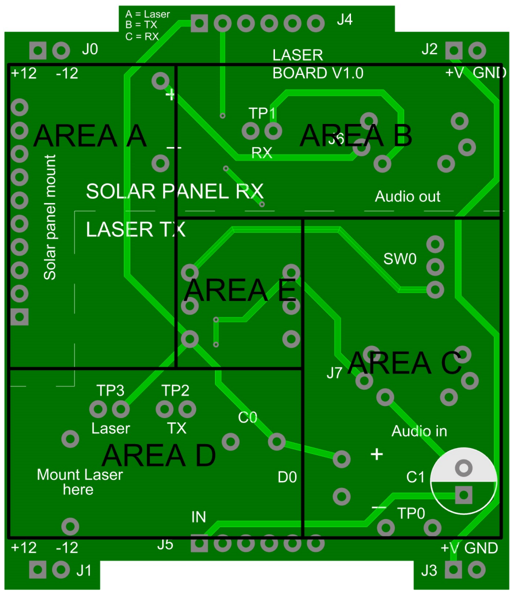
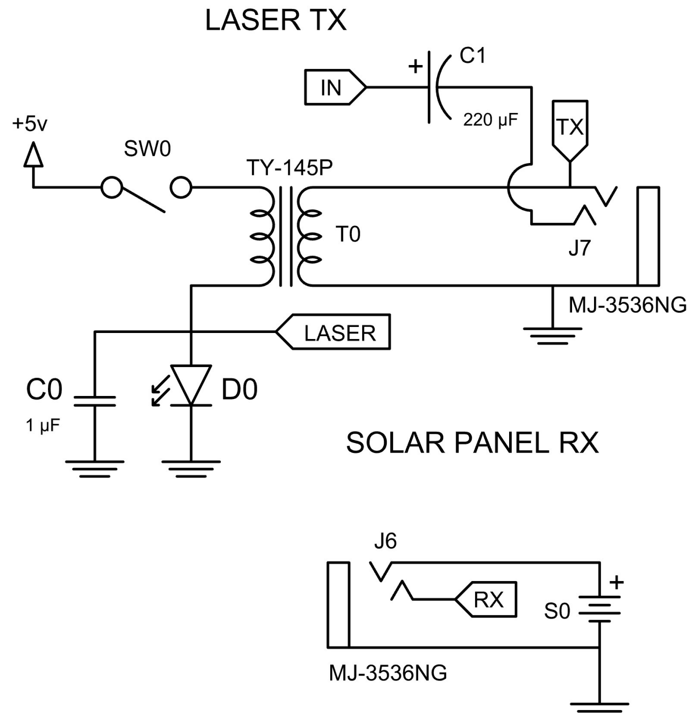
Massachusetts Institute of Technology
Electromechanical Systems Group

Electronics First: TRANSFORMERS

Board and **Circuit Schematic:**



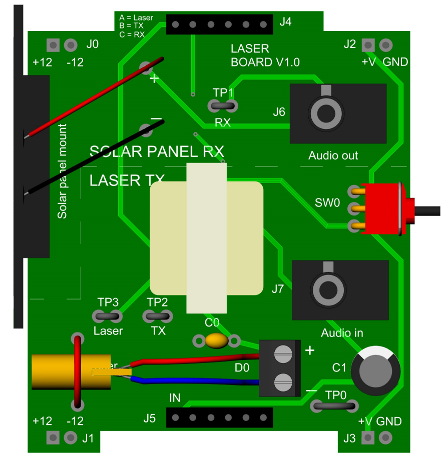


Materials:

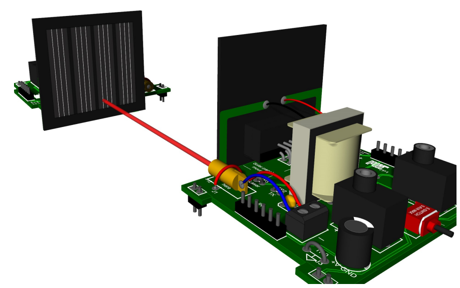
Part	Quantity	Part Number	Vendor	Part	Quantity	Part Number	Vendor
Breadboard	1	377 − 2646 − *ND*	DigiKey	Audio Jack	2	*WM*17366 − *ND*	DigiKey
Breadboard Power Supply Module	1	-	-	C_0 1 μF Capacitor	1	399 − 13923 − 1 − *ND*	Digikey
Multimeter	1	*MN*35 − *ND*	DigiKey	C_1 220 μF Capacitor	1	493 − 12562 − 1 − *ND*	DigiKey
6-pin Header	2	609 − 3263 − *ND*	DigiKey	10-pin Header	1	*S*7008 − *ND*	DigiKey
2-pin Rail Connector Pins	4	952 − 2262 − *ND*	DigiKey	2-position Terminal Block	1	*ED*1514 − *ND*	DigiKey
Micro USB Power Cable	1	102 − 4123 − *ND*	DigiKey	Laser Switch	1	*EG*4912 − *ND*	DigiKey
Soldering Iron and Solder Wire	1 ea	*T*0052918199*N* − *ND*	DigiKey	Solar Panel	1	*B*079452*SKC*	Amazon
Audio Transformer	1	237 − 1121 − *ND*	DigiKey	Diode Laser	1	*B*01*ITK*4*PEO*	Amazon

The Build:

Lasers are devices that can use electrical energy to emit concentrated, directed beams of light. They have a *wide* variety of uses. In this build, we will use a laser diode, like the kind you might find in a lecture hall laser pointer, to create a transmitter that can use a beam of light to send music to a receiver across a room. We will make a receiver from a solar cell. The transmitter and receiver, or transceiver set, can modulate the laser beam with a data source such as a music signal from an MP3 player. When the beam strikes the receiver solar cell, you will be able to hear the transmitted music on an earphone or audio amplifier board. Magic! To create the practical magic of a laser transceiver set, you will learn about **transducers** and **transformers**. These devices are essential tools in any engineer's arsenal for controlling and shaping the flow of energy.



The finished product


Transceivers in use

Energy is not always available in a useful way. Engineers design machines to convert energy from an available form to another form more suitable for a particular application. Think about different applications that use energy: moving a speaker to push air and make sound, heating a resistor to boil water in an electric kettle, and turning a shaft with a motor to grind coffee, as examples. Each of these applications expends energy in a particular way that we might call a *domain* of application. The domain might be defined by the "push" and "flow" variables that we use to track power in that application. The speaker delivers energy from the electrical domain to an acoustic or pneumatic domain. The resistor absorbs electrical energy and delivers it to a thermal domain. The motor delivers energy to a domain of rotary motion. As discussed for previous builds, power might be computed as the product of force and velocity in a linear mechanical domain, as the product of torque and angular velocity in a rotary mechanical domain, as the product of voltage and current in the electrical domain, and so on.

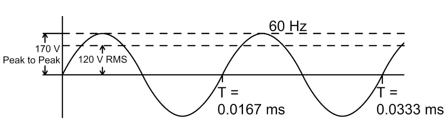
Transducers are machines that convert energy from one domain to another. A motor converts energy from electrical to mechanical. A microphone converts energy from acoustic to electrical. A speaker converts energy from electrical to acoustic. And a resistor converts energy from electrical to thermal. All of these devices – motor, microphone, speaker, resistor, and many others – might be called transducers.

Ignoring nuclear interactions, where energy and matter can be converted from one to the other, energy is always *conserved*. This observation is sometimes called the "First Law of Thermodynamics." Essentially, in the vast majority of engineering applications, energy is neither lost nor gained, but rather transferred from one form to another. We can track this flow and find that energy delivered to a system must be either stored in the system or transmitted from the system. A careful accounting always reveals that the net energy flow summing in to, and out of, and stored in, a system is zero. So, for a "perfect" motor, for instance, the electrical energy that flows into the motor must equal the rotary mechanical energy that leaves the motor. Said another way, the product of voltage times current into the motor should ideally equal the product of torque times angular velocity out of the motor.

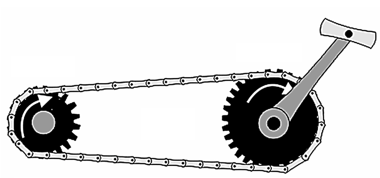
In real life, this never happens. There are always imperfections in the conversion process, an observation implicit in the "Second Law of Thermodynamics." These imperfections do not alter the fact that energy is conserved. But they do complicate the accounting to demonstrate conservation. For example, electrical energy delivered to our motor produces mechanical energy at the shaft as rotation. However, this input energy also produces "loss," or undesired energy expenditures, e.g., resistive heating in the windings of the machine, and acoustic noise as the rotor turns and whips the air, and so forth. Engineers often use the notion of *efficiency* as a figure-of-merit to quantify how perfectly a machine converts available energy to another desired form. A common definition of efficiency is the power "out," or delivered by a machine in the form we wanted,

We construct a laser "radio" or transceiver in this build. The board transmits music using a laser diode and receives the laser light on a solar cell. (Transmitter + Receiver = Transceiver) You can connect a special headphone, or your audio amplifier board, to the solar cell to hear the music. With two of these boards, you can set up simultaneous two-way communication, sometimes called *full duplex*, across long distances by aligning the laser on each board to "hit" the solar cell on the distant board. The laser and solar cell are important, but the heart of this build is an electrical component called a **transformer**.

“Wall” outlet provides 120 V RMS ac voltage between the “Hot” and “Neutral” connections.



Voltage waveform



Gears and chain, a mechanical transformer

divided by the power “in”. For the motor, efficiency might be defined as shaft mechanical power (torque times speed) divided by input electrical power (voltage times current). The first law of thermodynamics tells us that efficiency can be at most one, and the second law of thermodynamics implies that the practical efficiency will be less than one. There are always losses.

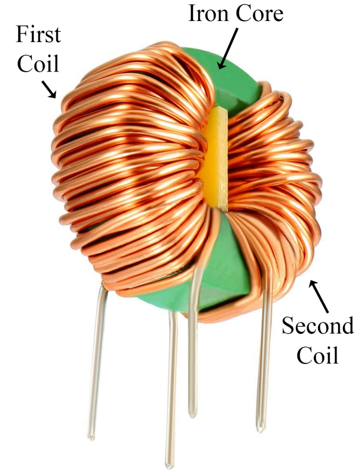
Within a single domain of application, energy may still not be available in the most useful form for a particular task. For example, a “wall plug” connection in North America typically provides a sinewave of voltage with a peak of 170 volts. It is common to refer to this sinewave amplitude by dividing the peak by the square root of two. For a sinewave with a peak of 170 volts, this division gives a new “root mean square” amplitude of 120 volts “RMS”. The RMS amplitude is helpful because the RMS AC voltage of 120 volts produces the same power dissipation in a resistor as would a 120 volt DC source. The sinewave oscillates at 60 Hz, or up-and-down 60 times a second. A typical residential or office wall outlet is able to provide current up to 15 amps (RMS). These numbers might be perfect for some applications, e.g., powering a “classic” incandescent lamp. Other applications might need a different voltage. For example, a soldering iron has a resistive tip with a relatively low resistance. The tip typically needs a voltage much lower than 120 volts RMS, instead possibly 20 or 10 or even as low as 2 or 3 volts depending on the soldering iron tip design. Applying 120 volts RMS directly to the tip would cause a disastrous overcurrent to flow.

Transformers resolve the mismatch between the available energy in a particular domain and the needed form of energy in the same domain. Many domains have devices that can serve as transformers. In the rotary domain, a *gearbox* serves as a transformer that, for example, matches the high-speed rotations of an electric motor to the lower speed rotation of a scooter wheel. The “gear ratio” defines the relationships between the push and flow variables. Torque that is increased by the gear ratio will be exactly balanced by speed that is decreased by the gear ratio, so that power flowing into the ideal “transformer,” or gearbox in this case, is precisely balanced by power flowing out. For a rotary system, power is the product of torque and speed. In the scooter with an ideal gearbox, the electric motor experiences a lower torque, higher speed shaft connection and the scooter wheel receives relatively higher torque and lower speed at the same power level.

A lever is another example of a mechanical transformer.

An electrical transformer is an analog of a mechanical transformer like a gearbox. The electrical transformer consists of two electrical coils sharing a magnetic field. The “turns-ratio” of the electrical transformer is the number of turns in one coil compared to the number of turns in the other coil. The turns-ratio is analogous to the gear ratio. Like the ideal gearbox, the ideal electrical transformer dissipates no energy and stores no energy. It simply converts the flow of energy from a “primary” side with a particular set of push (voltage) and flow (current) variables to the same flow of energy on the “secondary” side, but with different voltage and current variables.

There are some caveats for using a practical electrical transformer. The transformer only works for "alternating currents" or AC, as opposed to "flat" or "direct current" or DC. "Faraday's Law" requires a time-varying magnetic field to induce electrical activity in a neighboring coil. Practical transformers have other limitations. Like friction in a practical gearbox, each transformer winding has some resistance. So practical transformers, like practical gearboxes, consume some energy (losses) when used. Practical transformers have finite inductance, so they also store some energy internally instead of transferring all energy to the secondary side, just as gears in a gear box have mass and store some kinetic energy.



Electrical transformer. Each coil is analogous to a mechanical gear, and the core carries magnetic flux, analogous to the mechanical chain.

The electrical transformer in the laser transmitter for this build has a "one-to-one" turns ratio, analogous to a gearbox with a one-to-one gear ratio. Why would we bother to pay for and use a one-to-one transformer? Essentially, the one-to-one transformer acts as an electrical "photocopier." It copies the signal on its primary side, e.g., an AC music signal from an MP3 player, and reproduces the signal on the secondary side. Each circuit retains its own distinct electrical ground. Only the needed information, the music, is copied and transferred from the transformer primary to the transformer secondary.

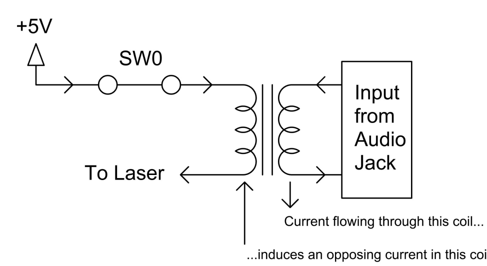
So a transformer can serve at least two useful roles for a designer. First, the transformer might change the push and flow variables to a more favorable set of values at the same power level. Second, the transformer may offer a new ground or "isolation" from the primary source of power. In our circuit for this build, we take advantage of the transformer isolation, or the fact that the transformer secondary is "floating," to inject a music signal into a laser transmitter.

"Wall" transformer converts 120V RMS ac to a lower ac voltage (Some "wall transformers" also have additional circuitry to turn the final output voltage into dc and to regulate or control the output voltage.)

Theory of Operation

THE "LASER TX" SCHEMATIC ON THE COVER SHOWS HOW THIS WORKS. The switch **SW0** turns the laser transmitter on or off by connecting or disconnecting the 5-volt source. Notice that the 5-volt source is not directly connected to the laser D_0. When the switch is on, the 5-volt source is connected in series with the secondary of the transformer **T0**.

Since the transformer secondary is "isolated" or "floating," we have a lot of flexibility in deciding how to connect it. Specifically, it is not necessary that the secondary be connected to ground. Together, the 5-volt DC source in series with the AC transformer secondary create a combined source with a "flat" or DC part plus a "wiggly" or AC part. The transformer action creates this AC part from the music signal injected by the audio jack **J7** into the primary of **T0**.



Injecting signals with a transformer

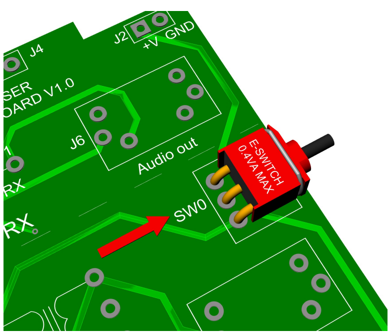
By itself, the 5 volts would create a beam of laser light with relatively constant brightness. The smaller, AC voltage from the transformer secondary makes the laser light slightly brighter or a little darker depending on whether the music signal is positive or negative. Wiggling or varying the otherwise constant laser light output is sometimes called "modulating" the laser light. Variation in the brightness of the laser beam carries the audio signal through space.

A solar cell can extract the audio signal from the laser light. The solar-cell receiver circuit, shown as "Solar Panel RX" on the cover schematic, is deceptively simple. The solar cell S_0 behaves as a light-dependent source of current. More light striking the cell will allow it to deliver more current; less light reduces the available current. In the receiver circuit, the solar cell is connected to an audio jack **J6**. A high-impedance earphone (not shown in the cover schematic) is a special kind of earphone that can operate with relatively low currents compared to other headphones. You can plug a high impedance earphone into the audio jack.

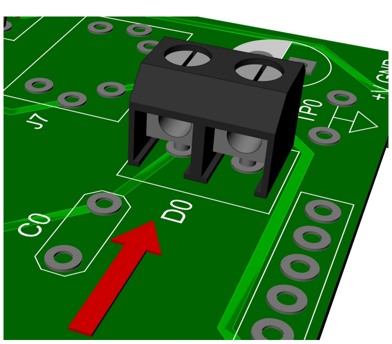
The earphone is a transducer that converters electrical energy into audio or pneumatic energy. The solar cell is a transducer that coverts light energy into electrical energy.

Remember that the transmitted laser light contains DC and AC components. When the laser light strikes the solar cell, a DC or steady component of voltage is established across the headphone. This DC signal does not cause the headphone to move back and forth, so no air is pushed or moved, and this component of the laser light makes no sound. The AC or flickering part of the laser light moves a mechanical element back and forth in the earphone. This motion, due to the audio signal injected in the transmitter circuit by the transformer, *does* move air, creating a motion that our ears detect as sound. We could also unplug the earphone and directly connect the "**RX**" signal to an audio amplifier board, which would have a similar effect of making audio sound, but louder than the earphone because of the amplification.

Assembly



Laser Switch Location



Terminal Block Location

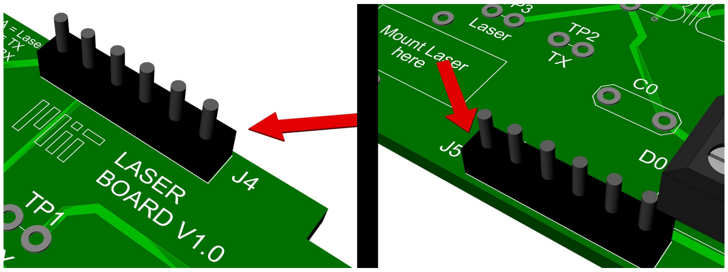
THIS BUILD INTRODUCES THREE NEW COMPONENTS: A LASER, A SOLAR PANEL, AND A TRANSFORMER. For orderly assembly, the board has been divided into separate areas. These are shown in a diagram on the cover page.

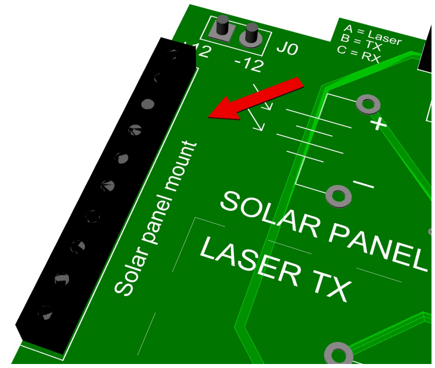
Begin by installing the laser switch in **AREA C**. It will be installed in the 3 PCB holes with silk-screen label **SW0**. Position the component on its side so that the switch lever extends off the board as shown in the figure. Press the 3 wire pins on the base of the switch through the corresponding contact points on the board. Make good solder connections between each pin and the solder pads located on the underside of the circuit board.

Next, install the two-position terminal block in **AREA C**. This component will accept the laser diode lead wires. Position the terminal block so that the side with the two wire insertion holes is facing the left side of the board, closest to the label for D_0. Insert the pins through the holes on the printed circuit board and make soldered joints on the underside of the board.

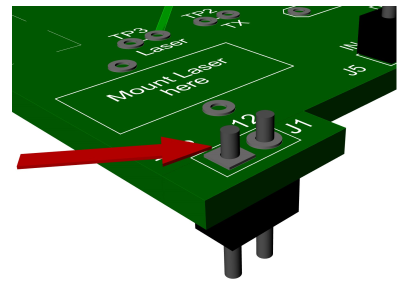
Install one 6-pin header into **J4** at the top of your board, and the other 6-pin header at **J5** at the bottom of the board. Insert the pins into the PCB pads and make soldered joints on the underside of the board.

Install 2-pin rail connectors into **J0**, **J1**, **J2**, and **J3** These are installed in the

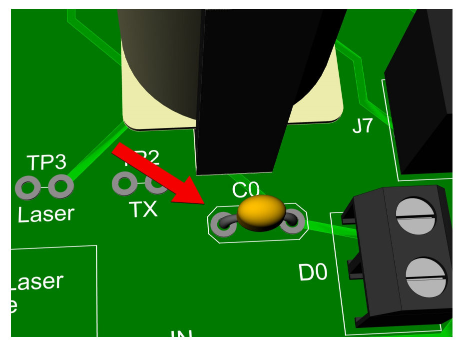




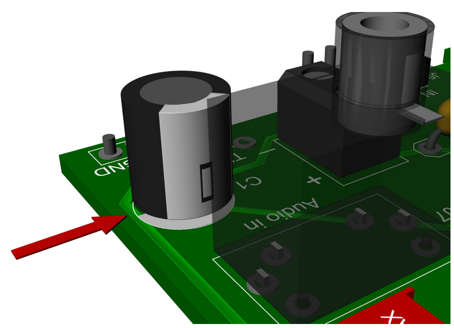
Solar Panel Mount Socket Installation



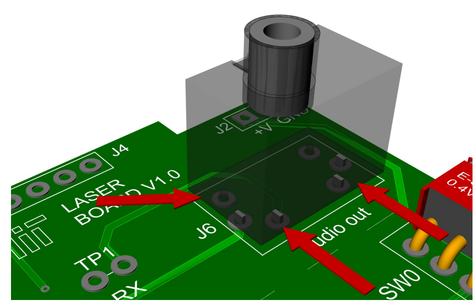
Rail Connector Pin Installation



Bypass Capacitor C0 Location



Input Audio Coupling Capacitor C_1 Location



Input Audio Jack Location

reverse direction, with the base of the pin on the underside of the board, and the location of the soldered joint on the top of the board. *BEFORE SOLDERING*, insert the bottom of the pins into your breadboard, and *then* make your soldered connections on the circuit board to ensure proper alignment.

Install your 10-pin header in **AREA A**. There are 10 PCB pads in the **solar panel mount** section. You will be attaching your solar panel to this for structural support. Insert the 10 socket pins into the PCB pads and make soldered joints on the underside of the board.

Install the laser bypass capacitor in **AREA D**. This capacitor protects the laser diode from high frequency transients. Properly install and solder the C_0 capacitor in the C_0 board location. Pull the leads through until the capacitor is secure against the board. Solder in the proper locations beneath the board, and when your joints have cooled, trim any excess wire. *Save your trimmed pieces of wire - you will use them to construct test points later.*

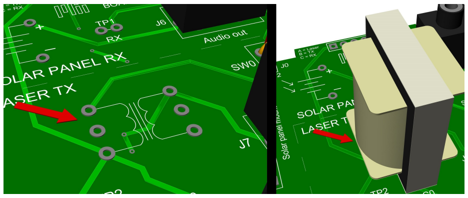
Also install the audio-input coupling capacitor in **AREA E**. This capacitor provides "AC coupling;" it blocks any DC signals and only permits AC to pass through to the transformer primary. Install one 220 μF capacitor at the location for C_1. Pull the leads through until the capacitor is secure against the printed circuit board. Make soldered joints on the underside of the board.

Add the input audio jack in **AREA C**. There are 6 PCB pads located at **J7**. Position the audio jack so that the 2 black plastic legs go into the upper 2 holes on the left and right, and the 4 metal legs are inserted into the 4 corresponding holes below them. Push the pins through the pad holes and make soldered joints on the underside of the board *only with the metal pins - NOT the plastic ones!*.

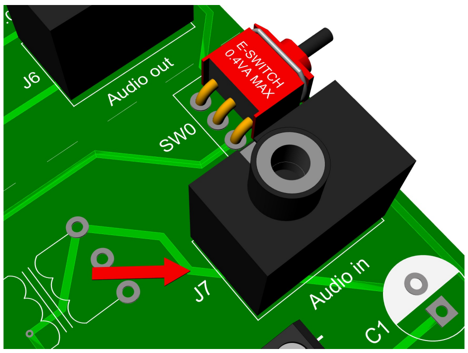
Repeat this process for the output audio jack at $J6$ in **AREA B**.

Add the transformer in **AREA E**. There are two rows of three vertical pins on each side of the transformer. Position the transformer so that its 6 bottom pins align with these PCB pads. Insert the pins into the pads and make soldered joints on the underside of the board.

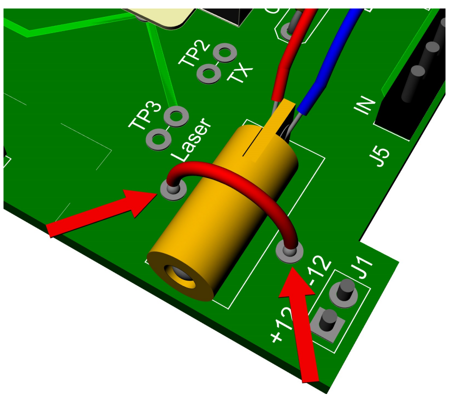
Take a fine screwdriver and loosen, but do not remove, the screws on the terminal block in **AREA C**. Insert the blue wire of the laser into the right channel of the two position terminal block (marked with a negative sign on the PCB silkscreen). Insert the red laser wire into the other channel of the block, marked with a positive sign on the silkscreen. Use the screwdriver to gently but firmly



Transformer Location



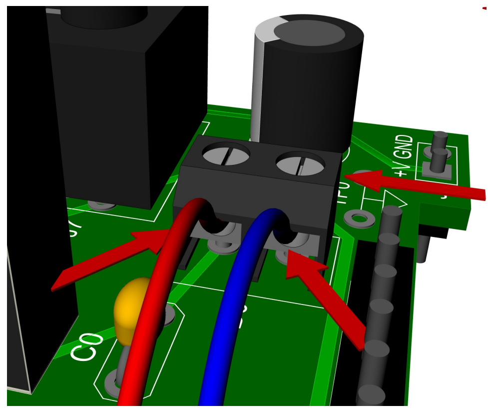
Output Audio Jack Location



Laser and Mounting Wire Positioning

tighten the screws on the top of the block to ensure a good connection between the circuit board and the laser wires.

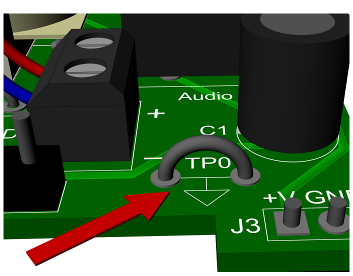
Next, secure the laser in **AREA D**. Position the laser housing on its side in the box labeled "**mount laser here**" so that the lens is pointing to the left, away from the center of the board. There are two pad holes above and below the laser - insert the two pins of the mounting wire in each of those holes so that the wire is securing the laser housing to the board. Make soldered joints on the underside of the board.



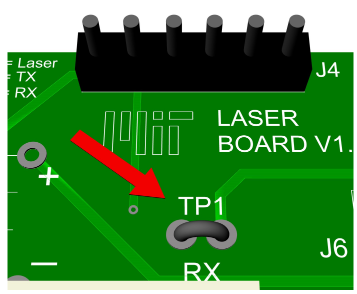
Laser Wire Locations

Construct the ground clip in **AREA C**. Take one of the capacitor wire cuttings you saved earlier and bend it into an arc, inserting each end into the PCB pad holes at **TP0**. Trim the length of the wire as necessary. Make soldered joints beneath the board. This is a ground clip.

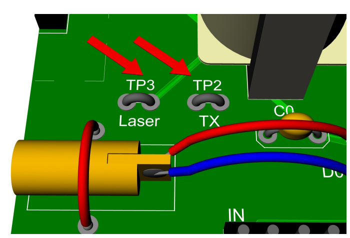
Repeat this process at **TP1** in **AREA B**. This is your receiver test point. Do this again at **TP2** and **TP3** in **AREA D**. These are you transmitter and laser test points, respectively.



Ground Clip Soldering Location



Receiver Test Point Soldering Location



Transmitter and Laser Test Point Soldering Location

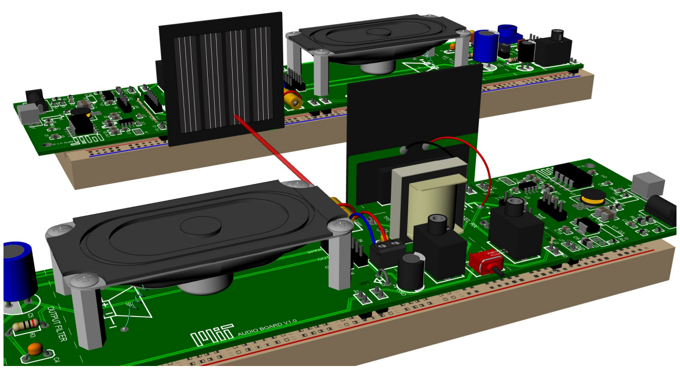
Finally, solder the solar panel wires to the PCB pads marked with the silkscreen identifier for S_0. The red wire from the solar cell goes to the pad marked with a "+", and the black wire goes to the "-" pad. You can (carefully!) secure your solar cell to the "solar panel mount" using a little bit of hot melt glue or double-sided tape. Be careful that the solar cell edge does not extend below the PCB. You want the PCB to fit correctly into the breadboard.

Testing

DO NOT LOOK DIRECTLY INTO THE BEAM OF THE LASER. DO NOT DIRECT THE BEAM OF THE LASER INTO THE EYES OF ANY OTHER PERSON.

Keep power off for now. Carefully connect your circuit board on the breadboard in line with the power supply module. Ensure that the pins of both boards are fully inserted into the breadboard contact holes. On the same breadboard, insert the audio board from your previous build in line with your laser board. You will use the speaker on this board to play the audio signal. Connect an MP3 player or similar sound source with a 3.5mm stereo jack to the input audio jack on your laser board.

Find a partner who has also constructed and assembled these boards. Connect the output audio jack on the partner's laser board to the input audio jack on the partner audio board via an auxiliary cable. Ensure that both USB power cords, yours and your partners, are properly fitted into the micro USB ports on the power supply modules. Power the boards and confirm that the indicator lights are illuminated. Now, play an audio file of your choosing for your laser board, and flip the laser switch on. Point your laser at your partner's solar panel. Keep the two breadboards, your board and your partner's board, about a foot apart for testing.



Boards, Power Supply, and Laser Beam Positioning

Continue playing an audio file on to your laser transmitter. Move your hand between the transmitting laser beam and the receiving solar panel. Can you hear the output sound? Move your hand away. How about now?

Questions to Consider

Obstructing that light effects the transmission. What other confounding elements could be present that would audibly interfere with the transmission? What effect does the ambient room lighting have on this process? Suppose you took two laser boards connected to different devices and pointed both lasers at the same solar panel - what would the output sound like? Why?