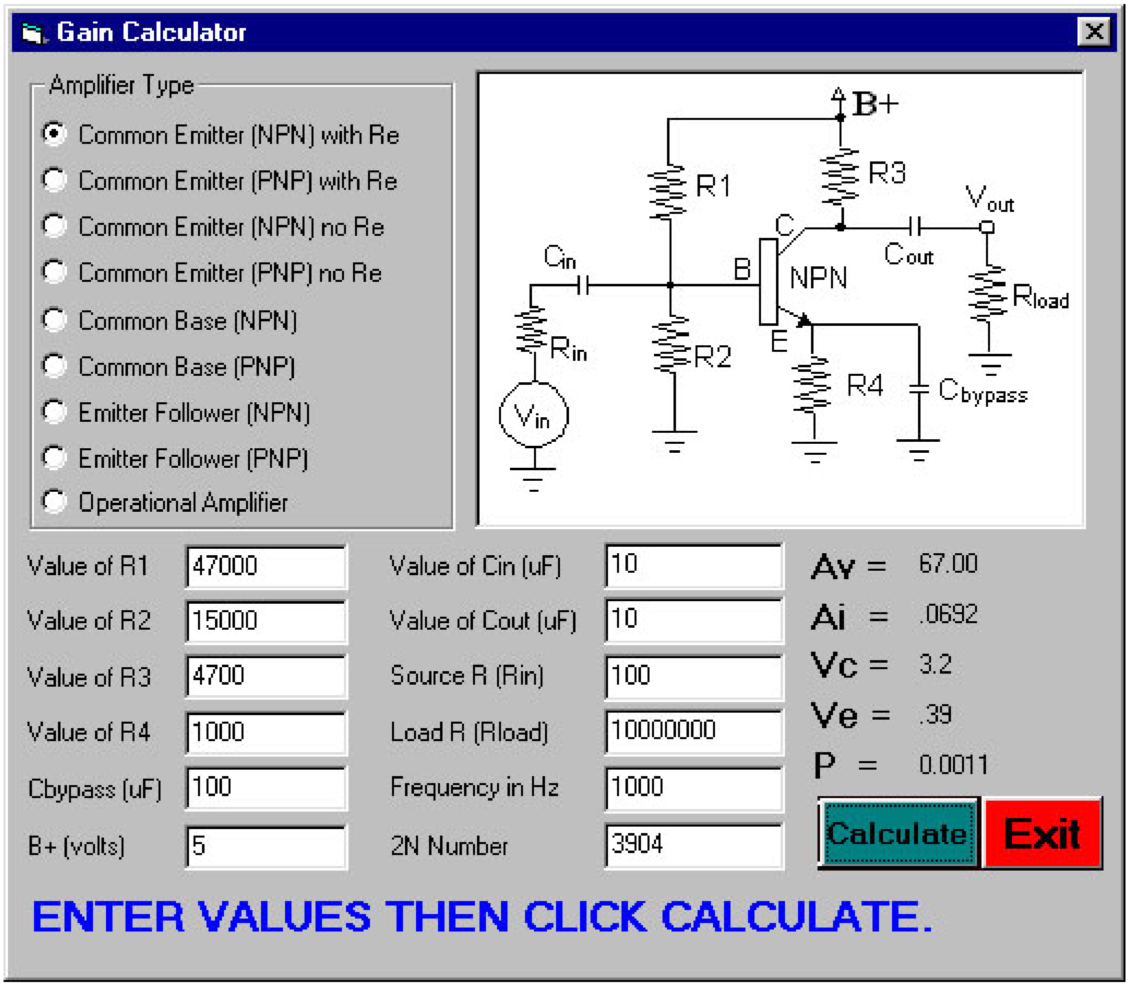



## Calculated Gain vs. Measured Gain

**When using the gain calculator on actual circuits, the differences between the calculated gain and the measured gain are due to the tolerances on electronic components and measuring inaccuracies. If the DC voltage on the collector of the transistor is different then the calculated values, use a multimeter to read the values of the resistors accurately and enter their values into the gain calculator. Also measure the value of the B+ voltage and enter that value into the gain calculator. The DC value of the voltage on the collector in each experiment should be within a few percent of the calculated voltage on the gain calculator.**

## Increasing AC Voltage Gain

**It is possible to increase the AC voltage gain and AC current gain by placing a capacitor in parallel with the emitter resistor. Repeat the previous exercise and calculate the voltage gain using the Gain Calculator (AmpGain.exe) with 100uf for the value of $C_{bypass}$. Compare the calculated gain to the previous amplifier with no bypass capacitor. The picture below shows the value of the voltage gain at 67.**




**This represents an increase in the AC voltage gain at 1000Hz of over 60. As the frequency is lowered toward DC, the voltage gain will start to drop and eventually equal the un-bypassed voltage gain.**

## Adding a Speaker.

**When a speaker is added to an amplifier's output you are able to hear signals that are very low in volts peak to peak. In this way very weak signals from microphones or radio detector circuits can be amplified and made audible.**

## Amplifier Bandwidth

**By subtracting the value of the low frequency where the voltage falls to .707 of the maximum value from the .707 high frequency, you calculate the amplifier Bandwidth. This is also called the 3DB Bandwidth or the half power Bandwidth. When the low and high 3DB points are measured with a voltmeter, the meter may give erroneous readings due to its frequency range. To insure the amplifier output is not overdriven into a square wave always take these readings at the lowest possible voltage level on the**

**meter. If possible use an oscilloscope and make sure clipping does not occur during the measurement.**

## Quick Review:

**Transistor:** **When two diodes are made atomically close to each other, a small amount of current into their center junction called the base will electronically open a channel that allows a large current to flow.**
**Collector:** **The diode gate that is forced off by a large reverse voltage.**
**Base:** **The junction of the two diodes in a transistor.**
**Emitter:** **The part of a transistor where base and collector currents meet.**
**Vbe:** **Voltage base to emitter on a transistor. In a silicon transistor one diode drop (Vbe) equals approximately .7 volts.**
**Vce:** **Voltage collector to emitter on a transistor.**
**Vcb:** **Voltage collector to base on a transistor.**
**Ib:** **Base Current**
**Ic:** **Collector Current**
**Ie:** **Emitter Current which equals the sum of the base current and the collector current.**
**NPN Transistor:** **A transistor made by tying the anodes together to make the base area.**
**Beta:** **Ratio of Collector Current to Base Current or measure of current gain in a transistor.**
**Transistor Switch:** **A single transistor can be switched from "ON" to "OFF" by simply changing the base voltage to produce base current.**
**Saturation Resistance:** **($R_{SAT}$ ) A measure of the amount of resistance in a transistor that is switched fully "ON".**
**Transistor Biasing:** **Biasing is setting the proper DC voltage levels for a transistor which sets the electrical current to the correct level and ensures proper operation of the circuit.**
**Class "A" Amplifier:** **The Class "A" amplifier varies the current to the load by increasing and decreasing its value around some nominal zero signal current.**
**Voltage Gain:** **The AC voltage gain of an amplifier is equal to $V_{OUT}$ divided by $V_{IN}$.**
**Gain Calculator:** **The program AmpGain.exe is a gain calculator for 9 different amplifier configurations.**
**AC Gain:** **It is possible to increase the AC gain in amplifiers by Proper placement of capacitors.**
**Amplifier Bandwidth:** **The range of frequencies between the half power points on an amplifier is called the amplifier's Bandwidth.**