Calipers

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Introduction

This document looks at old-style calipers. Today, the word "calipers" denotes dial, electronic, or vernier (DEV) calipers used for length measurements. A couple of generations ago, the term instead referred to old-style calipers. Though DEV calipers are useful and necessary tools, you may find old-style calipers still have a place in the shop and DIY projects. From here on, the word "calipers" will refer to these old-style calipers.

Calipers are devices that provide an adjustable gap or width and they are useful wherever things are made or fixed. To start with, we'll look at the different types and some recommendations. The majority of the document will look at typical uses of these calipers. There will also be a section on maintaining them and recommendations on which ones might be valuable to have.

This article is aimed at folks who like to design and build things themselves.

Notation

Calipers = old-style calipers (spring bow, firm or lock joint, or wing dividers)

DEV calipers = dial, electronic, or vernier calipers

DIY = do-it-yourself

Drawings are third-angle projections

[*abc:n:m*] = reference [*abc*], page *n* (page *m* in a PDF)

Syntax

Is the word "calipers" singular or plural? I can find no unambiguous definition and I've seen it used both ways in printed material from the last century or two. You'll also see e.g. "vernier caliper" and "vernier calipers". I will use the term "calipers" as plural, because saying "the outside calipers is applied" doesn't ring true as correct grammar. The word is similar to "scissors" in that two pieces are needed to make the whole object.

Thus, for example, I'll use "hermaphrodite calipers are used..." even though this is might be referring to a single device. Alternatively, I might use "a pair of hermaphrodite calipers is used...".

You'll also see the word "caliper" used as either a transitive or intransitive verb.

Types

Figure 1 shows a few of the different styles of calipers available. Caliper size is determined by the distance from the pivot to the tip of a leg, not the overall length of the device.

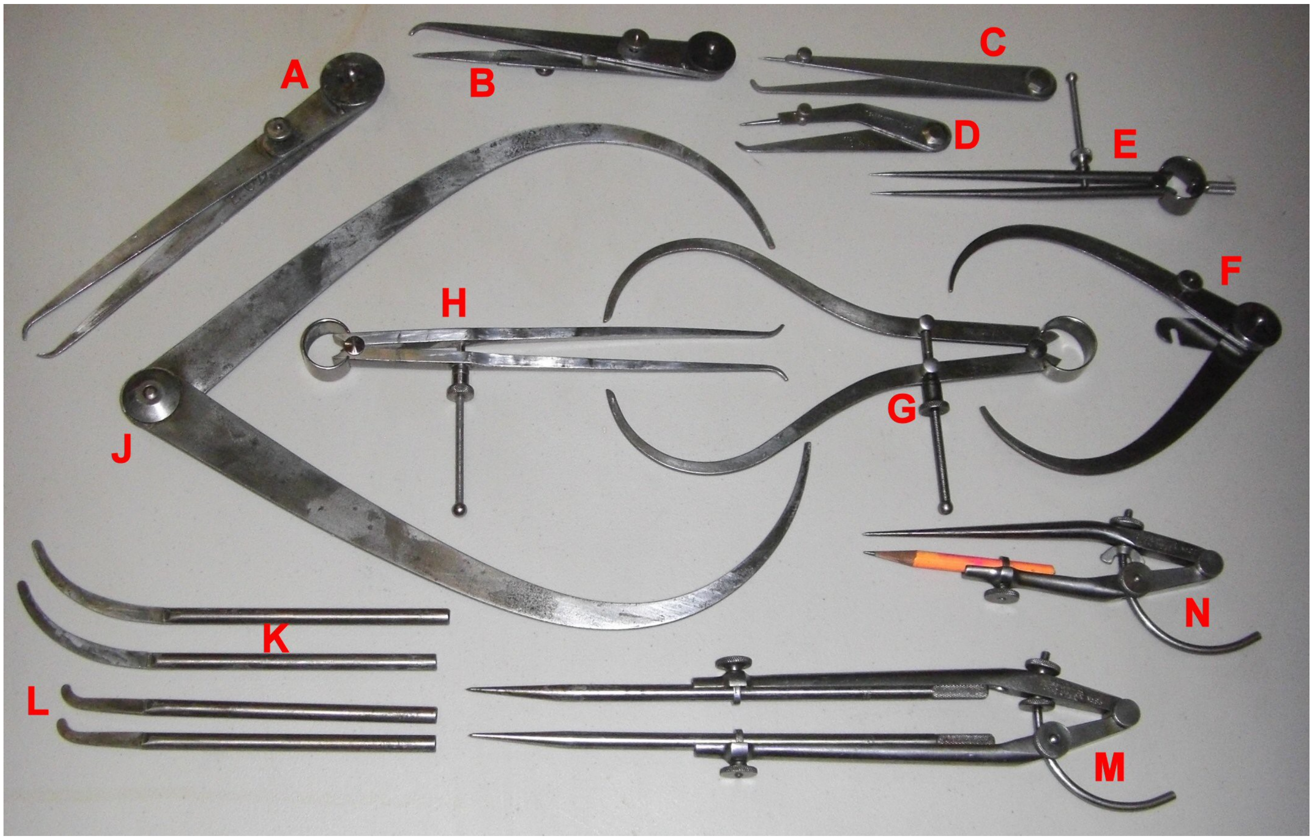


Figure 1

Key	Description
A	8 inch lock joint calipers (Starrett model 39)
B	6 inch lock joint hermaphrodite calipers (Starrett model 42, old style)
C	6 inch firm joint hermaphrodite calipers (Lufkin, model unknown)
D	4 inch firm joint bent-leg hermaphrodite calipers (Starrett 242)
E	6 inch toolmaker's-style spring bow dividers with solid nut (Starrett 277)
F	6 inch outside transfer calipers (Starrett 36) (short transfer leg visible)
G	8 inch Yankee-style spring bow calipers with solid nut (Athol Machine, model unknown)
H	8 inch Fay-style spring bow calipers with split nut
J	12 inch firm joint calipers (Starrett 26)
K	Outside caliper legs for Starrett 85 wing dividers
L	Inside caliper legs for Starrett 85 wing dividers
M	12 inch wing dividers (Starrett 85)
N	6 inch wing dividers ("carpenter's dividers", Starrett 92)

Spring bow calipers: These are the most common type (E, G, and H) and are probably what most people think about when the term "calipers" is used. The two legs have a pivot with a round spring that holds the legs against the pivot. The adjustment screw is used to change the position of the caliper legs. There are three different styles made: Yankee (G), made from flat stock Fay (H) made from rectangular stock, and toolmaker's (E) made from round stock. A solid nut refers to a plain thumbscrew; a split nut refers to an adjustment nut that can be slid quickly along the threaded shaft to the desired position, giving faster operation of the calipers.

Firm joint and lock joint calipers: These are made from flat stock and the legs pivot about a joint that has a suitable amount of friction to hold the setting. Firm joint calipers are at C, D, and J. Lock joint calipers can be locked in position and have a fine adjust; samples are at A, B, and F. Firm joint calipers can be closed slightly by knocking the leg against a piece of wood; they can be opened slightly by holding them vertically with the joint down and knocking the joint on a piece of wood. Good work can be done with firm joint calipers by an experienced user, but many folks prefer calipers with a fine adjustment screw.

Wing dividers: The legs attach at a hinge and an arc of metal (which looks like a wing, hence the name) is used to clamp the legs at a desired opening (M and N). This is a style often used by blacksmiths, carpenters, sheet metal workers, and similar trades.

Choosing a caliper type can depend on how they feel in your hand, how fast you need to get the measurement, weight, the sizes you need to measure, and how you like to work with them. Here's a table to help with selection of caliper types (*L* = pivot to tip of leg distance):

Type	Advantages	Disadvantages
Spring bow	♦ Simple construction ♦ Inexpensive ♦ Choice of split or solid nut ♦ Built-in fine adjustment ♦ Reliable and robust ♦ Measure dimensions up to about *L* ♦ Found in *L* = 2 to 12 inch sizes	♦ Slow to adjust to size (faster with a split nut). ♦ Measuring range will be smaller than firm/lock joint calipers of the same size.
Firm joint and lock joint	♦ Allow fast adjustment to size. ♦ Will measure larger dimensions than spring bow calipers of the same size (measure up to about 1.8 *L*). ♦ Versatile: inside calipers can be used for both inside and (restricted) outside measurements. ♦ Transfer calipers are made using lock-joints. ♦ Some models have a fine screw adjust. ♦ You can make your own. ♦ Found in *L* = 4 to 36 inch sizes	♦ Easy to bump and change the setting unless the joint is locked. ♦ May be tedious to adjust to the correct feel without a fine adjust. ♦ Heavier than similarly-sized spring bow calipers. ♦ Lock joint calipers are about three times the cost of firm joint calipers
Wing dividers	♦ Quick to adjust to size. ♦ Fine adjust is desirable. ♦ Robust to stand up to heavy use. ♦ Optional caliper legs and centering balls give a versatile tool. ♦ Used as log scribers for building log houses. ♦ Found in *L* = 6 to 12 inch sizes	♦ Often only found as dividers, not calipers. ♦ A bit too clumsy for precise metalworking.

Here's a relative cost comparison for Starrett's different calipers (prices from the web on May 2016) for 6 inch outside calipers:

Type	Relative cost
Firm joint	1
Yankee, solid nut	1.1
Yankee, split nut	1.2
Firm joint hermaphrodite	1.3
Toolmaker's	2.3
Lock joint transfer	3.1
Lock joint hermaphrodite	3.4

Recommendations

If you have never used calipers before, consider the $10 Harbor Freight set (94447) of 6 inch calipers. This set will give you inside and outside Yankee-style spring bow calipers and dividers and you'll be able to learn about their basic use. Harbor Freight also sells 6 and 12 inch wing dividers under $10 (these also hold a pencil to make a compass, but don't have a fine adjust). You may also eventually want to get or make some hermaphrodite calipers.

New calipers from a company like Starrett are expensive. Since calipers have been manufactured for more than a century, there are many used calipers available. If you know what you're looking for and are willing to shop around, you can find good used calipers for a fraction of the new cost. Be aware that on-line sellers often know nothing about calipers, describe them incorrectly, sometimes don't mention that the calipers are damaged, and many list them at inflated prices. It's definitely a buyer beware situation, but there are so many available, you can afford to wait to find a good deal. I feel used calipers should cost from $5 to $50, depending on type, size, and condition, with most of them in the $15-$25 range.

Most used calipers need cleaning, rust removal, and lubrication; this is straightforward to do. Unless you want a shiny new look, it's fine to buy old, dull calipers with rust on them -- they should clean up and operate well with lubrication if the moving parts haven't been damaged by rust. The advantage is that you'll pay many times less than what sellers want for the shiny new ones.

From here on, I'll give my personal opinions, as I've used a variety of calipers over the years and have developed my preferences. Of course, what works for me may not work for you.

A key thing to decide is the size of calipers to purchase, which will be governed by the maximum size of things you typically work on. The sizes available are typically 2, 3, 4, 5, 6, and 8 inches, as well as larger ones up to 36 inches or so. I have some toolmaker's calipers and dividers in the 2 inch size. They are perfectly functional, but I rarely use them because they are a bit small for my hands. My favorite size for use in the shop is 4 inches for calipers and 6 inches for dividers. I recommend getting the smallest calipers consistent with the sizes you typically work on. I keep 4 and 8 inch spring bow calipers on my lathe and those cover all the tasks I do on the lathe. The 4 inch sizes are used most of the time, particularly in metalworking tasks.

My favorite calipers for boring in the lathe are some 4 inch Starrett Fay style inside calipers. These have the best feel and leg shape for my tastes and a split nut for rapid adjustment. I use these in conjunction with my 6 inch dial calipers for boring to within about 0.002 inches. I'll use a telescoping gauge and a micrometer only if I need to do closer work.

In terms of the feel when calipering work to set the calipers to size, I've not be able to discern useful distinctions between the different styles. For metalworking, I prefer spring bow calipers to lock joint calipers because the spring bow calipers are easier to adjust to exact size.

For heavy or dirty work, consider the Fay style spring bow calipers because they will stand up to long tough duty in a machine shop.

For general DIY work, my favorite calipers are lock joint inside calipers (Starrett model 39). These let me measure both inside and outside diameters and fold into a compact form that slips into a narrow pocket on my tool apron. On one of my 12 inch pair, I made a smaller-diameter lock nut for it that allows me to use the calipers to transfer and measure angles (by measuring a chord), adding to the versatility. The calipers' leg edges also serve as a useful straightedge.

I have a number of larger outside lock joint calipers, but the outside calipers I seem to use the most for larger outside measurements are the 12 inch firm joint calipers J in Figure 1. For DIY work, the majority of measurements I make are inside dimensions.

For general work outside the machine shop, the Starrett 85 wing dividers with caliper legs could be a good investment for a lifetime of work, as they can make dividers, various calipers and a compass. They are the most versatile calipers/dividers available, but they are too clumsy for finicky machinist work. The 85F set will let the dividers be set to 23 inches, make outside measurements to over 20 inches, and inside measurements to 24 inches. Trammels like the Starrett model 59 can do similar work and store more compactly in a toolbox.

A busy general-purpose machinist would probably benefit from having the 6 inch inside and outside Starrett transfer calipers (models 36 and 37). They'll do a variety of work, yet fit well into a toolbox -- and a machinist will probably need the transfer abilities on a regular basis.

Specialty types

There are a number of specialty caliper types that are beyond the scope of this document. You can look them up on the web for more information; some are still being manufactured today.

- Keyhole calipers were used to measure from a hole to an edge.
- Dancing leg calipers were popular in the 1800's and up to around World War 2. These were small firm joint calipers that could be used to measure inside and outside dimensions. Most machinists made their own.
- Blacksmiths make a double caliper using riveted joints for rough sizing tasks.
- Registering calipers include a scale or indicator to get a dimension directly. Dental calipers are similar, but specialized for smaller tasks. Some woodworking places sell registering calipers that use electronic indicators.
- Golden mean dividers can divide a dimension into two dimensions whose ratio is the golden ratio. The idea extends to other ratios.
- Proportional dividers can be used to scale dimensions proportionately. You can build a simple model with two sticks and a nail, but expensive ones are adjustable with precision gears (these were used for scaling drawings in the drafting room in the days before computer aided drafting tools).
- Double calipers were versatile firm joint calipers made in the first half of the 20th century. Starrett made two models I'm aware of (see [*st26*] and [*leo:5*]): the model 44 had divider points and inside caliper legs, letting you measure inside and outside dimensions and make hermaphrodite calipers and dividers. The model 444 was for inside and outside measurements and had a fine adjust. It's not hard to find the model 44 calipers, but I have only ever seen one example of the model 444 calipers for sale.

History and patents

Firm joint calipers have been known from antiquity, being shown in drawings of Roman workers' tools. They are relatively easy to construct for oneself, although a more sophisticated joint than a rivet or bolt is needed for a good tool.

Lock joint calipers appeared commercially around 1895 with a patent by Laroy Starrett and Charles Fay. Starrett also patented a firm-joint design with a fine adjust in the early 1900's.

The late 1800's saw the refinement of the spring bow design. The basic designs were in place by about 1900 and are still in use today. Consult the references for a few of the key patents.

Techniques

Principles

The use of calipers appears simple, but you'll find they require more practice than DEV calipers to get accurate and consistent measurements. The plane of the calipers' legs needs to be oriented properly with respect to the diameter or linear dimension being gauged. For outside diameters, the plane of the legs needs to contain the diameter being measured. For inside diameters, the plane of the legs must be perpendicular to the plane of the circle being measured and, at the same time, contain the perpendicular to this plane through the center of the circle.

It is recommended that calipers not be applied to moving work because the caliper tips can be drawn over the work and give an incorrect reading. This is a guideline and you'll want to experiment to see when it's important. For example, in woodworking on the lathe, it's common to gauge rough sizes with calipers when the work is turning.

The caliper legs must touch the work lightly to avoid elastic deformation of either the calipers or the work. This is subjective and is a reason why calipers take more skill than DEV calipers. A corollary of this rule is that you must duplicate this feel when transferring the caliper setting to a machine or other calipers. A good exercise is to compare the calipers' feel when gauging two gauge blocks that differ in size by 0.001 inches.

An experienced caliper user will continuously move the calipers and adjustment screw, "hunting" for the correct feel.   For outside measurements, you'll hunt for the minimum diameter where the plane of the caliper legs is perpendicular to the work and the tips just brush the work. For inside measurements, you'll hunt for the maximum diameter while adjusting in two distinct planes (inside measurements are somewhat more difficult than outside measurements). You will need more practice than you think to master these tools.

Converting to a measured dimension

If possible, avoid converting caliper settings to dimensions to reduce errors and speed work. When a numerical dimension is needed, the most commonly-used tool is the rule or tape measure. A machinist's rule is the recommended tool for this conversion. Younger eyes can work to perhaps 0.01 inch (0.25 mm) resolutions and you can do better with a magnifier like a jeweler's loupe. With good lighting and a 5X to 10X loupe, you'll find you can work to 0.005 inch (0.1 mm) levels and even less, although this will require practice and care.

An important detail is to have good lighting for reading where the caliper legs are on a scale. Poor lighting or shadows easily lead to making small errors.

For inside caliper measurements, DEV calipers are convenient for conversion to a dimension. The requirement is that you duplicate the feel of the two measurements. I use this method with 4 inch inside calipers on the lathe for boring tasks and can work routinely to about 0.002 inch levels.

For outside measurements, taper gauges such as the Starrett 269 can be used. With care, you can measure to perhaps 0.002 inches or so.

When comparing two outside dimensions with calipers, you can use feeler gauges to quantify small differences. It works, but it's clumsy and a micrometer is the preferred tool.

For rough measurements, it can be handy to have a number of fixed gauges. For example, I made a set of disk gauges with accurately-machined outside diameters from a stack of old CDs. It took quite a bit of time to make these, but they allow for quick checking and double as templates for drawing arcs of known sizes.

You'll find through experimentation and calculation that practical measurements with calipers can ignore cosine errors for dimensions above approximately 10 mm.

Transferring dimensions

Calipers can transfer a dimension from one location to another. Since this is an important concept, I'll illustrate it with some examples.

I had a small plywood table top I made for a tool cart I use. I wanted this table to be removable, so I designed it to be held in place by a piece of wood that was a tight fit under the cart's handle and the plywood. Knocking this piece of wood out lets me remove the table, as there are no other fasteners.

To make this piece of wood, I used inside calipers to gauge between the plywood top and cart handle. Since the plywood's surface was somewhat rough, I had to adjust things to get what I felt was the proper feel so that the calipers were set to the mean thickness. I took the calipers to my shop and adjusted the fence of my table saw to rip a piece of wood to the needed dimension. This was done by using the calipers to set the distance between a tooth on the saw blade and the fence[1]. From experience, I knew that such cut parts may be a bit loose, so I set my saw's fence 0.15 mm larger than the caliper's setting (my saw has a digital readout of fence position that allows such settings). I cut the board and it fit the application perfectly, needing to be knocked into place with a soft hammer. Was I just lucky or did the calipers help me do a better job? I can't say for sure, but I also can't argue with the result

While such work could be done by e.g. measuring the gap with a rule or tape measure, there can be more cut-and-try work to get the fit you want.

Another need for transferring a dimension is to transfer the setting of some inside calipers to some outside calipers (or vice versa). I had an old 5-wheel base from an office chair that I wanted to use as a rolling stand for my shop light. I had to machine an adapter that fit in the steel tubing of the chair base and clamped onto the shop light's tubing. Exploratory measurements with inside calipers (H in Figure 1) told me the chair base tubing was slightly tapered on the inside. I wasn't able to machine the adapter and check it on the base during machining, so I had to get things right the first time. This was straightforward, but done with numerous checks. The basic technique was to set the inside calipers to the chair base tubing, then transfer this dimension to outside calipers and use this setting to machine the outside diameter of the adapter, which was made from 2 inch diameter aluminum bar stock. The same method was used to bore the hole in the adapter for the shop light's tubing. Hermaphrodite calipers were used to mark some clamping screw holes in the side of the chair base. The final result was a satisfyingly nice fit with no play and no mistakes.

Volume of a bucket

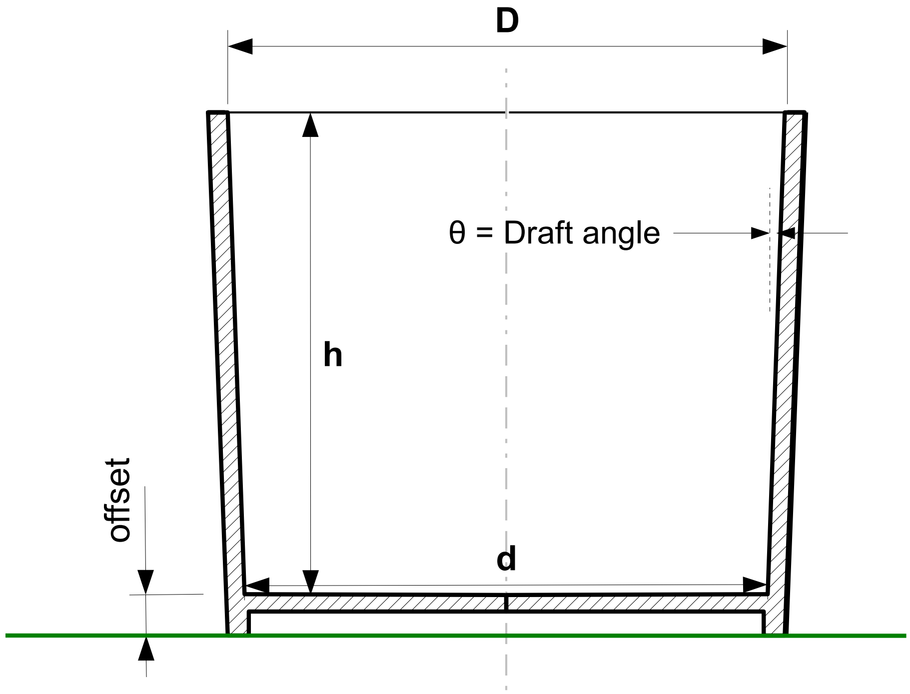
5 gallon paint buckets are useful around the house; they're even more useful if they have marks to let you assess the volume of material in the bucket. To make these marks, you need to measure the inside diameters of the bucket; 12 inch inside firm or lock joint calipers are handy for this (or you can make some measuring sticks to make this measurement). Then volume calibration marks on the bucket's side can be made with a tape measure.

Set the calipers to measure the inside diameter of the bottom of the bucket. Rotate the calipers around a vertical axis to assess how out-of-round the bottom diameter of the bucket is, as you'll want to estimate the mean diameters. Call the bottom diameter d.

With the calipers set to the bottom diameter d, measure the top diameter D by using the tape measure (a machinist's rule is better) to see how much larger D is than d. Also use the tape measure to measure the vertical height h between the points you measured d and D. Note that $D > d$ because the plastic bucket has to be withdrawn from its mold.

Here's a sketch of the dimensions:

1 For this to result in an accurate cut, the saw blade must be parallel to the fence.



Measure the indicated offset if you want to mark the outside of the bucket. The volume of the bucket is

$$V=\frac{h}{3}\left(A_d+A_D+\sqrt{A_d A_D}\right) \quad \text{where} \quad A_d=\frac{\pi}{4}d^2 \quad \text{and} \quad A_D=\frac{\pi}{4}D^2$$

Typical draft angles of buckets I have measured are around 2°. It's not difficult to use this equation to make marks on the bucket to indicate the volume (if you do the math, you'll find you have to solve a cubic equation with one real root to get the needed height to mark from the desired volume). For marking on the outside, remember to multiply the calculated vertical height by the secant of the draft angle to get the slant height (add the secant times the offset in too if measuring from the bucket bottom).

With careful measurement and a round bucket, you can get volume accuracies of about 1%.

Dividers

Dividers are adjustable points that can be used to make uniformly-spaced marks, divide a dimension into an integer number of equal smaller lengths, pick dimensions off an object, or make geometrical constructions.

Spring bow dividers are probably the most commonly-used type in the shop, but firm and lock joint types have been made and wing dividers are also popular. For picking off dimension, geared drafting dividers are handy (commonly used by navigators for picking off or setting dimensions on maps), but these aren't practical for shop work because it's too easy to accidentally change the setting.

Dividers are named for the process of dividing a length into an integer number of equal subdivisions. The approximately-needed subdivision length is set on the dividers, then the required number of divisions is stepped off on the length to be divided. If there is an error at the end, the dividers are appropriately adjusted and the check is repeated until the error is negligible. This division method also works approximately on curves where the radius of curvature is substantially larger than the divider setting (i.e., the curve is easily rectified).

A machinist's rule is often used with dividers to set the point separation. The best way to do this is to index one point in one division on the rule, then set the other point at the desired reading. It's critical to remember to account for the offset unless you use a drafting-style rule with a zero mark. Expensive mistakes will teach you to check the set dimension by putting one point at the rule end and reading the setting of the other point.

Some vernier calipers (e.g., the Starrett model 122) contain small marks that can be used to set and check divider settings. These can let you work to near 0.001 inch levels. You could use a prick punch to make some small marks on your DEV calipers to make this type of measurement if you can measure the offset accurately when the DEV calipers are set to zero.

With a 10X loupe and sharp dividers, you'll find that you can see 0.001 inch differences between a mark on some metal and a point on the dividers. This lets you construct an accurate metal story stick for a project.

Before vernier scales were invented, diagonal scales were used to get an extra significant measurement digit for setting dividers. You can construct a diagonal scale with a length standard, dividers, and a straightedge. When I was young, diagonal scales were commonly seen on carpenter's squares, allowing you to set dividers to 0.01 inch levels[2].

Dividers are made from high-carbon steel and the points are hardened and tempered to help them keep their sharpness. Keep your divider points sharp by honing them on a stone. Handle dividers carefully in the shop if you work on concrete floors, as dropping them on their tips can damage them. I like to have a rubber mat under my feet when using tools like DEV calipers and dividers in case I accidentally drop them. I slip a chunk of rubber fuel hose around the dividers' tips to protect them in storage and avoid poking myself.

For metalworking, I prefer toolmaker's style spring bow dividers in the 4 and 6 inch sizes. For woodworking, Fay style calipers are handy because they are heavier and can be pressed into the wood firmly to mark a point. For general DIY stuff, wing dividers may be a good choice.

If you're on a budget, consider the 6 and 12 inch under-$10 wing dividers from Harbor Freight. They don't have a fine adjust, but they should work for many tasks and one can't argue with the price.

There are vendors who sell the Starrett 85 wing dividers with a two-vial level assembly on the end so that they can be used for scribing log cuts when making log homes. The levels help you hold the dividers consistently. Look up log scribes on the web for more details. See *Fit a board to an uneven wall* for the technique.

Warning about divider settings

A lesson I have to learn over and over again is to not change the settings on some dividers until I know the project is finished. Time and again I've put the dividers back into my toolbox, then needed the just-used setting again minutes later.

Story stick: A practical method to avoid losing the divider setting is to use a scrap piece of metal to record the divider setting. Sheet aluminum is excellent for this. Scribe a straight line on the metal, then put a small prick punch mark on the line to act as the zero point to index the dividers; circle it with a Sharpie marker to make it visible. Then scribe an arc that intersects the line with the dividers set to the length of interest. Mark the arc with a Sharpie so you know what it's for. This saves the setting on the dividers and you can later set dividers exactly to the same setting within 0.001 inches with a 10X loupe.

In anticipation of doing this for different projects, you might want to make up some blank aluminum story sticks ahead of time.

Transfer calipers

Starrett invented transfer calipers in the late 1800's and still sells them as models 36 and 37 (Brown & Sharpe made some too). These are lock joint calipers have an extra leg that can be locked at a particular setting; a nut can then be loosened, allowing the main leg to be moved to clear an

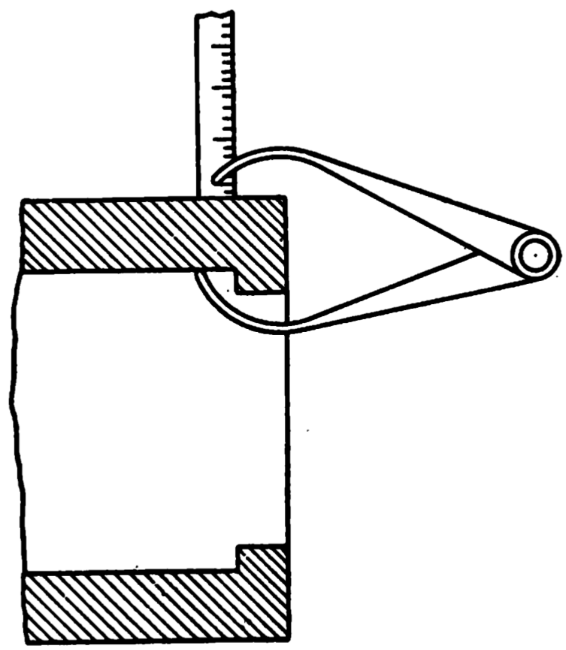
2 The Wikipedia page https://en.wikipedia.org/wiki/Diagonal_scale is incorrect, poorly written, and does not describe what I call a diagonal scale (accessed June 2018).

obstruction (the calipers at F in Figure 1 show this transfer leg). The main leg can then be returned to the measured setting and a rule used to measure the actual dimension. The benefit is that the desired dimension is gotten directly without having to do a subtraction. This reduces the chance of an error.

A busy person who works on a variety of tasks will probably find transfer calipers speed his work. The 6 inch size does a lot of work, but fits nicely into a toolbox. I occasionally need an outside transfer measurement (example: measuring the thickness of the sole of a shoe), but inside transfer measurements are rare for me (two examples are measuring an o-ring groove in a bore or measuring a tube's inside diameter while getting around a burr caused by a pipe cutter).

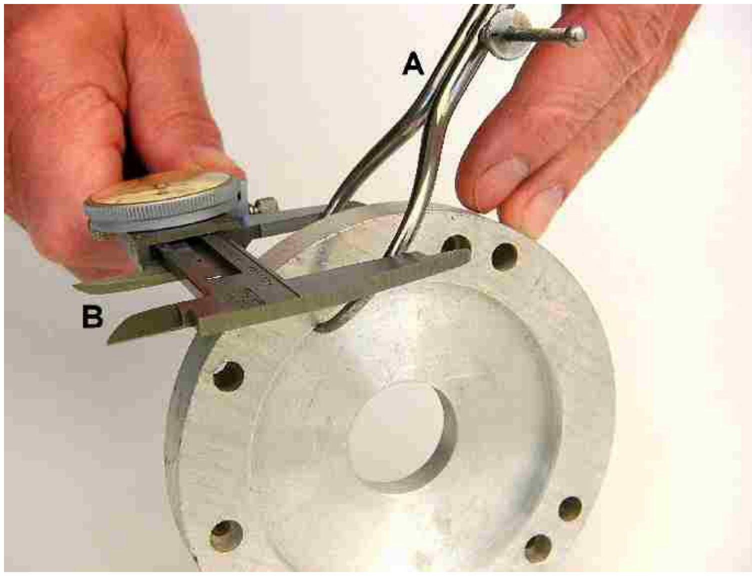
One thing I don't like about transfer calipers is they won't sit flat on a table (the transfer leg's thumb nut prevents this), which is why I prefer to use Starrett's lock joint calipers (models 38 and 39, unfortunately no longer made). Sitting flat is useful when e.g. transferring a reading from inside to outside calipers in the larger sizes or setting a table saw fence.

The method shown in the following picture is how to measure a wall thickness over an obstruction with regular calipers:



The calipers are removed from the work without changing their setting, then the opening is measured and the offset from the picture is subtracted. If you only need such types of measurements occasionally, it doesn't make sense to spend the money for transfer calipers, which are pretty expensive.

A similar method uses DEV calipers:



Outside calipers A are set to measure the desired dimension, then DEV calipers B are used to measure the outside dimension *D* over caliper A's legs. Calipers A are removed from the work and the DEV calipers are used to set A to the measured dimension *D* again. Now caliper A's gap can be measured with a rule.

Some people recommend measuring across the legs with calipers A closed, then subtracting this measurement from the first measurement. This is wrong unless you're certain both measurements are at the identical points on the legs. One way to ensure this would be to weld a small tooling ball to each leg.

Hermaphrodite calipers

B, C, and D in Figure 1 show hermaphrodite calipers, which have one bent leg and a scribing tip. Styles C and D have firm joints and style B has a lock joint. Style D has a bent pin leg which keeps the scriber more perpendicular to the work surface during use. 4 and 6 inch sizes are the most common, but you'll see hermaphrodite calipers up to around 12 inches in size.

These calipers will scribe or measure from an edge or shoulder. They are the machinist's analog to the woodworker's scratch gauge. They are called jenny calipers in the U.K. and were called compass calipers in the 1800's. They are sometimes called "odd-leg" calipers, but that is incorrect with respect to older usage.

Starrett made the model 42 calipers shown at B in Figure 1 for many years with the scribing leg made from a piece of flat stock, but then changed the design to a pin leg like the calipers shown at C and D. An advantage of the pin-style scribing leg is that it's easier to make specialty tips from welding rod or spring stock. For example, a simple bent leg can be made to turn the hermaphrodite calipers into inside, outside, or odd-leg calipers.

An advantage to the flat leg is it's mechanically stronger, allowing you to press the point into e.g. a piece of wood. I use this feature a lot when locating holes on a piece of wood, as the point can produce a hole suitable for starting a drill. In hard woods, I may follow up with a center punch unless I'm using a brad point bit.

A disadvantage of Starrett's flat leg design is that the length adjustment of the scribing leg is limited. If an edge has a fillet or bevel and you want to scribe from that edge, you want the sharp leg shorter than the leg with the curved tip. Starrett's design won't let you do this (and results in a cosine error), but e.g. the Lufkin design with the pin tip does this easily and quickly. I need this feature pretty often, which is why I prefer the pin tip style for layout work.

An advantage of the flat leg design is that it can be used to scribe small distances from a shoulder. The pin design is not able to do this because the pin and clamp interfere with the other leg for small settings (I've seen pictures of some pin leg hermaphrodite caliper designs that don't have this limitation).

Starrett made the model 43 hermaphrodite calipers that was a Yankee spring bow design. One leg was straight like those of dividers and the other was from outside calipers (this was easy to do from existing caliper leg stock). The fine adjust is an advantage (it came with a split nut), but these calipers can't scribe from a shoulder and the point can't be moved.

I use hermaphrodite calipers a lot in the shop. The most common use is to scribe a line or mark a distance from an edge or shoulder, often to find a center of something. The calipers are easily set from the end of a machinist's rule and the dimension can easily be set to 0.01 inches or 1/4 mm. I keep a pair of these calipers at the lathe, as they are useful to mark locations from the end of the work or a shoulder.

> A tip for lathe work is to use a blue Sharpie marker to mark a narrow band about where the line will be scribed while the work is turning. Set the hermaphrodite calipers to the desired dimension and the line is then quickly marked and is easily visible.

I use Torx wood screws a lot with woodworking tasks, as they make strong butt joints. I set hermaphrodite calipers to half the thickness of the wood piece being screwed to, then mark the hole locations with the calipers' point. This is followed up if needed with an automatic center punch and a pilot hole is drilled. This locates the screws at a uniform distance from the base. There's no unsightly scribe line like you'd get with a scratch gauge. With self-drilling screws, there's no need for a pilot hole[3] and the small mark made by the calipers is all that's needed to start the screw with an impact driver. When using bugle head Torx screws, I'll sometimes remove the screw and countersink the hole with a Weldon countersink, as this makes for neat construction (for rough work, I don't bother). Modern Torx wood screws have reaming edges cold-formed into the head and can countersink themselves below the surface.

> A decade or two ago I standardized on using these Torx wood screws for general wood and DIY construction tasks. I had some in an old pole fence for more than a decade. When I took that fence down, I salvaged all the screws and have used them in new project constructions. Plain galvanized hardware would have been rusted out in a couple of years in this application, as the wood was wet all winter long. You can install these Torx screws with a cordless drill, but you'll find a modern cordless impact driver is the tool of choice. My impact driver will easily drive 4 inch long screws into solid oak quickly and without breaking the screw, even without drilling a pilot hole.

> A decade ago, the Torx recesses of these screws had clumps of coating material in them, causing the Torx bit to strip the head or slip (worst-case was about 1 in 20 screws). Manufacturers have greatly reduced this problem, so it's rare enough to ignore. These fasteners will save you a lot of time and won't strip out like slotted, Phillips, or square drive fasteners.

Be cautious when using hermaphrodite calipers to scribe lines on wood, as varying grain hardness can cause the scribed line to vary (this happens with marking gauges too). I use a sharp pencil instead for marking such woods.

Another use for hermaphrodite calipers is to pick dimensions off something when referenced to an edge or shoulder, particularly over a feature that precludes the use of a rule. An example would be setting a specific fence-to-blade dimension on a table saw (inside calipers are a better tool for this).

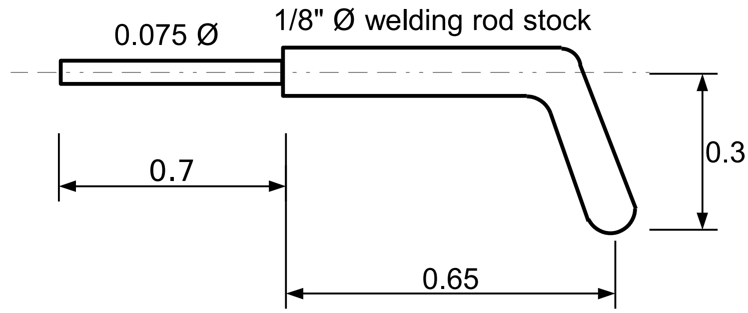
My favorite hermaphrodite calipers for metalworking are the 6 inch Lufkin firm joint calipers at C in Figure 1. These are easily adjusted to size using a machinist's rule and there's no chance of an off-by-one error since you index from the end of the rule. When folded, the point nestles in behind the leg so you won't get poked by it if you slip this into your pocket. These Lufkin calipers have the best firm joint I've ever used (I think Lufkin's joint works better than Starrett's design).

> A subtle advantage of straight-leg hermaphrodite calipers is that you can smoothly increase the opening by pulling your finger in the crotch of the two legs, prying the legs apart. I use this technique constantly, as it results in fast setting of calipers to a rule, especially with a good firm joint like on the Lufkin calipers. This is why I prefer a straight-leg pair of hermaphrodite calipers to a bent leg style. A quick tap

3 If the hole is near an edge, I always drill a pilot hole to minimize the chances for splitting (and if real close to an end grain edge, I'll also drill a clearance hole). Otherwise, with self-drilling wood screws and an impact driver, I don't bother.

of a leg against some wood reduces the setting. With a little practice, you'll adjust the size quickly and this tool will do good work for a lifetime.

Here's a shop-made leg to let these Lufkin hermaphrodite calipers act as inside, outside, or odd leg calipers, extending their versatility:



With this leg, these Lufkin calipers will measure 0 to more than 3.5 inch outside diameters and 0.8 to 10 inch inside diameters. I often use this leg to turn the Lufkin hermaphrodite calipers into odd leg calipers (see Figure 2).

Another useful addition is a straight leg with a point on it. Two rubber bands can hold this leg onto the bent leg, giving you a pair of makeshift dividers. The rubber bands can also hold a pencil, giving you a compass. You might want to file some small notches in the legs to help the rubber bands hold their position (or use tie wraps or waxed wire lacing twine). These Lufkin calipers were also made in larger sizes (I believe 8 inch and 12 inch).

Design subtleties

If you use hermaphrodite calipers for a while, you'll eventually come up against a limitation of the design you're using. For example, if you use a firm joint design, you'll see the desirability of a lock joint design when you accidentally bump the setting, causing an error. Such a limitation is a bit obvious on reflection, but the following limitations may not be. Here, I contrast the pin leg design compared to the flat leg design of older Starrett 42 hermaphrodite calipers.

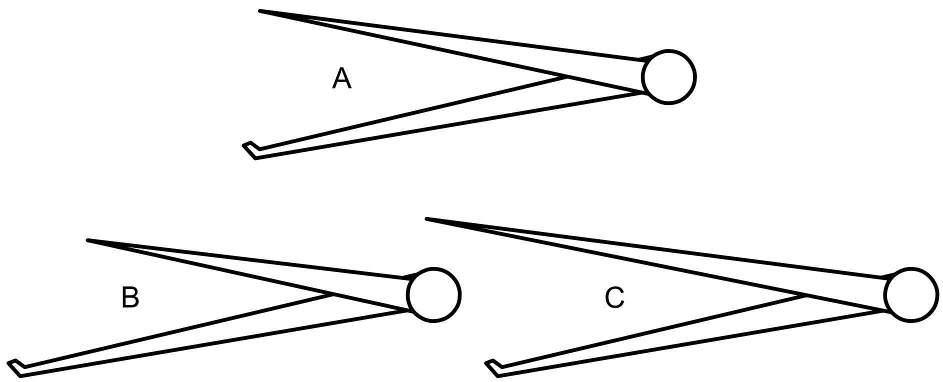
Pin leg advantages: Easy to adjust the pin up and down to allow scribing with offsets to e.g. avoid a fillet or chamfer. Allows making replacement points or specialty legs.

Pin leg disadvantage: the pin clamping assembly interferes with setting the calipers for scribing small distances from a shoulder. For example, the Lufkin hermaphrodite calipers C in Figure 1 have a minimum distance of 0.5 inches when scribing from a shoulder.

Flat leg advantages: Stronger to allow you to press the leg into e.g. wood to mark a point. Lets you scribe small distances from a shoulder or an edge.

Flat leg disadvantage: Leg longitudinal adjustment is limited, making it impossible to e.g. scribe from an edge with a significant fillet or chamfer (configuration B in the diagram below). This could be fixed by making or buying another leg and shaping it to a shorter length. The flat legs are a little harder to sharpen compared to a round pin.

The following picture illustrates the configurations needed when using hermaphrodite calipers:



Most routine work is done with a setting like at A. Small tilts result in (usually negligible) cosine errors.

To mark a distance from an edge with a significant fillet or chamfer, the configuration at B is needed. Making an accurately-located mark is more difficult because of cosine errors.

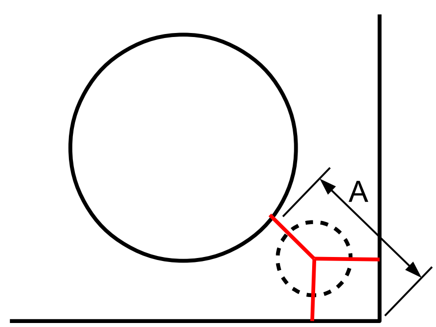
The need for configuration C is rare, but can occur when marking from an edge or shoulder down into a groove or clearing an obstruction.

I do virtually all of my metalworking scribing with the firm joint hermaphrodite calipers C in Figure 1 (I keep the bent-leg calipers D at my lathe). For woodworking and general DIY tasks, I like the old-style Starrett 42 hermaphrodite calipers with the flat leg design in both the 6 and 8 inch sizes.

Examples of use

Locating legs

I had a 3/4 inch thick pine board with a 1.25 inch hole through it near a corner. I wanted to attach a wood leg from 1/2 inch diameter dowel to this board.



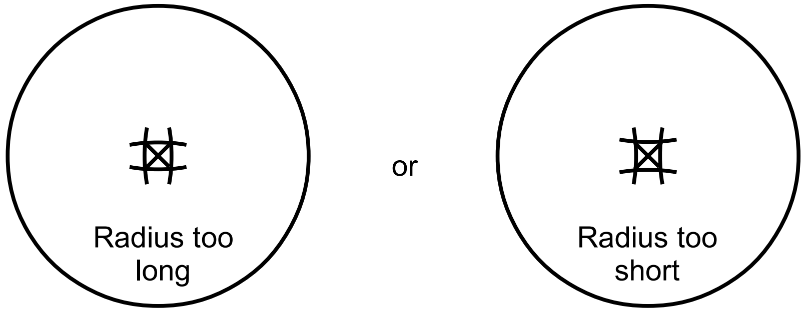
I used hermaphrodite calipers and adjusted the setting until I found the center point equidistant from the two edges and the hole edge. While I could have eyeballed it, this method was nearly as fast and I was also able to locate the three holes at the other corners by quickly scribing two lines from the edges once the calipers were set.

Metric conversions

If you have machinist rules with inch and metric markings, you can use hermaphrodite calipers to quickly convert between the two. Set a reading on one scale and read the conversion on the other.

Center of bar stock

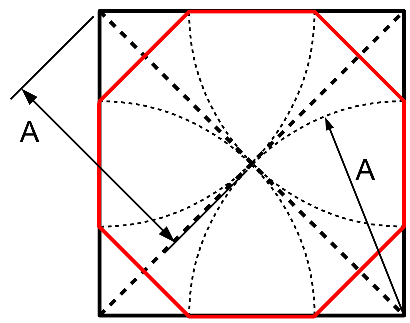
Set the hermaphrodite calipers to the approximate radius of the inscribed circle of the profile and make four marks about 90° apart:



Your eye is good at marking the actual center by judgment or you can draw the two lines from the corner, as they meet at the center.

Scribe an octagon

To scribe the portions of an octagon on a square, set the hermaphrodite calipers to half of the diagonal length:



You'd first mark the center point with the hermaphrodite calipers, set them to half the diagonal, and scribe the needed lines. For woodworking, use a compass with a [hacked] caliper leg so that the scribed marks are in pencil -- then you could hand plane the bar stock to octagon form or set the table saw's fence so that blade intersected the pencil marks.

Locating holes for a saw's miter gauge

To attach a board to my table saw's miter gauge, I set some hermaphrodite calipers to indicate the center point of the hole above the table (this is measuring from a shoulder). I drew two vertical lines on the board separated by the hole spacing, then used the calipers' point to mark a small hole on the line at the correct height. I followed this up with a center punch, then drilled the needed hole size and screwed the board to the fence.

A better tool for this task would be to clamp the board to the gauge and use a transfer punch, but using the hermaphrodite calipers was convenient and fast.

Locating holes for screws

I made a fixture to hold my belt sander to a chunk of plywood so I could use it like a stationary power tool. This involved making wooden pieces to prevent the sander from moving, locating the wooden piece on the plywood, clamping it, then securing it in place with a Torx wood screw from the opposite side. This was easily done by setting the hermaphrodite calipers to locate a desired hole on the front side, then transferring this dimension to the back side and making a small mark with the point. The first point was used to draw a line using a double square; the second point located the screw hole on this line. Even when things are tilted with respect to the edges, you get perfect locations quickly with no mistakes -- it's better than measuring things with a rule.

Here's a picture of the calipers I used while designing and making this fixture:

Figure 2

From the left, these are

- ♦ Lufkin firm joint hermaphrodite calipers with an auxiliary bent leg to turn them into odd leg calipers.
- ♦ Starrett model 39 inside lock joint calipers, 6 inches long. I use this style of calipers more than any other.
- ♦ Starrett old style model 42 hermaphrodite calipers. These get used a lot for locating screw holes.
- ♦ 6 inch Yankee style dividers. The red nail polish is used to distinguish them from an identical pair, which are painted with orange nail polish.

I do the majority of routine work in my shop with these calipers (I use 4 inch toolmaker's spring bow calipers for metalworking tasks).

Make a vee block from a 2x4

If you have a table saw, it's easy to make a handy vee block from a 2x4. Set the saw blade to 45° and mark how deep you want the vee on the 2x4. Set hermaphrodite calipers to this value, then use this setting to set the depth of cut (i.e., the blade height above the table). Locate the center of the 2x4 as described elsewhere, then make a small dent with the point from an edge. Set this edge against the fence as a shoulder and set the hermaphrodite calipers to this distance. Use this setting to adjust the fence position. Cut one groove of the vee, then flip the board 180° about a vertical axis and cut the other vee. There will probably be a small ridge at the center. I like to set the blade to 90° and cut a groove at the apex of the vee to remove it; this also gives clearance for a dinged edge on a workpiece.

While you've got the saw set up, make a number of these vee block lengths from random scrap pieces. You'll find them handy for throw-away fixture needs.

Keep a couple of these vee blocks at the drill press for drilling round stock. Cut the end square and screw on another chunk of 2x4. Drill a hole at the needed height and you have a drilling fixture for e.g. drilling a bunch of centered holes in stair balusters for hanger bolts. Test out-of-roundness with a dial indicator. Cut a short piece with a square end to hold a chunk of material for drilling vertical holes on the drill press. Attach a vee block with Torx wood screws to a sawhorse and attach a stop for planing the edges of boards.

Since these are throw-away vee blocks, you can make temporary clamps to hold material in the vee block and screw them to the vee block with Torx wood screws. You can use them with e.g. strap clamps, step blocks, studs, etc. from milling machine tooling (screw the vee block to a plywood base). Look up "finger clamp" on the web for similar tooling ideas.

For casual work, use chunks of 2x4 as-is. For more careful work, use a jointer and planer to ensure the four sides are flat and parallel -- then you'll have a usefully accurate vee block for little effort.

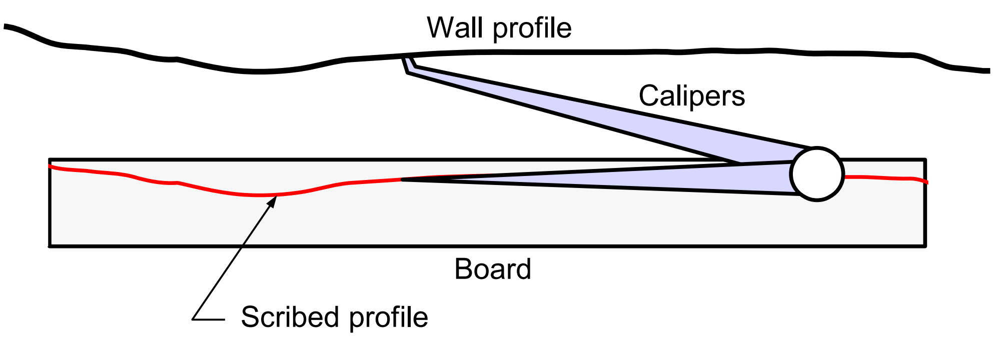
Fit a board to an uneven wall

A person new to DIY stuff around the home may be disappointed to find that things are rarely flat, straight, or at 90° angles. For example, you purchased a nice straight (and expensive) board to mount onto your wall, but then are surprised to find that it won't lie flat against the drywall. Cabinetmakers routinely encounter this problem when installing cabinets. The fix is to scribe the wall's topography onto the board, then cut the board so that its profile matches the wall.

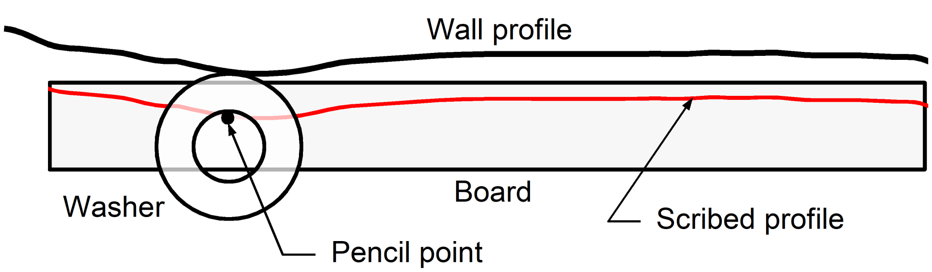
Hermaphrodite calipers are the tool of choice for this task. However, if you are scribing a mark onto a board, you'll probably want to use a pencil instead of a sharpened point because the point may incorrectly follow the wood grain when scribing. A practical tool in a pinch is a cheap school compass.

> You can attach a pencil to the point leg of hermaphrodite calipers with a rubber band, tie wrap, or lash it with some twine. The Starrett 85 wing dividers with a pencil and inside caliper leg are probably the preferred tool for this task (but they are expensive). A drafting compass with a bent leg (see *Drafting compass*) can also be used.

The board is put up against the surface it is to be fitted to (the separation distance doesn't matter as long as the board won't move while scribing). Then the hermaphrodite calipers are used to mark the surface's profile onto the board. Hold the calipers in a consistent orientation while marking.



A quick technique uses a pencil and washer:



This is a low pass filter -- the high-frequency variations in the wall that are smaller than about the washer's radius won't be seen in the scribed line.

Log scribing for building log houses uses a similar technique; look up the technique and tools on the web.

Find the center

A common shop task is to find the center of something. The most convenient tool for this is a drafting rule with a half scale, as you measure the object's width with the main scale, then mark this number on the half scale, indexed from the same edge. There's no chance of error unless you misread either of the scales. It has always bugged me that none of the tool companies have put such a scale on their machinist rules. These half scales are also useful for setting a compass or dividers to mark a circle given the diameter.

The most practical way with your rule or tape measure is to measure the width, divide by 2, and mark the half-width. The weak point is that an arithmetic mistake means you don't mark the correct point. A defense against such a mistake is to measure and mark the midpoint from both sides; if the two points don't coincide exactly, you made a mistake.

> For larger pieces that you measure with a tape measure, the equivalent method is to pull the tape across the width and tilt it so it reads an even number[4]. Then mark the midpoint at half the even number. For example, suppose the piece's width is 37 inches. Pull the tape measure across this width and tilt it so the side intersects the 38 inch mark on the tape. Mark the center at the 19 inch mark.

Another method is to tilt a rule to fit an odd number of divisions across the width, then mark the center at the middle division (this was called the "draftsman's method" in the days of manual drafting). There are centering rules to do a similar thing, but I feel they are a waste of money because they are essentially a one-trick pony.

In the shop, I use hermaphrodite calipers to find centers of both boards and bar stock for lathe work (the method works on regular polygon cross sections too). Set the calipers to about the required radius, then make four marks separated by about 90°. Then mark the center, as your brain is good at halving small distances. It doesn't matter if you set the calipers too long or too short. The same method works on a circle on a plane surface, but you'll use dividers instead. If you have to find the center of an arc, draw two chords and find the intersection of their perpendicular bisectors.

The same method is used to find the center of rectangular stock, but you only need to make two marks from parallel edges. This also works on tapered straight edges if you draw a line across the edges and measure with the calipers from the line's endpoints.

The combination square is a good tool for this centering task too. Measure the width, halve it, then set the blade to extend this amount from the head. Then mark from both edges like you do with hermaphrodite calipers. I usually allow 1/2 mm for the pencil or pen point. Because you can quickly locate the halfway distance between the marks, it doesn't matter if the setting is a bit off.

Though I have a center head for my combination square which is excellent at doing such center finding on round stock, it's usually faster to grab the hermaphrodite calipers, as I don't have to remove the combination square's head and substitute the center head.

This center-marking method is also useful and fast with DEV calipers. Measure the width and set the calipers to half the width. Then scribe marks with the sharp jaw tip from both sides. The middle of the two marks indicates the center. I do this quite a bit because it's so fast, but hermaphrodite calipers are the preferred tool for this to avoid wear on the DEV caliper tips. Scribing from both sides catches a divide-by-two error. There are DEV calipers with a sliding jaw to clear obstructions or a fillet and that are sharpened carbide, but they're expensive.

Some folks make a center-finding tool with a stick with two dowels and a hole exactly between the dowels. When the dowels are pressed against a board, the hole's center marks the board's center. I've made a few of these over the decades and they work, but I usually toss them out, as they have limited range and don't work near a board's end.

On a rectangular board, you can use a straightedge to find the center by finding the intersection of the diagonals.

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4 You can convince yourself this is identical to the draftsman's method if you note the starting division on the tape is 0, meaning there are the even number plus one main divisions.

Center of a circle

If the circle is something like a chunk of bar stock, then the center head on a combination square or the hermaphrodite calipers method are the most practical.

If the circle is marked in plane, then a quick method is to use a rule to find two nearly perpendicular diameters; their intersection is the center. For a large circle, use the same technique with a chalkline.

If the circle is sized so that a carpenter's square can be used, there are a number of ways to use such a tool (you can look them up on the web).

If you only have an arc of a circle, then the most practical method is to draw two chords and find the intersection of their perpendicular bisectors, which will be the center of the circle. For small arcs, this method can have substantial uncertainty.

Also consider a trial and error method. I had to find the center of a stone arc in the transition between our hallway and our living room. The edge of this arc was rough stone and wasn't amenable to drawing two arcs. Since I had pulled up the carpet in the living room, I just drove a nail into the plywood floor that looked near where the center would be. I used a string to measure to the stone and the underlying framing. A couple of iterations let me find the center; it was accurate enough to let me lay out and cut the arc on the plywood I needed to make the step down into the living room.

Table saw tune-up

There are specialty tools sold for this task, but they are expensive unless you can justify the cost. My preferred tool for this task is a dial indicator on a surface gauge, but even this is expensive unless you'll use these tools elsewhere in the shop.

You can do a table saw alignment just fine with some calipers and a combination square. The combination square is used to set the blade perpendicular to the table and inside calipers are used to set the blade, slots, and fence parallel.

Here's a description of the things I would do with a new table saw. The basic goals are

1. The table's slots must be parallel.
2. The plane of the saw blade must be parallel to the long axis of the slots.
3. The fence must be parallel to the plane of the saw blade.

Consult the saw's manual for the details on how to safely perform these tasks.

The first check is to verify the slots are parallel. This is most easily done with some larger odd leg or inside calipers, gauging at a few points along the slots' length. If the slots are not parallel, there's not much you can do about it other than return it to the manufacturer (unless you want to have a local machine shop fix it, which will be expensive).

Once you know the slots are parallel, you then set the plane of the blade parallel to the slots. This is done with the calipers by marking a tooth on the blade, setting this tooth at the front-most position, then setting the calipers to the edge of the tooth to the slot edge distance. Rotate the marked tooth to the back of the table and check again. If the measurements are not the same, the table's mounting bolts are loosened and the table's position with respect to the blade is adjusted. This is continued until the two measurements are identical. This adjustment is faster with tools that use dial indicators, but you'll find you can do an excellent job with calipers if you adjust the two points to give the same feel.

Calipers are a good tool for this because you don't care what the dimension is, just that the two measurements are equal.

When the blade's plane is parallel to the slots, you set the fence parallel to the plane of the blade. Since the table mounting bolts will be tightened securely, you'll find over the long run that the only adjustment you'll typically need for a saw is to verify the fence is parallel to the blade. If you rip a piece of wood and you see smoke or burned sections on the cut edge, it's likely the fence is not parallel to the blade (or you're feeding too slow or need a splitter because the kerf is closing). Fortunately, it's easy to correct with calipers -- and you won't need to buy a specialty tool for this task.

My favorite tool for this fence-to-saw-blade-tooth dimension check is some old Athol 8 inch inside spring bow calipers (the inside version of G in Figure 1). These Athol calipers have a finer feel than any other calipers I have.

Another technique for setting the fence parallel to a slot is to put a straightedge in the slot and bring the fence up to the straightedge, looking for non-parallelism. I don't like this method as much because it's possible that a small chunk of something can throw the measurement off. With the calipers, it only takes a minute or two to ensure the fence to blade distance is consistent.

A third technique is to use a combination square to gauge the distance from a slot to a tooth. This can be a good first step, but it is not as sensitive as using calipers because you can adjust with calipers to get the identical feel front and back -- and this can mean misalignments under 0.001 inches. I can't do this level of work with the combination square blade.

http://eberhardt.bz/GME_Wood_Land/GME_Woodworking_Stuff/2_Tool_Tune_Ups/8_Tuneup_Tablesaw.pdf is a copy of a published article on table saw tuning you might want to refer to.

Blade vibration

If you have some facility with electronics, you might like to see if you can spot excessive vibration in the table saw's blade when it is running. To do this, you'll need a stroboscope. Instead of spending money on one, you can use a function generator to power a bright LED using e.g. a Darlington transistor or MOSFET. Do this when it's dark to see things more easily. Obviously, this needs to be done carefully to avoid an accident. You'll find you can measure the saw's arbor's RPM too. Small changes in frequency may let you spot unwanted vibrations of the blade, which might indicate the need for e.g. a blade stiffener. Old analog function generators like the HP 200 series vacuum tube units with the big dials are nice for this type of work.

Blade runout

Lee Valley Hardware used to sell a truing flange for saw blades [*lvh*]. This is a disk of metal with a number of set screws on a circle; the set screws are adjusted to minimize the runout of the blade in a direction parallel to the rotation axis.

If you have a lathe, it's not difficult to make such a thing. I made mine from some 3/4 inch aluminum plate and used eight 10-32 set screws on a 3 inch bolt circle. It will take a bit of fiddling the first time you use this tool to find the optimum adjustments, but once you get a little experience, it's possible to adjust the TIR parallel to the rotation axis of the blade to less than 0.001 inches. After adjustment, my table saw made a crosscut that was noticeably smoother than before the adjustment (the adjustment reduced the longitudinal blade runout by nearly an order of magnitude).

Chipping a square hole

I needed a 1/2 inch square hole in a 1-1/8 inch square steel bar; this was for a torque wrench calibrator to fit standard 1/2 inch square drive torque wrenches. Using a scribe, I laid out the square on the stock, then drilled a centered 1/2 inch hole through the stock. Using a diamond-point cold chisel and some 4 inch inside toolmaker's calipers set to the square size of a commercial socket, I chipped out a suitable square hole. I used two chisels because they dulled fairly quickly (I touched them up on a grinding wheel). Final fitting was done with a pillar file.

This is a good exercise and illustrates that nearly anything can be built with cold chisels and files, although the process is slow and requires practice. The *Machinist's Bedside Reader* series [*lau*] described how some prisoners in a Japanese POW camp in World War 2 built their own lathe by using chipping and filing and, surprisingly, kept it hidden from the guards.

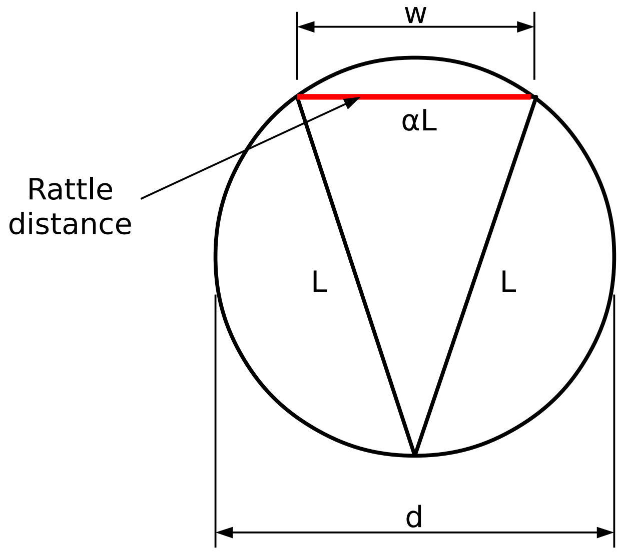
Rattle measurements

Rattle measurements of a bore are made by moving some inside calipers side-to-side in the bore and measuring this side-to-side movement with a rule (or you can use a rod of known length). If you know the setting of the calipers, this movement lets you compute the bore diameter. I'll call this first technique roll rattle (imagine you're in an airplane heading down the axis of the bore, just like the *Firefly* in Arthur C. Clarke's *Rendezvous With Rama*).

Another technique (I'll call it pitch rattle) is used to gauge for close fits, but the inside calipers are moved in a plane containing the hole's axis (i.e., in the airplane's pitch direction).

Roll rattle

Here's a sketch of the geometry of a roll rattle measurement ($\alpha \ll 1$); you're looking straight down the bore:



The diameter d of the circle in terms of the caliper setting L and the rattle distance $w = \alpha L$ is

$$d = \frac{L}{\sqrt{1 - \frac{\alpha^2}{4}}}$$

Since this technique is usually used when L is nearly equal to d, α is small and we use the approximation

$$d \approx L\left[1 + \frac{1}{8}\left(\frac{w}{L}\right)^2\right]$$

An important practical observation is that **we don't need to measure the rattle distance w to high precision** in order to calculate the diameter. Rattle measurements are thus made with an ordinary rule to perhaps 1 mm resolution.

> **Example**: a nominal 100 mm bore is measured using some inside calipers set to 99 mm with an uncertainty of 0.02 mm. If we measured the rattle distance at 5 mm with an uncertainty of 0.5 mm, the measured diameter is 100.125 mm with an uncertainty[5] of 0.032 mm.

A practical technique is to measure the bore with DEV calipers, then set the DEV calipers to a reading about 1% less. Set the inside calipers to this DEV caliper setting and make a rattle measurement of the bore and calculate the actual diameter. With a bit of practice, this can give you a more accurate measurement than using the DEV calipers directly. Or, use a micrometer to set the calipers.

5 Via linear uncertainty propagation.

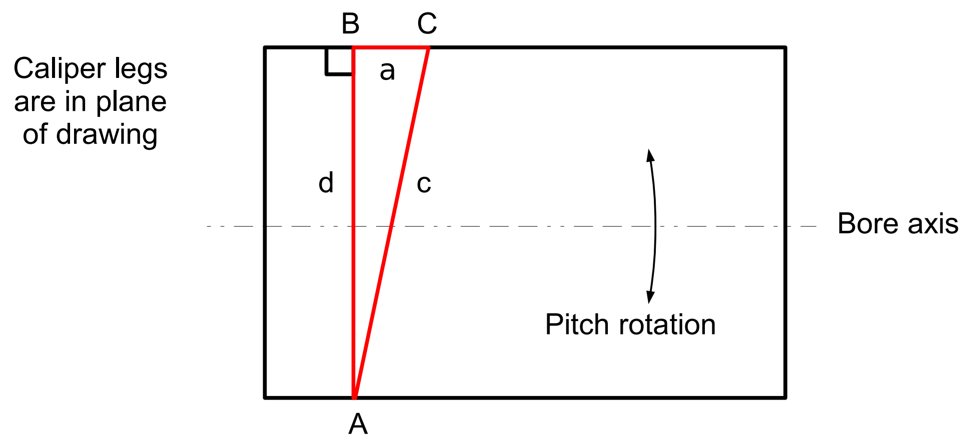
Practical rattle measurements are most easily made on larger bores where there is room to fit a small rule to measure the rattle distance *w*.

Pitch rattle measurements

Old time machinists were able to machine interference fits for a basic shaft diameter by boring the hole with old-style inside calipers and a rule. This may sound surprising to modern folks, but the method was routinely applied a century and more ago in railroad shops to machine axles and bores for railroad wheels, which were usually put on with a shrink fit.

If you've fooled around with inside calipers trying to measure a bore, you've noticed that the roll movement of the calipers yields a maximum setting that is the true bore, whereas rotating in the pitch direction yields a minimum setting that is the true bore. While these same two degrees of rotational freedom are present in outside caliper measurements, I find the internal measurements a little harder to do.

Here's a cross-section of a bore where the cutting plane contains the bore's axis and the plane of the calipers' legs:



You'd place the caliper's points at A and B (the pitch direction minimum), then rotate the calipers in the pitch direction while simultaneously unscrewing the calipers' adjustment nut, gently widening the distance between the legs. When the leg touches just at point C a calculated distance *a* from point B, then the calipers are set to the needed shaft diameter. Distance *c* will be slightly larger than diameter *d* and is approximately

$$a \approx \sqrt{2 d \epsilon}$$

where ϵ is the desired interference.

If you want to define the bore as basic, you'd transfer the inside caliper setting *c* to some outside calipers and machine the shaft to this dimension.

I've never used this method on a real project, as it is more appropriate for larger bores and I rarely need to bore interference fits for things more than perhaps 20 mm or so. But it would be a good technique for someone with a minimum set of tools.

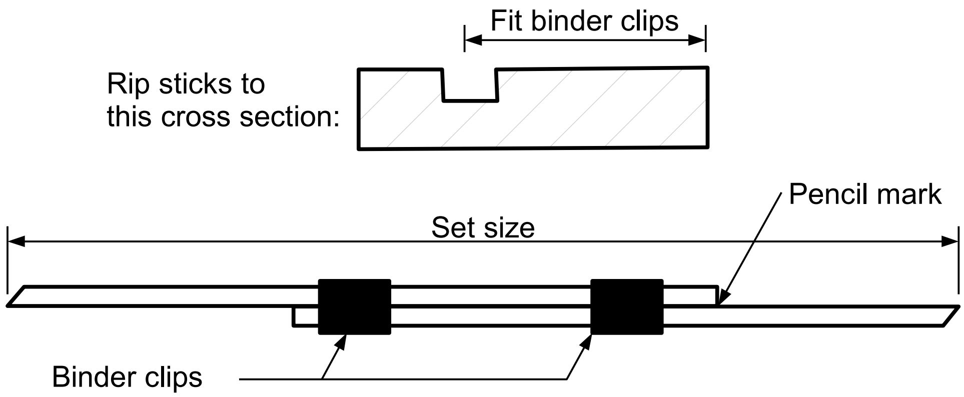
> **Example**: We have a 4 inch diameter ring to shrink fit onto a shaft. The hole is basic and we calculate (see here for details) that we need 6.5 mils of interference for this fit. We calculate that a is $\sqrt{2(4.5)0.0065} = 0.24$ inches (call it 1/4 inch). We set our inside calipers to the bore's diameter, then gently increase the setting until the calipers touch the bore at 1/4 inch away from where they first touched. The outside calipers are set to this dimension to machine the shaft.

Such work requires care and an experienced feel to do correctly -- and there are a number of places where one can make an error. The transferring of the inside calipers' setting to the outside calipers' setting is the one that has to be done most carefully. Modern tools like bore gauges and inside micrometers obviate these older methods.

The 1945 edition of [cs] discusses the method on page 721; it's on page 328 of the 1916 edition along with a discussion of the pitch rattle measurement on page 329.

Measuring sticks

For DIY tasks around the house, I find that 12 inch inside lock joint calipers are the tool of choice. They are most often used to gauge inside dimensions where I need to cut something to fit. They will measure up to around 20 inches or so. For larger dimensions, I use some measuring sticks made from scrap wood.



The wood is a 3 mm thick strip of oak. I cut a shallow 1 mm deep groove in each strip with my table saw. I then filed a sharp edge on one end of each stick.

These sticks are held together with office binder clips. The ends of the clips fall into the groove cut with the table saw, helping keep the sticks aligned. One clip is kept on the pair of sticks while the distance between the tips is adjusted to match the inside dimension being gauged. Once set, the other clip is installed. With two binder clips holding the sticks together, they are difficult to move unintentionally, meaning they hold their setting well. In a pinch, hold two wood scraps together with some rubber bands.

I either measure the tip distance with my tape measure[6] or use the sticks to mark the needed cut directly on the work.

I keep a few of these sticks in various lengths around the shop. The sticks get marked with the maximum measurable dimension. My wife once teased me that I have a shop full of expensive measuring tools, yet I do a lot of my work with these simple measuring sticks, which cost me next to nothing. You can't argue with their cost or utility.

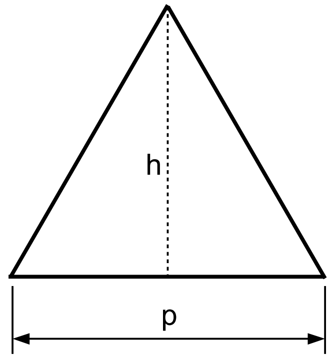
You can find a number of commercial offerings of such measuring sticks and it's not difficult to imagine more sophisticated designs with clamping screws and splines in slots to keep things aligned. However, the above design is so easy and quick to construct, you'll probably find that they are all you need.

Threading

Generations ago, routine thread turning in the shop was done with thread calipers and a rule because vee threads are often cut on the lathe. Duckbill thread calipers are useful for this because 1) they can gauge the major diameter of a thread and 2) measure to the root diameter of a thread, telling you when an external thread is cut to the correct depth.

After turning the major diameter to size, the thread is cut. The depth of cut for a 60° vee thread with pitch p is calculated from some simple geometry for equilateral triangles:

6 The cosine error is negligible.



The double depth *DD* of a vee thread is 2*h*. We have

$$\frac{p/2}{h} = \tan 30° = \frac{1}{\sqrt{3}} \qquad \text{or} \qquad DD = \sqrt{3}\,p$$

Given the major diameter *D* of the thread, you'd cut the thread until the thread calipers told you the root diameter of the thread was $D - \sqrt{3}\,p$. Since full external vee threads are rarely made because their sharp exterior can cause cuts, a small constant like 0.01 or 0.02 inches can be subtracted off both the major diameter and the double depth to eliminate these sharp edges.

Since the compound feed is typically set at 29° off the normal to the rotation axis, you'd multiply this by the reciprocal of the cosine of 29° to get how much you need to feed the compound in to cut the full thread. The cosine of 29° is nicely approximated by 7/8. You'd thus feed the compound in by

$$\frac{8}{7}\sqrt{3}\,p = 1.98\,p$$

This lets you cut most of the thread with the compound feed, then allows you to start checking near the end of cutting with the thread calipers. You can calculate this in your head by doubling the pitch *p*, then subtracting 1/100th of the resulting value. Example: For 16 threads per inch, the pitch is 0.0625; double this is 0.125, so subtract 0.125/100 or 0.00125 to get 0.124.

Today, industrial threading for interchangeable parts can involve more complicated tools and gauging, but a lot of routine one-off shop work can be done with vee threads, thread calipers, and a rule.

There are three types of thread calipers. The duck-bill style (Figure 3) allows you to measure major diameters over existing threads as well as measure root diameters because the tips are sharpened. Scissor-bill thread calipers can be made by filing the tips on some Yankee style outside calipers so that they can measure down into the root of a thread. Inside spring bow calipers can be filed to sharp points to let you measure the root diameter of inside threads. See [*leo:7*] for drawings of these three types of calipers.

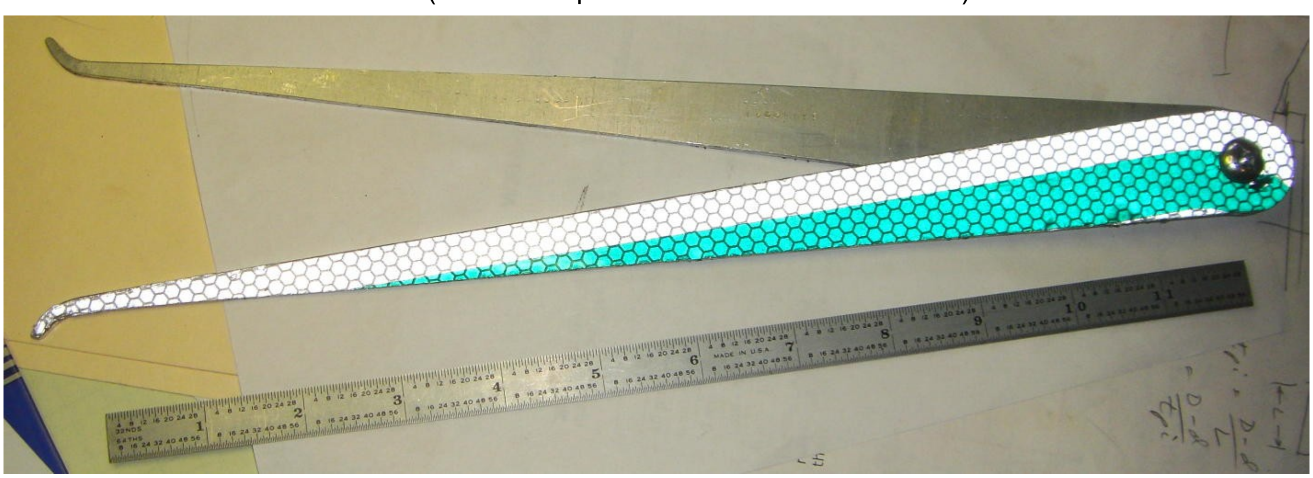
Figure 3

The 5-inch duck-bill thread calipers in Figure 3 were made by Stevens and probably date from the 1880's. They appear ho-hum in the picture, but they are the most beautifully machined calipers I have ever seen. My grandfather likely acquired these around 1910 when he became a machinist.

You can use outside thread calipers to find tap drills for machine and wood screws. Set them to the root diameter of the thread, then use them to find a drill a bit larger than the setting. A convenience is that no measurement is needed. For wood screws, I usually use my DEV calipers to measure the root diameter directly, but I need to use thread calipers on the small screws because the DEV caliper jaws are too wide to index on the thread's root.

Homemade firm joint calipers

The following picture shows some 12 inch inside firm joint calipers made from an old street sign that was 1/8" thick aluminum sheet (with some plastic reflective material on it):



A triangular leg pattern was laid out on the sheet and the material was cut on the band saw. A 1/4 inch hole was drilled in each leg at the large end and the legs were held together with a bolt and nut. The legs were clamped and filed to the same shape. The tips were bent around a suitable socket with a hammer and the legs were flipped. This ensures the tips meet, as they are mirror images of each other. A small polyethylene washer was inserted between the legs to reduce friction. A nylon locknut was used to adjust the joint friction.

While this bolted joint isn't as smooth as commercial calipers, no one can argue with the price. This is an elementary shop project that would be good for a parent to do with a child -- it will teach some useful shop skills and the result will be a useful tool.

Drafting compass

You may be able to find an old drafting compass (it must have a screw adjust) at a garage sale or a pawn shop for a few dollars. These can make a light-duty tool for the shop or toolbox. The tips and leads are 2 mm diameter. By making some bent tips, you can make some impromptu inside and outside calipers, along with hermaphrodite calipers.

A disadvantage of many such compasses are that their setting can be accidentally changed if you spring them or bump the adjustment screw. Some models have a locking feature to prevent this.

Chord angle gauge

For DIY tasks around the home, I use some 12 inch Starrett model 39 inside lock joint calipers. These calipers have two modifications to increase the calipers' versatility. I made a smaller lock nut so that the calipers can be used as an angle transfer gauge, just like a carpenter's bevel (the standard lock nut is a little too large to allow this use).

The second modification was two small concentric holes drilled in the legs a known distance from the calipers' pivot. These holes can then be set a known distance apart to set the calipers' legs to a known angle. An unknown angle can be measured by measuring the chord distance.

I took pains to drill the holes at exactly 10 inches from the calipers' pivot. This was done with some Starrett 251 trammels. The trammel points were set to 10 inches apart on a Starrett 122 vernier caliper, then a ball attachment was substituted for one of the legs. This let me scribe an arc at 10 inches from the pivot. The legs were set to lie on top of each other and clamped; then a 0.025 inch diameter hole was drilled through both legs. 5 mm diameter circles were scribed around the holes to make them easier to see.

Once made, the legs were set to a right angle with a precision square and the chord distance between the two holes was carefully measured. This gave the offset angle when the legs are coincident, as the legs are tapered. The formula determining the leg's angular separation is

$$\theta = 2\sin^{-1}\frac{a}{2r} - \theta_0$$

where a is the measured distance in inches between the holes, r is 10 inches, and θ_0 is 4.66°.

Since the distance a will be measured with a rule, the best resolution will be about 0.01 inches. If the distance a is 10 inches, then the angle is 55.34°. If the distance a is 10.01 inches, then the angle is 55.41°, for a change of 0.07°. This means the tool gives you a practical angle resolution of around 0.1°, which is about the same as a machinist's vernier protractor (which usually resolves to 5 minutes of arc).

By experimenting with the formula and its sensitivity, you'll find this is a practical angle measuring tool for angles up to roughly 120°.

Trammels

While trammels aren't calipers, they are tools that do tasks similar to calipers and usually are made to handle larger scribing, marking, and measuring tasks.

A tram is a single tool that holds a point, calipering jaw, or pencil and clamps to a beam. Two trams and a beam are used to make trammels. The General 523 trammels can be found for around $25 on the web (caution: some vendors charge a lot more) and appear to be a cast aluminum knock-off of the Starrett 59 trammels (which retail for around $85). These trams will clamp to a board from ¾ to 1½ inch thick and let you scribe arcs of nearly arbitrary radii. The points are ground eccentrically so that you can rotate them in the holder for a fine adjustment.

There are optional calipering legs and long points that make the Starrett 59 trammels more versatile.

The calipering legs have a fine adjust knob, letting you set the trams close to what you want to measure, then dial it in exactly. The advantage of these trammels is that you supply the beam, which means you can easily get a needed size. For example, you can clamp them to a 2x4 and be scribing large arcs quickly. Another advantage is that they take up little space in a toolbox. The Starrett 59F trammel is a complete set of legs and balls (the balls are used to scribe from circle centers). This set is expensive at over $300, but is quite versatile and stores compactly in a toolbox. It's suitable for nearly all work except fussy metalworking tasks.

Starrett made the model 89 Universal Divider and Beam Compass in the first half of the 20th century, which essentially is a small trammel with a bent leg and 4 inch beam [*leo:6*]. I have found them almost indispensable for scribing small circles in metalworking tasks, especially because the cone point allows scribing from the center of existing holes.

Starrett still makes the model 251 trammels for machine shop use. These are rigid trammels with a 5/16" steel beam (the beam has a flat so the trams won't rotate). Optional legs let you use them as calipers, along with a set of balls used to scribe circles using existing holes for the center. There's also a holder for 2 mm drafting leads, as you'd occasionally see a draftsman using them in the old days.

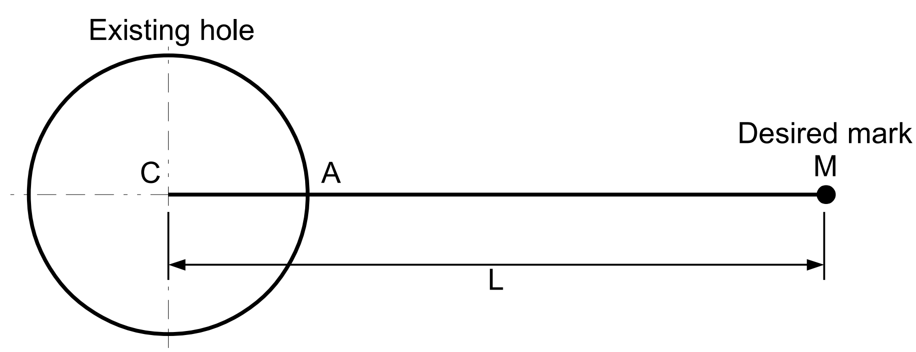
Drafting trammels have been made in many styles, but are light duty tools not really suited for shop work. They're fine for occasional use and you may be able to find some at a garage sale.

Many home shop machinists make their own trammels, either out of wood or metal. There are numerous designs on the web. A makeshift scribing tool can be made by driving a couple of nails through a board at the right distance, then using a hammer to bend them to the exact size needed.

Scribing from hole centers

When making or modifying something, you sometimes need to scribe a mark a known distance from the center of a hole. The challenge, of course, is that an existing hole no longer has material available for its center to be marked. I'll look at a few different ways of doing this in this section.

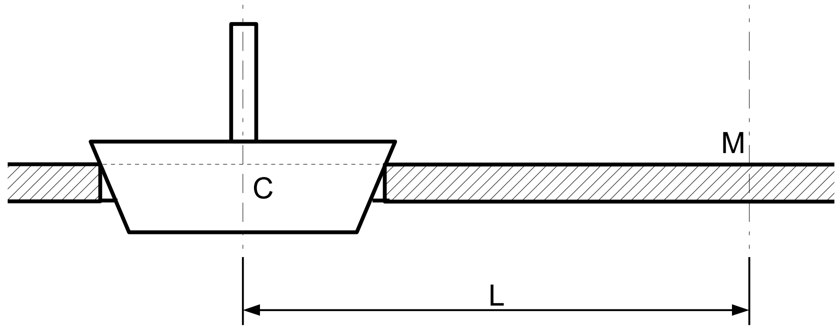
The task is to mark a location at point M that is a distance L from the hole center in a desired direction from the circle.



Hermaphrodite calipers: Draw a line from the approximate hole center such that the line contains the point you want to mark. Set the calipers to the distance AM by subtracting the hole radius r from the distance L. Hook the calipers' leg at the point A and mark M with the point.

Ball points: Starrett makes ball points that can be used with their 85 wing dividers, 59 trammels, and 251 machinist trammels. These are convenient because they will position the tool at the circle center. For precise work with trammels, set the marking point tip at the same distance from the beam that the ball's surface contacts the hole's diameter to avoid a cosine error. If you have this accessory, this is the fastest way of doing this task -- and, with care, it can be fairly accurate.

Homemade frustum: If you have a lathe, you can make a frustum attached to a shaft that does the same thing as the ball points described above (it does the same thing as a pipe center in the lathe's tailstock). Because things can tilt slightly, especially for larger holes, this isn't a terribly accurate method.



Temporary center: You fill the hole material with a temporary device such as a stick or an accurately-machined disk that is a light press fit into the hole. Locate a small prick mark at the center of the material and you can use dividers for marking as if the hole was not drilled yet. If the center mark is located accurately, this is probably the most accurate method.

Height gauge: Stand the surface with the hole vertically (e.g., against an angle plate on a surface plate) and set a height gauge to the bottom of the hole. Increase the height gauge's reading by the hole's radius and the height gauge's distance off the surface plate will be at the hole's center. Scribe the line AM. Then mark point M with a suitable method.

Surface gauge: Set the surface up the same as for a height gauge, then use a scriber tip on a surface gauge to pick up the bottom surface of the hole. Scribe this mark on the surface, then use dividers to mark a point that is the hole radius above the scribed line. This new point is at the height of the circle center. Rotate the plate 90° and repeat to locate the center with two scribed lines.

If you have the fabrication drawings for the part and know the location of the hole's center with respect to other features on the object, this information should be used to locate the point M.

Colored calipers

As I have a number of different calipers and dividers, I find it useful to paint them different colors. Some reasons for this are:

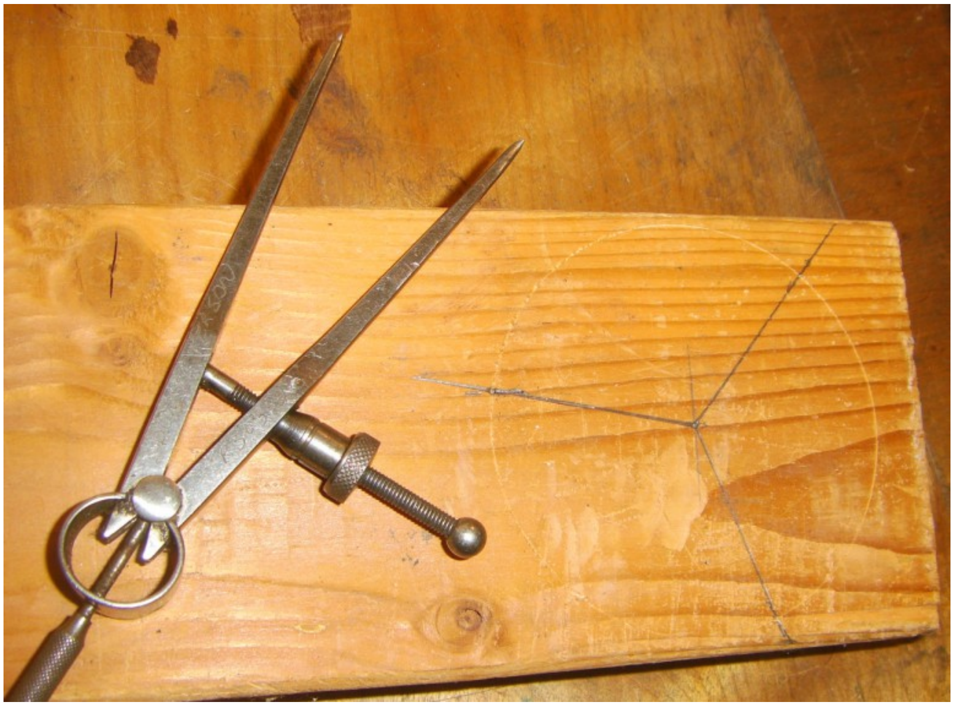
- ♦ It lets me keep a particular set of calipers together. For example, I have some 4 inch toolmaker's inside and outside calipers and dividers I keep at my lathe. They are painted yellow, so it's easy for me to know which set they came from and where they should be stored. An identical set of calipers at my toolbox are painted orange.
- ♦ At my lathe, I have three types of thread calipers. These are painted ruby red to indicate they are specialty calipers.
- ♦ When working on a project, it's not unusual to have multiple pairs of calipers or dividers for temporary distance standards. The color coding helps me identify a particular dimension. For example, the orange dividers might be the ones I'm using to lay out the circle center-to-center distances, while the red dividers are used to mark the screw holes.

3 flats on a drill shank

Cylindrical drill shanks can slip in a 3-jaw drill chuck, leading to galling damage to the shank that has to be filed or ground off. To avoid this, it's convenient to add three flats on the drill shank for the chuck to hold the drill better. A requirement is to make the flats symmetrical so the bit still rotates concentrically in the drill.

While a milling machine and indexing device are the tools of choice for this, few people have such things. Here's a way to do this with a file and a scrap piece of wood.

First, scribe a circle on the scrap and mark three lines separated by 120° by stepping off in two-radii steps around the circumference:



Drill a hole through the scrap that will be a snug fit to the shank to get the flats. I used a band saw to cut a kerf and installed a wood screw to clamp the wood to the shank, then aligned one of the pencil marks vertically in the vise:

I filed 15 strokes with a Nicholson 12 inch Magicut file held horizontally to make the following flat:

This was repeated for the other two locations. If you're unsure of your filing abilities, practice on a scrap piece of metal. Count your strokes and tilt the file towards the narrow-cut side until you can produce a constant-width flat.

Look up "hex collet block" on the web for more ideas.

Reusing PVC fittings

Glued PVC pipe fittings are convenient, but for fittings that are 1¼ inch NPT or larger, it may be expensive to buy replacement fittings. For example, a threaded union in 2 inch pipe is on the order of $10 and a filter head I use with my ditch pump costs around $80 to replace. If you have a lathe, it's not difficult to cut off the fitting and bore it out to near its original dimensions.

> I never use glued threaded unions any more; it's better if they have a thread on both ends. Then I just use a glue to thread adapter, which is cheaper and easily replaced.

Set the compound rest so that you bore a 2° included angle taper. Measure the pipe outside diameter with your external calipers and bore a hole in the fitting with this taper so that the pipe enters the cap about 0.2 inches and then sticks. This will make a nice glue joint, just like commercial PVC fittings. I've bored out that $80 filter head twice to reuse it over the last 30+ years.

Pipe penetration

In the spring of 2018, I needed to penetrate our 12" PVC irrigation pipe with a 3.5" ABS plastic pipe to provide one of our water association member's access to the ditch water. This needed to be done by digging down to the pipe, scribing the OD of the 3.5 inch pipe on the 12 inch pipe, cutting a hole in the 12" pipe, securing the 3.5" pipe to the 12" pipe, and building a form around the joint to encase the joint in concrete, sealing it and providing mechanical support.

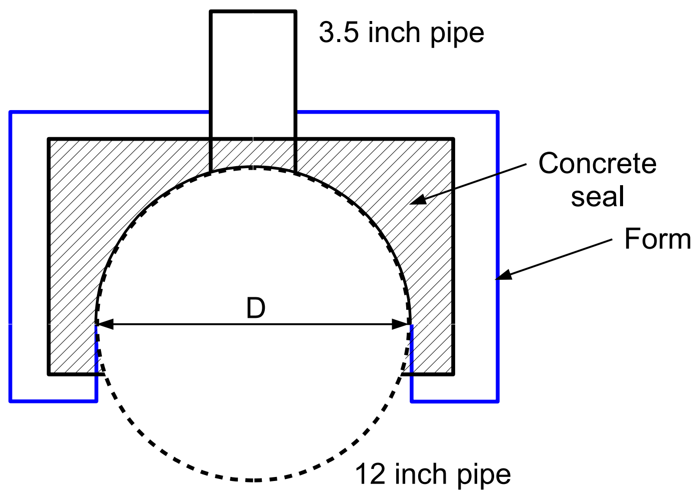
In the spring of 2017, we replaced a badly rusted and root-clogged section of this pipe. I had a 2 foot long section of this 12" pipe left over, so I used this for making a cutting template for marking the needed 3.5" hole and making the concrete form sections from scrap plywood. I wanted to do as much work as possible in the shop because there was still snow on the ground and we'd be doing the work in below freezing temperatures.

I used some 12" outside lock joint calipers to measure the pipe diameter. It was 12.34" maximum and 12.20" minimum. This let me make the concrete form to fit over the pipe by using 12.4" for the diameter D of the pipe (see diagram below). This guaranteed that the form would fit snugly over the pipe and not require any cutting to fit at the site.

I used a pencil and an inside caliper leg in the Starrett 85 wing dividers as hermaphrodite calipers to mark the end of the 3.5" pipe. When I positioned the 3.5" pipe vertically on the 12" pipe, I scribed the form of the outside diameter of the 12" pipe on the 3.5" pipe. I then used a bandsaw to trim to the scribed line (it only needs to be approximate). I similarly scribed a short piece of 3.5" pipe to act as a template to mark the hole that needs to be made in the 12" pipe. This required beveling the inside of the template pipe to get a close fit, which is why I didn't just use the cut piece.

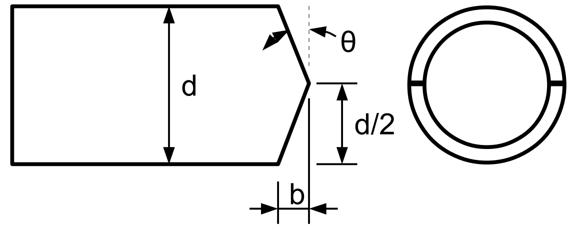
The next day, we dug down to the pipe and I marked around the template with a Sharpie marker. A Sawzall-style saw was used to cut out the hole and the 3.5" pipe fit perfectly, as we had to lightly pound it in.

I cut some additional pieces of 1/2" plywood for the sides and ripped some 1.25" square sticks from a 2x4 to act as corner posts; I screwed the form together with 1.25" Torx screws, four per corner. I just needed to place this form over the pipe, drive in two lengths of rebar into the ground for reinforcement, then fill the form with concrete. All the material was from the scrap pile, so cost was minimal.



If you have to do a lot of this type of work, it's worth your while to make templates for marking and cutting. For precision work (with e.g. machined tubing), you can lay out an accurate curve on paper, then wrap it around the pipe for cutting (it's not difficult to determine the parametric equations of the intersection curve). For average work, the pipes' dimensional tolerances don't warrant close work, so the template shapes can be determined empirically.

For practical plastic pipe joints where the pipes' axes intersect, you can cut the ends with a chopsaw or bandsaw in the following form:



This works pretty well when attaching a small pipe that is substantially smaller than the large pipe.

Put a square end on the smaller pipe and position it normally to the larger pipe. Using calipers or a rule, measure the distance the large diameter falls at the radius *d*/2 of the smaller pipe; this is dimension *b*.

The miter angle you'll set the chopsaw to is

$$\theta = \tan^{-1}\frac{2b}{d}$$

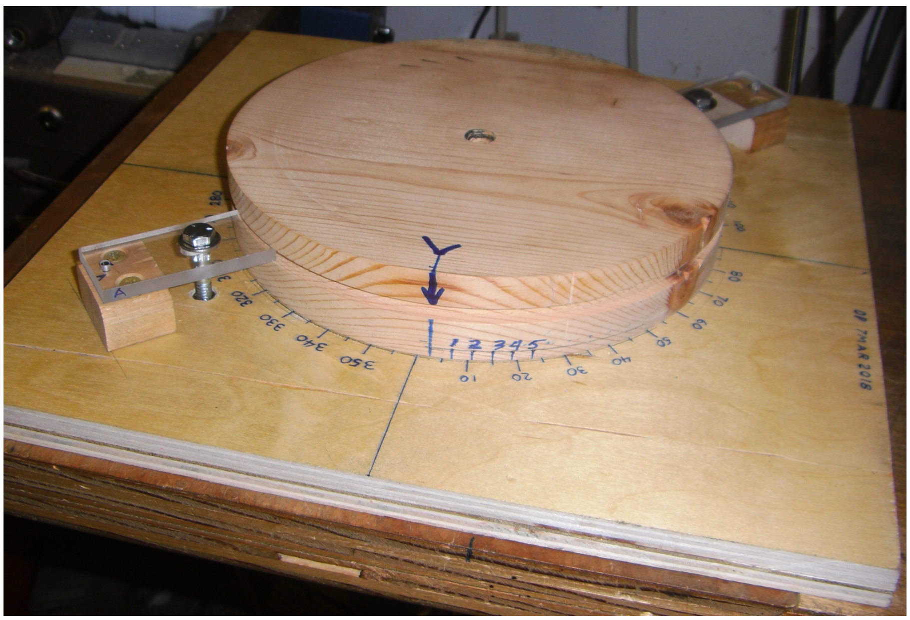
This works well for fusion-welding thin-wall metal pipe. For gluing PVC, you'll need to shape the cut to conform to the larger pipe's outside diameter. Also realize such a glued joint won't be mechanically strong, so you'll want to provide support for the pipes.

If the axes of the two pipes don't intersect, the principles are the same, but the cuts aren't symmetrical.

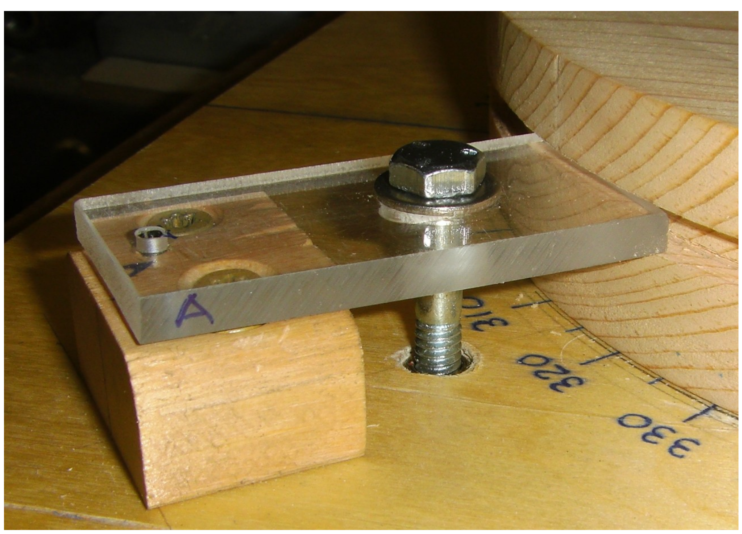
If the two pipes have similar diameters, this method won't work very well.

Degree scale

I made a rotary table from wood for general shop use. This was a chunk of 1.5 inch thick wood from old waterbed material turned to a disk 8.1 inch diameter. It rotates on a plywood base with a dowel pin (a chunk of 1/2 inch diameter cold rolled bar stock) that fits snugly in the disk's half inch center hole.

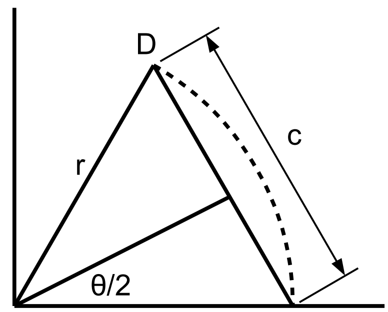


A groove around the disk's circumference allows it to be clamped to the base by two strap clamps.



The strap clamps were made from some scrap acrylic so that the degree graduations are readable through them.

The degree scale marked on the base plate allows me to angularly position the disk. I used dividers to lay the desired marks out by scribing a circle on the base, then locating degree marks by chords of this circle. Here's the relevant geometry for a degree mark at D:



The dividers are set to distance c to step off angles of θ around the circle. Given the radius of the circle *r*, the distance *c* is given by

$$c = 2r \sin \frac{\theta}{2}$$

The distance *c* is set on the dividers and they are stepped around the scribed circle's circumference. If the dividers don't wind up at the starting point, a small correction is made and the dividers are stepped off again.

Setting the dividers properly is a finicky task, as you'll want to check things repeatedly. Small grain irregularities can cause slight movements when putting down the divider points. Because of this, I drew a line intersecting the center point, then did the marking of each 180° section independently. The care was justified, as the 90° and 270° points coincided exactly when I started from the 0° and 180° positions.

Once the setting of the dividers is correct, the points are marked and the degree lines drawn. I chose to mark every 10° and writing the degree value using a fine point rollerball pen.

To mark the 10° lines, I drove a small 1/2 inch nail into the center of the circle and scribed two concentric circles to contain these marks. I put the pen point into the mark from the divider, butted my rule against the center nail, and marked the degree mark.

The 5° marks were made by setting another pair of dividers to the half-way point between two adjacent 10° marks. I set the approximate value, then made a small mark from either 10° point. Using a loupe, I adjusted to dividers to be equally between the marks. Then I marked the 5° point on either side of the two perpendicular Cartesian axes and stepped off the 5° points using the dividers set to the 10° chord. If the two 45° points coincided in the quadrant, then I had set the dividers correctly.

The final marking step was to put a vernier scale on the disk. This lets me read the angle set to 1° resolution. This was done with dividers by marking 5 divisions on the disk that took up four of the divisions on the base's scale (the base's scale was in 5° steps). I used a pencil to mark the disk's outside diameter on the base, then adjusted the dividers until 5 chord steps on the pencil mark was equal to 4 divisions. Then 5 marks were made with this setting on the disk's circumference; these were numbered from 0 to 5.

> The vernier scale is an interesting addition, as the graduations' spacing is enough that it's trivial to interpolate to 0.5° levels and a good guess can be made to about 0.25° levels. If this device was made with e.g. 3/4 inch aluminum plate, it would be possible to construct the vernier to read to 0.1° levels.

After finishing the marking, I sprayed the marks with an artist's fixative, then gave the plywood two coats of an acrylic spray.

Three Rosan inserts were equally-spaced on a 6 inch diameter circle on the top of the disk. These allow various tooling plates to be attached to the disk:

- ♦ A plate made from 3/4 inch plywood holds a cast aluminum vise for drill press work.
- ♦ A plate from 3/4 inch aluminum has numerous tapped holes to help mount work (it's the same as a lathe's faceplate).

The base plate for this fixture is about the same as the width of my drill press table, allowing for easy clamping with two C-clamps (this is why the base plate is a bit larger than you'd think it needs to be).

Vernier scale

The vernier scale was invented in 1631 by Vernier, a French mathematician. It is a method of getting another significant figure from a measurement scale. Suppose you have a scale with n equally-spaced divisions on it and these divisions are separated by a distance d.

The key idea is to separate the divisions on the vernier scale by a distance u such that

$$n\,u=(n-1)\,d$$

or

$$u=\left(1-\frac{1}{n}\right)d$$

In other word, the n divisions on the vernier scale covers n - 1 divisions on the main scale.

If the zero mark of the vernier scale is moved a distance u from the zero mark of the main scale, then the 1 mark on the vernier scale will line up with a division mark on the main scale. A movement of $2u$ causes the 2 mark on the vernier scale to line up with a division mark on the main scale, and so on.

If you move a distance $n\,u$, then the vernier scale has its last mark lining up with a division because $n\,u=(n-1)\,d$, an integer number of units of d.

If you're confused by this, a good exercise is to make an example of a vernier scale. All you need is a pair of dividers, a pencil, and two pieces of wood or some paper.

Note that vernier scales can be constructed for any values of n of 3 or larger. Common values for n are 10, 25, and 50.

For context, I'll describe how I made the vernier scale for the above rotary table. I positioned the disk on the base and used a pencil to mark the location of 4 main scale divisions on the disk (I used a double square to draw a pencil line on the disk). On the disk's circumference, I drew a pencil line parallel to the bottom of the disk (using the Starrett 85 wing dividers with an inside caliper leg and pencil) and set the dividers to step off 5 divisions between the zero mark and the pencil mark of 4 main scale divisions. I used a square to mark the divisions through these points made with the dividers. A quick check verified the 5 divisions on the disk matched the angular distance of 4 divisions on the base. After checking, I marked them with a blue Sharpie ultra-fine point marker for permanency and visibility.

Fitting a hammer handle

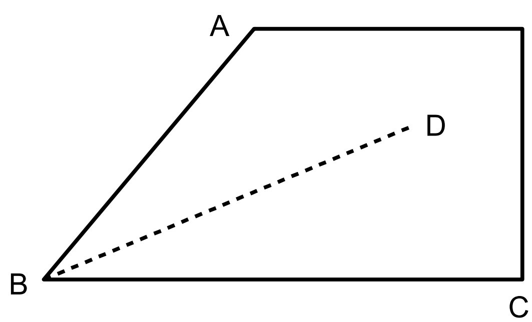
I bought a selection of used hammers for a good price. One of the cross-pein hammers was obviously made by a blacksmith from 1 inch square high-carbon steel stock. It was beautifully made and instantly became a favorite because of its shape, size and mass. Unfortunately, it had a poorly-made handle (it looked like cheap Douglas fir that had been whittled by someone) and the head unexpectedly fell off onto my son's living room floor while we were working on his stairs.

I had a broken handle from a larger 3 pound hammer, so I decided to retrofit it to this blacksmith's hammer. Inside calipers were used to gauge the needed size of the handle; it was about 1/2 inch wide and 3/4 inch long. I laid out cuts on the handle in pencil using my surface gauge, then cut the handle to the needed rectangular size on the bandsaw. 10 or 15 minutes of filing with a shoe rasp got the handle to fit the hammer head tightly. I used a 1 pound hammer to pound the new handle onto the head (I put a piece of wood on top of the hammer head being pounded), then drove in the wedge. It's such a nice, tight fit that this handle will never come off. The following picture shows two of the hammers I got in the group of hammers; the one with the retrofitted handle is the lower one:

The use of calipers allowed me to assess the taper of the hole in the head and orient the head on the handle properly. The wood expanded by the wedge into the taper is the only thing that holds the head onto the handle, so it's important to get right.

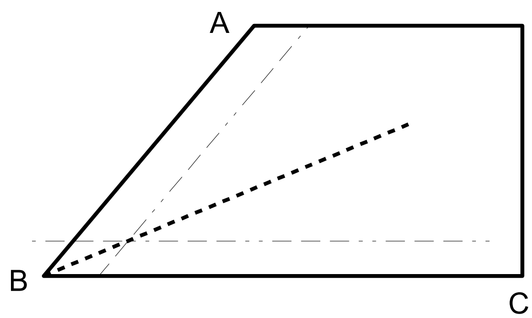
Bisect an angle

Everyone learns how to bisect an angle using compass or dividers in basic geometry. But suppose you need to bisect the angle ABC on a board to get the line BD:



The problem is caused by the board end at B -- you can't accurately place your compass or dividers' point at B.

One solution is to use hermaphrodite calipers to mark lines parallel to edges AB and BC, then perform the usual bisection with your compass/dividers:



This also guides you in an approximate but practical method: position the compass/dividers' point on the approximate bisector a small distance δ from point B. Then do the analogous thing at A and C to complete the construction.

Another solution is to use a shop angle gauge to measure the angle ABC. Divide this by 2 and mark the resulting angle using both sides AB and BC. Any errors will show up as a small angle, which you can bisect by eye.

Maintenance

Used calipers can be cleaned and lubricated to keep them operating well. Simple problems can often be fixed. The calipers' joint, tips, and smooth operation should be your first priorities. Calipers that are kept clean, lubricated, and not abused should last indefinitely.

All the calipers I have acquired used over the years have been dirty and in need of cleaning and lubrication. The easiest calipers to service are the spring bow types. Older firm and lock joint calipers virtually always need disassembly, cleaning, and lubrication.

This is consistent with the old saying that the cobbler's children are always barefoot. Most busy machinists don't take adequate care of these precision tools, though they certainly have the tools, equipment, and skills.

Disassembly

The threaded balls on lock joint and spring bow calipers can be removed using the non-serrated portion of the jaws of needlenose pliers.

Spring bow calipers: Remove the threaded ball and thumb nut. Some calipers can be disassembled by hand at this point; others need to have the bow expanded with needlenose pliers to get the spring off. Once the calipers are in pieces, they can be cleaned, lubricated, and reassembled. The threaded rod is held to the leg by a pin, but there's no real need to disassemble it. Larger calipers' bow springs can be hard to remove and install without a special tool.

Firm joint calipers: These usually have a hex nut or screw that is used to adjust joint tension. Remove this nut/screw and you should be able to take the calipers apart. Note that there's usually one or two thin plastic or fiber washers used for the joint's friction. Fits are quite close on commercial calipers to minimize play, so take things apart and reassemble carefully.

Lock joint calipers: I'm aware of only two designs: the CoastBilt style and Starrett's 1895 design. I've not worked on CoastBilt calipers, but the pictures I've seen suggest they should be easy to take apart. Starrett's design is covered in *Appendix: Starrett lock joint calipers*.

Cleaning

Quick clean/lube: You can remove gunk by using a carburetor spray without disassembling the calipers. A wire brush can help get the gunk out of the threads of the adjustment and the thumb nut. Follow with lubrication (I use Vaseline) and a hair dryer to melt the Vaseline so it wicks into joints and crevices. This can work well enough on spring bow calipers that you won't need to disassemble them. Try this method first, as it may be sufficient.

Old calipers may have a patina and scratches/dings from long use that could be valued by antique collectors. Consider this before cleaning some old calipers, particularly ones from the 1800's.

Many calipers I've purchased used have had rust on them. A light coating of rust is quickly removed with a worn wire wheel or steel wool. Be careful with large calipers and a wire wheel because if you feed it to the wheel in the wrong way, the calipers can be grabbed and bent in the blink of an eye (this is especially true for firm and lock joint calipers). Aggressive wire brushing can also damage a nicely ground finish.

If the rust has caused pitting, there's no easy way to fix this. Fortunately, pitting usually only affects the appearance, not the function. Badly rusted calipers may not function and should be disposed of, as they're not worth fixing.

> I purchased two pairs of Starrett lock joint calipers (12 inch inside and outside) and the seller had used electrolytic rust removal. It worked, but ruined the beautiful finish of the calipers. However, it didn't affect functionality or damage the precision-turned frustums necessary for smooth operation.

After cleaning, I apply Vaseline as a lubricant and rust protectant, so I have a thin film on my fingers which I wipe over the surface of the calipers. This does a good job of rust protection, is nearly cost-free, and is easy to renew periodically.

For calipers that will get used outside, I spray them with an acrylic spray to protect them from rust. This can also be done by dissolving Plexiglas chips in acetone, then brushing this solution on.

Fixing

- Bent tips
  - Probably made from low carbon steel, so can be bent back to shape.
  - Grab in vise with brass soft-jaws.
  - Inside firm/lock joint calipers have tips bent out-of-plane so they will touch when closed.
- Shaping and sharpening the tips
  - Dividers: hold the leg wrapped in cardboard so you can turn it while grinding. Do final sharpening on a stone by hand.
  - Calipers (show picture of outside toolmaker's caliper tips to show ideal)
    - Inside calipers: close & turn/polish on lathe
  - To get a smooth feel, file to shape and polish with sandpaper.
  - Special tips can be filed as needed.
- Ball: I make replacement balls from aluminum, as they are easy to shape with a file on a lathe. Pick a tap drill to give a 50% thread or a bit larger, then just force it onto the threaded rod enough to jam into place. This won't hurt the steel threads, but lets you take it off and replace it later if needed. You can make a proper part from steel if you have a bottoming tap, but calipers' threads are almost always some oddball size.
- Pivot: straightforward lathe work; it will likely be hardened and tempered.
- Spring bow (don't bother to make -- buy replacement calipers)
- Spring bow adjustment nut: knurling wears off on old calipers. Not difficult to make a larger nut for finer adjustments, although you may have to make or buy a special tap.
  - Making a split nut is a more sophisticated proposition (see [*p1905*] for construction details).
- Starrett 85 wing dividers, 92 carpenter's dividers
  - Lock nuts:
    - It's common to be missing one of the lock nuts. They are an 8-32 thread.
    - I make the outside fine adjust nut and the wing clamp nut from 3/4 inch diameter stock and make them 1/4 inch thick and 0.4 inches thick, respectively. I feel Starrett's thumb nuts are too small and don't have an aggressive-enough knurl.
    - The inside fine adjust nut is made from 5/8 inch diameter stock and 0.2 inches thick.
    - I put a sharp knurl on the nuts to make them easier to turn.
  - A split die can be handy to clean out the threads, as they are often filthy and dinged up.
  - A fine adjust spring can be made from 0.036 inch diameter wire, 3/4 inch long, and with a 0.196 inch inside diameter. The pitch is 0.1 inches and there are nominally 7 or so turns.

Flatten the ends by bending and grinding.

- ♦ New divider points or accessories can be made from 5/16" diameter bar stock; you need to turn it to 0.295-0.300 inch diameter to fit the clamping rings.
- ♦ Make a new clamp ring (8-32 thread) with a 0.47 inch diameter hole and you can clamp a Sharpie fine point marker.

Appendix: Technical details

Abbe's principle

Abbe's principle is that a measuring scale should be coincident with the thing being measured. An example of a measuring tool that violates Abbe's principle is DEV calipers. If you press too hard on the tool, you'll spring the jaws (because they need clearance to slide) and you'll get an erroneous reading. This is easily demonstrated by measuring something of a known dimension. This is a common error made by beginning users of DEV calipers.

In contrast, a micrometer more nearly conforms to Abbe's principle and it's easier to get more precise measurements. Of course, you can also convince yourself that the micrometer can be made to not conform to Abbe's principle by screwing down the thimble hard enough to spring the micrometer's frame, causing an error.

Old-style outside caliper measurements nearly conform to Abbe's principle when used with a rule. You can calculate that cosine errors are negligible for measured dimensions on the order of 10 mm or more.

Old-style inside caliper measurements essentially conform to Abbe's principle when used with a rule if you can position your eyes to eliminate parallax errors and ensure one of the tips is aligned properly with the end of the rule.

Errors

It is humbling to realize how many errors can be made when trying to make a "simple" measurement. Let's list some of these errors and their causes:

- ♦ Cosine errors
- ♦ Parallax errors
- ♦ Accidentally changing caliper setting
- ♦ Springing the calipers or work (too much measuring force)
- ♦ Out of plane (another type of cosine error)
- ♦ Wrong number from scale
    - ♦ Off by one
    - ♦ Poor lighting
    - ♦ Bias
    - ♦ Didn't put on your glasses
    - ♦ Poor scale design or scale error
- ♦ Arithmetic error

A cosine error is typically a small error caused by a violation of Abbe's principle. For example, measure the width of a table top with a tape measure. Tilt the tape slightly off the normal to the sides you're measuring and you will see the measured reading increase. This increase is proportional to the reciprocal of the cosine of the angle of tilt.

Violation of Abbe's principle also leads to parallax error, caused by the caliper tip and scale not being coincident; if you move your head, the measured reading changes. The goal is to keep your eye on a perpendicular to the rule surface that passes through the caliper's tip.

I've learned that I can reduce arithmetic errors if I deal with measurements in integers. For many practical tasks around the home and shop, this can be done if you use mm for your distance units and try to design to integer values.

Here are some ideas for defenses against such errors.

- ♦ Don't convert to a dimension -- use a transfer measurement instead.
- ♦ Double check before cutting (measure twice, cut once).
- ♦ Remeasure in different units.
- ♦ Have someone check your measurements.
- ♦ Confirm with a different measuring tool or method.

You'll find you're a creature of habit and will often make the same error if you choose the same measurement method. Probably the best defense is to ask another person to make the measurement, but if another person isn't available, the most practical check is with a different measuring tool. In particular, for me, an off-by-one error is easy to make when I get distracted by trying to get the last few digits of the measurement and make a mistake on the first digit.

With my older eyes, it's easy to make a 1 cm or 1 inch error in cutting some work to length, especially in DIY projects that have poor lighting. I use my inside lock joint calipers as a "second opinion" in such cases by setting the calipers to the required length. After marking the cut, the overall length is verified with the calipers before making the cut. It's just as easy to use a piece of scrap and mark the needed length on the scrap (a type of story board), then use this mark to check the layout on the work before cutting.

Another defense against these types of errors is to make simple wooden "rules" from handy scrap. I make these with a pencil and tape measure so that they have relatively large distances between the graduations, such as 1 cm or 1 inch. This tool is used to verify the first significant figure of a measurement.

Appendix: Starrett lock joint calipers

An 1895 patent [*p1895*] by Starrett and Fay resulted in Starrett's lock joint caliper design, which has been in production since then. If you acquire a used pair of calipers using this type of joint, it is virtually certain they will need disassembly, cleaning, and lubrication. I have serviced perhaps 20 used pairs of calipers with this joint and every one of them had significant rust and lack of lubrication. They all worked well after service.

This section discusses how to service these calipers. These techniques cover the following Starrett caliper model numbers 42, 36, 37, 38, and 39. Transfer calipers (36 and 37) will have one more leg than the other models, but the construction and operation is similar to the other models.

The 1895 patent drawing shows the construction:

(No Model.)

L. S. STARRETT & C. P. FAY.

CALIPERS AND DIVIDERS.

No. 539,759. Patented May 21, 1895.

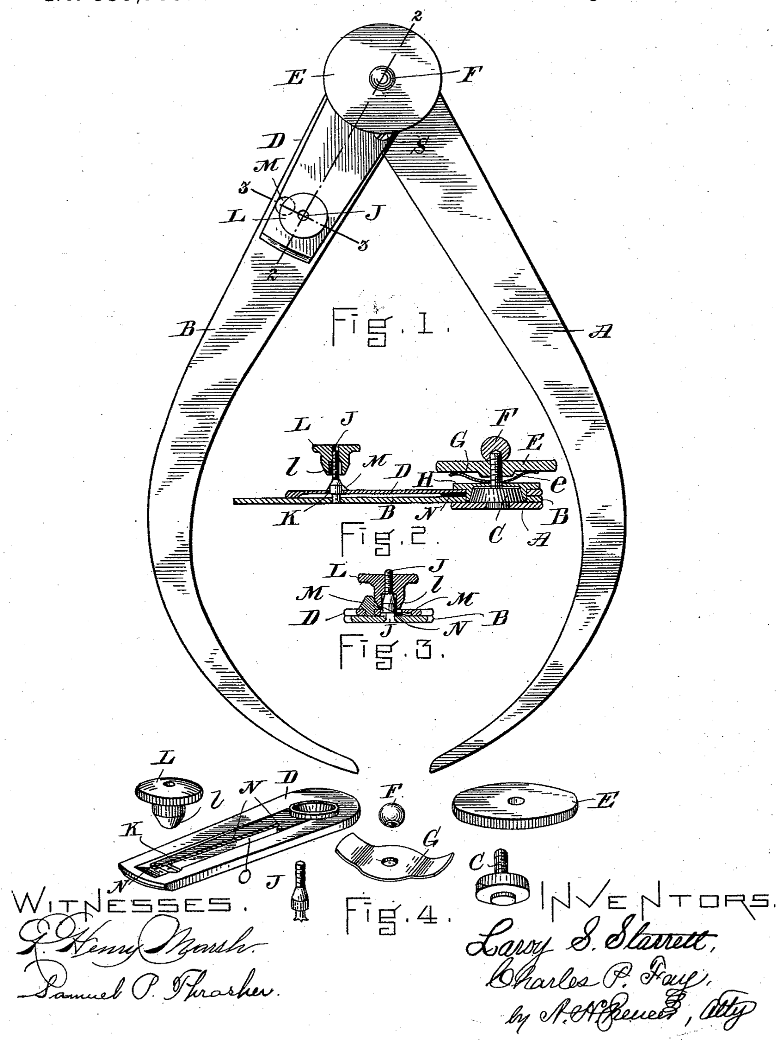


Figure 4

It's easy to test if these calipers need service. Tighten the lock nut E and loosen the fine adjust thumb screw L. Push the legs A and B together. If leg D does not move relative to leg B, then the calipers need service.

To disassemble:

- ♦ Apply a drop of penetrating oil to screw S to help ensure it can be removed (I've seen them rusted, but I've not had one be difficult to remove).
- ♦ Remove the ball F protecting the lock nut thread. I use the unserrated part of the jaws of needlenose pliers for this.
- ♦ Remove fine adjust thumb nut L.
- ♦ Remove lock nut E and spring e.
- ♦ Larger calipers may have a washer with flats on it fitting over a square portion of the threaded shaft on C (this washer is not shown in the patent drawing). Remove this washer.
- ♦ The legs may now be pulled apart. You may need a knife blade to gently separate them.
- ♦ Remove the small slotted screw S that threads into leg B and goes through the hole in short leg D.
- ♦ Separate the short fine adjust leg D from the caliper leg B. The inside surfaces of these parts are almost always without lubrication and are rusted. The fine adjust leaf spring N may press against the fine adjust stud J, making it hard to remove the fine adjust leg. You can unscrew leg D from the stud to avoid damaging the stud's threads (or you may be able to compress the spring with fine-tipped needlenose pliers).
- ♦ Clean and lubricate all parts (I like to use Vaseline), then reassemble. Note it's OK to lubricate the frustums, as they will still lock up when the lock nut E is tightened.

It's not uncommon to find the threaded studs bent; these can be judiciously bent back into position. If the threads are dinged, it may be challenging to find a suitable repair tool, as the threads can be oddball sizes. A thread file could be handy or a 3-cornered file may be used. The best tool is probably a split die.

To reassemble the fine adjust leg to the caliper leg, compress the leaf spring with needlenose pliers, then slip over the stud. Align the frustum piece with the hole in the leg and, if you're lucky, the parts will snap together. There may be a step at the bottom of the stud preventing the parts from snapping together; if so, the leaf spring can be pushed away with a suitable tool like an awl. Once the parts B and D are flush together, install the fine adjust nut L and screw it down so that the fine adjust leg D is centered in the caliper leg B. Then install the slotted screw S, being careful to not strip the threads. Tighten this screw so it is snug, then unscrew it 1/4 to 1/2 a turn, as the two legs need to move with respect to each other.

These calipers will rust easily in humid environments. You can protect them from this by coating the legs with e.g. an acrylic spray.

Inspect the tapered frustums that provide the joint's friction. If the joint doesn't operate smoothly, you might want to lap these tapered surfaces to get a smoother fit. This can be done with some suitable valve-grinding compound and relative movement. There must be adequate material to lap off; otherwise, the legs will rub against each other (then the calipers are probably not worth fixing).

I coat the under side of leg D heavily with Vaseline, making sure it's coating everything because this is the most common location for rusted parts. I also thoroughly cover the frustums and metal surrounding them, as rust can destroy the joint's smoothness. All other parts get a coating of Vaseline from my fingers, then I'll heat the calipers with a hair dryer or set it out in the sun to make sure the Vaseline wicks into all areas to protect against rust. I then mentally make a note to inspect and service all these calipers again in a few years.

A quickie maintenance tip is to run a bead of Vaseline along the short leg D and set the calipers out in the hot summer sun. The Vaseline will melt and will wick to between the legs, lubricating things.

In winter, use a hair dryer to warm the metal.

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