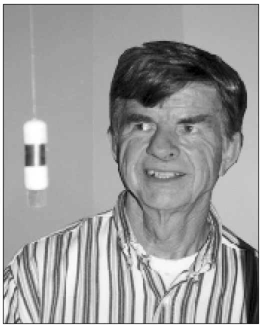
A Different Twist on the Lorentz Force and Faraday's Law

Bill Layton and Martin Simon



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In this paper we will describe some simple experiments involving the magnetic force on currents and electromagnetic induction. In every situation, the heart of the apparatus will be a "homopolar" or "unipolar" magnet structure (which is nothing more than two cylindrical magnets with like poles held together.) Homopolar structures make it possible to construct dc motors and generators without commutators. The experiments discussed here are not new; similar experiments were performed by Faraday in 1831.[1] However, the explanation of these experiments has been debated by physicists such as Faraday, Ampere, Hertz, Weber, Lorentz, Einstein, and others ever since. Indeed, Einstein addresses the homopolar generator in his famous 1905 paper on special relativity.

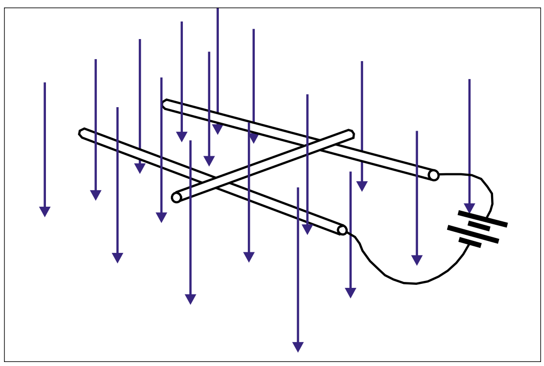


Fig. 1. The usual electromagnetic motor illustrated here is different from the homopolar motor discussed in this article.

The problem of the homopolar motor first came to our attention during a "Show and Tell" session at a recent Southern California AAPT section meeting when Roger Morehouse[2] presented it as a puzzle for us to try to explain; he even coyly suggested that the explanation might force us to reconsider the existence of the ether! Others have speculated that the lack of a reaction force on the magnet might violate Newton's third law and make a perpetual motion machine possible.[3] Our purpose here is to describe some simple but very thought-provoking experiments that can be done with even the most modest equipment. These experiments raise interesting questions. Do magnetic fields rotate with rotating magnets? Is the *v* in the Lorentz force equation the relative velocity between the magnet and the conductor or is it the velocity with respect to some rest frame (ether) in which the magnetic fields are always at rest?

We are not suggesting that the laws of physics be revised, but we do want to set the stage for a careful rethinking of some of the most basic and accepted laws presented in the traditional high-school course. Should you desire a more detailed mathematical treatment of these ideas, see the papers by Corson[4] and Webster.[5] The best brief representation of the spirit of our paper was presented in a "Little Stinker" and a "George" cartoon in an old issue of *The Physics Teacher*.[6] An extensive set of references as well as a demonstration experiment of the unipolar generator can be found on the Lecture Demonstration Home Page by Berg and Alley.[7] Finally, an outstanding in-depth study of unipolar induction can be found in "Essay 3" of Arthur Miller's book.[8]

Experiments with the "Homopolar Motor"

First we warn you of what this experiment is **not**, even though it looks very much like the traditional current-carrying wire moving through a magnetic field. The traditional picture is something like Fig. 1, and with a little bit of hand waving and a discussion of the charges moving in the wire, the Lorentz force expression will predict which way the wire will move. This is **not** the same thing we are talking about here.

In our experiment the magnet itself moves as a result of a current passing through a copper sleeve surrounding it, with seemingly no

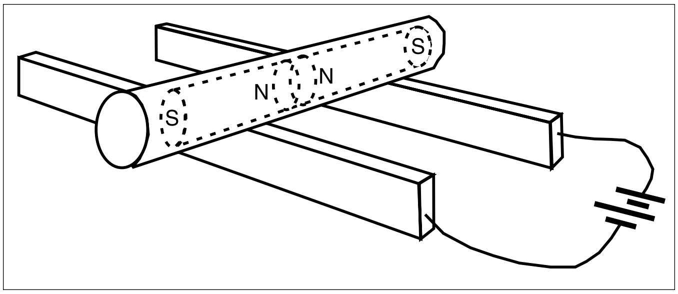


Fig. 2. The homopolar magnetic structure consists of two magnets with like poles facing each other inside of a conducting copper cylinder.

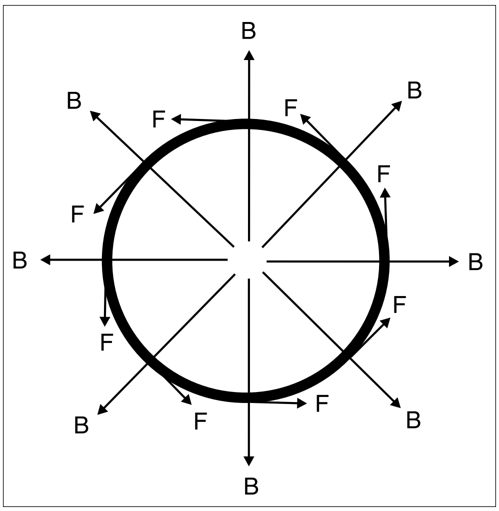


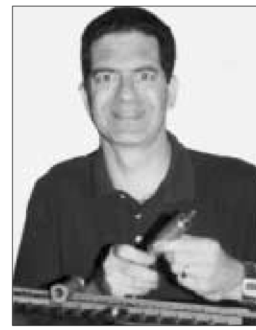
Fig. 3. Crossection of the homopolar armature taken perpendicular to its axis, through the center.

external magnetic field to "push on"! This paradox can be resolved, but an explanation did not come immediately to us. The apparatus is illustrated in Fig. 2; the key feature is that the two magnets inside the copper tube have *the same poles facing one another.* When the power supply is attached to the track, the magnet structure will roll one way, and when the direction of the current is reversed, the magnet structure will roll in the opposite direction. Observe that the current is passing through the magnet structure itself and it seems as though the structure is pulling itself along by its own bootstraps! We will partially resolve this "paradox" in the next paragraph, so if you would like to solve it yourself, put this article down and work it out now.

The understanding of the magnet's motion requires an appreciation that two magnets with the same poles facing one another produce a radially directed magnet field in the region between the poles. It is also important to realize that the track contacts the conducting copper tube only inside of the region between the centers of the two magnets. (That is, the current will flow through the copper tube only in a region where the radially directed field component is all outward or all inward.) Imagine a cross-sectional view of the conducting copper tube in the region between the two magnets. Consider only the radially directed components of the magnetic field, assume that two north poles face one another inside of the copper tube, and further assume that the current is coming toward you, out of the page (illustrated in Fig. 3). Hand waving and the Lorentz force equation should produce forces tangent to the circular tube and, since the magnetic field is radially outward, the forces will be in a counterclockwise direction. These forces will produce a torque that will rotate the tube counterclockwise, and if it rests on the track it will move to the left. Reversing the direction of the current will reverse the direction of the torque and cause the structure to move in the opposite direction. Naturally, there is no paradox and it is the copper tube pressing on the track that provides an equal and opposite force by the track on the copper tube, which in turn moves the tube in one direction or the other. We still can't pull ourselves up by our bootstraps; reactionless space drive must await a breakthrough in the laws of physics! However, there are a few more questions we can ask. What would happen if we suspended the magnet structure in a way such that it was free only to spin and we passed a current through it? (In other words, if the track were slippery, would the structure respond by spinning only?) This is the subject of our next investigation, but before we describe those results, we think it would be appropriate to give a few details on how we constructed the rolling magnet on the track apparatus so that readers can easily duplicate the apparatus.

Construction Details

For this experiment to work, the two magnets should be quite powerful and the track must be perfectly level. We used two powerful cylindrical magnets[9] that just fit inside of a 3/4-in copper pipe coupler. If you have access to a machine lathe, you can turn a tube of the correct size, but we were able to use a standard 3/4-in copper pipe coupler and two



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slightly altered 1/2-in PVC pipe caps to contain the magnets inside of the copper coupler and hold them in their repelling state. To make the PVC caps fit over the copper coupler, it was necessary to enlarge the inside using an appropriate drill bit. (Again a lathe would help, but we are trying to keep it simple. Carving with a pocketknife also works but takes a long time.) Our track was made from two pieces of aluminum angle spaced the proper distance apart and screwed to a piece of wood. If the track spacing is correct, track from a model train set can also be used. The complete apparatus is illustrated in Fig. 4. (Note, most of the aluminum you find in hardware stores is insulated and it will be necessary to sand all surfaces that are to make electrical contact.) The copper coupler, PVC pipe caps, and aluminum angle can all be obtained at a hardware store or a building supply warehouse. To avoid any problems that might arise from peculiar magnetic fields, we used brass screws. The current used was in the neighborhood of 5 A; even at this magnitude, the forces are quite small. The track should be perfectly level (a wedge at one end makes precise leveling easy) and the track surface must be quite smooth. With the minimum current required, some arc welding may occur at the contacts; try to avoid this so pits won't form.

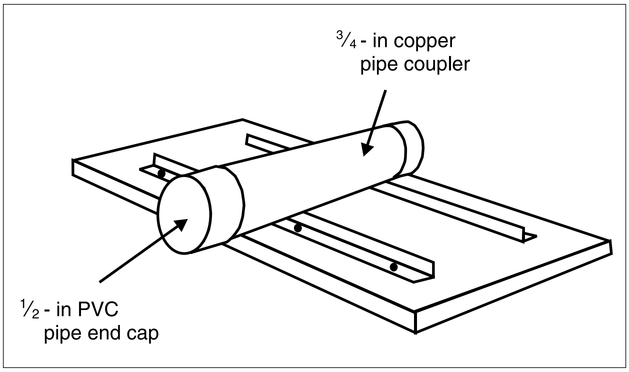

Fig. 4. Construction of the homopolar motor requires very little special equipment.

The apparatus as described is rather sensitive, and as we were to learn, the torque on the magnet structure is actually quite small. So showing that there really is a torque on the magnet structure was the object of our next investigation. In our first attempt we built a device that would support the magnet structure while allowing it to rotate freely (this device will be described later). It was our hope that we could use copper wire brushes rubbing on the copper tube to introduce the current that would make the structure rotate. No matter how much we tried to decrease the rotating friction, there was no hint of rotation. Any brush we used to make contact with the copper tube always introduced too much friction. In a similar experiment, Eagleton and Kaplan[10] floated the magnet structure in mercury and used special nonmagnetic bearings on either end. Even this special structure required a current of 25 A. Since mercury has been "outlawed" in schools, our alternate method described next should prove useful.

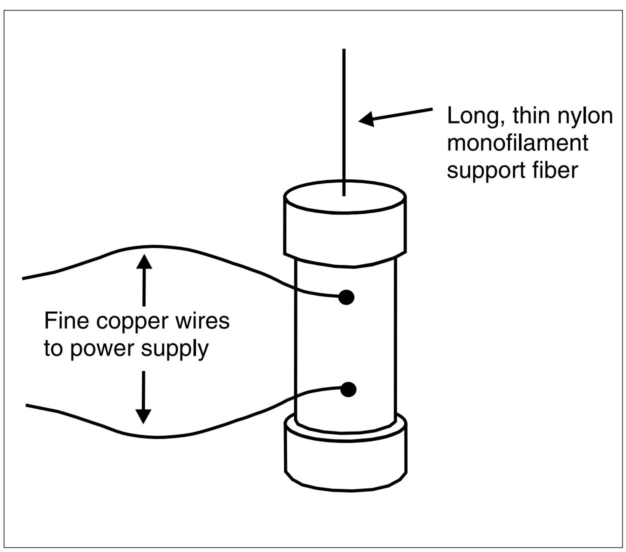

Fig. 5. Apparatus used to verify that the structure experiences a torque when not resting on the track.

Remembering the Cavendish experiment, we were able to build a simple torsion pendulum to detect the very small torques involved. The apparatus is illustrated in Fig. 5 and consists of a long fine piece of monofilament nylon supporting the magnet structure in a vertical position. Very fine wires are soldered to the copper tube at approximately the same places where the track would contact it in the horizontal rolling case. With the power supply set at to produce about 5 A (almost the maximum the small wires will carry), power is turned on and off at the resonant frequency of this torsion pendulum. The resulting oscillations will always start in one direction with the current flowing in one direction and will start in the opposite direction when the current direction is reversed. The torque, though very small, is predictable and always in a direction dictated by the direction of the current.

Now that we have demonstrated that the entire magnet structure and copper sleeve experiences a torque when a current passes through it, we realize we have a bigger question. The only way a single isolated object can experience a net torque is if something else in the universe experiences a countertorque (this follows from conservation of angular momentum.) What are the counter forces? An object that is supposedly hanging freely can be made to twist apparently without an observable countertorque! This and other experiments show that the countertorque is not applied to the source of the magnetic field (the homopolar magnet) nor, as in the case in the ordinary motor, back on to the field magnets or "stator." Perhaps we haven't violated Newton's third law, but we have a bigger problem with the conservation of angular momentum! Earth's magnetic field plays no role in causing the structure to rotate, since when the magnets were removed from the copper tube and the experiment was carefully repeated, no tendency to rotate could be observed.

Experiments with the "Homopolar Generator"

The next question we asked was: If we spin the magnet structure, will a potential difference be developed across the copper tube? Perhaps it would be good for readers to see an illustration of the apparatus we used, and then they could predict whether it will produce a current. The apparatus is actually a failed version of our earlier attempt to use current to produce torque. In this situation we will be driving the magnet structure with a drill, and so the small friction problems are of no consequence (Fig. 6). We made the magnet structure rotate by holding the outside edge of a rubber buffing and sanding disk (with the sanding disk removed) near the center of the copper coupler and using friction to force the structure into rotation. You need not build this apparatus to test the effect. Attaching the magnet structure directly to an electric drill using a length of wooden dowel (or other nonferrous material) and then using the track as a "brush" gives the same effect (Fig. 7). Here is the question: With a dc meter attached to the brushes, and forcing the magnet structure to rotate at, say, three or four revolutions per second, will a potential difference be observed?

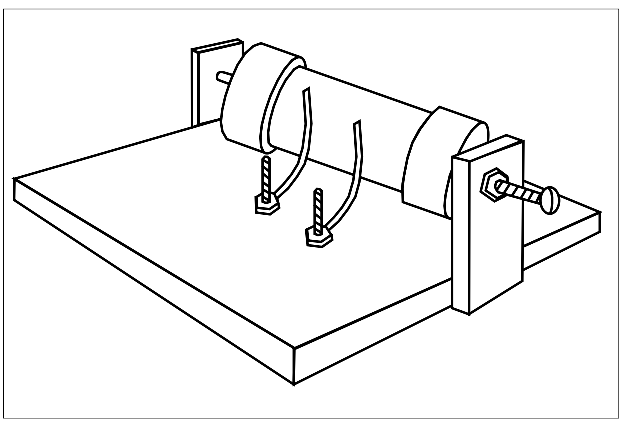

Fig. 6. The homopolar motor that failed.

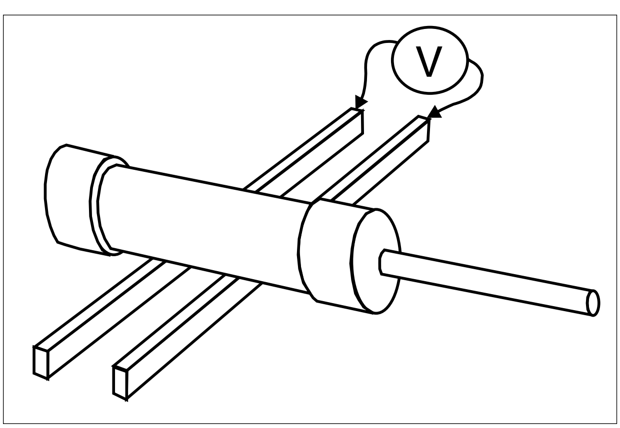

Fig. 7. Apparatus used to illustrate homopolar generator.

If you say "no," think very hard about the forces on the charges moving through the magnetic field. (It might help to look again at Fig. 3 and call the force vectors "velocity" vectors and ask what force the charges will experience.) Do the magnetic field lines rotate with the turning structure or remain fixed in space? Perhaps you think that there is no motion of the charges relative to the magnetic field. If this is your argument, what about symmetry, the reason the structure moved in the first place? If a current produces a torque on the magnet-and-copper-tube structure, why shouldn't rotating the structure produce a current? (Usually a motor can be used backward as a generator and vice versa. Surely a motor this uncomplicated should be able to be run backward as a generator!)

If you say "yes," where is the change in magnetic flux per time required by Faraday's law? We are rotating a symmetric magnetic structure but it is standing perfectly still. Whatever magnetic flux might exist in the closed circuit that includes the meter does not change. No flux change, no emf; no emf, no current!

So it seems we have a paradox, if indeed from the point of view of the Lorentz force we get a current, but from the point of view of Faraday's law, we don't. In our experience we have always been able to show that the Lorentz force follows from Faraday's law. In other words, they are consistent with one another. Here, however, the existence or nonexistence of a current suggests that one or the other must be the law to use. This is a situation crying out for an experiment. Is there or is there not a current?

Experiment says there is! Using an oscilloscope instead of a dc meter clearly shows that it is only dc and we are not being fooled by some ac that might make the meter read. So it seems that a nonchanging magnetic field in a "loop" of wire produces a dc current. What started as a "paradox" involving pulling a magnet along by its own bootstraps has ended with a "paradox" between the Lorentz force and Faraday's law!

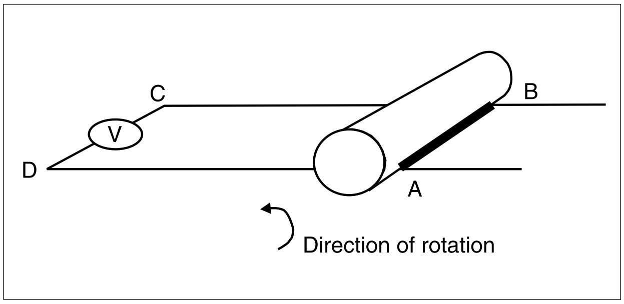

Fig. 8a. As the conducting cylinder begins to rotate, conducting segment AB is in contact with the track and will move to the right if the direction of rotation is counterclockwise as shown.

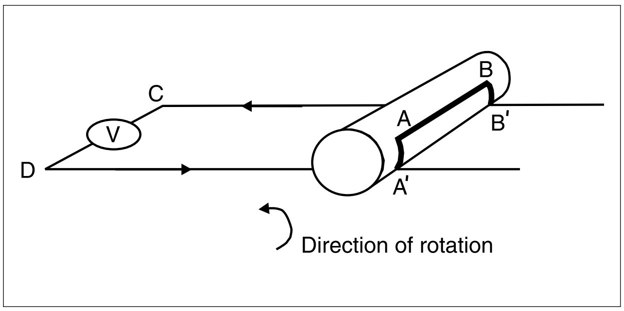

Fig. 8b. At some later time, conducting segment AB has moved in the radial magnetic field to the new higher position shown as a new conducting segment A′ B′ contacts the track in AB's previous position (see text for details).

Paradox Resolved?

It has been said that paradox is Mother Nature standing on her head in order to attract attention to herself. We have had many interesting discussions with several friends and finally believe that this paradox has been resolved and that the Lorentz force and Faraday's law are still completely consistent with one another. The following explanation is the result of much argument and contemplation and hopefully it will make sense to you. Better yet, you might even find it trivial.

Imagine the linear segment of copper between the two points of contact with the track labeled AB in Fig. 8a. The complete closed circuit, which includes the voltmeter, is labeled ABCD in the figure. As the copper tube rotates, this particular segment moves to a higher position on the copper tube and the complete circuit, which includes segment AB back to the track, is along the circumference on each side of the linear segment AB as illustrated in Fig. 8b. Imagine the magnetic field lines that thread through the closed circuit ABCD in Fig. 8b, now that AB has moved to a higher position. (As shown in Fig. 8b, a new linear segment A′B′ is now in contact with the track.) Notice how as the linear segment moves, more field lines are being included in the closed circuit ABCD, which is "behind" (or to the left of) the direction of rotation. This means that the amount of magnetic flux inside the closed circuit is always increasing as the copper tube rotates in the same direction. Of course this is only one of an infinite number of segments that make contact with the track and then move away from the point of contact. They all enclose an increasing amount of magnet flux in the closed circuit, which includes the return path through the circumference back to the track. (Naturally the return path can be through the circumference segment clockwise back to the track or counterclockwise back to the track. However, careful thought will reveal that one path along the circumference experiences an increasing flux and the other way around a decreasing flux. Applying Lenz's law to each side separately always produces an emf in the same direction.) Actually, the topology of this arrangement is no different from a single segment of wire moving along a semi-infinitely long track in the presence of an infinite external magnet field (see Fig. 1, but replace the battery with a voltmeter.) When the rotation is in one direction, it has the effect of producing a constantly increasing flux; rotating in the other direction has the same effect as moving a wire segment in the other direction, effectively decreasing the total flux in the circuit.

One last question to consider. What if you built a structure that forced the magnets inside of the copper cylinder to rotate, independent of the outside copper cylinder? That is, the copper tube is held motionless in contact with the track and only the magnets are rotated. Will a potential difference appear across the track as the magnet structure is rotated inside of the stationary copper cylinder? We know the answer to this question since we have done it (the answer is no!). A magnet structure with like poles facing one another will not produce an emf when rotated inside of a close-fitting copper tube. A consistent way to view this is that the magnetic field (lines) remain stationary as the magnets rotate. Does this violate any basic law of physics? We don't think so, but which part of the circuit represents the "seat" of the emf has been part of the debate about homopolar generators since Faraday.

Summary

- A simple experiment involving a current flowing through a radial magnetic field will cause the magnet and current-carrying structure to roll along a horizontal track.
- When the magnet and current-carrying structure is suspended freely, it will experience a torque and rotate, but the location of the countertorque has yet to be identified.
- When this magnet-and-copper-conductor structure is made to rotate, it will produce a direct current.
- The current thus produced can be explained either with the Lorentz force or with Faraday's law.
- Finally, when you spin the two like-pole facing magnets inside of a stationary copper cylinder, no potential difference is observed across the cylinder.

Suggestion for the Next Phase

The major unresolved question in the above experiments is: "Where does the angular momentum come from that causes the suspended structure to rotate?" Our theory is that the torque comes from the return current as it passes back through the homopolar magnetic field in the reverse direction. Since the power supply is attached to Earth, the angular momentum is returned to Earth. The next experiment should be to mount a self-contained power supply (say, four D cells) on the rotating support, activate the current with a light-activated switch (to make it possible to start and stop the current without adding angular momentum from the outside), and see if the system still twists. If the system does not rotate, the reverse current idea seems correct. To test this further, move the D cells farther out and repeat. With the D cells further away, the moment arm is now longer, but the intensity of the homopolar magnetic field at this greater distance will be smaller in just the right amount still to cause no net torque on the suspended apparatus. (A sketch of the proposed apparatus for this experiment is shown in Fig. 9.) When the power supply and the homopolar structure are suspended together, we are confident that the system will not rotate and the conservation of angular momentum principle will be secure.

In discussions we have had on this experiment, several physicists have suggested that the angular momentum is somehow carried away with the magnetic field produced by the current alone. We do not believe this should be a consideration with our experiment. (More on this idea can be found by reading Feynman's *Lectures*.)[11] All of these discussions have been concerned with the magnetic field produced by the current without regard for the interaction of this current with the homopolar magnetic field. Since we have observed that the suspended structure does *not* rotate when the homopolar magnet is removed, any angular momentum carried by the magnetic field of the current alone should not be a concern here.

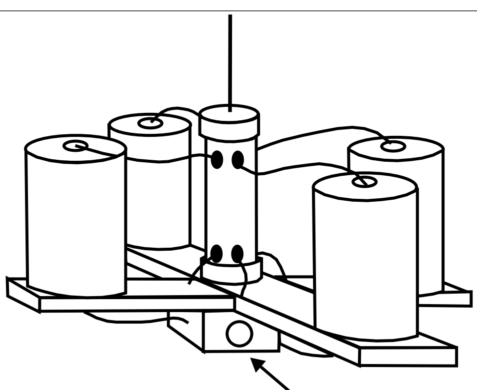

Fig. 9. Proposed apparatus to verify that the torque on the entire apparatus, homopolar armature and power supply, is zero.

Acknowledgment

As we were preparing this paper, we had several wonderful discussions with many friends who helped guide us through some of the more difficult aspects of the problem. In particular we would like to thank Walter Gekelman, David Goodstein, Lee Heflinger, Art Huffman, Nuria Rodriguez and Courtney Willis. And naturally, special thanks to Roger Morehouse for getting us started with this problem.

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