Calipers

someonesdad1@gmail.com

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♦ PD, sector, SR
♦ **Starrett caliper designs**: Add a section that shows the span of Starrett calipers from the 1938 catalog. Show the pictures, model numbers, sizes, and descriptions where necessary.
♦

Introduction

This document looks at old-style calipers and related tools. Today, the word "calipers" denotes dial, electronic, or vernier (DEV) calipers (also called slide calipers) used for length measurements. A few 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. You should be able to find the latest version at https://someonesdad1.github.io/hobbyutil/shop/Calipers.pdf.

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

" means inches.

[*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 (see plurale tantum).

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 inside 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 nut 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.

The latter half of the 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. The most important patent was probably Bullard's of 1886 (US335740), as it shows pretty much how most spring bow calipers are made.

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. *Appendix: Starrett lock joint calipers* shows how Starrett's lock joint works.

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. See *Wing dividers* for more details.

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, size ranges given are typical, not inclusive):

Type	Advantages	Disadvantages
Spring bow	♦ Simple construction, lightweight ♦ Resistant to accidental changes of size ♦ 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. ♦ 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. ♦ The fine adjust is rarely as good as spring bow 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. ♦ Clumsy for precise metalworking. ♦ Can be expensive with optional legs and centering balls.

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

An important feature of calipers is that they are more robust than DEV calipers. My dial calipers stay at my toolbox over the rubber mat; I know from experience that when they get dropped on my shop's concrete floor, they can be ruined. But I take old-style calipers anywhere I need to, as I don't worry about them getting wet, dirty, or dropped because they are easily cleaned and hard to damage.

Recommendations

If you have never used calipers before, consider starting with the $10 Harbor Freight set (94447) of 6 inch calipers (I've never used these, so I can't comment on how well they work). 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 for under $10 (these also hold a pencil to make a compass, but don't have a fine adjust).

I recommend getting at least one pair of hermaphrodite calipers, as you'll probably find you use them a lot.

New calipers from a company like Starrett are expensive. Since calipers have been manufactured for more than a century, there are thousands of used calipers for sale. 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. 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 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 $10-$20 range for brand-name calipers in good condition. If you want machinist-style calipers (and you do if you'll use them for shop work), beware that some sellers represent drafting tools as machinist calipers -- but drafting tools won't stand up under shop work.

The following group of calipers was purchased online for $20 delivered on 31 Oct 2018:

Figure 2

This means the calipers cost $2.50 each, a good price in my mind. The calipers at F are some

Yankee-style dividers converted to hermaphrodite calipers that measure from a shoulder.

The reason I bought this group of calipers was for the firm joint hermaphrodite calipers B, C, and D. The Lufkin design D with the hex nut at the lower left is a favorite, so now I have a back-up pair. C is an older Lufkin design. At B are some hardened and tempered calipers by Brown & Sharpe.

As shown in Figure 2, nearly all 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, dinged 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 type of work you do will determine the size and type of the calipers you use. Common sizes are 2, 3, 4, 5, 6, and 8 inches, with larger ones up to 36 inches or so. For general shop use, the 6 inch size is the most popular. I recommend getting the smallest calipers consistent with the sizes you typically work on.

The caliper style (spring bow, lock joint, or firm joint) depends on your needs and tastes. For careful metalworking tasks, I always use spring bow calipers because once set, they are difficult to knock out of adjustment. For casual shop work and larger tasks, I like firm joint and lock joint calipers (see *The versatile model 39* and *Frog leg calipers*).

If you use spring bow calipers or dividers a lot, you might prefer a split nut to let you set the calipers quickly. With a solid nut, you'll find yourself manually compressing the legs and adjusting the nut with the palm of your other hand for more speed.

For general fabrication work, consider the Starrett 85 wing dividers; they are particularly flexible with the optional inside and outside caliper legs, as they can make dividers, compass (the leg clamp holds a standard pencil), inside and outside calipers, odd leg calipers, and hermaphrodite calipers. 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. They are nearly unchanged from Starrett's 1889 patent (US411537). A new set is expensive ($360 in winter of 2018), but you can find them cheaper used (even new, I'd still consider them pretty cheap because you can use them for a lifetime). Trammels like the Starrett model 59 can do similar work and store more compactly in a toolbox.

In terms of the feel when calipering work to set spring bow calipers to size, I've not be able to discern differences between the different styles (Yankee, toolmaker's, or Fay). However, I've noticed pretty large differences in the finger torque required to adjust different spring bow calipers -- and if you use calipers a lot, this will become important (old calipers can have the knurling on the nuts worn off, which makes them harder to adjust). Fay style spring bow calipers will stand up to long tough duty in a machine shop -- I'm still using ones that my grandfather used more than a century ago.

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. A machinist will probably need the transfer abilities on a fairly regular basis, but these are expensive tools and not needed for average shop work (see *Transfer calipers* for measuring methods that avoid the need for outside transfer calipers).

My favorites

Over the years, I've had around 75 different calipers and dividers. I've given a number of them away to relatives, use a few of them a lot, sold off others, and use the others occasionally.

For metalworking tasks at the bench and toolbox, I use 4 inch toolmaker's style spring bow calipers and dividers the most. For inside metalworking measurements, especially on the lathe, I like 6 inch Fay calipers. For small tasks like fitting a hammer handle, 2 inch toolmaker's calipers are useful.

My favorite general-purpose calipers are the Starrett model 444 frog leg calipers because they are versatile and fold up to fit into a pocket, even the 8 inch size (I only have the 8 inch pair and would love to have the 6 inch size). The Starrett model 39 inside lock joint calipers get used a lot because they are also versatile. Both styles are no longer made, but the model 39 calipers are far easier to find than the frog leg models.

When building things from wood, I use some Starrett old-style model 42 hermaphrodite calipers to locate holes, as the point can make a mark in the wood that lets me start a drill or self-drilling screw. This saves a lot of time and reduces errors, especially for locating a hole from a feature. For general scribing and measuring from an edge in metalworking, I like 6 inch straight-leg firm joint hermaphrodite calipers, either Lufkin's design (C in Figure 1) or the Starrett 563. I often convert these to odd leg calipers using a leg made from some 1/8" welding rod (see Figure 4).

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 (e.g., Starrett model 82).
- Dancing leg calipers were popular in the 1800's and up to around World War 2. These were small firm joint calipers kept in a pocket that could be used to measure inside and outside dimensions. Most machinists made their own.
- 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.
- Bisecting dividers can find midpoints. You can buy dividers that divide up a given length into 10 parts.
- Golden mean dividers can divide a dimension into two dimensions whose ratio is the golden ratio. The idea extends to other ratios.
- "Double calipers" can mean different things:
  - Starrett (and others) made double calipers for machinists (see *Frog leg calipers*).
  - Woodturning double calipers are used to gauge the wall thickness while turning a bowl on a lathe.
  - Blacksmiths make double outside calipers that are used to gauge hot work. Starrett made a commercial version as model 173.
  - In the early 1900's, double calipers was also the term used for vernier calipers.

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 (look up US patent 672424 for how Starrett's firm joint is made).

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 1901 (their model 34 and 35 calipers were based on this patent).

If you're interested in details, here are a few US patents you can look up:

30009	229283	357487	672313	822397	1109467
37531	269754	402876	672424	887068	1194182
49337	319215	409828	689781	924073	1269336
75827	334764	411537	720773	988588	1562464
173802	335740	432578	732463	996591	1731954
179793	337531	539759	793850	1001219	

Split nuts

In 1905, Starrett patented a split nut design for spring bow calipers that has been used on many calipers (US793850):

The key idea is that notches 15 are driven by the tabs 14, yet the split nut halves 12 and 13 can pivot apart to allow the assembly to be moved freely longitudinally on the threaded rod 8. After assembly of parts 10, 12, and 13, the ridge 16 is bent down to capture the parts together.

The original Starrett patent calls these split nuts, but today Starrett calls them a "quick spring nut".

The versatile model 39

Starrett model 39 lock-joint inside calipers are versatile gauging tools. These fold up into a compact form that slips into a narrow pocket in my tool apron, yet allow me to make inside and restricted outside measurements:

Figure 3

Shown at A is the 4 inch size. These are small enough to slip into my pocket with a 4 inch rule when I go to the hardware store. I keep these and the 4 inch outside lock joint calipers at my desk or drafting table.

At my bench, I use the 6 inch size frequently (see Figure 5).

At B is the 12 inch size modified so that I can use it to measure angles (see *Chord angle gauge*), transfer angles like a carpenter's bevel (a smaller aluminum lock nut allows this), and use the leg edges as straightedges. The 12 inch size is most convenient for DIY tasks around the house.

At C is the 10 inch size which I keep in a tool cart for working on cars in the garage. These calipers are actually model 37 transfer calipers, shown by the fact that the leg locking nut on the back causes

them not to lay flat.

At D is the 24 inch size, which are large and clumsy, but are quite useful on larger projects. For example, I used them to compare heights of various locations on my son's 1972 Nova so we could determine if the frame or body was out of alignment.

A common use for the 4 inch to 12 inch sizes is to measure across the flats of a nut or bolt to determine the size of wrench needed (I usually have to walk back to my shop to get the wrench, so it makes sense to ensure I get the right size by measurement).

For careful work, the fine adjustment of lock joint calipers never works as well as comparable spring bow calipers. This is offset by the speed of adjustment, range, and ability to measure both inside and outside diameters.

Details

Principles

I find it most useful to think of calipers as adjustable gaps or widths. They aren't really measuring tools, but rather comparison tools, enabling you to say things like "dimension 1 is greater than, less than, or equal to dimension 2".

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 (a consequence of Abbe's Principle). 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.

You'll read in many places that calipers should not be applied to moving work because the caliper tips can be drawn over the work and give an incorrect reading. In general, this is a good principle, but I consider it a guideline and recommend you do some experimentation to find out 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. I've had occasions when turning smaller diameter metal parts that I couldn't tell the difference between the gauged dimension when the part was rotating versus when it was stationary. If someone argues that gauging moving work will wear the calipers out, well -- they're your calipers, the wear will be small, and any long-term wear is quickly fixed with some simple welding.

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.

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.

Comparing sizes

Calipers are useful for comparing two dimensions. For example, if you have two shafts, you can quickly use some outside calipers to say whether the shaft diameters are equal or not and, if not, which one is smaller.

Calipers are often used in a decision context:

- I set some calipers to a needed dimension and search for some stock that is larger or smaller

than that dimension.

- Outside calipers can be used to gauge the thickness uniformity of material. Set them to the nominal size and slide them around to feel the thickness variations. They drag more where the material is thicker and you wobble them back and forth to visually see the gap for thinner material. It doesn't quantify the variations, but it's fast. Inside calipers can be used similarly to look for diameter variations or out-of-roundness of inside dimensions.

  The reason these old-style calipers are useful for gauging uniformity in this way is because they are slightly flexible. If you tried this same uniformity checking method with a micrometer, its rigidity would not allow it to be moved around the material as easily.

- I set some inside calipers to a bore diameter, transfer that measurement to some outside calipers, then turn a shaft to fit that bore. The converse of fitting a bore to a given shaft is also done. This work can be done only with calipers, but you'll speed things up quite a bit using micrometers, telescoping gauges, DEV calipers, etc. because you'll be able to accurately quantify how much material to remove.

- I set some inside calipers to a gap, then go to my shop and cut a board to this dimension. I'll often do this by setting the table saw's fence distance from the blade directly from the calipers, removing the need to convert the calipers' setting to a dimension. Here, the decision is where to sent the saw's fence. Similarly, the calipers can be used to file an inside dimension to a desired size to fit a mating piece.

- My son and I used a variety of calipers many times on his 1972 Chevy Nova project car. Some homemade 24 inch outside calipers measured the distance between the centerlines of the holes on the custom engine mounting blocks to ensure the engine would fit in the car. 24 inch Starrett model 39 inside lock-joint calipers were used to check chassis and body heights above the driveway to look for a bent frame or body. Some 8 and 10 inch model 39 calipers were used many times for checking hose diameters, wrench sizes, thicknesses, etc. Calipers A and G in Figure 2 were used to compare exhaust system components and decide that some shims were needed to get good fits. Some 2 inch inside toolmaker's calipers were used to file an aluminum plate's oblong hole to get a close fit to the transmission's shaft to adapt to the 1972 shifting linkage to the GM LS1 engine. Calipers G in Figure 1 let me get the size of the crankshaft pulley shaft (a ground surface the pulley is pressed onto) and bore a hole in a homemade tool that fit this shaft tightly for aligning the front main oil seal.

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 routinely 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. A tape measure is only used for crude work or estimates.

With my older eyes, if I'm working in inches, I'll use a scale with 0.1 inch divisions and interpolate to the nearest 0.01 inches. This is much easier for me than trying to read finer divisions and is adequate for most work. Though I can read calipers and a rule with a good light and a jeweler's loupe to better resolutions, I'll use DEV calipers or a micrometer if I need to do closer work.

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 reading errors.

For inside caliper measurements, DEV calipers are convenient for converting inside caliper settings to a dimension. The requirement is that you duplicate the feel of the two measurements. I use this method with 6 inch inside calipers on the lathe for boring tasks and can work routinely to about 0.002 or 0.003 inch levels.

For outside measurements, taper gauges such as the Starrett 269 can be used for quantifying dimensions up to 1 inch. With care and practice, you can measure outside dimensions to perhaps 0.002 inches or so. Duckbill thread calipers are the calipers of choice for this method.

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.

See here for some handy gauges you can make on a lathe.

You'll find through experimentation and calculation that practical measurements with calipers can ignore cosine errors for dimensions above roughly 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 two 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 between the cart's handle and the plywood. Knocking this piece of wood out lets me remove the table, as there are no other fasteners (the table is secured in place with two pins while sitting on its supports).

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 (for this to result in an accurate cut, the saw blade must be parallel to the fence). 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. It's always satisfying to do such tasks on the first try, even if you think you did it through experience. ☺

I needed to cut a piece of wood to support a pipe under our house. I had to make the measurement in the crawl space of our house, which is dark and makes it harder to read a scale. I set some inside Fay calipers to the needed dimension, then put them into the small backpack I used to keep my tools. I crawled out from under the house and went to my shop and used the calipers to set the distance between the fence and blade on my table saw. The needed piece was cut quickly with no conversion to a measurement and it fit perfectly when I went back under the house to brace the pipe. A key feature of the spring bow calipers for this task is that it is difficult for the chosen setting to be changed while the calipers were being carried in the backpack.

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 (the calipers on the left in Figure 5 are odd-leg calipers).

Starrett made the model 42 calipers shown at B in Figure 1 for many decades 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 (see Figure 4 below).

An advantage of 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.

Another 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 its 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).

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 flat leg design won't let you do this (and results in a cosine error), but calipers with the pin tip do this easily and quickly. I need this feature pretty often, which is why I prefer the pin tip style for layout work.

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. Personally, I wouldn't want these because I adjust the point a lot.

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 quit using layout dye decades ago when I figured out that a blue Sharpie is a good substitute.

I use Torx wood screws a lot with woodworking tasks, as they quickly and easily 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[1] 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 year or two 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.

> Years 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 poor quality 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 easily 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 can happen with marking gauges too). I use a sharp pencil

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1 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.

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 measuring from the top of a lathe's compound feed to the rotation axis of the lathe (the bent leg would be on the compound and you'd set the point to touch the sharp tip of a center in the spindle.

My favorite hermaphrodite calipers for metalworking are straight 6 inch firm joint calipers at C in Figure 1 (the calipers pictured were made by Lufkin). 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. The Starrett model 563 firm joint calipers are also excellent and they use a 1/8 inch diameter pin, which makes it a little easier to fabricate special pins from welding rod (Lufkin's calipers use a 0.075 inch diameter pin).

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

Figure 4

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 leave this leg in a pair of the Lufkin firm joint calipers because I use them often as odd leg calipers (see the calipers at the left side of Figure 5).

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.

Straight leg advantage: 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. This is why I prefer the straight-leg design to the bent leg design. A quick tap of a leg against some wood reduces the setting.

In the following, 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. I use this feature a lot in layout work.

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. Starrett's flat leg design lets you scribe close to a shoulder and I've needed this feature a few times.

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.

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 Lufkin firm joint hermaphrodite calipers C in Figure 1 (these are lightweight and easy to slip into a pocket). 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 (the board holds 5C collets for my lathe). 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 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 intersect at the center. I use this method because it's fast, since I don't have find my center head and put it on the combination square blade.

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 by clamping or screwing it to a bench or sawhorse. 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. It's especially good for transferring a dimension from the front of a workpiece to the back.

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

Figure 5

These are all 6 inch calipers. From the left, they 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 for general DIY stuff because of their versatility.
- 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 (but 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); note you're measuring from a shoulder. 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 ([*tmbr*] has some nice design drawings).

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.

Odd leg calipers

The Lufkin calipers on the left side in Figure 5 are set up as odd leg calipers by an auxiliary leg. These calipers are quite useful for gauging step heights. The pin leg design of the Lufkin calipers let you adjust how much the leg protrudes for special measurement needs.

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 dimensions, 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. In the old days, a diagonal scale was used to set dividers.

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.

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. Dividers are precision tools that should be handled carefully.

For metalworking, I prefer toolmaker's style spring bow dividers in the 4 and 6 inch sizes. For woodworking, Fay style dividers are handy because they are stiffer and can be pressed into the wood firmly to mark a point.

Malco sells a type of dividers that was patented in 1927 (US 1731954) that is still sold today and is popular with sheet metal workers. Unfortunately, modern versions don't include the nice fine adjust shown in the patent.

Drafting dividers

Drafting dividers aren't robust enough to stand up to hard duty in the shop like machinist's dividers. Yet they still are valuable tools. Geared dividers (see Figure 9) will get a lot of use when designing things as they are fast to pick dimensions off things (this type of dividers is also used by navigators). Spring bow drafting dividers are useful for laying things out on paper and they can be used to scribe things on soft metal like aluminum.

Weems & Plath sells geared dividers with red LEDs in the legs. These are used for navigation to allow working on a navigation chart without impacting your night vision.

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 a 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.

Proportional dividers

Proportional dividers are used to change a dimension by a desired proportion. A common use is to enlarge or reduce dimensions of objects. The basic principle is two sticks with points at each end joined at a pivot. The pivot placement determines the ratio of the separation of the end points *a* and *b* from similar triangles:

Figure 6

Since the interior vertical angles θ are equal, we have

$$\frac{a/2}{A} = \sin\frac{\theta}{2} = \frac{b/2}{B} \qquad \text{or} \qquad \rho = \frac{A}{B} = \frac{a}{b}$$

Typical usage is to set dimension *a* to something on an object or drawing, then use dimension *b* for the corresponding proportional dimension. If you need a special ratio *ρ* for a task, it's not difficult to construct some dividers; the ratio is controlled by placement of the pivot point.

There are two types of commercial proportional dividers, artist's and technical. Artist's dividers are inexpensive, made from wood or plastic, and contain fixed holes for fixed proportions (I won't discuss these further). Technical proportional dividers are constructed from metal and have a continuously-adjustable pivot. When the pivot is properly positioned to the desired ratio, the pivot is tightened in position and the dividers act as firm joint dividers.

There are two types of these technical proportional dividers: sliding pivot and geared pivot.

Sliding pivot: This type is the most common:

Figure 7

The knob is loosened and the pivot can be slid to a desired ratio. Most commonly the ratio is given on a LINES scale which contains marks to divide a line into an integer number of equal parts. Some also have a CIRCLES scale which let you divide the circumference of a circle into an equal number of parts. For precise use, you'll need to iteratively set the ratio desired by using a machinist's rule. This page shows a variety of these proportional dividers in a collection. For more details on proportional dividers, see here (from *The Guild Handbook of Scientific Illustration*, E. Hodges ed., 2nd ed., Wiley, 2003). Proportional dividers are made for navigators for time/distance/speed problems (manual). These are the same construction as regular proportional dividers except they are marked with divisions representing speed (some also have a conventional LINES scale).

Geared pivot: These have a pivot that can be adjusted to a desired position using a pinion gear that mates with a rack on one of the legs (see Figure 8 below). The gearing makes it easier to make small changes in the dividers' ratio. There are two types of geared pivot dividers: regular and decimal. The regular type has the usual LINES and CIRCLES scales; they may be subdivided more than the typical sliding pivot dividers for better settability. Decimal proportional dividers have a linear scale with a vernier that allows setting the dividers' ratio to within nearly 3 significant figures. K&E called this type of dividers "universal proportional dividers".

Geared proportional dividers are still being manufactured, such as the 10 inch Alvin model 458 proportional dividers, but these don't come with a vernier nor are they graduated for direct precision use.

For technical work, decimal proportional dividers are the tool of choice. The advantage of these dividers is that **you can set the ratio and be confident the setting is accurate without iteration**.

Figure 8

The dividers in Figure 8 are 10 inch K&E proportional dividers; they are similar to the model 440X dividers shown in a 1936 K&E catalog on page 113. It appears K&E made decimal proportional dividers from about 1900 to at least until the 1960's, as they were popular with technical folks.

With the ratio set to maximum (minimum scale reading), these dividers are firm joint dividers and can work with dimensions up to about 12 inches or a bit larger.

A pinion gear on the bottom knob meshes with the rack on the leg, allowing fine adjustment of the pivot. The pivot has a vernier to read the linear scale on the leg, which goes from 10 to 110, corresponding to integer settings of 100 to 1100. The dividers shown in the picture can be set to actual readings of 174 to 1017, giving 844 distinct ratio settings from 0.094 to 1.034. Note the scale does not read out the dividers' ratio directly because a ratio scale would be nonlinear. With a little care, you can set the vernier to the midpoint between one vernier step, effectively doubling the number of settings, but this doesn't result in any practical increase in the resolution of the dividers.

The formula for setting a specific ratio ρ on the divider's scale is

$$2000\,\frac{\rho}{1+\rho} \tag{1}$$

This is shown from Figure 6 above by noting that the pivot's distance from the left end in terms of the overall length of the dividers' leg is A/(A + B) and dividing through by B. The factor of 1000 is used to convert the scale reading using the vernier to an integer and the remaining factor of 2 is because the overall scale length is exactly half the length of the dividers. Using the square root of ρ for the ratio gives you the proportion of a line length to a square with an area equal to the line's length and the cube root of ρ gives the volume of a solid proportional to the line length. Since *ρ* is a function of *A* and *B*, you can see that the scale for *ρ* can't be linear by differentiating by either *A* or *B*, as neither derivative will be a constant.

The formula (1) is easy to remember, which means you may be able to calculate the needed setting

in your head. For a 1/8 ratio, the needed setting is

$$2000\,\frac{1/8}{1+1/8} = 2000\left(\frac{1}{9}\right) = 222$$

which you can do in your head if you know the basic reciprocals of integers (they are worth memorizing).

To divide a circle's circumference into *n* equal parts, use $\rho = 2\sin(\pi/n)$ in formula (1) (calculate the sine in units of radians). This is the ratio of the chord length to the circle's radius. When *n* is less than 6, subtract the setting from 2000. As an example, I marked 9 equally spaced points around a circle with radius 105.4 mm. I set the dividers' setting to 812 and stepped off the points. The cumulative error (last point not coinciding with the first point) was less than 0.1 mm, which is impressive if you've ever done this with regular dividers where iteration for the correct setting is virtually always needed.

Regular and decimal proportional dividers are used as follows: 1) superimpose the legs so that the pin on one leg is located in its matching hole in the other leg, 2) set the pivot to the desired ratio. With decimal dividers, you're ready to use them, but sliding pivot models will typically need some checking and small adjustments to get the ratio you desire.

These K&E dividers appeared to be in nearly unused condition when I got them. They are an elegant and precision engineering tool and it's not hard to see why they were so popular with technical workers. They date to the 1950's or later because they are marked as being made in West Germany. The person who sold them said his mother used them in the 1960's, so it's possible they were made in that decade.

Uses

Note: the following comments deal with decimal proportional dividers.

Do you need them? Unless you deal with proportions frequently, it's unlikely you need decimal proportional dividers. For occasional needs, you can work with proportions using a rule and calculator or slide rule, a sector, or a suitably-drawn triangle. Or, if you're willing to iterate to get desired ratios, inexpensive regular proportional dividers work fine. The benefit of high-quality decimal proportional dividers are that they are set to the exact ratio with no iterative checking.

Panel layout: I needed to construct a panel for an electrical control box that had six toggle switches and an LED. I wanted them to be 10 mm from each edge and equally spaced. The decimal proportional dividers were the perfect tool for laying the holes out on the aluminum panel, as I marked the two outside holes from the edges with hermaphrodite calipers, then set the dividers to 286 to give the desired 1/6 ratio. I set the large end of the dividers to the distance between the two end points and marked off the five interior points. It was simple, fast, and foolproof -- a quick check with drafting dividers showed no sensible errors. An advantage is that I got equal distances between each switch, even if there was some layout error for the edge distances. This task of course can be done with regular dividers, but you'll almost always need one or two iteration checks to demonstrate you've got the correct setting. The proportional dividers did this task in one pass with no muss or fuss.

Unit conversions: A km is 0.621 of a mile. Formula (1) gives 766 for the dividers' setting. Using any handy linear scale, set miles on the long points, flip the dividers over, and read the equivalent number of km on the short points on the scale. An analogous use is with a map that has a scale in one unit, but you'd like to read distances in a different unit. Setting the proportion properly lets you read out the converted units directly from the map's scale, which can reduce conversion errors compared to e.g. using a calculator and making a typo.

Scaling a drawing: A practical use of proportional dividers is to generate a set of dimensions from a drawing that is drawn to scale, but has few or no dimensions on it. For example, here's a depth gauge from Colvin & Stanley's *Toolmaker's Kinks*, page 46, Hill Publishing, 1908:

It's made from riveted sheet metal and the adjustable slider has the nice feature of showing you how much material is left to remove in a slot or hole. Since no dimensions are given, you're free to pick one dimension and scale the remaining dimensions (this assumes the drawing is to scale). For example, suppose we had this drawing printed out on a piece of paper and we wanted the dimension X to be 75 mm. If on-paper dimension was 122 mm, then I would need to set the proportional dividers to a ratio of 0.615. After this was done (the setting was 762), I set the large end of the dividers to a particular feature on the print and used the other end of the dividers to read the scaled dimension from a machinist's rule. It's simple, fast, and difficult to make an error.

One practical way to do this is to use a copy machine to scale the printed version so that the X dimension measures life-size. Then you can scale the drawing directly.

The "modern" way to do this is with a drafting scale and a calculator. You use the scale to measure a particular feature on the print (or use dividers to pick off a dimension), type this measurement into the calculator, and multiply it by the scaling factor. This works well, but it's more error-prone: you might misread the drafting scale or make a typographical error on the calculator. After you've had shop experience where you've made such mistakes and wasted time fabricating something only to find out later you made a subtle error, you'll appreciate the error-reduction abilities the proportional dividers can provide.

Golden ratio: You can set proportional dividers to the ratio $1/\varphi = \varphi - 1 = 0.618$ to get the golden ratio φ. For decimal proportional dividers, the setting is 764 from formula (1). Then the two sets of divider points have the golden ratio. There are specialty dividers sold (or you can make some) that will generate this golden ratio in a slightly different fashion and Lee Valley sells golden ratio rules. If you need such a thing and don't have proportional dividers, one solution might be to make some dividers with the golden ratio per Figure 6. If you want a golden ratio rule, you could make a custom scale on a stick of wood, as described in the next section.

Make a custom scale: Proportional dividers can be a time-saver if you have to scale dimensions from photographs or a drawing. Of course, you have to know the scale ratio to get accurate numbers. This has to be measured, with the best method by including a length standard in one of the photographs (sometimes, one has to assume a standard length). When dealing with microscope

photographs, it's easy to trust the magnification factors engraved on the lenses, but experience will teach you to properly measure the real magnification by use of a known dimension.

For scaling dimensions with proportional dividers, it can be efficient to have a number of different drafting rules with different scales. Try to set the proportional dividers' ratio appropriately to a number between 0.5 and 1, which gives mid-range practical accuracy. For example, a triangular[2] inch-based engineer's rule has the scales 10, 20, 30, 40, 50, and 60. These can be used for ratios of 1:1, 1:2, 1:3, 1:4, 1:5, 1:6 and their reciprocals, along with the corresponding scales that are multiplied by a power of 10. A metric architect's rule (Alvin 740 PM) has scales of 1:100, 1:125, 1:20, 1:25, 1:50, and 1:75. By adjusting the proportional dividers to a suitable ratio, one of these scales can be used to read out dimensions from a photo and, with a little care, mistakes can be avoided.

Scales for this type of work can be found on the last two pages of this document. These can be used as-is, but if you want them to be accurately scaled, you'll have to adjust the print scaling factor of your PDF client. Choose the scaling factor judiciously and you can have a suitable scale that can work directly with the proportional dividers. I suggest cutting out the needed scale to avoid using the wrong one.

If you have a lot of scaling to do at one ratio, the most error-free method is to construct a custom scale on wood or paper so that you can read the measurements directly or with regular dividers. This isn't an onerous task with proportional dividers to mark off the major divisions. To minimize construction work, make the scale an open scale with the minor divisions only at the end of the scale:

If you like to work in both decimal inches and fractional inches, you can put decimal minor divisions on one end and fractional minor divisions on the other end. If you do this, you'll probably also want to number the major divisions from both ends like is done on some drafting rules.

To make a custom scale quickly on a piece of paper, use the proportional dividers to make small holes for the major divisions and use a sharp hard pencil lead to make the marks. Use spring-bow drafting dividers to mark the minor divisions. For close work, make sure the scale printed on paper is at room temperature and constant humidity. For more stability, spray with a transparent acrylic coating or an artist's fixative. For a wooden rule, coat it with e.g. a polyurethane coating to minimize changes due to humidity changes.

An advantage of constructing a single scale is you won't accidentally make an error use a similar scale on a drafting rule, something that happens more than we'd like to admit.

A related scale type is the diagonal scale, which used to be common on carpenter's squares for setting dividers to the nearest 0.01 inch:

2 A tip with a triangular scale is to use a binder clip to keep it oriented properly.

This is an open scale with auxiliary slanted lines at one end to help you get another significant figure. In the diagram, the reading's AB most significant figure is 2; the next significant figure is 3. The angled line's intersection at A with the horizontal line gives you the third significant figure of 7. Thus, the reading is 2.37. Using dividers, you'd set one end on the 2 and slide them up and down until the other point crosses one of the angled lines. A diagonal scale can be constructed with a length standard, dividers, straightedge, and scribe. These were in use before equipment to make vernier scales became common. They were also called transversals.

One you've made a scale, the most useful tool for picking off dimensions is a pair of geared dividers, common in drafting tool sets and also used by navigators (see Figure 9 below), as they are less cumbersome than proportional dividers or spring bow dividers and are easy to use with one hand (I use mine constantly at the drafting table when designing things).

Fixed-ratio work: If you need to scale a drawing but don't have proportional dividers, you can still do the job easily with regular dividers. If you don't want to make a custom scale (see above), you can draw a suitable triangle on graph paper. Lay out a triangle with an angle θ whose tangent is the desired ratio *ρ*:

Set your dividers to a dimension *x* on the drawing and put one point at point A on the triangle. Hold the other point at D, set the dividers to the distance *y* such that ED is perpendicular to AB. This gives the desired scaled value without measurement or converting to numbers. The lines on the graph paper help you get this perpendicular setting.

This is a fast and practical technique, but you'll want to use the right dividers for this task. Spring bow calipers (especially machinist's calipers) are slow and clumsy unless they have a spring nut (and they're still too slow if you have to do a lot of this type of work).

The geared dividers that come in drafting instrument sets are the best tool for this task because they are fast to set and can be used with one hand:

Figure 9

These are 5 inch Staedtler-Mars dividers from a drafting tools set. They are the perfect dividers for quickly picking off and transferring dimensions. The legs have sectors of gears on them that mesh together, ensuring they move together (note this divider design is distinct from geared proportional dividers). Some screw-adjust drafting compasses can be used as dividers, as they have fast-lead screws that let you adjust them by pulling on the legs (my old Schnellbow I bought in the 1970's works nicely for this). But nothing is as fast or convenient as the geared dividers design shown in Figure 9.

For larger dimensions, drafting trammels (a beam compass) are the tool of choice.

Proportions with a sector

Instead of using proportional dividers, you can do proportional work with plain dividers and a sector, something you can make in your shop. The principle is two identically-graduated strips that pivot about a common point P:

Figure 10

At A, a thin strip of material has a line through a pivot point P that has two distances a and b marked on it. Two of these strips are joined so they pivot at P as shown at B and separated by the angle θ. At B, if you use dividers to set a distance x on the joined strips, from similar triangles it follows that

$$\frac{y}{x} = \frac{b}{a} = \alpha$$

We want the strip to be thin so that we can ignore the cosine errors in setting the dividers and reading off the desired ratio (see the thickness analysis below).

A shop-made sector has identical graduated scales on each leg. Folding metal rules, such as the Lufkin 85 or the Rabone Stanley 60R are practical tools you can also use as a sector[3]. Here's a sector you might make yourself:

3 You might want to scribe centerlines on each rule leg to set your dividers from. You also need to count major divisions carefully so you're not fooled by the rule's graduations.

Figure 11

As an example of use, suppose you had a distance *T* set on your dividers and you wanted to set the dividers to 0.6 *T*. First set the distance *T* as the line AB on the 10 division mark on each scale by adjusting the sector's angle θ. Without changing the angle, set the dividers to the distance marked XY to have them set to 0.6 *T*. If instead you wanted to set your dividers to 5/8ths of a given setting, you'd set the distance AB on the 8 marks and take the distance XY off the 5 marks.

Note the numbered divisions you make can be any length you like. There's also no reason you have to number from 0 to 10, as 12, 16, or 20 might be convenient too -- it all depends on the ratios you think you'll use the most.

Measuring angles: This sector is also a good tool for measuring angles if you know the distance AC accurately and the lines are parallel to the edges. Set the edges to the unknown angle and measure the distance AB. The measured angle is then

$$\theta = 2\sin^{-1}\frac{\overline{AB}}{2\,\overline{AC}}$$

With care, you can measure angles to 0.1° levels or better. You can set the sector to a right angle with a square, then measure the distance AB and calculate the constant AC for your sector.

Some folding rules like the Rabone Stanley 60R include a scale (called the line of chords scale after the same scale used on sectors) letting you measure angles with dividers (I've seen pictures of folding rules from the early 1900's that had a table of chords stamped on them for measuring angles).

Effect of thickness: Let's examine the effect of a finite thickness t of the strips. The corrected distances X and Y using the Pythagorean theorem in Figure 10 are

$$X = \sqrt{x^2+t^2} \quad \text{and} \quad Y = \sqrt{y^2+t^2}$$

The ratio *Y*/*X* will be slightly different than *ρ*:

$$\left(\frac{Y}{X}\right)^2 = \frac{y^2+t^2}{x^2+t^2} = \frac{\rho^2+\beta^2}{1+\beta^2} \quad \text{where } \rho = \frac{y}{x} \text{ and } \beta = \frac{t}{x} \ll 1$$

Since *β* is much less than 1, we use the usual approximations to get

$$\left(\frac{Y}{X}\right)^2 \approx (\rho^2+\beta^2)(1-\beta^2) = \rho^2+\beta^2(1-\rho^2)$$

Thus, taking the square root, we get the approximation

$$\text{true ratio} = \frac{Y}{X} = \rho + \frac{1}{2}\beta^2\left(\frac{1}{\rho} - \rho\right)$$

Since ρ is less than 1, the finite thickness t results in the true ratio being larger than ρ by roughly $\beta^2/2$ -- and this correction will be small when β is small.

Suppose you made the distance x be 300 mm, y half of this, and t from some plastic strip 1 mm thick. Then ρ is 0.5 and β is 1/300. The true ratio will then be 0.5000083, which is undetectable. If t was 5 mm, the true ratio would be 0.5002 -- again, too small to be practically significant.

For smaller distances, the cosine error becomes important. Suppose x is 30 mm, y is 15 mm, and t is 5 mm. Then ρ is still 0.5 and β is 5/30 = 0.167. The true ratio is

$$0.5 + \frac{1}{2}\frac{1}{6^2}0.75 = 0.52$$

which is a 4% difference from the apparent ratio.

If you want to use your sector to a precision of 1 part in 1000, you'll want β to be roughly $\sqrt{0.001}$ (ignoring the value of ρ and being a little conservative). Then you could use the rule of thumb that the distance y in Figure 10 while using the sector must be larger than about 30 t.

Because of these cosine errors, the sectors from centuries ago were made with a hinge such that the two surfaces with graduations are at the same height, eliminating the cosine error. See the picture here for how these sectors were graduated so that the line went through the pivot (here's a more modern version). A shop-made sector like these could be made from wood by gluing or pinning in parts that would make a suitable metal hinge. You can see the riveted construction in this picture. Woodworkers sometimes make a sector from an old folding rule, but these aren't terribly practical, as the typical length of a section is 150 mm or so -- and practical work for DIY or woodworking tasks often needs dimensions on the order of 0.5 to 1 m. If you're still not convinced, ask yourself how many commercial sectors are on the market.

> One reason I like folding metal rules like the Lufkin 85 for this task is that they are under 1 mm thick, meaning the cosine errors will be small when used as a sector. They are 300 mm long, letting them fit into a small toolbox, yet letting you measure up to 600 mm dimensions. Also see *Chord angle gauge* for calipers you could make a sector from.

With careful work you can make an accurate sector, but you'd be wise to check its (and your) abilities before using it for real. Though I've made a number of sectors, I virtually never use them because it's easier to use a rule and calculator when I need a specific dimension -- and it's one more tool to keep in a crowded toolbox.

Proportions with a slide rule

Practical work like using proportions can be done to 3 significant figures or less, meaning a slide rule is a suitable tool. The benefit of a slide rule for proportion work is that you set the C and D scales to the proportion you're going to work with and the scales then display all the answers to the problems you can do. You can get answers faster than using a calculator.

> **Example**: You can use this slide rule emulator to do this problem (start with the side that has the A and B scales). Suppose I want to convert the dimensions on a photograph of a scale drawing to actual lengths in mm. A known feature of 68 mm is shown on the photo at 23 mm. Therefore, I need to use the ratio of 68/23 to multiply photo dimensions by to get actual dimensions. I decide to use the D scale for actual dimensions, so I move the slide so that 23 on the C scale is over 68 on the D scale.
>
> Now I can read off the answers to all proportion problems with this ratio.
>
> I measure a dimension of 14.2 mm on the photo. Opposite 14.2 on the C scale, I immediately read 42.0. It's fast and foolproof. I have to keep in mind that I'm basically multiplying by about 3 to proportionally scale things in case I need to place the decimal point.

> **A problem**: When I measure 40 mm on the photo and look at the 4 on the C scale, the answer is off the D scale. This illustrates a problem with straight slide rules: sometimes you have to move the slide to get the answer. To get the answer, put the cursor over the left 1 (called the index) of the C scale, then move the slide so the right 1 (index) of the C scale is under it. Then read 118.3 mm on the D scale under the 40 mm on the C scale.
>
> **A/B scales**: One fix for this problem is to do it on the A/B scales. You get extra range at the cost of less resolution. Put 23 on the left side of A over 68 on the left side of B. Under 4 on the left side of A, read 118 on B.
>
> **Folded CF/DF scales**[4]: Click on the button to show the other side of the slide rule and you'll see the CF and DF scales. On the CF scale, opposite the 4 (which we interpret as 40), you read a number slightly over 118 mm.
>
> **Circular slide rule**: These have the nice feature of never having off-scale answers. Concise circular slide rules are still being manufactured in Japan. You can find printable circular slide rules on the web to let you construct a functional tool for no cost. You can also program your own in PostScript if you're willing to spend some time learning the language.

Resolution: Let's figure out the approximate resolution of a pocket slide rule with an L = 125 mm scale length. A slide rule's D scale numbers' marks are equal to a distance of $y = L\log(x) = L(\ln 10)\ln x$ from the left index where x is the scale's number between 1 and 10. Differentiating and supposing we can only resolve setting differences of $dy = 0.25$ mm on the scales, we get

$$dx = \frac{x\,dy}{L\ln 10}$$

For a center scale reading of around 3, we get

$$dx = \frac{0.25(3)}{125(2.3)} = 0.0026$$

Thus, the logarithm of x could have been off by ±0.0026 or x is in the interval 3 ± 0.03. We conclude you can work to practical resolutions on the order of 1% with such a tool (you can do better with young eyes, a magnifier, or a longer slide rule).

Slide rule calculations have disadvantages:

- You have to put the correct numbers on the correct scale.
- You have to be careful to read the scale marks correctly.
- You only deal with significands, so you'll have to mentally figure the power of ten.

Most proportion work like scaling a drawing's dimensions doesn't need multiple powers of ten, so risk of an error is lower than e.g. doing scientific calculations.

You can do proportion calculations with some dividers and a slide rule scale; in particular, read the section on speed-time-distance problems with the x^3 scale, as this scale can handle significand proportional work with dividers without going off-scale.

Wing dividers

For general DIY tasks, wing dividers like the Starrett 85 models can be a good choice. Interestingly, these are nearly unchanged since the 1885 patent US411527. Here's a picture of my 85 wing dividers and the auxiliary legs; this is right out of the shipping box and the rust hasn't been removed (everything cleaned up nicely with a motorized wire brush):

4 These were first put on slide rules by K&E in the early 1900's.

The rule at the top is 6 inches long and these wing dividers are the 12 inch size. The auxiliary legs let you make inside, outside and hermaphrodite calipers. The sharp tips are ground eccentrically so that you can rotate them to make fine adjustments. The bottom outside caliper legs and pointed legs are actually options for the Starrett 59 trammels; note the fine adjustment knob.

A useful feature of these dividers is that the clamps will accept a standard pencil, so you can also use these dividers as a compass. The rods are about 0.300 inches in diameter. 6-sided standard pencils are 1/4 inch across the flats, making them $0.25\left(2/\sqrt{3}\right) = 0.289$ inches across the points.

Near the hinge, the knob on the side locks the approximate setting by clamping the wing rod. The outside knob on the bottom leg is a fine adjust. The inside knob is usually left in the position shown, but can be screwed up against the bottom leg to lock the setting so the legs cannot be moved.

An interesting leg design for wing dividers was given in the 1911 US Patent 1001219. Two of these legs would provide inside and outside calipers, dividers, and hermaphrodite calipers. I've never seen a commercial version.

I made a new leg clamp with a hole diameter suitable for clamping a Sharpie pen. This helps with layout tasks on things that don't mark well with a pencil. One day I may try to find or make some 9/32 inch outside diameter tubing that would let me make a felt pen from something like a Sharpie; this would be handy, as it could be clamped in the wing dividers like a pencil.

The knurl on the nuts for my Starrett 92 compass had been badly worn from use (this compass is a similar design to the model 85 wing dividers). It was a straightforward task to make new nuts from some 3/4" diameter aluminum bar stock. I gave them an aggressive knurl and the compass is now easier to operate. I also made them larger in diameter than the originals to make them easier to grab. They're not as attractive as Starrett's nuts, but they work better.

There are vendors who sell the Starrett 85 wing dividers with a two-vial bubble 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.

Transfer calipers

Starrett started selling 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 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 and speeds things up.

See US patent 720773 (1903) for a simpler idea for outside transfer calipers. US Patent 822397 (1906) shows a practical way to make outside transfer calipers from Fay style calipers:

The outside caliper modification makes sense, but I don't see how an inside measurement could be made using the transfer idea with the middle figure, at least for something like the depth of an o-ring groove. The modification for dividers might make sense to "remember" a smaller setting.

A busy machinist who works on a variety of tasks will probably find transfer calipers speed his work. 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 Starrett's transfer caliper design 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 jaw opening B is measured and the offset A 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. <u>This is wrong</u> unless you're certain both measurements are at the identical points on the legs (and they won't be, unless you e.g. attach tooling balls to the legs).

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 (they won't stand up to heavy-duty shop use). 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.

Thread calipers

A few 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 (see Figure 12 below) are useful for this because they can 1) gauge the major diameter of a thread and 2) measure to the root diameter of an external thread, telling you when the 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:

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

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

Given the major diameter *D* of the thread, you cut the thread until the thread calipers tell you the root diameter of the thread is $D - \sqrt{3}\,p$. 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; doubling this gives 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 (e.g., for National Form threads), such as thread wires or micrometers that can measure the pitch diameter of a thread. 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 (see [*leo:7*] for drawings of these three types of calipers):

- ♦ The **duck-bill** style (Figure 12) allows you to measure major diameters over existing threads as well as measure root diameters because the tips are sharpened. Starrett made Yankee-style model 80 thread calipers and Fay-style model 76, either with solid or split nuts. The duck-bill style is also handy for general-purpose gauging of outside dimensions. For outside dimensions up to 1 inch, the duckbill calipers' setting can be quickly estimated with Starrett 169 taper gauges to nearly 0.001 inch levels; these tools can be used in places where you wouldn't want to use a micrometer (e.g., dirty or wet locations).
- ♦ **Scissor-bill thread calipers** can be made by filing a taper on the tips on some Yankee style outside calipers so that they can measure down into the root of a thread. Starrett made the model 179 calipers in this style. They can gauge the root diameter of a thread with the plane of the calipers orthogonal to the thread axis, which can sometimes be more convenient than duck-bill calipers, which need to be oriented so that the plane of the calipers' legs contains the thread axis, meaning you'll have to pull the tailstock away from the work when working on the lathe.
- ♦ Inside spring bow calipers can be filed to sharp points to let you measure the root diameter of inside threads. Starrett made the model 184 calipers in this style.

Figure 12

The 5-inch duck-bill thread calipers in Figure 12 were made by Stevens. They appear ho-hum in the picture, but they are beautifully machined and precisely made. My grandfather probably 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.

Center gauges

If you cut threads on the lathe, you'll want a center gauge, sometimes called a fishtail gauge. In the old days, machinists often turned work on a lathe between centers and the 60° angles on this gauge are used to gauge the 60° angles on the lathe centers (they were turned in place to provide the best concentricity). The smaller 60° angle notches are used to help grind threading tools, then set these cutting tools orthogonally to the axis of the work's rotation. Auxiliary scales on inch gauges let you measure various threads per inch. The 20 scale is particularly useful to directly set small circle diameters in inches on your dividers.

Older Starrett model 391 center gauges had a thread double depth table that used the double depth formula $\sqrt{3}\,p$ where p is the thread pitch. Multiply this number by 8/7 to get the compound depth for cutting the thread when the compound is set to 29° (8/7 is a good approximation of the reciprocal of the cosine of 29°).

It's easy to tell the old-style gauge because the 10 threads per inch entry will be 0.173 inches, which is the square root of 3 divided by 10.

The newer Starrett 391 center gauges have a double depth table for national form threads; this is useful for finding tap drills.

I keep my center gauge attached to my lathe's tailstock with a magnet because that's where I virtually always use it.

Frog leg calipers

Starrett made the model 444 double calipers (the 8 inch model is shown with the legs positioned for inside diameter measurements):

Figure 13

My wife calls these "frog leg calipers" and I think that's a pretty descriptive name. The basic idea wasn't new (look up Bundy's 1865 patent US49337 for an interesting design). Starrett's contribution was the fine adjustment covered in the 1901 patent US672424.

The following picture shows the calipers in position to measure an inside diameter of 9 inches:

Figure 14

The maximum practical inside diameter measurement is over 15 inches.

Double calipers have smaller legs that pivot on firm joints in addition to the large legs with the firm joint. This allows adjustment to either inside or outside measuring positions. These calipers can measure the diameter of round objects a bit larger than 8 inches and over 15 inch widths (e.g., of a board). In the following, the legs are adjusted to make outside diameter measurements:

Figure 15

These calipers can be folded up and slipped into a pocket; the folded length is 5 inches and their mass is 161 g.

The model 444 double calipers have the following advantages over plain firm joint calipers:

- They fold up compactly for storage in a toolbox or tool apron pocket.
- They can measure inside and outside dimensions (inside firm joint calipers can measure both inside and restricted outside dimensions, but the double calipers can measure over wider

ranges).

- They have wide measuring ranges for their size, particularly for inside dimensions.
- They can measure in a bore while boring on the lathe by setting the small legs parallel; for suitable bore sizes, this may mean you don't have to withdraw the boring bar from the bore.
- Their fine adjust provides much more adjustment range than e.g. Starrett's lock joint calipers.

The model 444 calipers are only rarely seen for sale (I've only seen three pairs for sale in about 15 years of watching ebay). I'm not sure whether this is because they were made in smaller numbers or that people don't want to give them up because of their versatility.

Starrett also made the model 44 double calipers:

These let you measure inside and outside dimensions and make hermaphrodite calipers, odd leg calipers, and dividers. I have not used them, but I'd worry that I'd stick myself with the points accidentally during use. But they provide quite a bit of measurement and layout flexibility. These calipers appear on places like ebay fairly regularly, so I don't consider them very rare (despite what sellers say).

Interestingly, though I find the model 444 calipers extremely useful, I've never seen any written material about them (other than a description in a Starrett 1938 catalog). A few machine shop books from a century ago show the model 44 calipers. Personally, I find them about the most versatile calipers for general shop and DIY work, especially because they can be slipped into a pocket.

Trammels

While trammels aren't calipers, they are tools that do tasks similar to calipers and dividers 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 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 outside 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. 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 versatile and suitable for nearly all work except fussy metalworking tasks. They'll also store in a smaller toolbox.

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 and arcs in metalworking tasks, especially because the cone point allows scribing from the center of existing holes. I made an auxiliary cone point that lets me scribe from circle centers up to about 3/4 inch.

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 (you'd occasionally see a draftsman using them in the old days, although most draftsmen bought less expensive drafting trammels).

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 arc 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. If you need to scribe metal, use hardened concrete nails and grind the tips to a sharp point. If you grind the point eccentrically, you can twist the nail with pliers for a fine adjust.

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 thread 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.

Spring bow caliper dimensions

I have a number of spring bow calipers and find some of them more pleasurable to use than others. This has to do with how much I have to turn the adjusting nut to get the correct feel I'm looking for (more is better). It's also associated with how much torque I have to apply to the adjustment nut to get the desired movement, which is also affected by how sharp the knurl is (old calipers' knurls get worn smooth, making them harder to turn). I wondered if this desirable feel could be predicted from some of the calipers' measurements. After spending a few hours one afternoon fiddling with some heuristic models, I don't believe it can -- so I deleted the model fiddling and just left the dimensions measured.

I measured the following dimensions in inches from the calipers using a rule:

L = length from center of pivot to tip
M = length from center of pivot to centerline of adjustment thread
tpi = threads per inch of the adjustment thread
D = diameter of the adjustment nut
d = diameter of spring bow
w = width of spring bow
t = thickness of spring bow
K = knurl sharpness: 1 = dull, 2 = average, 3 = sharp

d, *w*, and *t* were measured with the caliper legs opened as far as they would go.

										Spring bow		
#	**N**	**Age**	**Type**	**I/O**	**L**	**M**	**tpi**	**D**	**K**	**d**	**w**	**t**
1	A	1967	4" Toolmaker's	out	3.90	0.98	54	0.41	2	0.72	0.55	0.044
2	C	1940	4" Yankee	out	4.08	0.92	36	0.50	2	0.76	0.54	0.046
3	A	1967	4" Toolmaker's	in	3.90	0.98	40	0.42	2	0.73	0.55	0.041
4	B	1940	4" Toolmaker's	out	4.00	0.99	54	0.41	2	0.72	0.55	0.046
5	B	1940	4" Toolmaker's	in	3.98	0.98	54	0.41	2	0.72	0.53	0.048
6	D*	1910	5" Steven's thd	out	4.70	1.13	30	0.46	1	0.81	0.65	0.050
7	B	1900	8" Athol Yankee	out	8.24	2.18	32	0.56	1	1.07	0.74	0.053
8	B	1900	8" Athol Yankee	in	7.96	2.14	32	0.57	1	1.08	0.74	0.058
9	B*	1900	6" Fay	in	6.04	1.12	36	0.49	2	0.82	0.56	0.046
10	B	1885	4" Fay	in	4.02	0.93	36	0.49	1	0.79	0.60	0.044
11	D*	1910	6" Fay	out	5.98	1.47	36	0.49	1	0.94	0.69	0.060
12	D*	1910	8" Fay	in	8.00	1.04	36	0.49	1	0.94	0.66	0.058
13	E	1950	2" Toolmaker's	out	2.33	0.54	60	0.38	3	0.58	0.39	0.036
14	E	1950	2" Toolmaker's	in	2.24	0.56	60	0.38	3	0.58	0.39	0.035
15	A	1970	4" Toolmaker's	out	3.90	1.00	40	0.41	2	0.74	0.56	0.041
16	B	1960	4" Yankee	in	3.92	0.90	36	0.50	3	0.74	0.53	0.048

Except for calipers 6, 7, and 8, all of these calipers were made by Starrett. The I/O column states whether the calipers are inside or outside types. My favorite calipers on this list in terms of measurement feel are the Athol 8 inch calipers and the 6 inch Fay inside calipers.

The Age column is my guess as to the approximate manufacturing decade of the calipers. Except

for the ones marked A which I purchased new, these dates are guesses.

Notes in the N column (* denotes that the caliper's adjustment thread's crests were rounded, indicating heavy use and probably large age):

- A I purchased these new in the 1970's. The two outside calipers are the same model, but were purchased a few years apart and show that Starrett changed the design (thread tpi and knurling on the nut). The 54 tpi is the old design and is approximate, as the thread measured between 50 and 56 threads per inch with my thread gauge.
- B These were part of a box of about 15 calipers purchased in 2018 from the web.
- C These belonged to an aunt and I got them from her estate. She was born around 1915 and I'm guessing she got them during the 1940's.
- D These belonged to my grandfather who became a machinist around 1910. They could possibly date to the late 1800's, but calipers 6 and 12 have Starrett's split nut design, suggesting they were made around or after the Starrett 1905 split nut patent date.
- E These were purchased used from an on-line auction in the early 2000's.

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 a nylon locknut. The legs were clamped together and filed to the same shape. The tips were bent around a suitable socket with a hammer, one leg was flipped, and the legs were joined together with the bolt. This flipping ensures the tips meet, as they are mirror images of each other. A small polyethylene washer was inserted between the legs to reduce friction. The locknut adjusts 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 basic shop skills and the result will be a useful tool.

Here are some outside firm joint calipers made from sheet aluminum:

The tip to pivot distance is 25.5 inches and these calipers will measure up to around 48 inch diameters. The only challenge was to bend the legs to the desired shape without excess distortion, as I was bending the "hard" way.

Chord angle gauge

For DIY tasks around the home, I use some 12 inch Starrett model 39 inside lock joint calipers (B in Figure 3, but not the calipers in the photo). These calipers have two modifications to increase their 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 too large to allow this use).

Figure 16

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 between these two holes.

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 10.000 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 θ_0 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°. The cosine error caused by the thickness of the caliper leg can be ignored for practical measurements.

As discussed in the *Proportions with a sector* section, you could also turn these model 39 calipers into a useful sector.

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. I have some 24 inch lock joint calipers, but they are heavy and a bit clumsy -- but still useful for larger measurements.

For larger dimensions, I use some measuring sticks made from scrap wood.

The wood is a 3 mm thick strip of oak about 20 mm wide. 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, which keeps 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 (the cosine error is negligible) 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 easy and quick to construct. It's surprisingly effective and you'll probably find that it's all you need.

Techniques and projects

This section contains example uses of calipers. To an experienced person, the examples may be tedious repetition, but my hope is that less experienced folks will see that old-style calipers find lots of use for DIY and shop tasks.

I've also put in tidbits that some folks may find useful, even if they don't involve calipers directly.

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 or the rod length, 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 from the generalized binomial theorem

$$d \approx L\left(1 + \frac{1}{2}\frac{\alpha^2}{4}\right) = L\left[1 + \frac{1}{8}\left(\frac{w}{L}\right)^2\right]$$

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 99.03 mm with an uncertainty of 0.02 mm via linear uncertainty propagation.

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 better measurement than using the DEV calipers directly because you won't spring the DEV calipers and the inside calipers will make point contact, where the DEV calipers make a line contact. Or, use a micrometer to set the calipers.

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 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 minimal 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 (1 mil is 0.001 inch) 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 1914 edition along with a discussion of the pitch rattle measurement on page 329 and roll rattle on page 330.

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:

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%, especially if you check your calibration marks with something like a graduated cylinder. More details are here.

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 solution 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 (waxed flat polyester wire lacing cord is excellent for this). 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 higher-frequency variations in the wall 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 (Veritas makes an aluminum scribe that shows instructive pictures of it being used). There are

vendors that sell Starrett 85 wing dividers modified to include a level for log scribing.

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 or mistakenly position either of the scales. It has always bugged me that none of the tool companies have put such a scale on their machinist rules[5]. These half scales are also useful for setting a compass or dividers to a desired diameter without dividing by 2.

The most practical way with your rule or tape measure is to measure the width, divide by 2, and mark the half-width. But an arithmetic mistake means you don't mark the correct point. One 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.

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 they are clumsy one-trick ponies.

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 (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). 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.

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). For bar stock, set the calipers to about the required radius, then make four marks from the edge 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.

As an example, I had to mount a mailbox on a 4x4 post.

Using my angle square, I drew a line across the center of the 4x4 as shown at A. Then I used the square to extend these pencil lines down the side of the post for about an inch. For the two 2x4 pieces that would be screwed to the 4x4, I use 8 inch hermaphrodite calipers to mark two points from each end after setting the calipers to about half the 2x4 length by eye. A pencil line was drawn across the 2x4, then extended onto the narrow edge. I screwed some 3 inch Torx screws through the 2x4 so that their points were extending slightly, then positioned the 2x4 on the 4x4 sides and drove the screws home. A chunk of 2x8 was set on the top and the mailbox was attached to the 2x8.

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. A similar method is described in the section *Proportional dividers*.

5 Here's a tape measure has a half-scale scale on it.

The combination square is handy 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. Again, 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 the edges 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, don't work near a board's end, and take up precious toolbox space.

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

If you have a line whose midpoint you want, the easiest and most accurate way could be to construct the perpendicular bisector with a compass or dividers. However, if there's not enough room for this construction, the sector and dividers are practical tools for this task.

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 tools. You can also make a centering gauge. When I do wood turning on my metal lathe, I'll often just make center marks by eyeball, as there's excess material to remove and accuracy isn't needed.

If the circle is marked in a 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. This method can have substantial uncertainty.

For smaller bar stock sizes, a bell-end center punch might be useful, but it's a one-trick pony.

Transparent plastic templates are made with concentric circle markings and holes to allow you to visually determine a center. Such a thing is easy to make with some dividers, but can be purchased if you're pressed for time. There are also plastic tools that function similarly to the center head of a combination square.

For wood turners, Veritas sells a die cast center finder that works like the center head of a combination square and marks a centerline on stock with a whack from a hammer. A friend with a wood lathe liked this tool and it was fast, so could be worth the expense if you do a lot of wood turning. There are instructions on the web showing you how to make a knock-off of this tool.

For DIY stuff, 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 arc was about 90° and a meter in diameter). The edge of this arc was rough stone and wasn't amenable to drawing two chords. Since I had pulled up the carpet in the living room, I just drove a nail into the plywood floor that looked to be 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.

Midpoint calipers

A tool for finding the midpoint of linear dimension could be made by combining the construction of hermaphrodite calipers and proportional dividers. Here's the basic idea:

The pivot point is chosen so that the ratio is exactly 2. You'd set the dimension x to e.g. the width of a board; then the other end of the dividers would be used to scribe a line at the half-width. For accuracy, you'd scribe a line from both edges of the board and use the midpoint between the scribed marks as the actual midpoint of the board.

Instead of making the A end hermaphrodite calipers, you could instead use a bent leg instead of the point, which would allow you to get the midpoints for an outside dimension like a board or from a shoulder.

I've never made such things, as they are a one-trick pony and the same job can be done with more compact regular hermaphrodite calipers.

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 inside calipers and a combination square. The combination square is used to set the blade perpendicular to the table and the inside calipers are used to set the slots and fence parallel to the blade.

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 task is to disconnect the saw from the electrical power.

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 and require non-standard widths of bars in the slots).

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 by far the best feel and adjustment of any calipers I have. They will measure from 1/2 inch to over 8 inches. The adjustment screw is 10-32 and gives a fine feel, better than any other calipers I've used.

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 contamination 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 and use a square wave. 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.

The basic technique is to put a single mark on the blade (say, with a Sharpie pen), start the generator with a frequency well above the rotation frequency, then reduce the function generator's frequency until you see two of these marks 180° apart. You then know that the function generator's frequency is twice the angular frequency of the blade. Divide by two and you'll have the blade's angular frequency in rotations/second. You have to approach the correct frequency from the larger side because a rate of half the angular frequency will also show only one mark (you'll see it every other revolution).

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 press against the saw blade and 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 [*tmbr*] 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.

A similar task was recently done by my son to make an adapter for a Chevy 4.8 liter LS engine's transmission to his old 1972 Nova linkage. He filed the rectangular hole in a chunk of 1/4 inch thick aluminum plate and used small 2 inch toolmaker's inside calipers to gauge when the hole's width w was correct:

The calipers were set from the hole in the original piece with just the right amount of drag so that the new part fit over the flat of the transmission shaft with no play.

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 M 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 on the line with the calipers' point.

Ball points: Starrett makes ball points that can be used with their 85 wing dividers, 59 trammels, and 251 machinist trammels (the set for my 251 trammels came with chrome-plated balls of 1/2, 3/4, 1, and 1½ inches in diameter). 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).

The easiest way to make such a thing would be to make the body C and silver-solder in a suitable shaft.

Temporary center: 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 and the hole is round, 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) such that the line AM is horizontal 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.

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, you can add three flats on the drill shank for the chuck to hold the drill better. You want to make the flats symmetrical so the bit 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, dividers, 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 a 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 another method of doing this.

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 so you can reuse it. This is because PVC pipe is joined via what's called solvent welding, meaning the material is softened with a solvent and joints as a single chunk of material.

> 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.

I like using calipers for this gauging better than a chunk of pipe because most PVC pipe is noticeably out of round.

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 members 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 (about a mile away from my shop).

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 onto 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 cordless 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 and out-of-roundness 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.

Measuring stick

I have a 20 mm square piece of hardwood about 2 m long. I have marked each side in various units to help with getting the first significant figure of a measurement. I use this stick as an independent check of important measurements to make sure I haven't made a mistake.

- Side 1 is in units of 0.1 m.
- Side 2 is in units of 5 inches.
- Side 3 is in units of 0.5 feet.
- Side 4 is marked with the center at 0. Then major marks are made every 5 inches on either side of 0; I marked these spots with dividers, then used a small double square and pencil to draw a line across the wood. This was followed up by a red Sharpie mark. Then I made indentations with dividers every 1 inch between the major marks and then put a blue dot with a Sharpie pen in each dot. This centering rule is handy for finding the approximate center of a gap by setting the gap edges to the same reading on each side.

You can make such measuring sticks pretty quickly by using dividers and a machinist's rule. Set the dividers to the major division marks, then step off a number of divisions and verify the setting with a measurement of the rule. Then use the dividers to divide the major divisions into the desired number of subdivisions.

Use a fine-grained hardwood to minimize the effects of the grain throwing the dividers' marks off slightly. Aluminum or steel flat stock can make a more accurate measuring stick.

Wooden rotary table

I made a rotary table from wood for general shop use. I used dividers to mark its graduations.

This table was made from a chunk of 1.5 inch thick wood turned to a disk 8.1 inch diameter. It rotates on a plywood base with a 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 the chord 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 dividers 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, such as:

- ♦ 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 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 the broken handle 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 and the hole was carefully tapered in both directions. 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 head hole's taper is the only thing that holds the head onto the handle, so it's important to get right.

After about a year of use, this hammer has become my favorite and sits on my bench next to my hacksaw, the two tools I use a lot at the bench. The measured weight of the hammer and handle is 1.4 pounds. I can use it for light-duty tapping on pins, yet it's heavy enough that I've pounded straight some 1/8" thick steel angle brackets that were accidentally bent.

When I adapted this hammer handle, I also used my calipers to help me make hammer handles from scrap pieces of wood for two other hammers. One was an 8 ounce ball pein hammer (its handle was made from some Asian pallet wood, which was surprisingly tough) and the other was a homemade brass hammer (its handle was made from some black cherry). The calipers work well to gauge the amount of taper in the hammer head to fit it properly to the handle.

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.

Timing belt cover alignment

On my son's 4.8 liter Chevy engine, we needed to align the timing cover's front main oil seal's hole with the crankshaft, as this lets you install the oil seal with it already aligned. You can buy a $40-$50 tool to do this, but it's just a chunk of bar stock with a bored hole and we were too cheap to buy such a one-trick pony.

The inside diameter needed to be roughly 1.5 inches and the outside diameter needed to be about 3 inches. The length needed to be about 1.5 inches.

I wanted to make this part from aluminum or plastic, but I didn't have any suitable material in my shop. However, there was a chunk of scrap 2x4 sitting on my table saw that a suitable piece could be made from. I laid out the piece in pencil, then cut it out with a bandsaw. I used a small faceplate held in a 1 inch collet and used two 2 inch 10-32 screws to bolt the 2x4 chunk to the faceplate after laying things out. A chunk of 1/4" Masonite scrap served as a spacer for the back.

One of the challenges of this task was that I recently had shoulder surgery and my arm was in a sling, so I had to do this turning task with one arm.

I first aligned the center punch mark with the spindle using a wiggler, then bored out the ID. This was done using my Athol 8 inch inside calipers that were set from some Athol 8 inch outside calipers (G in Figure 1) that fit over the ground surface on the crankshaft.

The OD was turned by setting the outside calipers from the inside calipers used to gauge the diameter of the hole in the timing chain cover. The catch was that this was a thin lip less than 1 mm thick, so it took a bit of care to get a good fit with the calipers.

The OD was turned with no further problems.

It was pleasing to see that the tool fit both the crankshaft and the hole in the cover with essentially no play. I had to turn the tool off the crankshaft's ground surface with a number of back-and-forth turns, so the clearance was less than 0.001". I couldn't remove the work from the spindle, so I had to check and recheck the caliper settings a few times to make sure I had gotten the inside and outside diameters correct.

After installing the tool over the crankshaft, the timing cover was put on with its gasket and the tool kept things aligned so we could install the bolts. After the bolts were torqued down, we used the tool and a rubber hammer to drive the oil seal into place. It fit perfectly. On the last whack with the hammer, the wooden tool split in half, but we were done. Thus, a scrap piece of cheap wood made the perfect tool to get the job done. The inside and outside 8 inch calipers were crucial to getting the close fits needed.

Measure hole separation

Inside calipers are useful for measuring the separation of holes, especially if the caliper tips can index on the inside edge of the holes. While this is elementary, it's useful to see:

Use the calipers to measure the separation L. The center-to-center separation C of the holes is then

$$C = L - \frac{1}{2}(d+D) = K + \frac{1}{2}(d+D)$$

It's usually faster to use DEV caliper tips to measure the dimension K directly and add the two hole radii to get the distance C.

If you have accurate pins to fit the holes, a better way is to insert the pins and use a micrometer to measure the outside dimension across the pins, then subtract the radius of each pin to get the center-to-center distance. If the pins don't tilt in the hole, this is probably the most accurate practical method unless you have a coordinate measuring machine.

Vacuum peg leg

I got a free shop vacuum from craigslist. The only thing wrong with it was that one of its four casters was missing, meaning it was cumbersome to move. It's light enough to pick up and carry, so I decided to make a wooden peg leg for the missing caster hole from a scrap piece of 3/4 inch diameter maple dowel I had:

I needed to turn the diameter d to match the slightly tapered hole that was molded into the plastic of the base. d was about 15 mm and the length L was about 40 mm.

I used some 4 inch Fay inside calipers to gauge the size of the hole this wooden piece needed to go into. The calipers let me feel the taper in the hole. I set the calipers to the size near the bottom of the hole, then measured that setting back in the shop using my micrometer. I turned the dowel to the needed size, measuring with the micrometer. This is an example where it's faster to use a tool like a micrometer rather than the calipers, as the micrometer told me exactly how much to take off to get the finished size.

It needed a couple of taps with a dead blow hammer to fully seat the peg, making a tight fit. I can use pliers to pull it out, but the fit is tight enough that it will stay in place. The Fay calipers were the tool of choice for reaching down into the hole to gauge the needed diameter.

Shipping tube cap

I needed to ship an ANSI C-size drawing to a relative. Drafting places sell shipping tubes, but they are $10 apiece -- which is pretty expensive for a one-use cardboard tube and it also involved a drive

into the nearest city to get it. Instead, I used a 1.9 inch diameter 0.16 inch wall cardboard tube that someone had sent me something in (such scrap stuff always gets saved in my shop because it will eventually find a use). I made a cap for it using calipers to gauge the dimensions:

The cap was turned on the lathe to fit the ID of the tube. I used a piece of scrap 2 inch diameter wood that someone gave me; it looks like mahogany. One end was measured with 4 inch Fay inside calipers and the diameter of the cap was made to be a tight fit to the tube using outside calipers. A short 8° taper was put on the end for about 0.2 inches to help get things started. This cap had to be pounded into the tube and can't be removed by hand.

The other cap was made a snug slip fit in a similar fashion. It is easy to remove by hand.

For shipping, both caps were secured with transparent packing tape.

I turned the pieces using a spur center. I made a mark on one of the spurs and the workpiece to let me take it out, try the fit, then put it back into the lathe to remove a bit more. The final fit took a couple of tests in the tube to get the desired diameter.

Handy gauges

Though I like to design and work in mm or decimal inches, fractions of an inch in a US shop are still commonly encountered. If you have a lathe, you can turn various diameters on a chunk of bar stock that will help you get the rough sizes of things. Here's a typical design:

Diameter in 1/8 inches

The widths of the steps were 1/4 inch and the knurled portion was about an inch long. I drilled a 1/4" hole 1.3 inches deep in the left end and drilled this out for 1/2 an inch to 7/16" diameter. This lets me store the gauge sitting on one of the screws of the parallel clamps clamped to the lid of my tool chest.

The indicated diameters were carefully turned to be the nominal size or less than 0.001 inches below the nominal size. This makes the gauge useful for quick sizing of a hole in some sheet metal by using the gauge like a pin gauge. When making a measurement with outside calipers, it allows you to quickly judge the approximate fractional size.

I turned the above tool from 1 inch diameter aluminum bar stock; smaller inch and metric gauges I've

made have been from steel bar stock.

I made a corresponding gauge made from 3/16" thick steel plate that has accurately bored holes (mostly used to size fasteners):

The bored sizes are stamped next to each hole; a 1/2 inch diameter hole is at the center.

A number of years ago I had lots of old CDs, so I made some simple tooling to allow me to turn these to various outside diameters within 0.0005 inches of the nominal size. They provide 2.0 to 4.7 inch diameters in steps of 0.1 inches. They are stored in a CD container:

Truthfully, they were more work than I anticipated and I don't use them very often. One use is to gauge radii that are larger that are outside the range of the typical machinist radius gauge set.

Measure a circumference

While it's straightforward to measure the outside diameter of a circular feature with calipers and a rule, then multiply the diameter by π to get the circumference, it's easier and less error-prone with a circumference rule (sometimes called tinner's rules) because the calipers' reading can be read off the rule directly as a circumference.

You may be surprised by the cost of circumference rules, as they are typically $50 to $150. A sheet metal worker rolling a duct from sheet material is a typical user and such folks can justify the expense because they'll use the rule so much.

It's not hard to make your own circumference rule from a stick and some dividers. For the

measurement unit you want to utilize, use your dividers to mark $1/\pi$ = 0.318 units for the major divisions on the rule. Then when you measure a diameter, this scale will read out in the length of the circumference. Since you'll probably be rounding up (i.e., cutting the stock a little long), you probably don't need any finer graduations (you can interpolate to the needed fraction if desired).

The recommended way of making such a rule is to decide on the unit of measure you'd like to use, then lay out the length of the circumference scale with an accurate rule. For example, if you wanted to measure circumferences up to 36 inches, you'd use a scale length of $36/\pi = 11.46$ inches. Carefully mark this distance on the rule, then use dividers to divide it into 36 divisions by stepping off 36 steps and verifying you get to the 11.46 inch mark. Then use the dividers to mark off each major division. You'll lay things out using an internal zero mark near an edge, then sand things off perpendicularly on a shooting board to make the zero mark flush with the edge.

Minimal kit

I sometimes have to go to friends' and relatives' houses to help with a do-it-yourself or fix-it project. It's convenient to have some calipers and a rule handy because most homeowners won't have such tools available.

Bare minimum

This kit contains only the firm joint hermaphrodite calipers (C in Figure 1) and stuff to adapt them to tasks other than scribing from edges or shoulders.

- ♦ Firm joint hermaphrodite calipers (4 or 6 inch)
- ♦ Jaws: bent for inside, regular, large for OD
- ♦ Spring steel point for dividers
- ♦ Regular point
- ♦ Pencil
- ♦ Rubber bands
- ♦ Rule
- ♦ Concrete nails: center punch, prick punch, 1/8" punch, finish nail punch

Airplane

- ♦ 8" inside lock joint
- ♦ 4" inside toolmaker's
- ♦ 6" hermaphrodite calipers in "bare minimum" kit
- ♦ 6" dividers

Note: this kit is made up of "excess" calipers that duplicated things I already had. Thus, if I lose the kit, I won't be terribly upset.

General

This kit is where I have room in a toolbox for the tools I normally use. For general DIY stuff, the 12 inch Starrett 85F wing dividers are the most versatile, making up calipers, dividers, hermaphrodite calipers, and a compass. For more careful work, I'll take the 12 inch Starrett model 38 and 39 calipers, 6 inch firm joint hermaphrodite calipers, and 4 or 6 inch dividers. For small stuff, I'll take 4 inch toolmaker calipers.

Caliper 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 always need disassembly, cleaning, and lubrication. Lock joint calipers require more work to disassemble and, perhaps surprisingly, firm joint calipers can be the most challenging to

disassemble, especially when the grease has hardened and there's some rust in the joint.

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

Disassembly

Take photos or makes sketches while you're taking things apart so you can put things back together correctly.

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 are usually one or two thin washers (brass or a fiber-bearing plastic) used for the joint's friction. Fits are very close on commercial calipers to minimize play, so take things apart and reassemble carefully.

I use a chip carving knife and a brass hammer to gently try to pry the legs and nut apart. It is not difficult to unknowingly damage one of the washers when doing this, so go slowly and inspect things closely with a loupe under a bright light. Pry gently at numerous points around the circumference; don't try to do it all at one point.

If you decide you don't want to take the firm joint calipers apart, one thing to try is to immerse the whole joint in some oil to rejuvenate the lubrication. This doesn't deal with any existing rust, but it may slow future rust down. The washers in the joint won't be damaged by oil.

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.

Most used 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 it ruined the beautiful finish of the calipers. However, it didn't affect functionality or damage the precision-turned frustums necessary for smooth operation.

Old firm joint calipers almost always have rust on the friction surfaces. These can be cleaned by rubbing them on 400 grit sandpaper on a flat surface or on a fine sharpening stone. A better tool is a narrow Cratex rubberized abrasive in the shape of a narrow cylinder with a gradual tree-type point. This tool can hand-scrub the rust off without damaging the nice finish on the legs.

The hex nuts on Starrett firm joint calipers aren't very tall. Use a socket to turn them and hold the calipers in a vise so you can press firmly on the socket to seat it; otherwise, the socket can slip and ding up the hex. Even better, turn the chamfer off the socket on a lathe.

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 cheap, and is easy to renew periodically.

An alternative lubricant I use is a molybdenum disulfide spray. This sprays on wet, but the solvent dries and leaves a dry lubricant. I particularly like this lubricant for firm joint calipers.

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.
  - To get a smooth feel, file to shape and polish with sandpaper.
  - Special tips can be filed as needed.
  - If you need a special tip, it shouldn't be difficult to weld on some new material and shape it as needed. For example, you could turn some outside calipers into duckbill thread calipers this way.
- 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 often an oddball size.
- Pivot: straightforward lathe work; it will likely be hardened and tempered.
- Spring bow: can be made from spring steel and given a spring temper, but might be easier to just buy another pair of calipers.
- Adjustment nut on spring bow calipers
  - Knurling wears off on old calipers. Use a fine needle file to file the knurled impressions to make the nut sharp again. This is finicky work.
  - I'll sometimes make a new nut from aluminum and give it an aggressive knurl.
  - You can make new nuts, but the thread may be an oddball size you won't have a tap for. Even if it's a common size, the pitch diameter may be different than modern threads.
- 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 (aluminum works fine) and make them 1/4 inch thick and 0.4 inches thick, respectively. I give them an aggressive knurl to make them easier to turn, as I've never liked Starrett's rope knurling.
    - The inside fine adjust nut is made from 5/8 inch diameter stock and 0.2 inches thick.
  - 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.

Tips

I've seen no documentation on what calipers' tips should look like and the numerous calipers I've purchased have had a variety of shapes, probably due to the taste of the machinist who last used them.

Here's a picture of the tips of some 4 inch Starrett toolmaker's outside calipers (this is the shape the factory put on the tips):

These look to be carefully made and symmetrical. As the gauged diameter gets larger, the contact point on each tip will move towards the bottom. Such shapes can be filed on caliper tips. Clearly, there's quite a bit of material, so if you make a mistake, it can be corrected.

Most of the inside calipers I've used have somewhat similar tips. However, the inside 8 inch Athol calipers (the same construction as G in Figure 1) appear to have had their legs chucked in a lathe and the tips were turned (or filed) and polished; this is perpendicular to the curved direction I've seen on all other calipers. I like using these calipers and I've done some close work with them; this may be due to the shape of the tips.

Adjustment nuts

On spring bow calipers and lock joint calipers, you'll find that the knurling on the adjustment nuts is important. You don't want the knurling to be so sharp that it abrades your fingers, but it should be aggressive enough to give you a good grip on the nut. Essentially all of the calipers I own have a knurl that I don't consider aggressive enough. Also, the nut diameters tend to be too small for my tastes.

Making a new solid nut with a lathe should be an easy fix. However, the screw threads are often an oddball size, especially on old calipers. Making a new split nut as shown in the drawing on split nuts would require making special tooling.

> I thought it would be easy to make a new solid nut for the Athol calipers show at G in Figure 1. I had measured the thread OD with DEV calipers and it was 0.187 inches and the threads per inch was 32, so it was a 10-32 thread. After making a new nut and tapping it, it wouldn't thread onto the caliper's threads. The thread's pitch diameter is larger than that produced by a standard tap. This could be fixed if I had a split die to resize the threads, but I don't. And my standard die clearly took too much material off and didn't start quite straight, so I immediately stopped using it. A new split die is $20 to $40, far too expensive for this one-off task, so I abandoned this approach.

Another problem is knurl wear. On old calipers, the knurl on the nut gets worn down and becomes less effective, making the calipers harder to operate. Starrett used a bead ("rope") knurl on many of their calipers and though it looks nice, it wears more quickly, making the nut harder to turn. In the late 1960's or 1970's, Starrett switched to flat knurling, as it's cheaper to make and works better. My 6 inch Fay calipers that belonged to my grandfather (they are probably more than a century old) had a badly worn bead knurl. I keep these calipers on my tool cart in the garage for working on cars and these calipers are almost impossible to use with greasy fingers because the knurl is so worn.

One way to fix a worn flat knurl on solid or split nuts is to get a triangular file and carefully file the knurl's grooves. This is finicky work for a fine knurl and will require a magnifier, good lighting, a small fine needle file, and a way to hold the nut steady while you file. But it does work.

Since I usually want a larger nut on the calipers I use, a practical fix is to turn off the knurl on the old nut and press or solder on a knurled sleeve. This is easy to do if it's not hard to grab the old nut in the lathe. Split nuts can be problematic because the knurled portion can wobble even if the nut halves are clamped tightly; in this case, I file the knurl grooves instead.

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 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:

- 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. Such tools are used to verify the first significant figure of a measurement.

Appendix: Firm joint calipers

In the section *Homemade firm joint calipers*, I showed how to make some simple inside firm joint calipers. These will work, but you'll find a bolted or riveted firm joint may not work as well as some of the commercial firm joint designs. If you take apart some commercial firm joint calipers, you may be surprised by their close fits and they can be a bit of a challenge to get the pieces apart.

I use a narrow knife blade and a brass hammer to gently pry the legs apart. The risk is that the knife blade may damage the outside diameter of the washer(s) used in the firm joint. Starrett's and Lufkin's design use two thin fiber washers and these are easy to damage, especially in old calipers where they are worn thin. The Brown & Sharpe design is a little more robust and uses only one thicker (0.012 inches thick) brass washer (it's easily sanded smooth if the outside diameter is nicked by the knife). Before disassembly, squirt some thin oil or mineral spirits into the joint to help lubricate things.

I've taken apart firm joint designs by Starrett, Lufkin, and Brown & Sharpe. The basic joint design is to mechanically constrain the clamping nut/screw to one leg so it cannot rotate with respect to that leg. This, in turn, means the screw won't back out with continued use. The other leg then freely rotates with respect to that leg, but the clamping screw and close fits add the requisite amount of friction. These joints are precision machined, so handle things carefully. I would imagine that the holes in the legs were carefully broached (maybe filed), as the fits feel to be on the order of 0.001 inches or less. When reassembling the parts, I usually have to just get them started, then use the clamping screw to finish the assembly, as the parts won't press together with finger pressure, implying the fits are very close.

I like the Lufkin and Brown & Sharpe firm joint designs better than the Starrett design, although all of them can operate satisfactorily. The B&S design is probably the most robust, as it uses one thin brass washer; the Lufkin and Starrett design use two thin fiber washers that are easy to damage or are worn into pieces after many years of use. Every pair of firm joint calipers I've taken apart have been desperately in need of cleaning and lubrication (few machinists take care of their calipers); I often have to give a light sanding with 400 grit sandpaper to remove rust in the joint.

In [*tmbr3:21*], Lautard commented about his old machinist friend Bill's firm joint calipers that Bill made as an apprentice. The legs were forged by a blacksmith and the joints were scraped for a good fit, then riveted for permanent assembly. On page 22 is a picture of a riveted joint using machined washers (I'd recommend silver-soldering the lower washer to the lower leg).

Use

Firm joint calipers are easy to use for simple measurements and comparisons. Their biggest advantage is speed of adjustment. However, for fine work (i.e., machining to close tolerances), they need to be adjusted and handled with more care.

To close firm joint calipers slightly, knock a leg lightly against a block of wood.

To open firm joint calipers slightly, hold them vertically with the joint facing down and knock the joint against a block of wood.

A disadvantage of firm joint calipers is that it's not difficult to accidentally bump them against something, causing a setting to unknowingly change, leading to an expensive mistake. The best protection against this is to be very aware of what you're doing when using them. It's also wise to adjust the firm joint to be as tight as is practical.

Starrett design

Here's a picture of some Starrett 563 firm joint hermaphrodite calipers disassembled:

The knife at the bottom is the tool I use to separate firm and lock joint caliper legs; it often takes some light pounding with a brass hammer to get them to separate, especially the old ones where the lubrication has evaporated and the metal has rusted. The knife blade is also used to free up the washers D, which are often glued by old grease to the legs. A 5/8 inch socket was needed to remove the nut.

To reassemble these calipers, a washer D is put over the nut F's shaft, then the nut F is pushed through the hole in leg B; it's a tight fit and can require light pounding with a brass hammer. The other washer D is put over the nut F's shaft and leg A is installed onto the nut shaft's square portion. This is also a tight fit and can require tapping with a brass hammer. When things are aligned well enough, the bolt E is started in the nut and tightened. Then nut E is adjusted until the desired friction in the joint is gotten.

I've never taken any firm joint calipers apart that haven't needed rust removal, a solvent to get rid of the dried-up grease, and perhaps some sanding of the joint area on some 400 grit sandpaper to flatten the legs again and remove burrs. After lubrication with Vaseline and reassembly, the calipers always operate nicely again, showing that Starrett's joint design is basically sound.

Lufkin design

To be written.

Brown & Sharpe design

The following picture shows some 4 inch B&S hermaphrodite calipers disassembled:

The round parts in the middle are, from the left:

Nut: rectangular projection (sticks out 1/8") that tightly fits the top leg and is tapped 0.150 inches major diameter and 40 threads per inch. The rounded portion is 0.2510" diameter and the square portion measures 0.1880"; both measurements were made with a micrometer.

Screw: Fits the nut; the screw length is 3/16 inches. A narrow slot is on the opposite side to enable tightening the joint.

Washer: 0.011 inch thick brass, 0.564" outside diameter, 0.251" inside diameter.

The hole in the lower leg is 0.252" in diameter.

I consider this firm joint design to be the best of the three I've seen. When I reassemble these calipers, I put molybdenum disulfide or Vaseline on all the parts to keep things lubricated.

Here's a picture of the fine adjust of some Brown & Sharpe firm joint calipers:

This is, in my opinion, a more elegant design than Starrett's fine adjust (1901 US patent 672424).

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 20 to 30 used pairs of calipers with this joint and every one of them had significant rust and lack of lubrication. Most of them worked well after servicing.

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 are 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.

WITNESSES.
G. Henry Marsh.
Samuel P. Thrasher.

INVENTORS.
Larry S. Starrett,
Charles P. Fay,
by N. A. Bennett, Atty

Figure 17

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. Make sure you have a screwdriver to fit the slot so you don't ding up the screw.
- ♦ 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 virtually 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 about 1/4 of 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 them 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.

References

The older references can be found on Google books.

brown R. Brown, *Using a Manufacturer's Specification as a Type B Error Contribution*, Agilent Technologies white paper, 5991-1264, 2006.

cmh F. Britten, *Watch & Clock Makers' Handbook*, 9th ed., Spon, 1896.

cs F. Colvin and F. Stanley, *American Machinist's Handbook*, McGraw-Hill. Numerous editions starting from around 1914. This reference is a work of art.

cstk F. Colvin and F. Stanley, *Toolmaker's Kinks*, Hill Publishing, 1908.

eomd L. Frank, *Essentials of Mechanical Drafting*, Milton Bradley, 1917.

gum GUM: Guide to the Expression of Uncertainty in Measurement. See https://www.bipm.org/en/publications/guides/gum.html.

jd A. Jackson and D. Day, *Tools and How to Use Them*, Knopf, 1979, ISBN 0394735420.

kid F. Kidder, *Triangulation applied to sheet metal pattern cutting*, The Sheet Metal Publication Company, 1924.

leo W. Leonard, *Machine-Shop Tools and Methods*, 5th ed., Wiley, 1908.

marks L. Marks and T. Baumeister, *Standard Handbook for Mechanical Engineers*, 7th ed., McGraw-Hill, 1967.

mh *Machinery's Handbook*, various editions, published by Industrial Press.

mms J. Rose, *Modern Machine-Shop Practice*, Scribner's, 1887.

ocw http://ocw.mit.edu/courses/mechanical-engineering/2-75-precision-machine-design-fall-2001/projects/topic3fundamentalprinciples.pdf

p1885 Fay, US patent 319215: Early spring caliper patent.

p1886a Bullard, US patent 335740: Figure 2 shows one of the most commonly-used spring bow caliper joint designs.

p1886b Fay, US patent 334764: Early split nut design.

p1889 Starrett, US patent 411527: Wing dividers with fine adjust and replaceable legs. The Starrett model 85 calipers are still made this way, virtually unchanged from the patent drawings.

p1895 Fay & Starrett, US patent 539759: Tapered lock-joint caliper with fine adjust. Used on Starrett model 36, 37, 38, 39, and 42 calipers.

p1901 Starrett, US patent 672424: Fine adjust for firm joint calipers. Also shows a firm joint design popular at the time.

p1903 Ball, US patent 720773: Bow spring outside transfer calipers. You could make these from some Yankee calipers.

p1905 Starrett & Simpson, US patent 793850: Split nut for calipers. This became the de facto split nut design. This design was apparently in figure 132 of [*vdv*], meaning it was being used in production years before this patent.

p1925 A. Nelson, US patent 1562464: Hermaphrodite calipers with fine adjust and square groove on leg for indexing on edge, 1925.

parr A. Parr, *Machine Tools and Workshop Practice*, Longmans, Green, & Co., 1905.

st B. Stewart and W. Gee, *Lessons in Elementary Practical Physics*, Vol. 1, Macmillan, London, 1904.

sthist The L. S. Starrett Company, *The Starrett Story*, 2012.

st26 Catalog 26, L. S. Starrett Company, 1938.

tmbr G. Lautard, *The Machinist's Bedside Reader*, volumes 1, 2, or 3, various years, published by the author (see http://www.lautard.com). *tmbr2* means volume 2.

tur F. Turner, O. Perrigo, and H. Fairfield, *Machine Shop Work*, American Technical Society, 1919.

vdv W. H. Van Dervoort, "Calipers" in *Machinery*, p. 54, Oct 1898. Similar material is given in Van Dervoort, *Machine Shop Tools and Shop Practices*, 6th ed., Henley, 1911.

whd W. Van Dervoort, "Calipers" in *Machinery*, October 1898. This appears to be the same material in chapter 5 of W. Van Dervoort, *Machine Shop Tools and Shop Practice*, 6th ed., Henley, 1911.

yates R. Yates, *Shop Practice for Home Mechanics*, Henley, 1920.

kohl F. Kohlrausch, *An introduction to physical measurements*, 3rd ed., Appleton, 1899.

lvh *The Importance of a True Running Blade* at http://www.leevalley.com/US/home/Articles.aspx?p=32&cat=32,47181