Project Phase 1: Front End

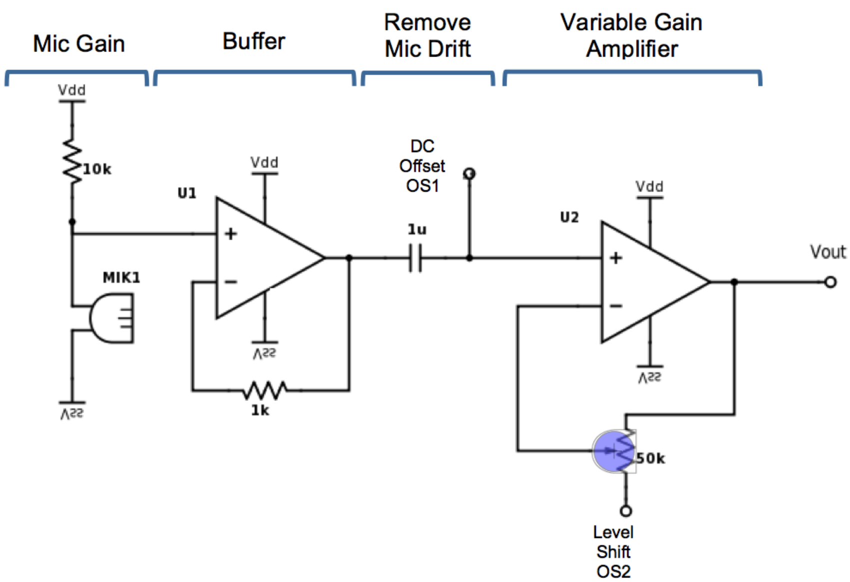
For the rest of this semester you will be designing SIXT33N, a mischevious little robot who *might* just do what you want - if you design it correctly. In this phase, **you will be desiging SIXT33N's ears**: a microphone front end circuit that processes the mic signal into something you can record using the Launchpad ADC.

The goals of this phase are as follows:

- Construct a band pass filter circuit
- Construct a level shift + gain circuit for ADC
- Construct motor controller circuits
- Prepare to use batteries to power SIXT33N

Part 2: Microphone Biasing Circuit

Our biasing[1] circuits will provide signals for the OS1 (DC Offset) and OS2 (Level Shift) pins of the mic board. Before we build the biasing circuits, let's take a closer look at our mic board. The mic board contains the following circuit:



- **Microphone Gain:** The electret microphone behaves as a *variable current source* depending on the size of the sound waves hitting it. Current signals are generally more difficult to work with than voltage signals, so you will turn that into a voltage signal using the Mic Gain part of the circuit.
- **Buffer:** This buffer helps keep the amplifier and the capacitor from affecting the microphone (see Note 4 for a review of loading). It looks a little different from the buffers we usually use (there's a resistor in the feedback loop), but it functions just the same.
- **Remove Mic Drift:** A capacitor placed between one circuit stage and the next is usually called a coupling cap, but it really just a high pass filter with a very low cutoff frequency. The microphone naturally has a lot of low frequency drift, so we use this coupling cap to remove any DC offset and noise. This allows us to ignore whatever DC value the mic gain stage had, and add in a suitable DC value in the next stage.

[1] "Biasing" a circuit means establishing predetermined voltages or currents at various points of the circuit in order to construct the proper operating conditions for the components [Wikipedia].

- **DC Offset:** For this project, **you will not have a negative power source**, only your 5V rail and ground (since the Launchpad cannot take negative voltage inputs). If you center your signal around ground, like we did in previous labs, then you will lose the negative half the signal as soon as you send it through the op-amp because your op-amp won't be able to supply those negative voltages (since all your op-amps' V_{SS} pins will be set to ground). To get around this problem, we want to center our signal in the center of our available voltage range.

  However, you will have to be careful and remember that a DC offset exists or it could become troublesome. Think of a 0.1V DC signal. Now put that signal through a non-inverting op-amp with a gain of 100 and a reference voltage of 0V. Suddenly that 0.1V DC signal becomes 10V!

- **Level Shift:** When we introduce the DC offset at OS1, we have to adjust our amplifier to expect signals centered around that offset. We will explain this further in the next part.

- **Amplifier:** Finally, the mic board uses a non-inverting amplifier (with a potentiometer) to amplify the microphone signal. Note that OS2 is on the inverting terminal of the op-amp - we can use this to help us deal with our DC offset problem.

Now, let's move **off** the mic board and focus on our biasing circuits.

- **OS1: DC Offset**

  Because we need our signal to be centered in our usable range (0 - 3.3 V), we will need to set the DC offset to the midpoint of this range: 1.65 V. This can easily be accomplished with a voltage divider of two equal resistors from the 3.3 V rail to ground.

- **OS2: Level Shift**

  When we introduce the DC Offset, we will encounter a problem when the signal passes through the non-inverting amplifier: that DC offset will be amplified along with the rest of the signal! This is because the amplifier will amplify the signal as referenced from *ground*. This is the key problem here.

  > If we want to avoid amplifying the DC offset, what value should we use for the amplifier's reference voltage?

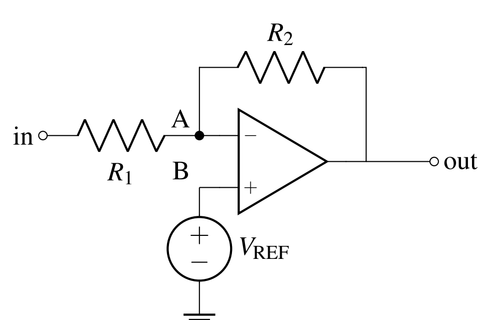
  If you guessed 1.65 V, congratulations! This is the key idea to a level-shifter.

  Recall that we connected OS2 to ground when we built color organ - this is how we told the non-inverting amplifier to use ground as a reference. To use 1.65 V instead, **we will need to connect OS2 to a non-zero voltage**. This voltage will need to match the DC offset we introduce to OS1.

  However, we have another problem: our resistors can vary by up to 5%. This means it will be very unlikely that we can find two matched pairs of resistors so both OS1 and OS2 will be at exactly the same voltage. To overcome this issue, we put a buffer between the OS1 and OS2.

  Refresher from lab note 1: Reference voltage (for amplifiers)

  We will discuss here how to set a reference voltage for inverting and noninverting amplifiers. Let's start with the inverting amplifier.



From the first golden rule, we know the fact that node B is at V_{REF} means that node A is as well. From the second, we have the equation

$$\frac{V_{\text{out}} - V_{\text{REF}}}{R_2} = \frac{V_{\text{REF}} - V_{\text{in}}}{R_1}$$

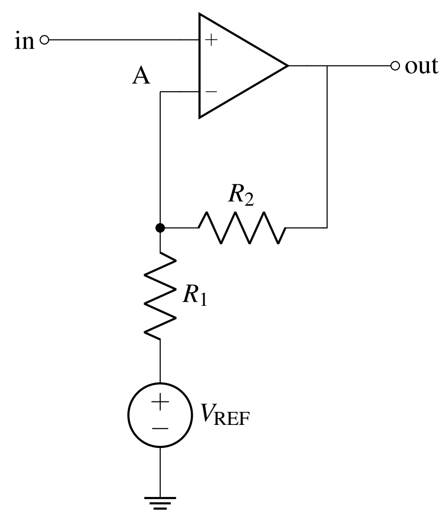
Let's perform a change of coordinates. Let $V_{\text{in}*} = V_{\text{in}} - V_{\text{REF}}$ and let $V_{\text{out}*} = V_{\text{out}} - V_{\text{REF}}$. Then, we have

$$\frac{V_{\text{out}*}}{R_2} = \frac{-V_{\text{in}*}}{R_1}$$

$$\frac{V_{\text{out}*}}{V_{\text{in}*}} = \frac{V_{\text{in}} - V_{\text{REF}}}{V_{\text{out}} - V_{\text{REF}}} = -\frac{R_2}{R_1}$$

Therefore, we're amplifying the difference between V_{in} and V_{REF} with respect to the difference between V_{out} and V_{REF}, which is what we wanted to achieve: we have essentially set the virtual ground for the amplifier to V_{REF}.

The process for the noninverting amplifier is similar.



From the first golden rule, we know $V_{\text{A}} = V_{\text{in}}$, so we can write

$$\frac{V_{\text{out}} - V_{\text{in}}}{R_2} = \frac{V_{\text{in}} - V_{\text{REF}}}{R_1}$$

Now, we'll perform the same change of coordinates: letting $V_{\text{in}*} = V_{\text{in}} - V_{\text{REF}}$ and let $V_{\text{out}*} = V_{\text{out}} - V_{\text{REF}}$, we have

$$\frac{V_{\text{out}*} + V_{\text{REF}} - V_{\text{in}}}{R_2} = \frac{V_{\text{in}*}}{R_1}$$

Substituting $-V_{\text{in}*}$ for $V_{\text{REF}} - V_{\text{in}}$, we have

$$\frac{V_{\text{out}*} - V_{\text{in}*}}{R_2} = \frac{V_{\text{in}*}}{R_1}$$

$$\frac{V_{\text{out}*}}{R_2} = V_{\text{in}*}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$\frac{V_{\text{out}*}}{V_{\text{in}*}} = 1 + \frac{R_2}{R_1}$$

So, once again, we set the amplifier's virtual ground to V_{REF} in order to amplify the difference between V_{in} and V_{REF} with respect to the difference between V_{out} and V_{REF}.

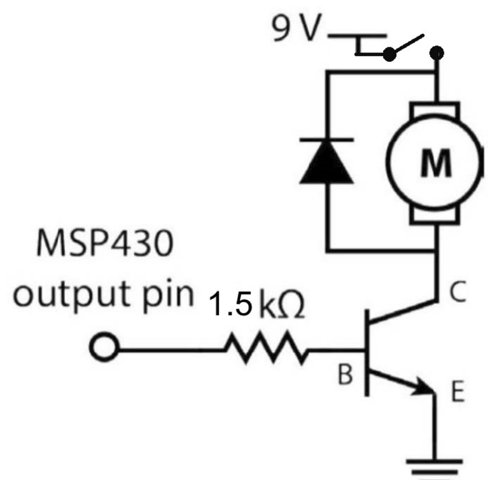
You are now ready to start Part 2! Go to the Jupyter Notebook and complete parts 2 and 3 of the lab.

Part 5: Motor Drivers

S1XT33N uses 9-Volt DC motors. This means the maximum voltage that can be delivered to the motors is 9V, but the motors will move (albeit more slowly) with voltages less than 9V. There is some minimum voltage required to deliver enough power to the motors to overcome the static friction and start them, but after that point, we treat the motor speed as approximately linear with the applied voltage (this will be the basis of the system model you develop in next week's lab).

Because it is difficult to use the Launchpad to control a true DC signal, we will instead make use of its PWM function. A PWM, or pulse-width modulated, signal is a square wave with a variable duty cycle (the proportion of a cycle period for which the power source is turned on). PWM is used to digitally change the average voltage delivered to a load by varying the duty cycle. If the cycle period is small enough, the on-off switching is imperceptible, but the average voltage delivered to the load changes proportionally with the duty cycle. Hence, changing the duty cycle corresponds to changing the DC voltage supplied to the motor.

We will use the Launchpad's PWM pins to set the duty cycle for each motor's PWM signal. However, the Launchpad's logical HIGH[2] voltage is 3.3V, which is not enough do directly drive the motors: even if your motor does turn on at 3.3V when you test it with the power supply, the Launchpad cannot supply enough current to power the motors. This is where the motor driver circuits come in.



The PWM pin from the Launchpad is connected via a resistor to the base of an NPN BJT (bipolar junction transistor). This transistor behaves differently from the NMOS with which you are familiar, but you can still consider it a switch in this application. The low-power, low-voltage signal from the Launchpad switches the BJT on and off: when the Launchpad signal is HIGH, the BJT is on and the motor circuit is grounded so that we have 9V from the power supply (or later, the motor battery) across the motor and current can flow through the motor and BJT, whereas when the Launchpad signal is LOW, the BJT is off and the motor is not connected to ground, so the circuit is open and no current flows through the motor. Therefore, the motor driver circuit supplies the motor with a high-power PWM signal.

You are now ready to start Part 4! Go to the Jupyter Notebook and complete the rest of the lab.

Appendix A: Electronics Glossary

In this appendix, we will elaborate upon terms we mentioned in the note whose explanations are too long to fit comfortably in a footnote. **PLEASE NOTE: if this material was not mentioned in lecture, it is NOT IN SCOPE, so do not panic if it seems complex.** It is just here to give some additional background to the lab if you would like some.

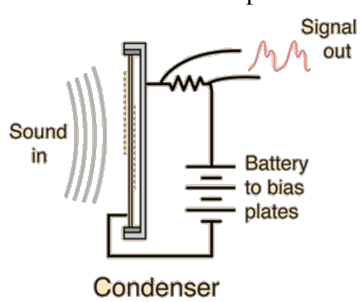
[2]The logic-level signals are denoted as HIGH and LOW, where HIGH=3.3V and LOW=0V for the Launchpad.

- **Electret microphone:** First, we will address the term "electret," and then we will discuss how the electret's properties are exploited to make a microphone.

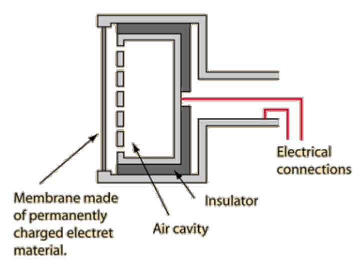
  An electret is a permanently[3] charged material (usually a piece of plastic). The term "electret" comes from the fact that an electret is the electrostatic equivalent of a permanent magnet: while in a permanent magnet, the magnetic field is generated by the natural alignment of the electrons' spins within the atoms of the material, the electrostatic field generated by the electret is created either by embedding additional negative charges within the material or by melting a suitable dielectric material and cooling it inside a strong electric field: while the material is liquid, the polar molecules (dipoles) align themselves with the electric field so that when the material cools, they are "frozen" in position, producing a dipole electret with a permanent electrostatic alignment or "bias". Just as there exist natural magnets, there also exist natural electrets: for example, quartz is a naturally-occurring electret.

  The electret microphone is a variation of the condenser microphone. A condenser microphone is essentially a sound-sensitive capacitor: it consists of a pair of charged plates (one flexible, one rigid) that can be forced closer by variation in air pressure. A sound wave is a pressure wave, so when the sound wave hits the flexible plate, it is pushed back toward the rigid plate, thereby changing the capacitance (recall, from physics, that the capacitance C of a parallel plate capacitor is given by the equation $C = \frac{\kappa\varepsilon_0 A}{d}$, where d is the distance between the plates, A is the area of one plate (assuming both plates have the same area), ε_0 is the permittivity of free space, and κ is the dielectric constant of the material between the plates.) and therefore the voltage between the plates.

  Condenser Microphone

  Electret Microphone

  While the condenser microphone requires an external voltage source to charge the diaphragm (the flexible plate), the electret microphone does not (because the electret has a permanent charge). In traditional electret microphones, the diaphragm is replaced by the electret, but this makes the diaphragm heavier and therefore less sensitive to sound waves, so most modern electret microphones attach the electret to the conductive backplate instead. Most electret microphones have a small transistor amplifier built into their packages, and this amplifier (like an op-amp) needs to be powered to work, so even though electret microphones do not require active biasing, most of them are still active components.

- **Bipolar Junction Transistor (BJT):** We will give a very minimal introduction to the BJT. This material is VERY out-of-scope, and the device physics is greatly simplified; the version of this material taught in EE 105 is much more in-depth/nuanced, so take that course if this piques your interest :).

  Like a FET (field-effect transistor, e.g. CMOSFET, JFET), a BJT can act as a switch or an amplifier. In this introduction, we will only address the switch application (but you can learn about the amplifier application in EE 105, EE 140, etc.).

  The BJT is a three-terminal (base, collector, emitter) device in which applying a small current to the base allows a larger current to flow between the collector and emitter. Like the MOSFET, it comes in two types, except for instead of NMOS and PMOS, those types are NPN (negative-positive-negative) and PNP (positive-negative-positive). These names come from the fact that a BJT is essentially made of three layers of semiconductor material: in the NPN case, one layer of positively-doped (p-type) material is sandwiched between two layers of negatively-doped (n-type) material.

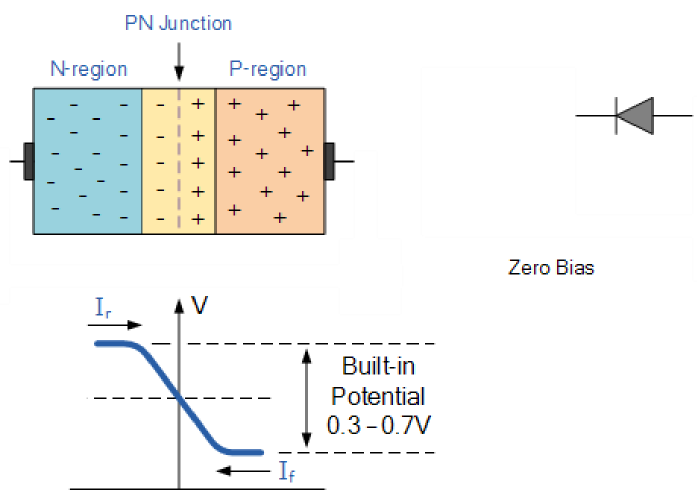
[3] Technically, quasi-permanently: see the Wikipedia article on electrets for more explanation.

A brief detour: diodes

Diodes[4] are also semiconductor devices, except they have only two layers (one each of p-type and n-type) instead of three.

We will define two kinds of charge carriers: electrons carry negative charge, and holes carry an equal and opposite (positive) charge[5]. The p-type material has excess holes, and the n-type material has extra electrons.

Let's examine how this device behaves in its open circuit condition (i.e., its terminals are not connected to anything). As you might have guessed, the electrons and the holes are attracted to each other, so as they diffuse across the junction, they recombine and neutralize each other, forming a depletion region around the junction.

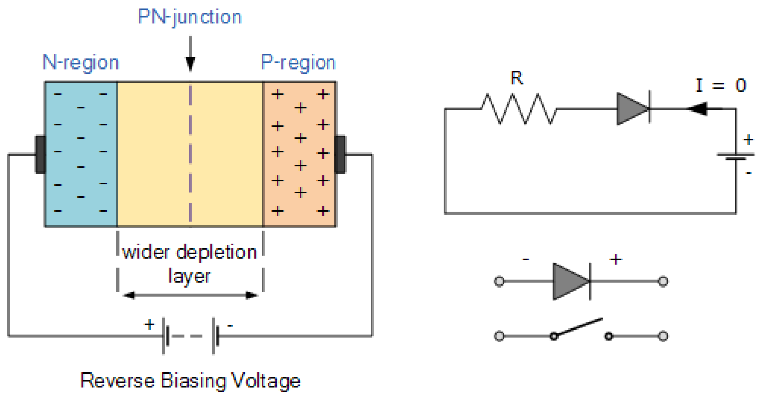


When a hole diffuses from the p-side to the n-side, it quickly recombines with one of the majority electrons on the n-side and disappears; as this continues to happen, the n-side depletion region loses its free electrons. When an electron is freed from its parent atom and then neutralized by a hole, the parent atom becomes positively charged: therefore, the depletion region on the n-side is positively charged. Similarly, the depletion region on the p-side becomes negatively charged. This creates a potential difference across the depletion region, known as the **barrier voltage**, which the carriers must overcome to continue to diffuse across the depletion region. As the depletion region grows, so does the barrier voltage, making it more and more difficult for more carriers to diffuse across the depletion region. With no voltage source connected across the terminals, the currents of electrons and holes are equal in magnitude and opposite in direction.

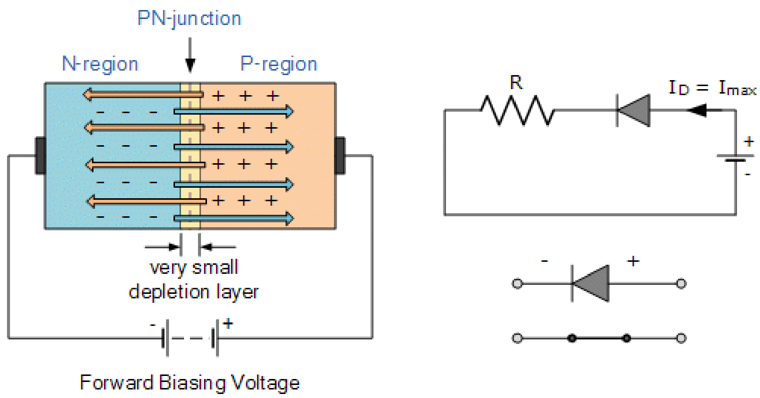
So, did we just break the first law of thermodynamics? Didn't we just generate a voltage out of thin air? Not quite. The voltage we have been discussing is the voltage *across the depletion region*, not across the junction terminals. Actually, the contact voltages at the metal-semiconductor junctions at the device's terminals perfectly balance out the barrier voltage so that when you measure the voltage across the open-circuited diode's terminals, you will read a voltage of 0V.

Now that we have explored the p-n junction diode's open circuit behavior, we are ready to see how it performs under an applied voltage. If we apply the voltage across the diode so that the p-side terminal is more positive than the n-terminal, the diode is said to be **forward-biased**, whereas if we apply the voltage so that the n-side terminal is more positive than the p-terminal, we say the diode is **reverse-biased**.

[4] It is important to note that not all diodes are made this way; however, this is the classical example.
[5] If you would like some additional background on this abstraction, see here.



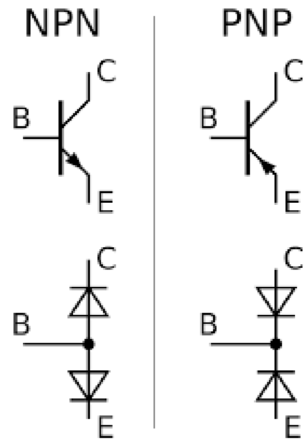
In the reverse-biased case, the external voltage is applied in the same direction as the barrier voltage, so it adds to the barrier voltage, making the effective barrier voltage the sum of the open-circuit barrier voltage and the applied voltage. This makes it much more difficult for electrons and holes to diffuse across the depletion region, so the device allows only a very small amount of current to flow: for the ideal diode abstraction, we consider this current to be 0.



In the forward-biased case, the external voltage is applied in the opposite direction as the barrier voltage, so it *subtracts* from the barrier voltage, greatly reducing the effective barrier voltage. This allows electrons and holes to diffuse more freely across the depletion region and therefore enables a substantial current to flow through the device. Since our voltage/current convention says that current flows from high voltage to low, we conclude that the current flows from the p-side to the n-side.

Back to BJTs

Now that we've been introduced to the underlying physics of the p-n junction diode, we can see that an NPN BJT is essentially two diodes connected back-to-back, where the base is connected to the p-region (shared by both diodes) and the emitter and collector are each connected to one of the n-regions:



Let's now explore how we can bias this component so we can use it as a switch. We want the current between the collector and the emitter to be controlled by the current between the emitter and the base.

Let's see how we can bias the BJT so that it does not conduct; i.e., so that the switch is off[6]. We will set the voltage at the base to be equal to the voltage at the emitter, and we will set the collector voltage to a significantly greater value. This reverse-biases the collector-base diode so that essentially no current can flow through it. Even though the base-emitter diode is not technically reverse-biased, (1) the fact that the collector-base diode is reverse-biased means essentially no current reaches the base anyway, and (2) the fact that the base and the emitter are at the same voltage means that there is no potential difference between them to incite current flow.[7]

Now, let's see how we can bias the BJT to turn it on[8]. We want both diodes to be forward-biased, so we will set the base voltage to be higher than both the emitter and the collector. Notice that the collector in our circuit is not connected to 9V but rather to the motor: almost all of the 9V is dropped across the motor, so even though the 3.3V at the base is much lower than 9V, the base voltage is still higher than the voltage at both the emitter and the collector, so both diodes are still forward-biased.

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[6]If you look this up to explore further, we are trying to operate the BJT in cutoff mode.

[7]Note that technically, the condition for the BJT to be in cutoff is that both the collector-base and base-emitter diodes are reverse-biased. We used the example of reverse-biased collector-base diode and unbiased base-emitter diode because that is how our actual motor controller circuit works.

[8]If you look this up to explore further, we are trying to operate the BJT in saturation mode.

Nave, R. (2000). *Microphones*. [online] Hyperphysics.phy-astr.gsu.edu. Available at: http://hyperphysics.phy-astr.gsu.edu/hbase/Audio/mic.html [Accessed 6 Oct. 2019].

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Notes written by Mia Mirkovic (2019)