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Wheelbuilding

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by Sheldon "Wheels" Brown

substantially expanded by John "Bespoke" Allen

Why build wheels?

The wide availability of inexpensive, well-built replacement wheels has reduced the need for wheelbuilding in retail bike shops. Nevertheless, there are still times when custom-built (or rebuilt) wheels are needed, especially in the case of higher-end bikes that have expensive hubs that are too good to throw away.

Also, the combination of hub and rim that you want may not be available off the shelf: commonly, for example, if you would like to use an internal-gear hub.

Learning to build wheels is an important milestone in the education of an apprentice mechanic. A "mechanic" who has not mastered this basic skill cannot be considered to be a fully-qualified, professional, and will always feel inferior to those who can list wheelbuilding among their skills.

Although this article was originally directed to shop mechanics, a knowledge of wheelbuilding can be invaluable to any cyclist who wishes to do his or her own maintenance and repair.

Building wheels from scratch is the best way to learn the craft of wheel truing, to get the feel for how a wheel responds to spoke adjustments. It is much easier to learn this with new, undamaged parts than to start right in trying to repair damaged wheels.

Getting started

While an experienced wheelbuilder can build a wheel in well under an hour, a beginner should expect to spend several hours on the task. It is best not to try to do this all at one sitting, because you are likely to get frustrated at the slowness of the truing and tensioning process. Better to put the job aside, even overnight, than to get careless and ruin a good wheel-in-progress.

This article focuses on building a rear wheel, because that is the more complicated one. For front wheels, disregard that which does not apply. This will be a 36 spoke, cross 3 wheel.

If you're doing a 32 spoke wheel, just substitute "32" wherever I write "36", "16" where I write "18" and "8" where I write "9."

Use a similar substitution for other spoke numbers.

Tools

You will need a spoke wrench (I use a DT spoke wrench, but most people aren't ready for a $50 spoke wrench. My favorite inexpensive spoke wrench is a plastic one with a metal bit, called a "Spokey"). You will also need a small flat-bladed screwdriver; and optionally, a truing stand and a dish stick.

The truing stand and dish stick are by far the most expensive of these tools. Improvised tools or the bicycle itself can substitute. If you are on a tight budget, read the section of this article on truing, so you know the technical terms, and then check out the section near the end of this article on improvised tools.

Spoke wrench	Truing stand	Dish Stick
		

Besides the essential tools, a spoke tensiometer (picture, right) and an

electric screwdriver with an appropriate bit are helpful. My preferred bit is a worn-out Phillips bit, on which I have ground off two of the four fins. This leaves a pointed flat blade. The point pokes into the hole in the middle of the spoke nipple, and helps keep the driver from sliding off.

Materials

- ## Hubs

  All modern hubs of decent quality have aluminum spoking flanges. Better-quality hubs are usually made by forging, and only forged hubs should be used for radial-spoked front wheels. I would generally advise avoiding overpriced "boutique" hubs which are made by CNC machining, since their flanges are usually weaker than those of forged hubs.

  Better hubs have thick flanges and spoke holes flared like the bell of a trumpet, to support the elbows of the spokes, though this is not essential -- aluminum is softer than steel, and the spokes will bed themselves into it. But if the flanges are not thick enough to pull the elbows against them, then you may need to use washers under the spoke heads.

  If you are buying new hubs, the best value for the money, in most cases, is Shimano. If you want the very best, cost no object, in many applications, this is Phil Wood.

- ## Spokes

  The material of choice for spokes is stainless steel. Stainless is strong and will not rust. Cheap wheels are built with chrome-plated ("UCP") or zinc-plated ("galvanized") carbon-steel spokes which are not as strong, and are prone to rust.

  The leading brands of spokes available in the U.S. market are DT and Wheelsmith.

  Titanium is also used for spokes, but, in my opinion it is a waste of money. Titanium spokes should only be used with brass nipples, and the combination is not significantly lighter than stainless spokes with aluminum nipples.

  Carbon fiber spokes have been available, but turned out to be brittle and dangerous. If you bend one, it breaks like uncooked spaghetti! Carbon fiber, aluminum alloy and polycarbonate plastic spokes all have to be thicker than steel spokes, and the added air resistance slows you down more than the weight saving speeds you up -- unless you only ride uphill.

  ### How Many Spokes?

  Up until the early 1980s, virtually all adult bikes had 72 spokes.

  32 front/40 rear was the standard for British bikes, 36 front and rear for other countries. The exception was super-fancy special purpose racing wheels, which might have 32 spokes front and rear.

  The Great Spoke Scam: In the early '80s a clever marketeer hit upon the idea of using only 32 spokes in wheels for production bikes. Because of the association of 32 spoke wheels with exotic, high-performance bikes, the manufacturers were able to cut corners and save money while presenting it as an "upgrade!" The resulting wheels were noticeably weaker than comparable 36 spoke wheels, but held up well enough for most customers.

  Since then, this practice has been carried to an extreme, with 28-, 24-, even 16-spoke wheels being offered, and presented as it they were somehow an "upgrade."

  Actually, such wheels normally are not an upgrade in practice. When the spokes are farther apart on the rim, it is necessary to use a heavier rim to compensate, so there isn't usually even a weight benefit from these newer wheels!

  This type of wheel requires unusually high spoke tension, since the load is carried by fewer spokes. If a spoke does break, the wheel generally becomes instantly unridable. The hub may break too; see John Allen's article.

  If you want highest performance, it is generally best to have more spokes in the rear wheel than the front. For instance, 28/36 is better than 32/32. People very rarely have trouble with front wheels:

  - Front wheels are symmetrically dished.
  - Front wheels carry less weight.
  - Front wheels don't have to deal with torsional loads (unless there's a hub brake).

If you have the same number of spokes front and rear, either the front wheel is heavier than it needs to be, or the rear wheel is weaker than it should be.

Spoke Gauges

The diameter of spokes is sometimes expressed in terms of wire gauges. There are several different national systems of gauge sizes, and this has been a great cause of confusion. A particular problem is that French gauge numbers get smaller for thinner wires, while the U.S./British gauge numbers get larger for thinner wires. The crossover point is right in the popular range of sizes used for bicycle spokes:

U.S./British 14 gauge is the same as French 13 gauge

U.S./British 13 gauge is the same as French 15 gauge

Newer I.S.O. practice is to ignore gauge numbers, and refer to spokes by their diameter in millimeters:

U.S./British 13 gauge is 2.3 mm

U.S./British 14 gauge is 2.0 mm

U.S./British 15 gauge is 1.8 mm

U.S./British 16 gauge is 1.6 mm

Spokes come in straight-gauge or swaged (butted) styles. Straight-gauge spokes have the same thickness all along their length from the threads to the heads.

Swaged spokes come in 5 varieties:

- **Single-butted** spokes are thicker than normal at the hub end, then taper to a thinner section all the way to the threads. Single-butted spokes are not common, but are occasionally seen in heavy-duty applications where a thicker-than-normal spoke is intended to be used with a rim that has normal-sized holes.

- **Double-butted** spokes are thicker at the ends than in the middle. The most popular diameters are 2.0/1.8/2.0 mm (also known as 14/15 gauge) and 1.8/1.6/1.8 (15/16 gauge).

  Double-butted spokes do more than save weight. The thick ends make them as strong in the highly-stressed areas as straight-gauge spokes of the same thickness, but the thinner middle sections make the spokes effectively more elastic, allowing them to stretch (temporarily) more than thicker spokes.

  As a result, when the wheel is subjected to sharp localized stresses, the most heavily-stressed spokes can elongate enough to shift some of the stress to adjoining spokes. This is particularly desirable when the limiting factor is how much stress the rim can withstand without cracking around the spoke holes.

- **Triple-butted** spokes, such as the DT Alpine III, are the best choice when durability and reliability is the primary aim, as with tandems and bicycles for loaded touring. They share the advantages of single-butted and double-butted spokes. The DT Alpine III, for instance, is 2.34 mm (13 gauge) at the head, 1.8 mm (15 gauge) in the middle, and 2.0 mm (14 gauge) at the threaded end.

  Single- and triple-butted spokes solve one of the great problems of wheel design: Since spokes use rolled, not cut threads, the outside diameter of the threads is larger than the base diameter of the spoke wire. Since the holes in the hub flanges must be large enough for the threads to fit through, the holes, in turn, are larger than the wire requires. This is undesirable, because a tight match between the spoke diameter at the elbow and the diameter of the flange hole is crucial to resisting fatigue-related breakage.

  Since single- and triple-butted spokes are thicker at the head end than at the thread end, they may be used with hubs that have holes just large enough to pass the thick wire at the head end.

- **Æro (elliptical)** spokes are a variety of double-butted spoke in which the thin part is swaged into an elliptical cross section, making these spokes a bit more ærodynamic than round-section spokes. The most widely available spokes of this type are the Wheelsmith Æro. These are 2.2 x 1.8 mm at the ends, and the middles are equivalent to 16 gauge, but in the form of a 1.8 x 1.2 mm ellipse. The Wheelsmith Æro is my favorite spoke for high-performance applications, not just because of whatever ærodynamic advantage it may offer, but because the flat center section provides an excellent visual indicator to help the wheelbuilder eliminate any residual twist in the spoke. This helps build a wheel that will stay true.

- **Æro (bladed)** spokes have a more pronounced æro shape, flat, rather than elliptical.

Although they are the most ærodynamic of spokes, they won't normally fit through the holes in a standard hub because they are too wide. To use "blades", the hub must be slotted with a file. Slotting the holes can weaken the flange, and will usually void the warranty of the hub. It is also a lot of trouble.

There was a fad in the early '90s for Hoshi "blades" which had a double bend instead of a conventional head. The double bend allowed the spokes to be inserted "head first" into the hub flange, so that they could be used with normal hubs. Unfortunately, they turned out to be prone to breakage, and I can't recommend them.

[Following comment is by John Allen]

I recommend thicker spokes for the right side of a dished rear wheel (a wheel used with a cassette) than the left side, because the left-side spokes are under lower tension. The thinner spokes on the left side will be working more nearly at the tension for which they are designed, and so they will be stretched more and less likely to go slack. For more details, see my article on spoke tension.

[Now, returning control to Sheldon...]

My Bicycle Glossary has a Table of Spoke Weights, for those who care about such things.

- ## Nipples

Nipples are commonly made of nickel-plated brass. This is a good material choice, because brass takes very smooth threads, and brass nipples don't get corroded into position too easily.

For light-weight, high-performance wheels, aluminum nipples are available. Aluminum nipples do save a small amount of weight, and they can be quite reliable if used properly. They should only be used with rims that have eyelets of some material other than aluminum, because aluminum/aluminum contact between rim and nipple can result in chemical welding, immobilizing the nipples.

- ## Rims

Older rims were made of steel, but steel rims are now obsolete, and only found on the cheapest, crummiest bicycles. Aluminum rims have superseded steel, because they are lighter, stronger, rust-proof and provide better braking.

Modern rims are made of extruded aluminum, that is, the semi-molten aluminum is squeezed out of specially-shaped openings which determine the cross section of the rim. The extrusions are formed into hoops, then joined either by welding or by the insertion of a filler piece into the hollows of each end of the rim.

[Following paragraphs added by John Allen]

An impact with a pothole edge, rock, etc. can damage a rim. Rim brakes wear down the sidewalls of aluminum rims, especially in wet-sandy conditions. Eventually, the air pressure in the tire can bulge a sidewall out, causing a blowout. You can usually just transfer the old spokes to a new rim, avoiding the need to relace the wheel -- see Jobst Brandt's article.

A *single-wall* rim has a simple U shape with a a single layer of metal across the bottom where the spokes attach. a *double-wall* (or *box-section*) rim has two layers, with a cavity in between. The spokes then attach at the lower layer, closer to the hub, and the upper layer has holes large enough to allow insertion of the nipple heads or a screwdriver. Many good quality rims have "eyelets" or "ferrules" to reinforce the spoke holes.The best double-wall rims have ferrules which spread the load to both layers, allowing these rims to be lighter and/or stronger.

There has been a trend toward deeper-section rims in recent years, in the interest of ærodynamics. Moderately deep-section rims are spoked like any others. Extremely deep-section rims can work with somewhat fewer spokes than conventional rims. As few as 20 in a front wheel may be practical -- also an ærodynamic advantage.

Extremely deep-section rims are excessively stiff, and must be very true as supplied, without coaxing from the fewer spokes. If the tire bottoms out on a rock or other obstacle, such a rim does not provide a "crush zone" to the same extent as a conventional rim. There is more likelihood of damage to the bicycle's fork and frame. The rim will probably crumple and be unrepairable, or if it is of carbon fiber, it will tear. These rims are heavier, too, all other things being equal.

The strength of the tried-and true wheel design is in the spokes, not the rim. Where high ærodynamic efficiency is important, a better technical solution is a rim of the required strength and stiffness, with a lightweight wind fairing for the rear wheel, and areodynamic spokes for the front. Triathletes and HPV racers have used wheels with fairings for many years. The hidebound rules of the

U.C.I, on the other hand, prohibit any part of a racer's equipment from serving *only* an ærodynamic purpose. The result has been "Frankenstein" equipment such as deep-section rims and "æro" helmets whose long, protruding tail adds weight and can twist the rider's neck if he/she lands the wrong way. Pro racers put up with all this because any tiny speed advantage could win a race, and because the team pays for their equipment.

Even less practical than wheels with very deep sections are wheels with unevenly-spaced spokes, or with spokes which attach to the rim and hub in unconventional ways and locations. Some of these wheels provide a real advantage to racers; others only a placebo effect. These wheels tend to be very expensive, and a real headache to repair or rebuild, because of the special parts and tools needed.

- ## Washers

[This section added by John Allen]

Flange thicknesses vary, but the spoke's elbow should be snug against the flange. If it is not, the spoke's tension will try to bend the spoke at the elbow -- a frequent cause of spoke breakage.

You solve this problem by sliding a small washer onto each spoke before inserting it into the hub. Most spokes will accept a 2 mm (metric bolt size) or #2 (US bolt size) washer. Brass washers are best. These are not commonly available through bicycle parts suppliers, but they can be purchased over the Internet, for example here, or at a hobby shop. Some hub/spoke combinations need two washers per spoke. Other combinations need washers only on the spokes that run from the inside of the flanges, or need two on inside spokes and one on outside spokes.

- ## Rim tape

[This section added by John Allen]

Spoke nipple heads or access holes in the bottom of the rim must be covered with a rim tape, so they can't puncture the inner tube. Rim tape must be thick and strong enough to smooth out any sharp edges and, with recessed spoke holes, to resist the pressure from the inner tube. Commercial rim tape is adhesive-backed and has a hole near one end which fits over the valve hole of the rim; When installing the tape, placing a valve temporarily in the hole will prevent the tape from slipping. The tape is wrapped around in the bottom of the rim, and the other end is trimmed just short of the valve hole.

Several widths of tape are available. The tape must be wide enough to fill the bottom of the rim, but it must not slop up onto the sidewalls, where it would unseat the tire. Duct tape and glass fiber-reinforced strapping tape are workable substitutes, if two layers are used. These can be torn lengthwise to the needed width.

Rim tape is not added until the wheelbuilding is complete.

Spoke-Length Calculators

Spoke length is measured from the inside of the elbow to the very end of the threads, most usually in millimeters.

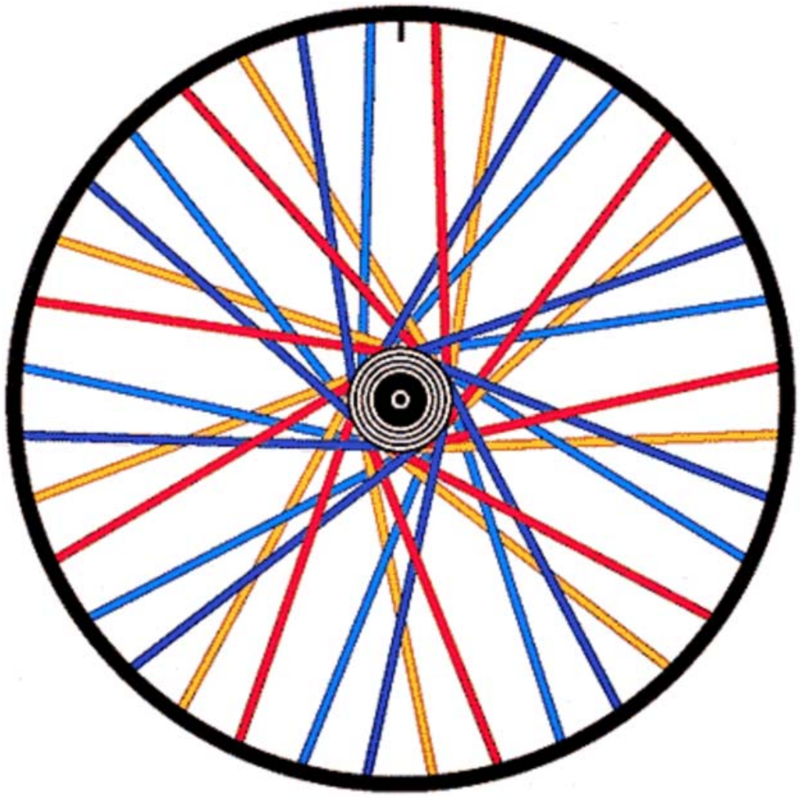
When you buy spokes to match the rim, hub and pattern you will use, your dealer should be able to determine the correct length(s) for you. Most dealers these days use a computer program called "Spokemaster" which comes bundled with a wholesale database called "Bike-alog on disc". If you need to do your own calculations, there are several spoke-length utilities available on the Web, including:

- Damon Rinard's Excel Spreadsheet, including a database of rims and hubs.
- Danny Epstein's requires numerical dimensions.
- Roger Musson's "Wheelpro" spoke calculator has a database of hubs and rims.

Sutherland's Handbook for Bicycle Mechanics, 6th Edtion, has charts and tables by which you can calculate spoke lengths. Alternatively, you can measure an existing wheel of the same lacing pattern and get reasonably close.

Most spoke calculators give results to the tenth of a mm, but spokes are usually sold in 1 mm size increments (some brands only in 2 mm increments.) Generally, I round upward to the nearest available larger size. The length is not super-critical, but it is worse to have spokes a bit too long than a bit too short. If spokes are too long, they prevent you from using the screwddriver. Unless a rim has recessed spoke holes, you will have to file off protruding spoke ends to avoid their puncturing the inner tube. The right-side spokes of a dished rear wheel are ideally 1 or 2 mm shorter than the left-side spokes.

Note: all of the wheel illustrations for this article show the wheel as viewed from the right (freewheel) side.



Preparation

Spoke threads and spoke holes in the rim should generally be lubricated with light grease or oil to allow the nipples to turn freely enough to get the spokes really tight. This is less important than it used to be due to the higher quality of modern spokes, nipples and rims, but it is still a good practice. In the case of derailer rear wheels, only the right-side spokes and spoke holes need to be lubricated.

Spoke threads are easily lubricated by holding the spokes together in a bunch, tapping it on the workbench to get them even with each other, and dipping them into a gob of grease which you have spread out on a paper plate or other surface. Spoke holes in rims may be lubricated using a spoke to carry the grease.

The left-side spokes will be loose enough that it will not be hard to turn the nipples even dry, and if you grease them they may loosen up of their own accord on the road. In fact, it is often a good idea to use a thread adhesive such as Wheelsmith Spoke Prep on the left-side spokes to make sure they stay put. This is only necessary on a rim with recessed spoke holes. On other rims, the rim tape and pressure from the inner tube will keep the nipples from turning, at least with a high-pressure tire.

If you are transferring spokes to a new rim, you lubricate the threads without removing the spokes from the hub. Follow the instructions in Jobst Brandt's article and skip the steps about lacing here. If you are cutting the spokes to take apart a wheel, be sure to **remove a thread-on sprocket, freewheel or brake drum first. You often can't get new spokes past thread-on parts.** This is good advice even if you are only transferring spokes, because you might find that you have to replace one or more of them. In case any spokes or nipples are damaged, it can be helpful to have a few spares on hand, and Vise-Grip pliers to turn rounded nipples.

Lacing

Lacing is most easily done sitting down, holding the rim on edge in your lap. People who build wheels all day long start by putting all of the spokes into the hub, then connecting them to the rim one after another. This approach is slightly faster on a production basis, but the occasional builder runs a higher risk of lacing errors this way.

Non-production wheelbuilders usually put the spokes in one "group" at a time. A conventional wheel has 4 "groups" of spokes: Half of the spokes go to the right flange, and half go to the left. On each flange, half are "trailing" spokes and half are "leading" spokes.

Different Spoke/Cross Counts

The instructions below assume a **36 spoke cross 3 wheel** but are easily adapted to different patterns by substituting appropriate numbers.

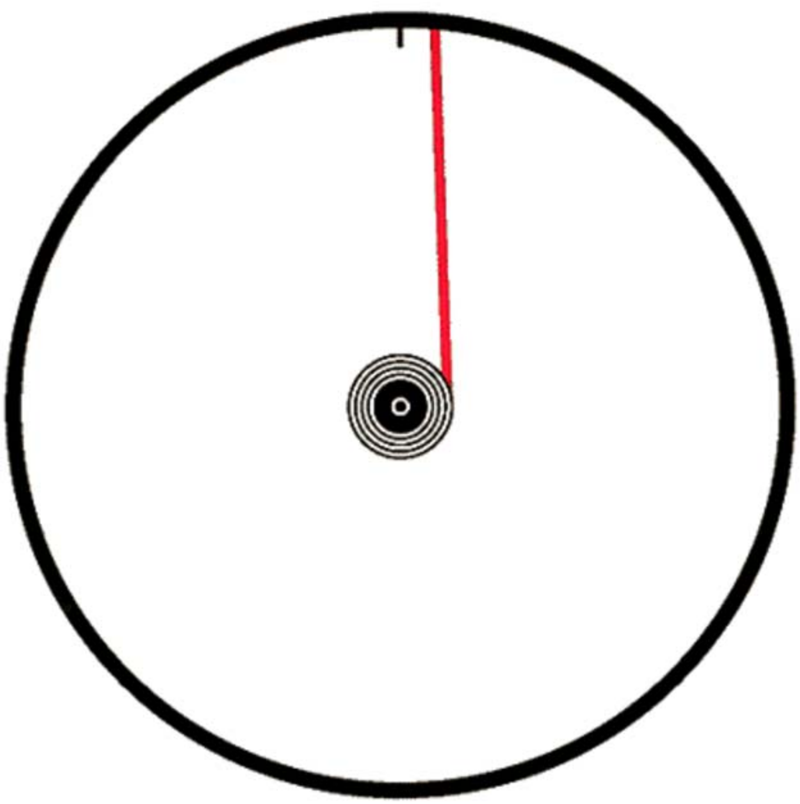
For example, if you're building a 32 spoke wheel, just:

- Substitute "32" where the instructions say "36"
- Substitute "16" where the instructions say "18"
- Substitute "8" where the instructions say "9"
- Substitute "7" where the instructions say "8"

If you're building a wheel with a different cross pattern, similarly add or subtract the appropriate number.

With all cross patterns, only the outermost crossing is "interlaced" so the spokes go behind one another.

The "key" spoke



I'm going to use use colored text here, corresponding to the color of the spokes in the illustrations.

The first spoke to be installed is the "key spoke" .

This spoke must be in the right place or the valve hole will be in the wrong place, and the drilling of the rim may not match the angles of the spokes. The key spoke will be a trailing spoke, freewheel side. It is easiest to start with the trailing spokes, because they are the ones that run along the inside flanges of the hub. If you start with the leading spokes, it will be more awkward to install the trailing spokes because the leading spokes will be in the way.

Since the key spoke is a trailing spoke, it should run along the inside of the flange. The head of the spoke will be on the outside of the flange. (see sidebar "Which side of the flange?")

It is customary to orient the rim so that the label is readable from the bicycle's right side. If the hub has a label running along the barrel, it should be located so that it can be read through the valve hole. These things will not affect the performance of the wheel, but good wheelbuilders pay attention to these things as a matter of pride and esthetics.

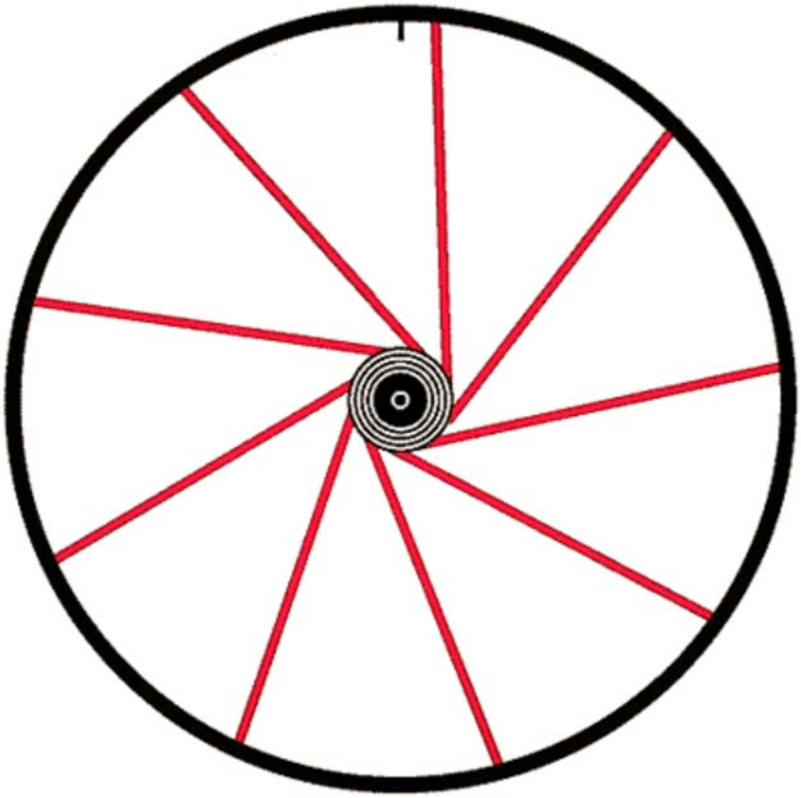
Rims are drilled either "right handed" or "left handed". This has to do with the relationship between the valve hole and the spoke holes. The spoke holes do not run down the middle of the rim, but are offset alternately from side to side. The holes on the left side of the rim are for spokes that run to the left flange of the hub. With some rims, the spoke hole just forward of the valve hole is offset to the left, with others it is offset to the right (as illustrated). Which type is "right handed" and which "left handed"? I have never met anyone who was willing to even make a guess!

The key spoke will be next to the valve hole in the rim, or one hole away.

As viewed from the right (sprocket) side of the hub, the key spoke will run counterclockwise, and it will go to either the hole just to the right of the valve hole (as illustrated) or the second hole to the right, depending on how the rim is drilled. The aim is to make the four spokes closest to the valve hole all angle away from the valve, giving easier access to the valve for inflation.

Screw a nipple a couple of turns onto the key spoke to hold it in place. Next, put another spoke through the hub two holes away from the key spoke, so that there is one empty hole between them on the hub flange. This spoke goes through the rim 4 holes away from the key spoke, with 3 empty holes in between, not counting the valve hole.

Continue around the wheel until all 9 of the first group of spokes are in place. Double check that the spacing is even both on the hub (every other hole should be empty) and the rim (you should have a spoke, 3 empty holes, a spoke, etc. all the way around. Make sure that the spokes are going through the holes on the same side of the rim as the flange of the hub. It should look like this:

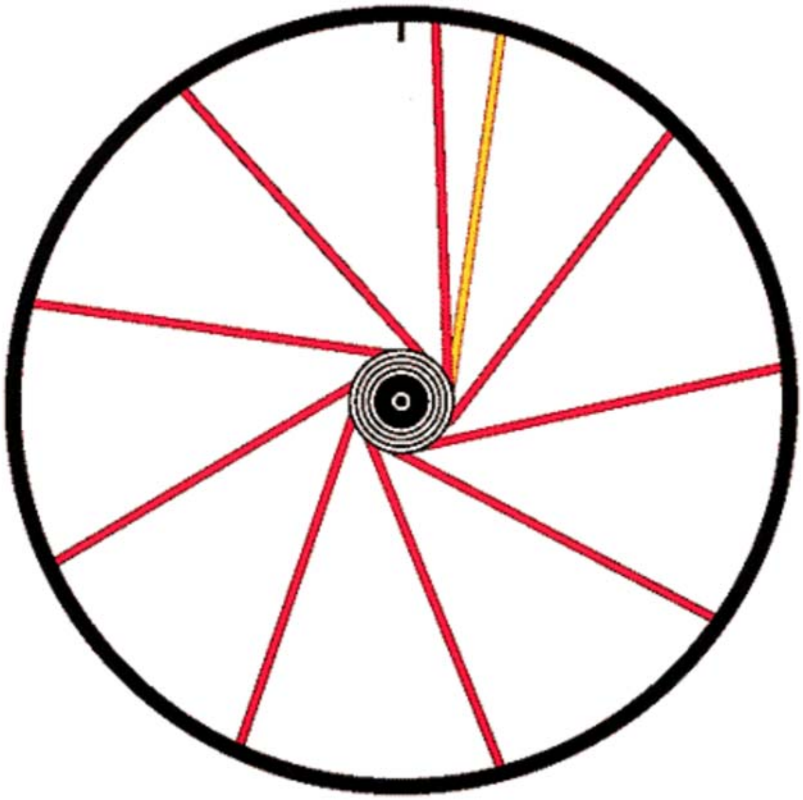


The second group

Now turn the wheel over and examine the hub. The holes on the left flange do not line up with the holes on the right flange, but halfway between them. If you have trouble seeing this, slide a spoke in from the left flange parallel to the axle, and you will see how it winds up bumping against the right flange between two spoke holes. Turn the wheel so that the valve hole is at the top of the wheel. Since you are now looking at the wheel from the non-freewheel side, the key spoke will be to the left of the valve hole.

If the key spoke is next to the valve hole, insert a spoke into the left flange so that it lines up just to the left of where the key spoke comes out of the hub, and run it to the hole in the rim that is just to the left of the key spoke.

The illustration shows it viewed from the right side:

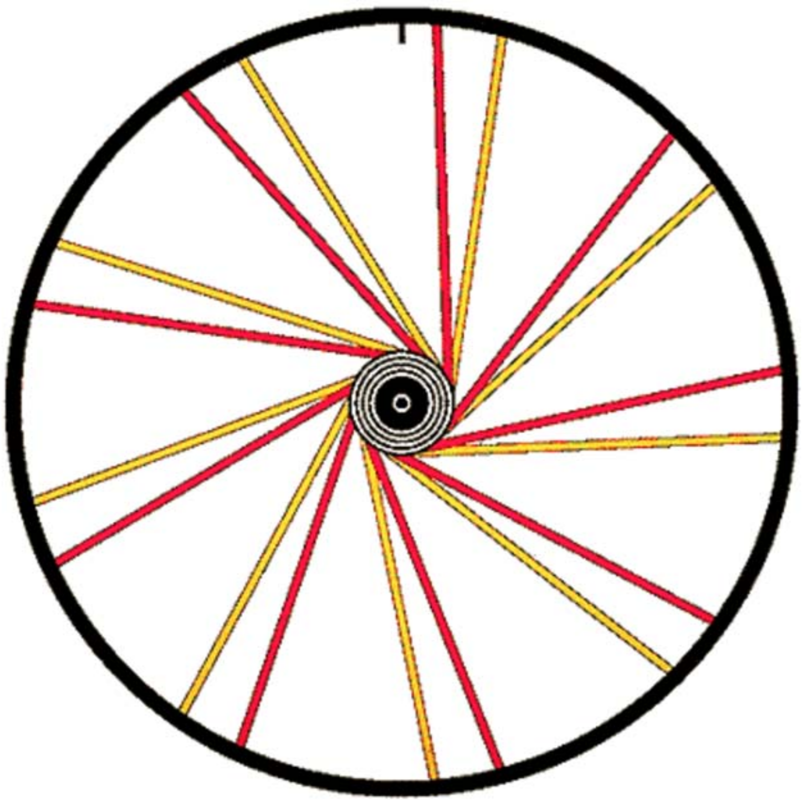


In the illustration, the key spoke is right next to the valve hole. Some rims are drilled with the opposite "handedness", so this may not be the case for your wheel.

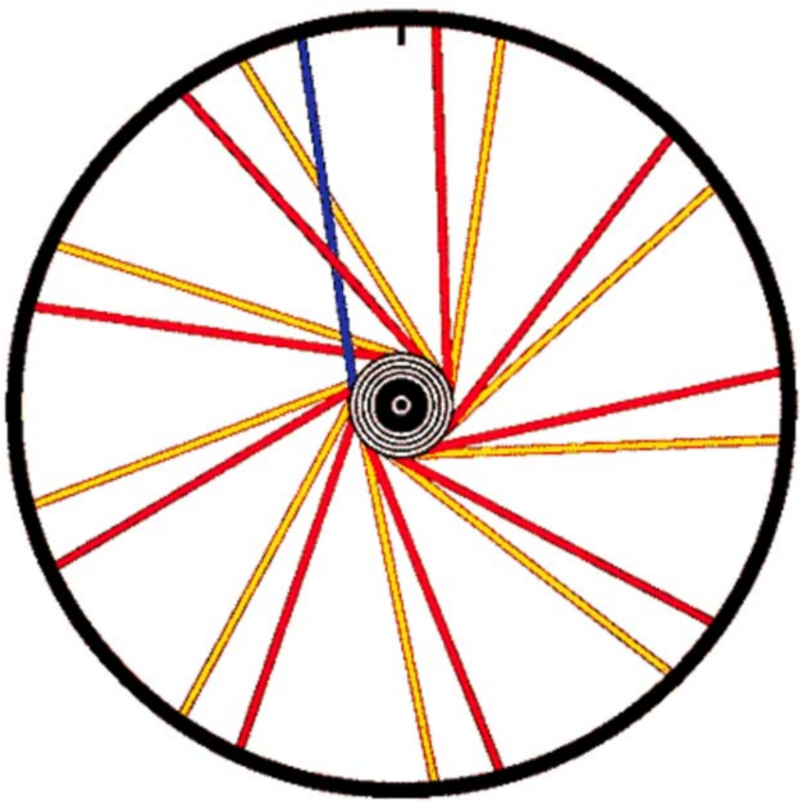
If the key spoke is separated from the valve hole by an empty spoke hole, insert a spoke into the left flange so that it lines up to the right of where the key spoke comes out of the hub, (looking at the wheel from the **left!**) and run this tenth spoke to the hole between the key spoke and the valve hole

If you have done this correctly, the spoke you have just installed will not cross the key spoke. When you flip the wheel back around so you're looking from the **right** side, if the tenth spoke is to the left of the key spoke at the hub, it will also be to the left of it at the rim. Like the first group of spokes, it will be a trailing spoke, it will run along the inside of the flange, and the head will face out from the outside of the flange. Install the other 8 spokes in this group following the same pattern.

At the end of this stage, the wheel will have all 18 of the trailing spokes in place. In the rim, there will be two spokes, two empty holes, two spokes, two empty holes...etc. as shown below:



The leading spokes



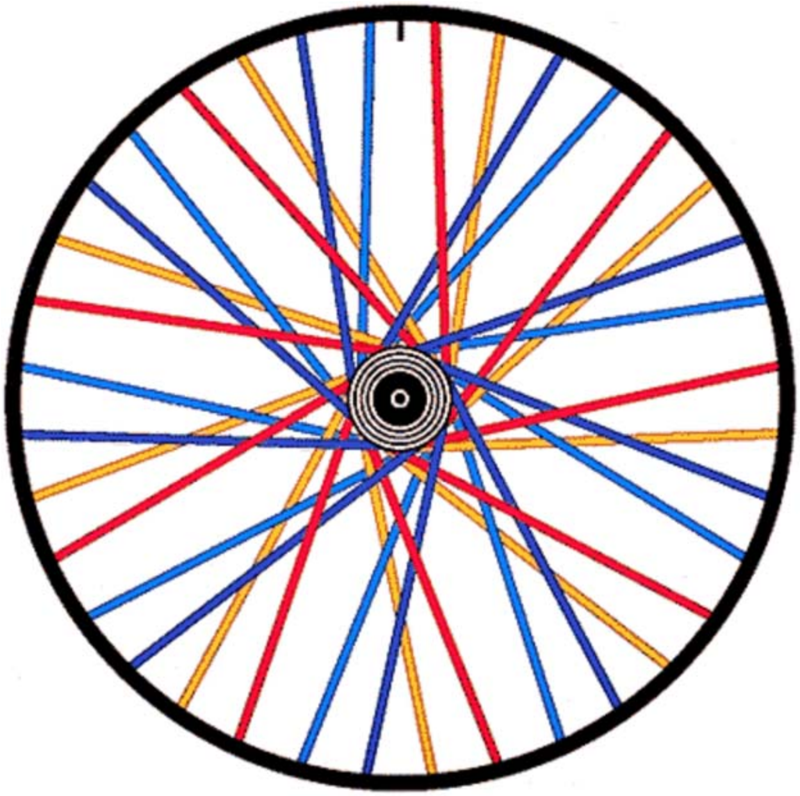
Turn the wheel back around so that the freewheel side is toward you. Insert a spoke into any hole, but this time from the inside of the flange. Twist the hub clockwise as far as it will conveniently go. Since we are building a cross 3 wheel, this new spoke will cross 3 trailing spokes that go to the same flange of the hub.

The first two crosses, this spoke will pass outside of the trailing spokes, but for the outermost cross it should be "laced" so that it goes on the inside of the last trailing spoke. You will have to bend this leading spoke to get it around the last trailing spoke on the correct side.

After this leading spoke has crossed 3 trailing spokes, there will be two possible rim holes to connect it to. Use the rim hole that is on the same side as the flange you are working from. It should not be right next to one of the trailing spokes that runs from the same flange of the hub.

Install the other 17 leading spokes following the same pattern. If you can't get some of the spokes to reach their nipples, make sure that the nipples on the trailing spokes are seated into their holes. When you are done, double check around the rim to make sure that every other spoke goes to the opposite flange of the hub.

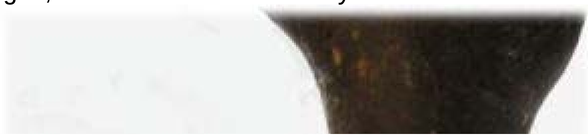
Different cross numbers: The instructions above are based on a normal cross 3 pattern. If you are using a different cross pattern, substitute the appropriate numbers in the instructions above. With any cross number, only the outermost crossing is "laced" so the spokes go behind one another.



Initial spoke adjustment

Once the wheel is laced, adjust all of the nipples so that each is screwed equally far onto its spoke. You should be able to do this with a screwdriver, preferably electric. A good starting point is to set them all so that the threads just disappear into the nipples. If the spokes are a bit on the short side, you may have to leave a few threads showing. The important thing at this stage is to get all 36 spokes to be as close as possible to the same setting, all pretty loose. Some may be a bit tighter or looser, but they should all be adjusted the same to provide a baseline. If you find some are much tighter than others, double check the spoking pattern. With some rims, the rim seam is thicker than other parts of the rim, so you may need to loosen up the two spokes closest to the seam (usually opposite from the valve hole) a couple of turns.

At this stage, the spokes will not be running straight, but will be noticeably curved where they leave the hub. The leading spokes, in particular, will be swooping outward as they leave the hub, then gradually curving back toward the rim. Before you start applying tension to the spokes,



you should bend them by hand so that they fit snugly against the sides of the hub flanges. This can be done easily by pressing on each spoke in turn with your thumb about an inch out from the hub. If you don't do this, the spokes will still be slightly curved when the wheel is finished. These curves will gradually straighten themselves out over the first few hundred miles on the road, and the wheel will lose tension and go out of true.

[I like instead to tension the spokes partway, then give each leading spoke a light tap with a hammer to straighten it, as in the photo at the right -- **only a light tap** so you do not bend the flange. Use a claw hammer, which has a nearly flat face. Hold the hammer so its face is parallel to the spoke. The advantage of this method is that the hammer face will not bend the spoke outside the flange. The spoke should bend over the edge of the flange, then run straight as shown.-- John Allen]

Tensioning and truing

Now you are ready to put the wheel into the truing stand. If you are lucky, it will already be fairly true, but don't be surprised if it is way off. If the spokes are still very loose, so that you can wiggle the rim back and forth easily, tighten each spoke one full turn. Start at the valve hole and work your way around until you get back to it, so that you won't lose count. *Make sure you are turning the nipples the right way.*

When you work with a screwdriver, it is easy to figure out which way tightens the screws, clockwise. It gets confusing when you start using the spoke wrench, because now you are working from the back side of the clock!

Continue bringing up the tension one full turn at a time until the wheel begins to firm up.

Once there begins to be a little bit of tension on the wheel, you should start bringing it into shape. There are 4 different things that you need to bring under control to complete the job: lateral truing, vertical truing, dishing, and tensioning. As you proceed, keep checking all 4 of these factors, and keep working on whichever is worse at the moment.

You can see the irregularities in the rim as you start to true the wheel, but as it comes more nearly into shape, you can listen to the scraping of the truing stand's feelers against the rim for a more sensitive adjustment. High-end truing stands have dial indicators, though these are not really necessary.

Try to make your truing adjustments independent of each other. For lateral truing, spin the wheel in the stand and find the place on the rim that is farthest away from where most of the rim is. If the rim is off to the left, tighten spokes that go to the right flange and loosen those that go to the left flange. If you do the same amount of tightening and loosening, you can move the rim to the side without affecting the roundness of the wheel. For example, if the rim is off to the left, and the center of the bend is between two spokes, tighten the spoke that goes to the right flange 1/4 turn, and loosen the spoke that goes left 1/4 turn; If the center of the left bend is next to a spoke that goes to the right flange, tighten that spoke 1/4 turn, and loosen each of the two left spokes next to it 1/8 turn; If the center of the left bend is next to a spoke that goes to the left flange, loosen that spoke 1/4 turn, and tighten each of the two right spokes next to it 1/8 turn. After adjusting the worst bend to the left, find the worst bend to the right, and adjust it. Keep alternating sides. Don't try to make each bent area perfect, just make it better, then go on to the next. The wheel will gradually get truer and truer as you go.

For vertical truing, find the highest high spot on the rim. If the center of this high spot is between two spokes, tighten each of them 1/2 turn. If the high spot is centered over one spoke, tighten that spoke one full turn, and each of the two spokes next to it that go to the other flange, 1/2 turn. It takes a larger adjustment to affect the vertical truing than the horizontal truing. Vertical truing should usually be done by tightening spokes, gradually building up the tension in the wheel as you go along.

As soon as the lateral truing gets reasonably good (within a couple of millimeters) start checking the dishing. Put the adjustable feeler of the dish stick over the axle on one side of the wheel and adjust it so that both ends of the dish stick touch the rim while the middle feeler rests against the outer locknut on the axle. Then move the stick to the other side of the wheel without re-adjusting the feeler. If the dish stick rocks back and forth while in contact with the outer locknut, the spokes on that side of the wheel have to be tightened to pull the rim over. If the ends of the dish stick sit on the rim but the feeler won't reach the locknut, the spokes on the other side of the wheel need to be tightened. If the dishing is off by more than 2 or 3 millimeters, you should start at the valve hole and work your way around the rim tightening up all 18 spokes on the appropriate side the same amount, perhaps 1/2 turn.

When the dish is starting to get within 1 or 2 millimeters of being correct, go back to working on the lateral truing, except now you will not be alternating sides. If the rim needs to move to the right to improve the dish, find the worst bend to the left, adjust it, then find the new worst bend to the left, and so on.

All the time you are doing this, you need to keep checking the vertical truing, and whenever the vertical error is greater than the lateral error, work on the vertical.

A rim may be a bit irregular at the seam -- usually directly opposite the valve hole -- see Machined Rim Sidewalls. If the rim is welded, grinding away excess metal may have left a slight hollow. If the rim is pinned, the ends may not line up perfectly. You may need to relax your truing standards slightly at the seam, average the vertical truing for the two sides, or guide by eye on the underside of the rim.

You also need to keep monitoring the tension on the freewheel-side spokes. There are three ways to check tension. One is by how hard it is to turn the spoke wrench. If it starts to get hard enough that you have to start worrying about rounding off the nipple with the spoke wrench, you are approaching the maximum. Fifteen years ago, this would be the limiting factor, and you would just try to get the wheel as tight as you could without stripping nipples. Modern, high quality spokes and nipples have more precisely-machined threads, however, and now there is actually a possibility of getting them too tight, causing rim failure.

The second way of judging spoke tension is by plucking the spokes where they cross and judging the musical pitch they make. If your shop doesn't have a piano, and you don't have perfect pitch, you can compare it with a known good wheel that uses the same length of spokes. This will get you into the ballpark. Before I started using a spoke tensiometer, I used to keep a cassette in my toolbox on which I had recorded my piano playing an F#, a good average reference tone for stainless spokes of usual length. (For more details on this method, see John Allen's article: *Check Spoke Tension by Ear.*)

The third, and best way is with a spoke tensiometer. Every well-equipped shop should have one. Average freewheel-side tension should be up to shop standards for the type of spokes and rim being used. More important is that it be even. Don't worry about the left-side tension on rear wheels. If the freewheel side is correctly tensioned, and the wheel is correctly dished, the left side will be quite a bit looser. You should still check the left side for uniformity of tension. (Using thinner spokes on the left side avoids most of the problems which the looseness causes -- also see John Allen's article.)

Spoke Torsion

As the wheel begins to come into tension, you start to have to deal with spoke torsion. When you turn your spoke wrench, the spoke will first twist a bit from the friction of the threads. Once the nipple has turned far enough, the twist in the spoke will give enough resistance that the threads will start to move, but the spoke will remain twisted. What a good wheelbuilder can do that a robot machine can't do is feel this twist. If you "finish" your wheel up, and it is perfectly true in your stand, but the spokes are twisted, the wheel will not stay true on the road. The twist in the spokes will eventually work itself out, and the wheel will go out of true.

This problem can be prevented by sensitive use of your spoke wrench. What you need to do is overshoot and backlash. In other words, suppose you want to tighten a particular spoke 1/4 turn. You don't just turn the wrench 1/4 turn, you turn it a little farther, then back it up that same little bit. The nipple winds up being 1/4 turn tighter, but the backing up releases the twist in the spoke.

This is much easier to do on straight-gauge spokes, because they are stiffer torsionally, and it is easier to feel the twist than it is with butted spokes. One of the reasons I like "aerodynamic" spokes so much is not so much for the aerodynamics, as that you can tell visually that they are twisted.

Seating and Stress-Relieving the Spokes

Before a wheel is ready for the road, it must be stress-relieved, because the bend in the spoke has to accommodate itself to the shape of the hub flange and vice versa, and a similar process may go on where the nipple sits in the rim. Some wheelbuilders do this by flexing the whole wheel, others by grabbing the spokes in groups of 4 and squeezing them together. My preferred technique is to use a lever to bend the spokes around each other where they cross. My favorite lever for this is an old left crank:

This particular technique has the added advantage of bending the spokes neatly around each other at the crossing, so they run straight from the crossing in both directions. As you go around the wheel this way you will probably hear creaks and pinging sounds as the parts come into more intimate terms with each other.

After you do this, you will probably have to do some touch-up truing, then repeat the stressing process until it stops making noise and the wheel stops going out of true.

Jobst Brandt , author of the excellent book *The Bicycle Wheel*, points out a less-obvious benefit of this stressing of the spokes:

> "...After cold forming, steel always springs back a certain amount (spokes are entirely cold formed from wire). Spring-back occurs because part of the material exceeded its elastic limit and part did not. The disparate parts fight each other in tension and compression, so that when the spoke is tensioned, it adds to the tensile stress that can be, and often is, at yield.
>
> "...When spokes are bent into place, they yield locally and addition of tension guarantees that these places remain at yield. Because metal at or near the yield stress has a short fatigue life, these stresses must be relieved to make spokes durable.
>
> "...These peak stresses can be relieved by momentarily increasing spoke tension (and

stress), so that the high stress points of the spoke yield and plastically deform with a permanent set. When the stress-relief force is relaxed, these areas cannot spring back, having, in effect, lost their memory, and drop to the average stress of the spoke."

If you have done this, you will wind up with a wheel that is true and round, and will stay that way better than most machine-made wheels. In addition, you will have learned a lot about truing wheels, and you will feel more like a real professional mechanic.

Definitions:

This article uses 3 non-standard terms, because standard terms have not been agreed upon in the industry:

- "**Key**" spoke. This is the first spoke to be installed in building the wheel. Its position determines the position of all the other spokes with respect to the valve hole.
- "**Trailing**" spokes. In a rear wheel, the trailing spokes are those which become tighter when the rider applies pressure to the pedals. They are called "trailing" because they point backward from the direction the hub is turned in. In the illustrations for this article, the trailing spokes are shown in red and yellow.
- "**Leading**" spokes. These are the spokes that exit the hub in the direction of rotation. They are illustrated in two shades of blue.

Trailing Spokes

The "trailing" spokes pull harder under drive torque to make the rim turn, and the "leading" spokes contribute by pulling less hard under driving torque. Each group of spokes contributes equally in its own way to turning the rim to keep up with the hub.

Some writers have referred to the trailing spokes as "driving" or "pulling" spokes, and have referred to the leading spokes as "tension" or "static" spokes. These terms may be confusing, because all of the spokes contribute to driving, they are all under tension and they all pull. Depending on how you look at it, either all of them or none of them are "static". (Thanks to John Forester for suggesting "leading" and "trailing".)

Which Side of the Flange?

Derailer rear wheels should be laced with the trailing spokes running up along the inside of the flange. There are three reasons for this:

1. The spokes are bent around each other at the outermost crossing. Under drive torque, especially in low gear, the trailing spokes straighten out and the leading spokes bend even more. If the wheel is laced with the trailing spokes on the outside of the flange, the crossing gets pulled outward toward the derailer cage, and in some cases will actually hit against the derailer under load.
2. If the chain should overshoot the inner sprocket due to the derailer being mis-adjusted or bent, it is likely to get more seriously jammed between the spokes and the freewheel if the spokes slant so as to wedge the chain inward under load.*
3. If the chain should overshoot the inner sprocket, it may damage and weaken the spokes it rubs against. Since the trailing spokes are more highly stressed than the leading spokes, it is better to protect them from this type of damage by keeping them inboard.

It really doesn't matter which way you go on the left side, but if you have all the trailing spokes face inward it makes lacing the wheel a bit easier.

* In the case of fixed-gear or coaster-brake wheels, it is better to lace the opposite way, because a derailed chain is more likely to get jammed by backpedaling in these cases.

Note: This is *not* an important issue! There is a sizable minority of good wheelbuilders who prefer to go the other way around, and good wheels can be built either way.

Spoke Patterns:

Semi-tangent

Conventional "semi-tangent" spoke patterns are indicated as "cross 3", "cross 4", etc. For example, cross 3 means that each spoke crosses 3 other spokes that run from the same flange of the hub. Most wheels are built cross 3. Higher cross numbers cause the spokes to leave the hub flange more nearly at a tangent. This makes them better able to withstand the twisting forces of hard pedaling in low gears, and also braking forces from hub brakes. Lower cross numbers make the spokes more nearly perpendicular to the hub flange, and to the rim.

In the case of the "radial" (cross 0) pattern, the spokes go straight out from the hub without crossing at all. Lower cross patterns use shorter spokes, so they are slightly lighter, and they can also be slightly stronger side-to-side.

The more spokes a wheel has, the higher the cross number for a similar spoke angle. 48-spoke wheels are usually built cross 5, 40 spokes, cross 4; 36 spokes, cross 3 or 4; 32 spokes, cross 3; 28 or 24 spokes, cross 2...

In the case of unusually large hubs, particularly large hubs in small rims, fewer crosses are often indicated, to avoid bending the spokes where they exit the nipples. For example, the Rohloff Speedhub has 32 spoke holes, but is usually laced cross 2.

Radial Spoking

Radial spoked (cross 0) wheels have the spokes going straight out from the hub. **This pattern is only suitable for front wheels that don't use hub brakes.** They are very cool-looking, and are often a good choice for the ultimate in performance, because they are slightly lighter and, in theory, may have a very slight ærodynamic edge.

There are two things to watch out for with radial wheels. Because the nipples point straight inward from the rim, they can turn more easily in most rims than when they are bent to a slight angle by a semi-tangent spoke pattern. This ease of turning increases the risk of their unscrewing themselves on the road. To prevent this, nipples on radial wheels should not be lubricated, and it is a good idea to use a spoke adhesive such as Wheelsmith Spoke Prep or one of the milder flavors of Loctite ® on them. (Or, if a rim does not have recessed spoke holes, the rim tape and air pressure in the inner tube will keep the spokes from turning -- at least with a high-pressure tire).

The other potential problem with radial wheels is that the spokes, trailing straight outward on the hub flange, can possibly rip the outer edge of the flange right off along the line of the spoke holes. This is most likely to happen with small-flange, 36 hole hubs, because there is less metal between the spoke holes. If a used hub is re-laced radially, the notches left by the old spokes can act as stress risers, further weakening the flange.

Many hub manufacturers specifically recommend against radial spoking for this reason, and will not honor warranties on hubs that have been spoked radially.

Some folks will say that no bicycle wheels should be radially spoked for this reason, so do this at your own risk. In my experience, it's generally OK with good-quality hubs that have forged shells.

[Note from John Allen: heed this! Back in 1980, unaware of these issues, I built a front wheel for my tandem with 40 radial spokes on a medium-flange, "boutique" hub with machined flanges. After a few months of use, the wheel mysteriously went slightly out of true, and I trued it. I might better have taken the loss of true as a red-flag warning. One day, I just happened to be sitting on the floor next to my tandem, glanced at the front hub and noticed a crack extending along the line between several spoke holes. I had been foolish, and I was very lucky. I rebuilt the wheel on a large-flange hub, using the same spokes in a semi-tangent pattern, and I have ridden that wheel for 30 years since without any problem. If you ever notice a radially-spoked front wheel -- or, actually, and front wheel -- I mysteriously going slightly out of true, stop, get off the bicycle and call for a ride home or to a bike shop.]

If you want to take your chances and try a radial-spoked front wheel, I would advise avoiding using thick spokes and very high tension. Since front wheels are generally pretty trouble-free compared with rears, you don't need super-high tension on a front wheel that uses a reasonable number of spokes.

[Another note from John Allen: I don't recommend leaving spokes slacker than their optimum. If you use the thin spokes, you can raise them to their optimum tension without their putting undue stress on a competent hub.]

Bicycle folklore has it that radial-spoked wheels give a "harsh" ride, because the shorter spokes are less "stretchy" than the longer spokes used in semi-tangent wheels. This is **hooey!**

Wheels with hub brakes and drive wheels should *never* be radially spoked. Due to the near-perpendicular angle of the spoke to the hub's tangent, any torque applied at the hub of a radial spoked wheel will result in a *very great* increase in spoke tension, almost certainly causing hub or spoke failure.

[Yet another note from John Allen: I have seen such a wheel. To protect the guilty, I will not say who built it. No, it wasn't Sheldon. A friend and I inspected the bike. He held the front brake and pushed down on a pedal with his foot. The spokes of the rear wheel changed angle noticeably, pinging as they rotated in the spoke holes of the hub, and ringing with rising musical pitch like an electric guitar when the player pulls up on the tremolo bar.]

Half-radial Spoking

More and more rear wheels now are built "half-radial" with semi-tangent spoking on the right side and radial spoking on the left. Radial front wheels offer mainly esthetic benefits, but half-radial rear wheels can be substantially more durable than conventional ones, if the wheel is highly dished. The high amount of dishing called for to make room for more and more sprockets has caused an increase in spoke breakage on the left side of rear wheels. This is caused by metal fatigue. Just as you can break a paperclip by bending it back and forth a few times, you can break spokes by flexing them back and forth by a much smaller amount, millions of times -- even if they don't flex enough to take a permanent set. (A bicycle wheel turns several hundred times per mile. In 1500 miles, it turns more than a million times.)

A spoked wheel relies on having all of the spokes in constant tension. A highly-dished rear wheel starts with very light tension on the left side spokes. The torque of hard pedaling combined with cyclical weight loading can cause the left-side "leading" spokes occasionally to go completely slack.

Repeated cycles of tension and slackness cause these spokes to fatigue at the bends, and ultimately break.

With half-radial spoking, the amount of dish is very slightly less to begin with if you run the radial spokes up along the inside of its flange ("heads out.") In addition, since there are no left-side "leading" spokes, no amount of torque on the hub can reduce the tension on any of the left-side spokes. In fact, if you have an old wheel that has been breaking left-side spokes, "half rebuilding" the wheel into a half radial will solve the problem once and for all.

I used to think that this was exotic, cutting-edge technology, until I happened to look at a couple of Model A Fords in a local parade. Their wheels were highly dished inward, and were laced in the same half-radial pattern, for the same reason.

[Note from John Allen: **The thin barrel of a conventional bicycle hub cannot withstand the torque of pedaling, or of a hub brake. A flip-flop rear hub, or one with a disk or drum brake, must resist torque on *both* sides, and should never be laced half-radial unless it has a large-diameter, one-piece shell**.

Also, I don't think that the Ford wheel is half-radial for quite the same reason as a bicycle wheel. The outboard spokes of the Ford wheel attach to the hub at a much smaller diameter than the inboard spokes, and would change tension very little due to torque if in a semi-tangent pattern.

The Ford, like any dual-track vehicle, imposes large sideways stresses on its wheels when turning. The wheels at the outside of the turn also bear most of the weight. The sideways force on these wheels increases the tension of outboard spokes at the bottom of the wheel, while the weight load decreases it. The large dishing angle of the outboard spokes tends to balance the increase and decrease in tension. The low dishing angle of the inboard spokes minimizes their decrease in tension.

Ford engineers must have carefully considered all these factors as they designed this wheel. Cutting-edge technology? No, the Model A was introduced in 1927, 51 years after James Starley introduced the tangent tension-spoke wheel. There had been plenty of time for thought and experimentation.

The Ford wheel has twice as many inboard spokes as outboard spokes, optimizing the tension despite the different dishing.

Doubling the number of spokes on the right side of a bicycle wheel might also be used to optimize tension -- for example, a wheel might have 24 spokes on the right side and 12 on the left -- though at the expense of special rim and hub drillings.]

Wrong-way Half Radial

Sometimes, rear wheels are spoked half-radial with the radial spokes on the right. This is generally done for reasons of improving derailer clearance, particularly on wheels with unusually thick spokes or unusual flange designs. **The hub must have a large-diameter, one-piece shell for torsional strength and stiffness, as the driving torque must then be transferred across the barrel to the left-side spokes.**

Exotic Patterns

These are not the only possibilities, but they are the practical ones. It you want information on whimsical patterns such as the crow's foot, et. al. check out http://www.terminalvelocity.demon.co.uk/WheelBuild/

Even more whimsical are my own POWerwheels spoking pattern, and the SYMMETRISPOKE nipples that go with it. To avoid dishing problems in a rear wheel, you might just try the ShelBroCo 5 and 5 system.

Further Reading

For a more thorough analysis of some of the theoretical aspects of spoked wheels, the standard reference book is *The Bicycle Wheel*, by Jobst Brandt (1981 Avocet, Palo Alto, California ISBN 0-9607236-6-8.) This is available at better bicycle shops everywhere.

John Forester's article Held Up by Downward Pull describes wheel theory in the light of some interesting experiments Forester conducted, and busts the myth that the wheel hangs from the spokes at the top.

The use of musical pitch to determine spoke tension is explained by John Allen at http://www.bikexprt.com/bicycle/tension.htm. John has written an article describing his experiment comparing musical and tensiometer measurement.

Want to try to build a wheel using mismatched hub/spokes with different drillings? See Benjamin Lewis's "Perverse Wheel Building" article on this site.

A useful set of charts for determining spoke lengths may be found in the 6th edition of *Sutherland's Handbook for Bicycle Mechanics* by Howard Sutherland et al, Sutherland Publications, Box 9061, Berkeley, California 94709. ISBN 0-914578-06-5

This is not the only wheelbuilding site on the Web. I'd also direct your attention to:

- Rowland Cook's article on exotic spoke patterns

Tools and Materials

If you have trouble finding tools and materials, in your local area, you can order from Harris Cyclery:

- Tools
- Materials

Improvised Tools

[This section can be blamed on John "Cheapskate" Allen :-)]

An old front fork chucked in a vise can work very nicely as a truing stand, though for only one overlocknut dimension and a limited range of rim diameters. For a rear wheel, you could modify a front fork by bending the blades apart. You could also use the entire bicycle when truing either wheel -- best if you start by lowering the bicycle onto the wheel so the bicycle's weight rests on the wheel and centers it -- or at least make sure that you pull the wheel up all the way into the forkends. Get the chain out of the way before working on the rear wheel. Hang the bicycle from a hook or ropes, or place it on a work stand so the wheel you are truing is off the ground, and the rim passes between the seatstays or fork blades at eye height.

This approach is not quite as convenient as using professional tools, but the results can be just as good. The following techniques work with improvised tools.

- A rim brake can provide a reference for lateral truing if rotated so one shoe is very close to the rim. You may use rubbing of the brake shoe on the rim as a reference, or you may observe the gap between the brake shoe and the rim. The distance from the brake shoe to its reflection in the rim sidewall is twice that to the rim, doubling the precision of this reference. Look at the brake shoe end-on to see the spacing most clearly,
- When truing a rear wheel on the bicycle, clip a small metal or plastic ruler to the seatstays with a rubber band to provide a reference for vertical truing and centering. Twist the rubber band where it passes behind the seatstays, to keep it clear of the rim. The scraping of the ruler against the rim flanges is your reference for vertical truing. As you true the wheel, tilt the ruler slightly to touch first one flange, then the other, to get an average height. When using a front fork as your truing stand, you can use a spoke instead of a ruler, held crossways ahead of the fork blades. The rubber band will clear the rim at the rear of the fork blades.
- Centering may be checked by flipping the wheel over (so the cassette is on the left, etc.). When the position of the rim between the brake shoes and frame parts remains the same after the wheel is reversed, the rim is centered. You may also check dishing by placing two piles of blocks, books etc. on a tabletop to support the rim at two places opposite one

another. The distance from the tabletop to the hub locknut on the underside should be the same, no matter which side of the wheel is down.

About the Illustrations

The spoking illustrations have been around! I created them in the early '80's on a modified Digital PDP-11, using Management Graphics (old MGI page archived) proprietary software, outputting Kodachrome slides. Years later, the slides were scanned onto a Photo CD, then manipulated on my Macintosh, using Adobe Photoshop.

Thanks to John Allen, Daniel Boals, Jobst Brandt , and John Forester for their kind assistance.

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