

The Impossible is Possible! Squaring the Circle in Euclidean Space-Time

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Abstract

Squaring the Circle is a famous geometry problem going all the way back to the ancient Greeks. It is the great quest of constructing a square with the same area as a circle using a compass and straightedge in a finite number of steps. Since it was proved that π was a transcendental number in 1882, the task of Squaring the Circle has been considered impossible. Here, we will show it is possible to Square the Circle in Euclidean space-time. It is not possible to Square the Circle in Euclidean space alone, but it is fully possible in Euclidean space-time, and after all we live in a world with not only space, but also time. By drawing the circle from one reference frame and drawing the square from another reference frame, we can indeed Square the Circle. By taking into account space-time rather than just space the Impossible is possible! However, it is not enough simply to understand math in order to Square the Circle, one must understand some “basic” space-time physics as well.

Key words: Squaring the circle, Einstein special relativity theory, Euclidian space-time, length contraction, length transformation, relativity of simultaneity.

1 Introduction

Before Lindemann (1882) proved that π was a transcendental number¹ there was a long series of attempts to square the circle. Hobson (1913) did a thorough job in reviewing and describing the long and interesting history of squaring the circle, and he concluded:

It has thus been proved that π is a transcendental number...the impossibility of “squaring the circle” has been effectively established. – Ernest Hobson

To get an idea of the impossibility of squaring the circle consider that we make a circle with radius $r = 1$, then the area of the circle must be $\pi r^2 = \pi$. To get a square with area π the length of each side must be $\sqrt{\pi}$. To construct a square with sides exactly $\sqrt{\pi}$ is impossible with only a compass and a straightedge in a finite number of steps.

In more recent times there have been a few claims of Squaring the Circle for certain non-Euclidean spaces such as the hyperbolic plane, also known as Bolyai–Lobachevskian geometry, see Jagy (1995) and Greenberg (2008). Still these “claims” have been overoptimistic. For example, there are no squares as such in the hyperbolic plane.

One cannot square the circle in Euclidean space alone, however as we will prove: *One can Square the Circle in Euclidean Space-Time* (at least hypothetically), and we are clearly living in Euclidean space-time and not only in space. Once we take into account how observations of time and distance are affected by motion then it surprisingly becomes possible to square the circle.

Before the late 19th century no one had figured out that the length of an object or the distance traveled or even time itself would be affected by how fast we moved. Interestingly, just a few years after it

*Thanks to my illustrator Line Halsnes for taking a illustration draft into the most wonderful illustration, and thanks to Victoria Terces for helping me editing this manuscript into a Golden thread.

¹Hermes (1873) had just years before proved that e was a transcendental number.

was proven that π was transcendental we got a break through in understanding that distances and time were affected by motion. FitzGerald (1889) was the first to suggest that the null result of the Michelson–Morley speed of light experiment possibly could be explained by assuming that the length of any material object (including the earth itself) contracts along the direction in which it is moving through the ether, or as explained in his own words:

I would suggest that almost the only hypothesis that can reconcile this opposition is that the length of the material bodies changes according as they are moving through the ether or across it, by an amount depending on the square of the ratio of their velocity to that of light.
– FitzGerald, May 1889

Lorentz (1892) mathematically formalizes length contraction, suggesting that objects and any type of matter that travels against the ether has to contract by $\sqrt{1 - \frac{v^2}{c^2}}$, where v is the speed of the object against the ether and c is the well-known experimentally tested speed of light.²

Larmor (1900) added time-dilation³ to the FitzGerald and Lorentz length contraction and was the first to develop a mathematical theory that is fully consistent with the null result of the Michelson–Morley result. Bear in mind that FitzGerald, Lorentz and Larmor all still assumed the ether existed and it was originally to “save” the ether that they introduced length contraction and time dilation. Even the famous mathematician and physicist Henry Poincaré believed in the presence of the ether. Still, in 1905 Poincaré concluded that it would be impossible to ever detect the earth’s motion against the ether. Henry Poincaré therefore suggested to synchronize clocks a distance apart using the “assumption” that the one-way speed of light for synchronization purpose was the same as the well-tested round-trip speed of light. Einstein instead abandoned the ether and assumed that the true one-way speed of light was the same as the round-trip speed of light and used this assumption to synchronize his clocks.

Bear in mind that FitzGerald and original Lorentz length contraction is actually not mathematically the same as Einstein (1905, 1916) length contraction, this even if it looks mathematically identical at first sight. For example, Patheria (1974) points out correctly that there is a major difference between FitzGerald and Lorentz transformation on one side and Einstein length transformation on the other side:

It must be pointed out here that the contraction hypothesis, put forward by FitzGerald and Lorentz, was of entirely different character and must not be confused with the effect obtained here [Einstein length contraction]. That hypothesis did not refer to a mutually reciprocal effect; it is rather suggesting a contraction in the absolute sense, arising from the motion of an object with respect to the aether or, so to say, from ‘absolute’ motion. According to a relativistic standpoint, neither absolute motion nor any effect accruing therefrom has any physical meaning.⁴

After Lorentz became heavily influenced by the view of Poincaré he seems to have changed his own view that motion against the ether likely not could be detected, so we should probably look at the speed v in the Poincaré (1905) adjusted Lorentz transformation⁵ as the relative speed between frames rather than the speed against the ether, even though Lorentz not is very clear on this point in 1904. With this in mind, it is not incorrect to use the term *Lorentz contraction* in the Einstein theory for length contraction as many physicists do today. Personally I like to distinguish between FitzGerald and the (original) Lorentz contraction: on the one hand where the speed v represents the velocity against the ether, and on the other hand in the Einstein theory, where v represents the relative velocity as measured with Einstein–Poincaré synchronized clocks. Even if several different relativity theories exist we will concentrate on Squaring the Circle inside Einstein’s special relativity theory here, that is inside what we can call Euclidian Einstein space-time.

2 Squaring the Circle in Space-Time

We will show that we can draw a square with area π without relying directly on π , but only indirectly on π . Assume a train platform (embankment) and a train. We first draw a circle on the embankment using only a compass, see figure 1 upper panel. We can call the radius of the circle one, that is $r = 1$. It could be one cm, one inch, one meter or whatever radius we prefer. Next we mark a straightedge with the compass so we have a length equal to the radius of the square. Next we build a perfect square based

²More precisely the well tested round-trip speed of light.

³Time dilation has been proven in a series of experiments, see for example Hafele (1970), Hafele and Keating (1971b,a) and Bailey and et al. (1977).

⁴See Patheria (1974) page 41.

⁵Which is the one referred to when physicists today talk about the Lorentz transformation.

on this length. In other words, we have constructed a one by one square, also known as a unit square. This square should be built in a solid material that we can transport.

Next we will move the square on board a train. This train is currently at rest relative to the embankment. Then we accelerate this train to a very fast velocity relative to the embankment; we will get back to exactly what velocity later. Naturally, we could just as well have constructed the square on the train while the train was standing still relative to the embankment or later while the train was moving relative to the embankment. What is important is that we build the unit square (side length equal to the radius of the circle) in and from the frame it is at rest in.

So far we have “only” worked in space, now we also need to work a little in time. At each corner of the square we mount a clock. Next we will synchronize these clocks using the Einstein clock synchronizing procedure. That is to say we are synchronizing the clocks with light signals assuming that the one-way speed of light is isotropic and the same as the well-tested round-trip speed of light.

Next we hang the square with the clocks out on the side of the train. At each clock we have connected a laser. At a given point in time, each clock will simultaneously trigger the lasers. Bear in mind the lasers are fired simultaneously as observed from the train. Einstein’s relativity of simultaneity means that the lasers on the train are not fired simultaneously as observed from the embankment. The embankment is covered with photosensitive paper. The lasers (photons) will hit the embankment and make a mark for each corner. See figure 1 middle and lower panels.

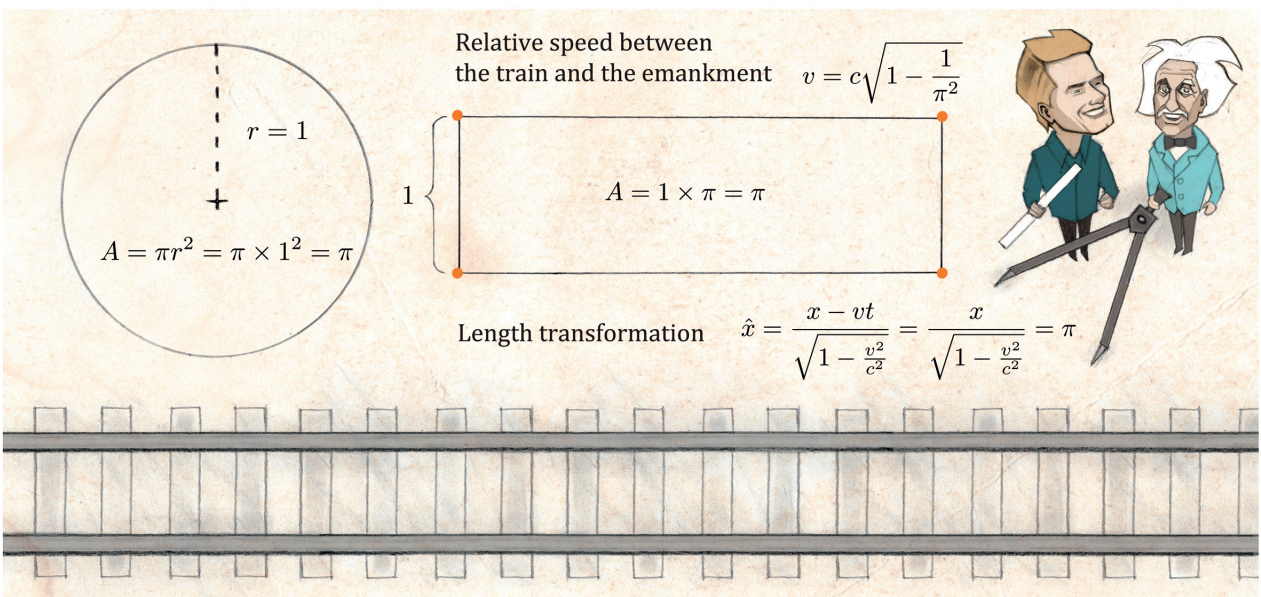
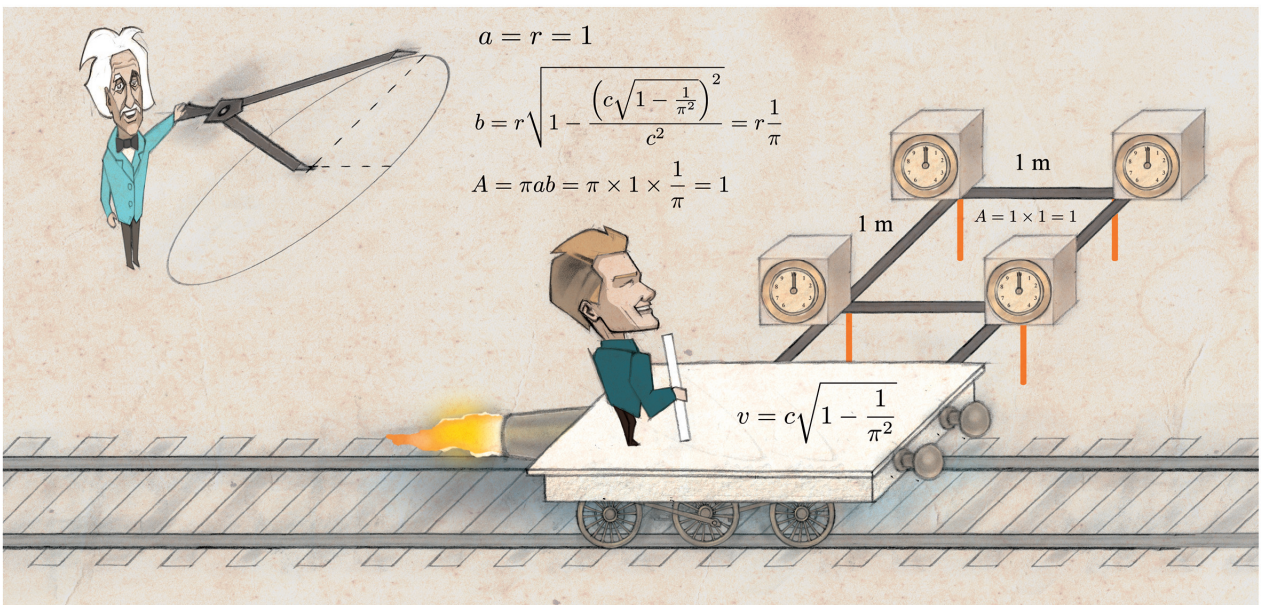
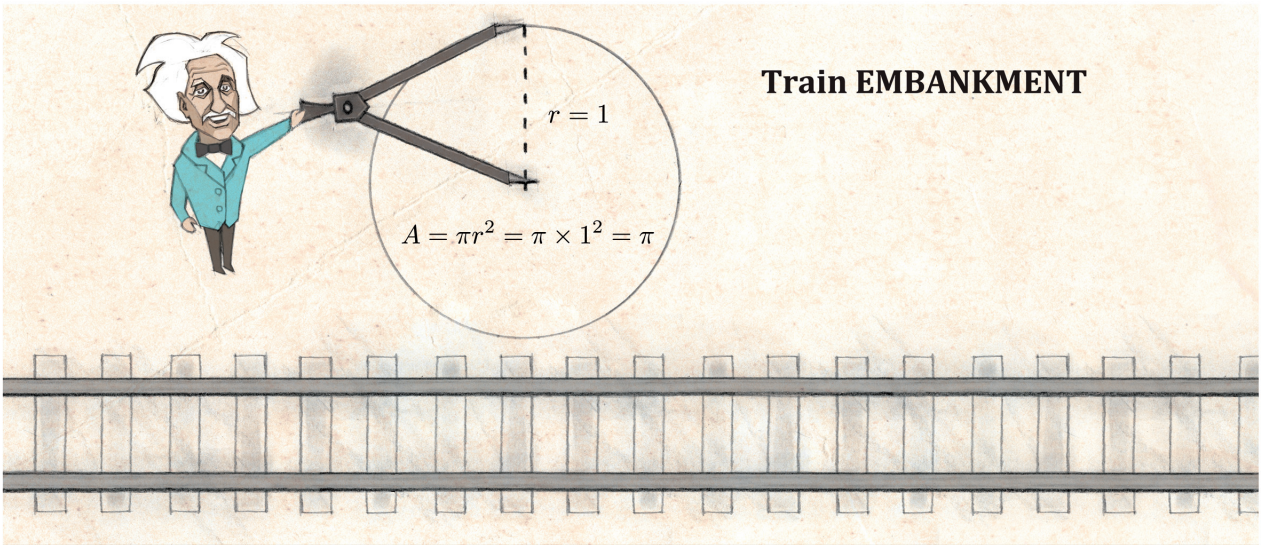
There is no length contraction in the transverse direction, so the distance between the two laser marks on the embankment in the transverse direction on the embankment must be one (for example 1 meter). However in the parallel direction we will have length contraction. The distance between the marks on the embankment will appear contracted from the train. Remember we are going to try to Square the Circle that is to make the area of the square equal to the circle. The area of the circle is π . The transverse length of the square is one. What is the speed of a train (second frame) that will give the sides of π in the embankment, but only 1 from the frame we draw the sides from (the train)? We must have a length contraction factor β equal to $\frac{1}{\pi}$ to accomplish this since $\pi \times \frac{1}{\pi} = 1$. This means we get the following equation to solve based on special relativity theory. Assume that \bar{v} is the percentage of the speed of light c that the two frames are traveling relative to each other. That is $\bar{v} = \frac{v}{c}$. Further assume $y = \bar{v}^2$, then we must have

$$\begin{aligned}
 \frac{1}{\pi} &= \beta \\
 \frac{1}{\pi} &= \sqrt{1 - \frac{v^2}{c^2}} \\
 \frac{1}{\pi} &= \sqrt{1 - \frac{\bar{v}^2 c^2}{c^2}} \\
 \frac{1}{\pi} &= \sqrt{1 - \bar{v}^2} \\
 \frac{1}{\pi} &= \sqrt{1 - y} \\
 \frac{1}{\pi} &= \sqrt{1 - y} \\
 \left(\frac{1}{\pi}\right)^4 &= y^2 - 2y + 1 \\
 \frac{1}{\pi^4} &= y^2 - 2y + 1 \\
 y^2 - 2y + 1 - \frac{1}{\pi^4} &= 0.
 \end{aligned} \tag{1}$$

This is a quadratic equation with the following solution

$$\begin{aligned}
 y &= \frac{2 \pm \sqrt{2^2 - 4\left(1 - \frac{1}{\pi^4}\right)}}{2} \\
 y &= \frac{2 \pm \sqrt{4 - 4\left(1 - \frac{1}{\pi^4}\right)}}{2} \\
 y &= 1 \pm \sqrt{\frac{1}{\pi^4}}
 \end{aligned}$$

Figure 1: Squaring the Circle.



$$y = 1 \pm \frac{1}{\pi^2} \quad (2)$$

Remember $y = \bar{v}^2$, this means

$$\begin{aligned} \bar{v} &= \sqrt{y} \\ \bar{v} &= \sqrt{1 \pm \frac{1}{\pi^2}} \end{aligned} \quad (3)$$

as we must have $\bar{v} \leq 1$ only the negative solution makes sense and we get

$$\bar{v} = \sqrt{1 - \frac{1}{\pi^2}} \quad (4)$$

and this means we must travel at the following speed relative to the frame where the circle and the square is at rest when drawing (or observing) the square to Square the Circle⁶

$$v = c\sqrt{1 - \frac{1}{\pi^2}} \quad (5)$$

and we have

$$\begin{aligned} 1 &= \pi\beta \\ 1 &= \pi \times \sqrt{1 - \frac{\left(c\sqrt{1 - \frac{1}{\pi^2}}\right)^2}{c^2}} \\ 1 &= \pi \frac{1}{\pi} \end{aligned} \quad (6)$$

This means that when we have two frames traveling at a relative speed⁷ of $v = c\sqrt{1 - \frac{1}{\pi^2}}$ we can indeed Square the Circle. There is nothing wrong with drawing the square in one frame and then “transferring” it to another frame. Some people might claim that this is bending the rules. This is partly true, but there were no rules about how fast we could move the pen, or if we should calculate the area as observed from the square itself, or from the moving pen (train) that is drawing it. We will return to some self-criticism a bit later in this paper. And as we soon will see this solution contains two solutions, including a simpler solution that we will discuss.

In Einstein’s special relativity theory, length contraction is reciprocal. So we could just as well have drawn the circle on board of the train and then we could draw the square⁸ in the train from the embankment. The situation would be symmetrical. The velocity of the train relative to the embankment is the same as the velocity of the embankment relative to the train as long as they are measured with Einstein-Poincaré synchronized clocks.

3 Checking the area

Again the circle is drawn on the embankment (or on the train) and the square is drawn on the train and then transferred to the embankment from the train, or visa versa. The circle is drawn with radius $r = 1$ as observed from the embankment frame, and the square is initially drawn with sides 1 by 1 from the frame it is at rest in.

The observer on the embankment sees a circle with radius one and a rectangle with sides 1 by π , both at rest on the embankment. The area of the circle is π and the area of the rectangle is π . The observer on the train can check the areas. The train observer sees a perfect square (a unit square) with area 1, the square is at rest with respect to the train. The circle (that is at rest on the embankment) is observed as an ellipse by the train observer. Figure 2 illustrates how the two different frames observe the circle (ellipse) and the square (rectangle).

As there is no length contraction in the transverse direction, the ellipse semi-major as observed from the train is the same as the radius of the circle as observed from the embankment, that is r . The semi-minor axis on the ellipse is contracted as observed from the train and must be

⁶The square is not a square from the rest frame, but from the observer frame. We are constructing from the observer frame.

⁷As measured with Einstein-Poincaré synchronized clocks.

⁸Or at least the side lines for the square.

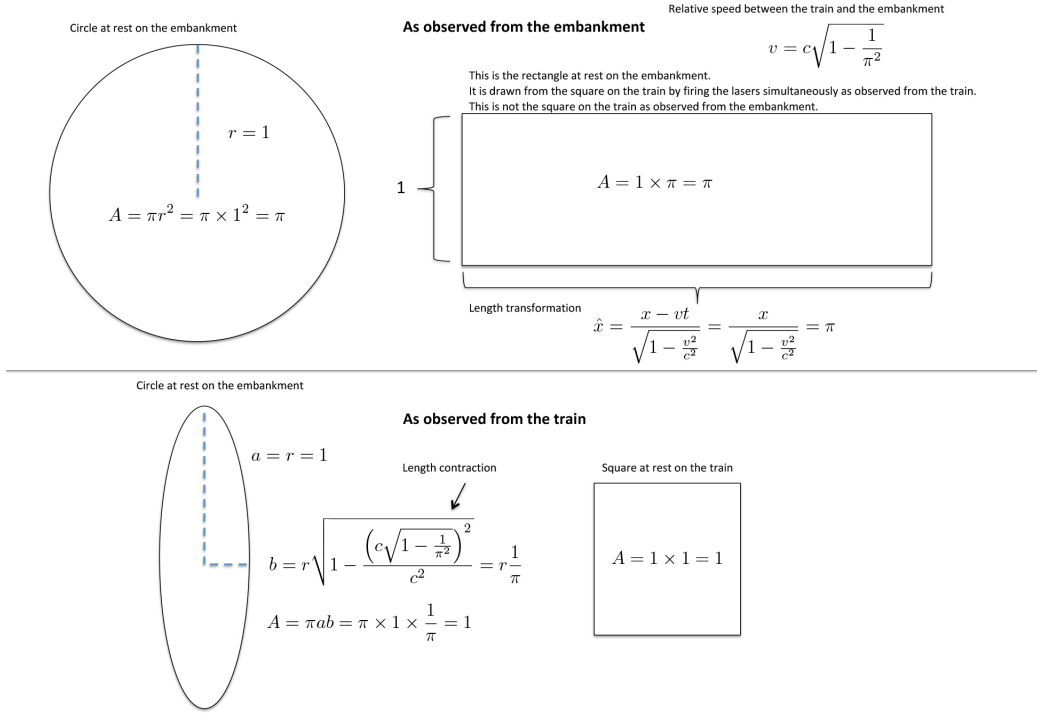


Figure 2: Comparison between embankment frame and the train frame.

$$r\sqrt{1 - \frac{\left(c\sqrt{1 - \frac{1}{\pi^2}}\right)^2}{c^2}} = r\frac{1}{\pi}. \quad (7)$$

And if we have chosen radius $r = 1$ this gives a semi-minor axis of $\frac{1}{\pi}$. The area of an ellipse is given by $A_{ellipse} = \pi ab$, where a and b are the semi-major and the semi-minor axes respectively. This gives us an area of the ellipse of $A_{ellipse} = \pi \times 1 \times \frac{1}{\pi} = 1$. This is the same⁹ as the area of the square on board the train as observed from the train.

Bear in mind that in the solution as observed from the train, we do not need to have any clocks mounted to the square to make marks on the embankment. Here we simply draw a unit circle on the embankment (in one frame) as observed from the embankment and then we draw a unit square on board the train from the train, for example on the floor of the train. The square can be drawn on board the train while we are standing still relative to the embankment, or later while we are moving relative to the embankment. Now we simply observe the circle on the embankment from the train. The circle will appear as an ellipse and the area of the ellipse and the square are the same: they are one. A drawn unit circle has the same area as a drawn unit square, quite remarkable indeed.

Both the train observer and the embankment observer can agree that the area of the circle and the square are identical. However, the embankment observer will claim that the square is a rectangle and the train observer will claim that the circle is an ellipse. Still, the circle was drawn and observed as a circle by the drawer and the square was drawn and observed as a square by the drawer. We have indeed Squared the Circle! And this seems to be the “only“ way to square a circle in Euclidian Einstein space-time.

4 How can this be?

Einstein's special relativity theory predicts reciprocal length contraction. Assume two identical meter sticks are made in the same reference frame $L = 1$. Next one of the meter sticks is carried on board the train. The train is accelerated to a speed of $c\sqrt{1 - \frac{1}{\pi^2}}$. Now from the train the meter stick at rest on the

embankment will be observed to have length contracted and have a length of: $1 \times \sqrt{1 - \frac{\left(c\sqrt{1 - \frac{1}{\pi^2}}\right)^2}{c^2}} \approx 0.3183$. At the same time the meter stick at rest in the train will be observed to have length ≈ 0.3183 as

⁹I must admit that I am not an expert on the area of ellipses, and I am not fully certain if this formula for the area of an ellipse created in this way is exact.

observed from the embankment. In Einstein's special relativity theory, length contraction is reciprocal. Still, in the section above we claimed that the laser signals sent out simultaneously (simultaneously as observed from the train) will make marks on the embankment that have a distance between them of π meters. How can a one meter stick in the train that is observed to be contracted from the embankment actually make marks on the embankment that are π meters apart?

The signals sent out simultaneously from each end of the rod (the rods making up the unit square) at rest in the train will not be observed to be sent out simultaneously from the embankment. Events happening simultaneously on the train as observed with Einstein synchronized clocks will from the embankment have an observed time difference of

$$\frac{Lv}{c^2 \sqrt{1 - \frac{v^2}{c^2}}}. \quad (8)$$

This is well-known from Einstein's theory as the relativity of simultaneity.¹⁰ Where L is the length of the rod as observed from the frame it is at rest in, for example 1 meter, the distance between the marks on the embankment from the lasers sent out from the two ends of rod simultaneously as measured from the train will make marks at the embankment with the following distance apart as measured from the embankment

$$\begin{aligned} & L\sqrt{1 - \frac{v^2}{c^2}} + \frac{Lv}{c^2 \sqrt{1 - \frac{v^2}{c^2}}}v \\ & \frac{Lc^2 \left(1 - \frac{v^2}{c^2}\right)}{c^2 \sqrt{1 - \frac{v^2}{c^2}}} + \frac{Lv^2}{c^2 \sqrt{1 - \frac{v^2}{c^2}}} \\ & \frac{L}{\sqrt{1 - \frac{v^2}{c^2}}} \end{aligned} \quad (9)$$

and since $v = c\sqrt{1 - \frac{1}{\pi^2}}$ we get

$$\frac{L}{\sqrt{1 - \frac{\left(c\sqrt{1 - \frac{1}{\pi^2}}\right)^2}{c^2}}} = \frac{L}{\sqrt{1 - \frac{c^2\left(1 - \frac{1}{\pi^2}\right)}{c^2}}} = L\pi \quad (10)$$

and if $L = 1$ meter then the length between the two marks on the embankment between the square sides parallel to the railroad will be π meters. This is just another way to check that our results in the previous section are correct and consistent with Einstein's special relativity theory. That we can Square the Circle in Euclidian Einstein space-time is also strongly related to how clocks are synchronized in special relativity theory: the clocks are Einstein (Poincarè) synchronized. We could also have found this directly from the Lorentz transformation:

$$\hat{x} = \frac{x - vt}{\sqrt{1 - \frac{v^2}{c^2}}}.$$

In the train frame the lasers (actually 4 if one includes each corner) are fired simultaneously as observed from Einstein synchronized clocks in the frame where the lasers-clocks are at rest relative to each other. This means the time between the clocks fired as observed from this frame must be $t = 0$. When the relative speed between the two frames as measured with Einstein synchronized clocks is $v = c\sqrt{1 - \frac{1}{\pi^2}}$ we get the following length transformation:

$$\hat{x} = \frac{x - c\sqrt{1 - \frac{1}{\pi^2}} \times 0}{\sqrt{1 - \frac{\left(c\sqrt{1 - \frac{1}{\pi^2}}\right)^2}{c^2}}} = x\pi \quad (11)$$

where x is the distance between two events in the rest frame, in this case the distance between the lasers on the straightened on the train, that is $x = L$. Further \hat{x} is the distance between these points plus the distance the train traveled in the time difference between these two lasers firing as measured

¹⁰Equation 8 is well known from the literature, see for example Comstock (1910), Carmichael (1913), Dingle (1940), Bohem (1965) and Krane (2012). The formula follows directly from the Lorentz transformation.

from the other frame. The length transformation takes into account length contraction and relativity of simultaneity.

We could also have Squared the Circle using other relativity theories, such as the ether theory of Joseph Larmor from 1900. One of the main differences would be that the Squaring of the Circle would not be reciprocal between the frames then, see Haug (2014) for detailed discussion on this topic. In this article we will limit ourselves to squaring the circle under Einstein's special relativity theory, which involves Einstein synchronization of clocks. However, this is more than just a theory; when using Einstein synchronized clocks these predictions are actually aligned with how we would observe the world in relation to squaring the circle.

5 Summary of procedure

In this section we shortly summarize the procedure for Squaring the Circle:

Solution one:

1. We are drawing a unit circle on the embankment (reference frame one) with a compass.
2. Without changing the compass, we construct a square where each side has a radius equal to the radius of the circle. The square could be drawn on the floor of the train. The train is currently at rest relative to the embankment.
3. Accelerate the train to a speed relative to the embankment of $v = c\sqrt{1 - \frac{1}{\pi^2}}$ as measured from both the embankment and the train.¹¹ The relative speed between the reference frames is in Einstein's special relativity theory reciprocal.
4. The circle on the embankment will now be observed as an ellipse with the same area as the square from the train. In this case, both the ellipse (that was drawn as a circle) and the square would both have area 1 (rather than π) as observed from the train. In other words we have squared the circle.

Solution two:

1. Draw a circle on the embankment (reference frame one) with a compass. Choose any radius and call this radius one (one meter, one foot, one cm or any other length). The radius is the distance between the two points of the compass.
2. Without changing the compass, construct a square where each side has a radius equal to the radius of the circle. The square should be made of a robust material so we can move the square.
3. Move the square on board a train that is currently at rest relative to the embankment; alternatively we could have constructed the square directly on board the train while the train is standing still or while it is moving.
4. Accelerate the train to a velocity relative to the embankment of $v = c\sqrt{1 - \frac{1}{\pi^2}}$ as measured from both the embankment and the train.¹² The relative speed between the reference frames is in Einstein's special relativity theory reciprocal.
5. Mount a clock to each corner of the square. Synchronize these clocks using Einstein-Poincaré synchronization while the train is moving at velocity $v = c\sqrt{1 - \frac{1}{\pi^2}}$ relative to the embankment.
6. Simultaneously, as measured by the clocks in each corner of the perfect square on the train, fire the lasers. These laser signals will burn four dots on the ground. These dots will mark the corners of a rectangle as observed from the embankment. The length of the sides of the rectangle parallel to the railroad will be related to length transformation rather than length contraction. If the signals arrived simultaneously as observed from the embankment, then it would be length contraction rather than length transformation. The square on the train is indeed observed as length-contracted from the embankment, but not the transferred square (rectangle)
7. Measure the area of the circle and the square and they will have the same area. From the train the circle is observed to have an elliptical shape and the square is a unit square. From the embankment the circle is a circle and the square is a rectangle. The areas of the circle and the square, both as observed from the train, are the same, namely one. The area of the circle and the transferred square (the rectangle on the embankment) have area π as observed from the embankment. In other words we have squared the circle.

¹¹This speed is as measured with Einstein synchronized clocks.

¹²This speed is as measured with Einstein synchronized clocks.

Solution two also contains solution one. Solution one is the simplest as it does not need the clocks and the lasers in each corner of the square. We could also have done this the other way around. That is to draw the unit circle onboard the train and to draw the unit square on the embankment. The result would be the same as above.

6 More general solution

The solution above only holds between a unit circle and a unit square. Here we will see if there is a more general solution. Again assume that we have drawn a unit circle, then what is the limitation we have on the length of the sides of the square and what is the velocity we need to travel at when transferring this square to the other frame? By transferring I mean when using the square that we move to fire the lasers simultaneously to mark the embankment. This time $\bar{v} = \frac{v}{c}$ and $y = \bar{v}^2$. We get the following equation to solve,

$$\begin{aligned}
 \frac{L^2}{\pi} &= \sqrt{1 - \frac{v^2}{c^2}} \\
 \frac{L^2}{\pi} &= \sqrt{1 - \frac{v^2}{c^2} \frac{c^2}{c^2}} \\
 \frac{L^2}{\pi} &= \sqrt{1 - \bar{v}^2} \\
 \frac{L^2}{\pi} &= \sqrt{1 - \bar{v}^2} \\
 \frac{L^2}{\pi} &= \sqrt{1 - y} \\
 \left(\frac{L^2}{\pi}\right)^4 &= y^2 - 2y + 1 \\
 \frac{L^8}{\pi^4} &= y^2 - 2y + 1 \\
 y^2 - 2y + 1 - \frac{L^8}{\pi^4} &= 0.
 \end{aligned} \tag{12}$$

This is a quadratic equation with the following solution

$$\begin{aligned}
 y &= \frac{2 \pm \sqrt{2^2 - 4\left(1 - \frac{L^8}{\pi^4}\right)}}{2} \\
 y &= \frac{2 \pm \sqrt{4 - 4\left(1 - \frac{L^8}{\pi^4}\right)}}{2} \\
 y &= 1 \pm \sqrt{\frac{L^8}{\pi^4}} \\
 y &= 1 \pm \frac{L^4}{\pi^2}.
 \end{aligned} \tag{13}$$

Remember that $y = \bar{v}^2$, this means

$$\begin{aligned}
 \bar{v} &= \sqrt{y} \\
 \bar{v} &= \sqrt{1 \pm \frac{L^4}{\pi^2}}
 \end{aligned} \tag{14}$$

as we must have $\bar{v} \leq 1$ only the negative solution makes sense and we get

$$\bar{v} = \sqrt{1 - \frac{L^4}{\pi^2}} \tag{15}$$

and this gives us the relative speed of the frames

$$v = c\sqrt{1 - \frac{L^4}{\pi^2}}. \quad (16)$$

Further in equation 16 we must have $\frac{L^4}{\pi^2} < 1$. Solved with respect to L this gives us

$$\begin{aligned} \frac{L^4}{\pi^2} &< 1 \\ L^4 &< \pi^2 \\ L &< \sqrt{\pi} \end{aligned} \quad (17)$$

when $L = \sqrt{\pi}$ then $v = 0$ and then it is not possible to square the circle, as we already know. In other words it is not possible to square the circle from only one reference frame, we need to use two reference frames to square the circle. The general solution is that we can draw any square with sides shorter than $\sqrt{\pi}$. I assume all lengths $0 > L < \sqrt{\pi}$ that are not transcendental can be used to square a unit circle. A square with length L is constructed on the ground or in the train and then moved onto the train. Then the train is accelerated to the following velocity: $v = c\sqrt{1 - \frac{L^4}{\pi^2}}$. Or we could have accelerated the train first and then constructed the square on the train while it was moving relative to the embankment, this makes no difference. Next accurate clocks in each corner of the square are synchronized while traveling and the lasers are fired simultaneously as observed from the train to mark the embankment. The area of the square as measured from the embankment or the train will have the same area as the circle. Again the square on the embankment drawn from the train will be observed as a rectangle from the embankment, but it was initially drawn as a square.

As the general solution holds for any velocity between $0 > v < c$ we do not need a super-fast futuristic train or space-rocket to square the circle. When the sides of the square are very close to $\sqrt{\pi}$, we do not need all the digits of π in the sides of the square, as long as $v > 0$. For example, we could theoretically construct a printer where the printer head moves at speed v relative to the paper. The printer head consist of a square with each sides lengths very close to $\sqrt{\pi}$ as observed from the printer head. Simply think of the paper as the embankment and the printer head as the train in the example above. The printer head is a perfect square with sides L as observed from the printer head. In each corner of the printer head is a clock that is Einstein synchronized while the printer head moves at velocity v relative to the paper. The corners of the square are simultaneously firing a laser as measured from the printer head clocks. The laser marks on the paper as observed from the paper will not be a perfect square, but a rectangle. The circle is drawn to be a perfect circle as observed from the rest frame of the paper. Again this is just a parallel to the train example, which is much more realistic in the way that the printer head just needs to move at a speed $v > 0$ and not at a speed close to that of light. Still we like the first non-general solution the best from a mathematical point of view. It is almost like magic to draw a unit circle and a unit square that both end up having area 1, or alternatively π from the embankment.

7 A critical look at the solution

Have I really squared the circle? It is not the first time someone has claimed to have squared the circle. One of the longest and most intense intellectual disputes of all time was between philosopher Thomas Hobbes who claimed that he had squared the circle and the mathematician John Wallis who claimed Hobbes not had squared the circle, see Jesseph (2008). The conclusion was that Hobbes not had squared the circle.

One could claim the solution to squaring the circle in this paper simply has moved the problem into the velocity between the two reference frames. The velocity needed to square the circle is indeed a function of π . Still there was never mentioned any restriction on the velocity of the observer in the quest for squaring the circle. One could also argue that I am bending the rules by using clocks in addition to compass and a straightedge. Even in solution one, where we simply draw a circle in one frame and a square in another frame, we would need two Einstein-Poincaré synchronized clocks to measure the one-way velocity of the train. So any solution requires clocks, as we are working in space-time rather than just space, that is we take into account motion. Or one could naturally try to argue that we simply by coincidence could be traveling at velocity $v = c\sqrt{1 - \frac{L^4}{\pi^2}}$ and therefore not would need clocks to find this velocity.

In addition, one could also argue that I have bent the rules since the square and the circle I have constructed are not a square and a circle in the same reference frame. They are a circle and a rectangle as observed from one reference frame and an ellipse and a square from the other frame. Still, the circle was drawn as a circle and the square drawn as a square. Further, the area of the circle and the square are the same as observed from the embankment or as observed from the train.

There are indeed several reasons to claim I have bent the rules of squaring the circle slightly. Still one could just as well argue that the claimed impossibility of squaring the circle is rooted historically in that the quest premises were outlined before we had developed good space-time theories. In my defense, one has to keep track of time when working in space-time, and again we do not only live in space, we live in space and time. Previous solution attempts have not taken time into account, nor have they considered that time and space are affected by motion. Furthermore, previous solution attempts have not been clear on from what reference frame the circle and square are drawn from and what reference frame they are observed from. It is indeed possible to square the circle if one takes into account space and time and how space and time measurements are affected by motion.

In practice it would be close to impossible to get a velocity of exactly $v = c\sqrt{1 - \frac{L^4}{\pi^2}}$. Or at least this would require infinite precision in our measuring devices. However, this is more of a measuring problem than a Squaring the Circle quest problem (?).

8 Is length contraction for real?

A question that often comes up when someone mentions length contraction is if length contraction is for real. This is an important question that we not will resolve here, but that we will mention briefly. We have to be very careful with what we mean about “real”. We will claim that Einstein length contraction is real in the sense that this is what we will observe with Einstein synchronized clocks. Both length contraction and length transformation require a minimum of two clocks in the cases discussed here.

We need two clocks as we also need to know the relative speed between the frames. Part of the length contraction and length transformation has to do with the synchronization of clocks and relativity of simultaneity. After studying the subject carefully for years, we are convinced that our conclusion above holds as long as we use Einstein synchronized clocks and special relativity theory is based on Einstein synchronized clocks.

One should think this question was fully resolved, and possibly it is, but reading through a series of university text books covering special relativity theory one can at least see there are still slightly different views among physicists on whether length contraction is real or not. For example Shadowitz (1969) claims

If the measurements are optical then, to avoid an incorrect result, the light photons must leave the two points at the same time, as measured by the observers: they must leave simultaneously. It is clear that the process of length measurement is different from the process of seeing. Amazingly, this distinction was not noticed until 1959, when it was first pointed out by James Terrell.¹³

Further Lawden (1975) claims

The contraction is not to be thought of as the physical reaction of the rod to its motion and as belonging to the same category of physical effects as the contraction of a metal rod when cooled. It is due to changed relationship between the rod and the instruments measuring its length.¹⁴

While for example Rindler (2001) claims

This length contraction is no illusion, no mere accident of measurement or convention. It is real in every sense. A moving rod is really short! It could really be pushed into a hole at rest in the lab into which it would not fit if it were moving and shrunk.¹⁵

and Freedman and Young (2016) claims

Length contraction is real! This is not an optical illusion! The ruler really is shorter in the reference frame S than it is in S' .¹⁶

and Harris (2008) claims

It is a grave mistake to dismiss length contraction as an optical illusion caused by delays in light traveling to the observer from a moving object. This effect is real.¹⁷

On the other hand Krane (2012) seems to partly claim something different

¹³See Shadowitz (1969) page 61.

¹⁴See Lawden (1975) page 12.

¹⁵See Rindler (2001) page 62.

¹⁶Freedman and Young (2016) page 1229.

¹⁷Harris (2008) page 11.

*Length contraction suggests that the objects in motion are measured to have shorter length than they do at rest. The objects do not actually shrink; there is merely a difference in the length measured by different observers. For example, to observers on Earth a high-speed rocket ship would appear to be contracted along its direction of motion, but to an observer on the ship it is the passing Earth that appears to be contracted.*¹⁸

Einstein length contraction will be observed as described also in this paper as long as we use Einstein synchronized clocks. Einstein length contraction is reciprocal between frames, while for example the FitzGerald and Larmor use of length contraction is not reciprocal, because in ether theories one has a preferred reference frame. In special relativity theory any frame watching an object in another frame it will appear contracted. A frame making marks in the other frame will, on the other hand, seem expanded. However this length expansion is due to length transformation as well as length contraction. Length contraction and length transformations are linked, but they are not the same.¹⁹

In our case we are actually making a circle in the rest frame of the circle so here there should be no disputes. The square we are first making on the train, but we are transferring it to the embankment by lasers in solution two. These laser pens are fired simultaneously as observed from the pen. The pen is the train or even a printer head that travels at speed $c\sqrt{1 - \frac{L^4}{\pi^2}}$ relative to the paper. The lasers are not fired simultaneously as observed from the embankment and this is the reason that we get a rectangle on the embankment. Our theory is fully consistent with Einsteins special relativity theory, and could at least hypothetically be performed in practice with the expected result we have described above.

9 Conclusion

It is possible to Square the Circle by constructing the circle and the square from two different reference frames traveling at speed $v = c\sqrt{1 - \frac{L^4}{\pi^2}}$ relative to each other.²⁰ More precisely it is not possible to Square the Circle in Euclidean space using only a compass and straightedge, but it is possible to Square the Circle in Euclidean space-time using compass, straightedge and Einstein synchronized clocks. We could argue that this is bending the rules and moving the problem of transcendental π into a transcendental velocity between the reference frames rather than directly into the construction of the Circle and the Square. Still, one could just as well argue that the previous attempts to square the circle have not taken into account that observations of space and time are affected by motion and that space and time are closely connected.

Have I really Squared the Circle? Have I made the Impossible Possible? Only space-time can tell if this paper leads to celebration, silence, death, or an intellectual War similar to that between Hobbes and Wallis. Before you shoot the messenger make sure you have studied length contraction, length transformation and relativity of simultaneity rigorously.

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¹⁸Krane (2012) page 35.

¹⁹See also Haug (2014).

²⁰As measured with Einstein synchronized clocks.

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From the Back of The Unicorn

There exists a circle with centrum everywhere and circumference no where!
The Circle said to me: To Square the Circle will be Your final Test!

With a compass I drew a unit Circle on the ground!
I was thinking of a Unicorn, and then it came to me a Unit Square!
On the back of the Unicorn I drew a Unit Square using a straightedge.

From the back of the swift Unicorn,
the area of circle was the same as the area of a unit square, they are one!
I have Squared the Circle!
I passed the final test!
But this is not my final Quest!

