The Vernier scale in measuring instruments

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ABSTRACT

The Vernier scale is an ingenious construct by which the scale of a direct-reading mechanical measuring instrument (*e.g.*, caliper, micrometer) can be read with far finer resolution than would otherwise be practical.

Its operation depends on the human visual system's uncanny ability to discern even a tiny misalignment between two abutting line segments.

This article describes the construct and gives examples of its application to familiar measuring instruments.

1 INTRODUCTION

The Vernier scale is an ingenious construct by which the scale of a direct-reading mechanical measuring instrument can be read with far finer resolution would otherwise be practical.

It is often used on such mechanical measuring instruments as calipers and micrometers (and is most clearly understandable if we consider its application to a caliper). In fact almost all direct-reading precision calipers today are equipped with this feature.

Typically, in its basic form (without a vernier scale) such a caliper carries on its fixed part a scale with graduations carefully and precisely applied. The moving part carries a fiducial line, which the user reads against the marking on the scale.

These graduations may be at a very fine pitch, but cannot be placed at such a fine pitch that the typical user cannot resolve them visually.

Nevertheless, a skilled user can often interpolate "by eye" to read the position of the instrument to perhaps a precision of 1/5 the graduation spacing. But this is not a "sure thing", and in some cases, we would like to be able to read the instrument confidently to a smaller increment than that.

The Vernier scale provides a powerful aid in that "interpolation".

It is named in honor of French mathematician and astronomer Pierre Vernier (1580-1637), who invented the scheme in 1631, initially for use on the angle measuring scales of astronomical navigational instruments (*e.g.*, sextants).

2 VERNIER ACUITY

The working of the Vernier scale depends on the human visual system's ability to discern even a tiny misalignment between two abutting line segments. We see that in figure 1.

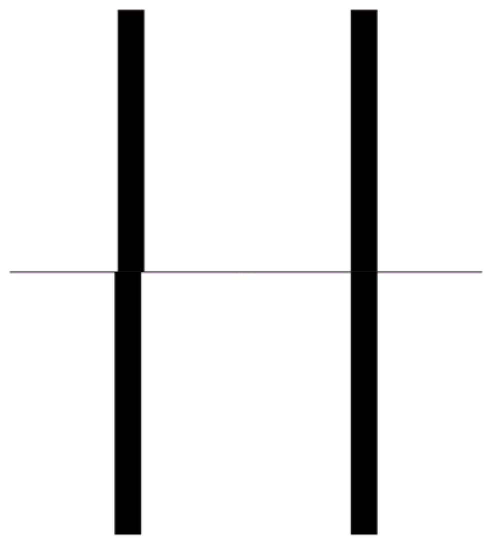

Figure 1. Vernier acuity

This figure is greatly enlarged from the typical context in which it important. At this size, it is not surprising that we can easily see the difference between the left and right pairs of line segments due to the offset between the two line segments of the left-hand pair.

But at the usual size at the usual size at which this is encountered, that offset, then very tiny, would still be discerned, and we still could see the difference between the left and right pairs of line segments.

Because of its importance to the working of the Vernier scale, this ability is often said to be the "Vernier acuity" of the human visual system. It is significally finer than the actual acuity of the visual system, and is sometimes called a "hyperacuity". It was for years a conundrum to students of the working of the human eye. A satisfying explanation of how this occurs was not really had until the late 1800s.

3 UNITS

Most of the actual measuring instruments discussed here are available either to operate with inch units or millimeter units (for many calipers, both). In this article, both for example hypothetical instruments and as to actual instruments, I will arbitrarily speak only of instruments using the millimeter unit. For instruments using the inch unit, the principles are the same, but typical numeric details will be different.

4 A TYPICAL MODERN VERNIER CALIPER

Figure 2 shows a typical modern vernier caliper, a Mitutoyo 503-101. I say “modern” because it is made today; its design, however, is quite old.

The parts are labeled for future reference; other names are used here and there. I hope that the operation of this instrument is obvious.

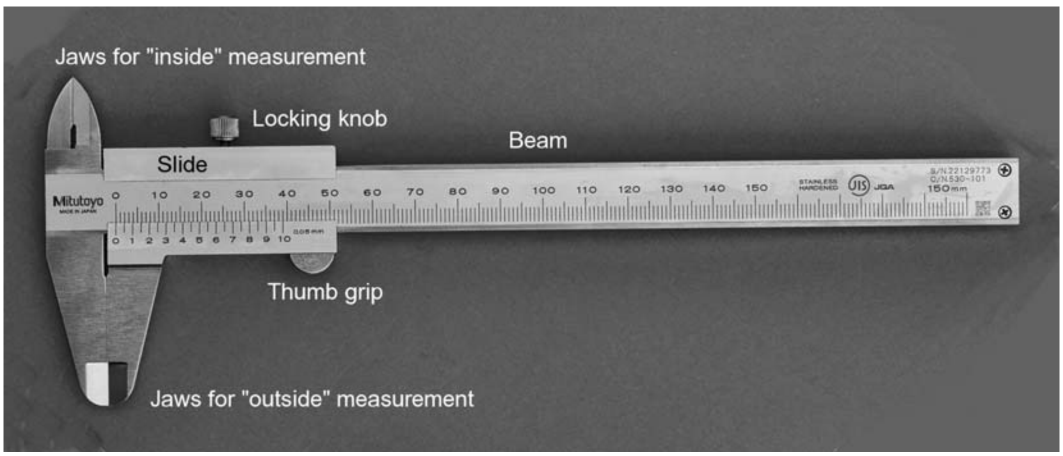

Figure 2. Mitutoyo 530-101 vernier caliper

It can measure dimensions up to 150 mm (about 6 inches). Not using the Vernier scale, it can be directly read to a resolution of 1.0 mm (although of course a skilled user can interpolate to a somewhat smaller resolution). As we will see later, with the vernier scale in use, it can be easily and reliably read to a resolution of 0.05 mm.

5 THE VERNIER SCALE

5.1 A basic caliper scale system

Figure 3 shows the scale system of a hypothetical precision caliper, for the millimeter system, without a Vernier scale.

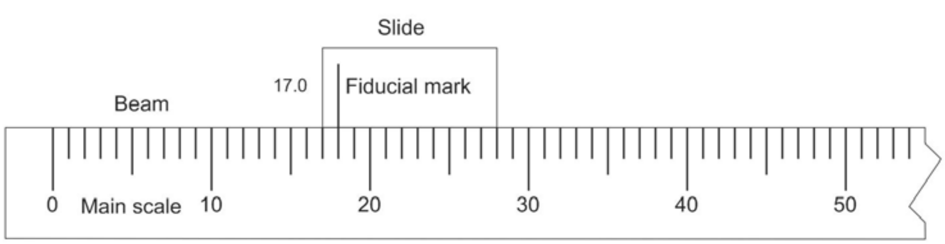

Figure 3. Basic caliper scale

The scale proper is engraved on the "beam" of the caliper, which carries one of the measuring jaws. The other jaw is part of a "slide", which can move along that track.

The slide bears a fiducial mark, which the user reads against the markings of the scale to obtain the reading of the dimension being measured.

This hypothetical caliper is marked in the millimeter system. The smallest gradations of the scale are spaced at a distance of 1 mm.

As seen in the figure, the reading is 17.0 mm. How do we know that the last figure is "0"? Because we can clearly see that the fiducial line is "exactly" on the mark for 17 mm.

In figure 3, the distance being measured is 17.1 mm.

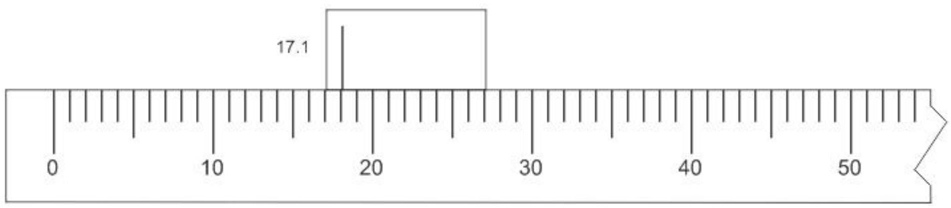

Figure 4. Basic caliper scale–dimension 17.1 mm

We can see that the fiducial mark is slightly to the right of perfect alignment with the 17 mm mark on the scale, so the value is greater than 17.0 mm. A skilled user might be able to correctly guess that the fractional part is 1/10 of a millimeter, for a reading of 17.1 mm. But that is tough to do reliably, and puts quite a strain on the user's eyes.

5.2 A Vernier scale for this same caliper

Figure 5 shows a vernier scale for this hypothetical caliper, again measuring a distance of 17.0 mm.

Do not be concerned that this seems different from the arrangement seen on the actual caliper in figure 5. This one has a simpler system, better (in my opinion) for explain the principle.

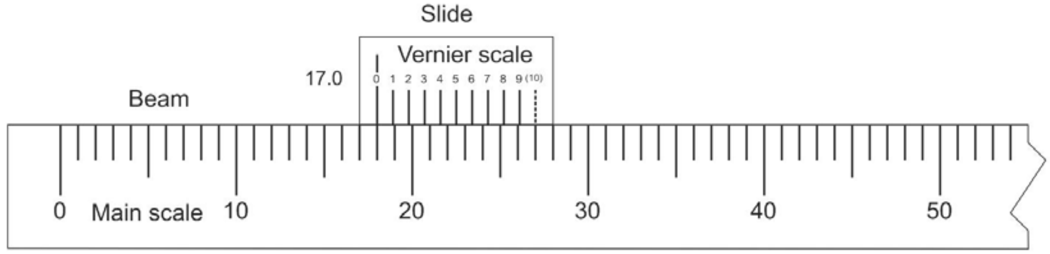

Figure 5. Vernier scale

Note that the slide now has not just a fiducial mark but also an array of other marks, numbered. We see that close-up in figure 6.

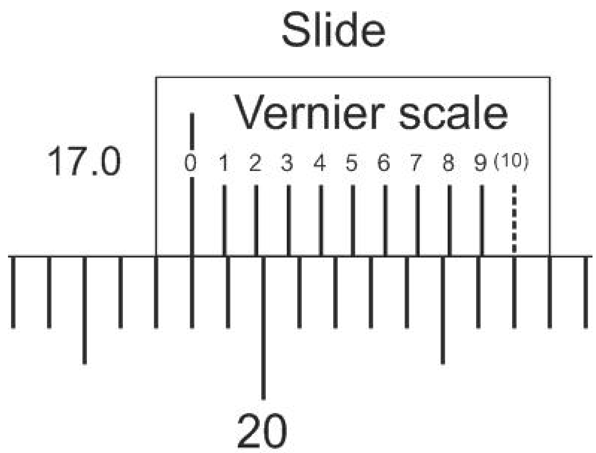

Figure 6. Vernier scale close-up

We see that there are now 9 additional marks (beyond the fiducial mark) on the slide. I have actually included a 10th line, shown dotted, which does not actually appear but which will play a role in my description. All 10 numbered lines (including the fiducial line) are part of the “Vernier scale”.

The spacing between all these lines on the slide is such that 10 of those spacings corresponds to exactly 9 divisions on the main scale. With the slide in this position (the 17.0 mm position), we can easily see that, since the dotted “construction line” is in perfect alignment with the 9th main scale division past where the fiducial line hits the main scale.

How do we read this Vernier scale? We note which of the 10 numbered lines (the dotted construction line is not really present) most seems to exactlty align with whichever line of the main scale it is most closely aligned with. In this case, it is Vernier scale line 0 (which is also the fiducial line). The other lines do not align so exactly with any main scale line.

Thus the least significant digit of the reading is “0”, for a reading of 17.0 mm.

In figure 7, we see (again in close-up) the same area with a slightly greater distance being measured:

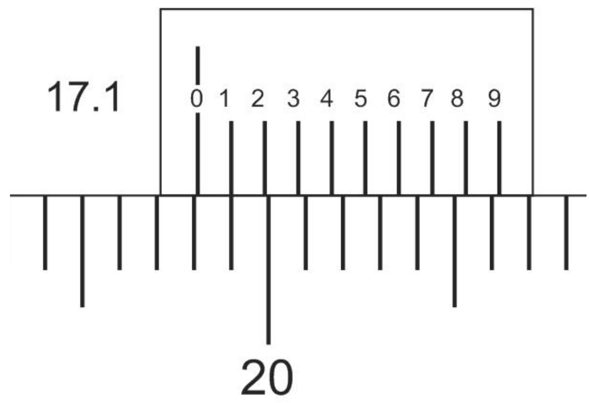

Figure 7. Vernier scale close-up–distance 17.1 mm

Now it is Vernier scale line "1" that most closely aligns with (any) main scale line. Thus the least significant digit of the reading is "1", for a reading of 17.1 mm.

At a measured distance of 17.9 mm, it will be line "9" of the Vernier scale that will most closely align with any line of the main scale.

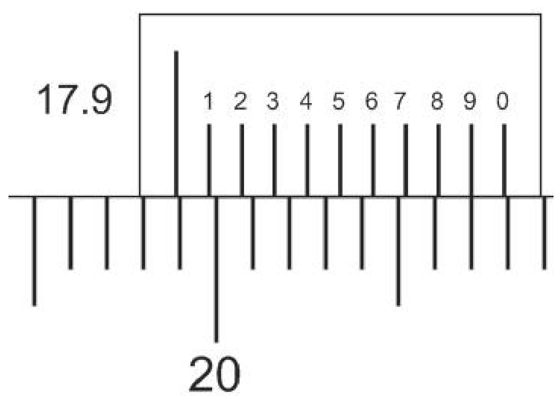

Figure 8. Vernier scale close-up–distance 17.9 mm

Then, at a distance of 18.0 mm, when the fiducial line will indicate that the dimension is "18.x" mm, Vernier line "0" (which of course is also the fiducial line) will again be the best aligned with "we don't care which" line on the main scale, so the least significant digit of the measurement is "0", for a reading of 18.0 mm.

5.3 Avoiding the dual task of the fiducial line

In some applications of this principle (especially in micrometers, when there is a secondary main scale, running around a cylinder, and the Vernier scale runs around a similar cylinder), the labeling does not work out well to have the same line as the fiducial line and as Vernier scale line "0".

Figure 9 shows, in our familiar caliper context, an alternate arrangement that avoids that dual task of the fiducial line.

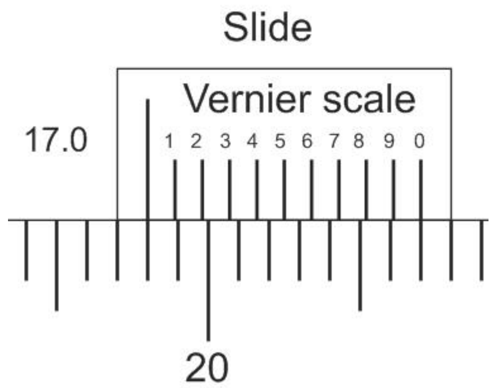

Figure 9. Alternate Vernier scale

Here, the Vernier scale has 10 numbered lines, none of which are the fiducial line. But line “0” is exactly 10 pitches of the Vernier scale (exactly 9 pitches of the main scale) beyond the fiducial line. In light of the cyclic nature of this scheme, it plays the same role that the fiducial line plays as “0”.

We note than when the fiducial line (actually a “0” line) is perfectly aligned with **some line** of the main scale, the line marked “0” is also perfectly aligned with **some line** of the main scale, leading either way to a reading of “0” for the least significant part of the measurement.

6 IN A REAL CALIPER

You might wonder whether it is really worth all this trouble to get a resolution of 0.1 mm on a precision caliper, when that could probably be done in practice with a credible visual interpolation.

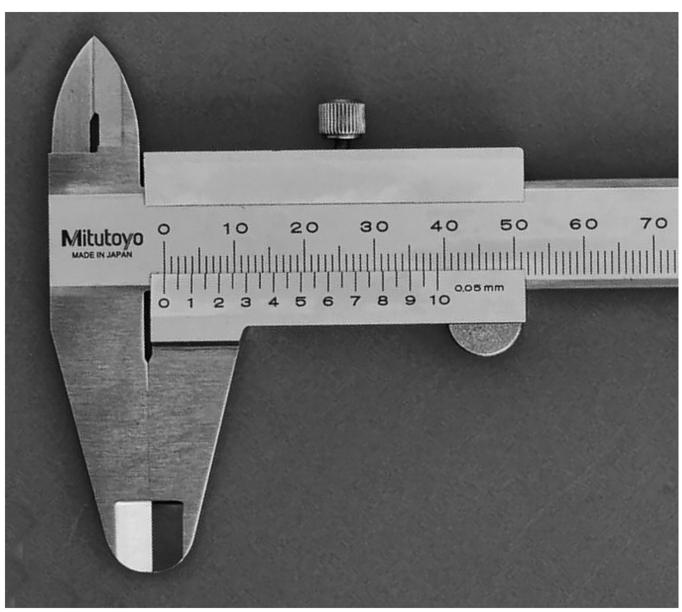

Figure 10. Mitutoyo 530-101

In fact when such calipers are equipped with a Vernier scale, it is usually arranged a little differently, so as to attain a finer resolution than that. I did not show it that way before, for simplicity's sake. But now we will see a typical actual arrangement.

In figure 10 we see a close-up view of the caliper seen earlier.

Here, as in the hypothetical instrument, the main scale divisions are at a spacing of 1.0 mm.

But the Vernier scale has 19 marks. every other one labeled, from 0 through 10. Their total span (10 "Vernier pitches") matches exactly a distance of 39 pitches of the main scale.

Thus the successive marks on the Vernier scale represent values at intervals, so far as the least significant part of the measurement is concerned, of 0.05 mm (50 μm), which is thus the reading resolution of the instrument.

Figure 11 is shows the business end of another similar caliper offered by Mitutoyo, with a finer resolution.

Figure 11. Mitutoyo 530-122 caliper

Here the Vernier scale has 51 lines (a span of 50 pitches), every fifth one labeled with a number, and it spans a distance of 49 mm on the main scale. Accordingly, the Vernier scale can be read to a resolution of 1/50 of 1 mm, or 0.02 mm (20 μm).

7 APPLICATION TO A MICROMETER

7.1 Background

When the Vernier scale is applied to a micrometer (the formal name of which is "micrometer caliper"), the arrangement is a little different because of the "linear-cylindrical" layout of that instrument's scales.

Figure 12 shows a typical modern one (but of a very old design) having a Vernier scale, with the major parts labeled. This one operates on the millimeter system.

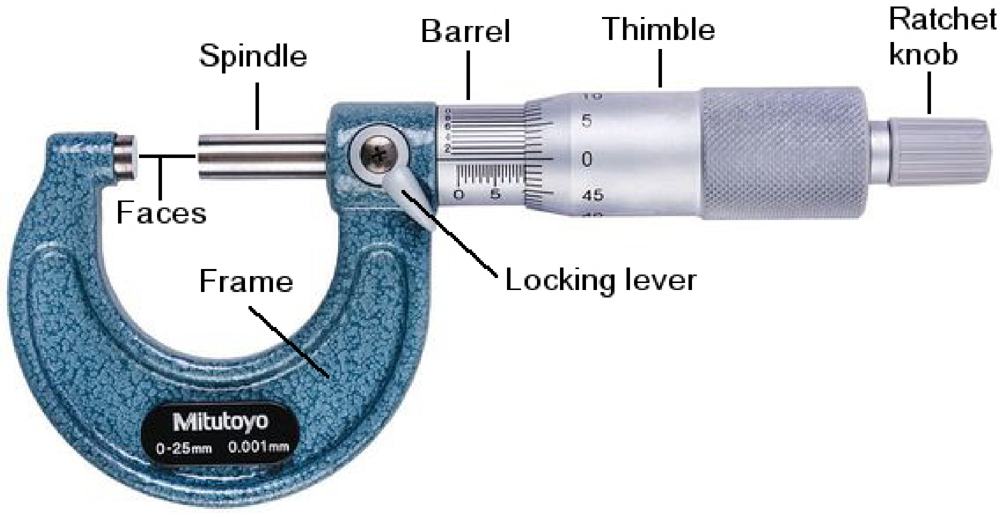

Figure 12. Mitutoyo 103-129 micrometer (mm)

The thimble turns the spindle, which has a thread with a pitch of 0.5 mm. Thus each full turn of the thimble moves the spindle a distance of 0.5 mm.

The “primary” scale (my term) is on the barrel, and is read at the left tip of the thimble. Its minor divisions are at a pitch of 0.5 mm, with longer lines at each millimeter, and it is labeled at intervals of 5 mm.

The “secondary” scale (again, my term) is around the tip of the spindle, and is read against the fiducial line running along the primary scale. It has 50 marks at intervals corresponding to 0.01 mm, labeled at intervals of 0.1 mm (0 through 40, in units of 0.01 mm), with a range of 0.5 mm per revolution.

If this were the end of the story (i.e., if there were no vernier scale), this micrometer could be explicitly read to a resolution of 0.1 mm. It does, in fact, have a Vernier scale, but I will discuss that shortly with a close-up illustration.

For most consistent readings, it is necessary to control the torque applied to the thimble as the jaws close on the part. The reaction to the force on the jaws springs the frame, although by a small amount.

Machinists were once taught to master the application of a consistent torque. Modern micrometers have a feature to take care of that. In the style shown, the thimble is turned with the ratchet knob. In the “tightening” direction, the ratchet will slip at a certain torque. (In the "loosening" direction, the ratchet is engaged, so as much torque as is needed to "disengage" the micrometer can be applied with the ratchet knob.

7.2 Vernier scale on a micrometer

Now we will finally get to the real story here: the application of the Vernier scale to a micrometer. In figure 13 we see the battle zone of a typical application (similar in this matter to the model seen in figure 12).

Figure 13. Vernier scale on a micrometer (millimeter)

As we saw before, the primary scale has marks at intervals of 0.5 mm, labeled at multiples of 5 mm. And the secondary scale, around the tip of the thimble, has 50 marks at intervals corresponding to 0.01 mm, with a range of 0.5 mm per revolution.

The vernier scale has 10 lines (and does not use the fiducial line as one of them, as described in section 5.3). They have values of 1-9 and then 0, which represent increments of 0.001 mm. Only the even numbered ones are labeled. The lines are long enough that the scale can work as intended regardless of the position of the thimble.

The result is that the micrometer can be read explicitly with a resolution of 0.001 mm (1 μm).

Note that the "mechanical multiplication" given by the thread system of the Vernier micrometer gives it a finer resolution that that of a typical Vernier caliper.

The "inch" Vernier micrometers of this general style can be read to 0.0001" ("a tenth"). That is "more coarse" (by about 2.5 times) than for the millimeter micrometer. a result of making both work in "rational" decimal subunits of the two systems.

8 RESOLUTION VS. ACCURACY

Note that the fineness of the resolution with which an instrument can be read (sometimes spoken of as its "precision") does not tell us how "accurate" the measurement is. One could imagine an instrument that reported a dimension as 47.38 mm, whereas the actual dimension was 47.2326 mm. But of course available "precision" instruments typically have accuracy (or "tolerance") values only perhaps 1.5 or 2.0 times their resolution values.

9 IN OTHER THAN MEASURING INSTRUMENTS

The discussion above has been cast in the context of mechanical measuring instruments, as that is where the Vernier scale is most often encountered. But is has also been equally valuable in apparatus where some distance must be set precisely, perhaps in connection with some scientific experiment, or to set some machine tool.

The principle is just the same, although of course the way the scale is deployed and its numerical properties may differ substantially from what is discussed here.

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