# Radial Engine Model
# Maker Manual

*Laser cutting parts.*

*Radial engine model 2.*

Model by Wesley Moore, modified by Keith Enevoldsen.

Document, diagrams, and photos by Keith Enevoldsen.

thinkzone.wlonk.com/Radial/RadialModel.html

# Contents

# 1 Introduction

## 1.1 Purpose of the radial engine model

The radial engine model is a hand-cranked transparent display model that demonstrates the operation of an airplane four-stroke radial engine.

## 1.2 Purpose of this manual

This **Maker Manual** is for makers of the radial engine model (model 2). It lists tools, materials, and parts, and gives instructions (section 4) for making all the parts for your own radial engine model. You will also need the provided laser templates (SVG files) and paper templates (PDF files) (section 4.2).

**Manuals.** The model has a **User Manual**, an **Assembly Manual**, and a **Maker Manual**. Before reading this Maker Manual, first read the User Manual for a description of how the radial engine model works, and then read the Assembly Manual for a description of all the parts and how they are assembled.

## 1.3 Maker project time and effort

Making all the parts for the radial engine model is a big project for a moderately skilled maker with a laser cutter and a lot of time. You will need to be meticulous and patient. You should first read through both the Assembly Manual and the Maker Manual to see what is involved. You must have access to a laser cutter, and you should have experience using a laser cutter to cut, score, and engrave acrylic plastic sheets. You should have several manual tool skills, including precision sawing, drilling & tapping, sanding, acrylic cementing/welding, and soldering. To make the custom parts, you will need to buy many materials (such as acrylic, metal, and wire) (see the material lists) and many standard parts (such as screws and LEDs) (see the parts lists). You may need to buy some small tools if you do not already have all the needed tools (see the tools lists). In addition to making the parts, you will need to assemble the model and do fine adjustments (see the Assembly Manual). Making all the parts may take multiple weeks (if you can devote full time to the project) or multiple months (if you can devote only weekends to the project).

## 1.4 Conventions

### 1.4.1 Tables

Throughout this Maker Manual are multiple lists of tools, materials, parts, and step-by-step instructions. These lists are formatted as tables with colored banners.

| Tools |
|---|
| Lists of the **tools** needed for making the custom parts. |

| Materials |
|---|
| Lists of the **materials** needed for making the custom parts. |

| Parts |
|---|
| Lists of the **custom parts** to be made. Lists of the **standard parts** (ready-made, store-bought parts) to be built into (bonded to) the custom parts. |

| Instructions |
|---|
| Construction **sequences** and step-by-step **instructions** for making each custom part. |

### 1.4.2 Measurement units

This model was designed using US customary units: Inches and fractions, for example 1+3/8" = 1.375". UTS screw sizes, for example #10-24. AWG wire sizes, for example 24 AWG.

### 1.4.3 Abbreviations

- ID = inner diameter, OD = outer diameter.

## 1.5 Overview of the model


*Radial engine model 2.*

Wesley Moore conceived of this transparent cross-section radial engine model with these key features:

| Radial engine model | |
|---|---|
| **Key feature** | **Description** |
| **Airplane radial engine model** | The 24”×24” model demonstrates the operation of an airplane four-stroke nine-cylinder radial engine. The power, valve, and spark systems are synchronized by gears. |
| **Power system** | The pistons move in and out within the cylinders. The pistons are connected by one master rod and eight con rods to the crankshaft, which is directly connected to the driveshaft and propeller. |
| **Valve system** | The intake and exhaust valves open and close. The valves are opened by valve pushers on rocker arms, which are connected by pushrods to cam follower wheels, which ride the cam tracks on the big cam disk. |
| **Spark system** | The spark plugs are flashing LEDs. A distributor with a rotor controls the sparks. The firing order is every alternate cylinder. |
| **Hands-on** | You turn the propeller with the crank handle, which turns the driveshaft and crankshaft, which makes all the other parts move. The model is hand cranked, not motorized, because it is more engaging to crank it yourself. |
| **Transparent, colorful, luminous** | The model is made of colored transparent acrylic plastic. You can clearly see all the moving parts. The colors are delightfully luminous when backlit. |
| **Cross-section** | The model is a stack of flat layers, made from flat laser-cut parts. The engine cylinders, pistons, and valves are 2D cross sections. The model is a hybrid between a 3D model and a 2D cross-section illustration. |

**WARNING: BREAKABLE.** Do not turn the propeller hand crank too fast or too forcefully, especially if the machine is stuck, because you could break the plastic parts! The acrylic (plexiglass) plastic parts are brittle and breakable when overstressed. This model may be operated by children and teens under the supervision of a responsible adult.

# 2 Tools for making mechanical parts

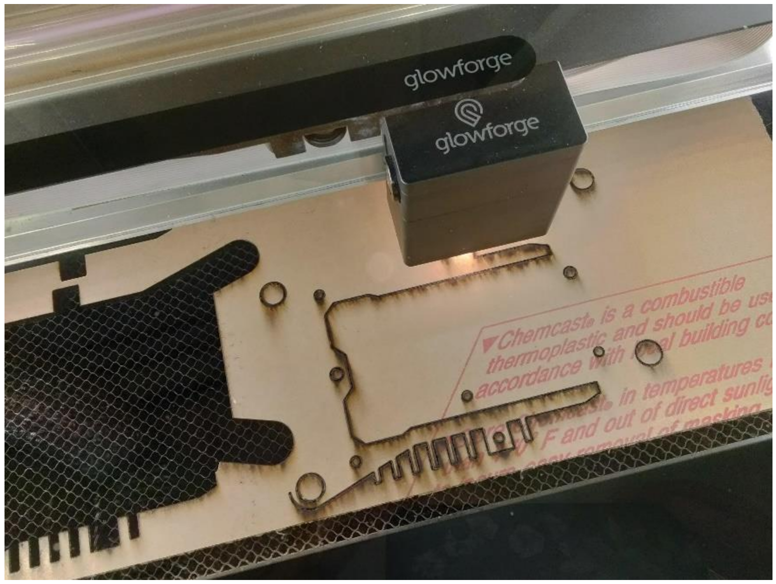
## 2.1 Laser cutter

*Glowforge 40-watt $CO_2$ laser cutter.*

A laser cutter is required. Most of the parts of this model are laser cut from acrylic (plexiglass) sheets (3.2). A few parts are also laser scored and/or laser engraved.

| Tools: Computer-controlled tools | |
|---|---|
| Tool | Usage |
| Laser cutter | Laser cutting acrylic sheets (and acetal sheets). |

**Accessing a laser cutter.** You will need access to a laser cutter. You may use a laser cutter at your local maker space, your school, your workplace, or your home. If you cannot directly access a laser cutter, you may be able to order the parts to be custom cut, scored, and engraved for you by a plastics store or laser cutting business, either local or online.




*Laser cutting a cylinder.*

**Using a laser cutter.** If you have never used a laser cutter, you will need to learn how to use a laser cutter. You can do this by reading or watching tutorials, taking a class at your local maker space, or learning from a friend. Practice on a smaller project before attempting this big project.

**WARNING: LASER CUTTER.** Read the safety precautions for your laser cutter. Wear laser safety glasses if so directed. Vent the toxic fumes. Watch out for fire.

**Laser templates.** The laser cutter application reads the cutting lines from the laser templates, which are 2D vector drawings (such as SVG, DXF, or PDF). Our laser templates (SVG) have different colors for cutting lines, scoring lines, and etching areas for different laser passes, with different power and speed settings. Cutting, scoring, and etching are always done in different passes, so they are always different colors in the template. Part outlines and holes are different colors, so you can cut the holes before cutting the part outline (to prevent the part from shifting).

**Laser settings.** You will need to cut small test squares to determine, by trial-and-error, your optimal laser settings for cutting different materials of different thicknesses, and for scoring and etching to different depths.

> *For example, for the Glowforge 40-watt $CO_2$ laser cutter, we used these settings (in Glowforge proprietary units): For cutting 1/8”-thick acrylic: speed 115, full power, 1 pass. For cutting 1/4”-thick acrylic: speed 115, full power, 2 passes. For cutting 1/8”-thick acetal: speed 115, power 70, 3 passes.*

**Laser cutter size.** You can laser cut most of this model’s acrylic parts on a small laser cutter. The large acrylic back and front plates may be cut on a larger laser cutter or made with common power tools (saw and drill). The five largest acrylic parts are: the back plate (24”×24”), the front plate (16” diameter), the middle plate (14” long), the cam disk (10.75” diameter), and the propeller (12” long). All other acrylic parts are less than 7”.

> *For example, our Glowforge laser cutter has a 20.4”×12” bed and a 19.5”×11” cutting area. It can cut all the acrylic parts except the large back and front plates.*

## 2.2 Handheld tools

These handheld tools are needed or useful for making the mechanical parts. All non-laser-cut parts can be made with small hand tools and handheld power tools (large power tools are not required).

| **Tools: Handheld tools** | |
|---|---|
| Assembly tools | |
| Assembly tools (including screwdrivers, wrenches, and pliers) are listed in the Assembly Manual. | |
| Cutting tools | |
| Tool | Usage |
| Fine-toothed hand saw (pull saw) | Cutting acrylic shaft tubes and rods. |
| Hack saw | Cutting metal parts of stand. |
| Miter box (make it yourself from scrap boards) | Cutting acrylic shaft tubes and rods. Cutting metal parts of stand. |
| Handheld rotary tool with cutting wheel | Trimming parts. Cutting snap ring grooves. |
| Razor knife | Trimming parts. Making precise markings on parts. |
| Metal snips | Cutting metal sheet for contact strip and spring clips. |
| Scissors | Cutting paper. |
| Drilling tools | |
| Handheld power drill and drill bits | Drilling screw holes in acrylic and metal. Drilling 1/2"-diameter shaft holes in plates. |
| Drill guide for handheld drill | Drilling straight screw holes. |
| Hole saw bit: 1.5” diameter | Driveshaft hole in front plate. |
| Drill & tap set: #29 drill bit and #8-32 tap (required) | Tapping #8-32 threaded holes: valve stems. |
| Drill & tap set: #43 drill bit and #4-40 tap (optional) | Tapping #4-40 threaded holes: valve pushers (optional), distributor cap lock screw (optional), spring clips (optional), plaque (optional). |
| Countersink bit | Countersunk screw holes on distributor cap. |
| Drilling lubricant (mineral oil or dish detergent) | Drilling holes in acrylic. |
| Hammering tools | |
| Small hammer | Forming the rotor contacts strip. |
| Center punch | Forming the rotor contacts strip. |
| Sanding tools | |
| Sanding disk for handheld power drill | Making D-shafts. |
| Handheld rotary tool with sanding drum | Smoothing parts. Making D-shafts. |
| Sandpaper and sanding block | Smoothing parts. |
| Clamping tools | |
| Clamps, medium and small | Holding parts. |
| Vise | Holding parts. |
| Magnets, small, strong | Holding acrylic sheets while laser cutting. Holding parts while cementing (where clamps do not reach). |

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| **Tools: Handheld tools (continued)** | |
|---|---|
| Adhesive tools | |
| Tool | Usage |
| Acrylic solvent cement, needle applicator, and funnel | Cementing acrylic parts (3.1). |
| Medium-bodied acrylic cement | Cementing acrylic parts (3.1). |
| Hot glue gun and hot glue stick (optional) | Gluing parts. Distributor rotor springs. |
| Craft glue | Gluing parts. Distributor rotor springs. |
| Spray adhesive (optional) | Affixing paper templates onto acrylic masking sheets (back and front plates). |
| Painter's tape (blue tape) | Holding parts temporarily. |
| Double-sided tape | Taping paper template to rotor contacts strip. |
| Painting tools | |
| Small paintbrush and paint, enamel or acrylic, black and white | Propeller (etched arrows). Distributor (scored numbers). Plaque (scored letters). |
| Wood for jigs | |
| Scrap boards and wood screws | Making miter box and jigs. |
| Thin sticks (craft sticks, popsicle sticks, cardboard) | Shims for miter box, vise, and jigs. |
| Measuring tools | |
| Ruler (inches and mm), tape measure, yardstick | Measuring parts (and wires). |
| Square or combination square | Making a 90° or 45° miter box. Measuring squareness, especially the squareness of the end cuts of acrylic shaft tube segments. A combination square is more versatile than a plain square. |
| Calipers, manual or electronic (inches and mm) | Precisely measuring lengths, thicknesses, and gaps. Used when making precise D-shafts. |
| Depth gauge, manual or electronic, or a small ruler with a sliding marker (inches and mm) | Precisely measuring the distances of parts from the back plate during assembly. |
| Protractor | Measuring angles (miter box, cam disk). |
| Marking tools | |
| Fine-tip permanent marker | Marking plastic or metal. |
| Pencil and paper | Marking wood, writing, drawing. |

## 2.3 Large power tools (optional)

These large (non-handheld) power tools are not required but they may work better than handheld tools. In particular, a drill press may be used to drill the holes in the large back and front plates (if you are not using a large laser cutter or CNC router).

| Tools: Large (non-handheld) power tools (optional) | |
|---|---|
| Tool | Usage |
| Table saw or circular saw | Long straight cuts. Cutting the square back plate (if not laser cut or purchased pre-cut). |
| Band saw, router, or jigsaw, with circle jig | Large circular cuts. Cutting the circular front plate (if not laser cut or purchased pre-cut). |
| Power miter saw | Cutting metal parts of the stand. Cutting acrylic shaft tubes and rods. |
| Drill press and bits | Drilling screw holes and shaft holes in the large back and front plates. |
| Disc sander, belt sander, or grinder | Making D-shafts. |

## 2.4 CNC router (optional)

A CNC router is not required. A CNC router may be used to drill the holes in the large back and front plates (if you are not using a large laser cutter or a manual drill or drill press).

| Tools: Computer-controlled tools (optional) | |
|---|---|
| Tool | Usage |
| CNC router | Drilling screw holes and shaft holes in the large back and front plates. |

We did not use a CNC router. You can make your CNC tool paths from the laser templates (SVG) for the back and front plates.

# 3 Materials for making mechanical parts

## 3.1 Acrylic cement


*Acrylic solvent cement with a needle applicator and a funnel.*


*Cementing acrylic parts with a needle applicator.*

| Materials: Acrylic cement | | |
|---|---|---|
| Material | Example product (in 2023) | Usage |
| Acrylic solvent cement (with needle applicator and funnel) | SCIGRIP Weld-On #4 (blush-resistant, recommended) or #3 (standard) | Cementing/welding acrylic |
| Medium-bodied acrylic cement | SCIGRIP Weld-On #16 | Cementing acrylic and filling gaps |

**Acrylic solvent cement.** Use thin acrylic solvent cement (such as Weld-On #4 or #3) wherever the surfaces to be bonded fit together very closely. In this model, almost all cementing should be done with thin acrylic solvent. Acrylic solvent welds are extremely strong, but the welds can fail when overstressed.

**How to apply acrylic solvent cement.** Use an applicator bottle or syringe with a hollow needle. In a ventilated area, pour a little solvent into the applicator using a funnel. Clamp the parts together and then apply the solvent with the needle applicator. The thin solvent is sucked into the narrow space between the parts by capillary action. Acrylic solvent *welds* the parts together very quickly. If you have never used acrylic solvent cement, you should first watch an instructional video and then practice with acrylic scraps before attempting to weld the real parts together. The thin solvent spreads quickly, so you are likely to accidentally wet surfaces that you did not intend to wet. The spills will evaporate quickly, but they can leave subtle stains call blushing. We recommend using a blush-resistant product (such as Weld-On #4).

**Medium-bodied acrylic cement.** Use a medium-bodied acrylic cement (such as Weld-On #16) only where the surfaces to be bonded do not fit together very closely. Medium-bodied acrylic cement will fill small gaps.

## 3.2 Acrylic plastic sheets

*Acrylic plastic is also called plexiglass or PMMA.*

Most of the parts are made from laser-cut acrylic plastic sheets.

| **Materials: Acrylic plastic sheets** | | | | | | |
|---|---|---|---|---|---|---|
| Material | Color (T=Transparent) | Thk. | Sizes (L×W) (approx.) | Area (in$^2$) (approx.) | Usage | Type |
| Acrylic | Clear | 1/4" | 24”×24” | 580 | Back plate | - |
| Acrylic | Clear | 1/4" | 16”×16” | 260 | Front plate | - |
| Acrylic | Clear | 1/4" | 14”×3” | 40 | Middle plate | - |
| Acrylic | Clear | 1/4" | 2 × (3.5”×3.5”) | 25 | Distributor cap wall (2 rings) | - |
| Acrylic | Clear | 1/4" | 1.5”×1.5” | 2 | Hole reinforcer | - |
| Acrylic | Clear | 1/8” | 3.5”×3.5” | 10 | Distributor cap lid | - |
| Acrylic | Clear | 1/8” | 4 × (3.5”×3.5”) | 50 | Distributor twist connector (4 rings) | - |
| Acrylic | Clear | 1/8” | 3”×3” | 10 | Plaque (scored/etched) | Cast |
| Acrylic | ■ Black | 1/4" | 2.5”×2.5” | 10 | Gear18 | - |
| Acrylic | ■ Black | 1/4" | 9 × (8”×6”) | 430 | Cylinders, front & back (9 pairs) | - |
| Acrylic | ■ Black | 1/4" | 36 × (0.5”×0.5”) | 10 | Cylinder spacers | - |
| Acrylic | ■ Black | 1/8" | 9 × (7”×4”) | 250 | Cylinders, mid-front & mid-back (9 sets) | - |
| Acrylic | ■ T-pink | 1/4" | 7”×7” | 50 | Crank, front & back | - |
| Acrylic | ■ T-pink or T-red | 1/4" | 5”×2” | 10 | Valves (exhaust) (9) | - |
| Acrylic | ■ T-pink | 1/4" | 3”×3” | 10 | Gear24 | - |
| Acrylic | ■ T-red | 1/8” | (6”×2”) + (6”×5”) | 40 | Master rod (and flange) | - |
| Acrylic | ■ T-red | 1/8” | 6”×1” | 10 | Cylinder numbers (9) | - |
| Acrylic | ■ T-orange or clear | 1/4" | 11”×11” | 120 | Cam disk, middle | - |
| Acrylic | ■ T-orange | 1/8” | 11”×11” | 120 | Cam disk, back (exhaust) | - |
| Acrylic | ■ T-orange or T-blue | 1/8” | 11”×11” | 120 | Cam disk, front (intake) | - |
| Acrylic | ■ T-orange | 1/8” | 18 × (6”×1”) | 110 | Pushrods (18) | - |
| Acrylic | ■ T-yellow | 1/4" | 4”×4” | 20 | Gear33_distributor | - |
| Acrylic | ■ T-yellow | 1/8” | 8 × (7”×1.5”) | 80 | Con rods (8) | - |
| Acrylic | ■ T-green | 1/4" | 2 × (8”×2”) | 30 | Rocker arms (18) | - |
| Acrylic | ■ T-green | 1/4" | 12”×1.5” | 20 | Propeller | - |
| Acrylic | ■ T-blue | 1/4" | 2 × (7”×2”) | 30 | Valve pushers (18) | - |
| Acrylic | ■ T-blue | 1/4" | 5”×2” | 10 | Valves (intake) (9) | - |
| Acrylic | ■ T-blue | 1/4" | 5.5”×5.5” | 30 | Gear48 | - |
| Acrylic | ■ T-blue | 1/4" | 3 × (2”×2”) | 10 | Distributor rotor (3 parts) | - |
| Acrylic | ■ T-blue | 1/8” | 9 × (3.5”×2.5”) | 80 | Pistons (9) | - |
| Acrylic | ■ T-violet or T-blue | 1/4" | 4”×4” | 20 | Gear33_driveshaft | - |

The table shows all the colors and thicknesses of acrylic sheets that you will need to make the parts, ordered by color and thickness. All the colors are transparent, except black.

**Laser cutting.** Acrylic is an excellent material for laser cutting. Acrylic fumes should be vented, but they are not as toxic as the fumes from some other kinds of plastic.

**Transparent colors.** Acrylic is available in many transparent colors. Transparent colors make it easy to see all the moving parts in the model. Transparent colors are beautiful when backlit. The colors shown in the table are colors we recommend, the colors we used in our model and our diagrams. You can choose different transparent colors.

**Sizes of sheets.** The table shows the thicknesses and approximate areas (in$^2$) of the sheets to make the parts but no spare parts. You should buy more than the minimum amount sheet so you can cut some extra parts. You can calculate the sizes of sheets to buy depending on your situation. Consider the size of your laser cutter bed, your chosen colors, the sizes and shapes of the parts (see the laser templates), the number of spare parts that you want, the amount of extra sheet you want to allow for cutting mistakes, the usable remainders you have from other projects, and the cost of acrylic sheets. Arrange your cuts to make efficient use of your material. (For example, the large remainder after cutting the cam disk's large front ring may be used to cut other parts, such as the pushrods.)

**Type: cast or extruded.** The two main types of acrylic are cast and extruded. You can use either cast or extruded acrylic for any of the parts of this model. Extruded acrylic has a lower melting temperature than cast acrylic, so the laser cuts will be slightly less precise, but the edges will be smoother. Clear acrylic sheets are typically available in both cast and extruded forms, but colored transparent sheets are typically available only in cast form. Scored or etched lettering is crisper and more readable on cast acrylic, so we recommend that the plaque be made from cast acrylic.

**Drilling.** You should learn some techniques for drilling brittle acrylic plastic without breaking it. Read or watch instructions online. Practice using acrylic scraps. Some hints: Use a drill guide or drill press to drill a straight hole. Drill a pilot hole first. Drill at slow speed to avoid cracking or melting. Use lubricant (such as oil or dish detergent). Use a backing sheet.

**Friction.** Acrylic-on-acrylic interfaces have medium friction (they may squeak). You can add dry lubricant (see the Assembly Manual).

**Brittleness.** Acrylic plastic is brittle (not tough) and breakable when overstressed. We would prefer a tougher material for making machine parts, but we chose to use acrylic for its transparent colors.

**WARNING: BREAKABLE.** Do not turn the propeller hand crank too fast or too forcefully, especially if the machine is stuck, because you could break the plastic parts! The acrylic (plexiglass) plastic parts are brittle and breakable when overstressed. This model may be operated by children and teens under the supervision of a responsible adult.

## 3.3 Acrylic rods

Clear acrylic rods and half rounds are used to make shafts and shaft connectors.

| Materials: Acrylic rods | | | | | | |
|---|---|---|---|---|---|---|
| Material | Form | Color | Diameter | Lengths (approx.) | Total length (approx.) | Usage |
| Acrylic | Rod | Clear | 1/2” | 21 × 2” | 42” | Rocker-pusher D-shafts (18), gears D-shaft, distributor D-shaft, back shaft. |
| Acrylic | Half round | Clear | 1” | 6 × 1.5” | 9” | Driveshaft connectors (4), crankpin connectors (2) |
| Acrylic | Rod (optional) | Clear | 1” | 1” | 1” | Propeller shaft hub core. (Alternative: You can make the round rod by cementing together two half rounds.) |

## 3.4 Acrylic tubes

Clear acrylic tubes are used to make shafts, hubs, and spacers.

| Materials: Acrylic tubes | | | | | | | |
|---|---|---|---|---|---|---|---|
| Material | Form | Color | ID | OD | Lengths (approx.) | Total length (approx.) | Usage |
| Acrylic | Tube | Clear | 1/2” | 5/8” | 19 × 0.5” | 10” | Spacer tube sleeves on rocker arm D-shafts and gear33_distributor shaft |
| Acrylic | Tube | Clear | 1” | 1.25” | 4 × 1.5” | 6” | Driveshaft segments (3), crankpin shaft (1) |
| Acrylic | Tube | Clear | 1.25” | 1.5” | 2 × 0.5” | 1” | Spacer tube sleeves on the driveshaft (2) |
| Acrylic | Tube | Clear | 1.5” | 1.75” | 2 × 0.5” | 1” | Master rod hub, cam disk hub |

**Nesting of tubes and rods.** Ideally, the 1”-diameter half round and 1”-diameter round rod fits inside the driveshaft tube (1” ID, 1.25”), which fits inside the larger tube (1.25” ID, 1.5” OD), which fits inside the largest tube (1.5” ID, 1.75” OD). Ideally, the 1/2”-diameter rod fits inside the smallest tube (1/2” ID, 5/8” OD). If you buy these at a local plastics store, you should hand select the pieces that fit inside each other. If they do not quite fit inside each other, you can sand some of the pieces to make them fit.

## 3.5 Plastic tubing

You can cut thin, stiff plastic tubing to make spacer sleeves on screws. (Alternative: You can buy ready-made sleeves.)

| Materials: Plastic tubing | | | | | | |
|---|---|---|---|---|---|---|
| Material | Form | ID | OD | Lengths (approx.) | Total length (approx.) | Usage |
| Any plastic | Tubing | ~3/16” (~0.2”) (~5 mm) | ~9/32” (~0.3”) (~7 mm) | 19 × 1” | 19” | Narrow spacer sleeves on #10 screws |
| Low-friction plastic | Tubing | ~3/16” (~0.2”) (~5 mm) | ~3/8” (~0.4”) (~10 mm) | 36 × 3/8” | 14” | Wide low-friction spacer sleeves on #10 screws |

**Low-friction plastic.** For making low-friction sleeves, you can use any low-friction plastic, such as nylon, PTFE (Teflon), or acetal (Delrin).

## 3.6 Low-friction acetal plastic sheets

*Acetal plastic is also called Delrin or POM.*

You can laser cut low-friction acetal plastic sheets to make low-friction rings. (Alternative: You can buy ready-made low-friction rings made of any low-friction material, such as nylon or PTFE.)

| **Materials: Low-friction plastic sheets** | | | | | |
|---|---|---|---|---|---|
| Material | Color | Thickness | Sizes (L×W) (approx.) | Area (in$^2$) (approx.) | Usage |
| Acetal | White | 1/8” | 14 × (1.75”×1.75”) | 50 | Low-friction rings |
| Acetal | White | 1/16” | 8 × (1.75”×1.75”) | 30 | Low-friction rings |

**Laser cutting.** Acetal is a good low-friction material for laser cutting. It has a lower melting temperature than acrylic, so your laser cutter settings should use lower power and more passes. Acetal fumes should be vented, but they are not as toxic as the fumes from some other kinds of low-friction plastic, such as nylon or PTFE (Teflon).

**Sizes of sheets.** The table shows the approximate areas (in$^2$) of the sheets to make the rings. For efficient use of material, the laser template arranges the small, medium, and large rings in concentric circles. The largest ring has 1.75” OD, the smallest ring has 1” OD.

# 4 Making the custom parts

## 4.1 Construction sequence

You can make the parts in any order that is convenient for you. This table shows one possible plan for making the parts in a sequence of construction phases. Most phases involve making some related parts (per this Maker Manual) and then assembling those parts (per the Assembly Manual).

| **Construction sequence** | | | |
|---|---|---|---|
| # | Phase | Parts to make | Rationale for sequence |
| 1 | Plates | Back, front, and middle plates. | Make the back plate first because it is the base for the model. Make the front plate at the same time because you will probably make the large plates with the same tools, such as a large laser cutter or a large drill press. (The distributor twist connector will be cemented to the front plate in a later phase.) |
| 2 | Stand | Stand. | We recommend that you make the stand early, after making the back plate and before you assemble the rest of the model. The stand is very helpful during assembly of the model. (Make the backlight and plaque later.) |
| 3 | Rings | Low-friction rings. | You will need low-friction rings throughout the assembly process, on the crankshaft, driveshaft, and D-shafts. |
| 4 | Sleeves | Sleeves. | You will need sleeves throughout the assembly process, on the main screws, driveshaft, and D-shafts. |
| 5 | Crankshaft-driveshaft | Crankshaft, middle driveshaft with gear33, and propeller with driveshaft. | You will need the crankshaft for the power system. Make the crankshaft and driveshaft segments at the same time because they are constructed similarly. (Make gear33_driveshaft during this phase.) |
| 6 | Power system | Cylinders, pistons, master rod, and con rods. | Make and assemble the power system, which is the first mechanical system. The crankshaft is a prerequisite. |
| 8 | Gears | Spur gears. | The gears will be needed to drive the cam disk (valve system) and the distributor rotor (spark system). |
| 9 | D-shafts | D-shafts for the gears and rocker-pushers. | Make the D-shafts after you have laser cut the gears with D-holes, so you can be sure they fit. D-shafts will also be needed to make the rocker-pushers. |
| 10 | Valve system | Cam disk, cam followers, pushrods, rocker arms, valve pushers, and valves. | Make and assemble the valve system after the power system. Prerequisites include the driveshaft, the middle and front plates, the gears, the D-shafts, and the sleeves. |
| 11 | Distributor | Distributor cap and rotor. | The distributor is the interface between the mechanical and electrical systems. Make the distributor after the gears and before the wiring. |
| 12 | Electrical wiring | Front cable, back wire harness (with LEDs), on-off switch, battery pack, spring clips. | Make the wiring for the spark system after the mechanical systems and the distributor. |
| 13 | Plaque | Plaque. | The plaque can be made last. |
| 14 | Backlight | Backlight with dimmer. | The backlight can be made last. |

## 4.2 Templates

To make the parts, use the provided laser templates and paper templates. Templates are provided in SVG format for laser cutting and PDF format for printing on paper. The templates may be downloaded from:

thinkzone.wlonk.com/Radial/RadialModel.html

Laser templates (SVG), to be used to control the laser cutter:

- Radial-LTemplate-CamDisk-Back
- Radial-LTemplate-CamDisk-Front
- Radial-LTemplate-CamDisk-Middle
- Radial-LTemplate-CamFollower (not used in model 2)
- Radial-LTemplate-ConRod
- Radial-LTemplate-Crank
- Radial-LTemplate-Cylinder-Back
- Radial-LTemplate-Cylinder-BackSpacers
- Radial-LTemplate-Cylinder-Front
- Radial-LTemplate-Cylinder-Front+Back
- Radial-LTemplate-Cylinder-MidBack
- Radial-LTemplate-Cylinder-MidFront
- Radial-LTemplate-Cylinder-MidFront+MidBack
- Radial-LTemplate-CylinderNumbers
- Radial-LTemplate-DistributorCapLid
- Radial-LTemplate-DistributorCapWall
- Radial-LTemplate-DistributorConnector
- Radial-LTemplate-DistributorRotor
- Radial-LTemplate-Gear18
- Radial-LTemplate-Gear24
- Radial-LTemplate-Gear33_distributor
- Radial-LTemplate-Gear33_driveshaft
- Radial-LTemplate-Gear48
- Radial-LTemplate-HoleReinforcer
- Radial-LTemplate-MasterRod
- Radial-LTemplate-MiddlePlate
- Radial-LTemplate-Piston
- Radial-LTemplate-Plaque
- Radial-LTemplate-Propeller
- Radial-LTemplate-Pushrod
- Radial-LTemplate-Rings-Thick
- Radial-LTemplate-Rings-Thin
- Radial-LTemplate-RockerArm
- Radial-LTemplate-Valve
- Radial-LTemplate-ValvePusher

Templates that may be used as laser templates (SVG) or paper templates (PDF):

- Radial-LPTemplate-BackPlate
- Radial-LPTemplate-FrontPlate

Paper templates (PDF) to be printed on paper:

- Radial-PTemplate-BackWireHarness
- Radial-PTemplate-CamDiskProtractor
- Radial-PTemplate-CylinderNumberPosition
- Radial-PTemplate-DistributorPosition
- Radial-PTemplate-DistributorRotorContacts
- Radial-PTemplate-DShaft-Distributor
- Radial-PTemplate-DShaft-Gears
- Radial-PTemplate-DShaft-RockerPusher
- Radial-PTemplate-FrontCable
- Radial-PTemplate-PlaquePosition
- Radial-PTemplate-SpringClips
- Radial-PTemplate-StandBrackets
- Radial-PTemplate-StandLegs
- Radial-PTemplate-StorageBox

Laser design templates (SVG) are design files that were used to make the laser templates:

- Radial-LXTemplate-CamDisk-AllLayers:
  Multi-layer cam disk design template used to make the cam disk laser templates.
- Radial-LXTemplate-Cylinder-AllLayers:
  Multi-layer cylinder design template used to make the cylinder laser templates.
- Radial-LXTemplate-DShaftHole: D-shaft outline used in several laser templates.
- Radial-LXTemplate-Gear99_internal: Gear outline used in the cam disk laser templates.

## 4.3 Fasteners

The fasteners are described in the Assembly Manual.

For this model, all the fasteners are store-bought parts, so there is nothing to make. (Alternative: Your model may use different fasteners, such as different pivot pin fasteners. These other fasteners may require some custom fabrication. See the Design Alternatives document.)

## 4.4 Plates

### 4.4.1 Parts list

| Plates: Custom parts | |
|---|---|
| Part | Quantity |
| Back plate | 1 |
| Front plate | 1 |
| Middle plate | 1 |

### 4.4.2 Making the back plate

*Back plate.*

The back plate is described in the Assembly Manual.

Make the back plate with one of these methods:

- Method 1. Laser cutter.
- Method 2. Hand tools (saw and drill or drill press).
- Method 3. CNC router.

**Method 1.** Make the back plate with a laser cutter (if your laser cutter is big enough).

| Instructions: Making the back plate with a large laser cutter | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut the back plate. | **Laser template: Radial-LPTemplate-BackPlate** |
| | | Material: 1/4”-thick clear acrylic. Larger than 24”×24”. |
| | | Use a laser cutter that is large enough. |
| | | Laser cut all the holes. |
| | | Laser cut the plate outline (24”×24” square). |
| | | Ignore all the other guidelines in the template. |

**Method 2.** Make the back plate with hand tools (saw and drill or drill press).

| Instructions: Making the back plate with hand tools | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Cut a 24”×24” square from acrylic sheet. | Material: 1/4”-thick clear acrylic. |
| | | You can buy the acrylic pre-cut to 24”×24” or cut it yourself. |
| | | Use any sawing tool that makes precise straight cuts. |
| 2 | Print the back plate template, full scale, on large paper. | **Paper template: Radial-LPTemplate-BackPlate** |
| | | The template shows where to drill all the holes in the back plate. The template shows the diameter of each hole and a crosshair at the center of each hole. |
| | | Print the large template (26”×26”), full scale, on a single large sheet of paper (at a print shop). Printing on a single large sheet is necessary to ensure accuracy. |
| 3 | Affix the paper template to the acrylic sheet. | Do not remove the masking sheet. |
| | | Precisely align the template with the edges of the acrylic square. |
| | | Affix the paper template to the masking sheet with spray adhesive. Make sure it lies flat without wrinkles. |
| 4 | Drill all the holes per the template. | You can pay a professional (a plastics shop) to drill the plate or drill it yourself. |
| | | Use a drill press or a drill guide to drill very precisely. |
| | | Drill directly through the paper template and the acrylic sheet. |
| 5 | Cut the cable slot per the template. | Cut the slot from the edge to the drilled cable hole. |
| 6 | Remove the paper template and masking sheets. | The paper template has no further use. |

**Method 3.** Make the back plate with a CNC router (if your CNC router is big enough).

We did not use a CNC router. You can make your CNC tool paths from the laser template (SVG) for the back plate.

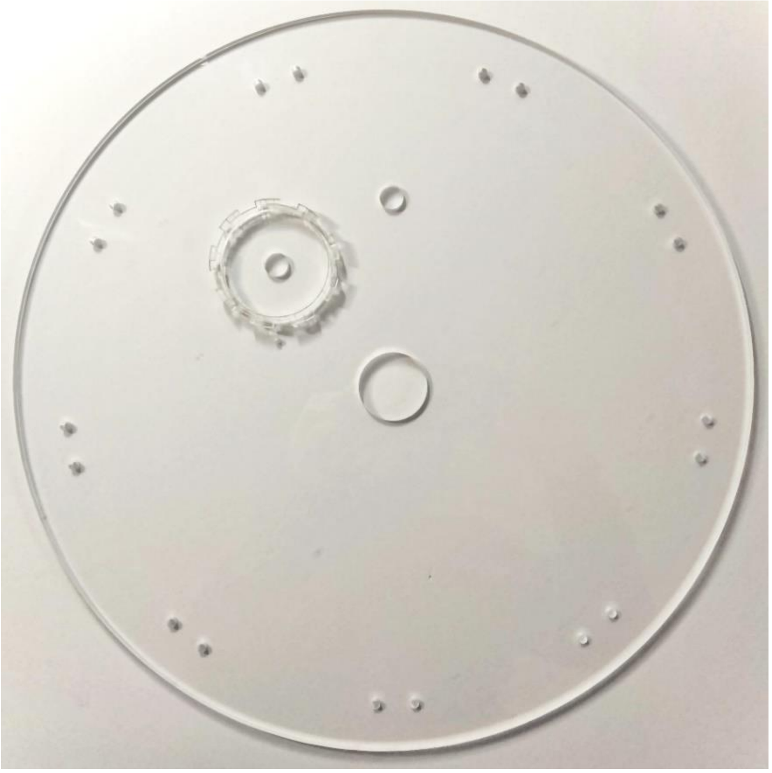
**Shaft hole reinforcer ring.** After making the plate, add a reinforcer ring behind the back shaft hole.

| Instructions: Making the back shaft hole reinforcer ring. | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut the reinforcer ring. | **Laser template: Radial-LTemplate-HoleReinforcer** |
| | | Material: 1/4”-thick clear acrylic. |
| 2 | Cement the reinforcer ring to the back side of the back plate. | Put the ring around the center back shaft hole on the back side of the back plate. You can align the ring by inserting a 1/2"-diameter shaft through both the ring and the shaft hole. |
| | | Hold the ring onto the plate by some method, such as clamp, weight, tape, magnet, or fingers. Remove the alignment shaft. |
| | | Apply acrylic solvent cement. |

**Finishing the back plate.** Instructions for cementing the cylinder numbers onto the back plate are in 4.4.5. Instructions for drilling threaded screw holes for the spring clips are in 4.13.9. Instructions for drilling screw holes for the plaque are in 4.16.2.

**Stand construction phase.** We recommend that you make the stand early, after making the back plate and before you assemble the rest of the model. The stand is very helpful during assembly of the model.

### 4.4.3 Making the front plate



*Front plate.*

The front plate is described in the Assembly Manual.

Make the front plate with one of these methods:

- Method 1. Laser cutter.
- Method 2. Hand tools (saw and drill or drill press).
- Method 3. CNC router.

**Method 1.** Make the front plate with a laser cutter (if your laser cutter is big enough).

| **Instructions: Making the front plate with a large laser cutter** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser score and cut the front plate. | **Laser template: Radial-LPTemplate-FrontPlate** |
| | | Material: 1/4”-thick clear acrylic. Larger than 16” circle. |
| | | Use a laser cutter that is large enough. |
| | | Laser score (lightly) the distributor alignment marks (the circle of nine crosshairs around the distributor shaft). |
| | | Laser cut the all the holes. |
| | | Laser cut the plate outline (16” circle). |
| | | Ignore all the other guidelines in the template. |

**Method 2.** Make the front plate with hand tools (saw and drill or drill press).

| **Instructions: Making the front plate with hand tools** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Cut a 16” circle from acrylic sheet. | Material: 1/4”-thick clear acrylic. |
| | | You can buy the acrylic pre-cut to a 16” circle or cut it yourself. |
| | | Use any sawing tool that makes a precise circular cut. |
| 2 | Print the front plate template, full scale, on large paper. | **Paper template: Radial-LPTemplate-FrontPlate** |
| | | The template shows where to drill all the holes in the front plate. The template shows the diameter of each hole and a crosshair at the center of each hole. |
| | | Print the large template (17”×17”), full scale, on a single large sheet of paper (at a print shop). Printing on a single large sheet is necessary to ensure accuracy. |
| 3 | Affix the paper template to the acrylic sheet. | Do not remove the masking sheet. |
| | | Precisely align the template with the edge of the acrylic circle. |
| | | Affix the paper template to the masking sheet with spray adhesive. Make sure it lies flat without wrinkles. |
| 4 | Drill all the holes per the template. | You can pay a professional (a plastics shop) to drill the plate or drill it yourself. |
| | | Use a drill press or a drill guide to drill very precisely. |
| | | Drill directly through the paper template and the acrylic sheet. |
| | | Use a hole saw bit to cut the 1.5”-diameter driveshaft hole. |
| 5 | Mark the plate at the distributor alignment marks per the template. | Mark the plate lightly where the template shows the distributor alignment marks (nine crosshairs). You can mark the plate at each crosshair by cutting with a razor knife, tapping a nail, or drilling a dot with your smallest drill bit. |
| 6 | Remove the paper template and masking sheets. | The paper template has no further use. |

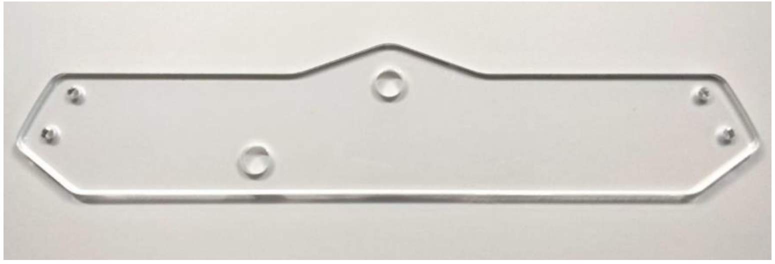
**Method 3.** Make the front plate with a CNC router (if your CNC router is big enough).

We did not use a CNC router. You can make your CNC tool paths from the laser template (SVG) for the front plate.

**Finishing the front plate.** Instructions for cementing the distributor twist connector to the front plate are in 4.12.7.

**Close-fit screw holes.** The 18 main screw holes (3/16” diameter for #10-24 screws) should be a close fit for precise alignment of the parts. But the close-fit holes can make it challenging to install the front plate. If the installation is too difficult for you, you can slightly widen the 18 holes by re-drilling them a couple more times with the same size drill bit (3/16”).

### 4.4.4 Making the middle plate



*Middle plate.*

The middle plate is described in the Assembly Manual.

| Instructions: Making the middle plate | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut the middle plate. | **Laser template: Radial-LTemplate-MiddlePlate** |
| | | Material: 1/4”-thick clear acrylic. At least 14”×3”. |
| | | Laser cut the plate (holes first). |

### 4.4.5 Making the cylinder numbers

*Cylinder numbers.*

*Cylinder numbers cemented on the back plate.*

The cylinder numbers are described in the Assembly Manual.

| **Instructions: Making the cylinder numbers** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut nine numbers. | **Laser template: Radial-LTemplate-CylinderNumbers** |
| | | Material: 1/8”-thick acrylic, color: transparent red. |
| 2 | Print the cylinder number position template, full scale, on one or more sheets of paper. | **Paper template: Radial-PTemplate-CylinderNumberPosition** |
| | | The template shows where to position one cylinder number adjacent to one cylinder. |
| | | Print the cylinder number template, full scale. Print one or more copies. |
| | | Alternative: Print the entire large back plate template, full scale, on one large sheet of paper or multiple smaller sheets of paper. The large back plate template shows all cylinder numbers adjacent to all cylinders. |
| 3 | Tape the paper template sheet(s) to the back of the plate, facing the front side. | Align the paper template with the cylinder screw holes, then tape it. |
| | | You will be able to see the template through the clear plate. |
| 4 | Lay the plate face up, elevated. | The plate is elevated (on blocks or on the stand brackets) so that you can put clamps or magnets on both sides of the plate. |
| 5 | Position, hold, and cement each acrylic number to the plate, one at a time. | Put the number on the front of the plate, directly over the position shown on the paper template taped to the back of the plate. |
| | | Hold the number onto the plate by some method, such as clamp, weight, tape, magnet, or finger. |
| | | Apply acrylic solvent cement. Try to avoid spilling too much solvent on the back plate. |

## 4.5 Rings

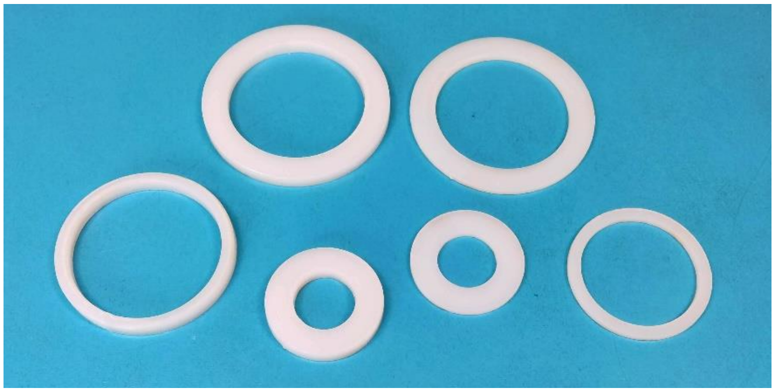
### 4.5.1 Parts list

Low-friction rings may be custom-made (by laser cutting) or ready-made (store-bought standard parts).

| **Rings: Custom parts or standard parts** | | | | | | |
|---|---|---|---|---|---|---|
| Part | Material | ID | OD | 1/8" thick Quantity (approx.) | 1/16" thick Quantity (approx.) | Usage |
| Spacer rings | Low-friction plastic | 0.5" | 1" | 6 | 8 | Spacer rings on 0.5" shafts. |
| Spacer rings | Low-friction plastic | 1" | 1.25" | 2 | 2 | Spacer rings in-line with 1.25" OD shafts. |
| Bushing rings | Low-friction plastic | 1.25" | 1.5" | 8 | 0 | Bushing rings on 1.25" OD shafts, inside 1.5" ID hubs. |
| Spacer rings | Low-friction plastic | 1.25" | 1.75" | 6 | 2 | Spacer rings on 1.25" OD shafts. |

Low-friction plastics include nylon, PTFE (Teflon), and acetal (Delrin). For laser cutting, you can use acetal, but not nylon or PTFE.

### 4.5.2 Making the rings



*Low-friction rings.*

Low-friction plastic rings are used as spacers and bushings on the driveshaft, crankshaft, and the gear shafts. The Assembly Manual tells where to put the rings.

You can try to find ready-made rings in all the sizes you need, but it may be easier to make them yourself. You can make the low-friction rings by laser cutting acetal plastic (Delrin).

| **Instructions: Making the low-friction rings** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut the 1/8"-thick rings. | **Laser template: Radial-LTemplate-Rings-Thick** |
| | | Material: 1/8"-thick low-friction plastic sheet (acetal). |
| | | Laser cut the rings (in order from smallest to largest). |
| 2 | Laser cut the 1/16"-thick rings. | **Laser template: Radial-LTemplate-Rings-Thin** |
| | | Material: 1/16"-thick low-friction plastic sheet (acetal). |
| | | Laser cut the rings (in order from smallest to largest). |

The laser templates have many concentric circles to make small rings nested inside large rings. Laser cut the concentric circles in order from smallest to largest. Cutting all the concentric rings in the two laser templates will make all the rings needed of all sizes, and more than you need of some sizes. See the rings parts list (4.5.1).

## 4.6 Sleeves

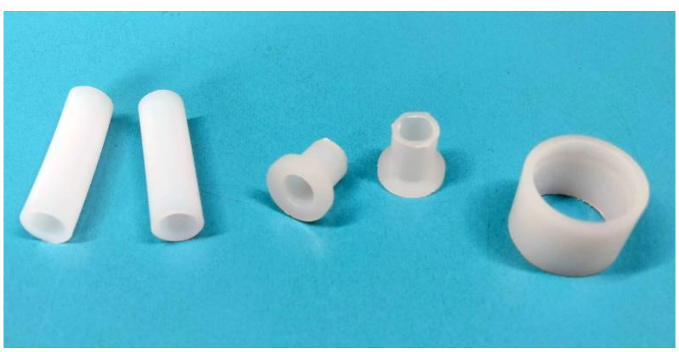
### 4.6.1 Parts list

Sleeves may be custom-made (by cutting tubes) or ready-made (store-bought standard parts).

| Sleeves: Custom parts or standard parts | | | | | | |
|---|---|---|---|---|---|---|
| Part | Material | ID | OD | Length | Quantity | Usage |
| Screw sleeves | Plastic tube | ~3/16” (~0.2”) (~5 mm) | ~9/32” (~0.3”) (~7 mm) | 1” | 14 | Spacer sleeves on #10 main screws. |
| Screw sleeves | Plastic tube | ~3/16” | ~9/32” | 3/4” | 4 | Spacer sleeves on #10 main screws. |
| Screw sleeves | Plastic tube | ~3/16” | ~9/32” | 1” | 1 | Rotating sleeve on propeller crank handle. |
| Screw sleeves, wide or flanged | Low-friction plastic tube | ~3/16” | ~3/8” (~0.4”) (~10 mm) | 3/8” (including flange) | 36 | Low-friction spacer sleeves on #10 main screws, wide or flanged where they touch the sliding pushrods. |
| Rod sleeve, narrow | Plastic tube (acrylic) | 1/2" | ≤5/8” | 7/16” | 1 | Sleeve on gear33_distributor shaft, narrow OD for clearance. |
| Rod sleeves | Plastic tube (acrylic) | 1/2" | ~5/8” | 3/8” | 18 | Spacer sleeves on rocker-pusher shafts. |
| Driveshaft sleeves | Plastic tube (acrylic) | 1.25” | ~1.5” | 3/8” | 2 | Spacer tube sleeves on middle driveshaft. |

Low-friction plastics include nylon, PTFE (Teflon), and acetal (Delrin).

### 4.6.2 Making the sleeves



*Sleeves, cut from plastic tubes or ready-made.*

*Sleeves, cut from acrylic tubes.*

Sleeves are used as spacers on screws and small and large shafts. The Assembly Manual tells where to put the sleeves.

You can try to find ready-made sleeves in all the sizes you need, but it may be easier to make them yourself. You can make the sleeves by cutting tubes or by shortening ready-made sleeves.

*Making a sleeve by cutting plastic tubing using a razor knife.*

*Sanding a sleeve to shorten it and to square the end.*

**Instructions: Making sleeves from tube stock**

| # | Step | Instructions |
|---|---|---|
| 1 | Cut tube stock to the needed lengths. | Materials: small-diameter flexible plastic tubing and larger-diameter stiff plastic tubes (acrylic tubes). See the materials list (3.4 and 3.5). The needed diameters are listed in the sleeves parts list (4.6.1).<br>(Alternative: You can shorten store-bought standard sleeves.) |
| | | The needed lengths are listed in the sleeves parts list (4.6.1). |
| | | For flexible plastic tubing of small diameter (< 1/2"), cut with a razor knife or a fine-toothed saw. A miter box is not required. |
| | | For acrylic or other stiff plastic tubes (≥ 1/2” diameter), cut with a fine-toothed saw and a miter box, or a power miter saw. |
| | | For store-bought standard sleeves that are significantly longer than desired, cut them as you would cut tube stock. |
| | | Err on the side of cutting them too long. |
| 2 | Sand/grind the ends of the sleeves. | Use sandpaper or a power sander or grinder to shorten the sleeves to the precise needed lengths and to square the ends. |
| | | Measure the lengths with calipers. |

## 4.7 Power system: Crankshaft, driveshaft, propeller

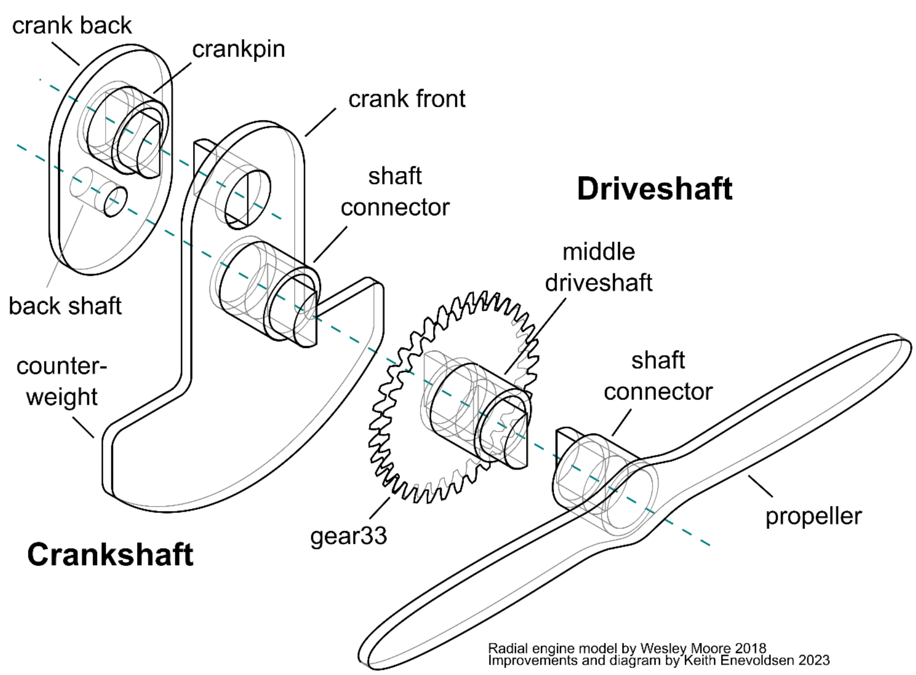
### 4.7.1 Parts list

| Crankshaft, driveshaft, propeller: Custom parts | |
|---|---|
| Part | Quantity |
| Crank back (with shafts) | 1 |
| Crank front (with shafts) | 1 |
| Middle driveshaft with gear33 | 1 |
| Propeller (with shaft) | 1 |

—

| Crankshaft, driveshaft, propeller: Standard parts (built into custom parts) | | | |
|---|---|---|---|
| Part | Size | Quantity | Usage |
| Machine screws, pan head | #4-40 × 1/2" | 2 | Propeller hub |

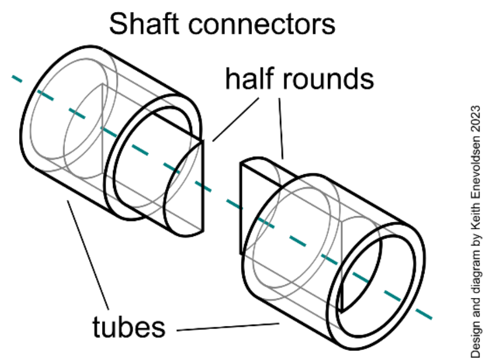
### 4.7.2 Crankshaft-driveshaft-propeller assembly




*Crankshaft-driveshaft-propeller assembly.*

The crankshaft-driveshaft-propeller assembly is described in the Assembly Manual.

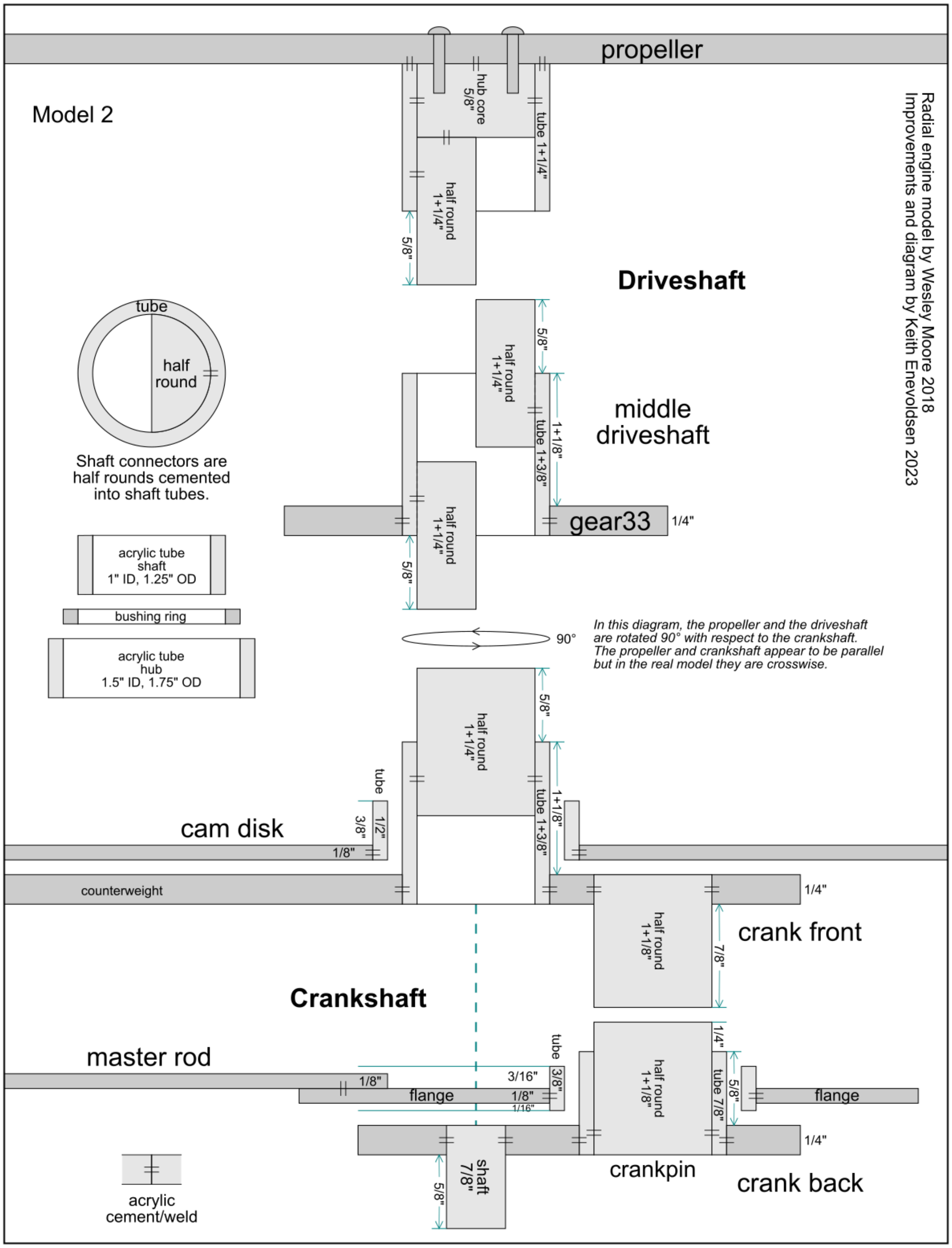
### 4.7.3 Shaft connectors




*Shaft connectors.*

Shaft connectors connect the segments rigidly, but they are easy to push together and pull apart. The end of the shaft tube has a protruding half-round rod, cemented to the inside of the tube on one side, leaving the other side hollow. Each connector is half plug and half socket, so two identical connectors will fit together.

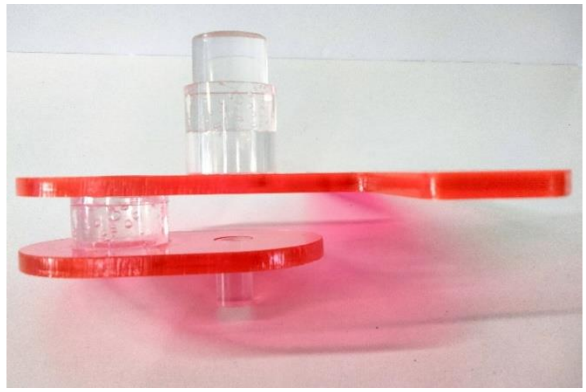
### 4.7.4 Crankshaft-driveshaft dimensions




*Crankshaft-driveshaft segments, section view, with dimensions.*

### 4.7.5 Crankshaft assembly

*Crankshaft.*



*Crankshaft, side view.*

The crankshaft assembly is described in the Assembly Manual.

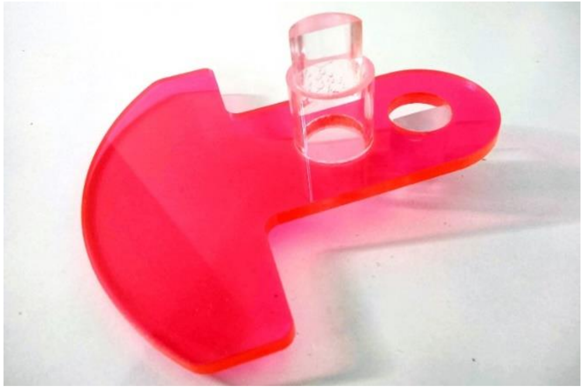
### 4.7.6 Making the crank back

*Crank back (front side).*

*Crank back (back side).*

| **Instructions: Making the crank back (with shafts)** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut the crank back. | **Laser template: Radial-LTemplate-Crank** |
| | | Material: 1/4”-thick acrylic, color: transparent pink. |
| | | Laser cut the crank back (holes first). |
| 2 | Cut the back shaft rod. | Material: 1/2”-diameter clear acrylic rod. |
| | | Cut to length 7/8”. |
| 3 | Cement the back shaft into the small back shaft hole. | Put the 7/8” rod flush with the front side of the crank back, with 5/8” protruding from the back side. See diagram 4.7.4. |
| | | Apply acrylic solvent cement to all edges. |
| 4 | Cut the crankpin shaft tube. | Material: 1” ID, 1.25” OD clear acrylic tube. |
| | | Cut to length 7/8”. |
| 5 | Cement the crankpin shaft tube into the crankpin shaft hole. | Put the 7/8” tube flush with the back side of the crank back, with 5/8” protruding from the front side. See diagram 4.7.4. |
| | | Apply acrylic solvent cement to all edges. |
| 6 | Cut the crankpin connector half round. | Material: 1”-diameter clear acrylic half round. |
| | | Cut to length 1+1/8”. |
| | | If necessary, sand the half round to fit closely inside one half of a shaft tube. |
| 7 | Cement the crankpin half round into the crankpin shaft tube. | Put the 1+1/8” half round flush on the back side of the 7/8” tube, with 1/4” protruding from the tube on the front side. See diagram 4.7.4. |
| | | Orient the half round such that, when the crank front and crank back are connected by the crankpin connectors, the front driveshaft and the back shaft will be aligned (on the same axis). We oriented the half round with the flat side aligned with the long axis of the crank. |
| | | Clamp the half round to the tube. (You can use a clamp, a clamping jig, or simply your gloved fingers.) |
| | | Apply acrylic solvent cement to all edges. |

## 4.7.7 Making the crank front


*Crank front (front side).*


*Crank front (back side).*

| **Instructions: Making the crank front (with shafts)** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut the crank front. | **Laser template: Radial-LTemplate-Crank** |
| | | Material: 1/4”-thick acrylic, color: transparent pink. |
| | | Laser cut the crank front (holes first). |
| 2 | Cut two connector half rounds for the crankpin and the driveshaft (different lengths). | Material: 1”-diameter clear acrylic half round. |
| | | Cut crankpin half round to length 1+1/8”. |
| | | Cut driveshaft half round to length 1+1/4”. |
| | | If necessary, sand the half rounds to fit closely inside one half of a shaft tube. |
| 3 | Cement the crankpin half round into the crankpin shaft hole. | Put the 1+1/8” half round flush on the front side of the crank front, with 7/8” protruding from the back side. See diagram 4.7.4. |
| | | Orient the half round such that, when the crank front and crank back are connected by the crankpin connectors, the front driveshaft and the back shaft will be aligned (on the same axis). We oriented the half round with the flat side aligned with the long axis of the crank. |
| | | Clamp the half round to the hole. (You can use a clamp, a clamping jig, or simply your gloved fingers.) |
| | | Apply acrylic solvent cement to all edges. |
| 4 | Cut the driveshaft tube. | Material: 1” ID, 1.25” OD clear acrylic tube. |
| | | Cut to length 1+3/8”. |
| 5 | Cement the driveshaft tube into the driveshaft hole. | Put the 1+3/8” driveshaft tube flush with the back side of the crank front, with 1+1/8” protruding from the front side. See diagram 4.7.4. |
| | | Apply acrylic solvent cement to all edges. |
| 6 | Cement the driveshaft half round into the driveshaft tube. | Put the 1+1/4” half round inside the tube with 5/8” protruding from the tube on the front side. See diagram 4.7.4. |
| | | We oriented the half round with the flat side aligned with the long axis of the crank. |
| | | Clamp the half round to the tube. (You can use a clamp, a clamping jig, or simply your gloved fingers.) |
| | | Apply acrylic solvent cement to all edges. |

After building the crank front and crank back, connect them together, using the crankpin shaft connector, and verify that the front driveshaft and the back shaft are aligned on the same rotation axis.

## 4.7.8 Making the middle driveshaft with gear33

*Gear33_driveshaft*

*Middle driveshaft with gear33.*

The middle driveshaft is described in the Assembly Manual.

| **Instructions: Making the middle driveshaft with gear33** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Make gear33_driveshaft. | Instructions for making gears are in 4.10.2. |
| 2 | Cut the driveshaft tube. | Material: 1” ID, 1.25” OD clear acrylic tube. |
| | | Cut to length 1+3/8”. |
| 3 | Cut two shaft connector half rounds (same lengths). | Material: 1”-diameter clear acrylic half round. |
| | | Cut length for both half rounds: 1+1/4”. |
| | | If necessary, sand the half rounds to fit closely inside one half of a shaft tube. |
| 4 | Cement the first half round into the back end of the driveshaft tube. | Put the first 1+1/4” half round inside the tube with 5/8” protruding from the tube on the back side. See diagram 4.7.4. |
| | | The orientation of the first half round does not matter. (The second half round will be on the opposite side of the tube.) |
| | | Clamp the half round to the tube. (You can use a clamp, a clamping jig, or simply your gloved fingers.) |
| | | Apply acrylic solvent cement to all edges. |
| 5 | Cement the second half round into the front end of the driveshaft tube. | Put the second 1+1/4” half round inside the tube with 5/8” protruding from the tube on the front side. See diagram 4.7.4. |
| | | Orient the second half round to be on the opposite side of the tube from the first half round. This will enable you to reach all sides of both half rounds with the acrylic solvent applicator needle. See diagram 4.7.4. |
| | | Clamp the half round to the tube. (You can use a clamp, a clamping jig, or simply your gloved fingers.) |
| | | Apply acrylic solvent cement to all edges. |
| 6 | Cement the driveshaft tube into gear33_driveshaft. | Put the 1+3/8” driveshaft tube flush with the back side of the gear, with 1+1/8” protruding from the front side. See diagram 4.7.4. |
| | | Apply acrylic solvent cement to all edges. |

### 4.7.9 Making the propeller with shaft connector

*Propeller assembly.*

The propeller assembly is described in the Assembly Manual.

| **Instructions: Making the propeller** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser score, etch, and cut the propeller. | **Laser template: Radial-LTemplate-Propeller** |
| | | Material: 1/4”-thick acrylic, color: transparent green. |
| | | Laser score the circle on the hub. |
| | | Laser etch the counterclockwise arrows on hub and blades. |
| | | Laser cut three pilot screw holes in the hub. We will use two screws in the two outer holes. (The center hole merely marks the exact center.) |
| | | Laser cut the propeller. |
| 2 | Paint the arrows. | Paint the etched arrows white. Paint with a brush before removing the paper mask. |

| Instructions: Making the propeller shaft connector | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Cut the driveshaft tube. | Material: 1” ID, 1.25” OD clear acrylic tube. |
| | | Cut to length 1+1/4”. |
| 2 | Cut the hub core rod. | Material: 1”-diameter clear acrylic rod.<br>(Alternative: You can make the round rod by cementing together two half rounds.) |
| | | Cut rod to length 5/8”. |
| | | If necessary, sand the rod to fit closely inside the driveshaft tube. |
| 3 | Cement the hub core into the driveshaft tube. | Put the 5/8”-long hub core in the 1+1/4” driveshaft tube, flush with the front of the tube. This should leave 5/8” for the half round to be inserted later. See diagram 4.7.4. |
| | | Apply acrylic solvent cement to all edges. |
| | | If there are any gaps between the hub core and the tube, fill the gaps with thick-bodied acrylic cement. |
| 4 | Sand the front end. | Sand the front end of the driveshaft tube and hub core. It must be flat and smooth to be cemented to the propeller. |
| 5 | Cut the shaft connector half round. | Material: 1”-diameter clear acrylic half round. |
| | | Cut to length 1+1/4”. |
| | | If necessary, sand the half round to fit closely inside one half of a shaft tube. |
| 6 | Cement the half round into the driveshaft tube. | Put the 1+1/4” half round in the tube, touching the hub core, with 5/8” protruding from the tube. See diagram 4.7.4. |
| | | Orient the half round (with respect to the propeller and the screw holes) such that, when the propeller, driveshaft, and crankshaft are connected, the propeller is crosswise to the crank. The propeller should not block the view of the crankpin when the model is viewed or photographed. We oriented the half round with the flat side crosswise to the propeller. |
| | | Clamp the half round to the tube. (You can use a clamp, a clamping jig, or simply your gloved fingers.) |
| | | Apply acrylic solvent cement to all edges. |

—

<table>
<tr><th colspan="3">Instructions: Bonding the propeller to the shaft connector</th></tr>
<tr><th>#</th><th>Step</th><th>Instructions</th></tr>
<tr><td rowspan="6">1</td><td rowspan="6">Screw the propeller hub to the shaft connector.</td><td>The propeller will be both screwed and cemented to the shaft connector. The screws are added for strength, not for disassembly.</td></tr>
<tr><td>The hub will have two screws through the two screw holes on either side of the center. (The center pilot hole is not used. It merely marks the exact center.)</td></tr>
<tr><td>Clamp the propeller to the driveshaft tube and hub core, centered. (If the hub core is made of two cemented half rounds, orient it so the screws will not split the seam.)</td></tr>
<tr><td>Drill two small (1/16”) pilot holes into the end of the core, using the three pilot holes in the propeller as your drill guide.</td></tr>
<tr><td>Drill two screw holes (starting with the pilot holes) through both the propeller hub and the hub core. You can drill and tap threaded holes for the #4-40 × 1/2" screws. (Alternative: You can drill unthreaded holes that are slightly smaller than the outer diameter of the screws.)</td></tr>
<tr><td>Screw the propeller to the hub core with two #4-40 × 1/2" pan head screws.</td></tr>
<tr><td rowspan="5">2</td><td rowspan="5">Cement the propeller hub to the shaft connector.</td><td>Plan for the solvent cement to penetrate all the way into the center between the propeller hub and the hub core.</td></tr>
<tr><td>Loosen the screws just enough for the needle applicator to reach the center.</td></tr>
<tr><td>Apply a little solvent cement in the center and then immediately tighten the screws.</td></tr>
<tr><td>Apply more solvent cement at the outer edge between the tube and propeller hub.</td></tr>
<tr><td>If necessary, you can add more solvent cement to the center through the center pilot hole.</td></tr>
<tr><td>3</td><td>If necessary, cement the screw threads.</td><td>If the screws are even slightly loose, unscrew them, add some medium-bodied acrylic cement to the screw holes and/or screw threads, and then put the screws back in.</td></tr>
</table>

**Crank handle.** The propeller assembly includes a crank handle. The crank handle is assembled from standard parts (a screw, a sleeve, and a nut). See the Assembly Manual.

# 4.8 Power system: Cylinders, pistons, rods

## 4.8.1 Parts list

| Cylinders, pistons, rods: Custom parts | |
|---|---|
| Part | Quantity |
| Cylinder backs | 9 |
| Cylinder fronts | 9 |
| Pistons | 9 |
| Master rod | 1 |
| Con rods | 8 |

## 4.8.2 Making the cylinders


*Cylinder layers: (1) back, (2) middle-back, (3) middle-front, and (4) front. After laser cutting, before cementing.*

*Cylinder back part, after cementing, (left) and cylinder front part (right).*

*Cylinder back part, back side, showing the spacer rings.*

The cylinders are described in the Assembly Manual.

Each cylinder is assembled from two parts: the cylinder back and the cylinder front. The cylinder back is made of four layers (0 to 3) cemented together. The cylinder front is a single layer (4). The table lists the features of each layer.

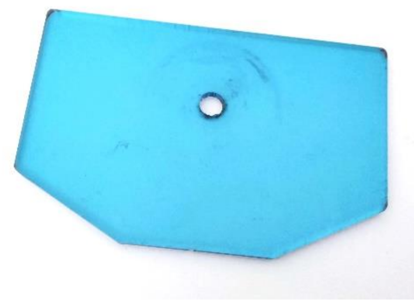
| Cylinder layers | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Part | Layer # | Layer | Thk. | Cylinder walls | Piston slots | Valve holes | Rocker supports | Screw holes | LED hole | Cooling fins | Spacer rings |
| Cylinder front | 4 | Front | 1/4" | ✓ | | | ✓ | ✓ | ✓ | | |
| Cylinder back | 3 | Middle-front | 1/8" | ✓ | ✓ | ✓ | | ✓ | ✓ | | |
| | 2 | Middle-back | 1/8" | ✓ | | ✓ | | ✓ | ✓ | | |
| | 1 | Back | 1/4" | ✓ | | | ✓ | ✓ | ✓ | ✓ | |
| | 0 | Spacers | 1/4" | | | | | ✓ | | | ✓ |


*Cementing the layers of the cylinder back part.*
*Use screws, nuts, and clamps to align and clamp the pieces.*
*Apply acrylic solvent cement to the edges after clamping.*

| Instructions: Making the cylinder fronts and cylinder backs | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut the back and front layers. | **Laser template: Radial-LTemplate-Cylinder-Front+Back**<br>or **Radial-LTemplate-Cylinder-Front** and **Radial-LTemplate-Cylinder-Back** |
| | | Material: 1/4”-thick acrylic, color: black. |
| | | Optionally, lightly laser etch the cylinder fronts at the surfaces that touch moving parts (the slots for the pistons, valves, and valve pushers). The laser template shows the areas to etch. The depth of the etching should be shallow, no more than 1/64” (0.015”) (0.4 mm). See the note about laser etching (below). Etching is optional, not required. |
| | | Laser cut nine pairs of pieces: nine back pieces and nine front pieces (holes first). |
| | | The cylinder front parts are now complete and should be set aside. The remaining instructions are for making the cylinder back parts. |
| 2 | Laser cut the middle-back and middle-front layers. | **Laser template: Radial-LTemplate-Cylinder-MidFront+MidBack**<br>or **Radial-LTemplate-Cylinder-MidFront** and **Radial-LTemplate-Cylinder-MidBack** |
| | | Material: 1/8”-thick acrylic, color: black. |
| | | Laser cut nine sets of six pieces: three middle-back pieces and three middle-front pieces (holes first). |
| 3 | Laser cut the cylinder spacers. | **Laser template: Radial-LTemplate-Cylinder-BackSpacers** |
| | | Material: 1/4”-thick acrylic, color: black. |
| | | Laser cut nine sets of four spacer rings. |
| 4 | Assemble all the layers of each cylinder back part. | Assemble all the pieces of each cylinder back part in layers, aligned with five screws: four #10 screws in the screw holes and one 1/4"-diameter screw in the LED hole. The screw heads are on the back, the nuts will be on the front. |
| | | Spacers layer. Start by placing one cylinder back spacer ring onto each of the four #10 screws. |
| | | Back layer. Put the single back-layer piece onto the four #10 screws, on top of the spacer rings. Insert the 1/4"-diameter screw into the LED hole. |
| | | Middle-back layer. Put the three middle-back pieces onto the five screws, on top of the back layer. |
| | | Middle-front layer. Put the three middle-front pieces onto the five screws, on top of the middle-back layer. |
| | | DO NOT put the front part onto the screws. The cylinder front part will not be cemented to the cylinder back part. |
| | | Put nuts on all five screws and tighten them to clamp the layers together. Check that all the pieces are straight and aligned. Especially check that the two smallest pieces with the LED holes in the middle layers are straight (because they have only one alignment screw). |
| | | Align and clamp the ends of the cylinder walls. The outer walls of all three layers should be flush. |
| 5 | Cement all the layers of each back part. | Apply acrylic solvent cement to all edges. |

**Cylinder fronts with laser-etched slots.** When the cylinder front and back are assembled with screws and nuts, they should not bind the enclosed moving parts (pistons, valves, and valve pushers). Binding is possible because the moving parts are the same thickness as the slots that hold them (1/8”-thick pistons in 1/8”-thick slots, 1/4"-thick valves and valve pushers in 1/4”-thick slots). There are two alternative methods to prevent binding: (A) The basic method is to simply not over-tighten the screws and nuts that squeeze the cylinder fronts and backs together (this is the method we used for our models 1 and 2). (B) The alternative method is to laser etch (or manually sand) the surfaces of cylinder fronts that that touch the moving parts (the slots for the pistons, valves, and valve pushers) so the slots are slightly roomier, and the cylinder front will not bind the moving parts even when you tighten the screws and nuts. The laser template for the cylinder front shows the areas to be laser etched. If you do laser etching, you should polish the rough etched surface to reduce friction. (You can use a hand-held rotary tool with sanding, buffing, and polishing heads.)

### 4.8.3 Making the pistons

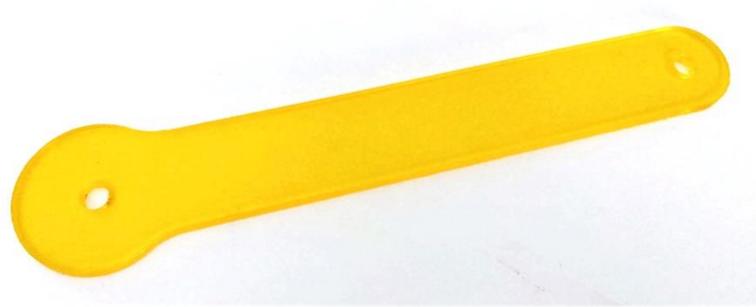


*Piston.*

The pistons are described in the Assembly Manual.

| Instructions: Making the pistons | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut nine pistons. | **Laser template: Radial-LTemplate-Piston** |
| | | Material: 1/8”-thick acrylic, color: transparent blue. |

### 4.8.4 Making the con rods



*Con rod.*

The con rods are described in the Assembly Manual.

| Instructions: Making the con rods | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut eight con rods. | **Laser template: Radial-LTemplate-ConRod** |
| | | Material: 1/8”-thick acrylic, color: transparent yellow. |

## 4.8.5 Making the master rod

*Master rod (and flange).*

The master rod is described in the Assembly Manual.

| Instructions: Making the master rod (and flange) | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut the master rod and flange. | **Laser template: Radial-LTemplate-MasterRod** |
| | | Material: 1/8”-thick acrylic, color: transparent red. |
| | | Laser cut the master rod and the flange (holes first). |
| 2 | Cement the master rod to the flange. | Choose one side of the flange to be the front side. |
| | | Put the master rod onto the front side of the flange. (The eight con rods will also be attached to the front side of the flange, so all nine rods will be at the same level.) |
| | | Set the overlap distance (0.75” in the template) to make the length of the rod match the length of a con rod. You can compare the lengths by aligning the two screw holes for the master rod with the two screw holes of a con rod. (Notice that the flange has nine screw holes, but there will be only eight screws. The extra hole is provided to help you measure the length of the master rod.) |
| | | Clamp the master rod onto the flange. |
| | | Apply acrylic solvent cement to all edges. |
| 3 | Cut the tube. | Material: 1.5” ID, 1.75” OD clear acrylic tube. |
| | | Cut to length 3/8”. |
| | | The master rod hub tube (1.50” ID) will fit around the crankpin shaft (1.25” OD) with room for a low-friction bushing ring (1.25” ID, 1.5” OD). |
| 4 | Cement the tube into the hole in the flange. | Put the 3/8”-long tube into the 1/8”-thick flange with 3/16” protruding from the front side of the flange and 1/16” protruding from the back side of the flange. The front side of the flange and the back side of the con rods should be at the mid-plane of the tube. (This position optimizes clearances for the moving parts.) See diagram 4.7.4. |
| | | Apply acrylic solvent cement to all edges. |

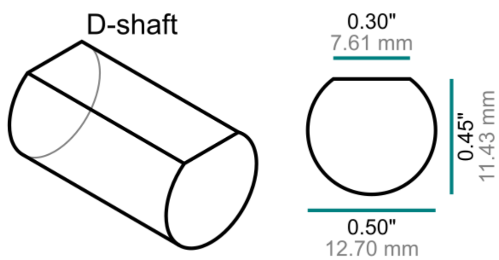
## 4.9 Small shafts for gears and rocker-pushers

### 4.9.1 Parts list

The model has 20 small shafts (smaller than the driveshaft): the gears shaft, the distributor shaft, and 18 rocker-pusher shafts.

| Small shafts: Custom parts (built into other custom parts) | | | | |
|---|---|---|---|---|
| Shaft | Shaft type | Cemented part | Assembled parts | Quantity |
| Gears shaft | D-shaft | Gear18 | Gear48, gear24 | 1 |
| Distributor shaft | D-shaft | Rotor spline connector | Gear33_distributor | 1 |
| Rocker-pusher shafts | D-shaft | Valve pushers | Rocker arms | 18 |

### 4.9.2 Making the D-shafts

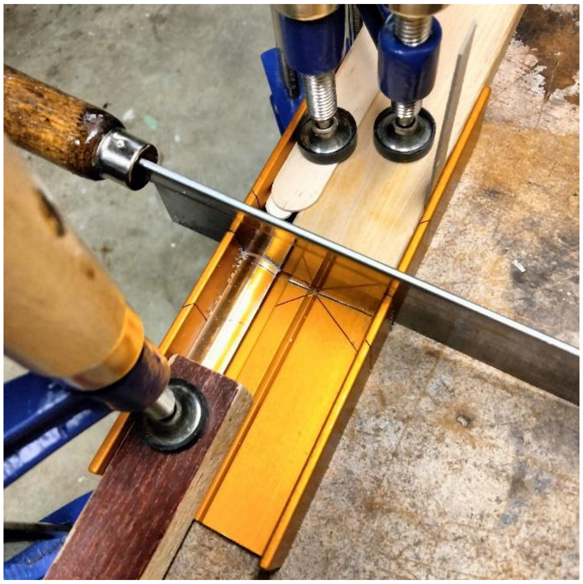



*D-shaft profile: diameter=0.50”,*
*flat diameter=0.45”, flat width=0.30”.*

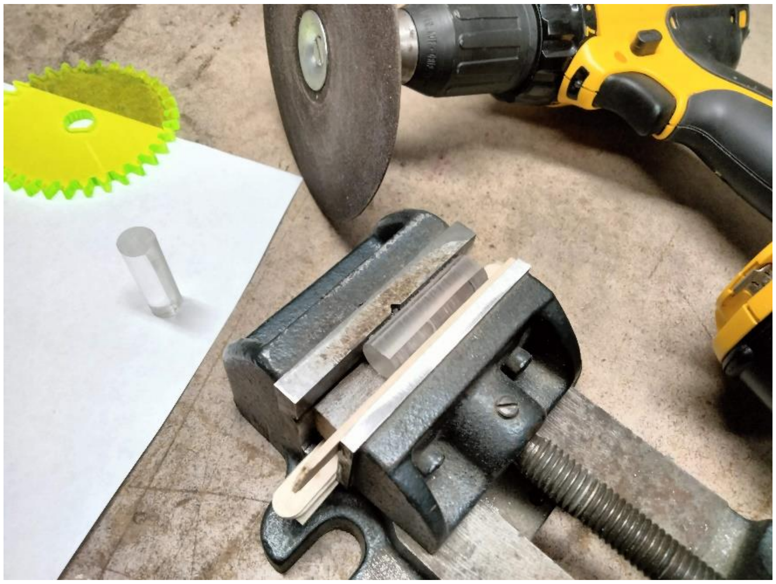
The D-shafts are described in the Assembly Manual.

All small shafts are 1/2"-diameter acrylic D-shafts connected to D-holes in the acrylic parts. (Alternative: You can use different kinds of shafts. See the Design Alternatives document.)

Make all the D-shafts. All three types of D-shafts are made the same way, but they have different lengths.



*Making a shaft by cutting an acrylic rod using*
*a fine-toothed saw, a miter box, blocks, shims, and clamps.*

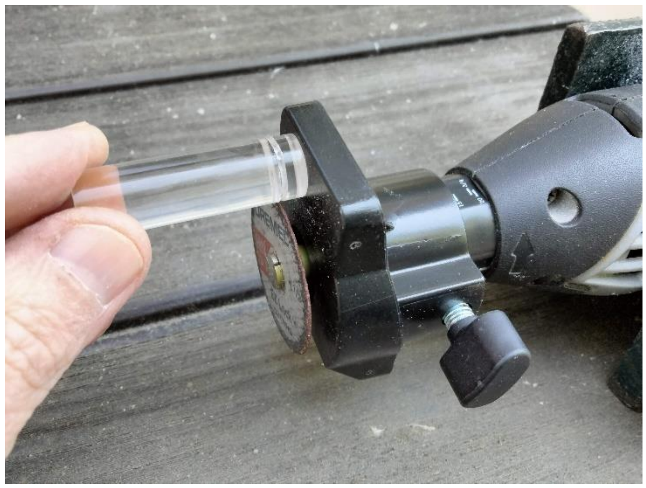


*Grinding a D-shaft using a disc sander, vise, blocks, and shims.*

*Grinding a D-shaft using a handheld rotary tool with a sanding drum, and a vise.*

—


*Measuring a D-shaft using electronic calipers.*



*Cutting a snap-ring groove in a D-shaft using a handheld rotary tool with a cutting wheel and a guide*

.

| Instructions: Making the D-shafts | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Print the D-shaft templates, full scale. | **Paper template: Radial-PTemplate-DShaft-Gears** |
| | | **Paper template: Radial-PTemplate-DShaft-Distributor** |
| | | **Paper template: Radial-PTemplate-DShaft-RockerPusher** |
| | | Each paper template specifies the D-shaft profile, the shaft length, where to cement the part to the shaft, and where to cut the groove for the snap ring. |
| | | Print the templates, full scale. |
| 2 | Cut the rods. | Material: 1/2”-diameter clear acrylic rod. |
| | | Cut one gears shaft to the length specified in the template (2+1/8”). |
| | | Cut one distributor shaft to the length specified in the template (1+3/4”). |
| | | Cut 18 rocker-pusher shafts to the length specified in the template (1+5/8”). |
| | | Cut the rod with a fine-toothed saw and a miter box (see photo), or a power miter saw. |
| | | To cut many shafts all the same length, you can use a stop block (see photo). |
| | | You can cut segments before grinding the flat sides, or grind the flat sides before cutting the segments. (We cut the segments before grinding the flat sides.) |
| 3 | Grind or sand the flat sides of the rods. | You will need remove 0.05” from the side of the rod to reduce the thickness to 0.45” (11.43 mm). |
| | | Hold the rod securely with a vise or clamp. Use or make some kind of jig to help you quickly sand all the rods to the same precise specified thickness. For example, we added shims (thin sticks and thin cardboard) to hold the acrylic rods exactly 0.05” above the metal edge of my vise (see photo). When my sander reaches the metal edge, it will have removed exactly 0.05” from the rod. |
| | | Sand or grind the rod using your preferred sanding/grinding tool, such as a disc sander (see photo), belt sander, grinding wheel, or handheld rotary tool with sanding drum. |
| 4 | Check the profile dimensions and make fine adjustments. | Check the D-shaft profile dimensions using calipers (see photo). The thickness of the rod to the flat side should be 0.45”. The width of the flat side should be 0.30”. |
| | | Check the fit by inserting the D-shaft into the laser-cut D-holes in the gears, rocker arms, or valve pushers. It should be very snug. The model will work the D-shafts are a tiny bit loose, but it will work better if the D-shafts are quite tight. |
| | | If necessary, do additional sanding using your preferred sanding/grinding tool, such as a handheld rotary tool with sanding drum (see photo) or a hand sanding block. |
| 5 | Cut grooves for the snap rings | The gears D-shaft and the rocker-pusher D-shafts use snap rings (retaining rings). The distributor D-shaft does not. The positions of the grooves are specified in the D-shaft templates. (Your model may differ.) |
| | | Cut thin, shallow grooves around the shafts for snap rings, about 1/32” thick. |
| | | Use a guide or make a jig to cut the grooves evenly all the way around the rod. For example, we used a handheld rotary tool with a cutting wheel and a guide (see photo). |
| 6 | Cement one acrylic piece to each D-shaft. | Each D-shaft will be cemented to one acrylic piece, at the position shown in the D-shaft templates. |
| | | The gears D-shaft will be cemented to gear18 (4.10.2). |
| | | The distributor D-shaft will be cemented to the distributor rotor spline connector (4.12.4). |
| | | The rocker-pusher D-shafts will be cemented to the valve pushers (4.11.3). |

## 4.10 Gears

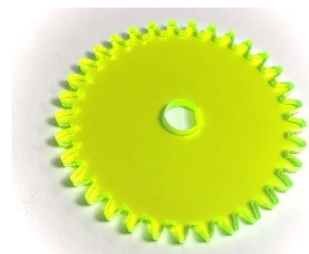
### 4.10.1 Parts list

| **Spur gears: Custom parts** | |
|---|---|
| Part | Quantity |
| Gear33_driveshaft (on middle driveshaft) | 1 |
| Gear18 (with D-shaft) | 1 |
| Gear24 | 1 |
| Gear48 | 1 |
| Gear33_distributor | 1 |

### 4.10.2 Making the gears

*Gear33_driveshaft will be cemented onto the middle driveshaft.*

*Gear18 (with D-shaft), gear48, and gear24.*



*Gear33_distributor.*

The model has six gears: five spur gears and one internal gear. The gears and the operation of the gear train are described in the Assembly Manual.

Here are the instructions for making the five spur gears:

| **Instructions: Making gear33_driveshaft** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut gear33_driveshaft. | **Laser template: Radial-LTemplate-Gear33_driveshaft** |
| | | Material: 1/4”-thick acrylic, color: transparent violet or blue. |
| 2 | Cement gear33_driveshaft to the middle driveshaft. | Instructions are in 4.7.8. |

—

| **Instructions: Making gear18 (with D-shaft)** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut gear18. | **Laser template: Radial-LTemplate-Gear18** |
| | | Material: 1/4”-thick acrylic, color: black. |
| 2 | Cement gear18 to the D-shaft. | **Paper template: Radial-PTemplate-DShaft-Gears** |
| | | Use the gears D-shaft (2+1/8” long). See 4.9.2. |
| | | Put gear18 flush on the end of the D-shaft. The position is shown in the D-shaft template. (Notice that the laser cut edges of the gear teeth may be slightly beveled, which is probably not significant, but you can decide which side is the front side before you cement it.) |
| | | Apply acrylic solvent cement. |

—

| Instructions: Making gear24 | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut gear24. | **Laser template: Radial-LTemplate-Gear24** |
| | | Material: 1/4”-thick acrylic, color: transparent pink. |

—

| Instructions: Making gear48 | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut gear48. | **Laser template: Radial-LTemplate-Gear48** |
| | | Material: 1/4”-thick acrylic, color: transparent blue. |

—

| Instructions: Making gear33_distributor | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut gear33_distributor. | **Laser template: Radial-LTemplate-Gear33_distributor** |
| | | Material: 1/4”-thick acrylic, color: transparent yellow. |

**Beveled edges of gears.** Your laser cutter may make slightly beveled edges. Ideally, the gear teeth contact surfaces should not be beveled, but the gears will work even if the edges are slightly beveled. You can reduce the beveling by adjusting your laser cutter settings. (To reduce the beveling, we laser cut 1/4"-thick sheets with two passes, the first pass focused at the top of the 1/4" sheet, and the second pass focused at 1/8”, half the thickness of the sheet.)

**Smoothed edges of gears.** The gears will probably work just fine even if the edges are slightly bumpy, so the gears probably do not need any additional smoothing after laser cutting. You can smooth the edges (and reduce the beveling) with a handheld rotary tool using sanding, buffing, and polishing attachments.

### 4.10.3 Gear design

**Involute gears.** The gears are standard involute gears based on standard gear parameters.

| Gear parameters definitions | | | |
|---|---|---|---|
| Gear parameter | Symbol | Description | Equations |
| Number of teeth | Z | Number of teeth. | |
| Pitch diameter | D | Diameter of the reference pitch circle. | $D_{mm} = M \times Z$<br>$D_{in} = Z/DP$ |
| Outer diameter | OD | Outer diameter. | $OD_{mm} = M \times (Z+2)$ |
| Module | M | Pitch diameter (mm) per number of teeth. | $M = D_{mm}/Z$<br>$M = 25.4/DP$ |
| Diametral pitch | DP | Number of teeth per pitch diameter (inches). | $DP = Z/D_{in}$<br>$DP = 25.4/M$ |
| Pressure angle | PA | Angle of the face of the tooth at the pitch circle. | |
| Clearance | C | Gap between the gear’s tooth tip and the meshing gear’s tooth root. | |

Our gears use the following gear parameters:

| Gear parameters | | | | | | |
|---|---|---|---|---|---|---|
| Gear name | Type | # Teeth | Module | Pressure angle | Clearance | Shaft hole |
| Gear33_driveshaft | Spur | 33 | 2.55644 | 20° | 0.5 mm | 1.25” diameter |
| Gear18 | Spur | 18 | 2.55644 | 30° | 0.5 mm | 0.5” D-hole |
| Gear24 | Spur | 24 | 2.55644 | 20° | 0.5 mm | 0.5” D-hole |
| Gear48 | Spur | 48 | 2.55644 | 20° | 0.5 mm | 0.5” D-hole |
| Gear33_distributor | Spur | 33 | 2.55644 | 20° | 0.5 mm | 0.5” D-hole |
| Gear99_internal_cam_disk | Internal | 99 | 2.55644 | 30° | 0.5 mm | N/A |

**Module.** All gears in our model have M = 2.55644 (equivalently, DP = 25.4/M = 9.93569). Why this precise number? We (Keith) did not know Wes’s original value of M (or DP), so we calculated M from a key distance L in Wes’s original SolidWorks CAD model. We used the SolidWorks viewer to measure the exact distance L between the centers of the driveshaft (gear33) and the gear shaft (gear48). We measured L = 103.536 mm (4.07622 inches, roughly 4+5/64”, not a nice round number). We then calculated $M = L \times 2/(33+48) = 2.55644$.

**Pressure angle.** Most of the gears in our model have PA = 20°, but gear99 and gear18 have PA = 30°.

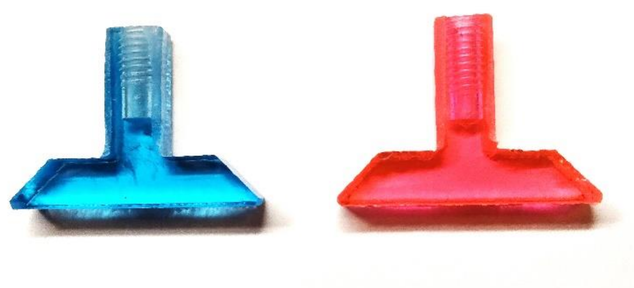
**Gear generators.** You can use any standard involute gear generator to make new gear outlines for laser templates. Wes originally used the SolidWorks gear generator. Keith later used a free online gear generator (Evolvent Design) to regenerate the gear outlines. Inkscape has a basic gear generator (Inkscape > Extensions > Render > Gear).

## 4.11 Valve system: Valves, rocker-pushers, pushrods, cam disk

### 4.11.1 Parts list

| Valve system: Custom parts | |
|---|---|
| Part | Quantity |
| Cam disk | 1 |
| Pushrods | 18 |
| Rocker arms | 18 |
| Valve pushers (with D-shafts) | 18 |
| Valves | 18 |

### 4.11.2 Making the valves



*Valves, intake (blue) and exhaust (pink or red).*

The valves are described in the Assembly Manual.

| Instructions: Making the valves | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut at least nine intake valves and at least nine exhaust valves. | **Laser template: Radial-LTemplate-Valve** |
| | | Material: 1/4”-thick acrylic, color: transparent blue (intake).<br>Material: 1/4”-thick acrylic, color: transparent pink or red (exhaust). |
| | | Laser cut at least nine intake valves and at least nine exhaust valves. Laser cut several extra valves because you are likely to break several valve stems when you drill and tap them. |
| 2 | Drill and tap a threaded screw hole in each valve stem. | Drill (#29) and tap #8-32 threaded screw hole into the valve stem, at least 1/4" long. |
| | | It is very difficult to drill a hole in the thin stem without breaking the stem. Learn techniques for drilling acrylic. Practice with scrap acrylic. Hold the part in a vise. Use a drill guide or drill press to drill a straight hole. Drill a pilot hole first. Drill slowly to avoid breaking or melting the acrylic. Use lubricant. |
| 3 | Sand the valve stem, if necessary. | If the square valve stem does not slide easily in the square valve hole in the cylinder (and loosening the cylinder screws does not allow it to slide), then you can sand the valve stem to make it smaller. |
| | | A 3/8”-diameter valve spring (see the Assembly Manual) will surround the valve stem. If the spring does not slide easily over the square valve stem, then you can sand the valve stem to slightly round the corners. Do not completely round the stem, because it needs to remain square, so it does not rotate inside the square valve hole. Make sure the valve stem is smooth over its entire length, so it will not catch any edges as it slides. |

### 4.11.3 Making the valve pushers

*Valve pusher with D-shaft.*

The valve pushers are described in the Assembly Manual.

| Instructions: Making the valve pushers (with D-shafts) | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut 18 valve pushers. | **Laser template: Radial-LTemplate-ValvePusher** |
| | | Material: 1/4”-thick acrylic, color: transparent blue. |
| 2 | Cement the valve pushers to the D-shafts. | **Paper template: Radial-PTemplate-DShaft-RockerPusher** |
| | | Use the rocker-pusher D-shafts (1+5/8” long). See 4.9.2. |
| | | Put the back end of the D-shaft into the valve pusher, with 1/4" protruding on the back side. The position is shown in the D-shaft template. |
| | | Apply acrylic solvent cement. |

The valve pushers are cemented to the D-shafts. (Alternative: The valve pushers may be fastened to the shafts with screws. See the Design Alternatives document.)

### 4.11.4 Making the rocker arms

*Rocker arm.*

The rocker arms are described in the Assembly Manual.

| **Instructions: Making the rocker arms** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut 18 rocker arms. | **Laser template: Radial-LTemplate-RockerArm** |
| | | Material: 1/4”-thick acrylic, color: transparent green. |

### 4.11.5 Making the pushrods

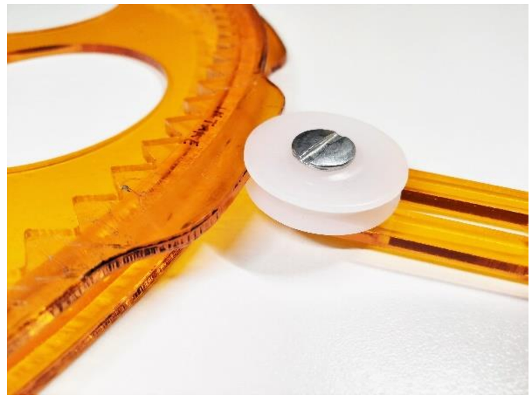
*Pushrod.*

The pushrods are described in the Assembly Manual.

| **Instructions: Making the pushrods** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut 18 pushrods. | **Laser template: Radial-LTemplate-Pushrod** |
| | | Material: 1/8”-thick acrylic, color: transparent orange. |

### 4.11.6 Cam followers

*Cam follower (grooved wheel).*



*Cam follower (grooved wheel) on cam track.*

The cam followers are described in the Assembly Manual. They are store-bought nylon grooved wheels.

### 4.11.7 Making the cam disk

*Cam disk with intake cam track (front) and exhaust cam track (back).*


*Clamping and cementing the layers of the cam disk.*

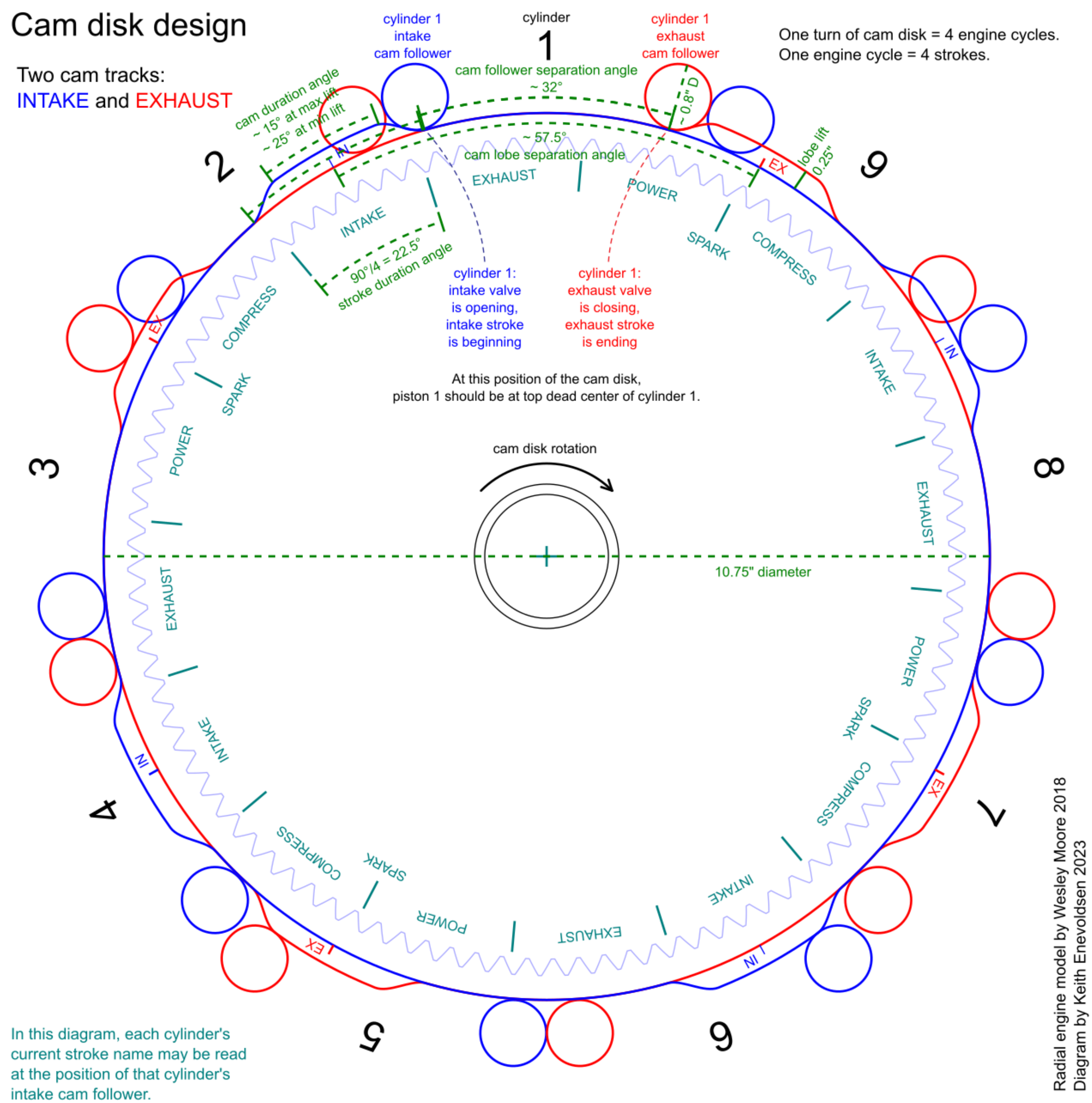
The cam disk is described in the Assembly Manual. The detailed design is in 4.11.8.

| **Cam disk layers** | | | | | |
|---|---|---|---|---|---|
| Part | Layer | Thk. | Cam track | Gear99_internal | Hub |
| Cam disk | Front cam ring | 1/8" | Intake | ✓ | |
| Cam disk | Middle ring | 1/4" | | ✓ | |
| Cam disk | Back cam disk | 1/8" | Exhaust | | ✓ |

| Instructions: Making the cam disk | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser score and cut the back cam disk. | **Laser template: Radial-LTemplate-CamDisk-Back** |
| | | Material: 1/8”-thick acrylic, color: transparent orange. |
| | | Laser score the short lines marking the centers of the four lobes. |
| | | Laser cut the back cam disk (hole first). |
| 2 | Laser score and cut the front cam ring. | **Laser template: Radial-LTemplate-CamDisk-Front** |
| | | Material: 1/8”-thick acrylic, color: transparent orange or transparent blue. See the color note below. |
| | | Laser score the short lines marking the centers of the four lobes. |
| | | Laser cut the front cam ring (hole first). |
| 3 | Laser cut the middle ring. | **Laser template: Radial-LTemplate-CamDisk-Middle** |
| | | Material: 1/4”-thick acrylic, color: transparent orange or clear. |
| | | Laser cut the middle ring (hole first). |
| 4 | Cement the middle cam ring to the front cam ring. | Align the gear99 teeth in both rings. Together they make one extra thick gear99. The laser cut edges of the teeth may be slightly beveled, so try flipping the two pieces to find the orientation that makes the teeth match up most smoothly. Ensure that gear99 will engage well with gear18. |
| | | Clamp the two rings together with several small clamps. |
| | | Apply acrylic solvent cement to all edges. |
| 5 | Choose your cam lobe separation angle. | The front cam track is rotated with respect to the back cam track by the cam lobe separation angle. See the cam disk design diagram (4.11.8). Our cam lobe separation angle is 57.5°. You can choose a different angle for your model, especially if your model geometry is different. |
| 6 | Print the protractor template, full scale, and mark your angle. | **Paper template: Radial-PTemplate-CamDiskProtractor** |
| | | The template is a protractor that is the size of the cam disk. |
| | | Print the protractor template, full scale. |
| | | Mark your chosen cam lobe separation angle. Our angle (57.5°) is pre-marked. |
| 7 | Put the protractor on the back side of the back cam disk. | Put the paper protractor on the back side of the back cam disk. It should be centered and rotated until the center line of one back cam lobe (as indicated by the laser-scored marking) is aligned with the 0° angle on the template. |
| | | Tape the paper protractor to the disk. |
| 8 | Put the front cam ring (with the middle ring) onto the back cam disk. | Put the front cam ring (with the cemented middle ring) onto the back cam disk. It should be centered and rotated until the center line of one front cam lobe (as indicated by the laser-scored marking) is aligned with your cam lobe separation angle on the protractor. It should look like the cam disk design diagram (4.11.8). |
| | | Clamp the ring to the disk with several small clamps. |
| 9 | Cement the ring to the disk. | Apply acrylic solvent cement to all edges. |
| 10 | Cut the cam disk hub tube. | Material: 1.5” ID, 1.75” OD clear acrylic tube. |
| | | Cut to length 1/2”. |
| | | The cam disk hub tube (1.50” ID) will fit around the driveshaft (1.25” OD) with room for a low-friction bushing ring (1.25” ID, 1.5” OD). |
| 11 | Cement the hub tube into the disk. | Put the hub tube into the center of the cam disk, flush with the back side of the disk. See diagram 4.7.4. |
| | | Apply acrylic solvent cement to all edges. |

**Cam disk colors.** We made all three layers of our cam disk the same color (transparent orange). You may want to make the front intake cam track another color (transparent blue) to distinguish it from the back exhaust cam track (transparent orange). Also, the middle ring can simply be clear.

### 4.11.8 Cam disk design




*Cam disk design.*

The diagram shows the detailed geometry of the cam tracks. The diagram shows the cam disk at the position at which cylinder 1's exhaust valve has just closed, and its intake valve is just about to open. In other words, cylinder 1 is just at the end of its exhaust stroke and just at the beginning of its intake stroke.

One turn of the cam disk = four engine cycles (a quarter turn = one engine cycle). One engine cycle = four strokes: intake, compress, power, and exhaust.

| Cam disk dimensions | |
|---|---|
| Parameter | Value |
| Stroke duration angle | 90/4 = 22.5° |
| Cam disk diameter, track baseline | 10.75” |
| Cam lobe maximum lift | 0.25” |
| Cam duration angle (lobe length) at maximum lift | ~ 15° |
| Cam duration angle (lobe length) at minimum (>0) lift | ~ 25° |
| Cam follower separation angle | ~ 32° |
| Cam lobe separation angle | ~ 57.5° |

The intake and exhaust cam tracks have identical profiles, each with four lobes spaced at 90°, angularly offset from each other. Each lobe has a maximum lift of 0.25”. Each lobe is a curve that ramps up, then stays steady at maximum lift, then ramps back down. The length of the lobe is called the cam duration angle.

The intake and exhaust lobes are offset by the **cam lobe separation angle**. The cam lobe separation angle is the angular distance from the center of an exhaust lobe to the center of the next (counterclockwise) intake lobe. The cam lobe separation angle is roughly the sum of the cam follower separation angle and the cam duration angle at minimum (>0) lift. The cam lobe separation angle is permanently set when the two cam tracks are cemented together.

If your model’s geometry is different than our model, then you can adjust these parameters. For example, if the diameter of your cam follower wheels is different, or your cam follower separation angle is different, then you can use a different cam lobe separation angle.

## 4.12 Electrical system: Distributor

### 4.12.1 Parts list

| Distributor: Custom parts | |
|---|---|
| Part | Quantity |
| Distributor cap | 1 |
| Distributor spline connector (with D-shaft) | 1 |
| Distributor rotor (with springs) | 1 |
| Distributor rotor contacts strip | 1 |

—

| Distributor: Standard parts (built into custom parts) | | | |
|---|---|---|---|
| Part | Size | Quantity | Usage |
| Conical springs | Approx. 6 mm × 4.25 mm × 5.5 mm (large diam. × small diam. × length) | 2 | Distributor rotor |

### 4.12.2 Materials for making the distributor

#### *4.12.2.1 Metal for rotor contacts strip*

Contacts are made from very thin metal sheet (foil). Very thin stainless steel or brass are preferred, but other metals are acceptable.

| Materials: Metal for rotor contacts strip | | | | |
|---|---|---|---|---|
| Material | Form | Size | Thickness | Usage |
| Preferred: stainless steel or brass.<br>Acceptable: steel, copper, or aluminum. | Sheet or strip | ~2”×1” sheet/strip | ~0.01” (~0.3 mm) | Rotor contacts |

**Metal form, size, thickness.** The contacts strip is folded from a T-shaped metal sheet, ~2” × 1”, cut out of one piece of metal sheet (foil) or 1”-wide strip. It should be very thin and flexible (about as thin as the aluminum in a fizzy drink can), so it can be moved by the little springs on the rotor.

| Metal properties | | | | | |
|---|---|---|---|---|---|
| Metal | Fitness for purpose | Conductivity | Resistance to tarnish and oxidation | Wear-resistance (hardness) | Resilience (springiness) |
| Stainless steel | Preferred | ✓ | ✓ | ✓ | ✓ |
| Brass | Preferred | ✓ | ✓ | ✓ | ✓ |
| Steel | Acceptable | ✓ | | ✓ | ✓ |
| Copper | Acceptable | ✓ | | | |
| Aluminum | Acceptable | ✓ | | | |

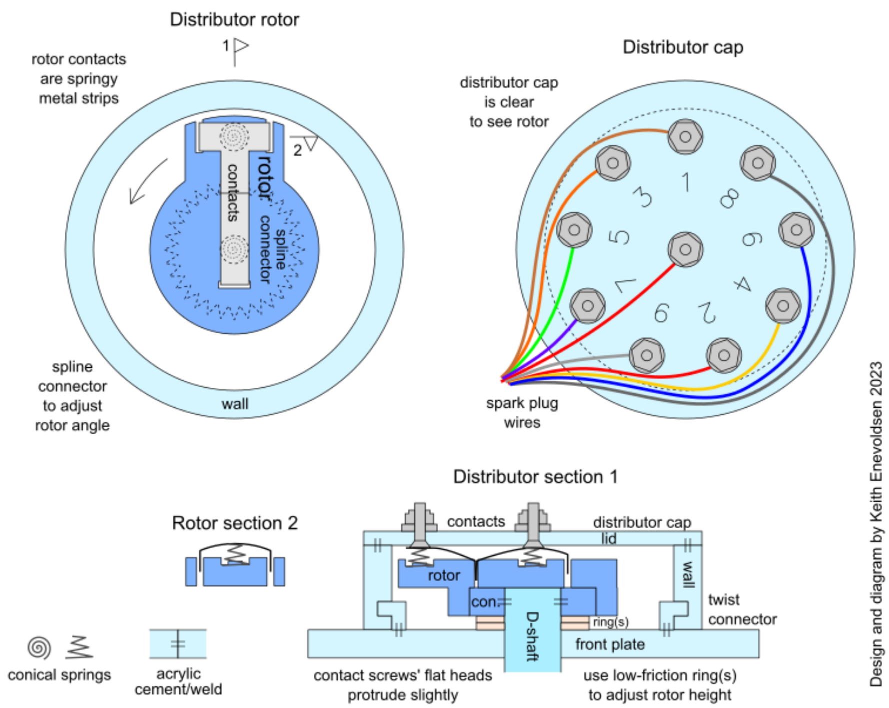
**Metal properties:**

- Contacts must be electrically conductive. All metals are conductive.
- We prefer a metal that is resistant to tarnish or oxidation. Otherwise, you may need to periodically remove the tarnish or oxidation (with fine sandpaper).
- We prefer a metal that is resistant to wear. Our original thin aluminum contacts strip started to wear out, just from occasional hand-cranked (non-motorized) usage, so we replaced it with thin stainless steel.
- The resilience (springiness) of the metal itself is not significant in our model because our rotor has little springs under the contacts strip. If your model does not have springs, then your contacts strip itself should be resilient (springy).

### 4.12.3 Distributor

*Distributor cap and rotor.*

The distributor is described in the Assembly Manual. The distributor has a cap and a rotor.




*Distributor cap and rotor diagram.*

### 4.12.4 Making the rotor spline connector

*Rotor spline connector with D-shaft.*

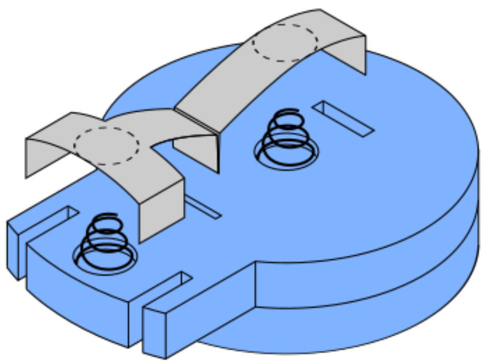
The rotor spline connector is described in the Assembly Manual.

| Instructions: Making the rotor spline connector (with D-shaft) | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut the inner spline connector. | **Laser template: Radial-LTemplate-DistributorRotor** |
| | | Material: 1/4”-thick acrylic, color: transparent blue. |
| | | Laser cut the inner spline connector, the star-shaped piece with the D-hole (cut the hole first). |
| | | After you have made both inner and outer spline connectors, check that they fit together well. They should be easy to connect and disconnect. |
| 2 | Cement the inner spline connector to the D-shaft. | **Paper template: Radial-PTemplate-DShaft-Distributor** |
| | | Use the distributor D-shaft (1+3/4” long). See 4.9.2. |
| | | Put the inner spline connector flush on the end of the D-shaft. The position is shown in the D-shaft template. (Notice that the laser cut edges of the spline connector may be slightly beveled, which is probably not significant. You can decide which side is the front side before you cement it.) |
| | | Apply acrylic solvent cement. |

### 4.12.5 Rotor and contacts strip

*Rotor with springs and contacts strip.*

*Rotor-&-contacts assembly.*



*Rotor with springs and contacts strip.*

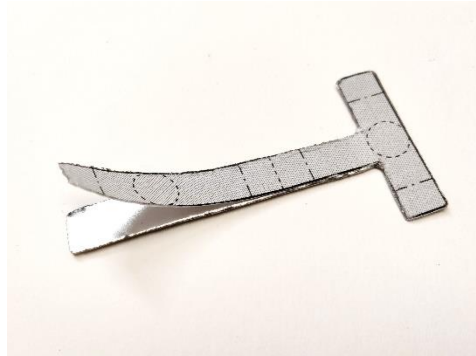
The rotor and contacts strip are described in the Assembly Manual.

#### 4.12.5.1 Making the rotor

| **Instructions: Making the rotor (with springs)** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser cut the rotor and the outer spline connector. | **Laser template: Radial-LTemplate-DistributorRotor** |
| | | Material: 1/4”-thick acrylic, color: transparent blue. |
| | | Etch two circular pits in the rotor to hold the two conical springs. The circular pits have an etched depth of about 1.2 mm (<1/16”). Each pit has a slightly deeper outer ring with same outer diameter and an etched depth of about 1.8 mm (>1/16”). (We did two laser etching passes for the circular pits and one more pass for the outer rings.) |
| | | Laser cut the rotor (cut the slots first). |
| | | Laser cut the outer spline connector, the circular piece with the star-shaped hole (cut the hole first). |
| | | After you have made both inner and outer spline connectors, check that they fit together well. They should be easy to connect and disconnect. |
| 2 | Cement the outer spline connector to the rotor. | Put the outer spline connector on the back side of the rotor and center it by aligning the circular outer edges. |
| | | Clamp the two pieces together. |
| | | Apply acrylic solvent cement to all edges. |
| 3 | Glue two conical springs into the rotor. | Put the two conical springs into the two pits in the rotor. The size of the springs is in the parts list. The big end of each conical spring should fit into the deeper outer ring of the pit. The small end of each spring should protrude from the front side of the rotor at least 1/8” (3 mm). |
| | | Glue the two conical springs into the two pits so they will not fall out and get lost. Use any glue that sticks well but is removable so you can replace the springs if necessary. You can use craft glue or hot glue, but not acrylic cement. |

### 4.12.5.2 Making the rotor contacts strip

*Cutting the T-shaped contacts strip with metal snips, using the paper template as a guide.*



*The paper template is taped to the metal contacts strip with double-sided tape.*

*Bending the metal strip with needle-nose pliers, using the paper template as a guide.*

*Hammering bumps at contact points, using a hammer, center punch, and washer.*

The contacts strip is handcrafted. You will make the contacts strip by cutting a T-shape from a metal sheet, then bending it and hammering it. (We tried making the T-shape by soldering two 1/4"-wide metal strips, but the soldered join was prone to failure, so we recommend cutting the T-shape from a single sheet.)

| **Instructions: Making the rotor contacts strip** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Print the rotor contacts template, full scale. | **Paper template: Radial-PTemplate-DistributorRotorContacts** |
| | | The template has the flat folding pattern for the contacts strip. |
| | | Print the template, full scale. |
| 2 | Cut the T-shape from thin metal sheet. | Material: stainless steel or brass metal sheet or 1”-wide strip, very thin: ~.01” (~0.3 mm). See the materials list (4.12.2.1). |
| | | Tape the paper template to the metal sheet with double-sided tape. |
| | | Cut a single T-shaped piece from thin metal sheet, using the template as a guide. Use metal snips, a fine-toothed saw, or a handheld rotary tool with a cutting wheel. |
| | | Sand all sharp edges and corners. |
| 3 | Fold and bend. | Make sharp folds and smooth bends, using the paper template as a guide. Use needle-nose pliers to make sharp folds. |
| 4 | Hammer two contact bumps. | Make slight contact bumps or buttons (upward-pointing indentations) at the two contact points. Put the contacts strip upside-down on your worktable with a washer centered underneath the contact point. Center a stubby center punch (or metal rod) over the contact point and tap it with the hammer to form a shallow indentation. |
| 5 | Check the fit. | Insert the contacts strip into the rotor, as shown in the diagram. The middle tab of the strip should fit snugly into the middle slot (between the two contact points), but the other ends of the strip should be free to move up and down on the springs. Bend the metal to make it fit. |

### 4.12.6 Making the distributor cap

*Distributor cap with lid, wall, and twist connector base all cemented together.*

*Distributor cap lid.*

*Distributor cap wall.*

The distributor cap is described in the Assembly Manual.

| Instructions: Making the distributor cap lid | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser score and cut the distributor cap lid. | **Laser template: Radial-LTemplate-DistributorCapLid** |
| | | Material: 1/8”-thick clear acrylic, cast or extruded. The scored numerals will be clearly readable with either cast or extruded acrylic, but they will look crisper with cast acrylic. |
| | | Laser score the nine guidelines, the cylinder numbers, and the arrow. |
| | | Laser cut the distributor cap lid (pilot holes first). |
| 2 | Paint the numerals and arrow. | Paint the scored numerals and arrow black. Paint with a brush before removing the paper mask. |
| 3 | Drill the 10 screw holes. | Drill 10 screw holes (starting with the pilot holes) to fit the #4 screws. The screws will have lock nuts, so it is not necessary for the holes to be threaded, but you can make threaded holes. For threaded holes, use #43 drill bit and #4-40 tap. For unthreaded holes, drill holes that are a close fit for #4 screws (#32 drill bit). |
| 4 | Countersink the screw holes on the back side. | On the back side of the lid, slightly countersink the screw holes for flat-head #4-40 screws. |
| | | Use a countersink bit, not a drill bit, to make precise countersinks. |
| | | Countersink the holes just enough so that the flat heads of the contact screws will be almost flush with the surface but will protrude slightly to make contact. |
| | | If you countersink too much, the flat-head screws will not make contact. If you accidentally countersink some holes a little too much, you can fix them by adding a layer of thick-bodied acrylic cement to the countersink surface, but it is better to start over and make an entirely new lid. |

—

| Instructions: Making the distributor cap wall | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser score and cut two wall rings. | **Laser template: Radial-LTemplate-DistributorCapWall** |
| | | Material: 1/4”-thick clear acrylic. |
| | | Laser score nine guidelines on each ring (optional). |
| | | Laser cut two rings (holes first). |
| 2 | Cement the two rings together to make one 1/2"-thick ring. | Put the two rings together. Align the scored guidelines. |
| | | Clamp the two pieces together. |
| | | Apply acrylic solvent cement. |

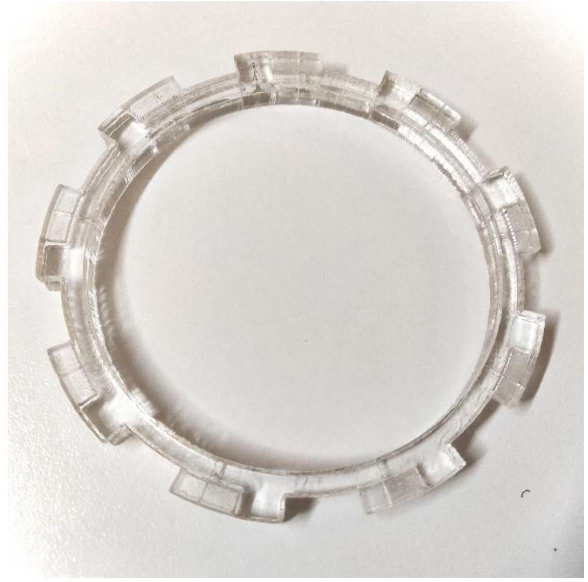
—

| Instructions: Joining the distributor cap lid to the wall | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Cement the lid to the wall. | Put the lid onto the wall, centered, and align the scored guidelines. |
| | | Clamp the pieces together. |
| | | Apply acrylic solvent cement. |

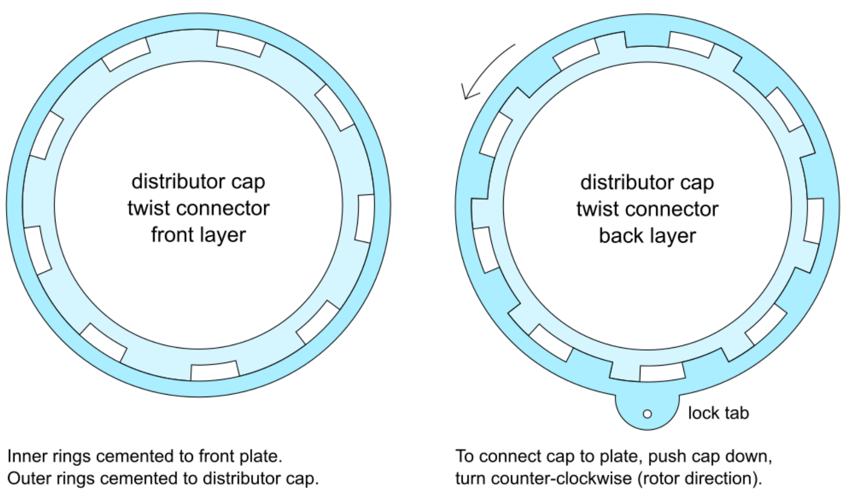
## 4.12.7 Distributor cap twist connector

### *4.12.7.1 Making the twist connector rings*

*Twist connector outer rings to be cemented to distributor cap.*



*Twist connector inner rings to be cemented to front plate.*




*The distributor cap twist connector is made from four laser-cut rings.*

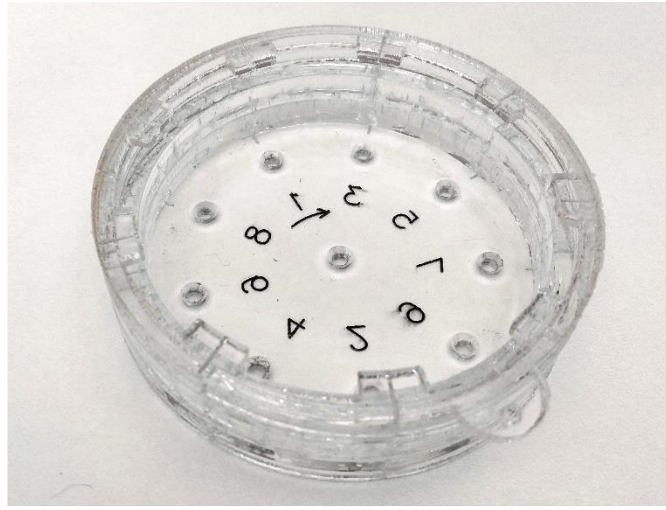
The distributor cap twist connector is described in the Assembly Manual.

| Instructions: Making the distributor twist connector rings | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser score, etch, and cut the distributor cap twist connector rings. | **Laser template: Radial-LTemplate-DistributorConnector** |
| | | Material: 1/8”-thick clear acrylic. |
| | | There are four rings: inner front, inner back, outer front, outer back. |
| | | Notice that the template shows the front sides of three of the rings, but the BACK side of the inner front ring (so you can etch the back side). |
| | | Laser score nine guidelines on each ring. |
| | | Laser etch the sliding contact surfaces on the back side of the inner front ring, as shown in the template. The depth of the laser etching should be very shallow, no more than 0.01” (0.2 mm). See the note about laser etching (below). |
| | | Laser cut all four rings (holes first). |
| 2 | Cement the inner rings together. | Put the two rings together, with the back side of inner front ring against the front side of the inner back ring. Align the scored guidelines. |
| | | Clamp the two rings together. |
| | | Apply acrylic solvent cement. |
| 3 | Cement the outer rings together. | Put the two rings together, with the back side of outer front ring against the front side of the outer back ring. Align the scored guidelines. |
| | | Clamp the two rings together. |
| | | Apply acrylic solvent cement. |
| 4 | Test the twist connector before cementing it to the cap and plate. | You must test the twist connector before you cement the outer rings to the distributor cap and the inner rings to the front plate. |
| | | Hold the inner ring down tightly onto a flat plate, as if it were cemented to the plate. Push the outer ring down over the inner ring and twist it counterclockwise. Verify that the rings connect snugly, but not so tight that it is difficult to connect or disconnect. |
| | | You can do this better test: Make an extra (disposable) set of inner rings and cement them to a small test plate, then test the twist connector. |

**Laser etching the tab slots.** When you attach the distributor cap to the front plate, the tab slots should be just roomy enough to allow the tabs to slide, with a little friction to make a snug connection. But the tabs and slots may be too tight if they are exactly same thickness (1/8”). If it is too tight, the cemented seams may split. To make the slots slightly roomier, lightly laser etch (or manually sand) the sliding contact surfaces on the back side of the inner front ring, as shown in the laser template. Do not polish the etched surfaces. Ideally, the twist connector will stay snug, even without the lock pin or lock screw.

*4.12.7.2 Joining the twist connector outer ring to the distributor cap*

*Distributor cap with lid, wall, and twist connector all cemented together.*



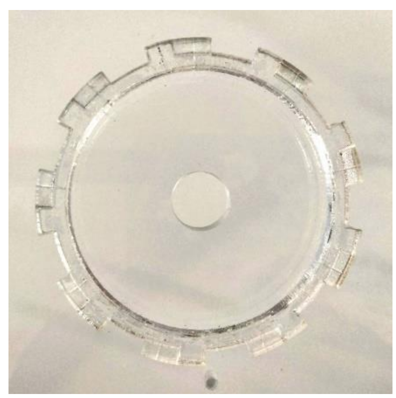
*Distributor cap back side (inside), showing the twist connector.*

—

| **Instructions: Joining the twist connector outer ring to the distributor cap** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Cement the twist connector outer ring to the distributor cap. | Put the twist connector outer rings onto the distributor cap wall, centered, and align the scored guidelines. |
| | | Clamp the pieces together. |
| | | Apply acrylic solvent cement. |

*4.12.7.3 Joining the twist connector inner ring to the front plate*

*Clamping and cementing the twist connector inner ring to the front plate.*



*Twist connector inner ring cemented to the front plate.*

—

| **Instructions: Cementing the twist connector inner ring to the front plate** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Test the twist connector before cementing it to the plate. | Verify that the twist connector works before you cement it to the front plate. See the previous instructions for testing the twist connector. |
| 2 | Mark the front plate with the distributor alignment marks, if not previously marked. | If you previously marked the distributor alignment marks when you made the front plate, then you can skip this step. |
| | | **Paper template: Radial-PTemplate-DistributorPosition** |
| | | The template shows the correct position and orientation of the twist connector outer ring on the front plate, and where to make the distributor alignment marks (nine crosshairs). |
| | | Print the template, full scale. |
| | | Tape the template to the front plate, aligned with the distributor shaft and other holes. |
| | | Mark the plate lightly where the template shows the distributor alignment marks (nine crosshairs). You can mark the plate at each crosshair by cutting with a razor knife, tapping a nail, or drilling a dot with your smallest drill bit. |
| | | Remove the paper template. |
| 3 | Align the twist connector inner ring on the front plate. | Put the twist connector inner ring on the front plate (with the back side of the ring on the front side of the plate). Center and orient the ring using the alignment marks (nine crosshairs) on the plate and the nine scored guidelines on the inner ring. |
| | | When the distributor cap is later connected and twisted into place, the cylinder #1 contact will be at the top (12 o’clock position) and the lock pin tab will be at the bottom (6 o’clock position). |
| 4 | Hold the inner ring to the plate. | Hold the inner ring onto the plate by some method, such as clamp, weight, or magnet. |
| | | You can make a clamp with two wooden sticks, a screw, and a nut. The sticks go above the ring and below the plate, the screw goes through both sticks and the shaft hole, and the nut tightens the clamp (see photo). |
| 5 | Cement the inner ring to the plate. | Apply acrylic solvent cement to all edges. Try to avoid spilling too much solvent on the front plate. |

#### *4.12.7.4 Making the lock screw or pin holes*

*Distributor cap lock screw or lock pin.*

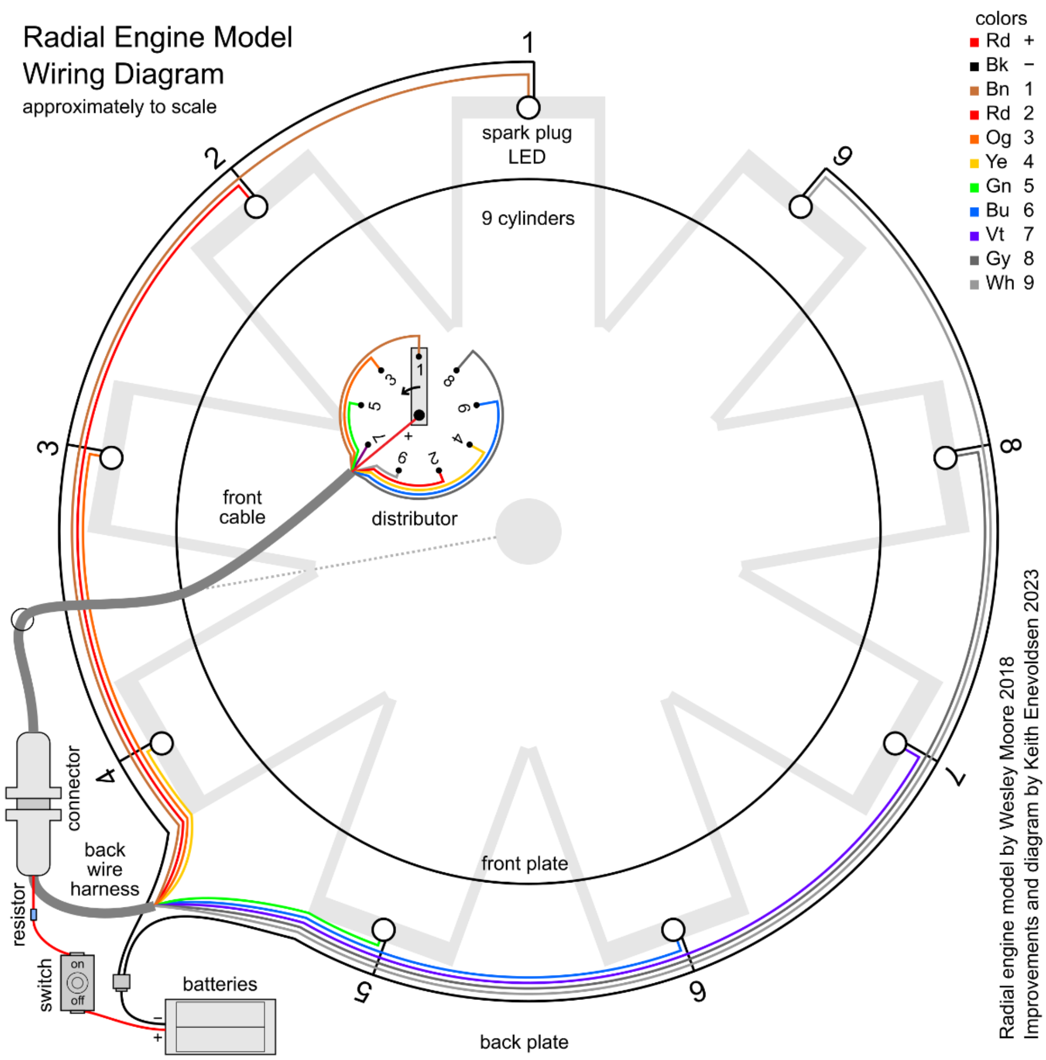
A lock screw or pin is used to lock the distributor cap in position. If you decide to use a screw you will need to make threaded holes. One advantage of using a lock screw is that it will stay attached to the distributor cap when the cap is off (if the lock screw hole in the cap is threaded). One advantage of using a lock pin is that you will not need a screwdriver to insert or remove it. The lock screw (#4-40 × 3/8”) and lock pin (split pin, 3/64” diameter, 3/8” long) are listed in the Assembly Manual.

| **Instructions: Drilling the lock screw or pin holes in lock tab and front plate** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Decide whether to use a lock screw or a lock pin. | Decide whether to use a lock screw or a lock pin. (We chose a lock screw.) |
| 2 | Connect the twist connecter outer ring to the inner ring. | Push the outer ring (which may or may not be cemented to the distributor cap) onto the inner ring (which is cemented to the plate). Turn the outer ring counterclockwise until the tabs reach the ends of the slots. The lock tab on the outer ring should be at the bottom (the 6 o'clock position). |
| 3 | Mark the position on the plate for the lock screw or pin hole. | The outer ring has a lock tab with a pilot hole. Using this pilot hole as a guide, mark the position on the plate for the hole to be drilled for the lock screw or pin. You can mark the position on the plate by drilling with a thin drill bit or tapping a thin nail. |
| 4 | Drill and tap threaded and/or unthreaded holes in the lock tab and the plate. | For lock screw: Drill holes through both the lock tab and the plate. At least one of the two holes should be threaded. (We made threaded holes in both the lock tab and the plate.) For threaded holes, use #43 drill bit and #4-40 tap. For unthreaded holes, drill holes that are a close fit for #4 screws (#32 drill bit). |
| | | For lock pin: Drill unthreaded holes through both the lock tab and the plate. The holes should be a close fit for the lock pin (about 1/16" diameter). |
| 5 | Test the lock screw or lock pin. | For lock screw: Test that the lock screw fits the threaded hole(s). |
| | | For lock pin: Bend the split pin to fit snugly in the holes. |

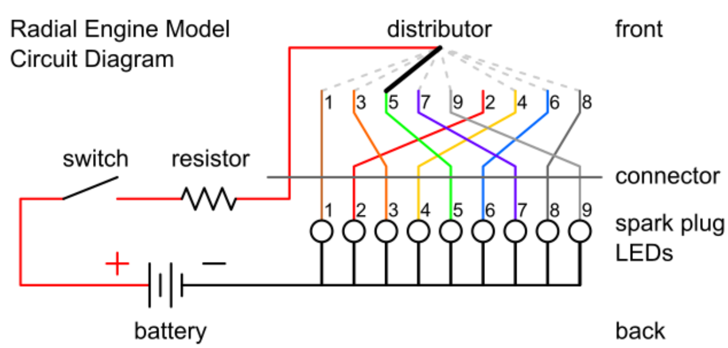
If the threaded hole in the plastic gets stripped, you can fix it. Fill the hole with thick-bodied acrylic cement, let it harden, then drill and tap the threads again.

# 4.13 Electrical system: Wiring, LEDs

## 4.13.1 Wiring diagram




*Wiring diagram.*




*Schematic circuit diagram.*

The wiring consists of a distributor and front cable on the front plate, a back wire harness with nine spark plug LEDs (and one resistor) on the back plate, an on-off switch, and a battery pack.

### 4.13.2 Electrical corner diagram

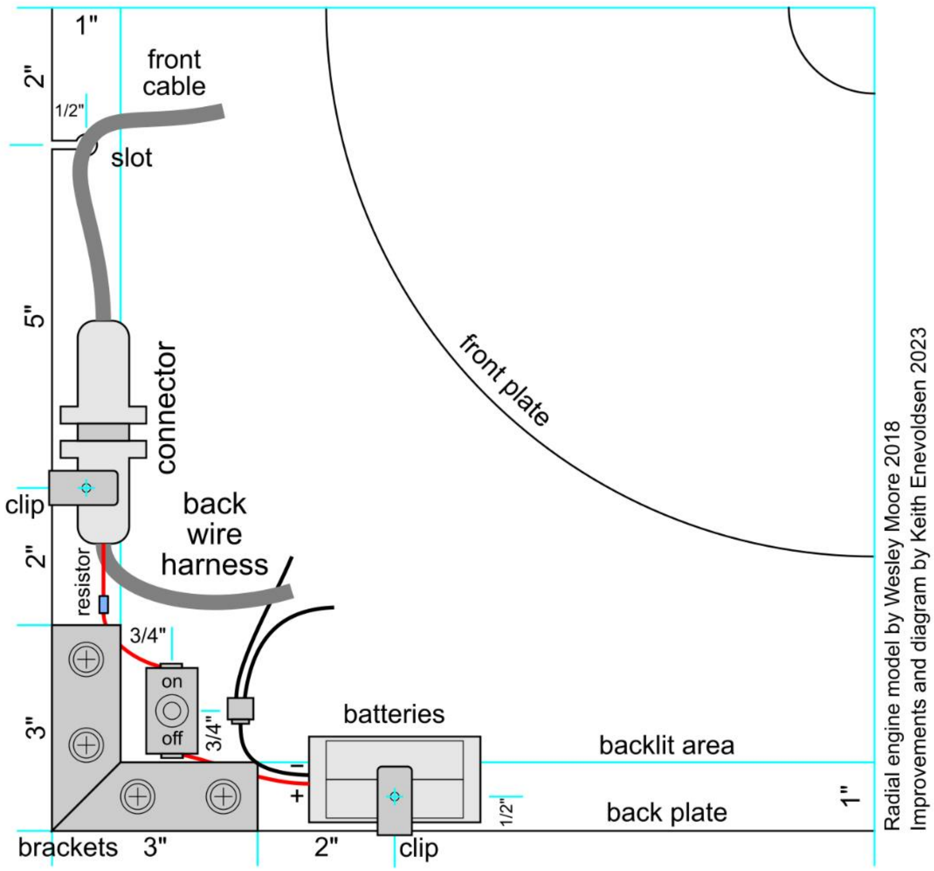



*Diagram of the lower left corner of the back plate, showing the locations of the cable connector, the battery pack, and the on-off switch.*

### 4.13.3 Tools for making electrical parts

These tools are needed or useful for making the electrical parts.

| **Tools: Tools for making electrical parts** | |
|---|---|
| Tool | Usage |
| Wire cutter/stripper | Cutting and stripping wires. |
| Crimper or pliers | Crimping wire terminals. |
| Soldering iron with solder and flux | Soldering wires. |
| Helping hands soldering stand | Holding wires while soldering. |
| Heat gun, lighter, or matches | Heat-shrinking tubes. |
| Multimeter (voltmeter and ohmmeter) | Measuring voltage and resistance. |
| Test leads with clips (alligator clips or hook clips) | Testing electrical components. |

### 4.13.4 Materials for making the wiring

#### *4.13.4.1 Wire*

| Materials: Wire | | | | | |
|---|---|---|---|---|---|
| Material | Type | Gauge (AWG) | Color | Total length (approx.) | Usage |
| Wire | Stranded | 24 | ■ Red | 3 ft | DC positive |
| Wire | Stranded | 24 | ■ Black | 8 ft | DC negative (ground) |
| Wire | Stranded | 24 | ■ Brown | 5 ft | Cylinder 1 |
| Wire | Stranded | 24 | ■ Red | 5 ft | Cylinder 2 |
| Wire | Stranded | 24 | ■ Orange | 4 ft | Cylinder 3 |
| Wire | Stranded | 24 | ■ Yellow | 3 ft | Cylinder 4 |
| Wire | Stranded | 24 | ■ Green | 3 ft | Cylinder 5 |
| Wire | Stranded | 24 | ■ Blue | 4 ft | Cylinder 6 |
| Wire | Stranded | 24 | ■ Violet | 5 ft | Cylinder 7 |
| Wire | Stranded | 24 | ■ Gray | 5 ft | Cylinder 8 |
| Wire | Stranded | 24 | ■ White | 6 ft | Cylinder 9 |

The two wire harnesses are made from wires of 10 colors.

**Stranded.** We recommend stranded wire rather than solid wire because it is more flexible and less likely to break.

**Gauge.** 24 AWG to 28 AWG. We used 24 AWG. If the wire is thicker than 24 AWG, the bundle of 10 wires will be too thick. If the wire is thinner than 28 AWG, it will be difficult to work with.

**Color.** For the non-spark-plug wires, we used the DC standard positive = red and negative = black. For the nine spark plug wires, we used colors 1 to 9 from the standard electronic color code:

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| ■ Black | ■ Brown | ■ Red | ■ Orange | ■ Yellow | ■ Green | ■ Blue | ■ Violet | ■ Gray | ■ White |

Notice that we used red for both DC positive and cylinder #2.

You could use the same color for all the spark plug wires, but using different colors is more fun and educational. The multi-colored wires will inspire the viewer to trace the wires to learn how it works.

**Length.** The table shows the approximate total lengths needed for each color of wire. For more details, see the templates for the front cable and back wire harness. You will need about 8 ft of black wire and 8 ft red wire, and less of the other colors. A 10-color pack of wires (or a 10-color ribbon cable) with 10 ft of each color should give you enough of each color.

#### *4.13.4.2 Heat-shrink tube*

| Materials: Heat-shrink tube | | | |
|---|---|---|---|
| Material | Diameter | Length | Usage |
| Heat-shrink tube | 1/8” | ~30” | Soldered wires. |

Use heat shrink tube to insulate soldered wire joins. Slide it over the solder joins and heat it (with heat gun, lighter, match, or soldering iron) to shrink it. You can use any color. We used clear, black, and red.

#### *4.13.4.3 Cable wrap*

| Materials: Cable wrap | | | | |
|---|---|---|---|---|
| Material | Type | Diameter | Length | Usage |
| Cable wrap | Spiral cable wrap, clear | 1/4" (6 mm) | ~12” | Front cable. |

Use cable wrap to wrap the main trunk of the front cable. Use removable cable wrap, such as spiral cable wrap. We recommend clear or translucent cable wrap, so viewers can trace all the colored wires, befitting the transparency of the model.

#### *4.13.4.4 Metal for spring clips*

| Materials: Metal for spring clips | | | | | |
|---|---|---|---|---|---|
| Material | Form | Width | Thickness | Total length | Usage |
| Resilient alloy:<br>brass, steel, or stainless steel | Strip | 1/2" | ~1/32” (.03”) (~1 mm) | 2×3”=6” | Spring clips. |

Spring clips should be made of a resilient alloy (brass, steel, or stainless steel) of a thickness that makes them hold tightly.

### 4.13.5 Parts list

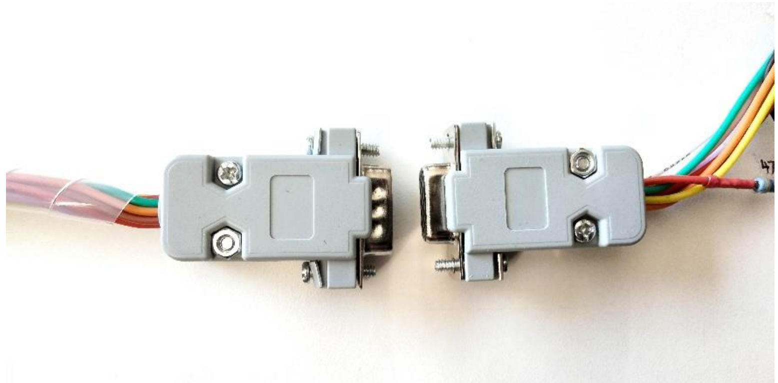
| Wiring: Custom parts | |
|---|---|
| Part | Quantity |
| Back wire harness (with LEDs) | 1 |
| Front cable | 1 |
| Battery pack (with wires and terminals) | 1 |
| Spring clip for battery pack | 1 |
| Spring clip for cable connector | 1 |

—

| Wiring: Standard parts (built into custom parts) | | | |
|---|---|---|---|
| Part | Size | Quantity | Usage |
| 10-pin cable connectors, plug and socket | At least 10 pins. We used D-Sub DE-15 cable connectors with 15 pins, with solder cups. (Your model may differ.) | 1 pair | Front cable (plug) and back wire harness (socket) |
| Ring terminals | Crimped/soldered to 24 AWG wire. Rings fit the distributor contact #4 screws and the toggle switch screws. | 12 | Front cable, back wire harness, battery pack |
| Tab terminals, plug and socket | Crimped/soldered to 24 AWG wire. | 1 pair | Back wire harness, battery pack |
| LEDs, frosted white | 5 mm, 3 to 3.2 V, 20 mA | 9 | Back wire harness |
| Resistor | 47 ohm (Ω) (your model may differ), 1/4 watt or 1/2 watt | 1 | Back wire harness |
| Single-pin terminal sockets (optional) | Crimped/soldered to 24 AWG wire, socket fits a 1/2-watt resistor lead: about 22-24 AWG (0.6-0.5 mm). (Example product: crimp pins for BLS housing.) | 2 | Back wire harness (optional for plug-in resistor) |
| Battery holder | Fits two AA batteries. (We used a transparent battery holder befitting the transparency of the model.) | 1 | Battery pack (with wires and terminals) |
| Zip ties | Small | ~20 | Back wire harness, front cable |

### 4.13.6 Cable connectors

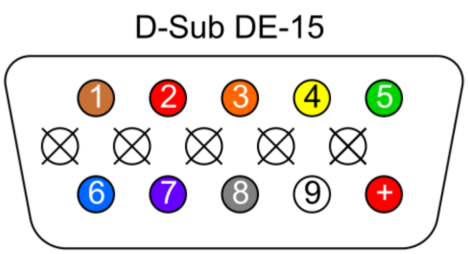
Cable connectors (D-Sub DE-15), before soldering, plug (left) and socket (right).



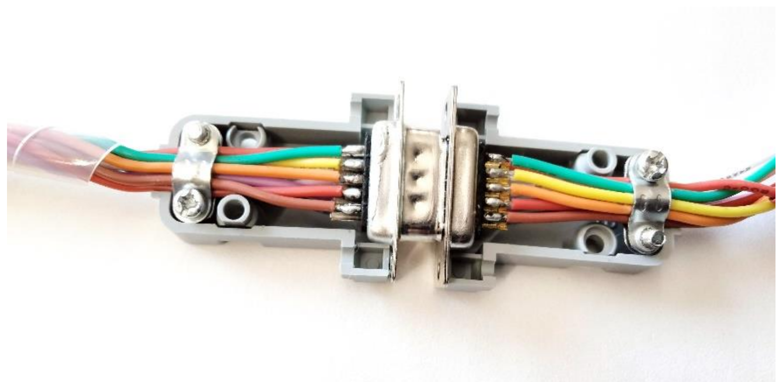
Cable connectors (D-Sub DE-15) on front cable (left) and back wire harness (right).

The cable connectors are described in the Assembly Manual. A pair of cable connectors (plug and socket) connect the front cable to the back wire harness.

The cable connectors have 10 conductors for the nine spark plug wires and the one center positive (red) wire. Our model uses a D-Sub DE-15 connector with 15 pins, but only 10 pins are used (see the pin assignments diagram). (In our model, the back wire harness has the socket, and the front harness has the plug.)




Pin assignments for D-Sub DE-15.



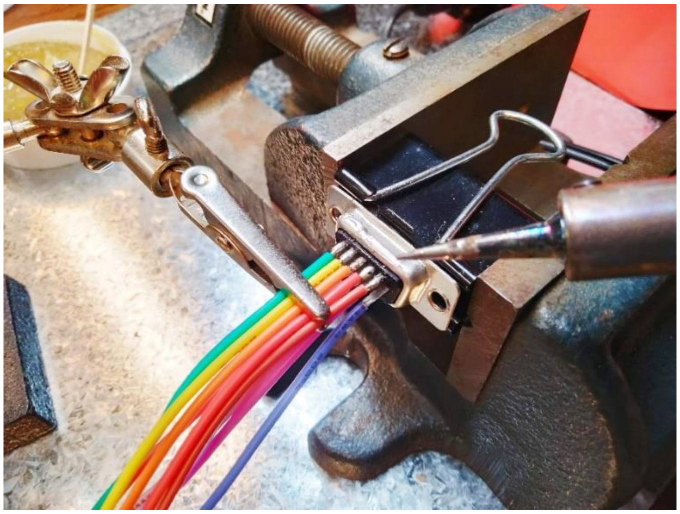
Cable connectors, opened to show soldered wires inside.

To make the front cable (4.13.7) or the back wire harnesses (4.13.14), you will start by soldering long wires to the cable connector.

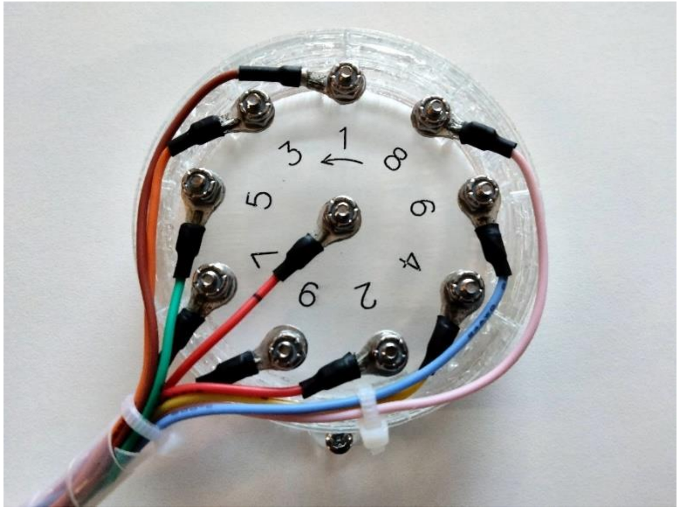
### 4.13.7 Making the front cable

*Front cable.*

The front cable is described in the Assembly Manual.



*Soldering the wires to the solder cups in a cable connector.*



*The ring terminals on the front cable will be connected to the contact screws in the distributor cap.*

—

| Instructions: Making the front cable | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Print the front cable template, full scale preferred. | **Paper template: Radial-PTemplate-FrontCable** |
| | | The template shows all the wires in the front cable. The wires are shown as parallel straight lines, starting from the cable connector. |
| | | Print the large template (21”×8”), preferably at full scale, on a single large sheet of paper (at a print shop) or print on multiple smaller sheets and tape them together. If printed at full scale, you can measure the wires directly against the printed template. If printed at a smaller scale, you can read the numerical wire lengths and measure the wires with a ruler. |
| | | If your model differs, you can modify the wire lengths shown in the template. |
| 2 | Determine the wire type, size, and colors. | Our recommended wire type, gauge, and colors are shown in the wire materials table. |
| 3 | Determine the cable connector pin assignments. | Our pin assignments for D-Sub DE-15 connector are shown in the cable connectors pin assignments diagram. |
| 4 | Cut the wires, a little longer than needed. | Cut all 10 wires. The first cut should be a little (1” or 2”) longer than shown in the template. |
| 5 | Solder the wires to the cable connector. | Use the plug (not socket) connector for the front cable. |
| | | Strip the ends of the wires to be joined to the solder cups. |
| | | Hold the connector with a clamp or vise. Hold each wire end in the connector’s solder cup with a helping hands tool. |
| | | Solder each wire to a solder cup. (Use soldering flux.) |
| 6 | Cut the other ends of the wires, to the exact lengths needed. | Determine the exact lengths of the wires by measuring directly against the template. |
| | | Alternative: Determine the exact lengths of the wires by measuring directly against the model. Install the unfinished wire harness in the model by mounting the cable connector on the back plate, then routing the harness up to the front plate and to the distributor. Each spark plug wires should just reach its corresponding distributor contact screw, with very little slack. |
| | | Cut the wires to the determined length. |
| 7 | Mark the center positive wire. | According to our color code, the center positive wire and the spark plug wire for cylinder #2 are both red. Put a distinguishing mark on the center wire, perhaps a (black) mark on the wire, or perhaps a distinct color (red) of heat shrink tube. |
| 8 | Attach ring terminals to the ends the wires. | Strip the ends of the wires to be joined to the wire terminals. |
| | | Slide a heat-shrink tube onto the wire before crimping or soldering. |
| | | Crimp and/or solder a ring terminal to the end of each wire. (The ring terminals will be connected to the distributor.) |
| | | Slide the heat-shrink tube over the join and apply heat. |
| 9 | Bundle the wires. | Bundle all 10 wires with one zip tie at the end of the trunk, where all the wires branch out. |
| | | Wrap the trunk with removable (spiral) cable wrap. |

### 4.13.8 On-off switch


*On-off toggle switch.*

The on-off switch is described in the Assembly Manual. It is store-bought part, so there is nothing to make, but you can modify it.

| **Instructions: Modifications of the toggle switch** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Bend the screw terminals (optional) | If the toggle switch screw terminals are at the wrong angle for the screwdriver when the switch is installed, then bend the screw terminals (with pliers) to a better angle. |
| 2 | Improve the ON-OFF label plate (optional) | If your switch has no ON-OFF label plate, add one. |
| | | If your label plate letters are stamped but not painted, you may improve the readability by filling the grooves with paint. |
| | | If your label plate is painted but the paint is easily scratched by the wrench, you may protect the paint with varnish or clear tape. |

### 4.13.9 Making the spring clips

*Spring clips for battery pack and cable connector.*

The spring clips are described in the Assembly Manual.

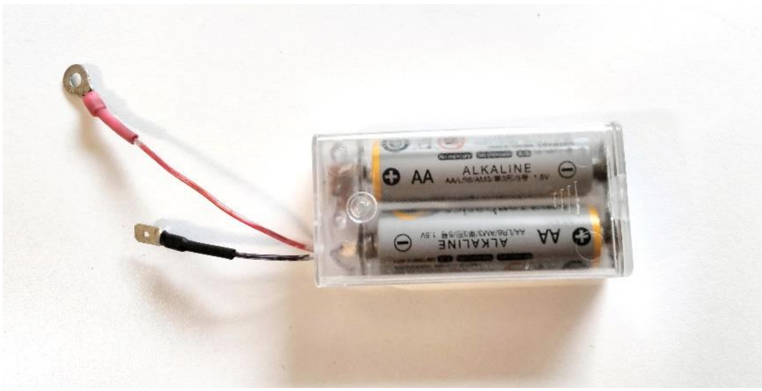
| Instructions: Making the spring clips | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Print the spring clips template, full scale. | **Paper template: Radial-PTemplate-SpringClips** |
| | | The template has the flat folding pattern for the spring clips. |
| | | Print the template, full scale. |
| 2 | Cut a metal strip for each clip. | Material: 1/2"-wide metal strip.<br>Preferred: brass, steel, or stainless steel, ~1/32” (~1 mm) thick.<br>See the materials list (4.13.4.4). |
| | | Cut two strips to the length specified in the template (3”), or the lengths that will fit your battery pack and cable connector. |
| | | Sand all sharp edges and corners. |
| 3 | Drill screw holes. | Drill a screw hole in each strip that will be 1/2" from the edge of the plate when the clip is installed, as shown in the template. The hole should be a close fit for a #4 screw (#32 drill bit). |
| 4 | Bend the strips. | Smoothly bend each strip at the four places shown in the template, or at the places that will fit your battery pack and cable connector. |

The spring clips should be made to fit your battery pack and cable connector. Our two clips are the same size because our battery pack and our cable connector happen to be the same thickness (about 5/8”).

| Instructions: Drilling screw holes in the back plate for the spring clips | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Determine where to locate the spring clips on the back plate. | The battery clip screw hole is 1/2" from the bottom edge and 5” from the left edge. See diagram 4.13.2. |
| | | The cable connector clip screw hole is 1/2" from the left edge and 5” from the bottom edge. See diagram 4.13.2. |
| 2 | Drill and tap threaded holes in the back plate. | Drill and tap threaded holes through the back plate. Use #43 drill bit and #4-40 tap. |

You should install the spring clips on the back plate before you start making the back wire harness, so you can put the battery pack and cable connector in their intended positions before you start cutting wires to make the back wire harness.

## 4.13.10 Making the battery pack



*Battery pack, with short wires and wire terminals.*


*Ring terminals.*

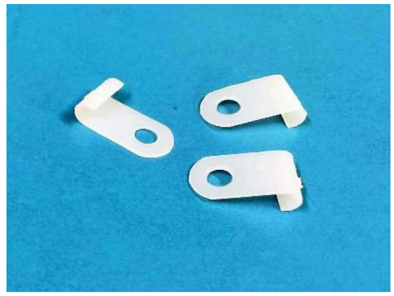

*Tab terminals.*

The battery pack is described in the Assembly Manual. The battery holder is a store-bought part, but you will cut the wires and add wire terminals.

| **Instructions: Making the battery pack with wires and terminals** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Start with a store-bought battery holder. | Battery holder for two AA batteries. |
| 2 | Determine the length of the positive and negative wires. | The battery pack's positive wire must reach from the battery pack to the on-off switch. For our model, the positive wire length (including the ring terminal) is 3". |
| | | The battery pack's negative wire must reach from the battery pack to the negative (black) wire of the back wire harness. For our model, the negative wire length (including the tab terminal) is 1.5". (You can wait until you have built and installed the back wire harness.) |
| 3 | Cut the wires. | Cut the positive and negative wires to the determined lengths. |
| 4 | Color the wires red and black (optional). | If your battery pack positive and negative wires are not red and black, you can color them red and black (with permanent markers). |
| 5 | Attach a ring terminal to the positive (red) wire. | Strip the end of the positive wire to be joined to the wire terminal. |
| | | Slide a (red) heat-shrink tube onto the wire before crimping or soldering. |
| | | Crimp and/or solder a ring terminal to the end of the positive wire. (This ring terminal will be connected to the on-off switch). |
| | | Slide the heat-shrink tube over the join and apply heat. |
| 6 | Attach a tab terminal to the negative (black) wire. | Strip the end of the negative wire to be joined to the wire terminal. |
| | | Slide a (black) heat-shrink tube onto the wire before crimping or soldering. |
| | | Crimp and/or solder a tab (plug) terminal to the end of the negative wire. (This tab terminal will be connected to the negative wire tab socket on the back wire harness.) |
| | | Slide the heat-shrink tube over the join and apply heat. |

### 4.13.11 Cable clips

*Loop cable clips.*



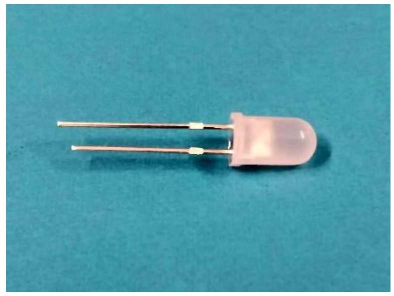
*Half-loop cable clips.*

The cable clips are described in the Assembly Manual. They are store-bought parts, so there is nothing to make, but you can modify them.

| **Instructions: Modification of the cable clips** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Cut the cable clips (optional) | If you have loop clips, but you prefer half-loop clips, you can simply cut the loops to make half loops. |

You should install the cable clips on the back plate before you start making the back wire harness. This will help you test that the wires in the back harness are the correct length before you cut the wires.

### 4.13.12 LED specifications



*Frosted white LED.*

The spark plug LEDs are soldered to the back wire harness (4.13.14).

| LED specifications | |
|---|---|
| Characteristic | Value |
| Diameter | 5 mm |
| Length | 6 to 9 mm |
| Forward voltage | 3 to 3.2 V |
| Current rating | 20 mA (typical) |
| Color | White |
| Finish | Frosted or diffuse |
| Shape | Round dome |
| Viewing angle | Wide angle, ~120° |
| Brightness | Bright |

**Viewing angle.** The LEDs should have a wide viewing angle (roughly 120°) so viewers can see the flashes from all nine LEDs even if they are not standing directly in front of the model. All frosted LEDs have a wide viewing angle, so you can ignore the numerical angles if you use frosted LEDs.

**Brightness values.** The LEDs should be bright enough to be eye-catching, even in a daylit room, or with the backlight on. Total brightness (luminous flux) is measured in lumens (lm). Brightness per solid angle (luminous intensity) is measured in millicandelas (mcd). 1 candela = 1 lumen per steradian. But we found that the brightness numbers are not very useful because the brightness varies a lot with viewing angle and the advertised brightness numbers are not very reliable for frosted LEDs. So, we recommend that you simply buy some frosted white LEDs that are advertised as bright, ignoring the advertised brightness numbers, and then test them to see whether they look good. We simply bought a popular brand of frosted white LEDs and they look great.

You can modify the finish of your LEDs.

| Instructions: Modification of the LEDs | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Sand or buff the LEDs (optional) | If you have clear LEDs, you can give them a frosted finish by sanding or buffing. Use fine-grit (#400) sandpaper. |

## 4.13.13 Resistor specifications

*Resistor (47 Ω, 1/2 W).*

A single resistor is in the circuit. Its purpose is to prevent burnout of the LEDs and to increase the lifetime of the batteries and the LEDs. The distributor fires only one LED at a time. The single resistor is in the DC-positive (red) wire of the back wire harness (4.13.14), so it is always in the circuit with whichever single LED is currently lit. See the wiring diagram (4.13.1).

**Resistance (ohms).** The resistor should have enough resistance to prevent burnout of the LEDs, but not so much resistance that it makes the LEDs too dim. The LEDs should be bright enough to be eye-catching, even in a daylit room, or with the backlight on. To calculate the resistance in ohms (Ω) for your resistor, you can use any online LED resistor calculator or use this formula: $R = (V_2\text{-}V_1)/I$, where R is resistance, $V_2$ is battery supply voltage, $V_1$ is LED forward voltage, and I is LED forward current (typical) (amps). Our model's power supply is two AA alkaline batteries. New alkaline batteries are nominally 1.5 V but may be as high as 1.65 V, so the power supply is nominally 3 V but may be as high as 3.3 V. Our white LEDs are 3 to 3.2 V at 20 mA (30 mA max). We calculated the needed resistance for three cases, (1) the nominal supply voltage, (2) the maximum expected supply voltage, and (3) a higher-than-expected supply voltage, as follows:

| Case | Supply voltage, $V_2$ | LED forward voltage, $V_1$ | LED forward current, I | Resistance, $R = (V_2\text{-}V_1)/I$ |
|---|---|---|---|---|
| Nominal supply voltage | 3 V | 3 V | 0.020 A | 0 Ω |
| Maximum expected supply voltage | 3.3 V | 3 V | 0.020 A | 15 Ω |
| Higher-than-expected supply voltage | 4 V | 3 V | 0.020 A | 50 Ω |

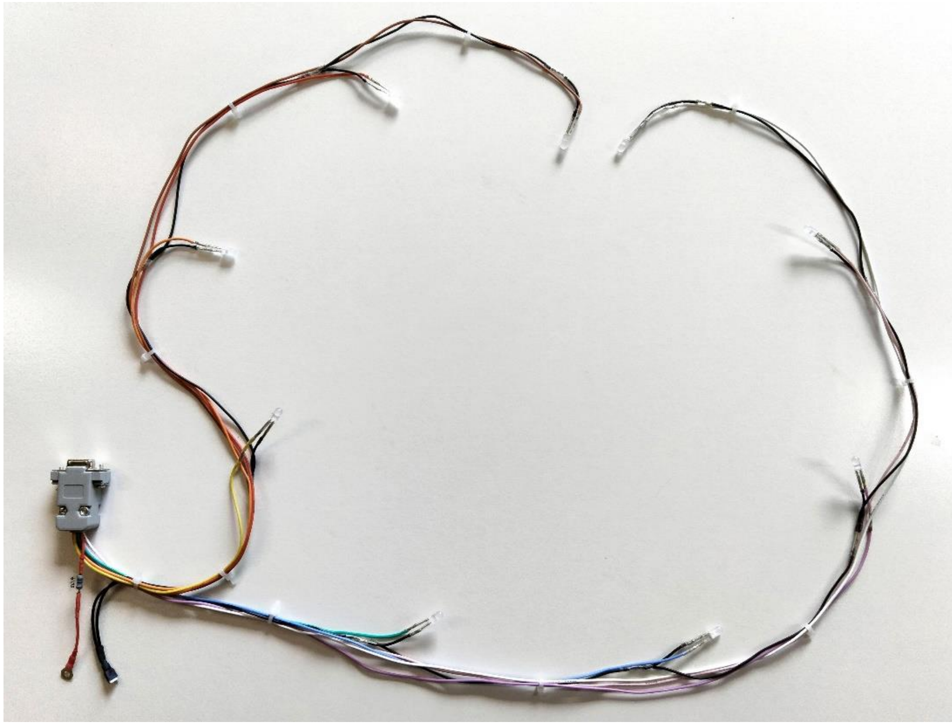
So, we could choose a resistor as low as 15 Ω, but to be conservative, we chose 47 Ω. We tested the 47-Ω resistor with our LEDs and verified that the LEDs flashed brightly. So, 47 Ω works for our model.

| E12 standard resistor values between 10 and 100 Ω |
|---|
| 10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, 82, 100 |

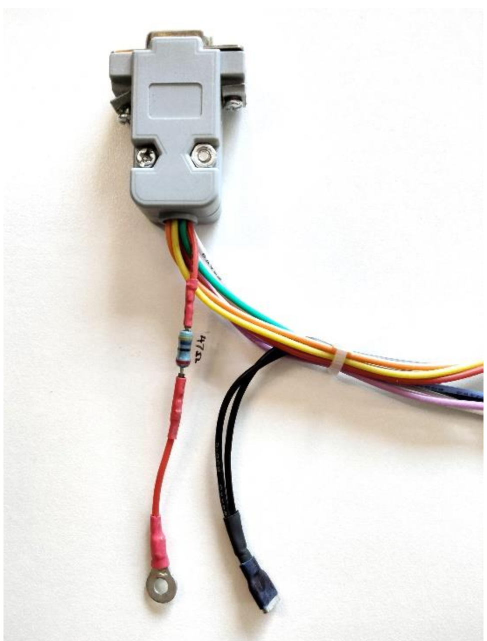
**Power (watts).** A small 1/4-watt resistor is electrically adequate for the single lit LED. The power of the LED is calculated by P = V×I. The power of our LED is less than P = (3.2 V × 0.030 A) = 0.10 W. However, if you make a plug-in resistor (see 4.13.14), you should use a larger 1/2-watt resistor, only because its thicker leads will fit better in the pin sockets.

## 4.13.14 Back wire harness, LEDs

### *4.13.14.1 Making the back wire harness*



*Back wire harness with two main branches and nine LEDs*



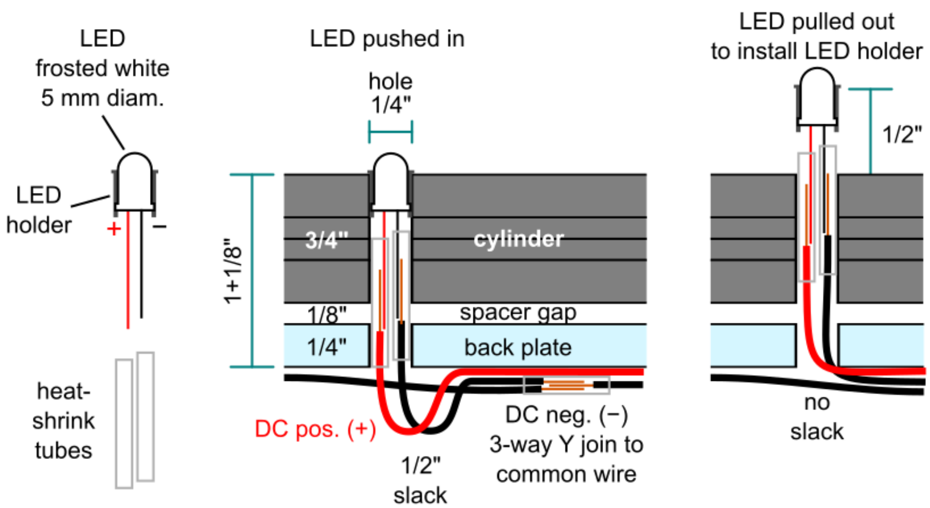
*The back wire harness has three electrical connections:*
*the cable connector, the positive terminal, and the negative terminal.*

*LED soldered to*
*the back wire harness.*

*Y join of three negative wires.*

The back wire harness is described in the Assembly Manual.

| Instructions: Preparing to make the back wire harness | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Print the back wire harness template, full scale preferred. | **Paper template: Radial-PTemplate-BackWireHarness** |
| | | **The positive wires** are shown as parallel straight lines, rooted at the cable connector, and terminating at the LEDs. |
| | | **The negative wires** are shown as a tree with nearly parallel straight lines, rooted at the negative wire terminal, and terminating at the LEDs. |
| | | Print the large template (41”×11”), preferably at full scale, on a single large sheet of paper (at a print shop) or print on multiple smaller sheets and tape them together. If printed at full scale, you can measure the wires directly against the printed template. If printed at a smaller scale, you can read the numerical wire lengths and measure the wires with a ruler. |
| | | If your model differs, you can modify the wire lengths shown in the template. |
| 2 | Determine the wire type, size, and colors. | Our recommended wire type, gauge, and colors are shown in the wire materials table. |
| 3 | Determine the cable connector pin assignments. | Our pin assignments for D-Sub DE-15 connector are shown in the cable connectors pin assignments diagram. |




*LED wires, section view. LED wires need 1/2” slack so LEDs can be pulled forward.*

| Instructions: Making the back wire harness, positive wires | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Use the previously printed template. | **Paper template: Radial-PTemplate-BackWireHarness** |
| | | **The positive wires** are shown as parallel straight lines, rooted at the cable connector, and terminating at the LEDs. |
| 2 | Cut the 10 positive wires, a little longer than needed. | Cut all 10 positive wires, the nine (multi-colored) spark plug wires and the short positive (red) wire. The first cut should be a little (1” or 2”) longer than shown in the template. |
| 3 | Solder the 10 positive wires to the cable connector. | Use the socket (not plug) connector for the back wire harness. |
| | | Strip the ends of the wires to be joined to the solder cups. |
| | | Hold the connector with a clamp or vise. Hold each wire end in the connector’s solder cup with a helping hands tool. |
| | | Solder each wire to a solder cup. (Use soldering flux.) |
| 4 | Cut the ends of the nine spark plug wires, to the exact lengths needed. | Determine the lengths of the nine spark plug wires by measuring directly against the template. |
| | | Alternative: Determine the lengths of the nine spark plug wires by measuring directly against the model. Install the unfinished wire harness in the model, routing the wires through the cable clips on the short cylinder screws. See the Assembly Manual. |
| | | Each wire should just reach the corresponding LED when the LED is pulled 1/2" in front of the hole. See the LED wires diagram (above). |
| | | Cut the ends of nine spark plug wires to the determined lengths. |
| | | Note: The tenth positive wire, the short positive (red) wire, will be cut and finished later. |
| 5 | Solder the nine spark plug wires to the positive leads of the LEDs. | Strip the ends of the wires to be joined to the LEDs. |
| | | Slide a (clear) heat-shrink tube onto the wire before soldering. |
| | | Hold the wire onto the LED’s positive lead with a helping hands tool. (You do not need to twist the wire to the LED.) |
| | | Solder the wire to the LED’s positive lead. (Use soldering flux.) |
| | | Slide the heat-shrink tube over the join and apply heat. |

—

| Instructions: Making the back wire harness, negative wires | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Use the previously printed template. | **Paper template: Radial-PTemplate-BackWireHarness** |
| | | **The negative wires** are shown as a tree with nearly parallel straight lines, rooted at the negative wire terminal, and terminating at the LEDs. |
| 2 | Cut all the wire segments, a little longer than needed. | The negative wire tree is made from 16 wire segments: 9 medium-length wires (ranging from 7+" to 9+") and 7 short wires (2+"), joined at Y joins. |
| | | Cut 16 black wire segments. The first cut should be a little (1") longer than shown in the template. The lengths shown in the template are the distances between the centers of the Y joins, so the final wire lengths will be slightly longer so you can overlap the wire ends (about 3/8") to make each Y join. |
| 3 | Solder the first two wires to the tab socket wire terminal. | Strip the ends of the two wires to be joined to the wire terminal. |
| | | Crimp and/or solder a single tab socket wire terminal to the ends of the two wires, as shown in the template. (This tab socket terminal will be connected to the battery negative wire tab terminal.) |
| | | Slide a (black) heat-shrink tube over the join and apply heat. |
| 4 | Make the tree by soldering the wires together with Y joins. | To make the wire tree, start from the root end and add wires, two at a time, to make Y joins, as shown in the template. |
| | | Determine the distance between the Y joins by measuring directly against the template. |
| | | Alternative: Determine the distance between the Y joins by measuring directly against the model. Install the unfinished wire harness (both positive and negative wires) in the model, routing the wires through the cable clips on the short cylinder screws. See the Assembly Manual. |
| | | Each pair of positive and negative wires should just reach the corresponding LED when the LED is pulled 1/2" forward of the hole. See the LED wires diagram (above). |
| | | Cut the wires to the determined lengths. |
| | | Strip (about 3/8") the ends of the three wires to be Y joined. |
| | | Slide a heat-shrink tube onto the first (root-most) wire before soldering. |
| | | Lay the stripped ends of the three wires in parallel, overlapping (about 3/8") as shown in the Y join photo. Twist the three wires together if you can, but it may be difficult, and it is not required. Hold the three wires together with a helping hands tool. |
| | | Solder the three wires together. (Use soldering flux.) |
| | | Slide the heat-shrink tube over the Y join and apply heat. |
| 5 | Solder the nine wire ends to the negative leads of the LEDs. | Strip the ends of the wires to be joined to the LEDs. |
| | | Slide a heat-shrink tube onto the wire before soldering. |
| | | Hold the wire onto the LED's negative lead with a helping hands tool. (You do not need to twist the wire to the LED.) |
| | | Solder the wire to the LED's negative lead. (Use soldering flux.) |
| | | Slide the heat-shrink tube over the join and apply heat. |
| 6 | Bundle the wires. | After the entire wire harness is installed, bundle the positive and negative wires together with at least 10 zip ties: at the trunk (1), at the main branches (2), and on the smaller branches between adjacent cylinders (7). |

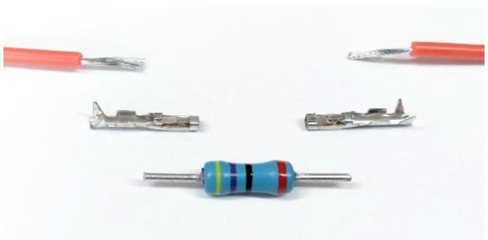
### *4.13.14.2 Making the short positive (red) wire with in-line resistor*

The back wire harness has a short positive (red) wire from the cable connector to a ring terminal that connects to the on-off switch. The wire should be just long enough to reach from the cable connector to the on-off switch.

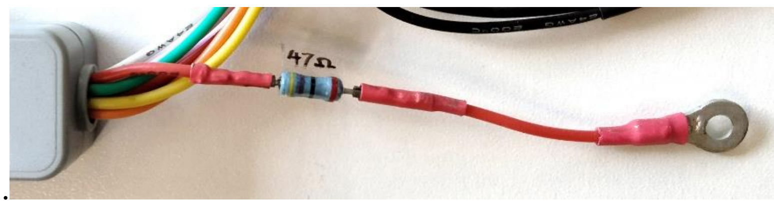
**In-line resistor.** A resistor is installed in-line in the short positive (red) wire. We used a 47-ohm resistor. See the resistor specifications (4.13.13).

You can simply solder the resistor in-line. For a soldered resistor, a small 1/4-watt resistor will work fine.

*In-line soldered resistor, in the short positive (red) wire.*



*Resistor, single-pin sockets, and wires.*



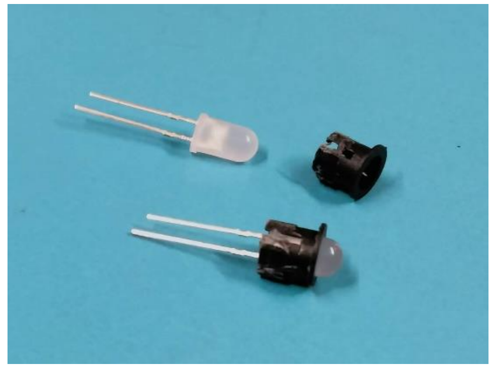

*In-line plug-in resistor, in the short positive (red) wire.*

Alternative: You can add single-pin sockets to plug in the resistor. This will allow you to experiment with different resistors while you are building the model (or even after the model is completed) to see which resistor works best with your LEDs and your battery pack. You will solder two single-pin sockets in-line and then plug the resistor leads into the pin sockets (see photo above). A larger 1/2-watt resistor has leads that will fit the pin sockets. Typical pin connectors fit solid wire of size 22 AWG (.025”, .64 mm) so the resistor leads should be at least 24 AWG (.02”, .5 mm).

| Instructions: Making the short positive (red) wire with in-line resistor | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Use the previously printed template. | **Paper template: Radial-PTemplate-BackWireHarness** |
| | | The template shows that the short positive (red) wire, including the in-line resistor, is about 3.5” long. |
| 2 | Select the resistor. | Selecting the resistance (ohms) and power (watts) is described in the resistor specifications section. |
| 3 | Snip the resistor leads. | Snip the resistor leads short (1/4" to 3/8”) because the wire is short, but it should be bendable. (If you are making a plug-in resistor, the length of resistor leads should fit the sockets, about 1/4".) |
| 4 | Solder the short positive (red) wire to the cable connector. | You previously soldered one end of the short positive (red) wire to the cable connector’s internal solder cup (see previous instructions). |
| 5 | Cut wire #1. | Cut wire #1, the wire from the cable connector’s internal solder cup to the resistor. This wire is about 2” long if you are soldering the resistor or shorter if you are adding a single-pin socket. |
| 6 | Cut wire #2. | Cut wire #2, the wire from the resistor to the neck of the ring connector. This wire is about 1” long if you are soldering the resistor or shorter if you are adding add a single-pin socket. |
| 7.1 | Option 1. Solder the resistor to the wires. | Strip the ends of both wires to be soldered to the resistor. |
| | | Hold the wires onto the resistor leads with a helping hands tool. (You do not need to twist the wire to the lead.) |
| | | Solder the wires to the resistor leads. (Use soldering flux.) |
| | | Slide a (clear) heat-shrink tube over the resistor and both joins, then apply heat. Use a clear tube so everyone can see the resistor. |
| 7.2 | Option 2. Add single-pin sockets to the wires so you can plug in the resistor. | Strip the ends of both wires to be crimped/soldered to the single-pin sockets. |
| | | Crimp and/or solder two single-pin sockets to the ends of both wires. (Use soldering flux.) |
| | | Slide a (red) heat-shrink tube over the join on each wire and apply heat. |
| | | Plug in the resistor by inserting the two resistor leads (pins) into the two pin-sockets. |
| 8 | Attach the ring terminal to the end of wire #2. | Strip the end of the wire to be joined to the ring terminal. |
| | | Slide a (red) heat-shrink tube onto the wire before crimping or soldering. |
| | | Crimp and/or solder a ring terminal to the end of the wire. (The ring terminal will be connected to the on-off switch.) |
| | | Slide the heat-shrink tube over the join and apply heat. |
| 9 | Label the resistor with the number of ohms (optional). | You may make a tiny tag for the resistor by folding a piece of transparent tape and writing the number of ohms on it. (The maintainer of the model and a few users may want to know the number of ohms.) |

### 4.13.15 LED holders

*LEDs and holders, unmodified.*



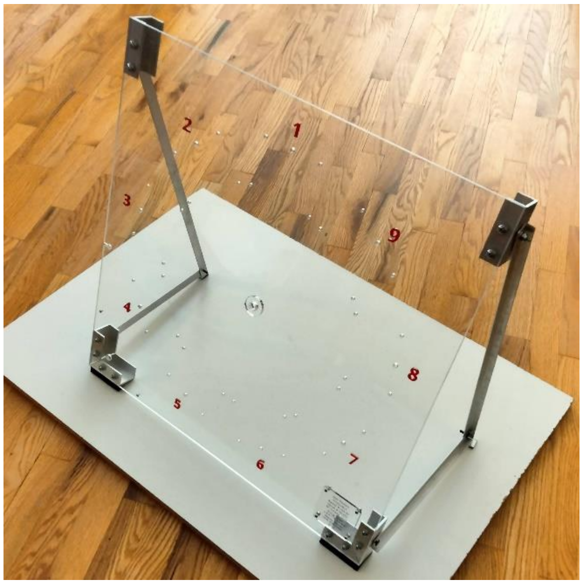
*LEDs and holders, modified.*

The LED holders are described in the Assembly Manual. They are store-bought parts, so there is nothing to make, but you can modify them.

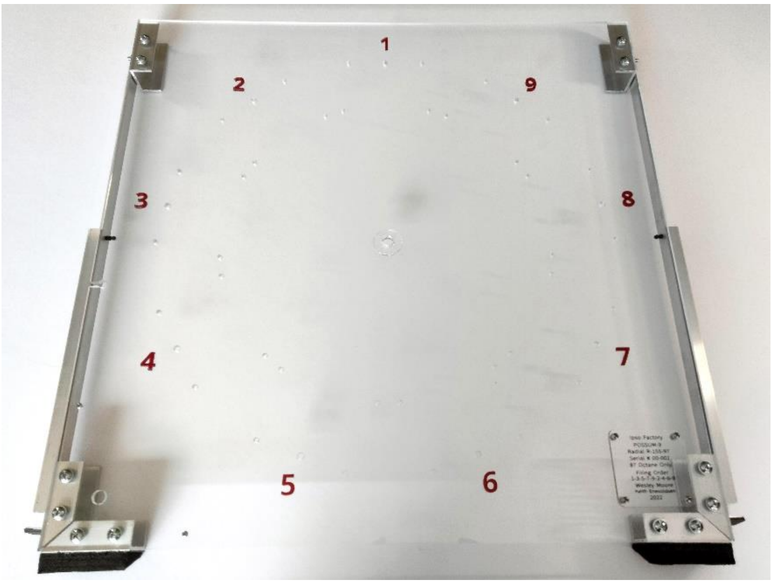
Common LED holders have detent bumps to make them snap into thin panels, but the cylinders are thick, not thin panels, so the bumps may need to be reduced in size.

| **Instructions: Modification of the LED holders** | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Reduce the size of the detent bumps (optional) | If the LED holders have detent bumps that make them too big to fit in the holes, shave the bumps with a razor knife or sand the bumps with sandpaper or a small sanding tool. |

## 4.14 Stand




*Stand, upright.*




*Stand, lying face up with legs stowed.*

The stand is described in the Assembly Manual.

**Construction phase.** We recommend that you make the stand early, after making the back plate and before you assemble the rest of the model. The stand is very helpful during assembly of the model.

### 4.14.1 Materials for making the stand

#### *4.14.1.1 Metal for brackets, legs, and crossbars*

| **Materials: Metal for brackets, legs, and crossbars** | | | | | |
|---|---|---|---|---|---|
| Material | Form | Size | Thickness | Total length | Usage |
| Aluminum | U-channel | 1.5”×1” | 1/8” | 6×3”=18” | Brackets |
| Aluminum | L-angle | 3/4”×1/2"<br>(or 3/4”×3/4") | 1/16” | 2×(2’+1’)=6 ft | Legs and crossbars |

The stand brackets are made from aluminum (or other metal) U-channel stock.

The stand legs and crossbars are made from aluminum (or other metal) L-angle stock.

#### *4.14.1.2 Rubbery materials for footpads*

| **Materials: Rubbery materials for footpads** | | | | |
|---|---|---|---|---|
| Material | Form | Size | Quantity | Usage |
| Rubber, rubbery plastic, or dense foam | Block | 3”×1.5”×5/8” | 2 blocks | Footpads on brackets |
| Rubber or rubbery plastic (such as vinyl) | Sheet | 2"×1"×1/16” | 1 sheet | Footpads on legs |
| Double-sided mounting tape (heavy duty) | Tape | 12"×1"×1/16” | 1 roll | Attaching footpads |

The two large footpads on the brackets are wedges cut from blocks of rubber, rubbery plastic, or dense foam.

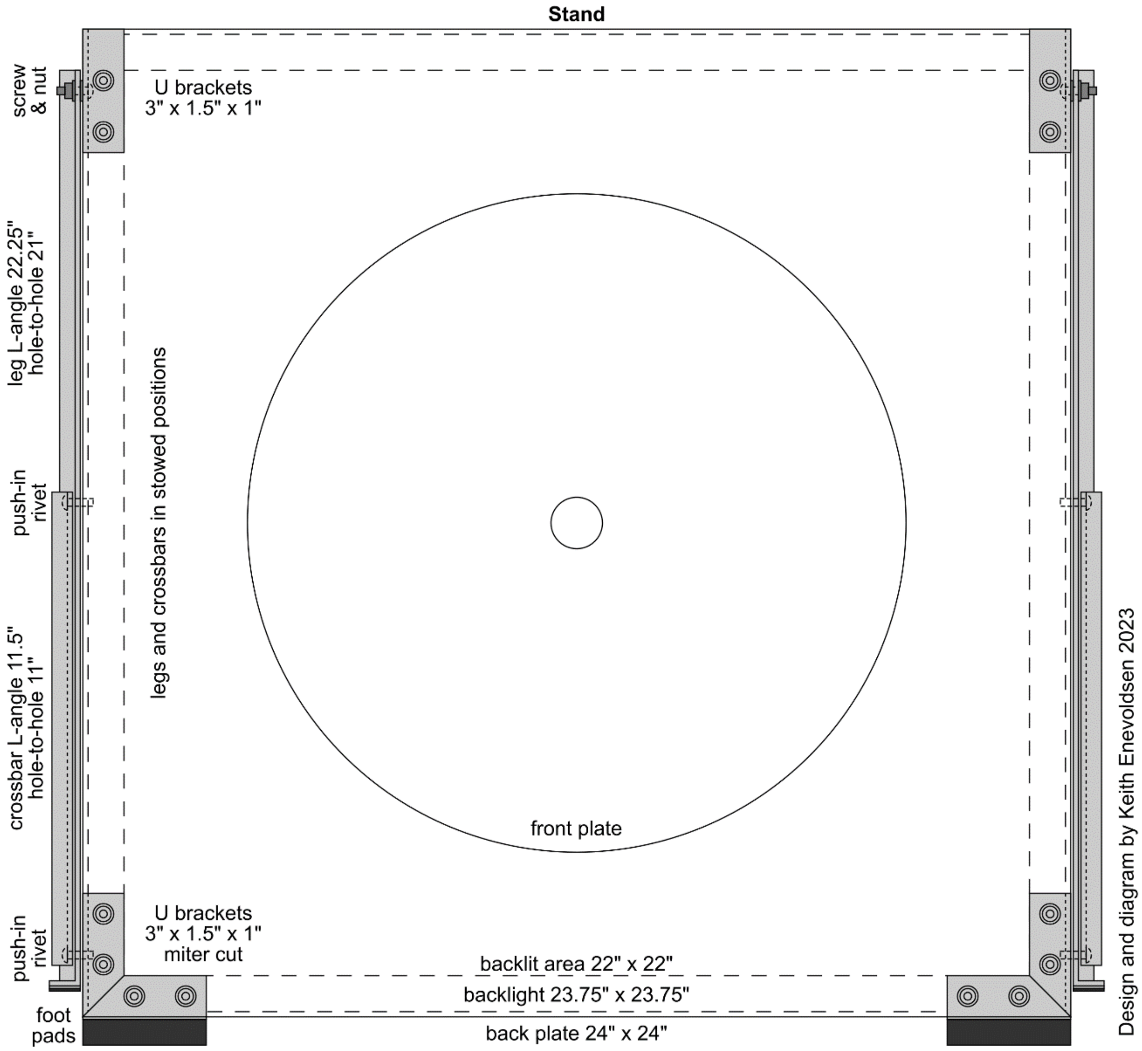
The two small footpads on the legs are small squares cut from a sheet of rubber or rubbery plastic. (We cut pieces of vinyl wall base.)

The footpads are attached to the brackets and legs with heavy-duty double-sided mounting tape.

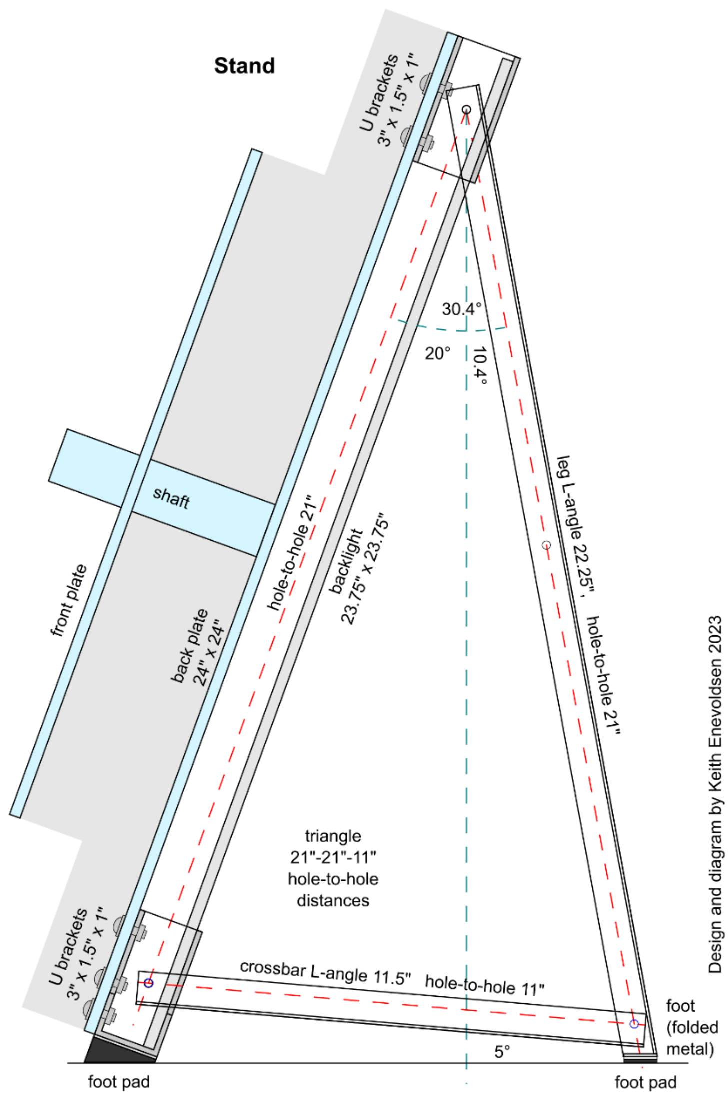
### 4.14.2 Parts list

| **Stand: Custom parts** | |
|---|---|
| Part | Quantity |
| Stand brackets | 6 |
| Stand legs | 2 |
| Stand crossbars | 2 |

### 4.14.3 Stand diagrams

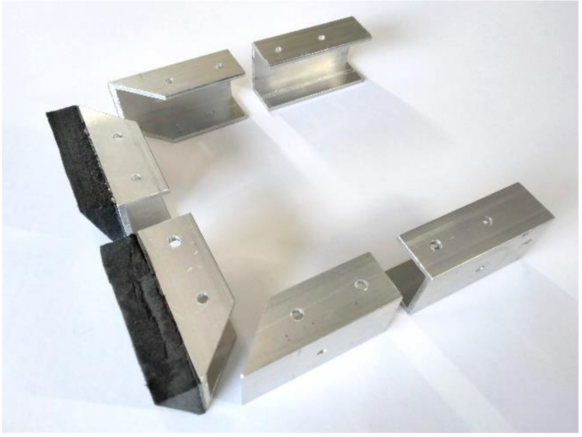



*Stand, front view, with legs and crossbars stowed.*




*Stand, side view, with legs and crossbars deployed.*

### 4.14.4 Making the brackets



*The six U-brackets. The two bottom brackets have footpads.*

The brackets are described in the Assembly Manual.

| Instructions: Making the stand brackets | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Print the brackets template, full scale. | **Paper template: Radial-PTemplate-StandBrackets** |
| | | The template shows where to cut the metal and where to drill holes. |
| | | Print the template, full scale. |
| 2 | Cut six brackets from U-channel. | Material: Aluminum U-channel, 1.5”×1”, 1/8” thick.<br>See the metal materials list (4.14.1.1). |
| | | Cut two 3”-long brackets that are straight-cut on both ends. |
| | | Cut four 3”-long brackets that have a 45° miter-cut on one end. See the template. |
| | | Sand all sharp edges and corners. |
| 3 | Drill screw holes. | Cut out the paper template (10 pieces) and tape the pieces to the brackets as guides for drilling the holes. |
| | | Take care to drill all holes very precisely. The holes in the brackets must align with the holes in the back plate and the holes in the legs (when the legs are stowed). |
| | | On the front of each of the six brackets drill two 3/16” holes for the #10 screws that will attach the brackets to the back plate. |
| | | On the side of each of the four side brackets drill one 3/16” hole for the #10 screws or push-in rivets that will attach the brackets to the legs and crossbars. |
| | | Sand all sharp edges of the holes. |
| 4 | Make two large footpads. | Material: Two rubber, rubbery plastic, or dense foam blocks. Each block is 3”×1.5”×5/8”.<br>See the rubbery materials list (4.14.1.2). |
| | | Cut the two blocks into 20° wedges (see the template). Use a razor knife, a fine-toothed saw, or a handheld rotary tool with a cutting wheel. |
| 5 | Attach the footpads to the bottom brackets. | Attach the two footpads to the two bottom brackets with heavy-duty, double-sided mounting tape. |

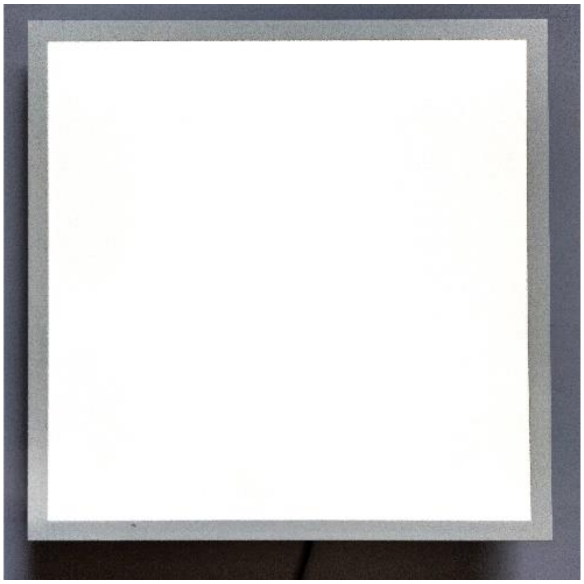
### 4.14.5 Making the legs and crossbars


*Legs and crossbars. The legs have small footpads.*
*Also shown are screws, nylock nuts, washers, and plastic push-in rivets.*

The legs and crossbars are described in the Assembly Manual.

| Instructions: Making the stand legs and crossbars | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Print the legs and crossbars template, full scale preferred. | **Paper template: Radial-PTemplate-StandLegs** |
| | | The template shows where to cut the metal and where to drill holes. |
| | | Print the large template (8.5”×24”), preferably at full scale, on a single large sheet of paper (at a print shop) or print on multiple smaller sheets and tape them together. If printed at full scale, you can measure the metal directly against the printed template. If printed at a smaller scale, you can read the numerical lengths and measure the metal with a ruler. |
| 2 | Cut the legs and crossbars. | Material: Aluminum L-angle, 3/4”×1/2" (or 3/4”×3/4"), 1/16” thick.<br>See the metal materials list (4.14.1.1). |
| | | Cut two 23” lengths of L-angle for the legs. See the template. |
| | | Cut two 11.5” lengths of L-angle for the crossbars. See the template. |
| | | Use a sander or grinder to round the corners of the crossbars that are near the screw holes, for added clearance when folding the stand. See the template. |
| | | Sand all sharp edges and corners. |
| 3 | Drill screw holes. | Take care to drill all holes very precisely. The holes in the legs must align with the holes in the brackets (when the legs are stowed). The holes in the crossbars must align with the holes in the legs (when the crossbars are stowed). |
| | | On each leg drill three 3/16” holes for the #10 screws and/or push-in rivets that will attach the legs to the brackets and crossbars. See the template. |
| | | On each crossbar drill two 3/16” holes for the #10 screws and/or push-in rivets that will attach the crossbars to the brackets and legs. See the template. |
| | | Sand all sharp edges of the holes. |
| 4 | Cut the L-angle before bending. | To allow the metal to be bent, cut off a 3/4" length of one side of each L-angle, at the foot end of each leg (see the template). Use a fine-toothed saw or a handheld rotary tool with a cutting wheel. |
| | | Sand all sharp edges and corners. |
| 5 | Bend the legs to make the feet. | To make the feet, bend the metal at a right angle (90°) at 3/4" from the end of each leg. The bend lines are at a 10° angle (see the template) to make the feet lie flat on the tabletop, because the legs will be tilted about 10° from vertical. |
| 6 | Make two small footpads. | Material: Rubber or rubbery plastic (such as vinyl) sheet, 1/16” thick.<br>See the rubbery materials list (4.14.1.2). |
| | | Cut two small square pads, 3/4"×3/4". See the template. |
| 7 | Attach the footpads to the legs. | Attach the two footpads to the bottoms of the feet with heavy-duty, double-sided mounting tape. |

## 4.15 Backlight



Backlight, front.

Backlight, back.

The backlight is described in the Assembly Manual.

### 4.15.1 Custom-made vs. ready-made

We considered whether it was possible to buy a ready-made 24”×24” dimmable LED light panel. We found many ready-made artists’ light pads with the desired brightness and dimmer control, but we could not find one that was the desired size, 24”×24”.

On the other hand, dimmable ceiling LED panels that are 24”×24” are a standard and inexpensive product. So, we will give instructions for making a custom backlight from a dimmable ceiling LED panel.

### 4.15.2 Parts list

| Backlight: Custom parts | |
|---|---|
| Part | Quantity |
| Backlight (with dimmer control and power cord) | 1 |

—

| Backlight: Standard parts (built into custom parts) | | |
|---|---|---|
| Part | Size | Quantity |
| Ceiling LED panel, dimmable | 24”×24” nominal (23.75”×23.75” actual), 1/4" thick at edges (within 1” of edges). | 1 |
| On-off-dimmer control, enclosed box | The dimmer type must be compatible with your light panel.<br>The box should be compact (our box is 3.5”×3.5”×2”). | 1 |
| Power cord with wall plug, grounded | Wire gauge greater than or equal to your LED panel’s AC wires (perhaps 14-18 AWG). At least 4 ft long, to reach from table to wall socket. | 1 |
| Strain-relief cable clamp | Fits your LED panel’s electrical box knock-out and your power cord. | 1 |
| Wire connectors | Appropriate sizes to connect your AC power wires, your DC LED panel wires, and your dimmer wires. Any type (lever connectors, push-in connectors, or wire nuts), 2-port and 3-port. | 3 to 5 |
| Extra wire (if needed) | Short lengths of appropriate wire gauge (perhaps 14-18 AWG), solid or stranded. | ~6” |
| Screws, nuts, washers | Appropriate sizes to mechanically attach your dimmer control box to your LED panel. | 2 sets |
| Cord tie | Fits your power cord. | 1 |

### 4.15.3 Light panel specifications

**Dimmable light panel.** The light panel should be dimmable, so you can add a dimmer control. The light panel should be bright enough to make the model light up brightly, even in a daylit room, but not so bright that it is uncomfortable to look at. In other words, it should be at least as bright as a typical artist's light pad, but less bright than a typical undimmed ceiling light panel. The best way to get the appropriate brightness with a ceiling LED panel is to buy a dimmable ceiling LED panel and attach a dimmer control. Then you can easily select whatever brightness looks best, depending on the room lighting.

**Brightness values.** Total brightness (luminous flux) is measured in lumens (lm). Brightness per area (luminance) is measured in lux. 1 lux = 1 lumen per square m. For this model, the panel's area is about 2×2=4 square ft = 0.37 square m. The panel's brightness per area should be about 3000 to 4000 lux. The panel's total brightness should be about 1000 to 1500 lumens. Ceiling LED panels are typically too bright without dimmer controls (2000 to 3000 lumens at low settings and 4000 to 5000 lumens at high settings), so you should add a dimmer control.

**Size of light panel.** The light panel should be the same size as the back plate, 24”×24” (or slightly smaller). Fortunately, 24”×24” (23.75”×23.75” actual size) is a standard size for ceiling LED panels, so these panels are common and inexpensive. It is acceptable if the panel has an opaque frame up to 1” wide, making the lighted be only 22”×22”. The light panel edges should be about 1/4" thick, so the edges can be slid into the stand's U-channel brackets. The entire edge area, within 1” from the edge, should be no more than about 1/4" thick. The rest of the back of the panel (including the electrical box on the back), farther than 1” from the edge, may be thicker (up to about 3” thick).

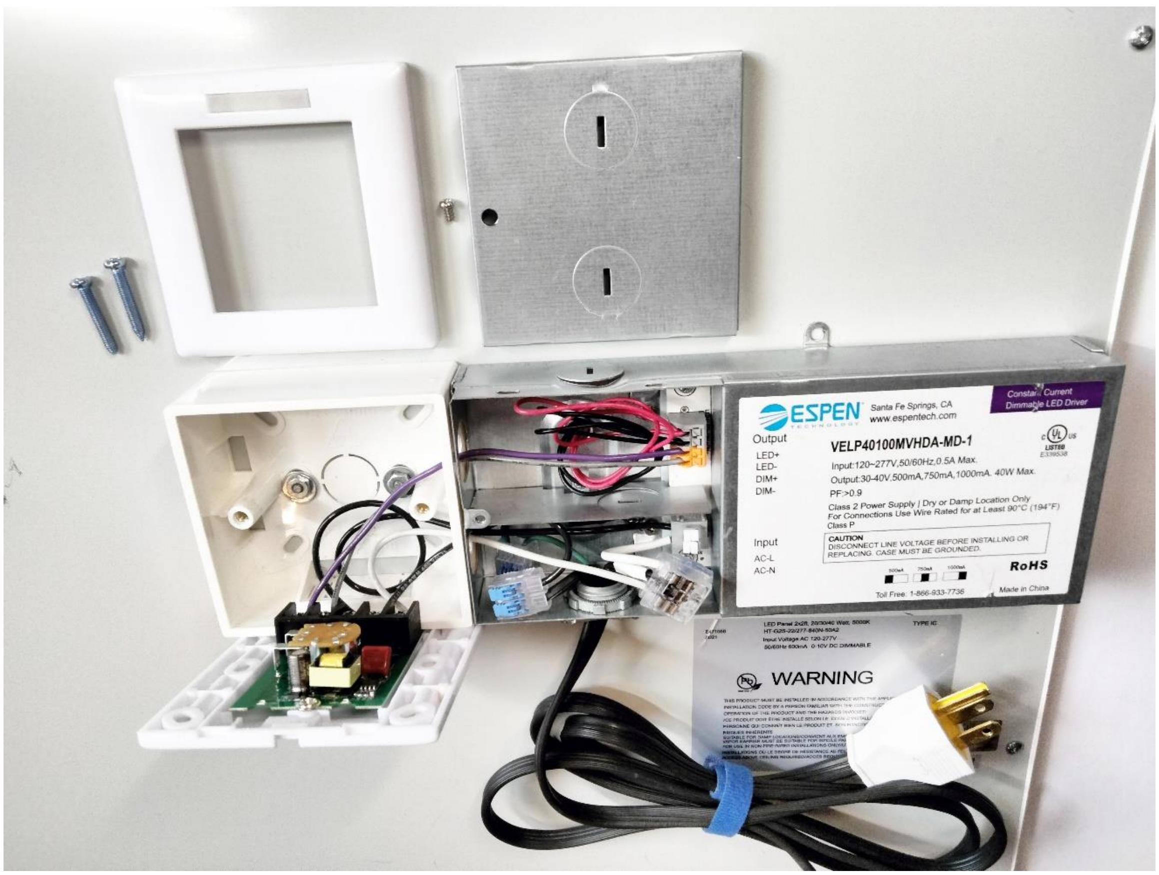
### 4.15.4 Dimmer control specifications

The dimmer type must be compatible with your light panel. (For example, our light panel required a 0-10V dimmer.) The dimmer control should include both dimmer and on-off functionality, so you do not need to install a separate on-off switch.

Buy a dimmer control that has a compact, fully self-enclosed box, so you do not need to buy or make a box. (Most dimmers are not fully self-enclosed because they are made to be installed inside wall switch boxes.)

## 4.15.5 Making the backlight


*Backlight, back side, with dimmer control box and power cord added.*




*Backlight, back side, with the electrical boxes open.*
*AC wires are black, white, and green. DC LED wires are red and black. DC dimmer wires are purple and gray.*

**WARNING: ELECTRICAL.** Take precautions with the backlight panel and power cord, as you would with any other appliance that is plugged into a (grounded) wall socket. Ensure that the custom-made electrical wiring connections are safely enclosed in an electrical box (on the back of the panel) and that the power cord is safely secured to the electrical box.

| Instructions: Making the backlight (with dimmer control and power cord) | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Attach the power cord to the light panel. | Read the manufacturer’s wiring instructions for your ceiling LED panel. |
| | | Install a strain-relief cable clamp, in the knock-out hole of the electrical box, to hold the power cord securely and safely. |
| | | Inside the panel’s electrical box, connect the three wires (L=line, N=neutral, and GRD=ground) of the power cord. Use correctly-sized wire connectors. |
| 2 | Attach the dimmer control to the light panel. | Read the manufacturer’s wiring instructions for your ceiling LED panel. |
| | | Read the manufacturer’s wiring instructions for your dimmer control. |
| | | Mechanically attach the dimmer control box to the back of the LED panel and adjacent to the electrical box on the panel. You may need to drill some holes for screws and/or wires. Use machine screws, nuts, and washers of appropriate sizes for your LED panel and dimmer control. |
| | | Inside the dimmer control box and the panel’s electrical box, connect all the wires for the dimmer, the LED panel, and the AC power cord, per the manufacturers’ instructions. Use correctly-sized wire connectors. |
| 3 | Finishing steps. | Label the back of the panel with an UP arrow, to show which way is up when the panel is inserted into the stand. |
| | | Add a cord tie for the power cord. |

Save the cardboard box of the purchased LED panel, so you can reuse it to store your backlight.

## 4.16 Plaque

### 4.16.1 Parts list

| Plaque: Custom parts | |
|---|---|
| Part | Quantity |
| Plaque | 1 |

### 4.16.2 Making the plaque


*Plaque for model 2 with laser-scored lettering.*

The plaque is described in the Assembly Manual.

You can make a plaque with scored or etched lettering (our plaque has scored lettering). You can replace our text with your text. (Alternative: You can make a clear plaque cover without text, then you can print the text for your plaque on paper or transparency film to be placed underneath the clear cover.)

| Instructions: Editing the template text | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Copy the template. | **Laser template: Radial-LTemplate-Plaque** |
| | | Make a copy of our template SVG file. |
| 2 | Edit the text. | Open your template SVG file in an SVG editor (such as Inkscape). |
| | | If you want a clear plaque cover without text, delete our text. |
| | | If you want your own text, delete our text and write your text. |
| 3 | Convert the text. | For laser etched text, select your preferred font, then convert the text to filled paths. |
| | | For laser scored text, convert the text to a one-stroke font. (In Inkscape, we used the Hershey Text extension.) |

—

| Instructions: Making the plaque | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Laser score or etch the lettering and laser cut the plaque. | **Laser template: Radial-LTemplate-Plaque** (or your template) |
| | | Material: 1/8”-thick clear acrylic, cast. Scored or etched letters will look crisper if you use cast acrylic rather than extruded acrylic. |
| | | Laser score the text if your template has one-stroke lettering. |
| | | Laser etch the text if your template has filled lettering. |
| | | Laser cut the plaque (pilot holes first). |
| 2 | Paint the letters. | Paint the scored or etched letters black. Paint with a brush before removing the paper mask. |
| 3 | Drill the screw holes. | Drill (starting with the pilot holes) unthreaded close fit holes for #4 screws (#32 drill bit). |

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| Instructions: Making the screw holes in the back plate for the plaque | | |
|---|---|---|
| # | Step | Instructions |
| 1 | Drill four pilot holes in the back plate. | If you previously cut the pilot holes for the plaque when you made the back plate, then you can skip this step. |
| | | **Paper template: Radial-PTemplate-PlaquePosition** |
| | | The template shows the position of the plaque screw holes on the back plate. |
| | | Print the template, full scale. |
| | | Tape the template to the back plate, aligned with the edges of the plate. |
| | | Drill four small (1/16”) pilot holes through the paper template and the back plate. |
| 2 | Drill four screw holes in the back plate. | Drill four screw holes (starting with the pilot holes) in the back plate. |
| | | If you prefer threaded holes (which can hold the plaque without nuts), drill (#43) and tap #4-40 threaded holes. If you prefer unthreaded holes, drill unthreaded holes for close fit to #4 screws (#32 drill bit). In either case, you will secure the screws with #4-40 nylock nuts on the back side. |

## 4.17 Storage box

*Storage box containing the model.*

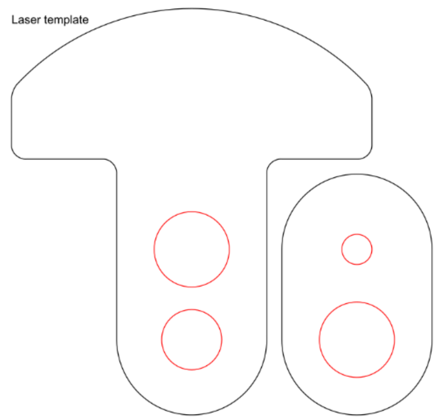
You can store the model in a box that is at least 27" × 27" × 7", big enough to hold the model when the backlight is removed, the stand is stowed, and the propeller hand crank is detached.

If you cannot find a box or container of the right size, you can make a box. Instructions for making a box out of corrugated cardboard or corrugated plastic are in this template file: **Radial-PTemplate-StorageBox** .

We stored the backlight in a separate box. We stored the spare parts and manuals in additional boxes.

# 5 Customizing your model

## 5.1 Design files




*Example of 2D design for model 2.*
*The 2D laser templates (SVG) are directly edited with Inkscape.*

For model 2, all design files are 2D, not 3D. The design files are the templates (laser templates for making laser-cut parts and paper templates for making other parts) and the documents (Maker Manual and Assembly Manual) with diagrams. All the primary templates and diagrams are provided in SVG format (2D vector graphics), more specifically Inkscape SVG format.

## 5.2 Inkscape SVG

Inkscape is a popular free SVG graphics editor. You can download and install Inkscape for free.

**Inkscape SVG versus Plain SVG.** Inkscape SVG format is standard SVG format plus some added attributes (hints) to represent added features. Most notably, Inkscape allows your SVG drawing to have layers. Inkscape layers are simply SVG groups with an extra attribute telling Inkscape UI to treat the group as a layer. You can use Inkscape to export or save an Inkscape SVG file to Plain SVG format. It will render identically, but the Inkscape extensions (such as the layer hints) will be removed.

We used Inkscape to edit our templates and diagrams, so the SVG files are in Inkscape SVG format. The laser templates are very simple and do not need any Inkscape extensions. But there are a few multi-layer design templates and a few multi-layer diagrams that use the Inkscape layers feature.

## 5.3 Modifying the design files

You, the maker, can customize your model by copying and editing the SVG laser templates or paper templates.

You can do the following with the SVG design files:

- **Control** your laser cutter with the SVG laser templates.
- **View** the SVG files in a graphics viewer (such as a browser) or an SVG graphics editor (such as Inkscape).
- **Edit** the SVG files in an SVG graphics editor (such as Inkscape).
- **Convert** the Inkscape SVG files to other vector formats (such as Plain SVG, DXF, EPS, or PDF) using Inkscape or another vector graphics application or website.

To edit the provided templates, we recommend using Inkscape (because our templates are in Inkscape SVG format), but other SVG graphics editors may also work just as well.

## 5.4 Design alternatives

If you are thinking about modifying the design of the model, you should look at these two supplementary documents:

- **Design Alternatives** describes some possible design alternatives that we considered but did not implement for model 2. If you are thinking about changing the design of this model, then you might be interested to read about these design alternatives.
- **Revision History** lists the past design revisions of models 1 and 2, including reasons for the changes and lessons learned. If you are thinking about changing the design, then you might be interested to read about the lessons learned from the past revisions.