CLOCK AND WATCH ESCAPEMENT MECHANICS

Mark V. Headrick (Copyright 1997).

Section 1: Clock Escapements.

The first nine chapters are explained without math. These chapters are less complicated, and they introduce the reader to the logic behind the drawing techniques, so as to serve the needs of those who want to learn about escapements but would not be drawing them on their own computers. The tenth chapter explains the math behind the previous chapters. This way the reader has the option whether or not to become involved with the math.

References:

Britten's Watch & Clock Maker's Handbook, Dictionary and Guide (1978 Edition).

Donald de Carle: Watch and Clock Encyclopedia (1977 Edition).

Henry B. Fried: The Watch Escapement (1974 Edition).

View animations of the escapements in this book on my website at
http://www.geocities.com/mvhw/

Section 2: Watch Escapements.

Chapters 12 to 18 are similarly presented in order to introduce the reader to the logic behind the drawings, though these drawings are more involved and require some understanding of watch theory, such as lock, drop, draw, and impulse. Chapter 19 and beyond become more involved with the math that is required to create the drawings. The reader who does not want to become involved with the math could benefit from the logic of the latter chapters by passing over the math.

I would like to thank the following for their invaluable assistance and encouragement:

Daniel Henderson — Cecil Mulholland

Roy Hovey — Steve Conover

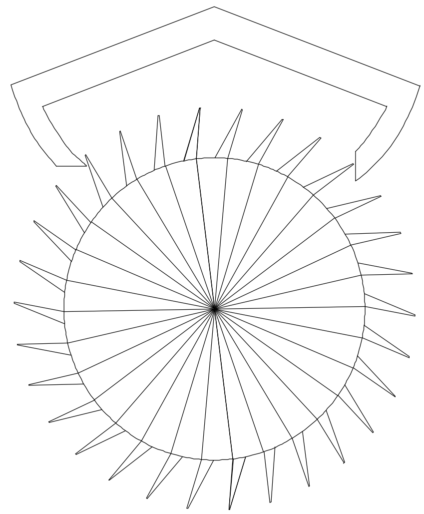
Nino Gonzales — Harry and Sue Wysong

Introduction.

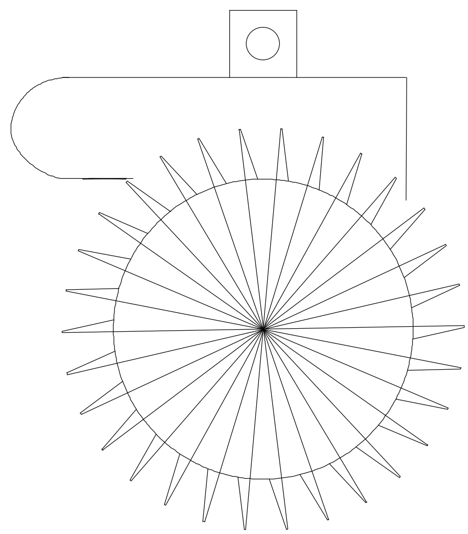
Discover how much more there is to know about escapements by creating your own drawings. The purpose of this project is to introduce the reader, whether professional or hobbyist, to a hands-on method for drawing a mechanical clock or watch escapement. While it is more obvious that a manufacturer needs to know how to design a pallet, the repairman could do a better repair with an improved understanding of design theory. The ability to draw an escapement enables one to experiment more easily with the effects of changing the variables and to compare different types of escapements, their similarities and differences.

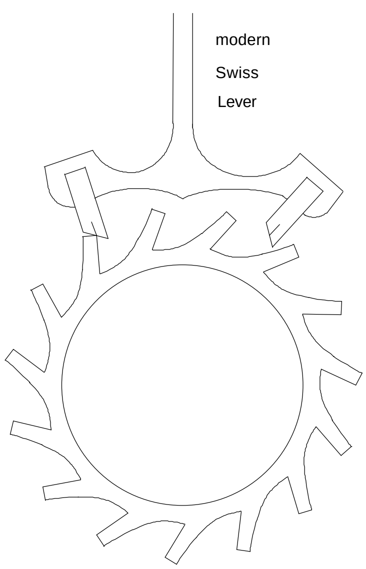
The most important reason for careful attention to design is efficiency. The escapements most frequently encountered at the bench are the Recoil, the Graham (or dead-beat), and the Swiss Lever. These all have efficiencies *below 50%*. This means that more than half the power is lost in the escapement alone, after all the power losses in the gear train.

Graham escapement



Strip-pallet recoil





These drawings are not dissimilar to what I have seen in escapement literature. They do not reveal the methods by which they were designed, why the lines and curves are positioned so. If these drawings ignite your curiosity, this project is for you.

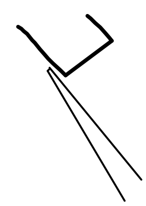
1: Efficiency and Power Losses.

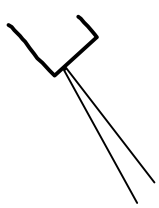
A clock is usually taken to the shop for repair because the clock fails to keep running. It runs for a while and stops because not enough power reaches the pendulum to keep it running. One way to get it running is to double the weight, but this causes enormous wear and consequent damage in the long run. The other way is to overhaul the clock. The job of the repairman is to do whatever is necessary to minimize the power losses between the weight and the pendulum. The clock is cleaned. Pivots are polished. Worn bushings are replaced. Adjustments are made to the escapement to improve its action. The clock is carefully lubricated. Other repairs are made as needed. These all have the ultimate goal of reducing power losses.

There are two kinds of power losses in a clock: frictional losses and losses caused by the action of the escapement (which result in additional frictional losses). Frictional losses are easily understood. The lubricant has failed, causing drag. The bushings are worn, so the gear and pinion teeth grind together. The pivots are scored, causing frictional losses from rough surfaces. Dirt particles become imbedded in the worn bushing, causing binding of the pivot, and so on.

Power losses caused by the action of the escapement are less obvious. The following reasons are explained in detail in subsequent chapters. If the escape wheel rotates clockwise, the force it exerts on the pallet would be in a different direction to that of the pallet's movement. The greater the angle between the two directions, the greater the loss of power as it is transferred from the escape wheel to the pallet. Consider that the pallets rotate clockwise as the escape tooth pushes on the entry pallet, and counterclockwise as the tooth pushes on the exit pallet, yet the escape wheel continues to rotate in the same clockwise direction.

As the escape tooth pushes on the pallet, the tooth exerts a force in the same direction as its direction of travel at that point. If the point of contact on the pallet were at 90º to this direction, such as on the locking face of the Graham pallet, the escape tooth would not move forwards and no power would be transferred to the pallet.





If the point of contact were in the same direction as the escape tooth, so that the pallet's impulse face were parallel to the path of the tooth, the tooth would pass by freely and provide no impulse to the pallet.

No power is transferred to the pallet when the angle is 90º or 0º. An angle in between is needed: the angle that maximizes the power transfer. Find what direction the escape tooth is moving in as it passes over the pallet, and the direction of the pallet. Then determine the direction in which the pallet should receive power from the tooth. The direction should be half way between those of the tooth and of the pallet. For maximum efficiency, the pallet's impulse face needs to be at right angles (90º) to this direction.

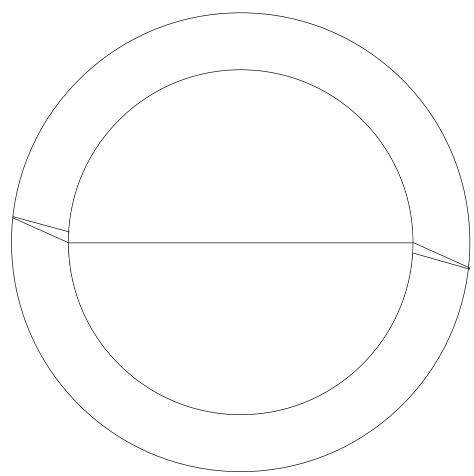
If the angle between the directions of the tooth and of the pallet were 90º, the maximum achievable efficiency would be only 50%. This is achieved when the impulse face's angle is at 45º to the direction of the tooth's travel. If the impulse face's angle were 25º, the efficiency would be merely 38%. That is a 24% power loss caused by improper design. If the repairman could see this, he could adjust the impulse face's angle more closely to what it should be, and maximize the pallet's efficiency, given the original design he has to work with. Ideally, the impulse face's angle should be at 90º to the angle half way between the directions of the tooth and of the pallet.

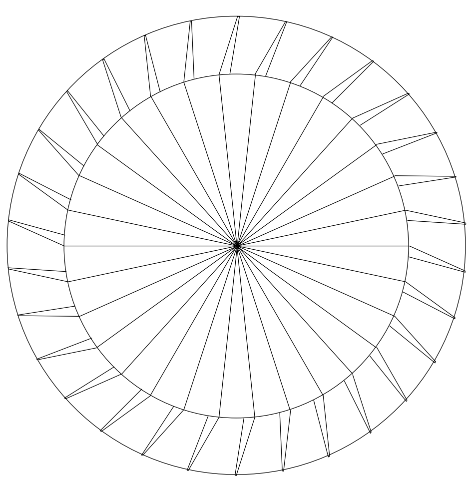
You may not find this easy to understand: power losses by escapement design are less obvious. This will become clearer in the next chapters, as we draw the Graham escapement. It should, however, have become clear to you how important the design of the escapement is. I have seen clocks in which one pallet received a negligible impulse from the escape wheel, so the maximum achievable efficiency was only 25%. Why would they would not keep running?

2: Drawing an Escape Wheel.

I am currently using an IBM with Windows and a drawing program called Key-Draw. If you have AutoCAD, you are well equipped. The most important features you need are the ability to draw lines and circles on a grid, and the ability to rotate the lines by angles that you determine. You may have a different method. This is just one way to do it.

First, draw a large circle. A diameter of 6 inches worked well for me. Draw another circle of 4.5 inch diameter and center it inside the first. Draw a horizontal line across this circle, bisecting it. Draw a tooth on one side until you are satisfied: I chose a line at 15º and another at 25º from horizontal, positioned to fit, and with a small gap to allow for tooth thickness. Duplicate, rotate, and place a tooth on the other side. Your drawing should look like this:



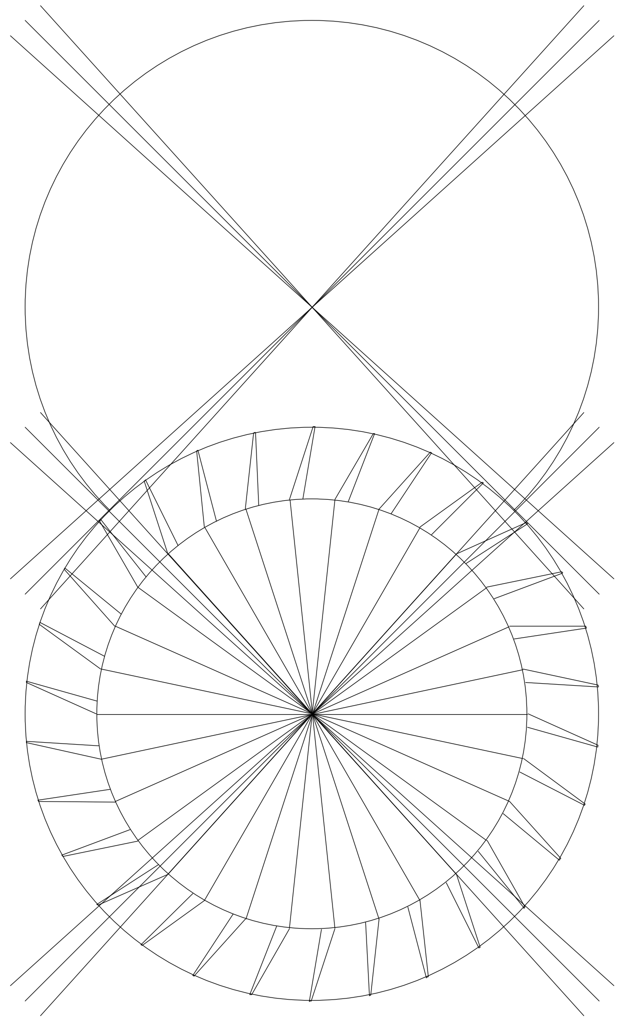


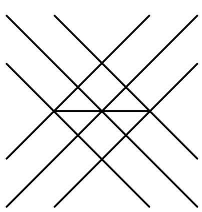
Move the inner circle outside. Group the outer circle with the line and the two teeth, duplicate and rotate by 12º. Duplicate the new group and rotate it by 12º again. Repeat this until you have thirty teeth. Ungroup all the elements and remove the outer circles, one at a time, until only one is left. Place the inner circle in its original position, and group all the teeth and circles. The reason for placing a tooth in a circle before rotating is because the circle makes the tooth rotate about the center of the circle, in order to achieve the desired result.

Rotate the groups by 12º at a time because there are 360º in a full circle, so if you want a 30 tooth circle: 360 / 30 = 12º. If you want a 48 tooth circle, divide 360 by 48 to get 7.5º. Thus escape wheels with different numbers of teeth could easily be made. Escape wheels with the teeth pointing in the other direction could be made by flipping the image, or with teeth of different shapes, such as the club-tooth escape wheel in Swiss watches.

3: Drawing the Graham Pallets.

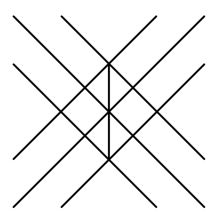
Over the escape wheel, draw two radius lines at 90º to one another. Draw two more lines at 90º to the radius lines and place them at the edge of the circle. The point where these new lines intersect is the center of the pallet circle, the radius of which should measure three inches. Draw the pallet circle about this point. You now have four radius lines. Draw two more radius lines next to each one, positioned at 3º on either side of each. I chose to extend all the radius lines:

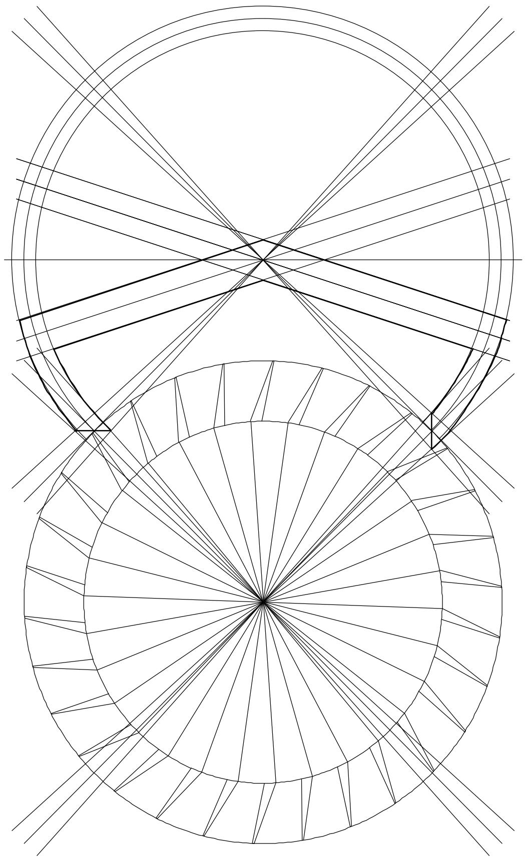




Since the escape wheel rotates clockwise, the entry pallet is on the left side of this drawing. Draw a horizontal line between the three lines.

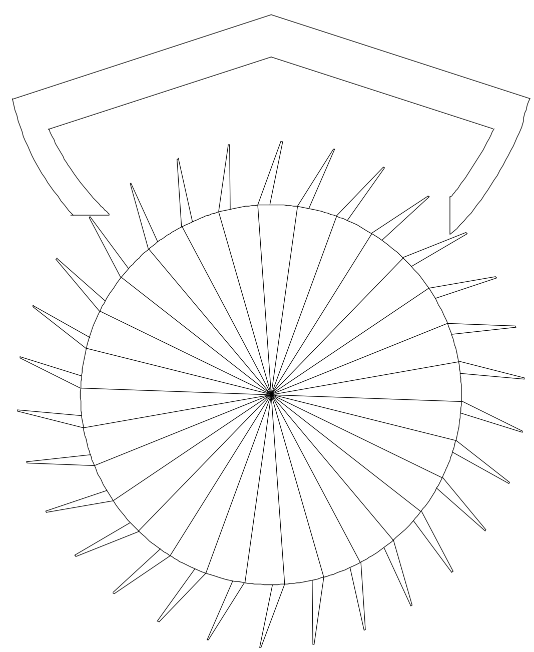
The exit pallet is on the right side: draw a vertical line between the three lines there.



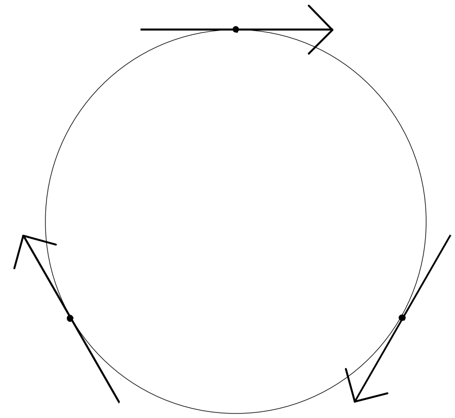


It is important to draw the locking faces, which will consist of curves drawn over circles, such as to preserve the dead-beat nature of the design. Draw two more pallet circles with diameters of 5.69 and 6.31 inches. Once these lines have been completed, the rest of the pallet could be drawn any way you wish. I drew the this one by drawing a horizontal line across the pallet circle, then rotating it by 24º, duplicating it and placing one line 0.25 inches above the center line and the other 0.25 below. I grouped these two lines, duplicated them, flipped them horizontally, and placed one pair on the other side.

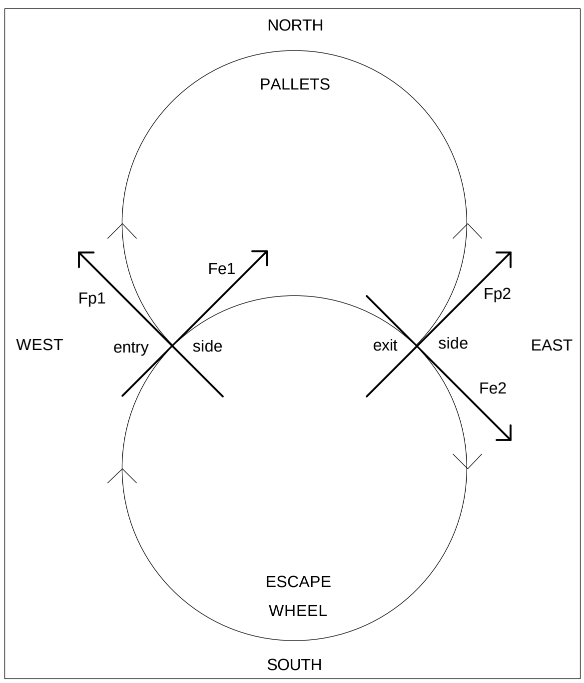
Remove the excess lines to get the result. This is the *ideal* Graham design as its angles maximize the power transferred from the escape wheel to the pallets.



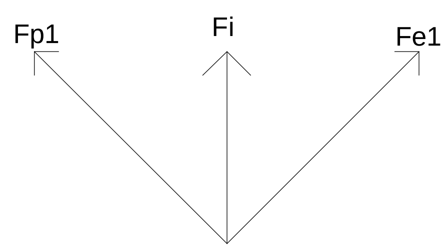
4: The Graham Explained.



As the escape wheel rotates, it exerts a force upon anything it encounters in its path. The direction of this force depends on what point on the escape wheel the pallet is located, as shown here: the arrows show the different directions of force for three points on the escape wheel.

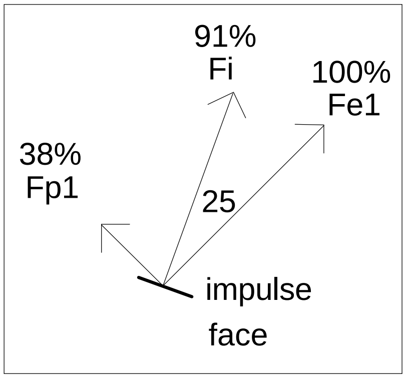


If the top of the page were North, the escape wheel would push on the entry pallet towards the North-East. This force has *size* and *direction*. I have labeled it 'Fe1,' or the force exerted by the escape wheel. At this point, the pallet rotates clockwise: a force should push it in a North-West direction, marked 'Fp1' (force to pallet). The angle between Fe1 and Fp1 is 90º. If a third line were introduced, labeled 'Fi' (force of impulse), with an angle half way in between, you could think of an impulse force in that direction:

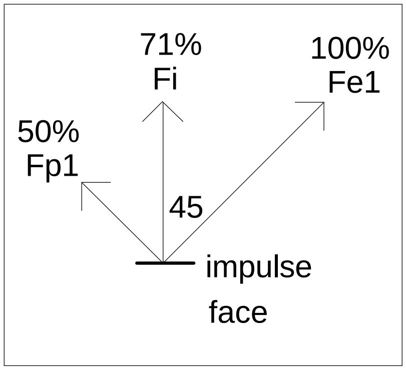


We have Fi because a force cannot be rotated by 90º in the Graham escapement, which is why no power is transferred to the pallet from the escape wheel when the pallet's impulse face is at 90º or 0º to Fe. It could be rotated twice by 45º, though. Fi is at 90º to the impulse face's angle, so if the impulse face's angle were changed, Fi would change. As Fe1 goes North-East, imagine that a portion of that force is received by the impulse face at right angles to its angle: Fi due North. Then imagine that a portion of Fi acts in a North-West direction, Fp1, to rotate the pallet. The portion of Fe1 not received in Fi is lost, and so is the portion of Fi not received in Fp1, which means that power is lost in each step.

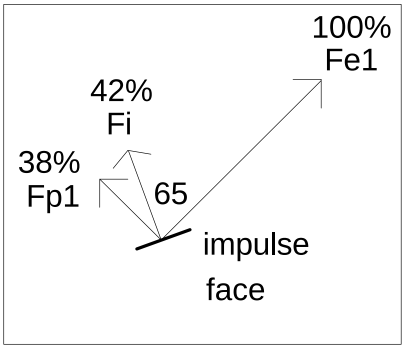
If the lines were drawn to scale, you could see how much power is lost. Scale drawings could be used to show the effect of angle on Fi and Fp: changing the angle of the impulse face has a dramatic effect on the force Fp1 that rotates the pallet, even though the angle between Fe1 and Fp1 remains unchanged at 90º. If the angle FeFi were 25º, the efficiency would be 38%.

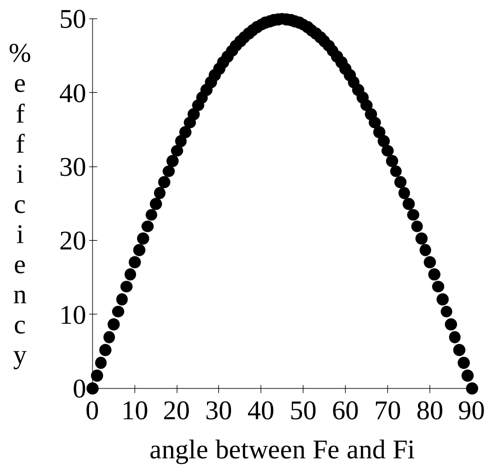


If the angle were 45º, the efficiency would be 50%.



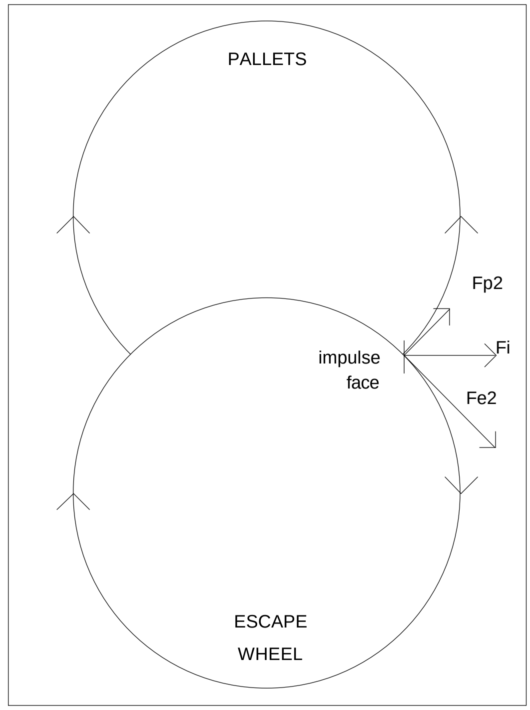
If the angle were 65º, the efficiency would be 38%.

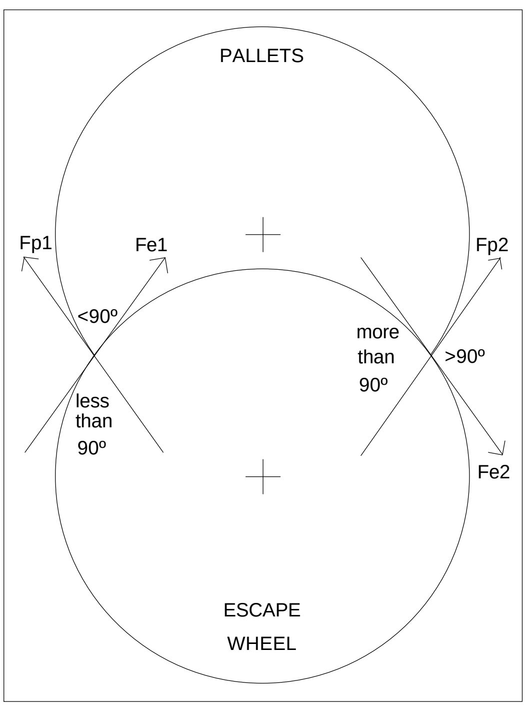




The greatest efficiency is achieved when the angle of Fi is half way between those of Fe1 and Fp1.

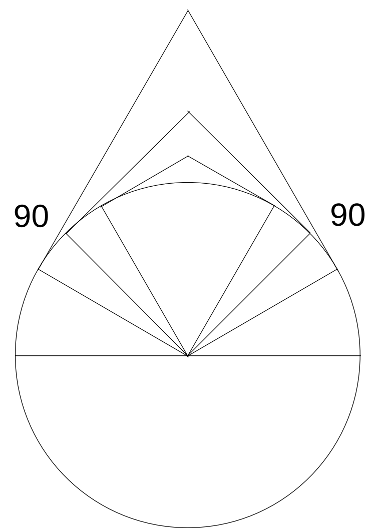
On the exit side, Fe2 goes South-East and Fp2 goes North-East. Since Fi should go at an angle half way in between, Fi goes East:





An angle of 90º between Fe and Fp is preferred because of symmetry: the angle Fe1Fp1 plus the angle Fe2Fp2 always equals 180º. Therefore, if the angle Fe1Fp1 were greater than 90º, the angle Fe2Fp2 would be less than 90º to the same extent. Or vice versa.

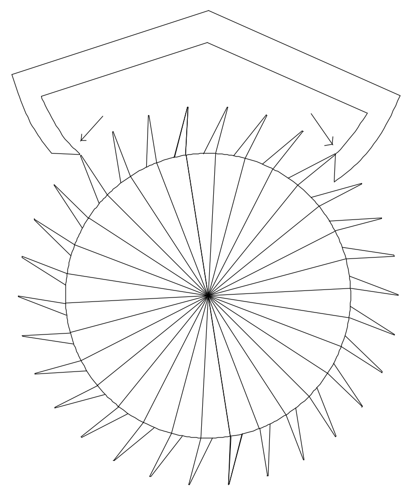
As the angle FeFp increases, the maximum achievable efficiency decreases, so the smallest angle possible is preferred. The loss of efficiency on one side is equal to the gain in efficiency on the other side, but there is no advantage in an unequal arrangement. When the efficiencies are unequal, the push the pendulum receives on one side is different versus the other side, instead of the same. In the Graham escapement, therefore, the angle FeFp should be 90º because of symmetry. This is illustrated by the following drawing, which should be familiar to many clockmakers.

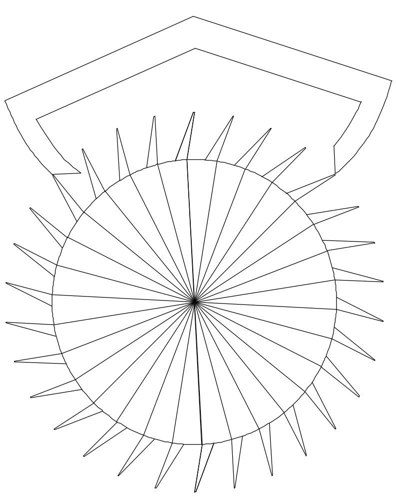


This approach could be used to determine the distance between the escape circle center and the pallets' circle center for the tooth span (the number of teeth between the pallets) of your choice: choose a 4.5 tooth span for a wide pendulum swing, or an 11.5 tooth span for a narrow swing. It is generally accepted that a 7.5 tooth span gives the most desirable results in practice for a 30 tooth escape wheel.

5: The Importance of the Simulation.

You need to simulate the action of the escapement on a computer to determine if the drawing works in practice, without having to make the parts first to find out. I was able to rotate the escape wheel by one degree at a time, and the pallet in the same manner, to simulate the action in practice. There was binding because there was no inside drop.

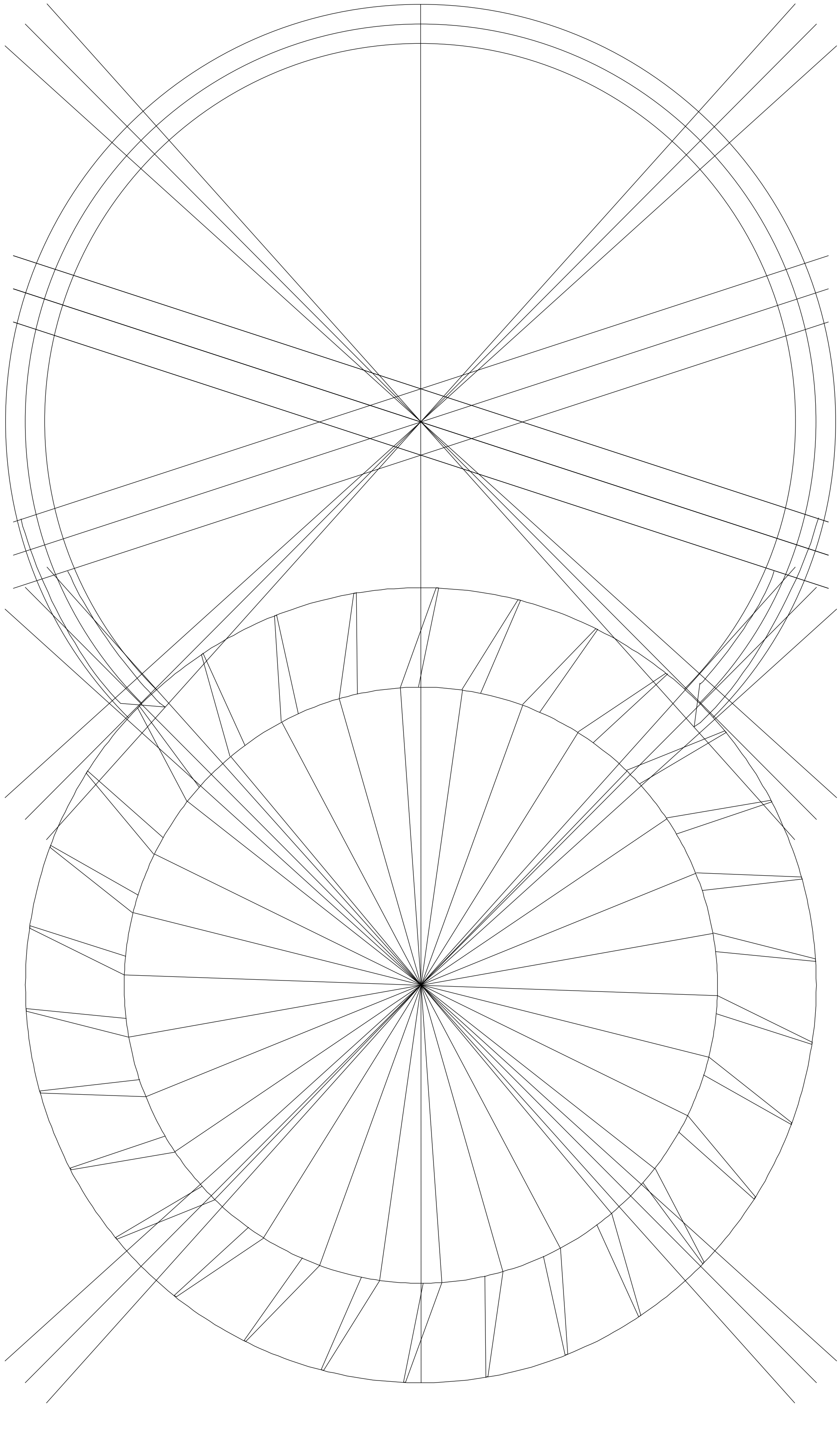




There was also no outside drop.

The creation of drop results in the escape tooth landing on the pallet's impulse face, which causes recoil action. In order to avoid this, the pallets must be designed with impulse face angles that result in lowered efficiency. See the drawing on the next page. This is the *modified* Graham design as the ideal design had to be modified before it could be used in a simulation.

In theory, there should be 1º of lock and 1º of drop. However, the simulation works better with 2º of lock and drop.



During the simulation, the escape wheel and the pallets are rotated by one degree at a time in their respective directions.

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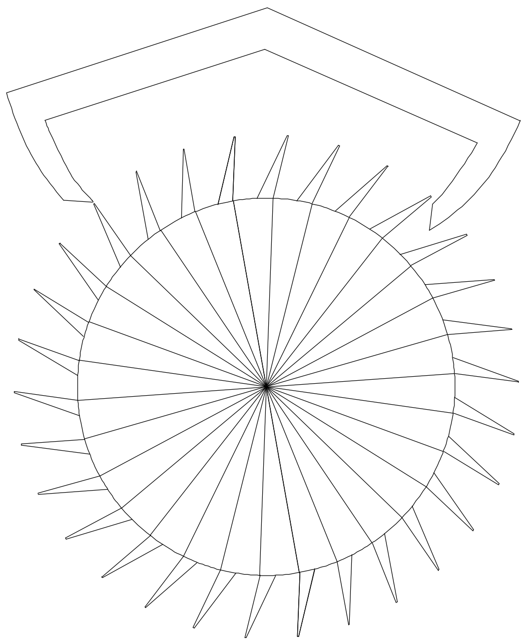

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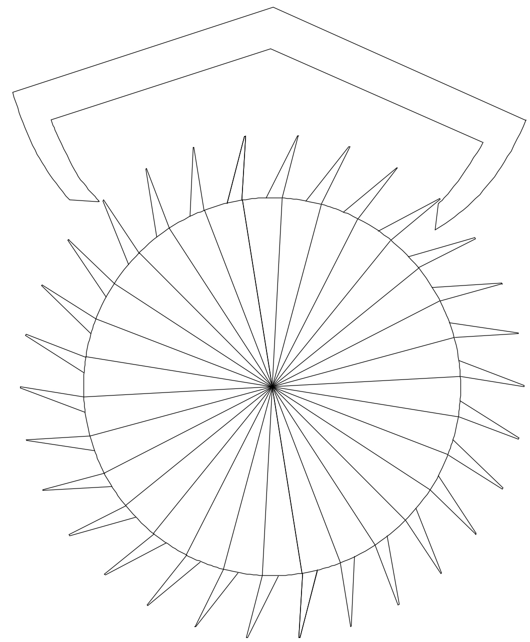

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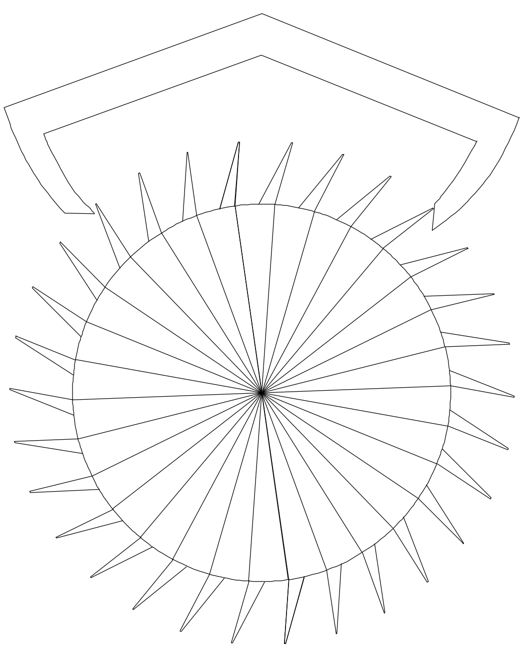

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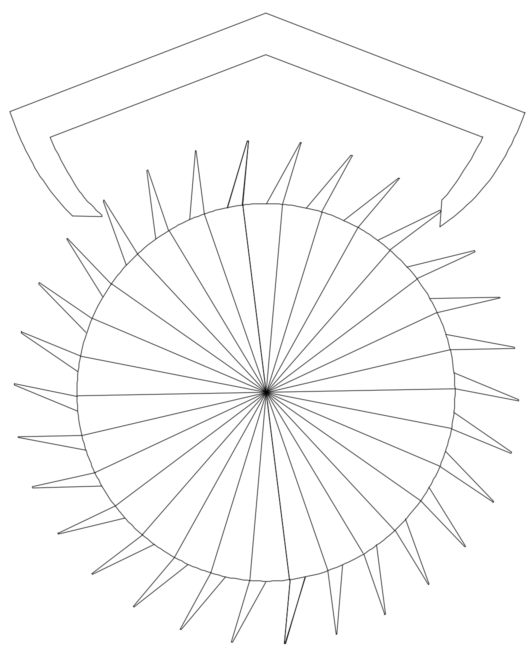

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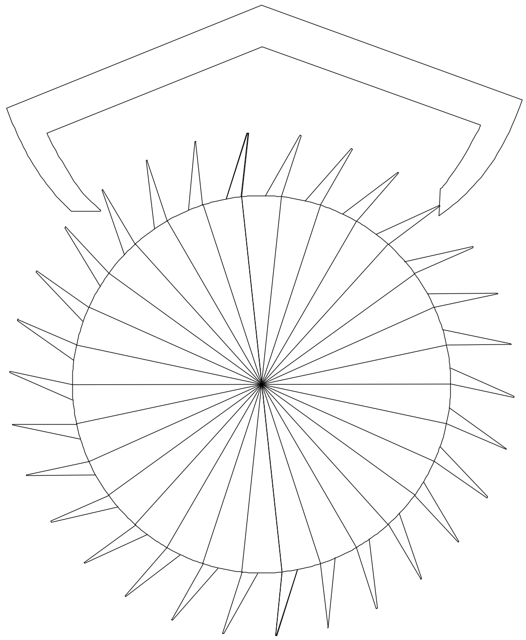

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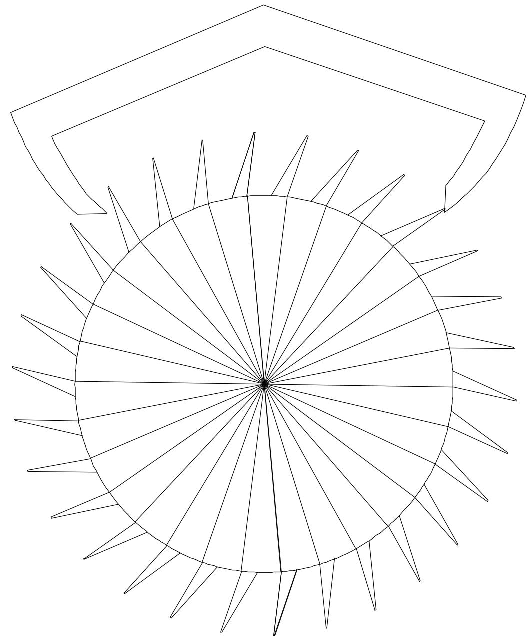

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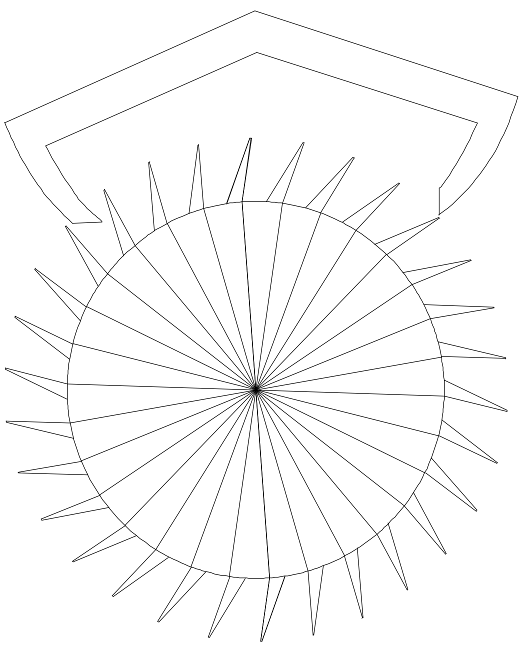

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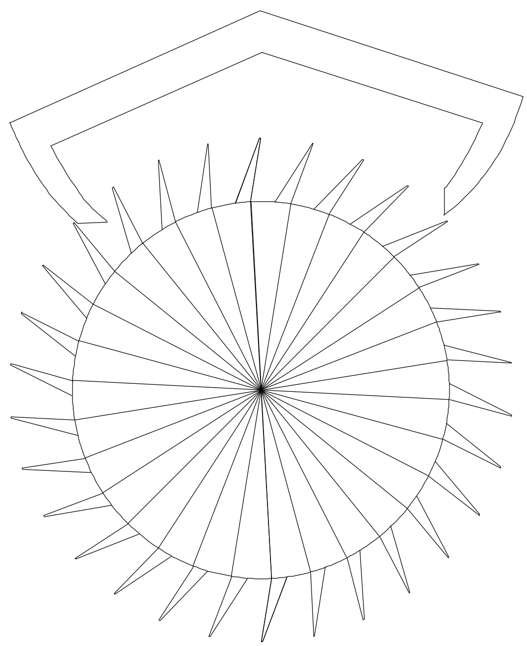

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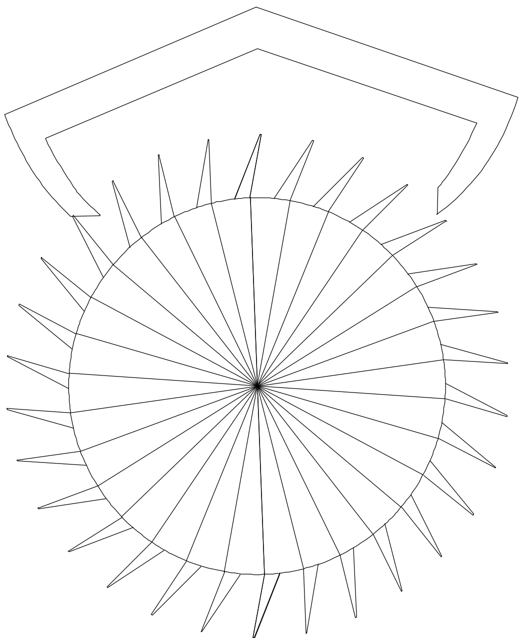

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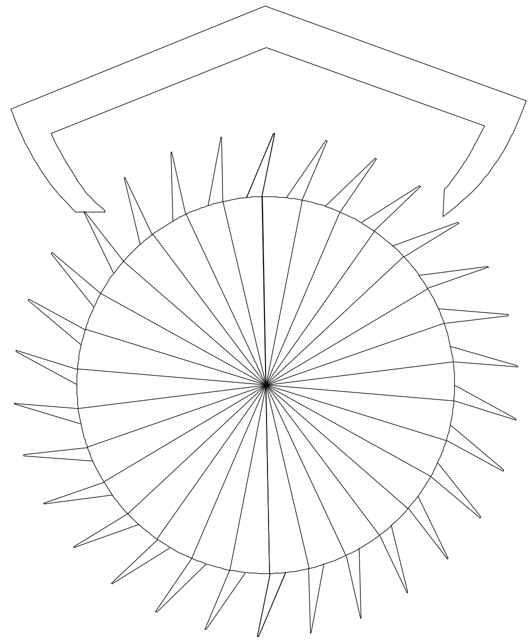

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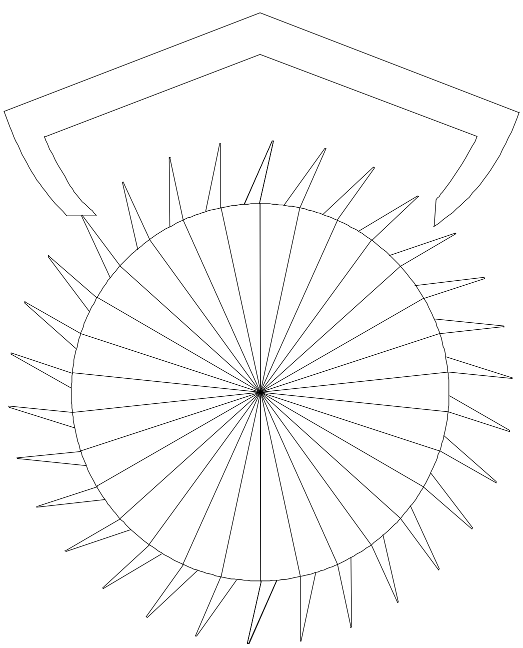

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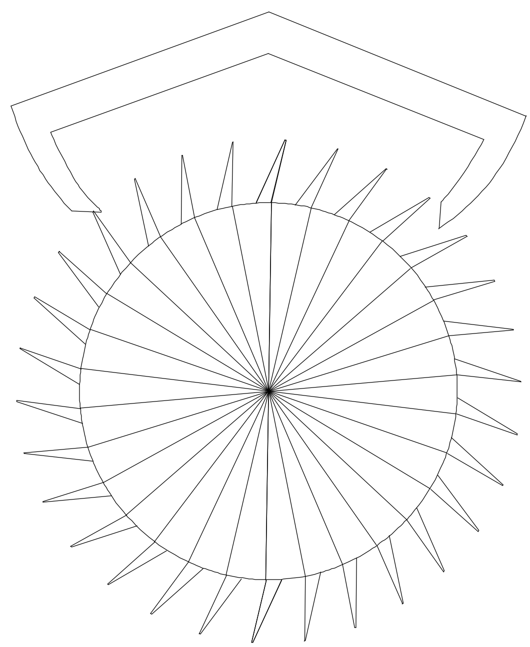


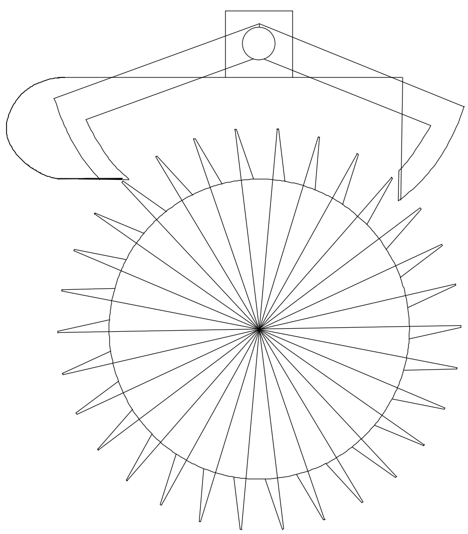
Be aware, when you prepare to do a simulation, that the group of lines comprising the pallets and the escape wheel must be symmetrical about the point you intend to rotate, because if the center of the group were not the same as the center of the pallets, for example, then the rotation would not take place the way you want it to. Therefore, the circles should be included in the groups being rotated, as shown in the drawing that preceded the simulation.

6: The Recoil Escapements.

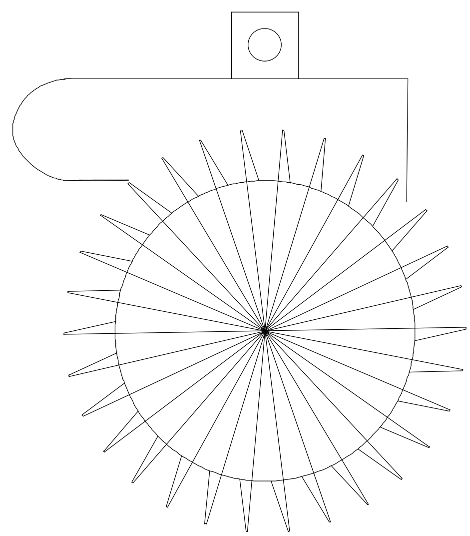
Once you have the Graham escapement drawings, drawing the recoil escapements is easier because the images could be superimposed for reference.

With the recoil escapements, there is no need to adjust for lock, only drop. This really simplifies the issue. Just create some inside and outside drop, and make sure that the angle FeFi is 45º. Since no adjustment is made for lock, use the ideal Graham drawing for reference. Shorten the entry pallet slightly and move the exit pallet slightly outwards, parallel to the impulse face of the Graham exit pallet:

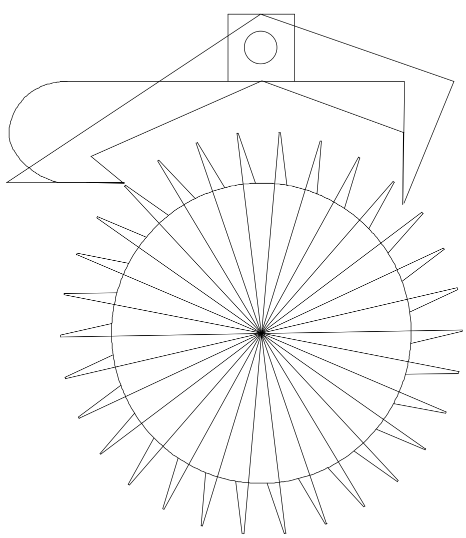
Notice that the escape wheel has been changed.

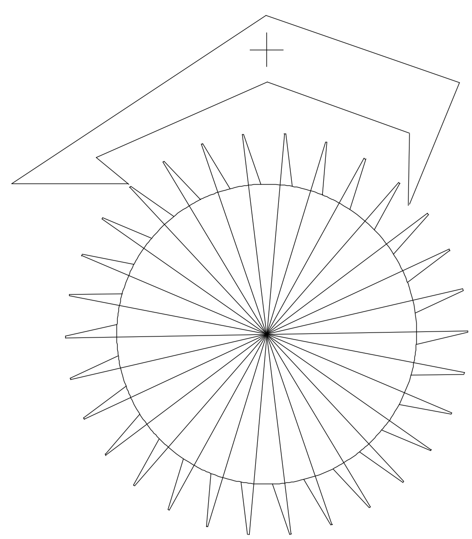


Once the Graham is removed:

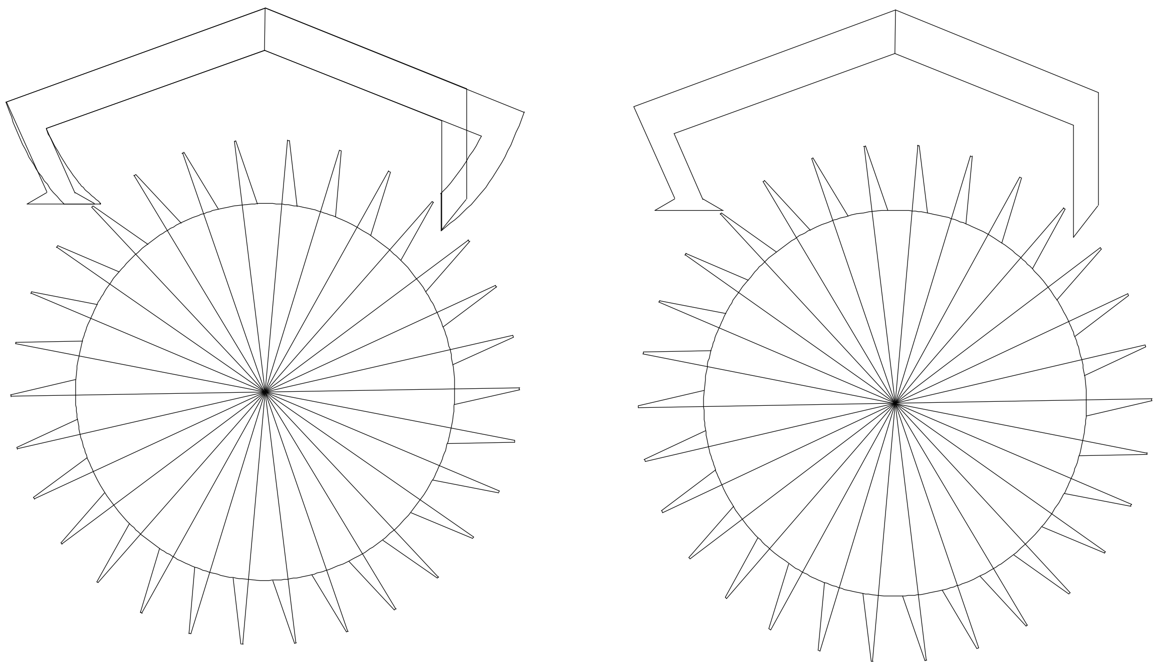


Now for another recoil pallet, this time superimposing one recoil pallet over another:





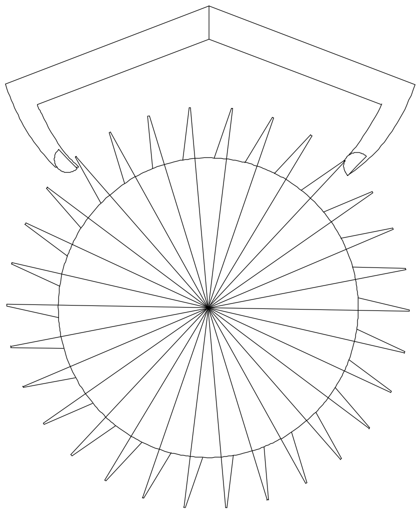
This design is similar to one I saw recently in an antique British grandfather clock:



The following is the most important fact about recoil escapements: the angle FeFi *must* be 45º, regardless of the angle FeFp. This is because of recoil action. If the efficiency were 50%, or 1/2, moving forwards, then the deceleration of recoil would have *twice* the magnitude of Fe (in the opposite direction). Some power is "stored" in the recoil action because the escape wheel moves back a little, as if it were winding the clock. However, the power stored is only 50% of Fe, so we have a very significant power loss, even under the best conditions.

If the impulse face's angle were 15º, the efficiency would be 25%, or 1/4. The deceleration of recoil would be *four* times as large as Fe in the opposite direction. Having the impulse face's angle at 15º causes two problems: (1) more efficiency is lost moving forwards because of the incorrect angle, and (2) much more power is lost in recoil (going backwards).

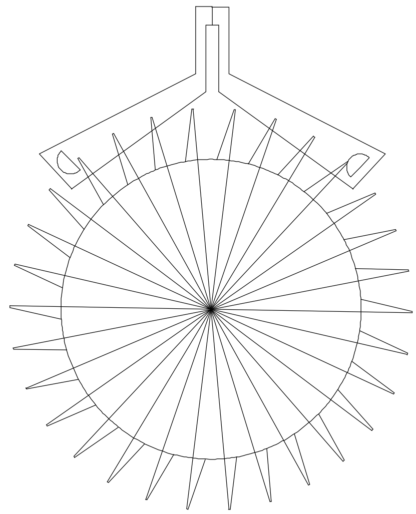
This example demonstrates how important the impulse face's angle is in a recoil escapement. The angle FeFi must be 45º to minimize power losses in recoil. Therefore, the angle FeFp should be 90º in order to maximize efficiency moving forwards. How many recoil escapements have you seen that had the correct angles?



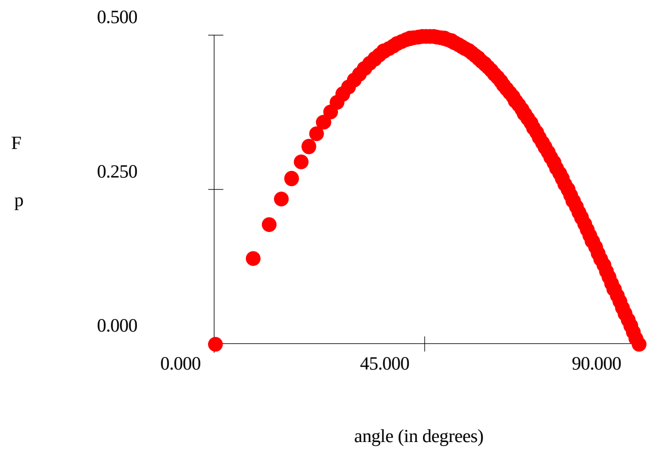
7: The Brocot Escapement.

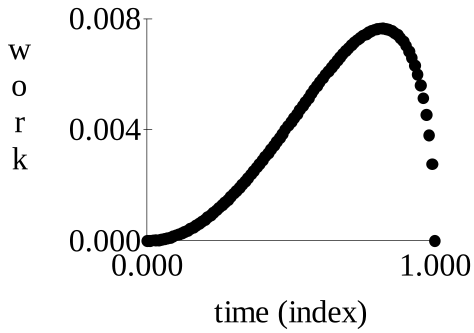
Drawing the Brocot pallets is made easier by using a Graham drawing as background. Choose the modified Graham, which works in the simulation, because both lock and drop must be considered. Quite simply, the radius of the pallet is equal to the thickness of the modified Graham pallet. Then just position it over the Graham drawing so that the lines meet.

This escape wheel drawing is borrowed from the recoil escapement and flipped over horizontally. The rest of the Brocot pallet could be drawn as you wish:



The Brocot pallets require both lock and drop. Correctly adjusted, they could behave much like a Graham escapement. Since the pallet is essentially half a circle, the impulse surface is a quarter of a circle. The impulse angle changes as the tooth slides across the impulse face. The impulse angle is therefore very inefficient at first, becoming more efficient until reaching a peak, and then losing efficiency towards the end of the stroke. Compare the Graham, which has a straight and horizontal line for Fp, with this.

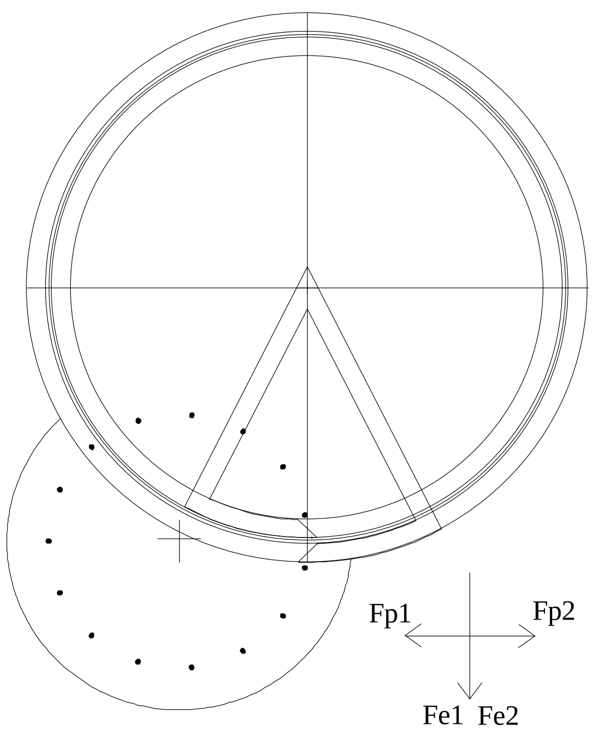




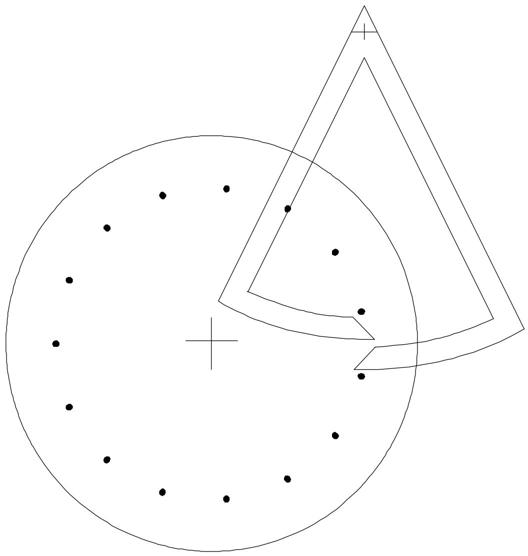
The impulse face's angle changes unevenly over the time it takes the escape tooth to pass over the impulse face. If you consider the *displacement* (or distance moved) of the pallet in the direction of Fp, and multiply this by the *force* Fp that rotates the pallet at each instant in time, you get a 'work done' curve. This curve looks very different and reveals how inefficient the Brocot design really is.

8: The Pin Wheel Escapement.

Drawing the pin wheel escapement proved to be a considerable challenge. A simulation of the action of the pin wheel escapement is interesting when compared with that of the Graham escapement: the action is different because of the directions of the forces Fe and Fp, but the results are the same.



You will have noticed that, in the Graham escapement, the angle Fe1Fe2 was 90º, and so was the angle Fp1Fp2. In the pin wheel escapement, the angle Fe1Fe2 is *zero* (both go in the same direction), and the angle Fp1Fp2 is 180º. However, the angle Fe1Fp1 is 90º, and so is the angle Fe2Fp2. Another consideration in this drawing is that the thickness of each pallet is equal to half the arc between two escape wheel teeth, as in the Graham escapement, minus enough pallet thickness to allow for drop. The angle of the pallet's impulse face needs to be 45º relative to Fe. The pallet locking face should be designed about circles, as in the Graham, in order to preserve the dead-beat nature of the action.



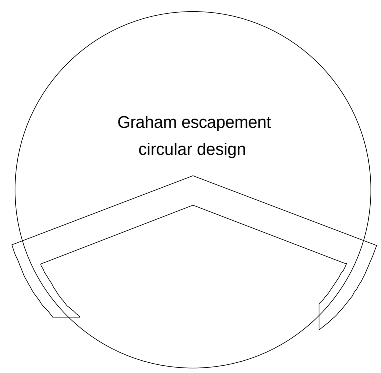
Changing the pallet circle's diameter does not affect the number of teeth between the pallets, as it does in the Graham. However, it does affect the angle of swing of the pallets (from side to side). If the pallet circle radius were increased, the angle of swing could be decreased, which is desirable for a fine regulator. This would make it possible to minimize the circular error in the movement of the pendulum.

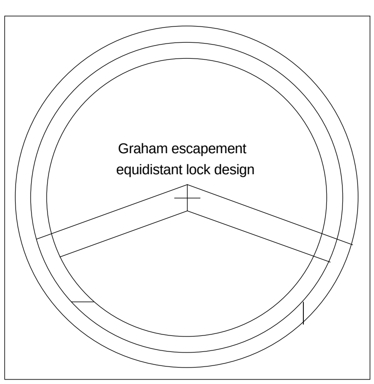
The lack of popularity of the pin wheel escapement could be explained in the difficulty in manufacturing the pallets because of their intolerance for error: if the design were not *perfect*, it probably would not work at all, which becomes very obvious when preparing drawings for a simulation. The recoil escapement, on the other hand, could be imprecisely designed, and it would be much more likely to work.

9: Other Design Considerations.

In previous chapters, all the pallet designs were created with an emphasis on symmetry so that the impulse received by the pendulum would be equal in each direction. All designs, whether for clocks or watches, should be based on the same method of vector analysis. This should be clear because of the simple method of drawing one type of escapement over another, as shown in chapters 6 and 7. Draw the impulse face first, and then the rest of the pallet.

In watch theory, the symmetrical design is referred to as either a "circular" design or an "equidistant impulse" design. In the circular design, the impulse faces are bisected by the same circle. However, the entry pallet's locking face is outside the circle, and the exit pallet's locking face is inside the circle. The locking faces clearly are not symmetrical. This problem is unimportant in pendulum clocks, but it is an issue in watches.





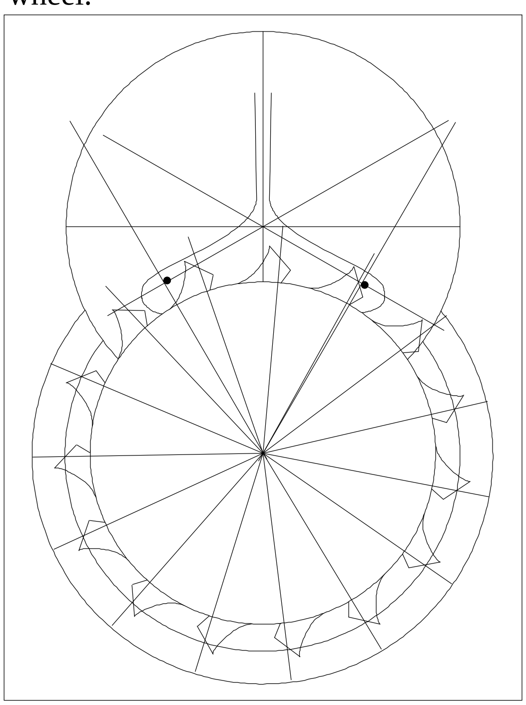
If the pallets were modified to make them with equidistant lock, the locking faces would be drawn on the same circle. However, the pendulum would receive unequal impulses in each direction.

A pallet with equidistant drop could similarly be designed, but it has no practical application in horology.

The Graham pallet has curved locking faces in order to achieve what we call a "dead-beat," where the escape wheel does not move either forwards or backwards during lock. When the escape wheel is pushed backwards, there is recoil. In clocks, a dead-beat action is preferred because the movement of the pallets is controlled by the pendulum at the point where, for example, the crutch pin goes into the suspension leader. At no time are the pallets independent of the pendulum.

Modern Swiss watches have pallets that are independent of the balance wheel's movement most of the time: this system is referred to as the "detached lever." The single and double-rollers are designed so that the pallet fork would not accidentally jump across to the wrong side of the roller jewel if the watch were jolted by a fall, for example. In addition to the roller table, it is necessary to keep the pallet fork over to the side, in its place, until the roller jewel returns. If the escape wheel were allowed to move forwards slightly, beyond the entrance corner, as the pallet moves over, then it would be necessary to move the escape wheel backwards by the same amount when the roller jewel returns to unlock the pallet. The need to push the escape wheel backwards slightly results in a small binding action, which encourages the pallet to stay in its place. Watch pallets, therefore, instead of having curved locking faces, have flat locking faces at an angle of about 15º from the escape circle radius at the pallet entrance corner, such as to make the escape wheel rotate by about 1º extra. Watchmakers call this "Draw."

An equidistant lock design is important in watches because of the need for symmetrical lock. In a circular design, the locking faces are at unequal distances from the pallet center, causing a need for unequal torque to unlock, torque that adversely affects the oscillation of the balance wheel. Any asymmetry in the oscillation of the balance wheel could add to a factor that causes positional error, such as the poise of the balance wheel.



Since clocks do not have pallets that are independent from the pendulum, there is *no need for draw*. Therefore, the equidistant lock design is of no advantage in pendulum clocks. The equidistant impulse design is the obvious choice for the Graham, Recoil, and Brocot escapements. (It cannot be applied to the Pin Wheel escapement, as its drawing demonstrates.)

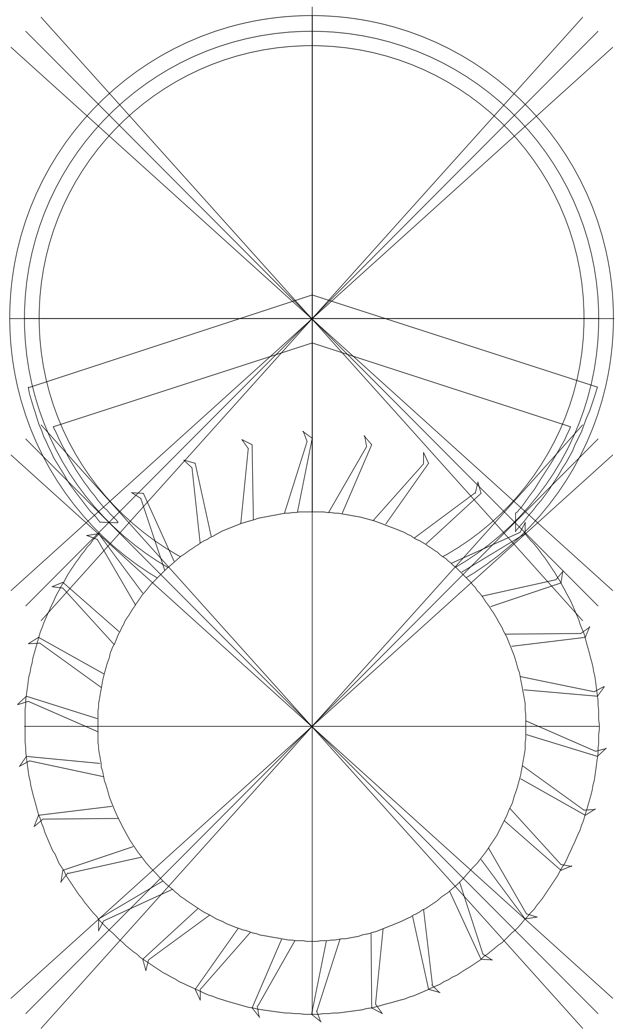
The same principles of lock and draw apply to pin pallet escapements in watches and clocks with balance wheels, but the impulse and locking faces and the angle of draw are designed into the escape wheel's tooth rather than the pallet. (A pin pallet escapement for a pendulum clock, such as the Brocot, requires no draw and should have a dead-beat action.)

If you look at a clock with a floating

balance, such as a Hermle, you would see that the impulse face is part of the escape tooth. In a drawing, the pallet radius lines bisect the pallet pins. The escape radius lines bisect the impulse faces of the teeth. The locking faces of the escape teeth are not parallel to the escape radius lines, but appear to lean forwards to create draw. The length of the escape impulse face lines is shortened to allow for at least 1º of drop, and these lines are at 45º to the escape circle's radius lines that bisect each of them.

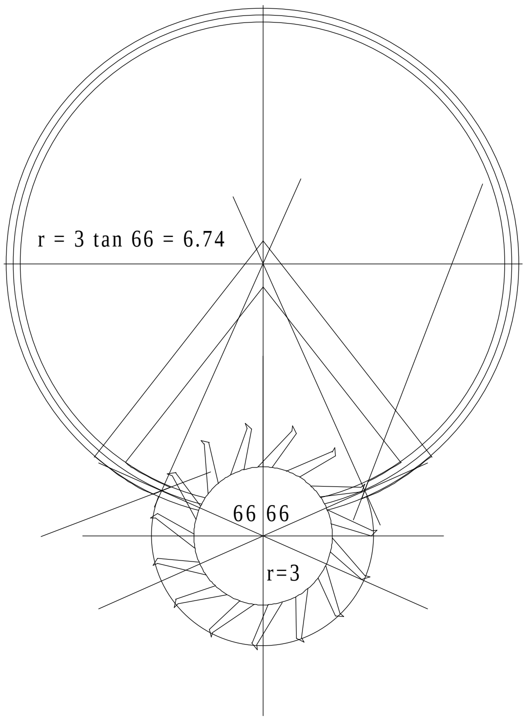
By drawing the different escapements, you could see how the principles, by which they are formed, apply to *all* of them. They look different, but they actually behave in similar ways.

10: The Graham Reconsidered.



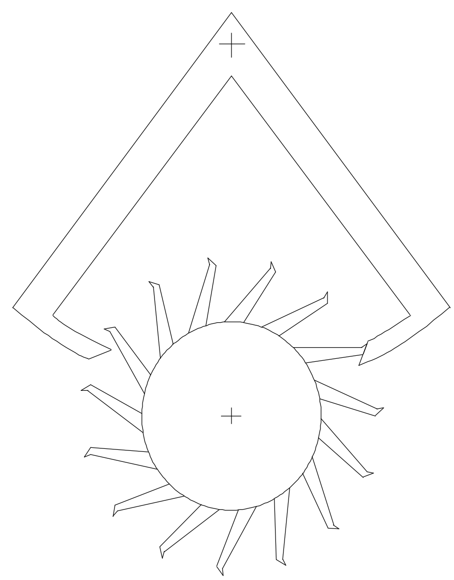
The Graham design in chapter 5 did not maximize efficiency, whereas the drawing in chapter 3, before modification, had the maximum achievable efficiency. The modified Graham was less efficient because of lock: if modified with maximum efficiency, the escape tooth would always land on the pallet's entrance corner. The reason the Graham pallets could not be modified as efficiently as possible, whereas an efficient watch escapement could be created (and it would work in a simulation), is because of the design of the escape wheel. The watch escape wheel has an impulse face of its own and its let-off corner is *above* its entrance corner, which creates lock. The back of the tooth makes it possible to reduce drop without binding. The watch escape wheel offers these two design advantages. If the Graham escapement were designed with a club-tooth type escape wheel, the pallets could easily be modified in a more efficient design that would work in a simulation. These pallets would be much thinner and of equidistant impulse.

There are other ways to change the design of the Graham. The 30 tooth escape wheel is the most widely accepted choice because grandfather clocks with the one-second pendulum could display a second hand moving by one second at a time. If the issue of efficiency were considered, the 15 tooth escape wheel would be more efficient by 8.33%. Since the drop requirement is the same for both the 15 and 30 tooth designs, the 15 tooth design loses 1º for drop out of every 12º, but the 30 tooth design loses 1º out of every 6º. If the Graham were designed with a 15 tooth escape wheel, its efficiency could be improved significantly.



However, the 15 tooth escape wheel rotates by 12º per beat, so if the pallet circle's radius were equal to the escape circle's radius, the pendulum would have a greater arc of swing, which would be undesirable. By increasing the pallet circle's radius to approximately double the escape circle's radius, (because the angle of rotation per beat is doubled), the arc of swing of the pendulum could remain virtually unchanged. With a 5.5 tooth span, the pallet circle's radius increases from 3" to 6.74". Thicker, stronger pallets and escape teeth could then be designed.

This drawing shows how the impulse face of the escape tooth extends *beyond* the circumference of the escape circle, which passes through the tooth's entrance corner. This is how lock could be created and yet maximize the efficiency of the pallet impulse face's angle.

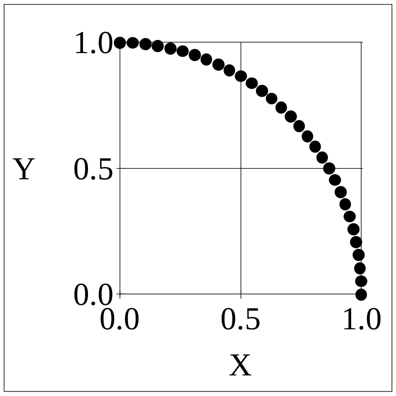


This design has practical limitations. It would require either a two-second pendulum or that a different set of gear train ratios be used to keep the one-second pendulum. An appropriate gear train combination could be found in the De Carle "Watch and Clock Encyclopedia." If a two-second pendulum were used, a 60 second dial could be used, but the second hand would move forwards every two seconds.

Nevertheless, this example should be useful to clockmakers interested in escapement design because an efficiency improvement of over 8% is well worth considering.

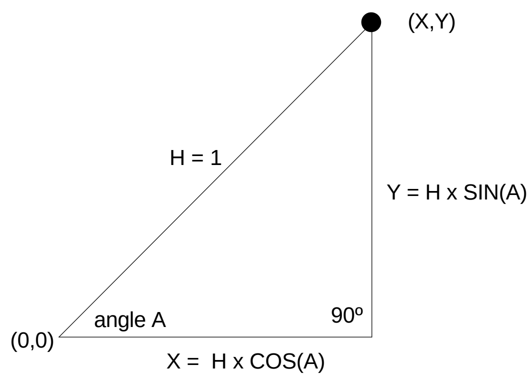
11: Efficiency in Numbers.

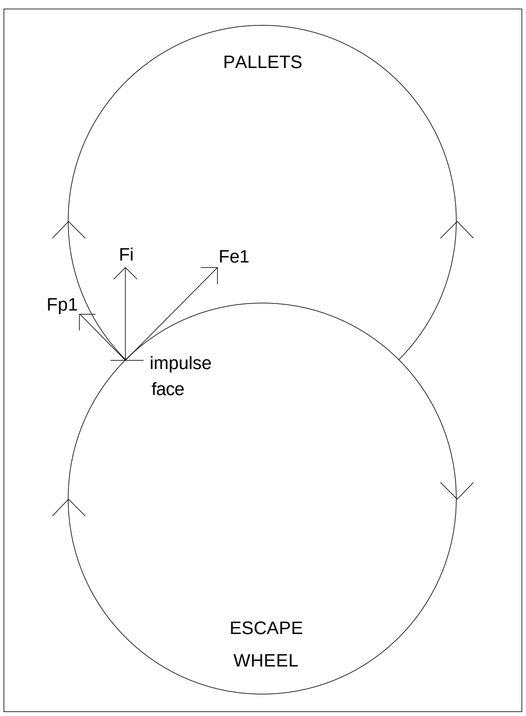
This chapter addresses the math behind the drawings: first, how changing the directions of the forces results in reductions in magnitude; how the efficiency of an escapement design could be calculated; and how to design a pallet blank, by using these calculations, for a clock that is missing the pallets.



Consider the coordinates of a quarter circle. If you take a horizontal line one inch long and rotate it by one degree at a time until you trace a quarter of a circle, you have points on a drawing which shows the position of each point relative to a horizontal line and a vertical line.

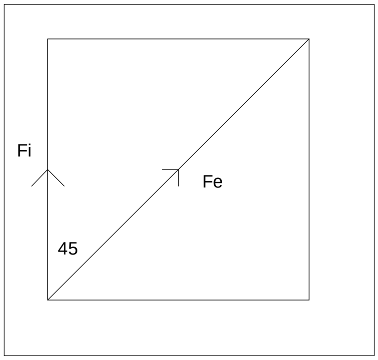
In the above graph, the value of each point along the X line is given by:
X= cos (A)
where A is the *angle* of the line from the horizontal line. The value of each point along the Y line is given by:
Y= sin (A)
So each point has a coordinate (X, Y), which could be seen as (cos (A), sin (A)).

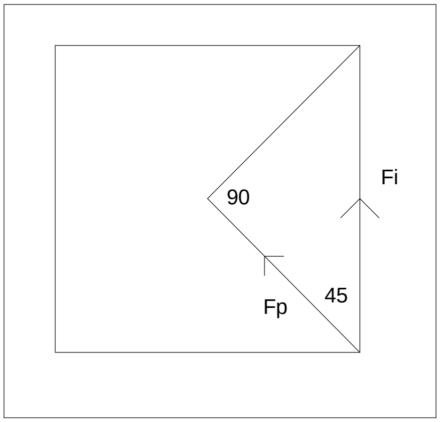




This could be applied to clock escapements. In chapter 4, we considered the action of the escape wheel's tooth as it pushed upon the entry pallet. The tooth exerted a force Fe in a North-East direction. Since the impulse face was horizontal, it received the impulse due North.

If the lines were positioned to create a triangle, they could be used for calculation. Fe (100%) goes North-East. Fi is the portion acting due North:
Fi = Fe *x* cos (45) = 100% *x* 0.707
= 70.7%
29.3% efficiency has just been lost!

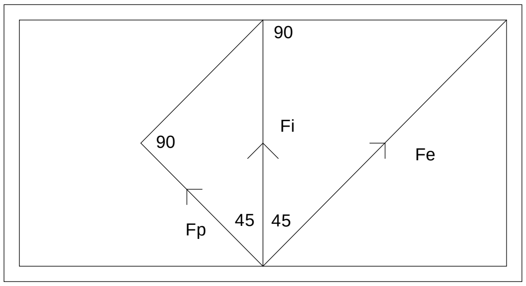




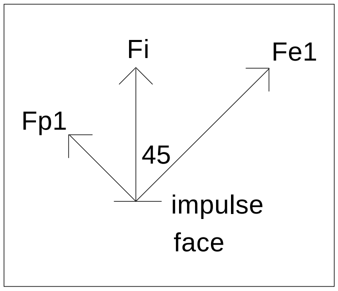
As the pallet is pushed by the tooth, it rotates clockwise, so a portion of Fi is received by the pallet to push it in a North-West direction.

As before, calculate the size of Fp:
Fp = Fi *x* cos (45) = 70.7% *x* 0.707
= 50%
Fp is therefore half as large as Fe. The efficiency is 50%.

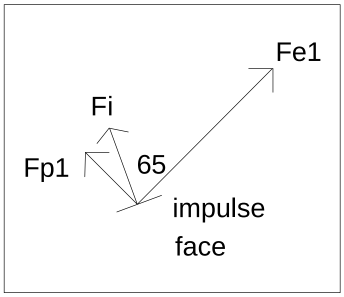
This...

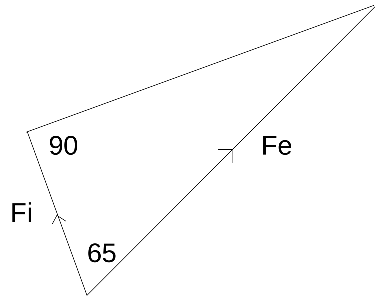


could be used to create this:

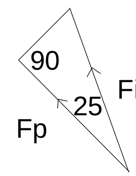


If the angle of the pallet's impulse face were changed, the direction of Fi would change, and therefore the proportion of Fe that could be used to rotate the pallet:

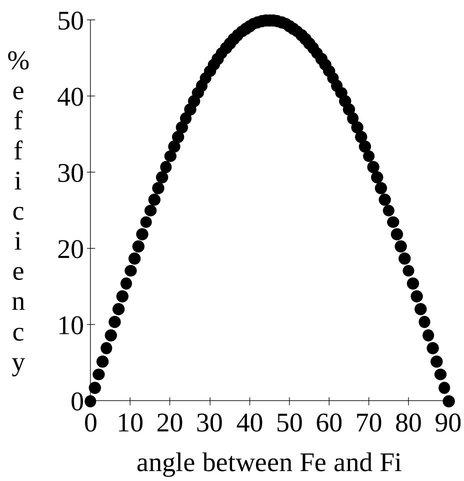




Fi = Fe *x* cos (65) = 100% *x* 0.423
= 42.3%



The angle FeFp is 90º, and the angle FeFi is 65º, so the angle FiFp is 25º.
Fp = Fi *x* cos (90-65) = 42.3% *x* cos (25)
= 42.3% *x* 0.906
= 38.3%
This is less efficient by almost 24% (divide 38.3 by 50) because Fi is not half way between Fe and Fp.



When the angle between two vectors is small, the loss of efficiency is small: when the angle FiFp is only 25º, the efficiency drops from 42.3% to 38.3%, a decline much smaller than occurs between Fe (100%) and Fi (42.3%) when the angle is larger (65º). Therefore, the angle FeFp should be as small as possible. The effects of angles could be computed on a spreadsheet. Look at the chart after this page. As the angle FeFi increases, the efficiency increases until Fi is half way between Fe and Fp, beyond which the efficiency decreases. The graph was created using the data in this chart. In order for a computer to do the calculations, the angles need to be expressed in radians: multiply the angles by pi (3.1415) and divide by 180.

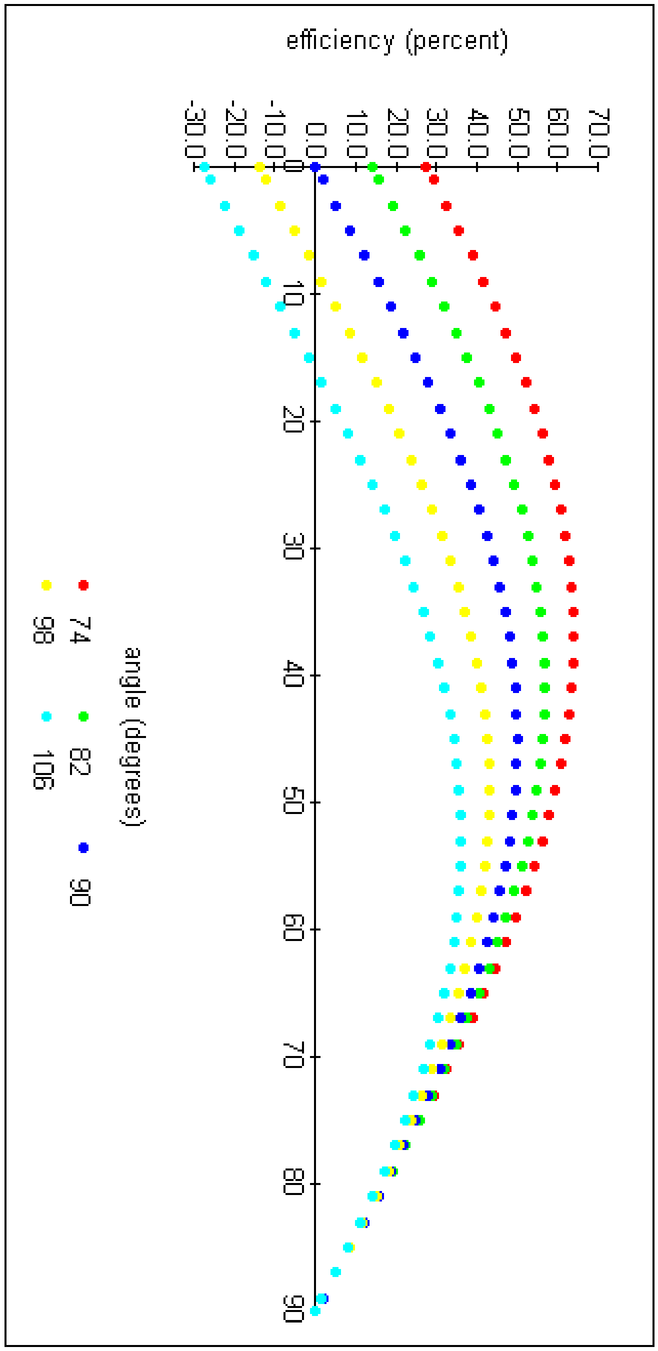
The same chart could be used to see what happens when the angle FeFp is changed. The second chart on the following page shows that as the angle FeFp increases, the maximum achievable efficiency decreases. The maximum efficiency consistently occurs when Fi is half way between Fe and Fp. This chart was used to create the graph on the page after it. The graph illustrates how the maximum efficiency changes.

Use this chart to determine the effect of having an angle greater than 90º between Fe and Fp on the entry side. Then determine the effect of having an angle smaller than 90º to the same extent on the exit side. (See page 10.) You would see that the gain in efficiency on the exit side is offset by the loss of efficiency on the entry side, so the overall efficiency remains the same. Since there is no advantage in this asymmetry, an angle of 90º on both the entry and the exit sides is preferred.

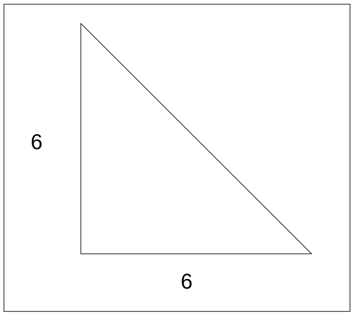
Anyone with a computer spreadsheet could create this chart. I am using MS Works. The chart on the page following the graph shows the formulas used. Enter one of the Fp formulas in the appropriate cell, and then use the "fill-right" and "fill-down" functions to complete the chart. You could create a chart showing the angles increasing by 1º at a time. (I chose 2º so as to fit the chart on one page.)

Fe = vector force by escape wheel = 100%			
Fi = vector force received by pallet impulse face			
Fp = vector force acting to rotate pallet			
	angle between Fe and Fp in degrees		**90**
		(radians)	1.571
angle between Fe and Fi			
degrees	(radians)	**Fi**	**Fp**
0	0.000	100.0	0.0
1	0.017	100.0	1.7
3	0.052	99.9	5.2
5	0.087	99.6	8.7
7	0.122	99.3	12.1
9	0.157	98.8	15.5
11	0.192	98.2	18.7
13	0.227	97.4	21.9
15	0.262	96.6	25.0
17	0.297	95.6	28.0
19	0.332	94.6	30.8
21	0.367	93.4	33.5
23	0.401	92.1	36.0
25	0.436	90.6	38.3
27	0.471	89.1	40.5
29	0.506	87.5	42.4
31	0.541	85.7	44.1
33	0.576	83.9	45.7
35	0.611	81.9	47.0
37	0.646	79.9	48.1
39	0.681	77.7	48.9
41	0.716	75.5	49.5
43	0.750	73.1	49.9
45	0.785	70.7	50.0
47	0.820	68.2	49.9
49	0.855	65.6	49.5
51	0.890	62.9	48.9
53	0.925	60.2	48.1
55	0.960	57.4	47.0
57	0.995	54.5	45.7
59	1.030	51.5	44.1
61	1.065	48.5	42.4
63	1.100	45.4	40.5
65	1.134	42.3	38.3
67	1.169	39.1	36.0
69	1.204	35.8	33.5
71	1.239	32.6	30.8
73	1.274	29.2	28.0
75	1.309	25.9	25.0
77	1.344	22.5	21.9
79	1.379	19.1	18.7
81	1.414	15.6	15.5
83	1.449	12.2	12.1
85	1.484	8.7	8.7
87	1.518	5.2	5.2
89	1.553	1.7	1.7
90	1.571	0.0	0.0

Fe = vector force by escape wheel = 100%					
Fi = vector force received by pallet impulse face					
Fp = vector force acting to rotate pallet					
	angle between Fe and Fp in degrees		**90**	98	106
		(radians)	1.571	1.710	1.850
angle between Fe and Fi					
degrees	(radians)	**Fi**	**Fp**		
0	0.000	100.0	0.0	-13.9	-27.6
1	0.017	100.0	1.7	-12.2	-25.9
3	0.052	99.9	5.2	-8.7	-22.5
5	0.087	99.6	8.7	-5.2	-19.0
7	0.122	99.3	12.1	-1.7	-15.5
9	0.157	98.8	15.5	1.7	-12.0
11	0.192	98.2	18.7	5.1	-8.6
13	0.227	97.4	21.9	8.5	-5.1
15	0.262	96.6	25.0	11.8	-1.7
17	0.297	95.6	28.0	15.0	1.7
19	0.332	94.6	30.8	18.0	4.9
21	0.367	93.4	33.5	21.0	8.1
23	0.401	92.1	36.0	23.8	11.2
25	0.436	90.6	38.3	26.5	14.2
27	0.471	89.1	40.5	29.0	17.0
29	0.506	87.5	42.4	31.3	19.7
31	0.541	85.7	44.1	33.5	22.2
33	0.576	83.9	45.7	35.4	24.5
35	0.611	81.9	47.0	37.2	26.7
37	0.646	79.9	48.1	38.7	28.6
39	0.681	77.7	48.9	40.0	30.4
41	0.716	75.5	49.5	41.1	31.9
43	0.750	73.1	49.9	41.9	33.2
45	0.785	70.7	50.0	42.6	34.3
47	0.820	68.2	49.9	42.9	35.1
49	0.855	65.6	49.5	43.0	35.7
51	0.890	62.9	48.9	42.9	36.1
53	0.925	60.2	48.1	42.6	36.2
55	0.960	57.4	47.0	41.9	36.1
57	0.995	54.5	45.7	41.1	35.7
59	1.030	51.5	44.1	40.0	35.1
61	1.065	48.5	42.4	38.7	34.3
63	1.100	45.4	40.5	37.2	33.2
65	1.134	42.3	38.3	35.4	31.9
67	1.169	39.1	36.0	33.5	30.4
69	1.204	35.8	33.5	31.3	28.6
71	1.239	32.6	30.8	29.0	26.7
73	1.274	29.2	28.0	26.5	24.5
75	1.309	25.9	25.0	23.8	22.2
77	1.344	22.5	21.9	21.0	19.7
79	1.379	19.1	18.7	18.0	17.0
81	1.414	15.6	15.5	15.0	14.2
83	1.449	12.2	12.1	11.8	11.2
85	1.484	8.7	8.7	8.5	8.1
87	1.518	5.2	5.2	5.1	4.9
89	1.553	1.7	1.7	1.7	1.7
90	1.571	0.0	0.0	0.0	0.0


efficiency (percent)
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
0
10
20
30
40
50
60
70
80
90
angle (degrees)
74
82
90
98
106

		angle FeFp (deg)	**90**	98	106
angle		(radians)	=E6*PI()/180	=F6*PI()/180	=G6*PI()/180
FeFi					
degree	(radians)	**Fi**	**Fp**		
0	=B10*PI()/180	=100*COS(C10)	=$D10*COS(E$7-$C10)	=$D10*COS(F$7-$C10)	=$D10*COS(G$7-$C10)
1	=B11*PI()/180	=100*COS(C11)	=$D11*COS(E$7-$C11)	=$D11*COS(F$7-$C11)	=$D11*COS(G$7-$C11)
3	=B12*PI()/180	=100*COS(C12)	=$D12*COS(E$7-$C12)	=$D12*COS(F$7-$C12)	=$D12*COS(G$7-$C12)
5	=B13*PI()/180	=100*COS(C13)	=$D13*COS(E$7-$C13)	=$D13*COS(F$7-$C13)	=$D13*COS(G$7-$C13)



These figures consider the action of the ideal Graham escapement. In this case, the 30 tooth escape wheel rotates by 6º and the pallet rotates by 6º as the escape tooth pushes on the pallet's impulse face.

In practice, if 1º were lost for drop, the triangle would become smaller.

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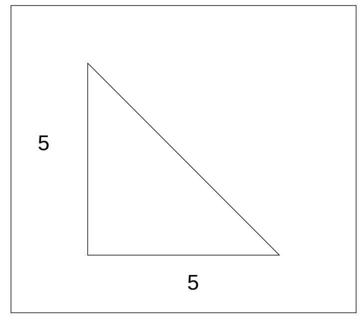


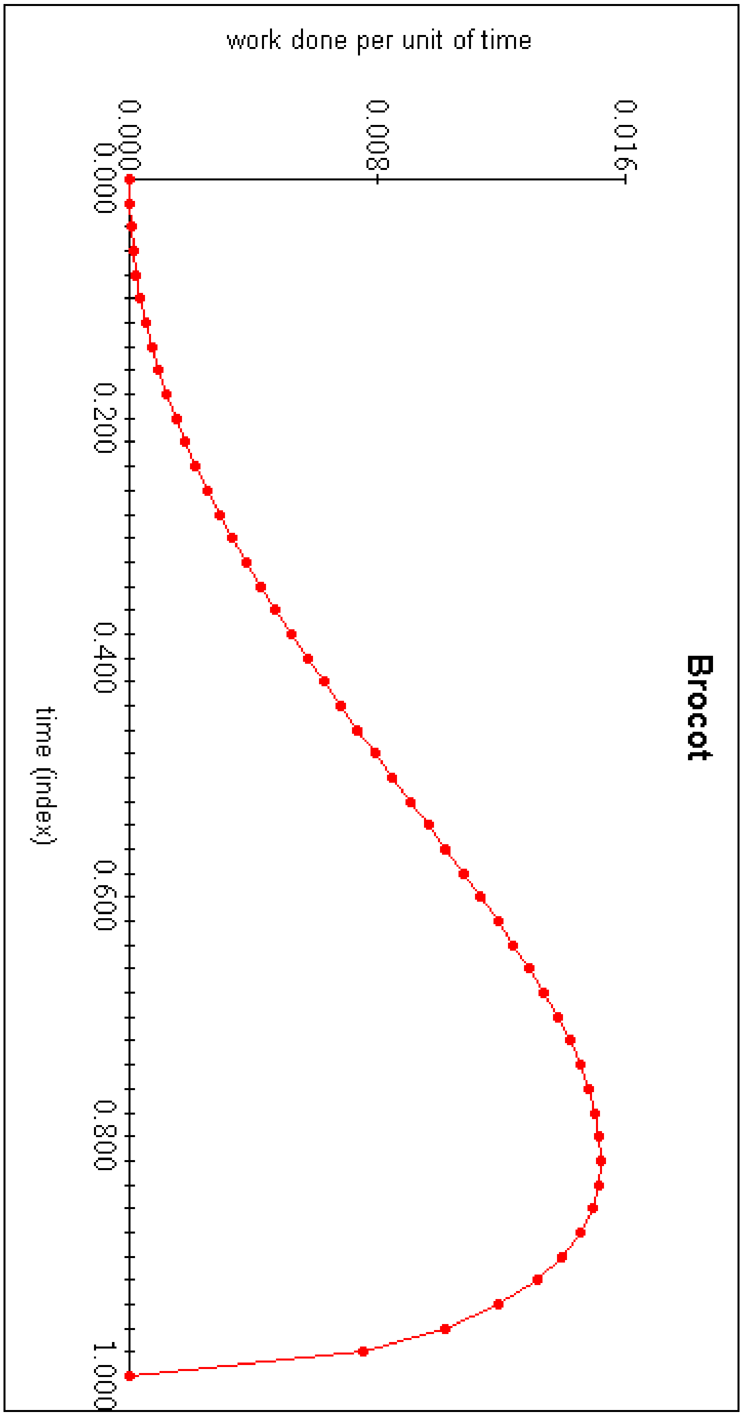
To calculate the work done, multiply the force, which was calculated to be 50% (or 0.5), by the distance (in the direction of Fp) that the pallet is pushed during impulse. Take the distance as an index of 1 (or 100%), so the work done is: 1 *x* 0.5 = 0.5. Divide the distance into six parts because there are 6º of rotation and you need to compare it with the distance in the practical pallet, after losing 1º to drop. In the practical example, the distance is: 1 *x* 5/6 = 0.833. The work done is: 0.5 *x* 0.833 = 0.417. Therefore, *over 16%* efficiency is lost to drop.

Compare the Graham's efficiency with that of the Brocot. This is more complicated because the angle of the impulse face changes as the tooth slides across the pallet surface. Since the Brocot impulse surface is a quarter of a circle, the cosine function could be used to find the angles of the impulse face over the time it takes the tooth to slide from one end of the pallet to the other. Then Fi and Fp could be calculated for each angle, followed by the distance the pallet travels in the direction of Fp (in each instant of time). The force Fp and the distance (X) could be multiplied to get the work done in each instant, which, all added together, would give the total work done to rotate the pallet in the direction of Fp. See the Brocot chart on the next page. The total at the bottom gives the total work done as an index, which could be compared with the ideal Graham escapement. Since the Brocot has a work done index of 0.384 and the Graham of 0.5, *the Brocot is less efficient by over 23%!*

To get a work done index for the Brocot, allow 1º of drop, as for the Graham. Just multiply the index by the same factor: 0.384 *x* 5/6 = 0.32. Therefore, you could say that the Brocot is only 32% efficient in practice (at best).

The Brocot chart could be used to create a graph. The Brocot graph, on the following page, shows the work done to rotate the pallet in each instant (over the time it takes the tooth to slide across the pallet).

BROCOT						
Fe=1						
time	angle (rad)		fv			
t	a	X	y	D	dD	fv*dD
0.000	1.571	0.000	0.000	0.000	0.000	0.000
0.020	1.551	0.020	0.020	0.000	0.000	0.000
0.040	1.531	0.040	0.040	0.002	0.001	0.000
0.060	1.511	0.060	0.060	0.004	0.002	0.000
0.080	1.491	0.080	0.080	0.006	0.003	0.000
0.100	1.471	0.100	0.099	0.010	0.004	0.000
0.120	1.451	0.120	0.119	0.014	0.004	0.001
0.140	1.430	0.140	0.139	0.020	0.005	0.001
0.160	1.410	0.160	0.158	0.026	0.006	0.001
0.180	1.390	0.180	0.177	0.032	0.007	0.001
0.200	1.369	0.200	0.196	0.040	0.008	0.001
0.220	1.349	0.220	0.215	0.048	0.008	0.002
0.240	1.328	0.240	0.233	0.058	0.009	0.002
0.260	1.308	0.260	0.251	0.068	0.010	0.003
0.280	1.287	0.280	0.269	0.078	0.011	0.003
0.300	1.266	0.300	0.286	0.090	0.012	0.003
0.320	1.245	0.320	0.303	0.102	0.012	0.004
0.340	1.224	0.340	0.320	0.116	0.013	0.004
0.360	1.203	0.360	0.336	0.130	0.014	0.005
0.380	1.181	0.380	0.351	0.144	0.015	0.005
0.400	1.159	0.400	0.367	0.160	0.016	0.006
0.420	1.137	0.420	0.381	0.176	0.016	0.006
0.440	1.115	0.440	0.395	0.194	0.017	0.007
0.460	1.093	0.460	0.408	0.212	0.018	0.007
0.480	1.070	0.480	0.421	0.230	0.019	0.008
0.500	1.047	0.500	0.433	0.250	0.020	0.008
0.520	1.024	0.520	0.444	0.270	0.020	0.009
0.540	1.000	0.540	0.454	0.292	0.021	0.010
0.560	0.976	0.560	0.464	0.314	0.022	0.010
0.580	0.952	0.580	0.472	0.336	0.023	0.011
0.600	0.927	0.600	0.480	0.360	0.024	0.011
0.620	0.902	0.620	0.486	0.384	0.024	0.012
0.640	0.876	0.640	0.492	0.410	0.025	0.012
0.660	0.850	0.660	0.496	0.436	0.026	0.013
0.680	0.823	0.680	0.499	0.462	0.027	0.013
0.700	0.795	0.700	0.500	0.490	0.028	0.014
0.720	0.767	0.720	0.500	0.518	0.028	0.014
0.740	0.738	0.740	0.498	0.548	0.029	0.015
0.760	0.707	0.760	0.494	0.578	0.030	0.015
0.780	0.676	0.780	0.488	0.608	0.031	0.015
0.800	0.644	0.800	0.480	0.640	0.032	0.015
0.820	0.609	0.820	0.469	0.672	0.032	0.015
0.840	0.574	0.840	0.456	0.706	0.033	0.015
0.860	0.536	0.860	0.439	0.740	0.034	0.015
0.880	0.495	0.880	0.418	0.774	0.035	0.015
0.900	0.451	0.900	0.392	0.810	0.036	0.014
0.920	0.403	0.920	0.361	0.846	0.036	0.013
0.940	0.348	0.940	0.321	0.884	0.037	0.012
0.960	0.284	0.960	0.269	0.922	0.038	0.010
0.980	0.200	0.980	0.195	0.960	0.039	0.008
1.000	0.000	1.000	0.000	1.000	0.040	0.000
						0.384


Brocot
work done per unit of time
0.000
0.008
0.016
0.000
0.200
0.400
0.600
0.800
1.000
time (index)

Brocot						
Fe=1						
time	angle (rad)		Fv			
t	a	X	y	D	dD	Fv*dD
0	=ACOS(A10)	=COS(B10)	=C10*SIN(B10)	=C10*COS(B10)	0	=D10*F10
0.02	=ACOS(A11)	=COS(B11)	=C11*SIN(B11)	=C11*COS(B11)	=E11-E10	=D11*F11
0.04	=ACOS(A12)	=COS(B12)	=C12*SIN(B12)	=C12*COS(B12)	=E12-E11	=D12*F12
0.06	=ACOS(A13)	=COS(B13)	=C13*SIN(B13)	=C13*COS(B13)	=E13-E12	=D13*F13
0.08	=ACOS(A14)	=COS(B14)	=C14*SIN(B14)	=C14*COS(B14)	=E14-E13	=D14*F14
0.1	=ACOS(A15)	=COS(B15)	=C15*SIN(B15)	=C15*COS(B15)	=E15-E14	=D15*F15

In calculus, the total work done is found by integration, that is, by finding the area under the curve. I approximated the area by using Simpson's Rule. The Brocot graph divided the time index into 50 parts, accurate to 2 decimal places. By dividing it into more parts, I could get a more accurate approximation: dividing it into 10,000 parts, easy to do on a computer, gave a work done index of 0.3927. If you would like to try this on your computer, use the formulas on the page after the Brocot graph.

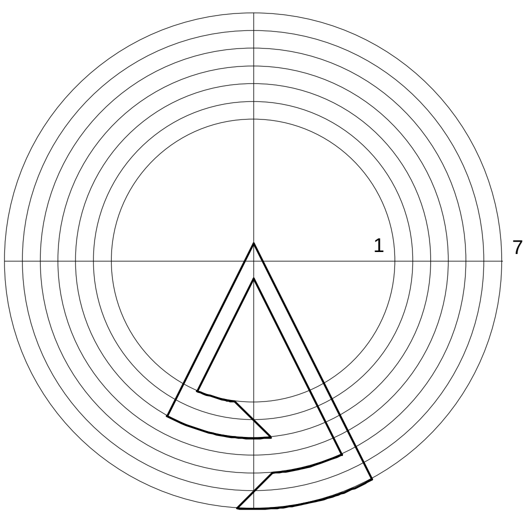
A practical example would demonstrate the usefulness of this information. A friend asked me to look at the escapement of a Seth Thomas regulator wall clock with Graham-style pallets. By inspection, I could see that the design was based on a square, so the impulse face's angle of the entry pallet should have been horizontal and the impulse face's angle of the exit pallet should have been vertical. On the exit side, the impulse face was almost vertical, so I decided to leave it alone. On the entry side, the impulse face was almost parallel to Fe. I estimated the angle FeFi to be about 70º.

Fi = 1 *x* cos (70) = 0.342 Fp = 0.342 *x* cos (20) = 0.321

This does not account for drop, so compare this efficiency of 32% with 50%. The clock was less efficient by more than a third on the entry side because the impulse face's angle was incorrect. Since there was plenty of lock, I decided to change the impulse face's angle by as much as I could without sacrificing all the lock. I did this using an Arkansas stone, installing the pallet frequently to check the lock. The result was not horizontal, but an improvement over the previous angle. Then I polished, cleaned and oiled the impulse face. By decreasing the angle FeFi by about 10º, there was an improvement in efficiency:

Fi = cos (60) = 0.5 Fp = 0.5 cos (30) = 0.433

Efficiency improved by over 20%. This example demonstrates how this information is useful to the repairman. While it may not be possible to adjust the impulse face's angle by as much as would be ideal, an improvement is surely better than none.



The most difficult part of an escapement drawing is the calculations for the verge circle radii, which is critical for the Pin Wheel escapement. Here there are seven circles (not drawn to scale). If the 4th circle, between the pallets, has a radius of 6", the others must be calculated from this circle. If the escape wheel's pin has a diameter of 1/16 of an inch, or 0.0625", the gap between the two pallets must be greater than this, say 0.1": the radii of the 3rd and the 5th circles would be 5.95" and 6.05" respectively. The gap between the locking face of the entry pallet and the let-off corner of the exit pallet must be equal to the arc between two escape wheel pins (less the diameter of one pin and less the allowance for drop). If the escape wheel had fifteen pins and a radius of 3", its arc would be:

arc = 3 *x* (24º *x* pi) / 180 = 1.26"

(because 24º *x* 15 = 360º), but you allow 1.5º for drop:

arc = 3 *x* (22.5 *x* pi) / 180 = 1.18"

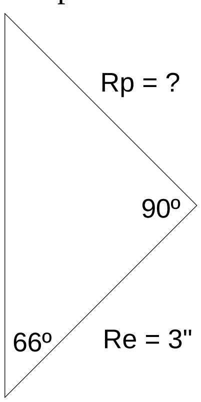
and for the pin diameter: arc = 1.18 - 0.0625 = 1.12" (to two decimal places).

The radius of the 1st circle is therefore: 6 - (1.12 / 2) = 5.44" and the radius of the 7th circle is 6.56".

The radius of the 2nd circle is half way between the 1st and the 3rd:
(5.95 + 5.44) / 2 = 5.70"
and the radius of the 6th circle is half way between the 5th and the 7th:
(6.05 + 6.56) / 2 = 6.30"

The radius of the 4th circle may appear to be arbitrary because it is not determined by the tooth span between the pallets, as it would be for the Graham, Recoil, and Brocot. It is determined only by the desired angle of pendulum swing.

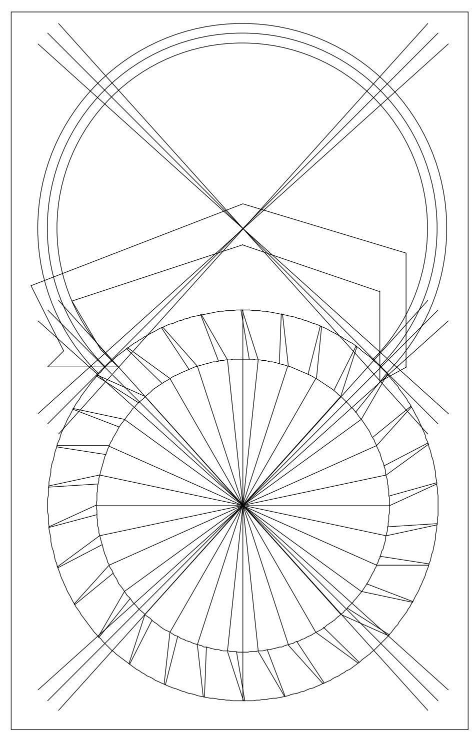
Consider a pallet circle that was determined by a tooth span, such as the Graham escapement with the 15 tooth escape wheel in chapter 10. It had a tooth span of 5.5 teeth, so the angle between the pallets was: (5.5 / 15) *x* 360 = 132º, half of which was 66º. The escape circle radius was 3", so the pallet circle radius could be found by triangulation:

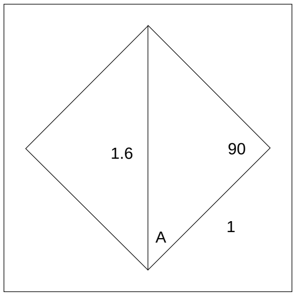


tan (66) = Rp / Re
Rp = Re *x* tan (66) = 3 tan (66) = 6.74"
Continuing with the Graham in chapter 10, its escape wheel had a radius of 3", so the arc between two teeth was:
arc = (3" *x* 24º *x* pi) / 180º = 1.26"
The arc per beat (12º): 1.26 / 2 = 0.63"
Allow 1.5º for drop:
arc = (0.63 *x* 10.5º) / 12º = 0.55"
This is the thickness of the pallets.
Therefore, the entry pallet locking face has a pallet circle radius of:
6.74 + 0.27 = 7.01"
and the exit pallet locking face has a pallet circle radius of : 6.74 - 0.27 = 6.47".

Replacing the Pallets.

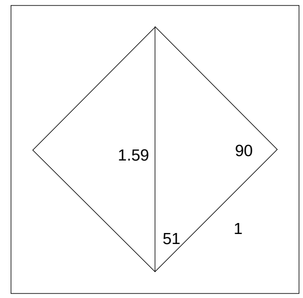
Suppose a British grandfather clock movement were brought for repair with no pallets. You determine by inspecting the 30 tooth escape wheel that the clock had a recoil escapement. The distance between the escape wheel bushing and the pallet bushing is 1.6". The escape wheel has a diameter of 2", so the escape circle's radius is 1". First, draw the pallet you want over an ideal Graham pallet and remove the latter:

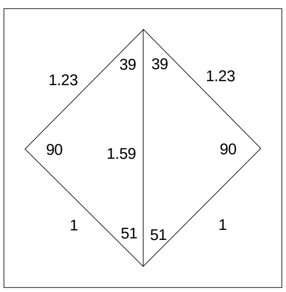




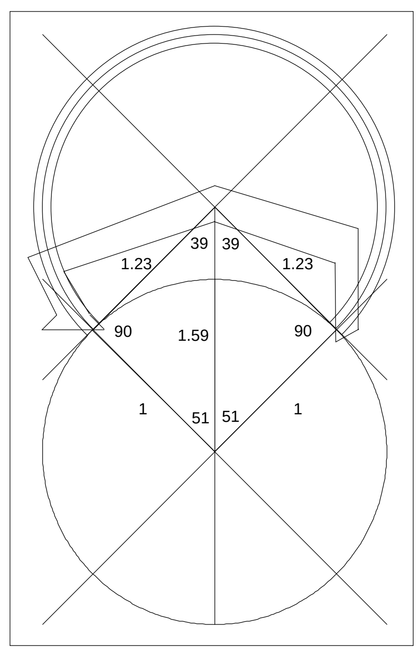
Draw two triangles using this arrangement:
cos (A) = 1 / 1.6
A = acos (1 / 1.6) = 51.3º
Use this to determine the tooth span:
30 *x* (2 *x* 51.3 / 360) = 8.553
so you should use a span of 8.5 teeth.

To recalculate the angle A: (8.5 *x* 360) / (2 *x* 30) = A = 51º



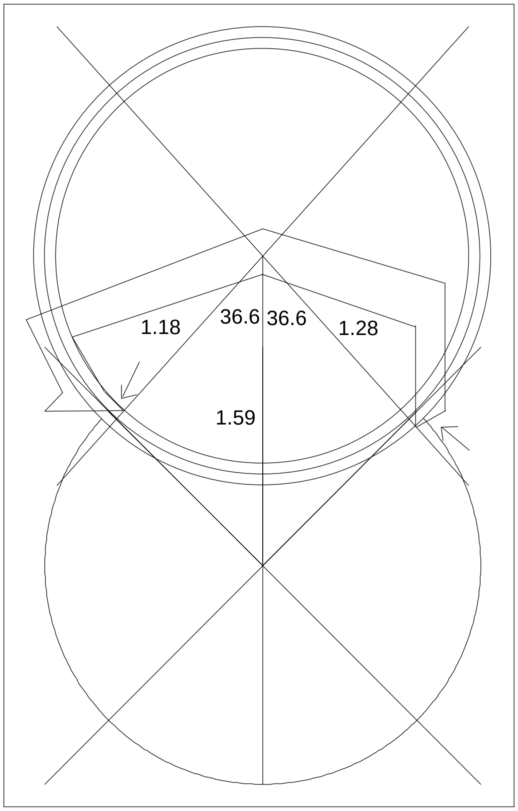


Assume a small error in measurement:
cos (51) = 1 / h
h = 1 / cos (51) = 1.59"
The pallet angle is : 180 - 90 - 51 = 39º
The pallet circle radius is:
Rp = 1 *x* tan (51) = 1.23



By comparing this drawing with the one on the previous page, calculate the positions of the tips of the pallets. The inside tip of the entry pallet needs to be at a slightly smaller angle from vertical:
Angle = 39 - (3 *x* (1 / 1.23) = 36.6º
and the radius:
r = 1.23 - ((2 *x* pi) / (4 *x* 30)) = 1.18"
Similarly for the exit pallet:
Angle = 36.6º.
r = 1.23 + ((2 *x* pi) / (4 *x* 30)) = 1.28"

The rest of the pallet could be drawn any way you wish. To explain the numbers above, the escape wheel has an angle of 12º between two teeth. A tooth will travel 6º per beat. The pallet angle lines were divided into 3º on either side. Since the pallet radius is 1.23 and the escape radius is 1", multiply the escape angle of 3º by the ratio of the radii. Since the pallet radius is larger, the pallet arc is smaller than the escape wheel arc (which has an angle of 3º).



For the radius calculation, decrease the pallet radius on the entry pallet by the amount of a quarter of the arc between two escape wheel teeth, and increase the pallet radius on the exit pallet similarly. This is only a close approximation because the change in the pallet circle's radius is assumed to be equal to the arc of the escape circle, but an arc is not a straight line.

Once the pallet blank is made, it must be fitted because there is no drop. By filing on the surfaces pointed to by the arrows, some inside and outside drop could be created.

When designing a Graham pallet, the issue becomes more complicated because of lock. I would suggest that the best way to design the pallets would be to make the blank with impulse faces that have angles relative to Fe smaller than 45º, such as 25º. When fitting the pallets to the clock, file first on the inside and outside surfaces to create enough inside and outside drop. Then file on the impulse face to increase the impulse angle until the lock has been reduced to about 1º. To be practical in a manufacturing situation, the measurement deviations must be accounted for to keep rejects statistically below 5%. The need to account for these deviations means that a compromise situation arises because fitting each verge by hand would interfere with mass production and economies of scale.

Fitting a Brocot pallet requires the calculation of the pallet circle's radius. If the escape wheel rotates 6º per beat, and its radius were 1", the arc would be:

arc = (1 *x* 6 *x* pi) / 180 = 0.105"

I suggest 1.5º of drop, so the radius of the pallet's circle should be:

r = (1 *x* 4.5 *x* pi) / 180 = 0.08"

Using the recoil example, the Brocot pallet should be positioned such that the point where the pallet releases the escape tooth should have a pallet circle radius of 1.18" and an angle of 36.6º from vertical for the entry pallet, and a radius of 1.28" and an angle of 36.6º for the exit pallet. Then the lock and drop could be further adjusted by raising or lowering the pallets, or by changing the gap between the pallets.

By studying the above example, you could see how you could use one type of escapement for the calculations, and then apply them to the type of escapement you want to create. A step-by-step process makes the calculations easier.

Watch

Escapements

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Introduction:

Drawing watch escapements requires much more detail than drawing the Graham (clock) escapement. I will pay most attention to the modern Swiss watch with the club-tooth escape wheel as it is the most commonly encountered at the bench.

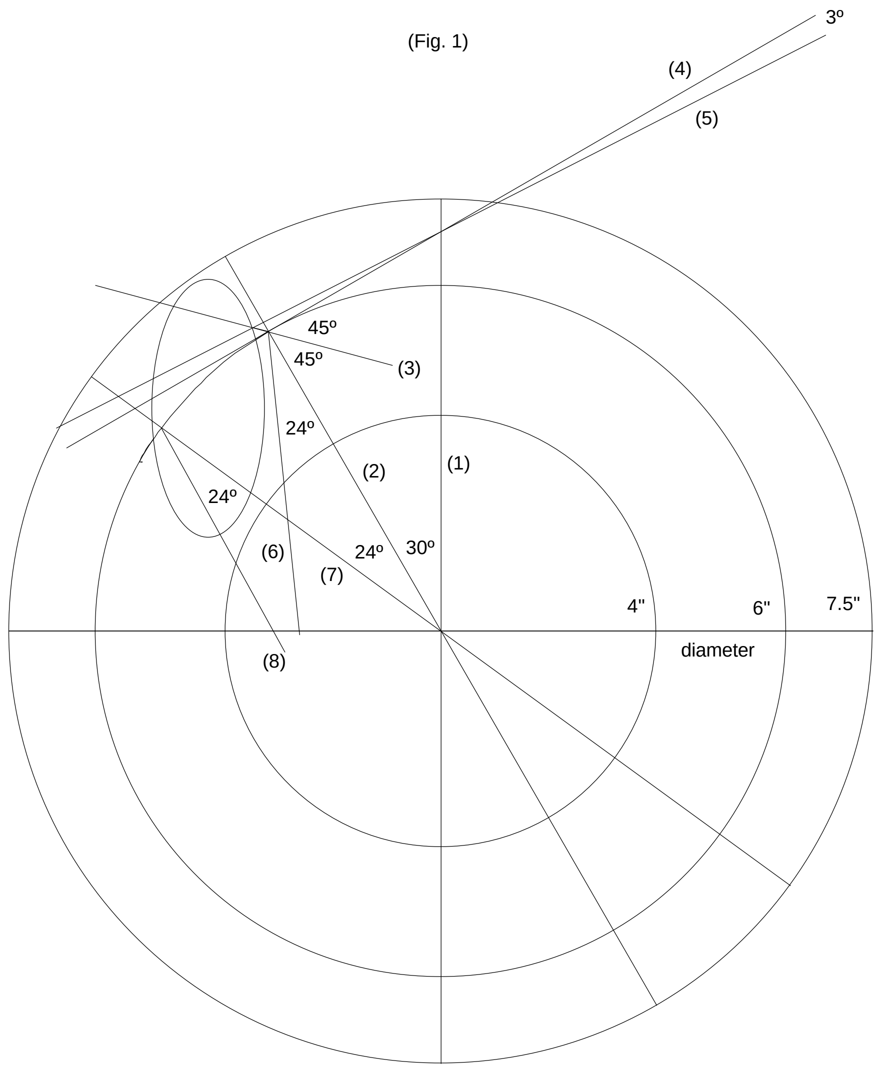
Watch and clock escapements are similar in that they should have symmetrical designs, so that the impulses the pallets receive would be equal. The efficiency of the escapement should be the same for both pallets. The impulse face of each pallet should have an angle of 45º relative to the direction of the force that the escape tooth applies to the pallet during impulse if the angle between this force and the force that acts to rotate the pallet were 90º. If the pallet's impulse face angle were not correct, there would be a considerable loss of efficiency, or the ability of the balance wheel to receive impulses from the escape wheel. This is covered in detail in Chapter 4 of the Clock Escapement section.

The most significant difference between clock and watch escapements, such as the Graham escapement and the Swiss Lever, is that the clock's pendulum is not independent of the pallets, whereas the watch's balance wheel is independent of the pallets most of the time. This means that the clock escapement should have pallets with curved locking faces to achieve a dead-beat, so that there would be no recoil as the escape tooth slides along the pallet locking face. The watch escapement, however, should have pallets with locking faces that allow the escape tooth to move forwards slightly as it slides up the pallet's locking face, so as to create draw. The draw is a small binding action that helps to keep the pallet fork over to the side, against the banking pin, until the balance wheel's roller jewel returns, so that the fork's guard pin would not rub against the balance wheel's roller table and thereby interfere with the freedom of rotation of the balance wheel. Since watches require draw, the equidistant lock of the pallets is desirable in order to have equal draw for both pallets. This is covered in detail in Chapter 9 of the Clock Escapement section.

If you are a watchmaker with no interest in clocks, I would recommend that you consider reading the chapters concerning clock escapements because the logic behind the drawings is the same, and it is easier to introduce a reader to the drawing techniques with less difficult examples, (in other words, examples of simpler escapements that apply to clocks). It would be necessary to understand the basic principles behind escapement drawings before attempting to draw complicated watch escapements that would work in a simulation on a computer.

12: Drawing a Club-Tooth Escape Wheel.

While reading this chapter, please refer to the drawing in figure 1 on the next page. First, draw three circles with diameters of 4 and 6 and 7.5 inches. Center them on the page and draw a horizontal and a vertical line across the largest circle. Take the vertical line (1) and rotate it counterclockwise by 30º to get line (2): this will be the escape circle's radius for the first tooth. Rotate line (2) counterclockwise by 45º to get line (3): this will be the impulse face of the escape tooth. I have shortened line (3) and several other lines only in order to make this drawing easier to understand. Place line (3) onto the point where line (2) intersects the six inch circle. Then rotate line (3) counterclockwise by another 45º to get line (4): this line will become the pallet circle's radius. Place line (4) on the edge of the six inch circle at the point where the circle intersects with lines (2) and (3). At the point where the vertical line (1) intersects with line (4), rotate line (4) clockwise by 3º: this will determine the amount of lock that this design will have. While the ideal amount of lock is recommended to be only 1º, I recommend 3º in this drawing because it will make the lock easier to see during the simulation. It will also make the simulation more forgiving if errors were made during the preparation of the drawing. The best way to ensure that line (4) is rotated about the point where it intersects line (1) is to center line (4) on the page shown on your computer screen before rotating, since line (1) has already been centered on the page.

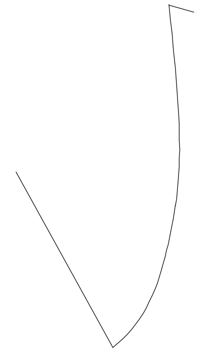


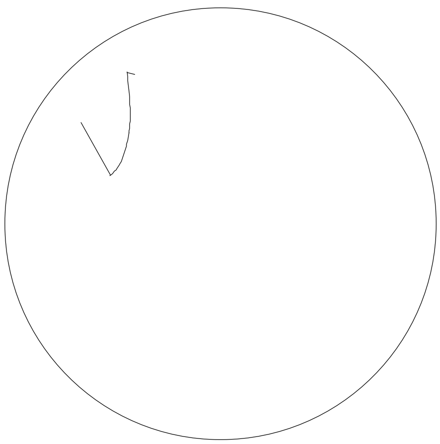
Rotate line (2) clockwise by 24º to get line (6), and place it onto the point where lines (2), (3), and (4) intersect. Line (6) will be the tooth's locking face, and the point where it intersects the other three lines will be the entrance corner of the tooth.

Rotate line (2) counterclockwise by 24º, since there are 24º between each tooth of a 15 tooth escape wheel, to get line (7). Rotate line (7) clockwise by 24º to get line (8). Place line (8) onto the point where line (7) intersects the six inch circle. Line (8) will be the locking face of the *next* tooth. The locking faces of the teeth will appear to lean forwards by 24º.

Draw a three inch circle and place in onto the point where lines (3) and (5) intersect. This circle can be made larger or smaller, or stretched at will until the desired shape is achieved to trace the curve of the tooth. I recommend that you draw a relatively thin tooth that would allow the pallet to clear during the simulation. After the simulation, when you know how much clearance you have, you could draw the escape wheel again.

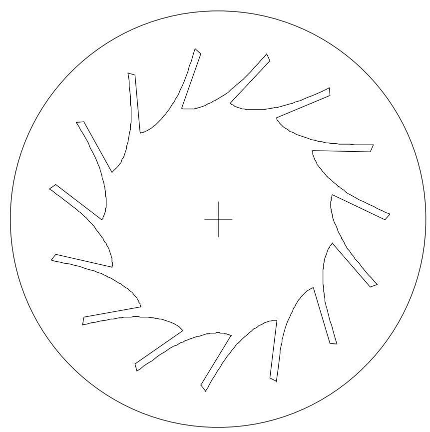
Draw the first tooth over lines (3) and (8), and trace the curve over the ellipse, so that you get a tooth that looks like this:





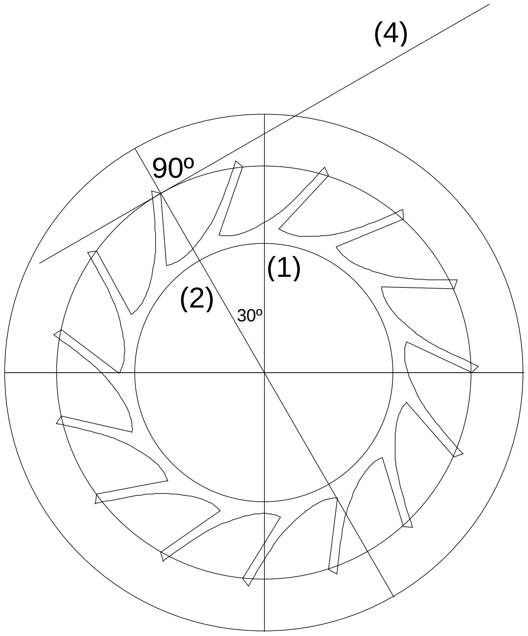
Move all the lines and the two inner circles to one side, so that all you have on the page is the 7.5 inch circle and the tooth in the same position.

Group the tooth and the circle, and rotate the group by 24º in whichever direction you choose. Duplicate the group and rotate again. Duplicate the group again and rotate again. Repeat this until you have 15 groups, all in the same place. Then ungroup all 15 groups, so that you end up with 15 teeth and 15 circles. Delete 14 of the circles, one by one, until you have the complete wheel.



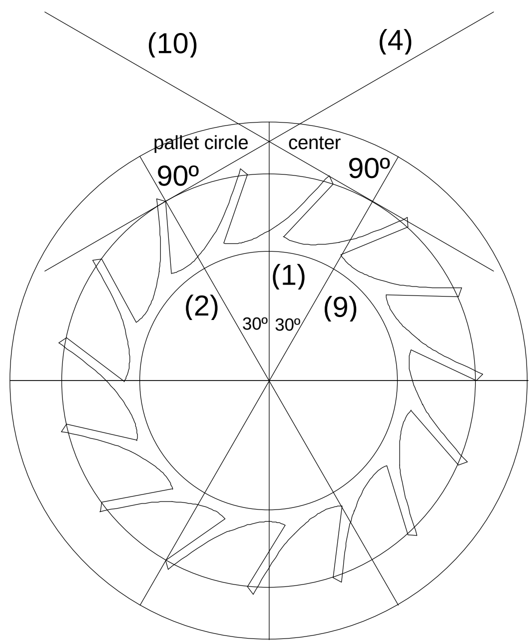
In order for the escape wheel to be true (or perfectly centered), it is necessary to rotate the tooth inside a circle that extends beyond the tooth. Since the tooth extends slightly beyond the edge of the six inch circle, a larger circle is needed for the drawing.

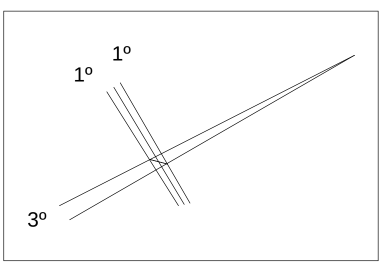
13: Drawing the Pallets.



The first tooth was drawn next to line (2), which had an angle of 30º relative to the vertical line (1). The 30º angle was chosen so that there would be a 2.5 tooth span between the pallets for a 15 tooth wheel. The angle between lines (2) and (4) was 90º so that the angle between the force exerted by the escape tooth and the force that acted to rotate the pallet would be 90º.

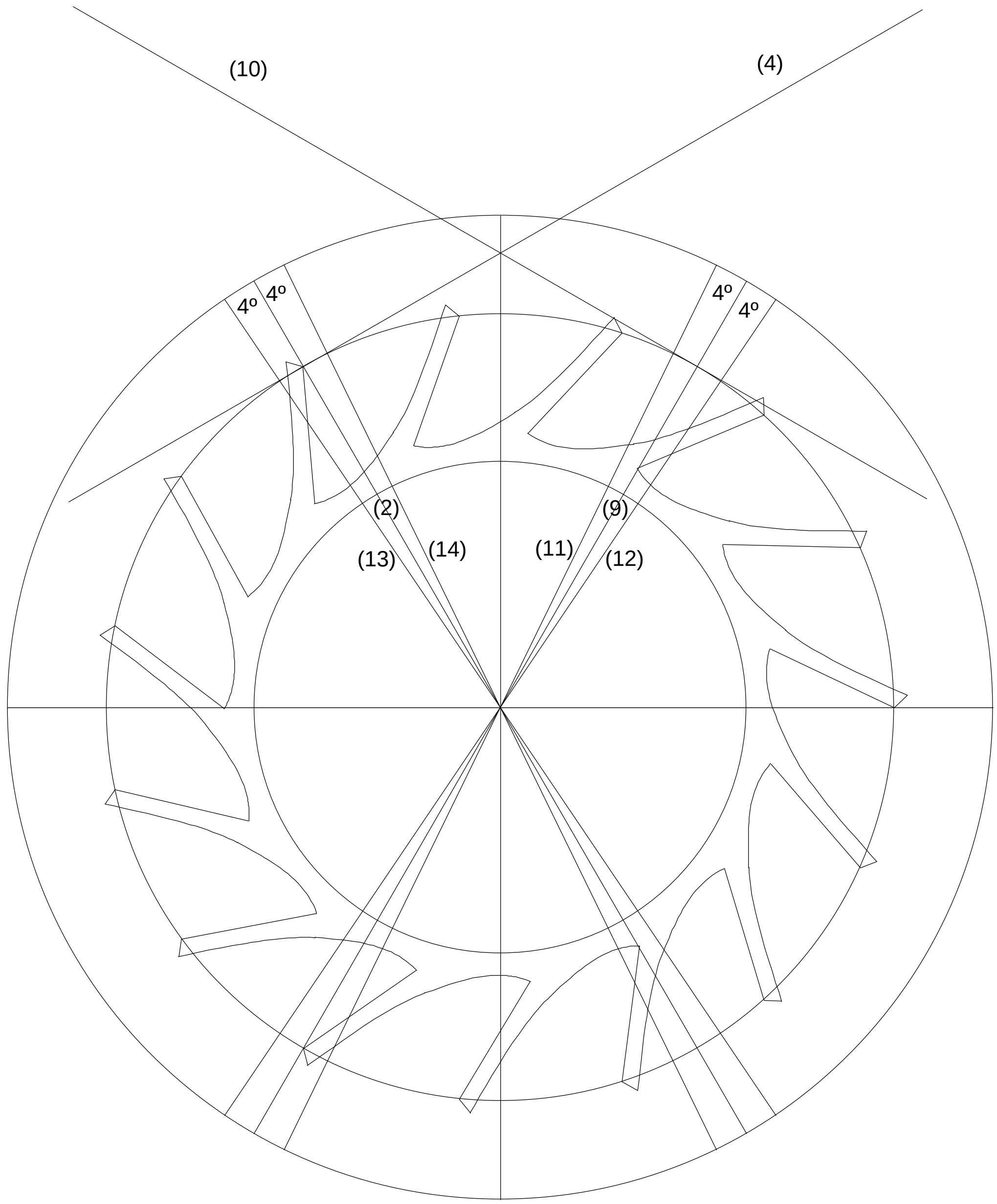
Rotate line (1) clockwise by 30º to get line (9). Rotate line (9) by 90º to get line (10). Place line (10) onto the point where line (9) intersects the edge of the six inch circle. The point where lines (1), (4) and (10) intersect will be the pallet's circle center.



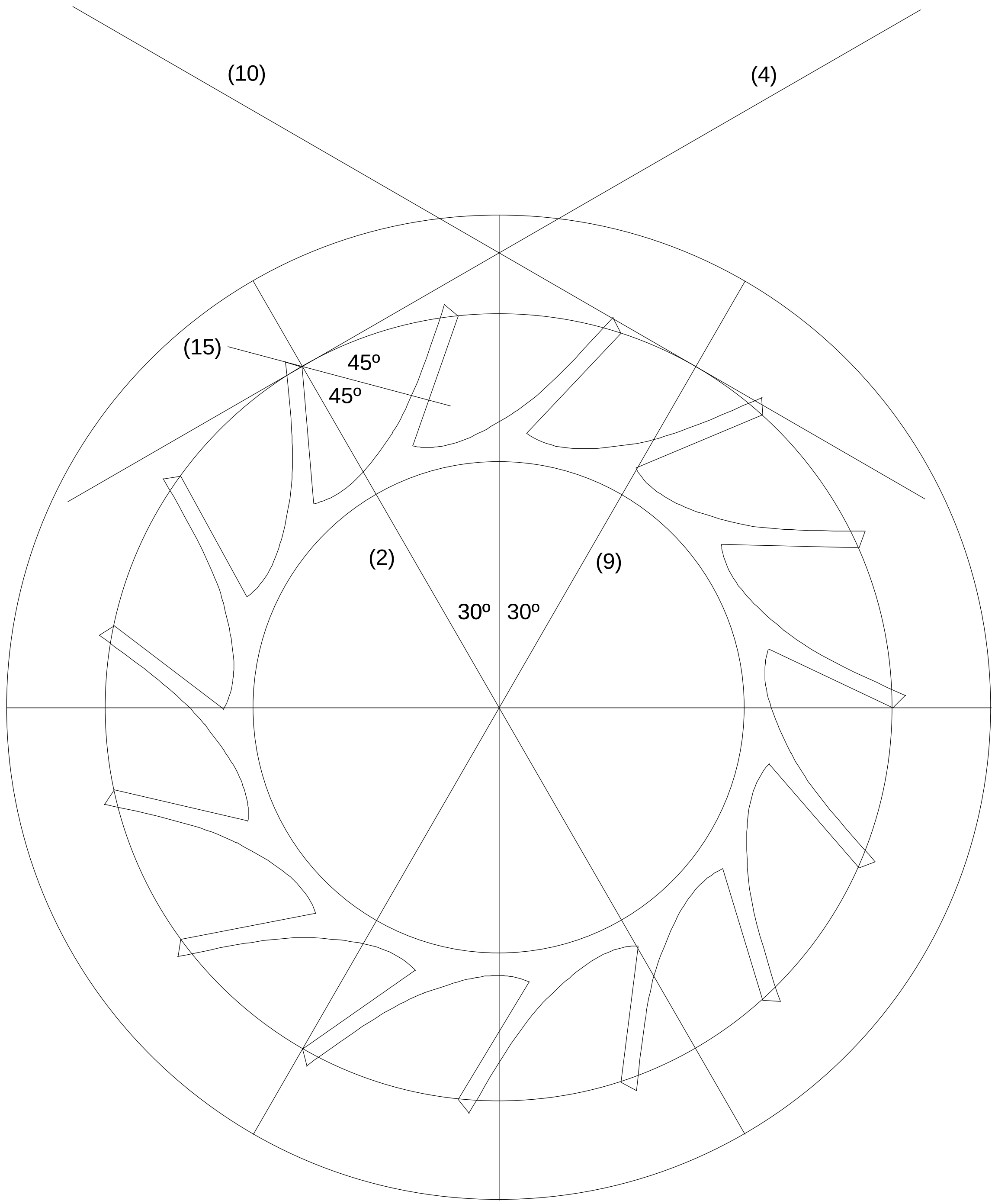


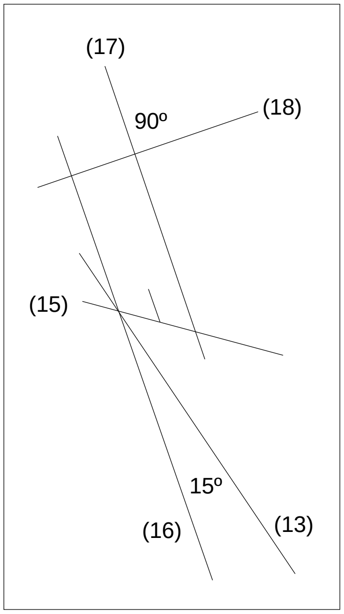
If you rotate line (2) counterclockwise by 2º, you would see that the escape wheel's impulse face occupies a span of 2º of escape wheel rotation. (The impulse face also provides 3º of lift and lock.)

Since the escape wheel rotates by 12º per beat and you want 2º for drop and 2º for the escape tooth's impulse face, the pallet should occupy a span of 8º. Rotate line (9) counterclockwise by 4º to get line (11). Rotate line (9) clockwise by 4º to get line (12). Repeat with line (2) to get lines (13) and (14):

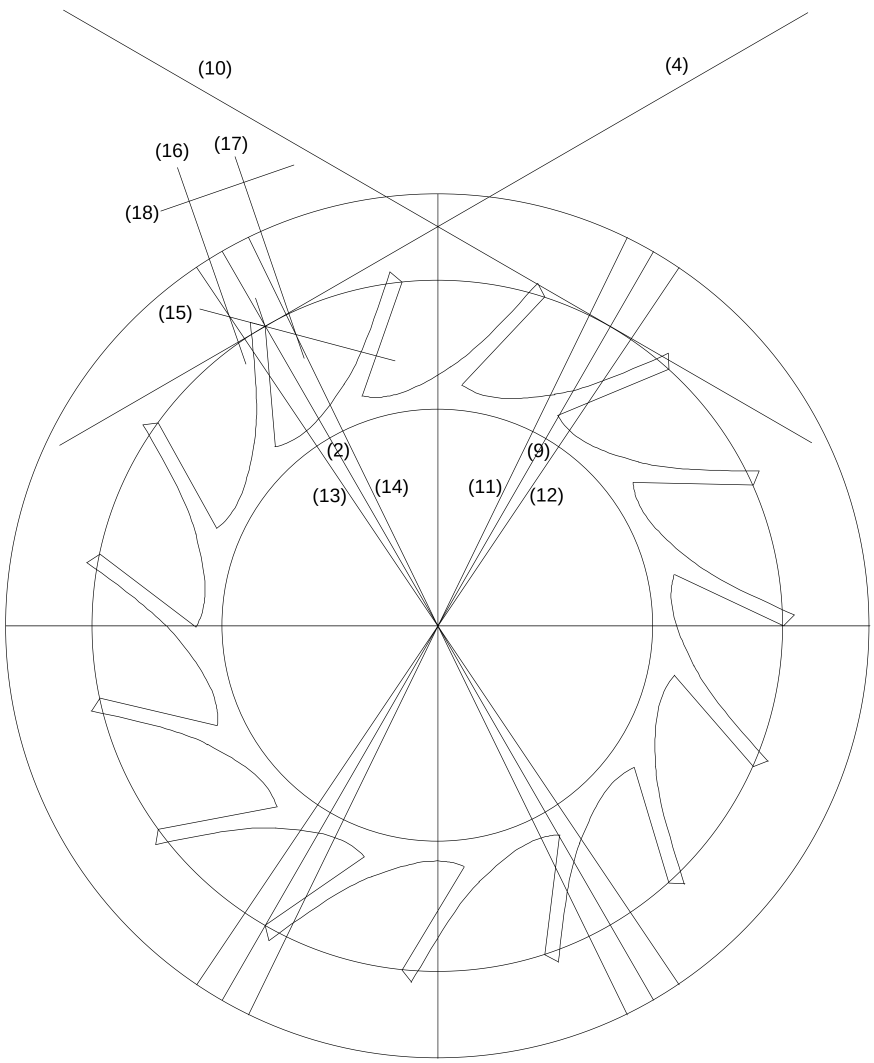


Rotate line (2) counterclockwise by 45º to get line (15). Notice that it is at an angle half way between the escape circle's radius and the pallet circle's radius, shown by lines (2) and (4) respectively:



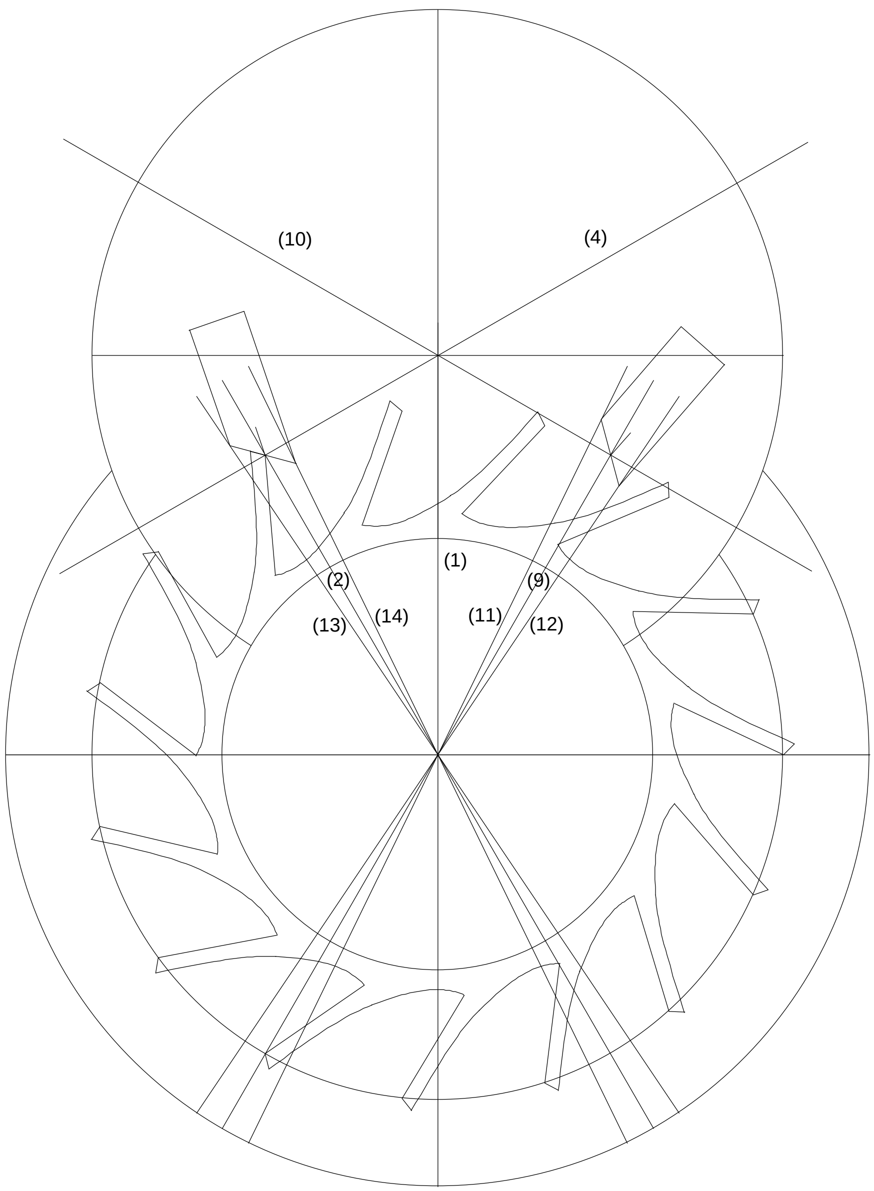


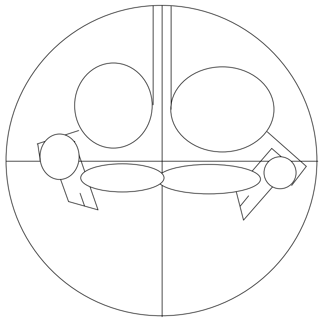
Rotate line (13) clockwise by 15º to get line (16), and place it onto the point where lines (13) and (15) intersect. Line (16) will be the pallet's locking face, and it will have a draw angle of 15º. Duplicate line (16) and place it onto the point where lines (14) and (15) intersect: lines (16) and (17) are parallel. Rotate line (17) by 90º to get line (18) and place it in a suitable position along lines (16) and (17). The pallet is now recognizable. You could place a small line at the point where lines (2) and (15) intersect: this small line would show the mid-point of the pallet.



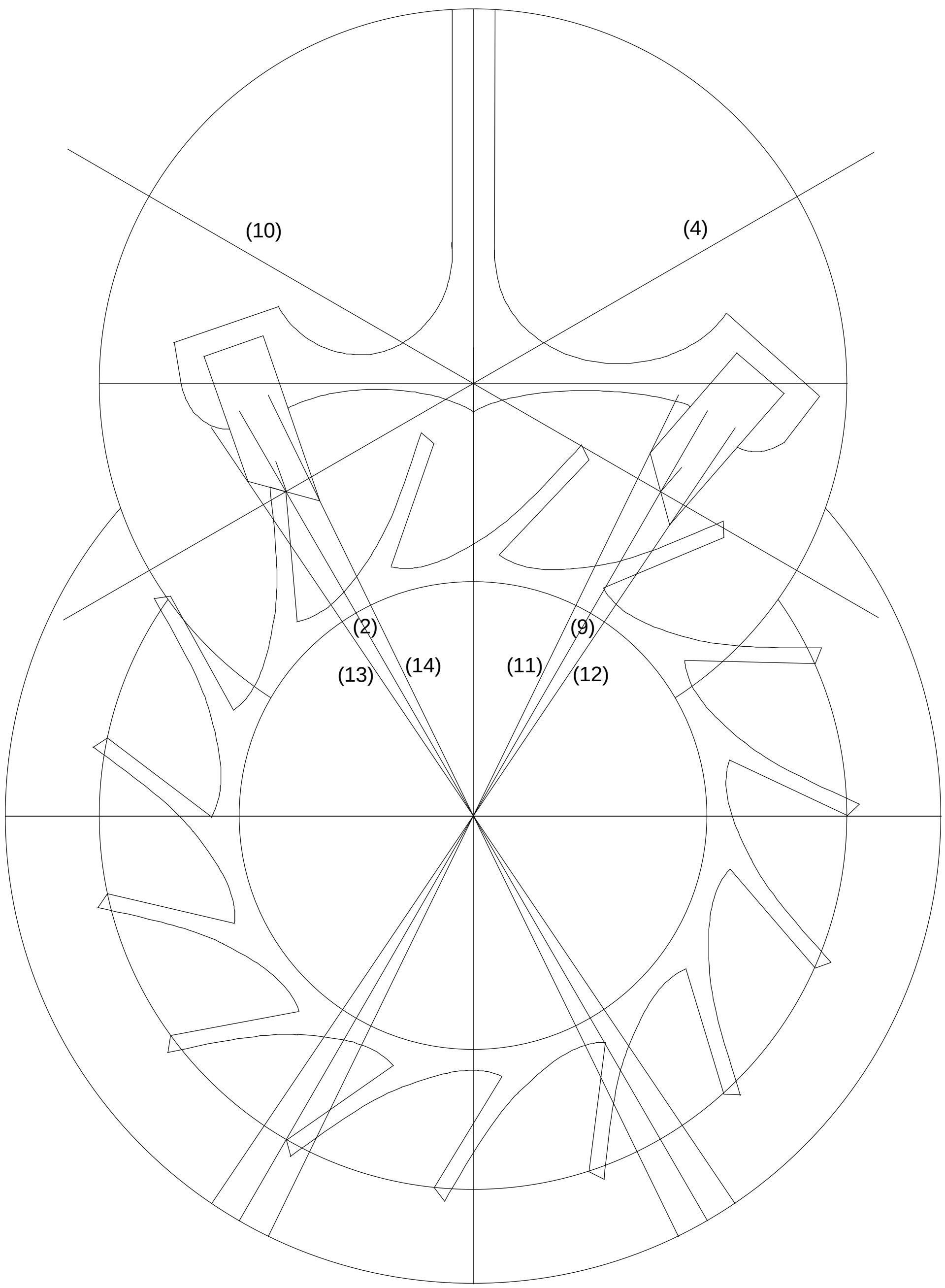
Once you finish the entry pallet, group the lines and duplicate them. Rotate the second pallet clockwise by 60º because that is the angle between lines (2) and (9), and then place the pallet on the exit side such that the mid-point of the impulse face lies on the point where lines (9) and (10) intersect. Most watches have different pallets, but an escapement using the same pallet on both sides can be designed, and using the same pallets makes manufacture easier.

It will be necessary to draw the pallet circle to perform a simulation. The circle must be larger than the drawing of the pallets, so I chose a six inch diameter circle, placed a horizontal and a vertical line in it, grouped the circle and the lines, and then placed them such that the circle center would lie on the point where lines (1), (4) and (10) intersect.



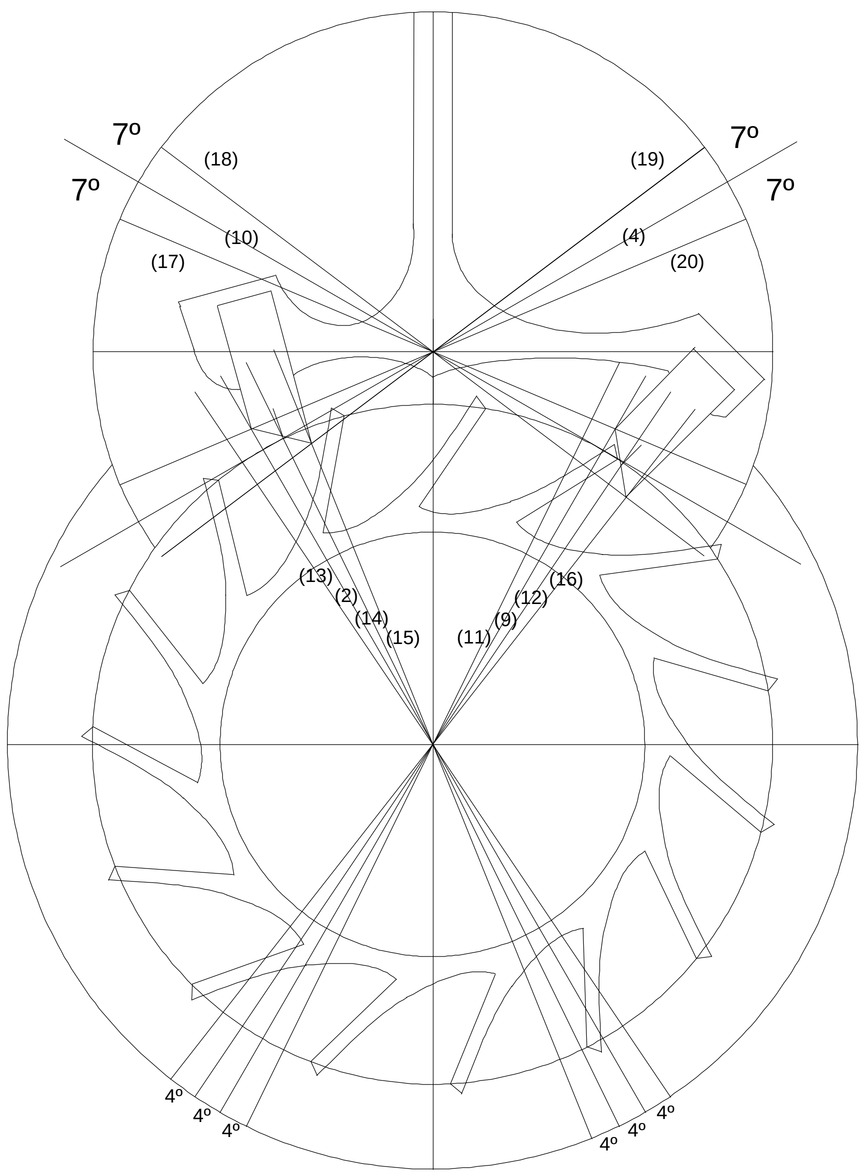


To draw the pallet arms, you could use circles, stretched and shaped to give the outline you desire. It should be obvious by looking at the drawing below that the design is of equidistant impulse.

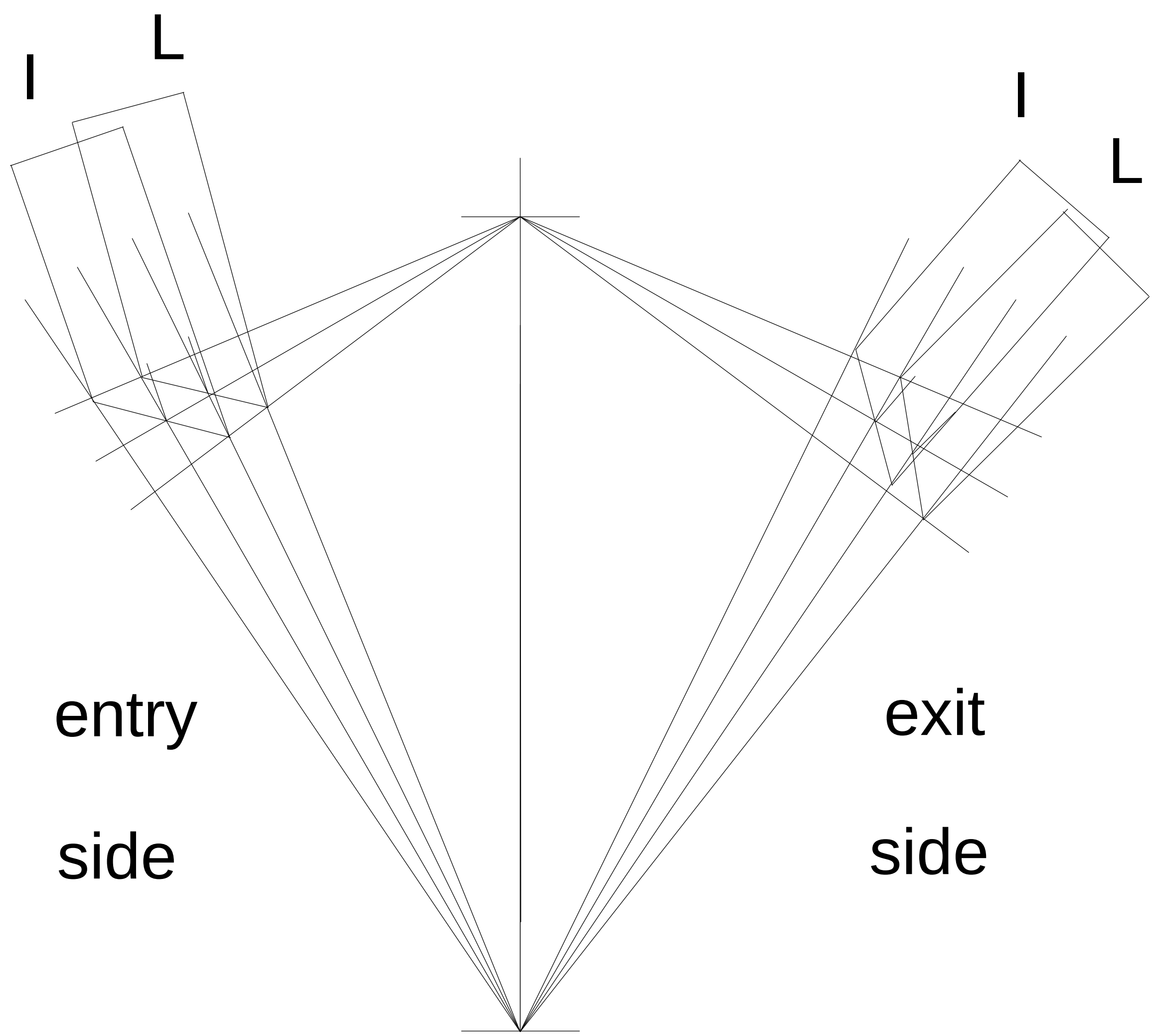


14: Changing the Design.

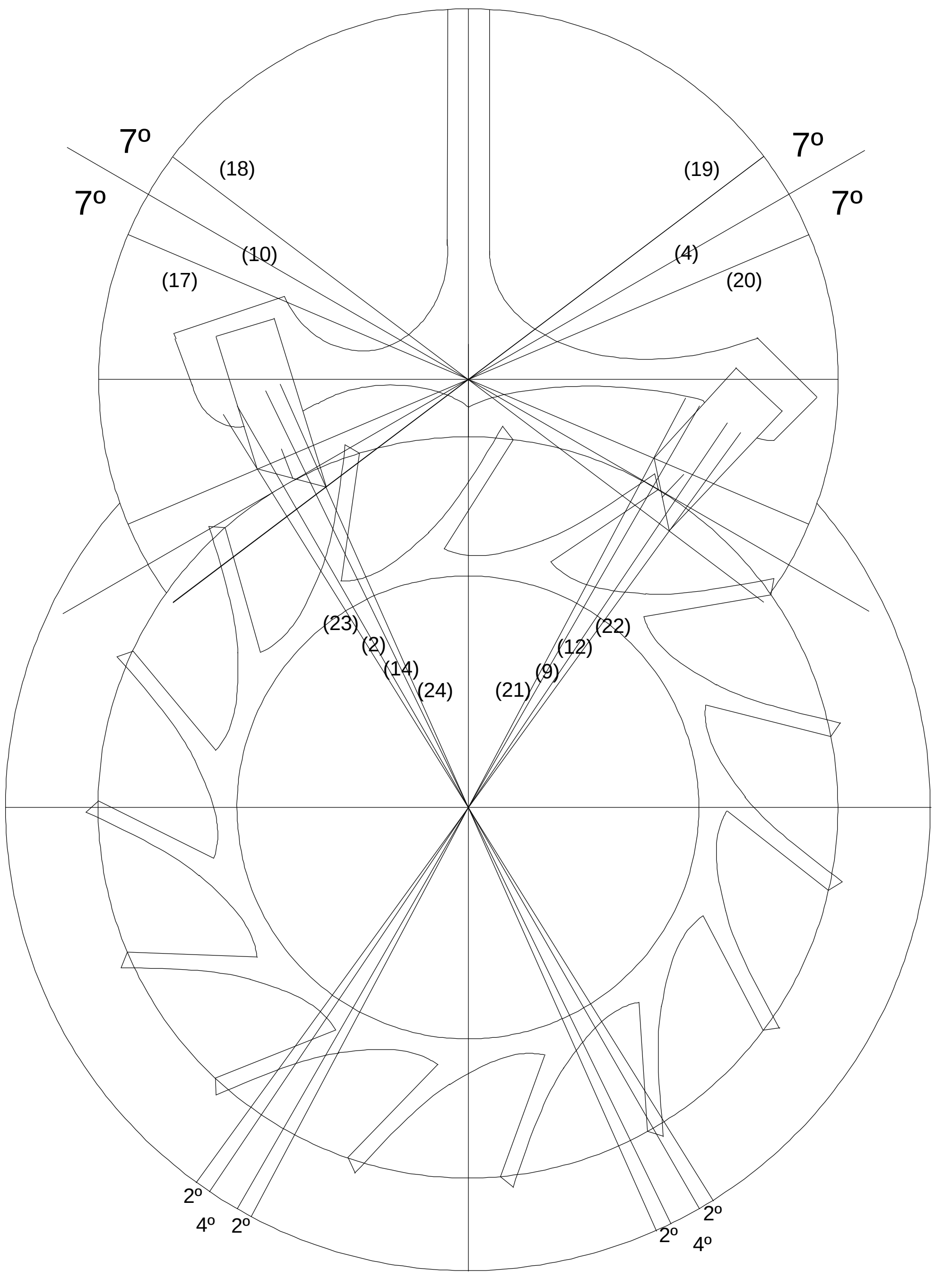
A different approach is required to create different designs, such as the equidistant lock drawing below. Rotate lines (14) and (12) clockwise by 4º to get lines (15) and (16) respectively. Rotate lines (10) and (4) clockwise by 7º to get lines (18) and (20), and counterclockwise to get lines (17) and (19). Draw the entry pallet's impulse face from the point where lines (2) and (20) intersect to the point where lines (15) and (19) intersect. Draw the exit pallet's impulse face from the point where lines (9) and (17) intersect to the point where lines (16) and (18) intersect. Rotate lines (2) and (9) clockwise by 15º to draw the locking faces of the pallets. In order to maintain the action of the pallets as symmetrical as possible (and to keep the impulse face's angle as close to 45º as possible), the lift is reduced slightly to 14º and the impulse angles are no longer at 45º, which reduces efficiency, but the lock and drop are the same on both sides and the pallets are not "out of angle." The pallets are no longer identical.



Drawings could be superimposed for comparison, such as this comparison between the equidistant impulse and lock designs. It reveals that, in the equidistant impulse design, the exit pallet's impulse face does not exactly fit between the lines: while the exit pallet is identical to the entry pallet, it is not a *mirror image* of the entry pallet. The entry pallet does not have a perfect fit either, but the difference is very small and inconsequential. The result of the unequal fit on both sides is that the exit pallet releases the escape tooth a little prematurely, causing the design to be out of angle: the angle on the left side to the drop-lock position is one degree greater than on the right side. This problem is corrected in Chapter 22.

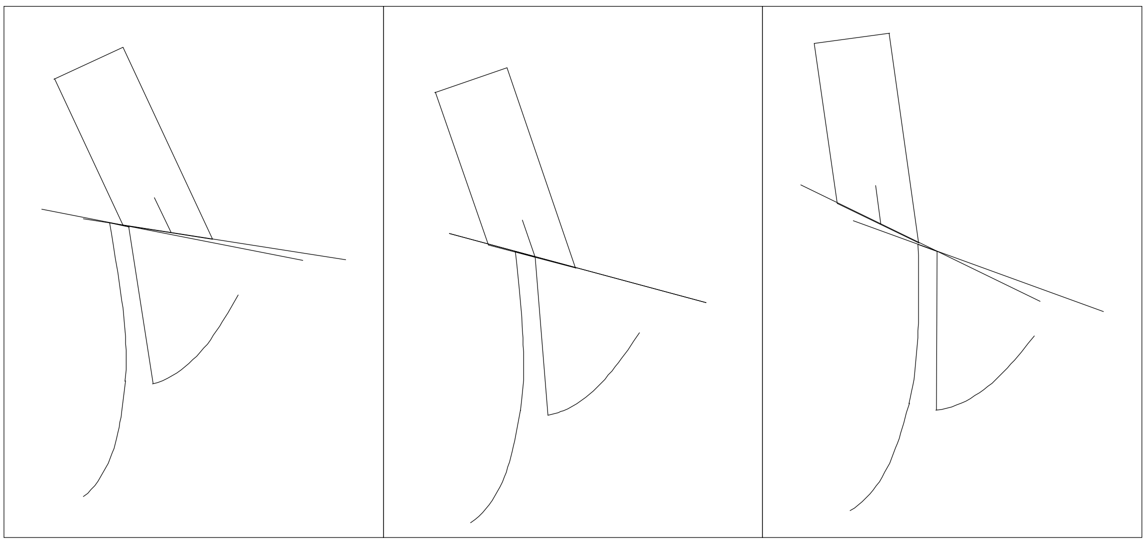


To combine the advantages of equidistant impulse and equidistant lock, watchmakers have designed an escapement half way between the two, called the *semi-tangental* escapement. Here, the angle between lines (2) and (23) and between lines (9) and (21) is 2º, so rotate lines (2) and (9) counterclockwise by 2º to get lines (23) and (21). Rotate lines (12) and (14) clockwise by 2º to get lines (22) and (24). Draw the entry pallet's impulse face from the point where lines (23) and (20) intersect to the point where lines (24) and (19) intersect. Draw the exit pallet's impulse face from the point where lines (21) and (17) intersect to the point where lines (22) and (18) intersect. Rotate lines (23) and (21) clockwise by 15º to draw the locking faces of the pallets.

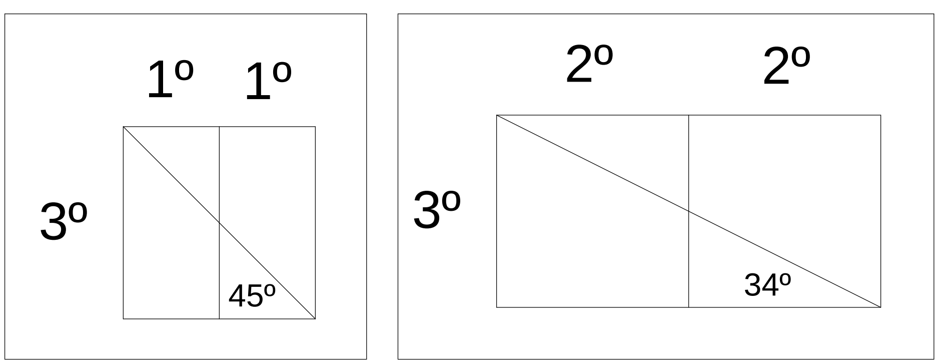


15: Improving the Design.

In order to maximize efficiency, the impulse face of each pallet should have an angle half way between its corresponding escape circle radius line and pallet circle radius line. Looking at the design with equidistant impulse, if the angle between lines (2) and (4) were 90º, then the impulse face's angle should be 45º and line (15) is half way between lines (2) and (4). A change in design is needed in practice because the escape wheel's teeth are too narrow and therefore too fragile. Thus far, I have assumed that the escape tooth's impulse face should be parallel to the pallet's impulse face in the drawing. However, the simulation reveals, as suspected, that the lines do not remain parallel during impulse:

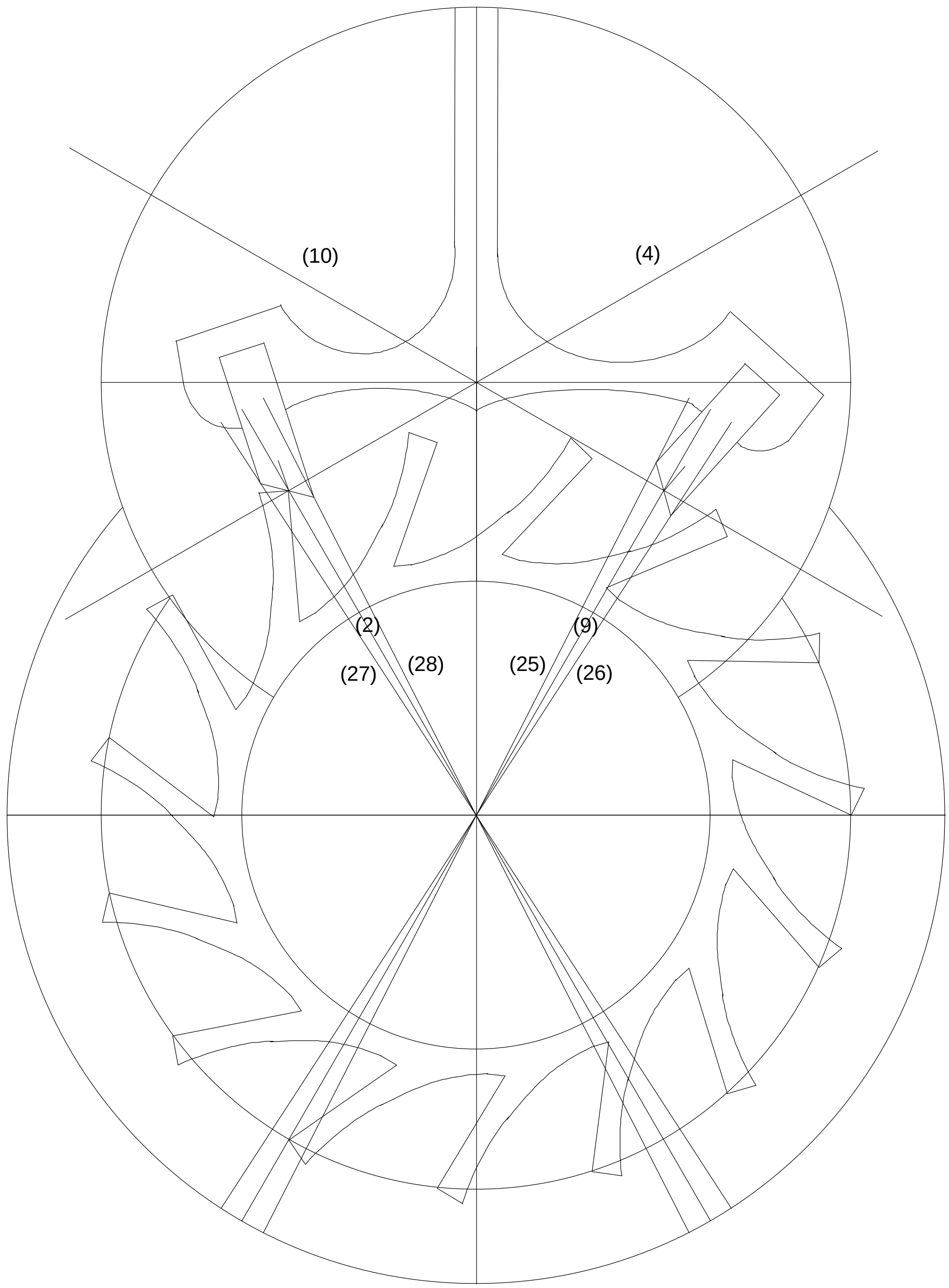


This means that they need not be parallel in the design. If the pallet's impulse face remained unchanged, the efficiency of the escapement would remain unchanged, and we could change the shape of the escape tooth without sacrificing efficiency. The span of the tooth's impulse face could be increased from 2º to 4º so as to draw a wider tooth. The amount of lock would remain unchanged at 3º for the purpose of the drawing:

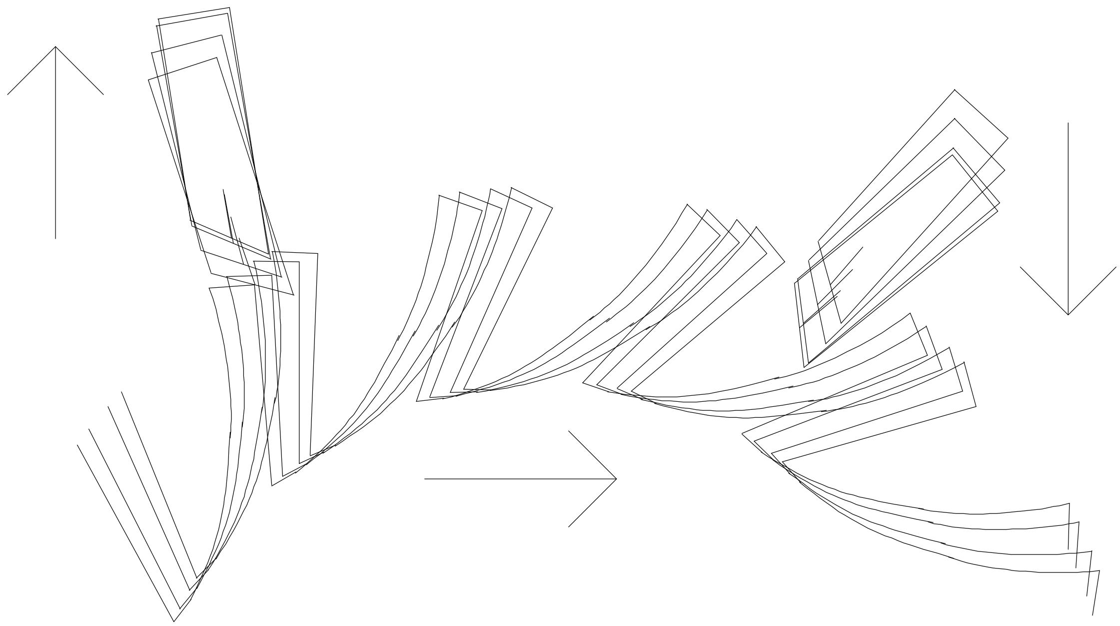


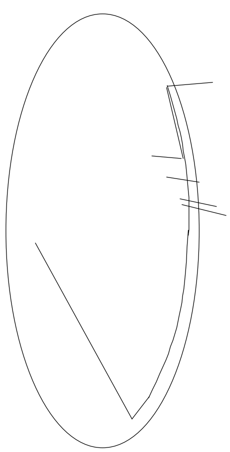
If the escape tooth occupied a span of 4º and there were 2º of drop, the pallet would occupy a span of 6º, for a total span of 12º per beat. New pallets must be drawn.

Rotate line (9) counterclockwise by 3º to get line (25), and clockwise by 3º to get line (26). Rotate line (2) counterclockwise by 3º to get line (27), and clockwise by 3º to get line (28). Rotate line (27) clockwise by 15º and draw the locking face. Draw the rest of the pallet as before, then duplicate it and rotate it clockwise by 60º, placing it on the exit side. The pallets are narrower, but the teeth are wider. Notice the difference in the angles of the pallet and escape tooth impulse faces.



Another way to make a stronger tooth would be to trace the path of the pallet during the simulation, and then to draw the curve on the back side of the tooth again. If the simulation were superimposed for the action of the escapement as the tooth pushed on the entry pallet,

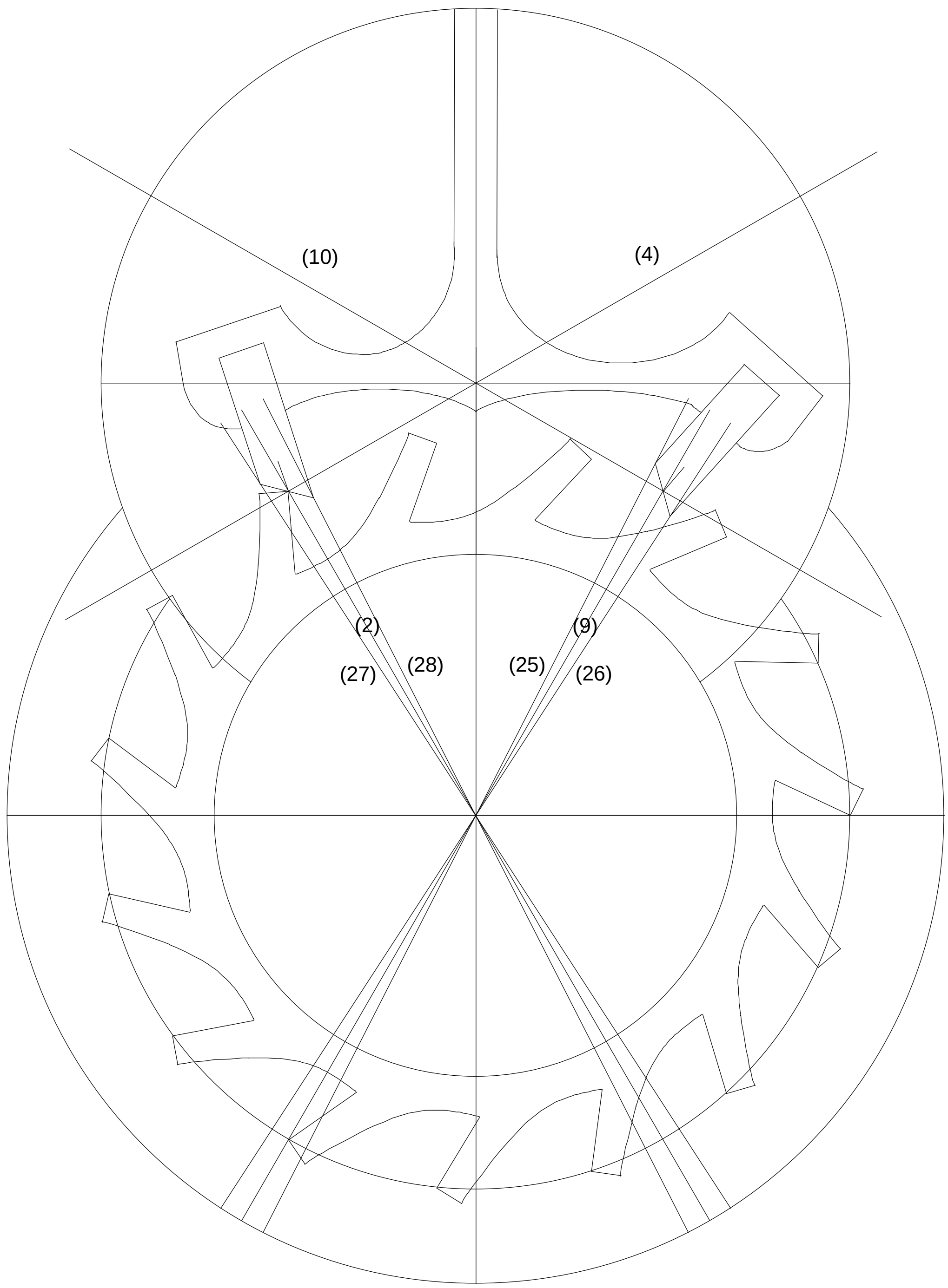




the exit pallet enters the space between two teeth. The distance between the exit pallet and the tooth that just passed it could be measured by drawing lines from the pallet to the tooth. These lines could be used as a guide when drawing a new curve. Move the ellipse to other positions and change its shape until you trace a path for a new curve more like the path of the pallet. If you draw the lines on the tooth next to the *exit* pallet and are drawing the new tooth next to the *entry* pallet, you must rotate the lines by 24º for every tooth in between, that is, by 72º counterclockwise. I drew a new escape wheel using the same principles as in the first drawing plus these lines as a guide. Unfortunately, the path of the pallet would be very difficult to predict before doing a simulation.

It is preferable to draw the first escape wheel with narrow teeth because it would be much more likely to work in a simulation. For the same reason, I recommend designing the first drawing with no less than 2º of lock and 2º of drop. The simulation would show the lock and drop more clearly and it would be more forgiving if errors were made. In addition, the simulation would be much more likely to work when changes in design are made, such as when going from equidistant impulse to equidistant lock. Once you have some practice, then try a design with the theoretically correct 1º of lock and 1º of drop. You would find that *any* error made in the drawing would result in binding or recoil.

This drawing has the same, smaller pallets and a new escape wheel:



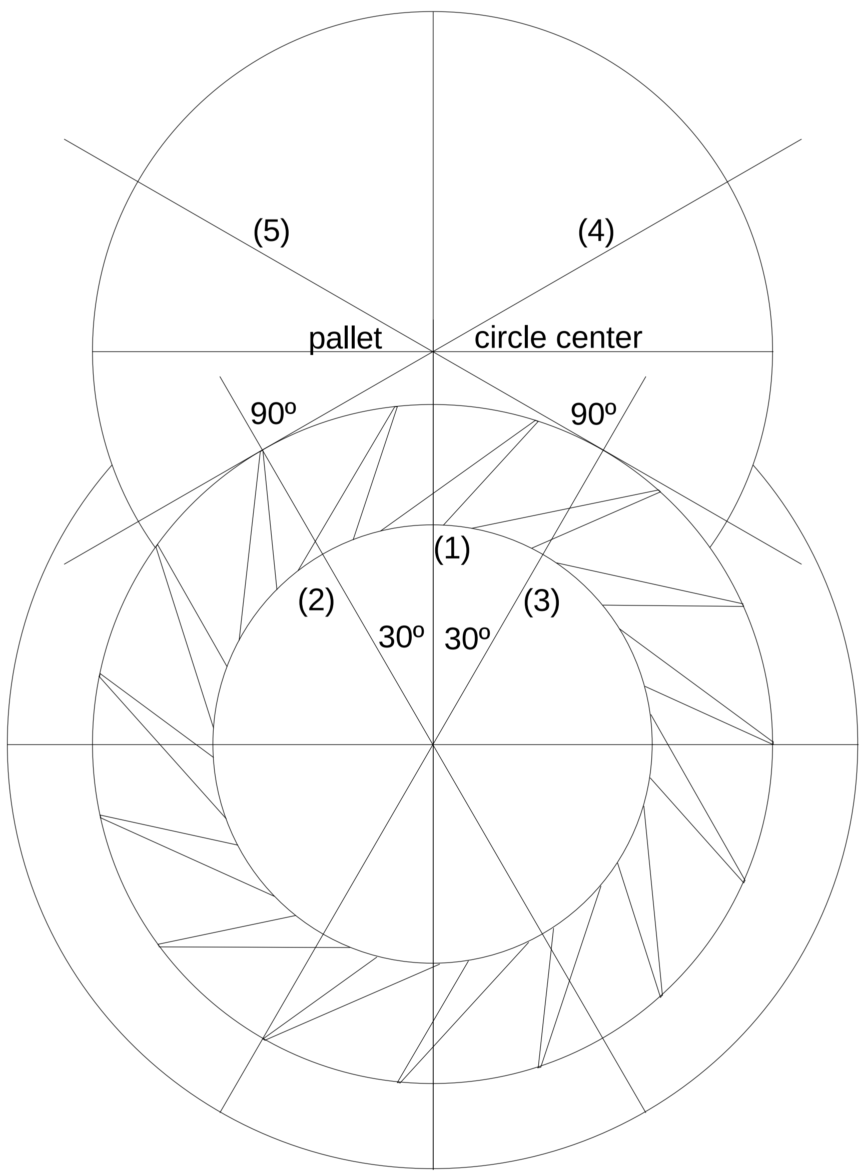
This drawing does not include the pallet fork and the roller table, primarily because of the math involved. These are added in Chapter 22.

16:The English Lever.

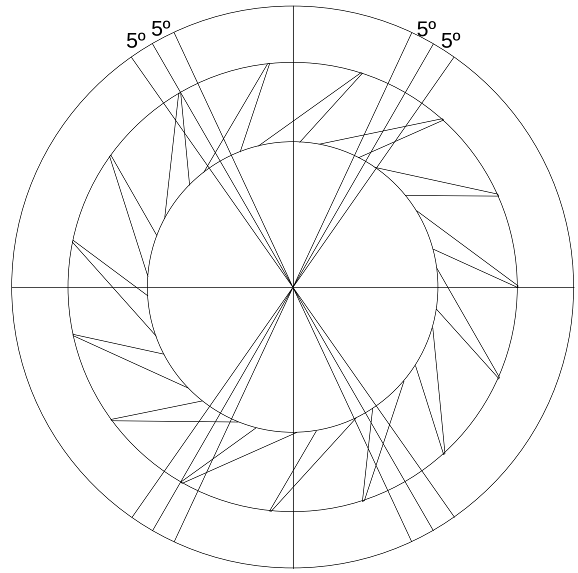
This escapement has several disadvantages. The escape wheel's teeth are pointed, so they lack the strength of the club-tooth design. The escape wheel's teeth do not have impulse faces of their own, so the lock must be created by changing the design of the pallets. This results in the pallets having impulse faces with angles other than the optimal angle, so the design is less efficient.

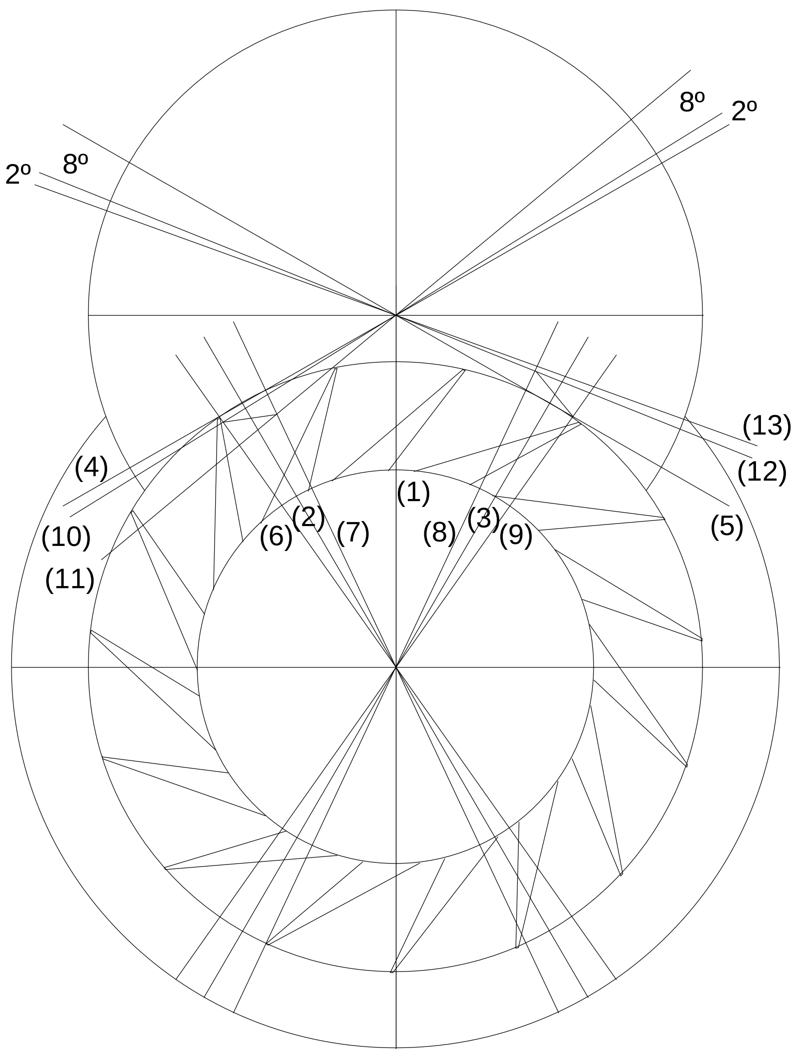
The escape tooth is simple. The locking face appears to lean forwards by 24º. There is an angle of 12º between the front and the back of the tooth, and there is a small gap to create some thickness.

As in the Swiss Lever, there is 30º between the vertical line (1) and the escape circle radius lines, (2) and (3), which are used to design the pallets. Rotate line (2) by 90º to get line (4). Rotate line (3) by 90º to get line (5). Place the pallet circle such that its center lies on the point where lines (4) and (5) intersect.

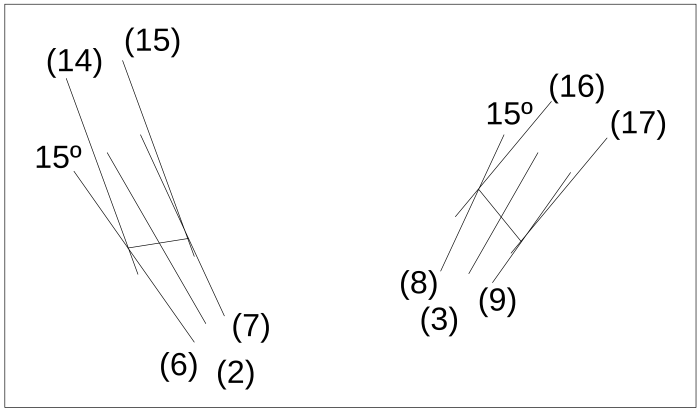


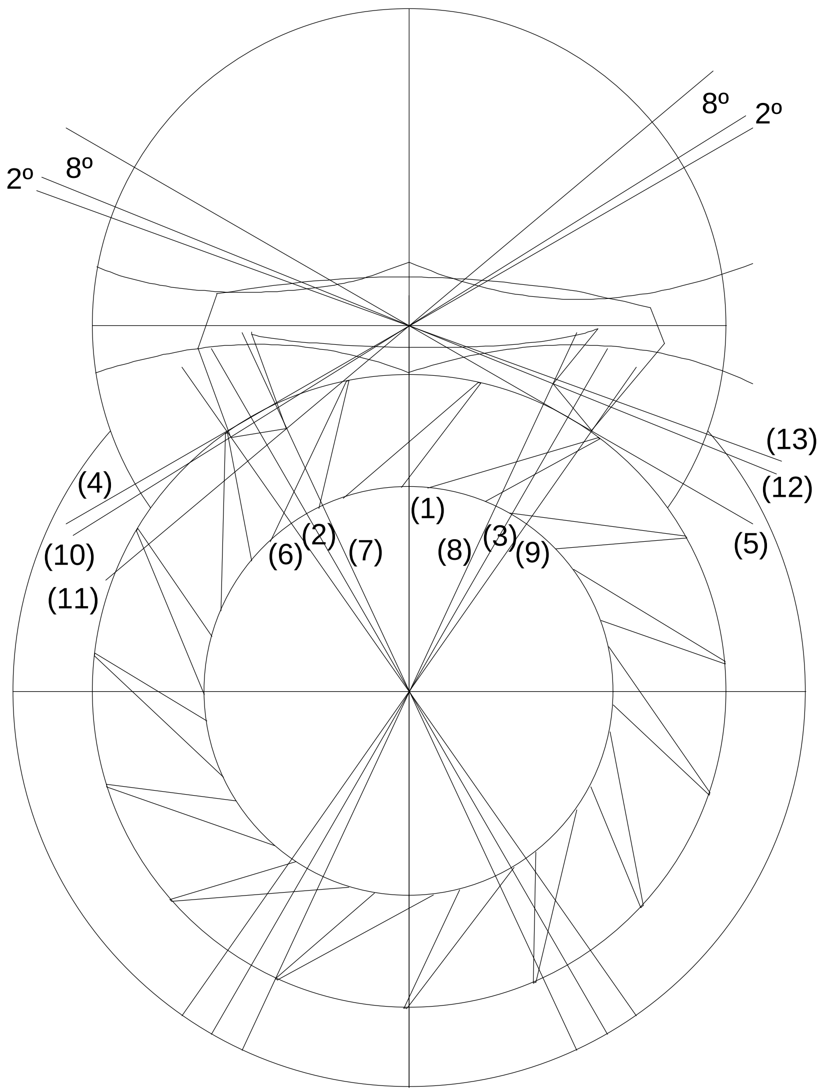
The 15 tooth escape wheel rotates by 12º per beat, so make the pallet occupy a span of 10º, in order to allow 2º for drop.





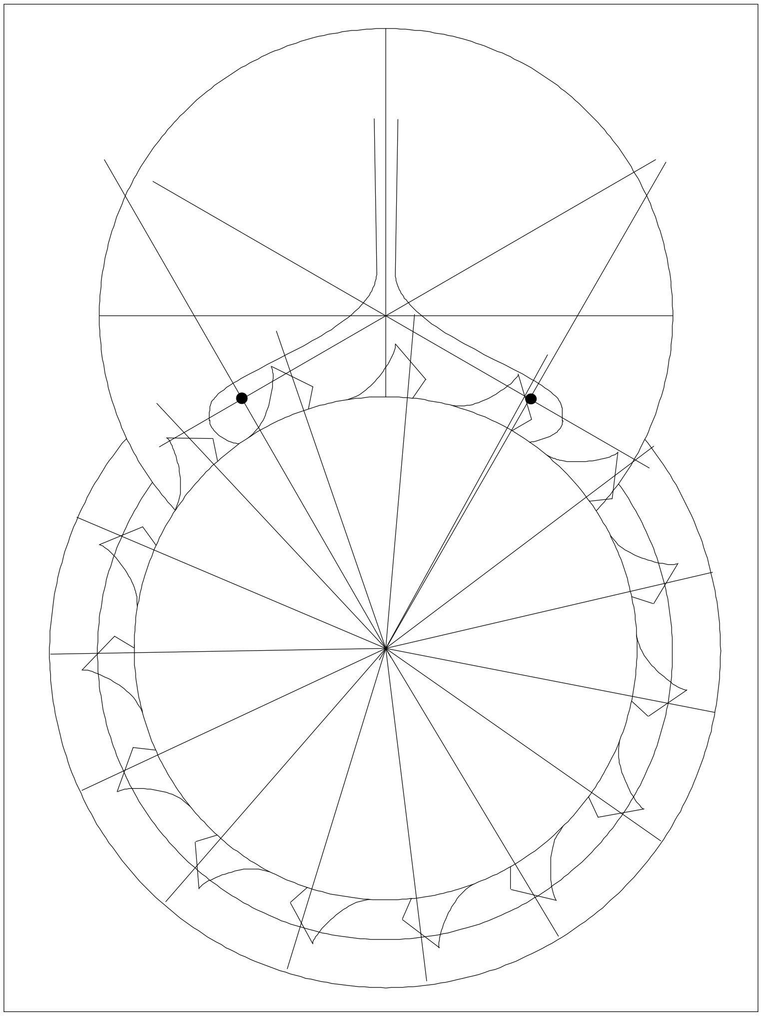
To draw the impulse face lines, it is necessary to determine their positions. Rotate line (4) by 2º (for lock) counterclockwise to get line (10). Then rotate line (10) by 8º counterclockwise to get line (11). Rotate line (5) by 8º counterclockwise to get line (12), and by 2º more to get line (13). Draw a line from the point where lines (6) and (10) intersect to where lines (7) and (11) intersect: this will be the entry pallet's impulse face. Draw a second line from the point where lines (8) and (12) intersect to where lines (5) and (9) intersect: this will be the exit pallet's impulse face.





Rotate line (6) clockwise by 15º to get line (14), which will be the entry pallet's locking face with a draw angle of 15º. Duplicate line (14) and place it on the point where lines (7) and (11) intersect. Repeat this procedure for the exit pallet: rotate line (8) clockwise by 15º to get line (16). Duplicate line (16) and place it on the point where lines (5) and (9) intersect. Finish the drawing as you wish.

17: The Pin-Pallet Escapement.



You will recognize this drawing from chapter 9 of the Clock section. In order to avoid repetition, I will discuss only how it differs from the modern Swiss Lever Escapement.

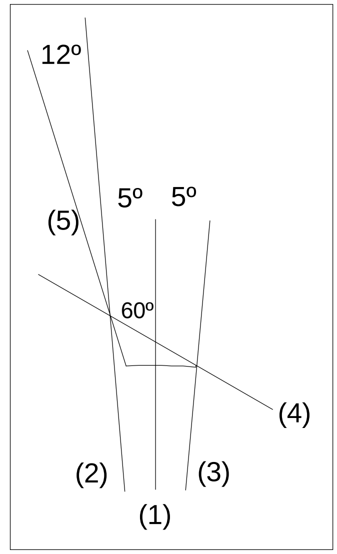
In the club-tooth design, the escape circle radius of each tooth meets the impulse face and the locking face at the entrance corner. In the pin-pallet wheel, however, the escape circle radius of each tooth *bisects* the impulse face. The method used for the pin-pallet wheel is the correct approach, and it must be used here. I used the other method for the club-tooth escape wheel because it enabled me to place the entry pallet in line with the tooth's impulse face at the mid-point of the impulse: in other words, to create a better-looking drawing. The tooth's impulse face was less important because the relationship between the angles changed during impulse, (see chapter 3). In fact, the last drawing of the Swiss Lever showed tooth and pallet impulse faces that were not parallel. The important criteria in the Swiss Lever are the angles of the *pallet's* impulse and locking faces, and that the pallet's impulse face always be bisected by the pallet circle's radius line.

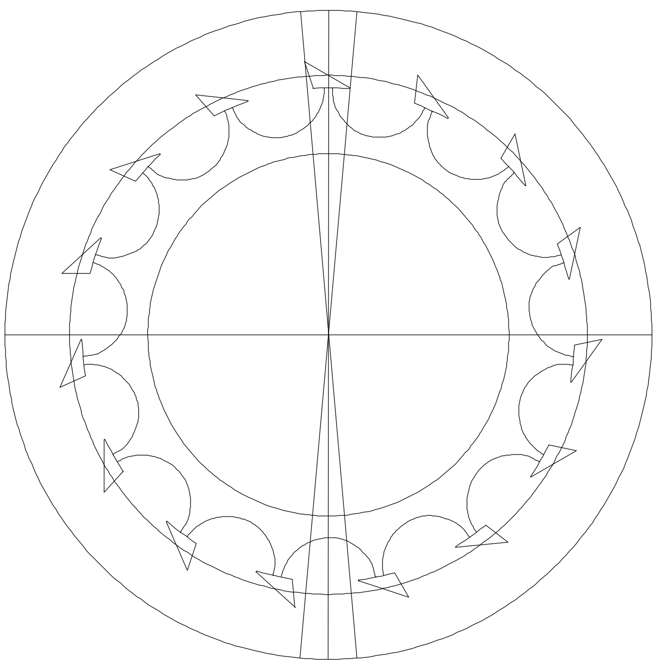
In the pin-pallet escapement, the angle of impulse is determined by the *tooth's* impulse face rather than the pallet's impulse face, so the tooth's impulse face should always be bisected by the escape radius line, and the angle between these two lines should always be 45º. The pallets are bisected by the pallet circle's radii. The pallets are also bisected by the escape circle's radii, in order to have equidistant impulse. The amount of lock is determined by the radius of the pallet pin.

Both escapements were designed with the same number of escape wheel teeth and with the same number of teeth between the pallets. Therefore, the other design principles apply to both designs.

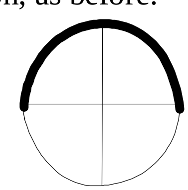
18: The Cylinder Escapement.

Rotate line (1) counterclockwise by 5º to get line (2) and clockwise by 5º to get line (3). The tooth will occupy a span of 10º, and the escape wheel will rotate 12º per beat, so there will be (no less than) 2º left over for cylinder thickness and for drop. Rotate line (1) counterclockwise by 60º to get line (4); place it on the point where line (1) and the six inch diameter circle intersect. Rotate line (2) counterclockwise by 12º to get line (5); place it on the point where lines (2) and (4) intersect. Line (4) will become the tooth's impulse face. Line (5) will become the back side of the tooth. Draw a curve between them to form a triangle, but give the entrance corner a slightly rounded edge. The curve could be drawn by tracing it over a six inch diameter circle.



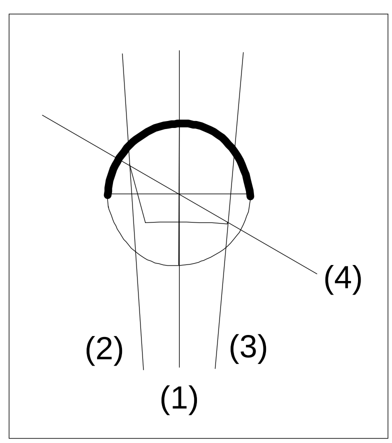


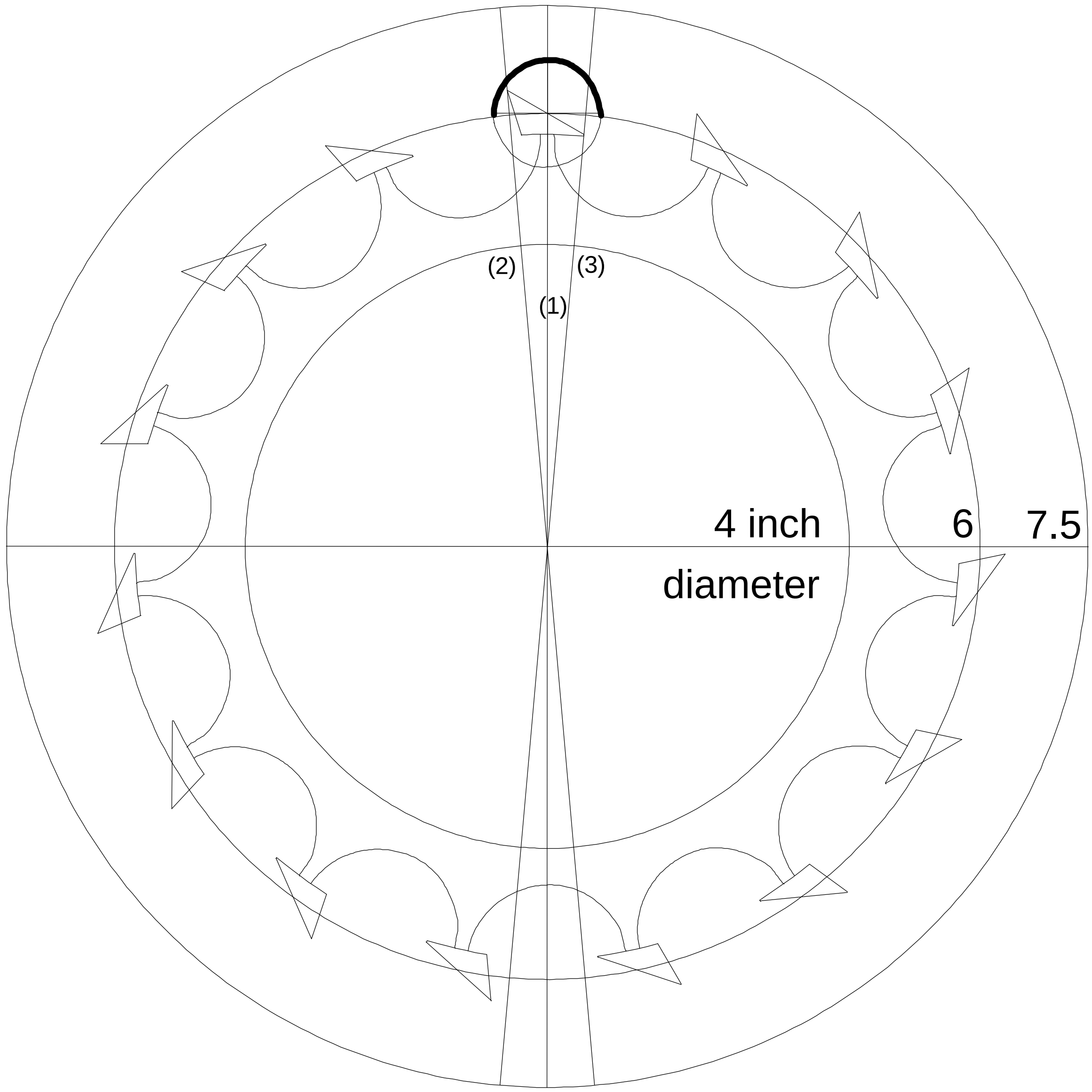
Rotate the tooth in the 7.5 inch circle by 24º. Draw a curve to connect the two teeth by tracing over a small circle. Then draw the escape wheel by duplication and rotation, as before.



The cylinder will be a circle with two crossing lines and a thick curve traced over the edge of the circle.

The thick curve will cover just over half the circumference of the circle. The inside diameter of the curve will be slightly greater than the diameter of the tooth. I chose a circle diameter of 0.73 inches (by trial and error). Place the cylinder such that its center lies on the point where the six inch diameter circle and lines (1) and (4) intersect.





Increasing the diameter of the cylinder circle results in a proportional increase in the inside drop and an equal decrease in the outside drop.

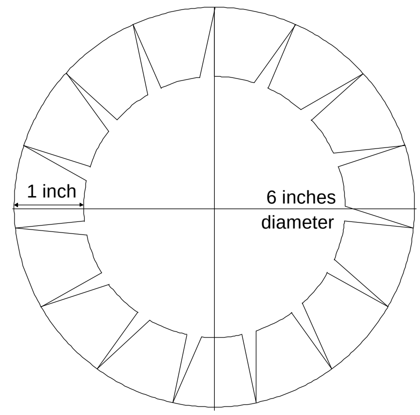
The tooth impulse face's angle and length determine the lift. The cylinder occupies just over half a circle in order to create lock: if it occupied half a circle, there would be no lock.

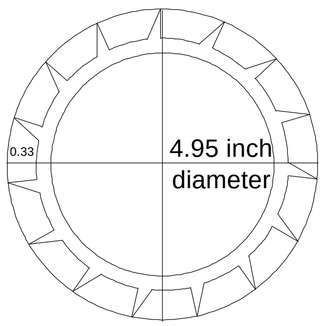
A tooth impulse face angle of 45º would be more efficient, but this tooth does not fit inside the cylinder as well as a tooth designed with an impulse face angle of 30º because it would result in unequal inside and outside drops. In practice, cylinder escapements appear to have escape tooth impulse faces with angles of *less* than 30º.

19: The Duplex Escapement.

All the drawings thus far have not included the action of the balance wheel, in order to simplify the drawings and the simulations. The inclusion thereof complicates everything, but is certainly necessary in this drawing.

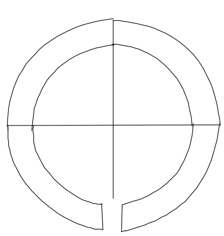
This escapement should be thought of as having two escape wheels, hence its name. Draw the first escape wheel in a six inch diameter circle, each tooth having a perpendicular locking face and a height of one inch. This escape wheel has 15 teeth, so there are 24º between each tooth.



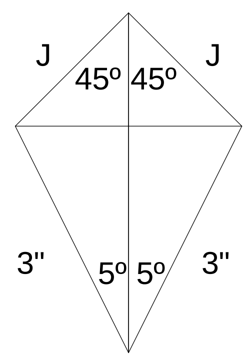


The inner escape wheel has smaller teeth, but they are similar and also have perpendicular locking faces. Draw it in a 4.95 inch diameter circle, each tooth having a height of a third of an inch. Both escape wheels need to be designed so that they could be rotated either together or independently.

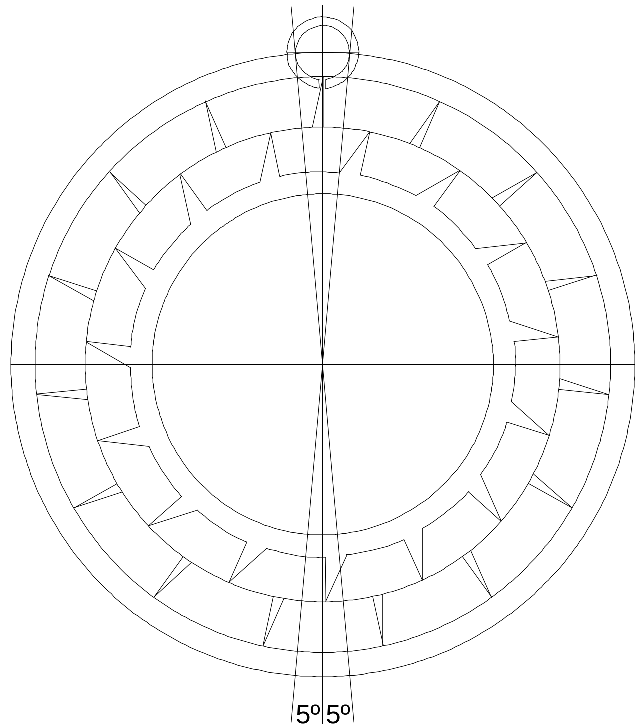
The difficult part is calculating the relationships of the variables: how far from the escape circle center the locking jewel's circle center needs to be, and the diameter of the latter. If the locking span were taken to be 10º, and the locking jewel's circle center were placed on a circle 3.25 inches away from the escape circle center, its diameter could be calculated.



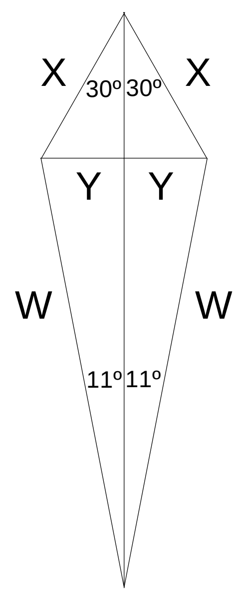
The radius of the locking jewel would be:
3 sin 5 = J sin 45
J = 3 sin 5 / sin 45 = 0.370"
if the locking jewel rotated 90º during lock. Draw a circle with a radius of 0.37 inches, and draw a jewel in it as you wish.



Since the angle between two escape teeth is 24º, rotate one escape wheel by 12º so that, when combined, the inner teeth would appear to be half way between each pair of outer teeth. Place the two escape wheels together inside a larger circle with a radius of 3.25 inches. Place the locking jewel such that its center lies on the circumference of the larger circle. Notice that the escape wheel rotates by 10º during lock.



The impulse arm's length could be found by trial and error, or it could be calculated. In this example, the impulse arm rotates by 60º during impulse. The escape wheel rotates by 24º, less 2º for drop, or 22º. The impulse arm's circle radius will be given by 'X', and the inner escape wheel's circle radius by 'W'.



Y / X = sin 30 = 0.5

Y / W = sin 11 = 0.191

so, 0.5 X = 0.191 W

X = 0.382 W

X cos 30 + W cos 11 = 3.25

(0.382 W)(0.866) + W(0.982) = 1.312 W = 3.25

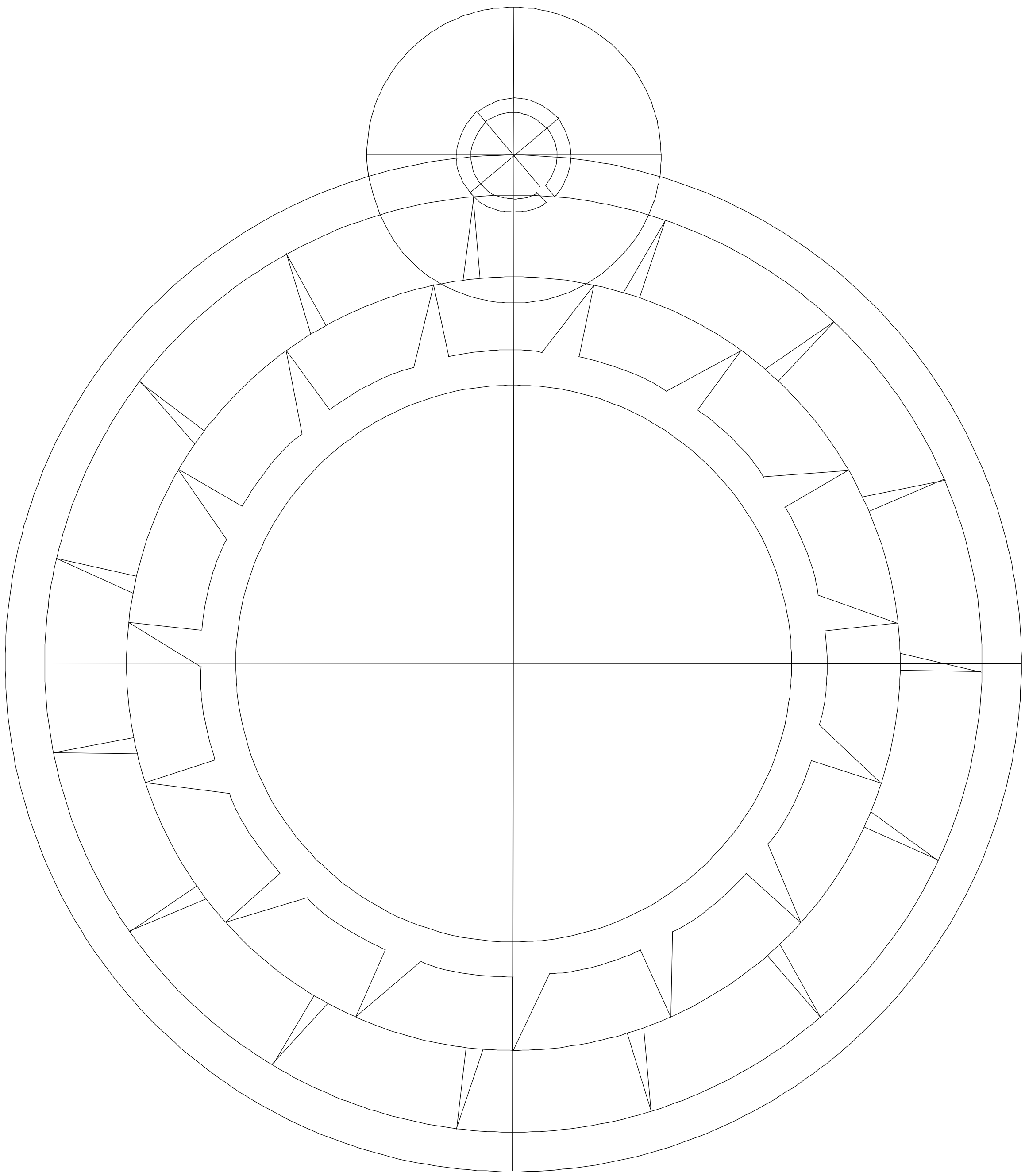
W = 2.476

(and 2W = escape circle diameter = 4.952 inches)

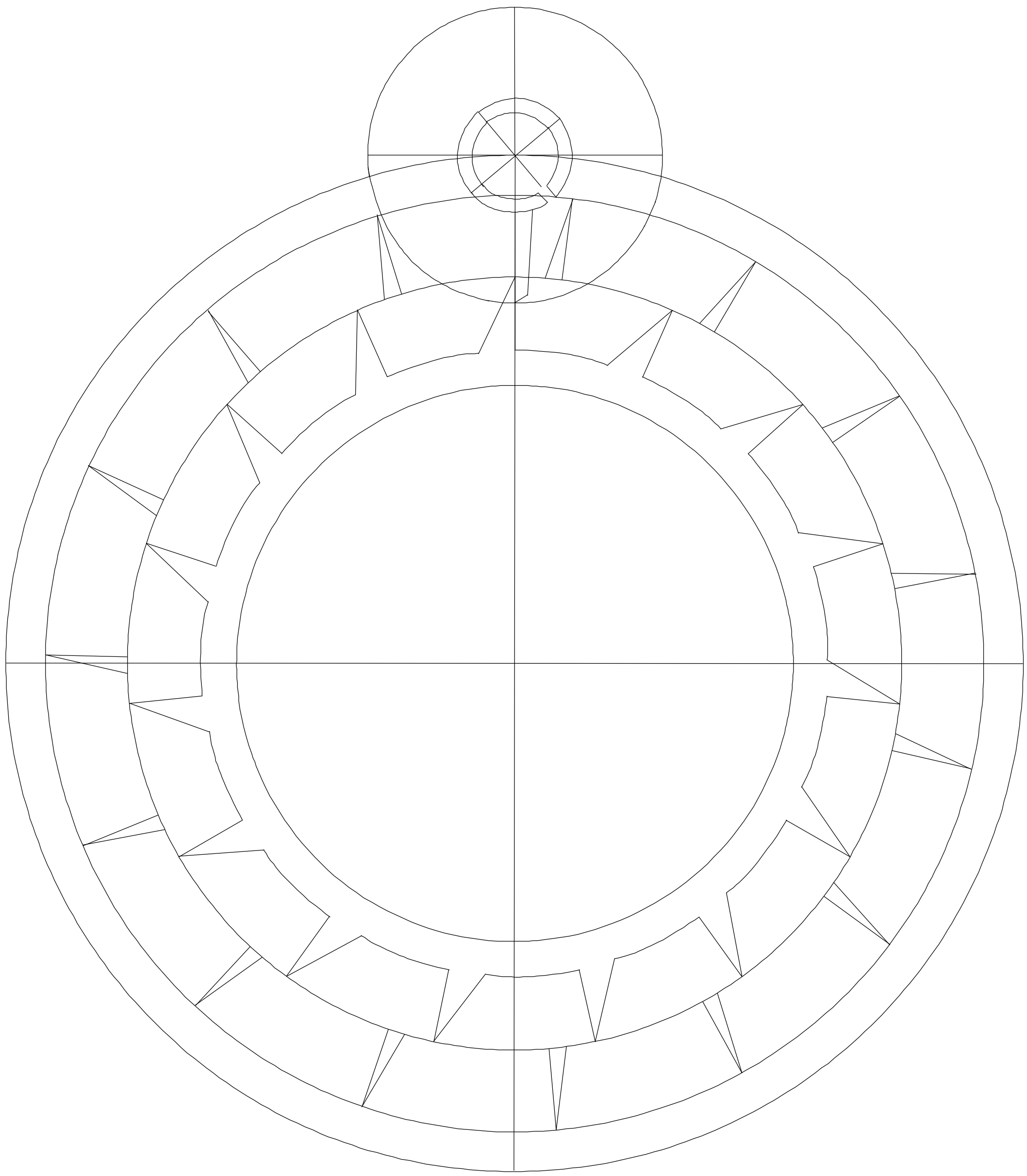
X = 0.382 x 2.476 = 0.946

(and 2X = impulse arm's circle diameter = 1.892 inches)

Draw the impulse arm's circle with two lines to indicate its center and with a diameter of 1.89 inches. Place it such that its center lies on the center of the locking jewel. Rotate the outer escape wheel clockwise until a tooth touches the locking jewel. Then rotate the inner escape wheel until the impulse arm's circle becomes centered between two inner escape teeth. Group the two escape wheels so that they would rotate as one.



Rotate the escape wheel clockwise by 12º: in other words, 2º after the tooth has been released by the locking jewel. Rotate the locking jewel until it is at the point where it has just released the escape wheel's tooth. Then draw the impulse arm next to the inner escape wheel's tooth in its path.

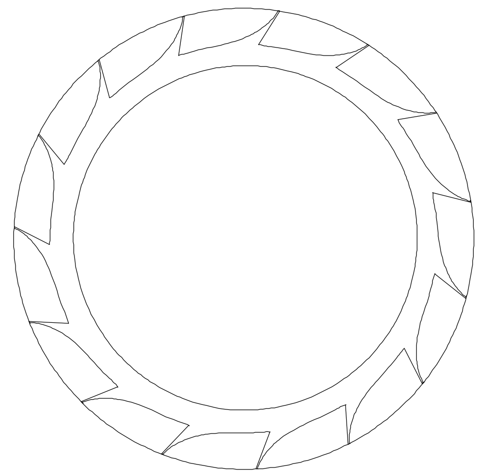


By analyzing the drawing, you would find that the escape wheel provides a considerable impulse during the locking phase, not only during the impulse phase.

In this example, I chose that the locking jewel would rotate by 90º during lock and the escape wheel by 10º, and that the impulse arm would rotate by 60º during impulse and the escape wheel by 22º. Try using different angles to determine what effect such changes would have on the sizes of the locking jewel, the impulse arm, and the inner escape wheel.

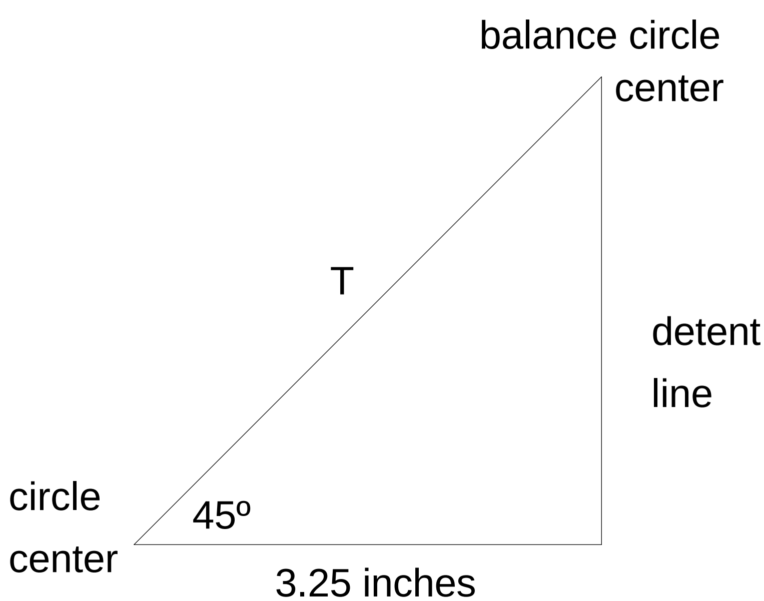
20: The Chronometer Escapement.

The most important advantage that the Chronometer Escapement has over the Swiss Lever is that lubrication of the escape wheel teeth is *not* required: the balance's impulse pallet and the escape tooth appear to *roll* together rather than to *slide* across one another (as in the Swiss Lever), so there is much less friction in the Chronometer escapement. Since the lubricant may change viscosity as the temperature changes, and may even dry up over time, it is preferable not to lubricate the escapement unless necessary: since the Chronometer escapement has a much lower friction loss, the ability to make it run dry would result in a *more consistent timekeeper*.



While the principles of this escapement are straightforward, the drawing is difficult to create, and there is plenty of math involved. Draw a 15 tooth escape wheel inside a 6 inch diameter circle.

Draw a 3.25 inch line from the center of the escape wheel to the edge of the circle. Then draw a vertical line, which will represent the detent, a quarter of an inch away from the edge of the circle. Rotate this line clockwise by 45º, and place it over the center of the circle and crossing the detent line to create a triangle:

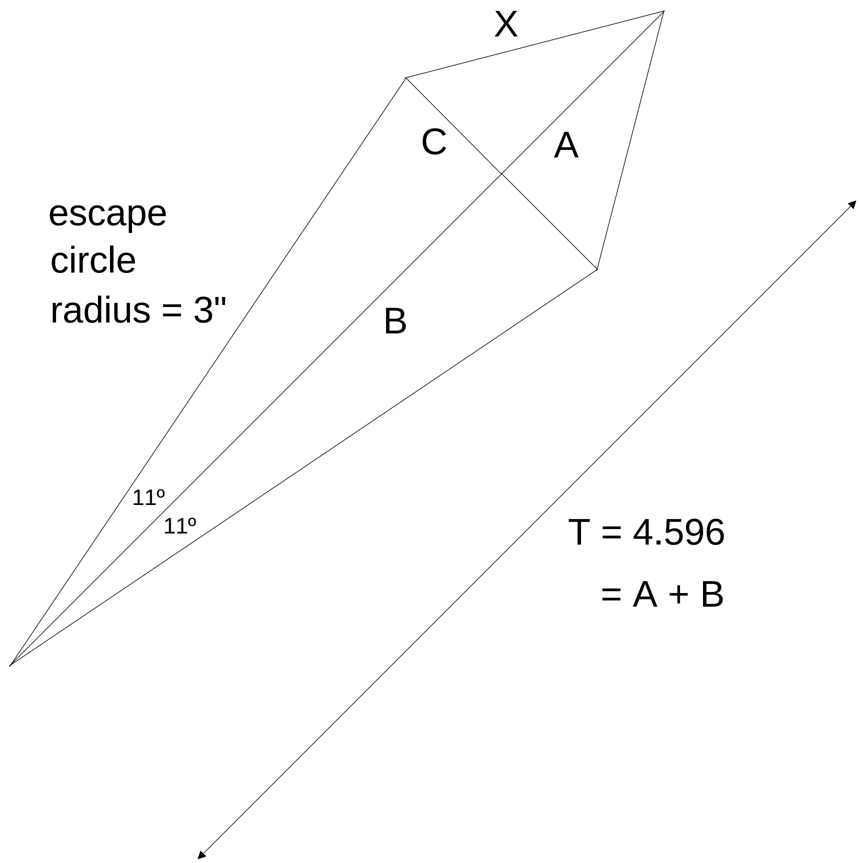


The top right corner will become the balance's circle center. To calculate the distance (T) between the two circle centers:

let T = 3.25 / cos 45

= 4.596"

You need to find the radius of the impulse pallet's circle (X), that is, the circle that will trace the path of the impulse pallet. If the escape wheel rotates by 22º (24º less 2º for drop) during impulse, you could draw the following triangles:



B = 3 cos 11 = 2.945

T = A + B = 4.596

A = 4.596 - 2.945 = 1.651

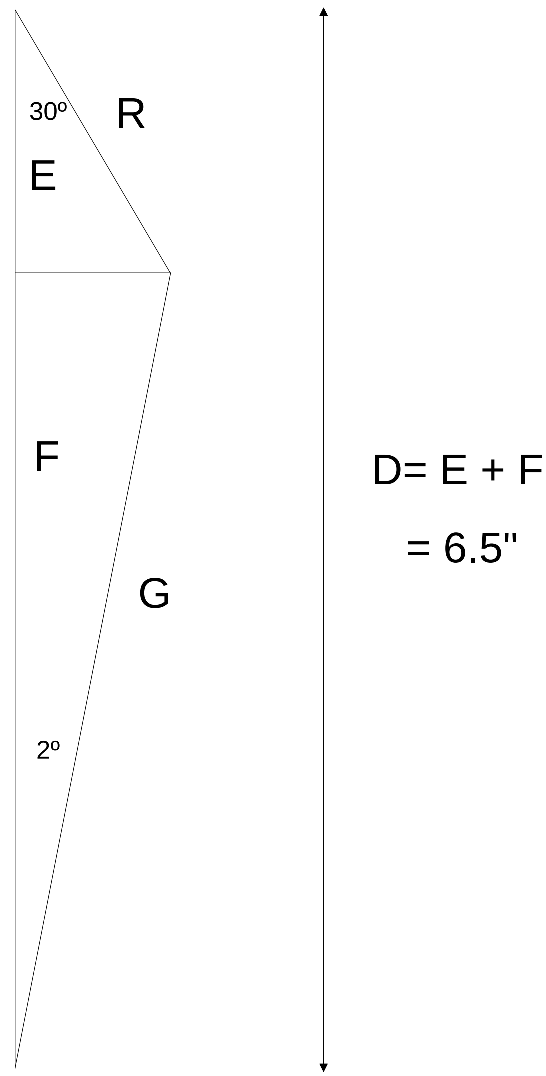
C = 3 sin 11 = 0.572

$X^2 = A^2 + C^2 = 1.651^2 + 0.572^2$

X = 1.747

Draw a circle with a radius of 1.747 inches and place its center on the point where the detent line and the T line meet. Another method could be used to calculate X: it is shown on page 73.

Once the impulse portion of the escapement it finished, it is necessary to calculate the dimensions of the discharging pallet's circle and the gold spring's circle for the detent. If the discharging pallet rotates by 30º, and the gold spring rotates by 2º, during discharge, we get another set of triangles. (These are not drawn to scale.)



$R \cos 30 + G \cos 2 = 6.5$

$R \sin 30 = G \sin 2$

...and solve the equations.

$0.5 R = 0.035 G$

so $R = 0.07 G$

Substituting:

$0.866 R + 0.999 G = 6.5$

$(0.866 \times 0.07) G + 0.999 G = 6.5$

$1.060 G = 6.5$

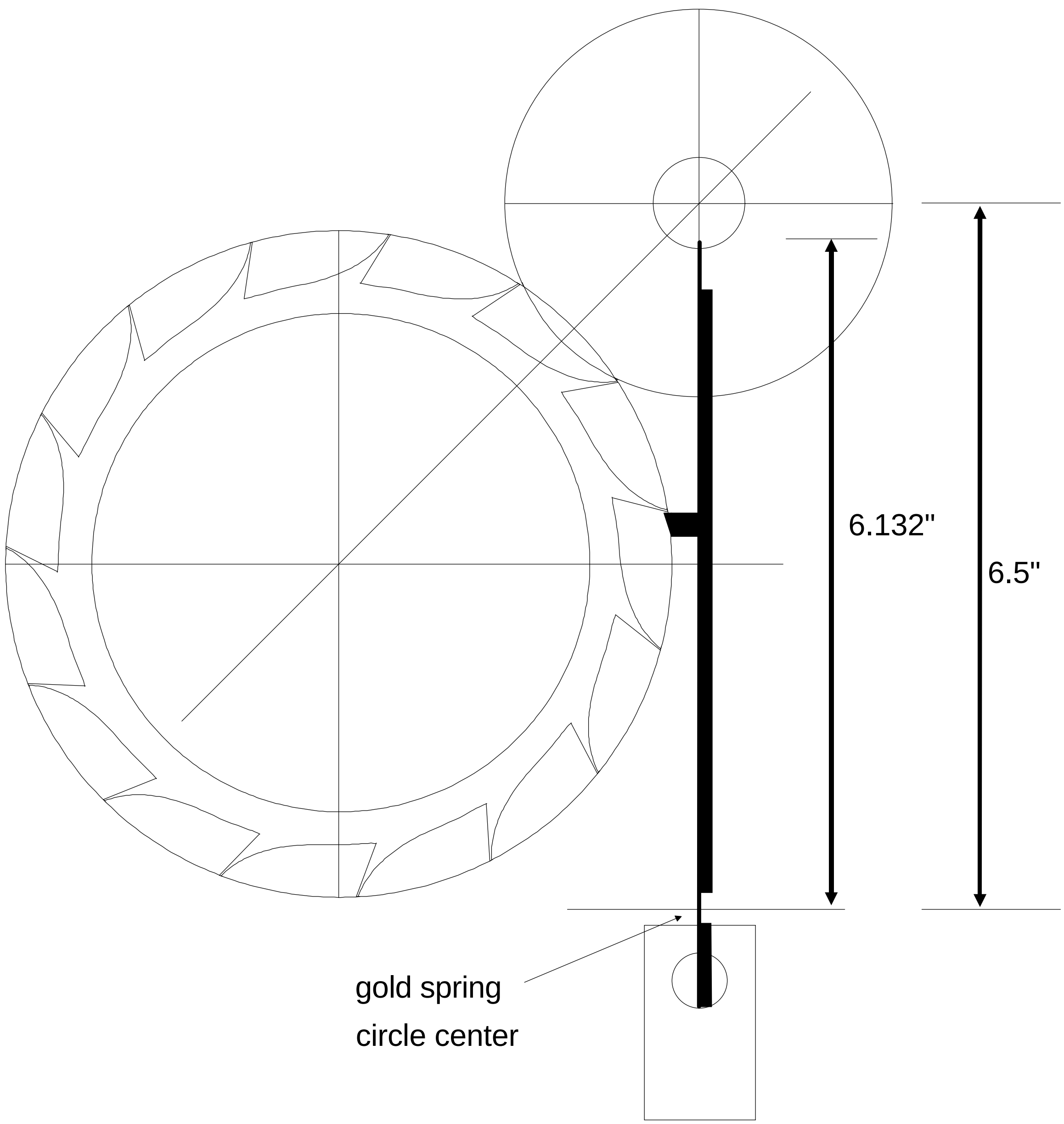
$\underline{G = 6.132''}$

$R = 0.07 G = 0.07 \times 6.132$

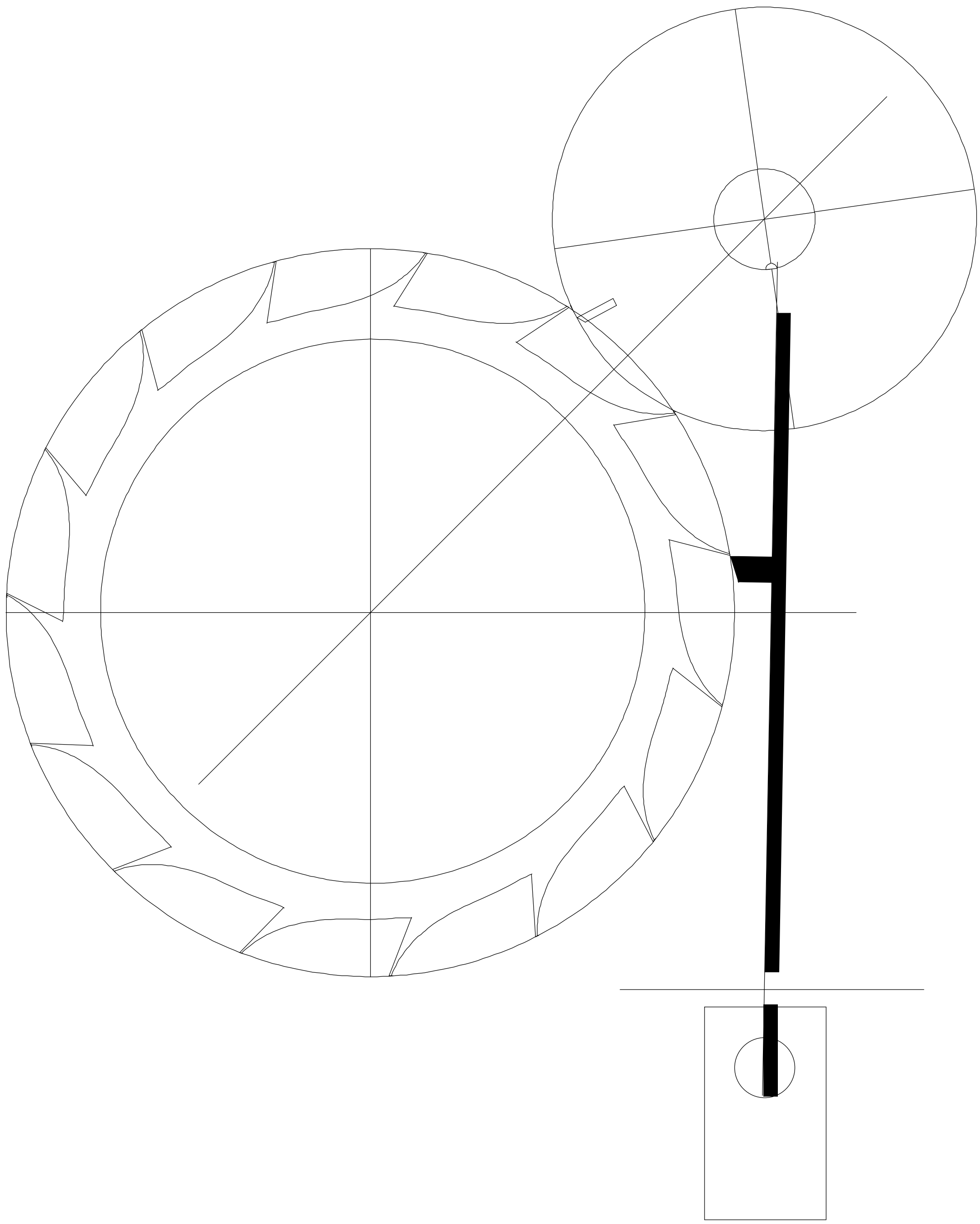
$\underline{R = 0.429''}$

Draw a circle with a radius of 0.429" and place it such that its center lies on the point where the detent line and line T intersect. The discharge pallet's circle will then be centered inside the impulse pallet's circle. Draw the gold spring's line on the detent line and make it 6.132 inches long from the point about which it would rotate, 6.5 inches below the center of the impulse pallet's circle. The longer the gold spring's line, the better, because the locking pallet would have a greater arc relative to the arc of the gold spring's line as it rotates to discharge the escape wheel. I chose a length of 6.5 inches, or twice the displacement from the horizontal line to the impulse pallet's circle center.

Rotate the escape wheel until the impulse pallet's circle is centered between two escape teeth. Then draw the detent pallet on the detent arm: place it just below the tooth, as shown, and with a small amount of lock. The thick line next to the gold spring line represents the detent arm. The rectangle below represents the base of the detent arm. The gold spring's circle is not included in this drawing because of its size, but it would be needed for the simulation.



Rotate the detent arm and gold spring assembly clockwise by 1º, until the detent pallet just releases the escape tooth. Rotate the discharge pallet counterclockwise by 8º. Draw the impulse pallet at the edge of the impulse pallet's circle, just inside the escape wheel's circle.

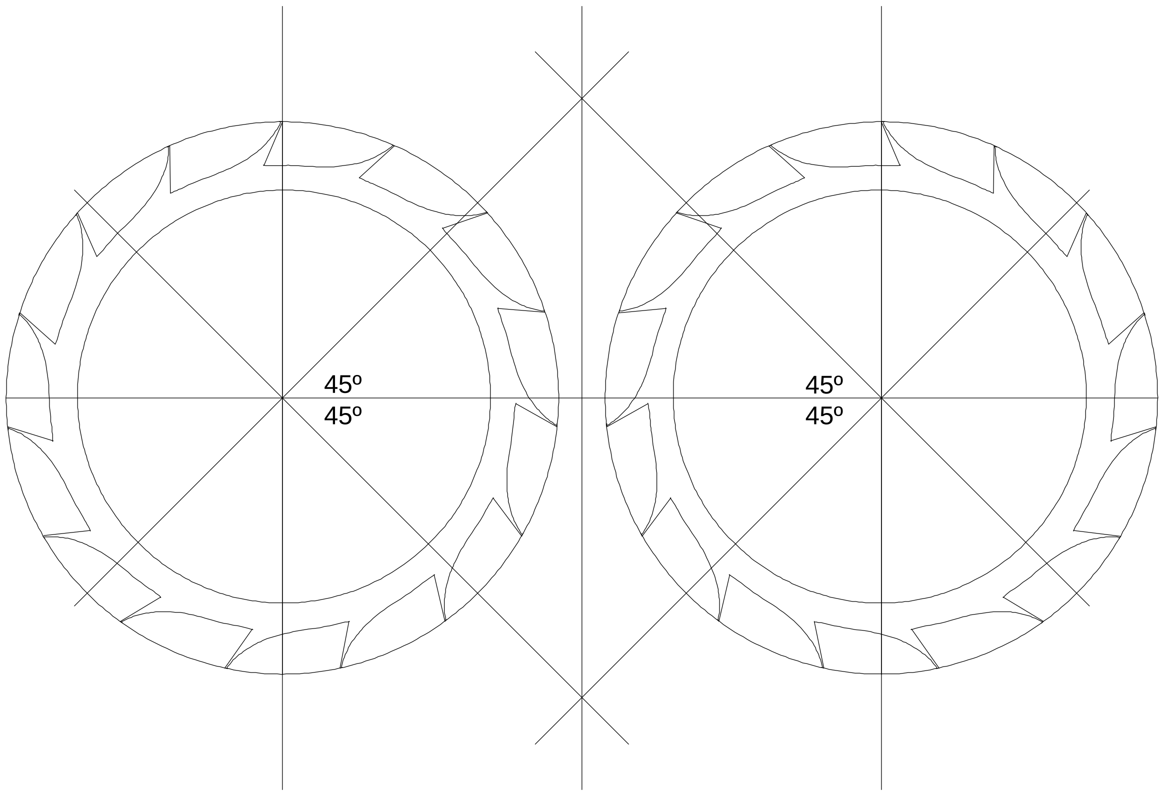


Rotate the detent clockwise by 1º extra, and the discharge and impulse pallets counterclockwise until the discharge pallet meets the gold spring. Then rotate the escape wheel until it meets the impulse pallet. The discharge and impulse pallets must rotate by enough to allow the escape wheel to move forwards until the tooth clears the detent before the detent is released. Otherwise, there will be some bent escape teeth.

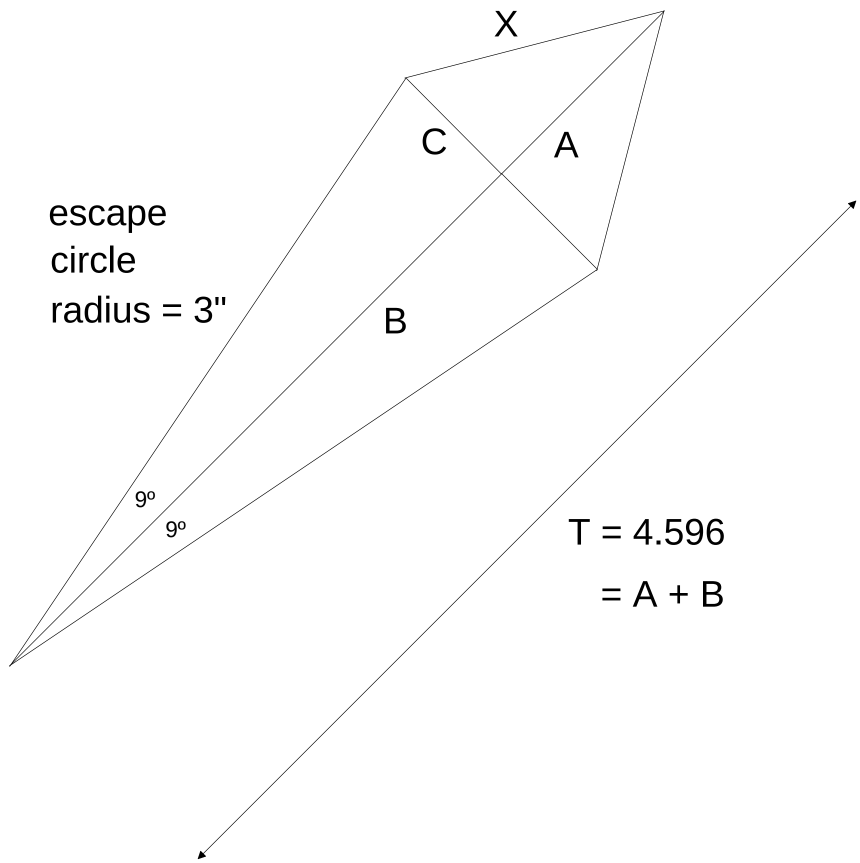
21: Daniel's Independent Double-Escape Wheel Escapement.

This escapement brings together the best of the Chronometer and the Swiss Lever. The Swiss Lever is essentially self-starting. The Chronometer is more efficient and its escape wheel is not lubricated. The combination is the best of both worlds.

Take the Chronometer's escape wheel, duplicate it, flip it over (to create a mirror-image of it), and place it next to the other with a gap of half an inch. Draw a horizontal line, rotate it by 45º, and place it over the center of each escape wheel. Rotate it by 90º, and place it over the center of each escape wheel.



You need to find the radius of the impulse pallet's circle (X), as for the Chronometer. If the escape wheel rotates 18º (24º less 3º *twice* for drop) during impulse, you could draw the following triangles:



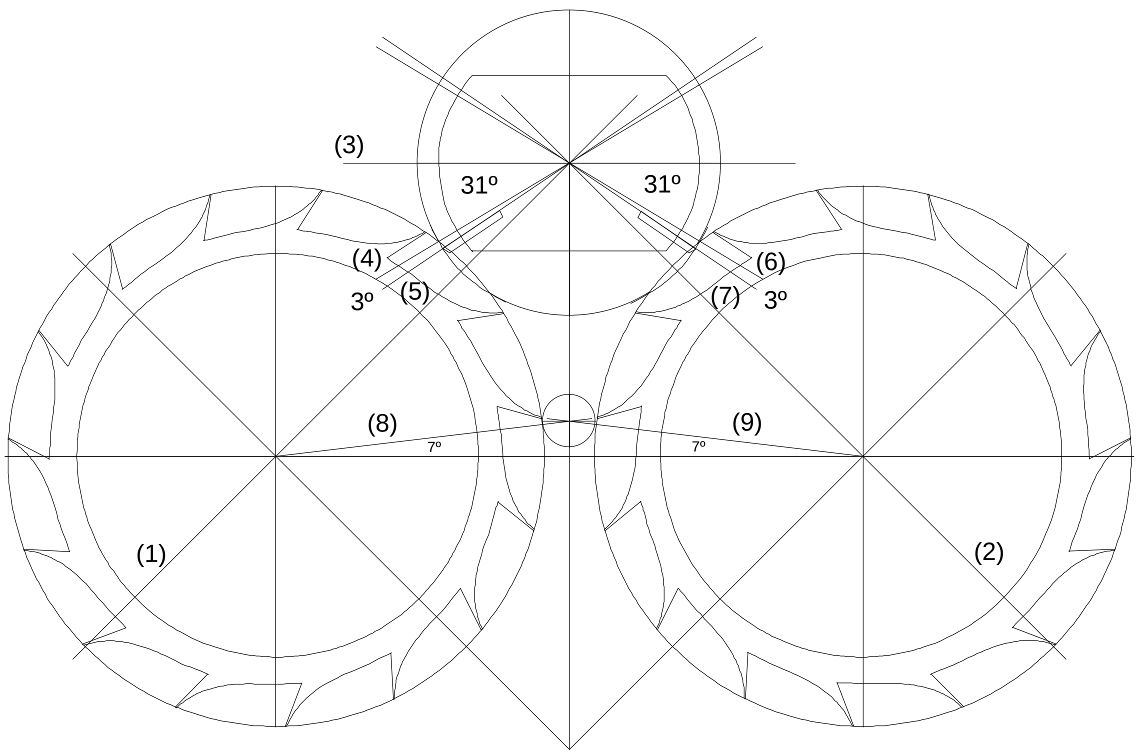
This calculation is similar to the one on page 68. It could also be calculated using a different method, and one formula:

$$X^2 = 3^2 + 4.596^2 - (2)(3)(4.596)(\cos 9)$$

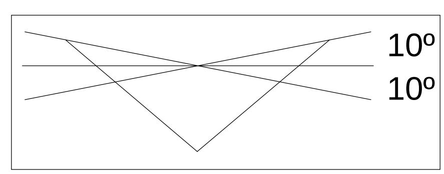
X = 1.699

Draw a circle with a radius of 1.699 inches and place its center on the point where lines (1) and (2) intersect.

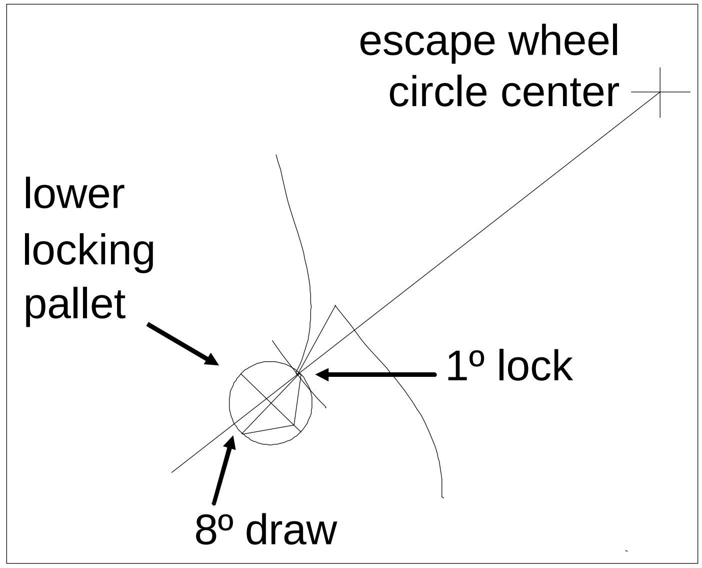
Draw a horizontal line, (3), through the impulse pallet's circle center. Rotate line (3) counterclockwise by 31º (to the point where the pallet circle and the escape wheel's circle meet) to get line (4). Rotate line (3) clockwise by 31º to get line (6). In order for the pallet to be inside the escape circle path, rotate line (4) counterclockwise by 3º to get line (5), and rotate line (6) clockwise by 3º to get line (7). This way the pallets would rotate by 3º inside the path of the escape wheel at the moment when the escape wheel is released.

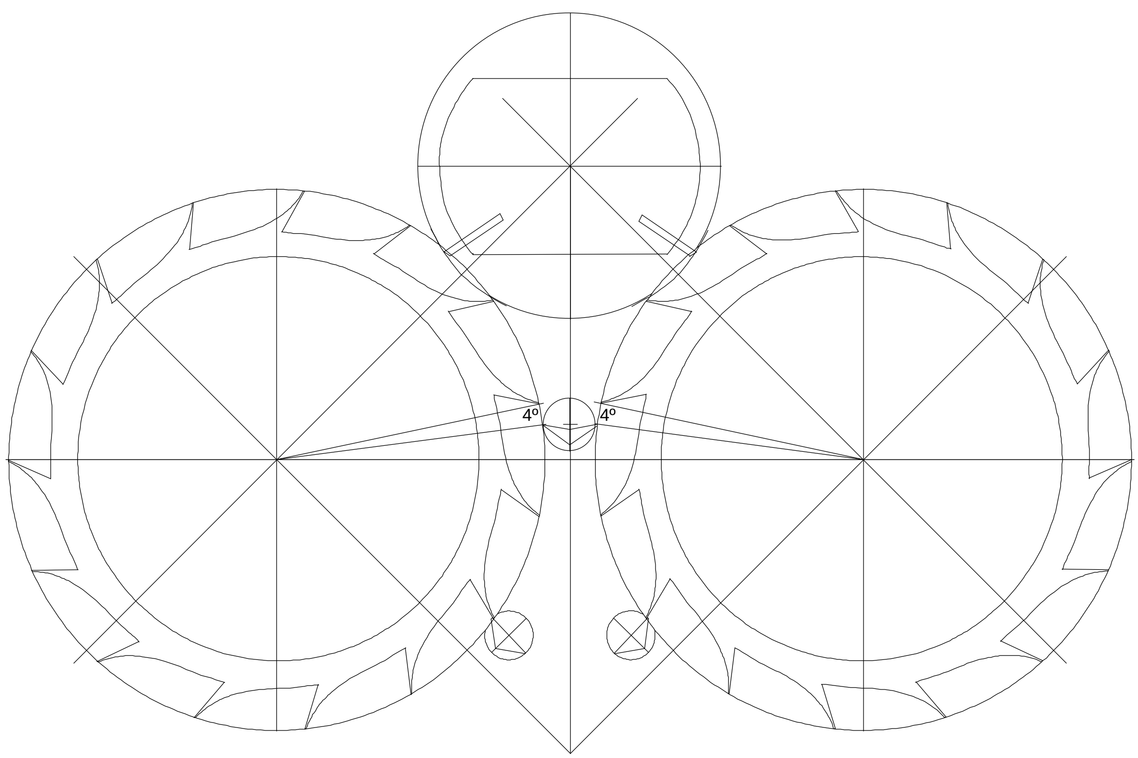


The upper locking pallet should have a width equal to the gap between the escape wheels and should have a "V" shape to allow for a draw angle of 10º. Place the pallet 7º above the horizontal line, shown by the point where lines (8) and (9) intersect.

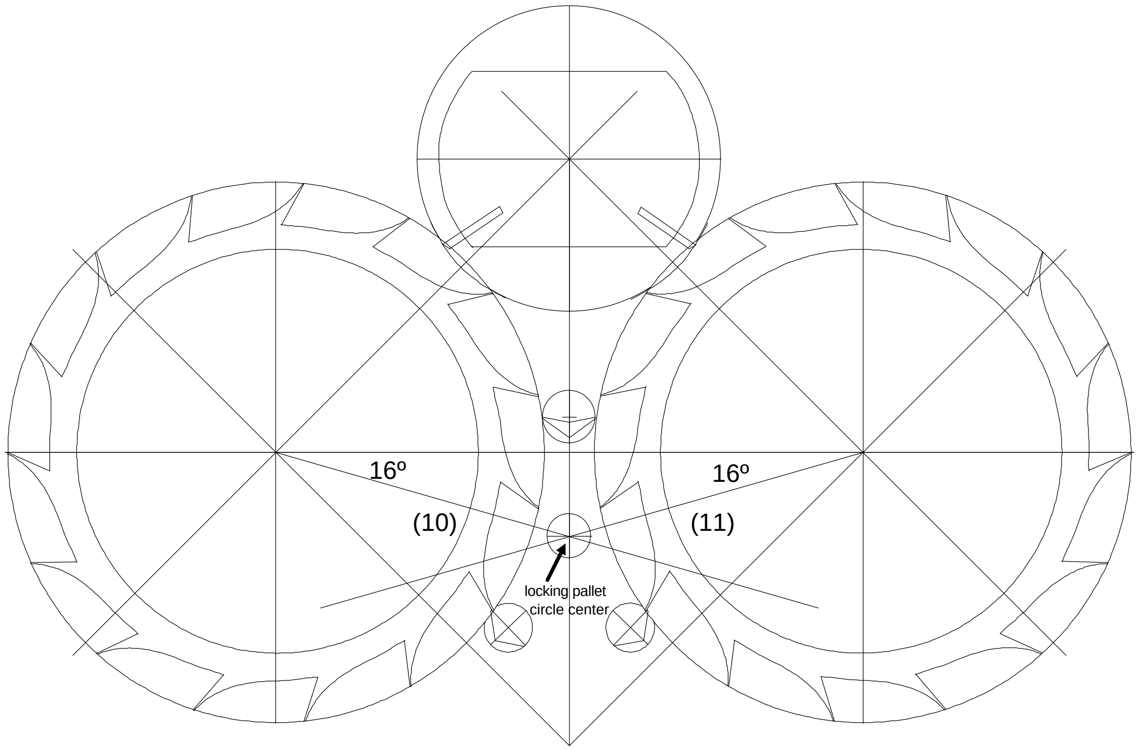


The lower locking pallets have flat locking faces, however. Rotate the left escape wheel counterclockwise by 4º and place one lower locking pallet next to the escape tooth, below the pallet's circle center, giving the pallet 1º of lock and a draw angle of 8º. Rotate the right escape wheel clockwise by 4º and place the other lower locking pallet next to the escape tooth, as shown below, giving the pallet 1º of lock and a draw angle of 8º. Notice that the sum of 10º for upper draw and 8º for lower draw gives 18º for total draw: this is similar, if only slightly more than the 15º for draw designed into the Swiss Lever pallets.





The locking pallets must be placed into position before you could locate their circle center. The upper locking pallet lies 7º above the horizontal line. The lower locking pallets each lie 38º below the horizontal line, so there are 45º between the upper and lower pallets. Place the locking pallet's circle center 16º below the horizontal line, as shown by the point where lines (10) and (11) intersect. The axis of rotation is important because the displacement of each pallet should be the same during rotation.

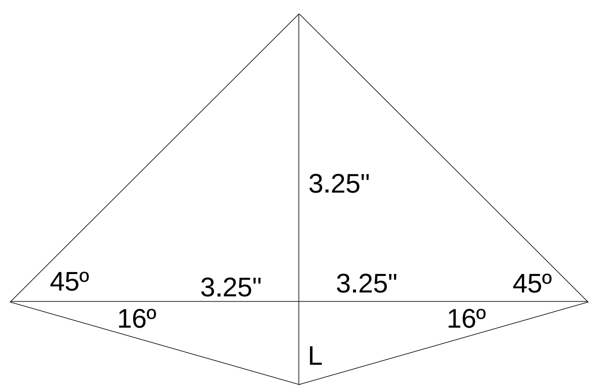


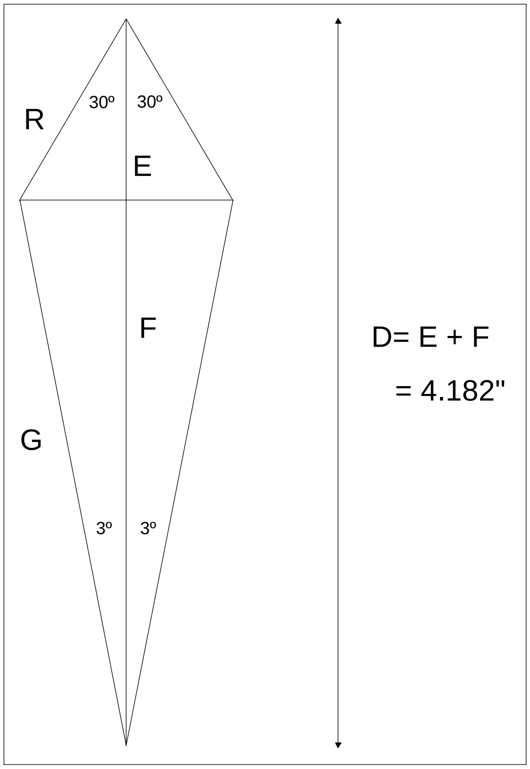
Before drawing the roller jewel that moves the locking pallets from side to side, you need to find the distance from the roller jewel's circle center to the locking pallets' circle center. I will call this distance "D."

D = L + 3.25

= (3.25 tan 16) + 3.25

= 4.182 inches





R will be the roller jewel's circle radius.

R sin 30 = G sin 3 (i)

0.5 R = 0.052 G

R = 0.105 G

R cos 30 + G cos 3 = 4.182 (ii)

0.866 R + 0.999 G = 4.182

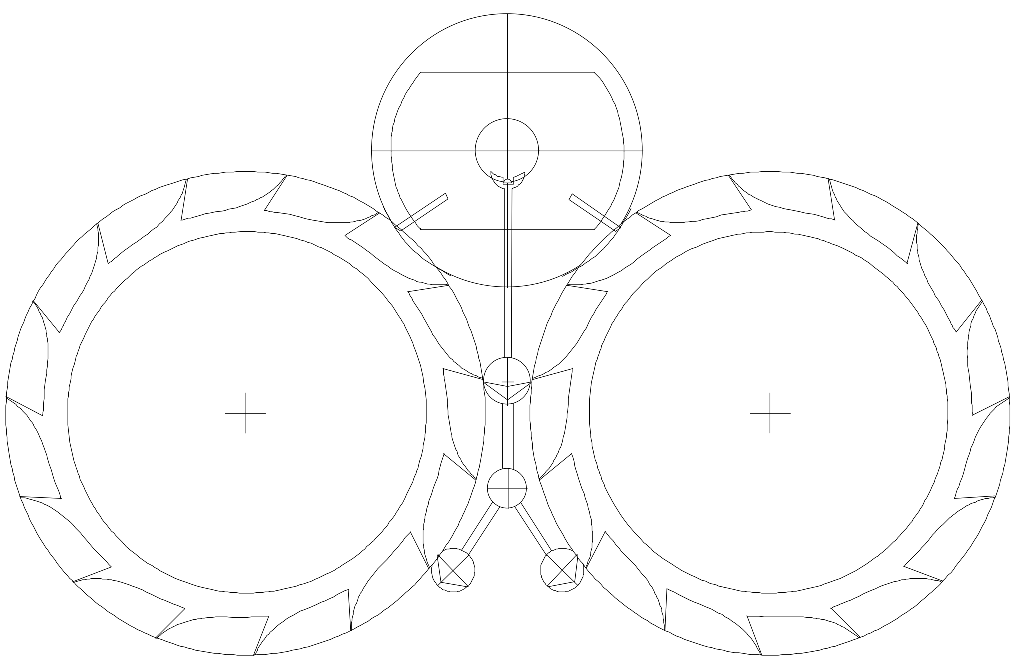
0.866 (0.105 G) + 0.999 G = 1.089 G = 4.182

G = 3.839

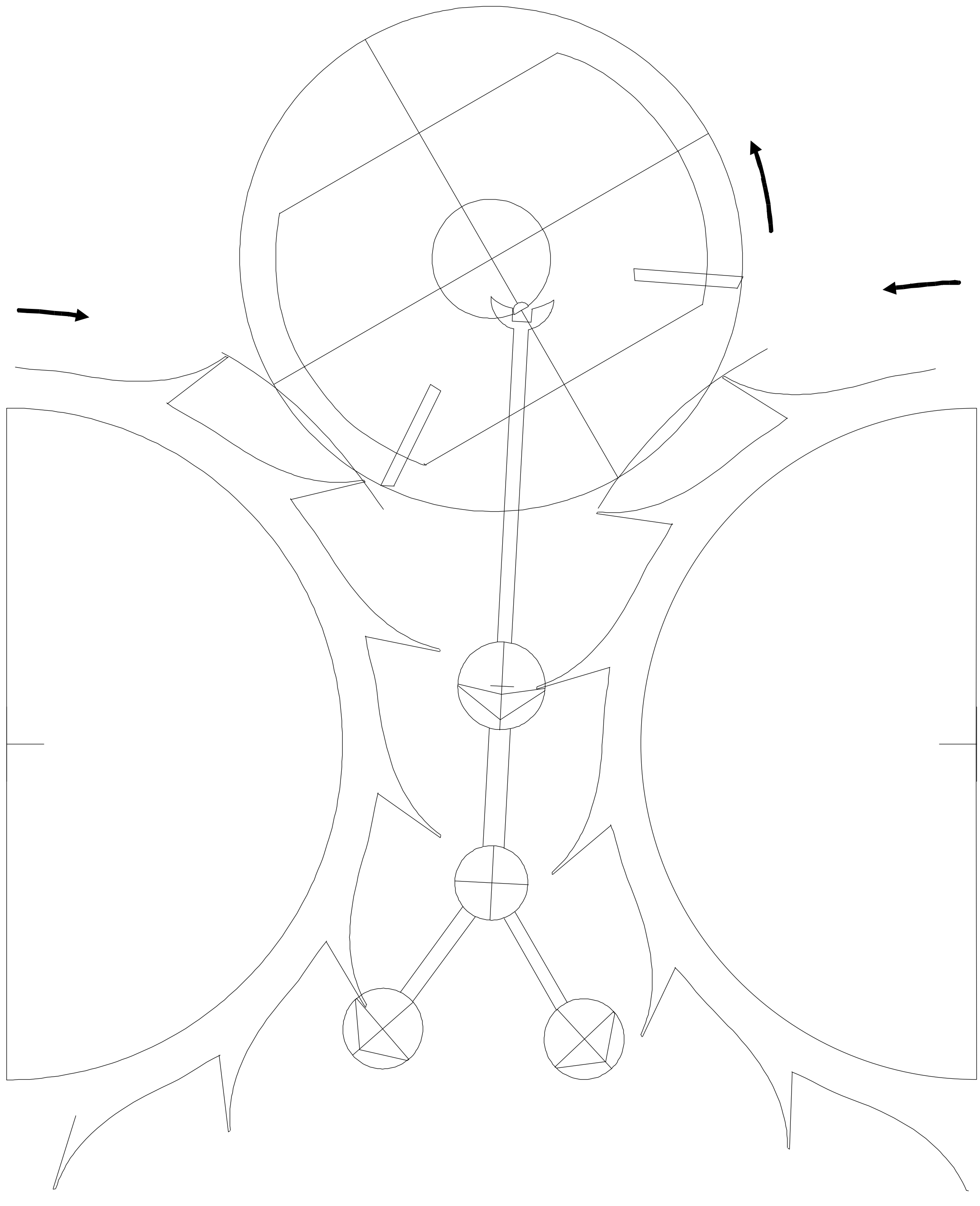
R = 3.839 x 0.105 = 0.402

(3.839 + 0.403) - 4.182 = 0.060

Draw the roller jewel's circle with a radius of 0.402 inches, and place it such that its center lies on the center of the impulse pallet's circle. Draw the pallet fork with a radius of 3.839 inches from the locking pallets' circle center to the entrance corner of the fork horn: the roller jewel would have a depth of 0.06 inches inside the pallet fork. I have not included the locking pallets' circle in this drawing, but it would be needed for a simulation.



In this drawing, I have rotated the locking pallets clockwise by 3º and the impulse pallet / roller table assembly counterclockwise by 30º. The left escape wheel has just been released by the impulse pallet and is detained by a lower locking pallet. The right escape wheel is detained by the upper locking pallet.



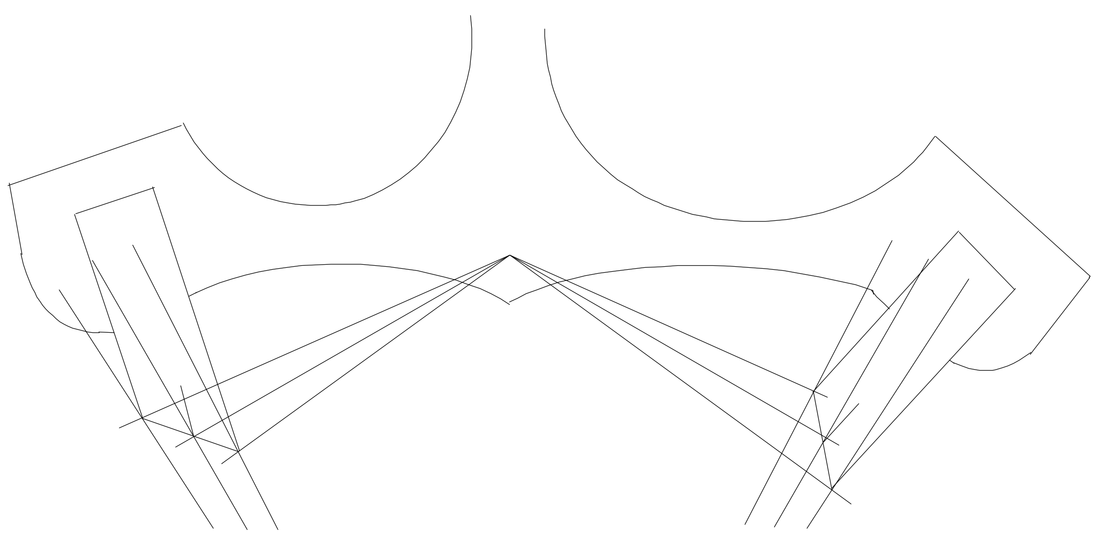
The drawing on the previous page reveals how complicated the design is. Notice how the escape wheel and the impulse pallet appear to *roll* together, instead of sliding across one another, and therefore why the escape wheels and the pallets need not be lubricated.

There are several differences between my drawing and the original specifications. I made these changes in order to enhance the actions of the escapement during the simulation. The gap between the escape wheels was not drawn in proportion to the original, but the only effects this had were to change the impulse pallet's circle radius and the diameter of the upper locking pallet. The convenience of using the gap of half an inch, in allowing me to use the "snap to grid" function in the computer's software, outweighed the compulsion to draw it as closely to the original as possible. Furthermore, I chose an angle of 60º for the rotation of the roller jewel during engagement with the pallet fork. The original design called for 24º, but increasing the angle also increases the depth of the roller jewel inside the fork: by exaggerating the actions of the escapement, the actions become more easily visible during the simulation. Other side effects of increasing this angle from 24º to 60º are that the pallet fork becomes longer and the roller jewel's circle radius becomes smaller by half. The depth increases by a factor of three.

This example demonstrates how creating your own drawings would allow you to change the variables and observe the consequences. The idea is not necessarily to create the drawing as closely to the original specifications as possible, but rather to make changes and to experiment. You may be able to improve a design or even invent an all-original design.

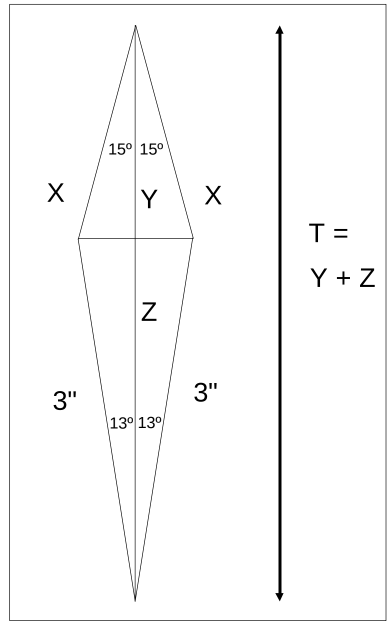
22: The Double Roller.

In this chapter, we will design the pallet fork and the double roller for the last drawing of the Swiss Lever Escapement in Chapter 15. Once the drawing with the theoretically correct impulse face angle of 45º is completed, it must be modified slightly to correct the 1º out-of-angle condition, which could be corrected in two ways. The fork and roller table could be rotated together by 0.5º using the pallet circle center as the center of rotation. The second method involves changing the angles of the impulse faces to compensate. If these angles were changed from 45º to 49º, the amount of lift of each pallet during impulse could be equalized (though there would be a small efficiency loss of 0.5%):



This was not mentioned in Chapter 15 in order to focus attention upon the need to maximize the efficiency of the impulse face angles. The result is two *identical* pallets with impulse face angles as close to 45º as possible.

In the drawing, the pallets rotate by 18º in every beat. If the pallet fork were three inches long and it were assumed to rotate by 26º in every beat while in contact with the roller jewel (in order to create plenty of depthing for the simulation), and the roller jewel were assumed to rotate by 30º, we could draw these triangles, which would be used to calculate the roller jewel's circle radius (X).



X = 3 sin 13 / sin 15 = 2.607"

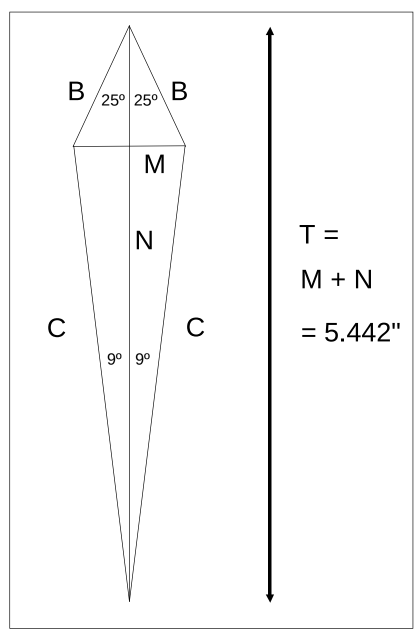
The distance between the pallet's circle center and the roller jewel's circle center is given by T:

T = Y + Z = X cos 15 + 3 cos 13

T = 2.519 + 2.923 = 5.442"

Draw a pallet fork with a distance of 3 inches from the pallet's circle center to the edge of the fork horn. Draw a roller jewel in a circle with a radius of 2.607 inches and place it at a distance of 5.442 inches from the pallet's circle center.

The double roller has two roller tables, the larger one for the roller jewel and the smaller one for the safety action. You need to find what dimensions the smaller table needs to have to ensure proper safety action.



B sin 25 = C sin 9 (i)

B = 0.370 C

B cos 25 + C cos 9 = 5.442 (ii)

(0.370 C) x 0.906 + 0.990 C = 1.323 C = 5.442

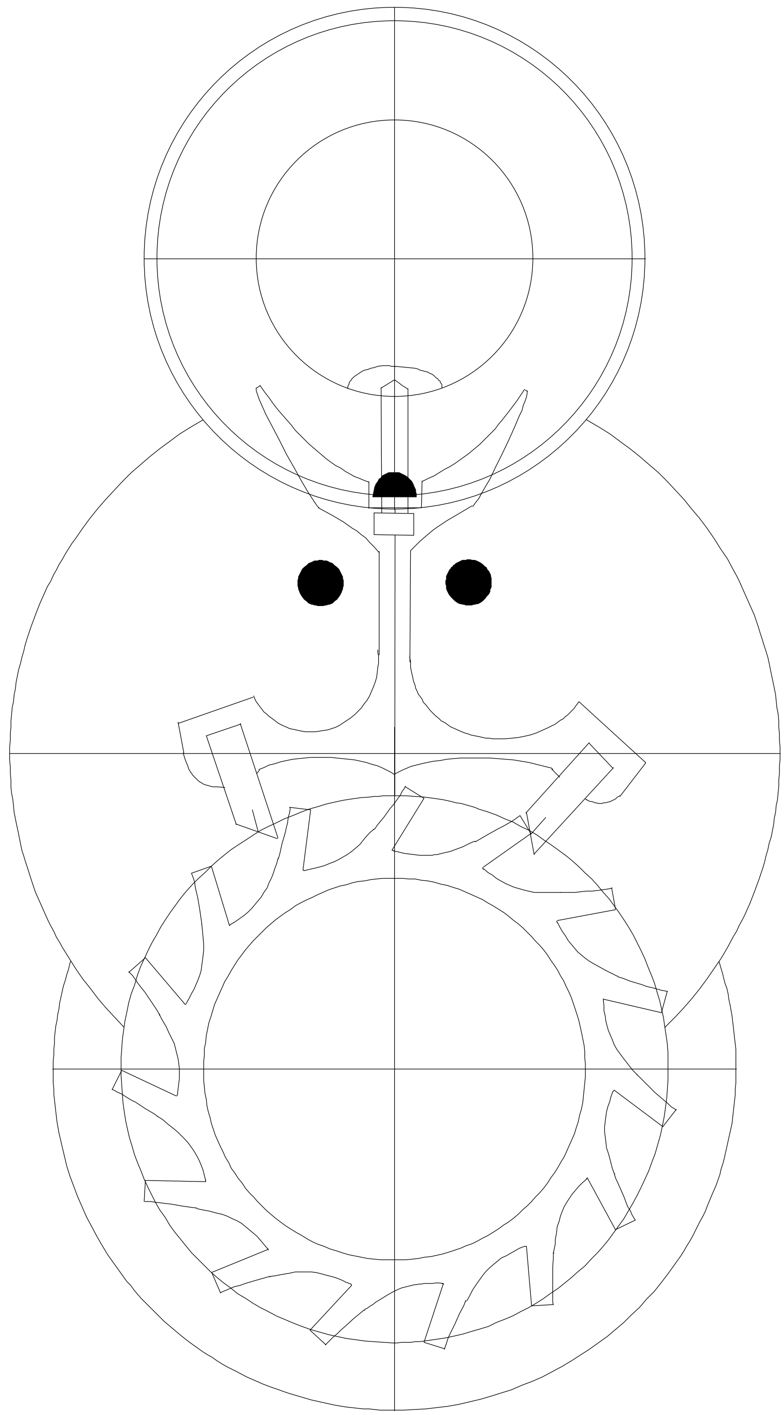
C = 4.113

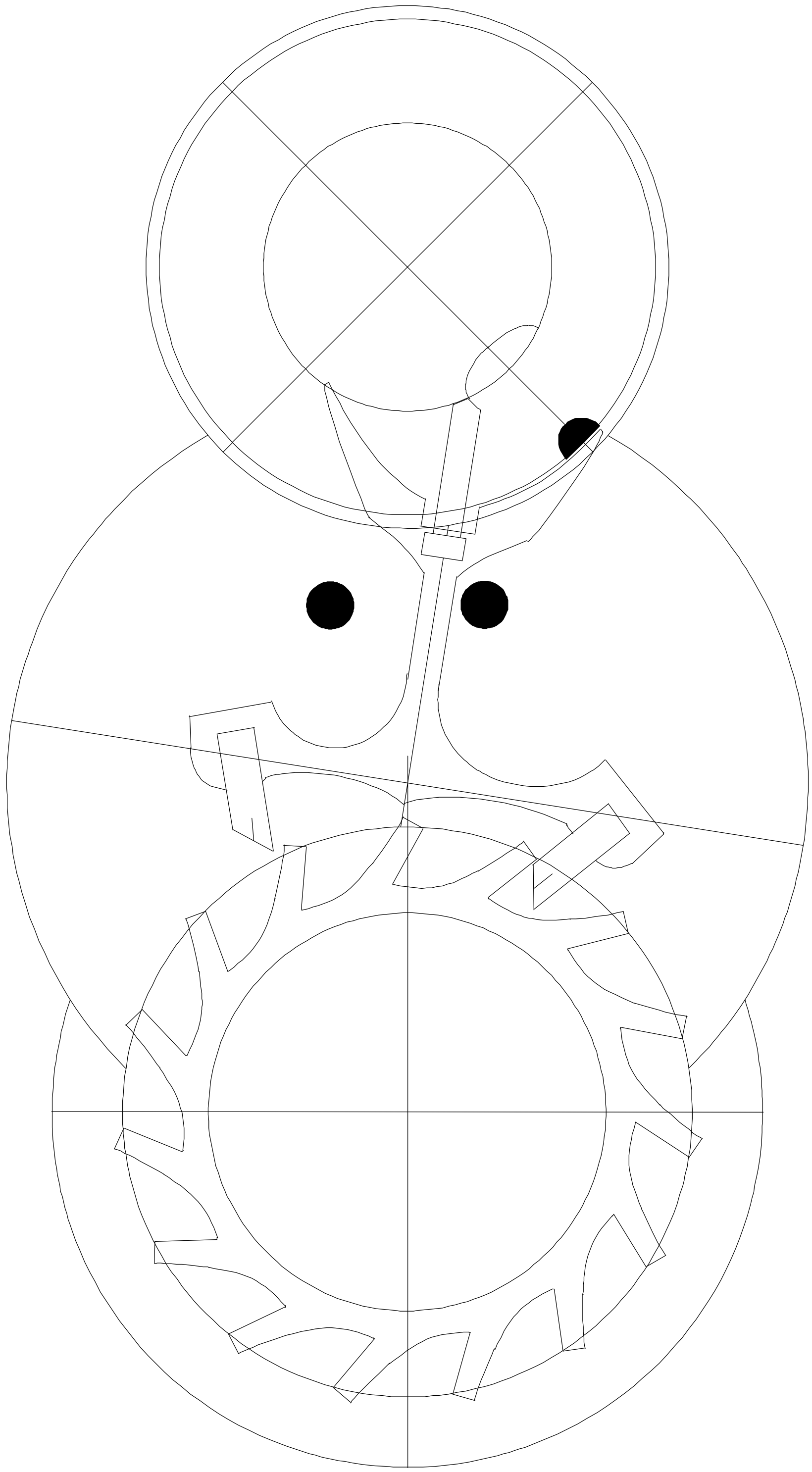
B = 0.370 x 4.113 = 1.522

B + C - T = depth = 1.522 + 4.113 - 5.442 = 0.192"

Draw a small roller table with a radius of 1.522 inches and center it inside the roller jewel's circle. Draw the guard pin with a radius of 4.113 inches from the pallet's circle center. Draw a notch in the smaller roller table that would allow the guard pin to clear it because the latter would have a depth of 0.192 inches.

To place the banking pins, rotate the pallets by 9º from the vertical position, or until the pallet has just released the escape tooth, plus 2º extra for slide, for a total of 11º. Place a small circle next to the pallet fork in an appropriate position. Repeat on the other side.



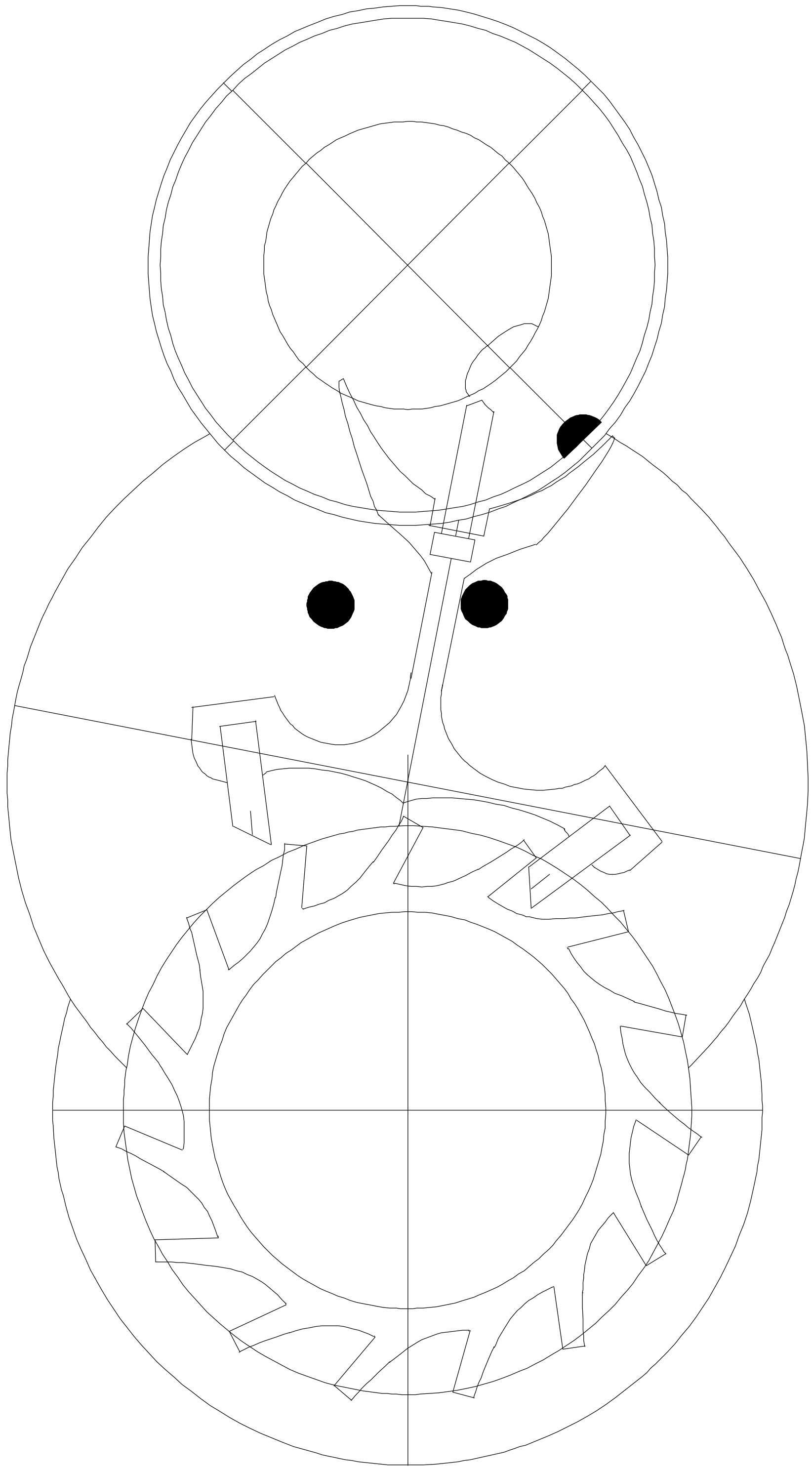


Rotate the pallets until a tooth is released: this is the "drop-lock position." Rotate the roller table until the safety notch is just beyond the guard pin, which appears to be pressed against the safety roller. Draw the fork horn just outside the path of the roller jewel, and extending to the jewel's other side, as shown. This design prevents premature unlocking. Repeat on the other side.

The fork rotates by 18º in each direction while the guard finger is in the safety notch. The fork also rotates by 18º in each beat. This way there is lock whenever the guard finger is against the safety roller: if there were no lock, there would be no draw to keep the guard finger away from the safety roller.

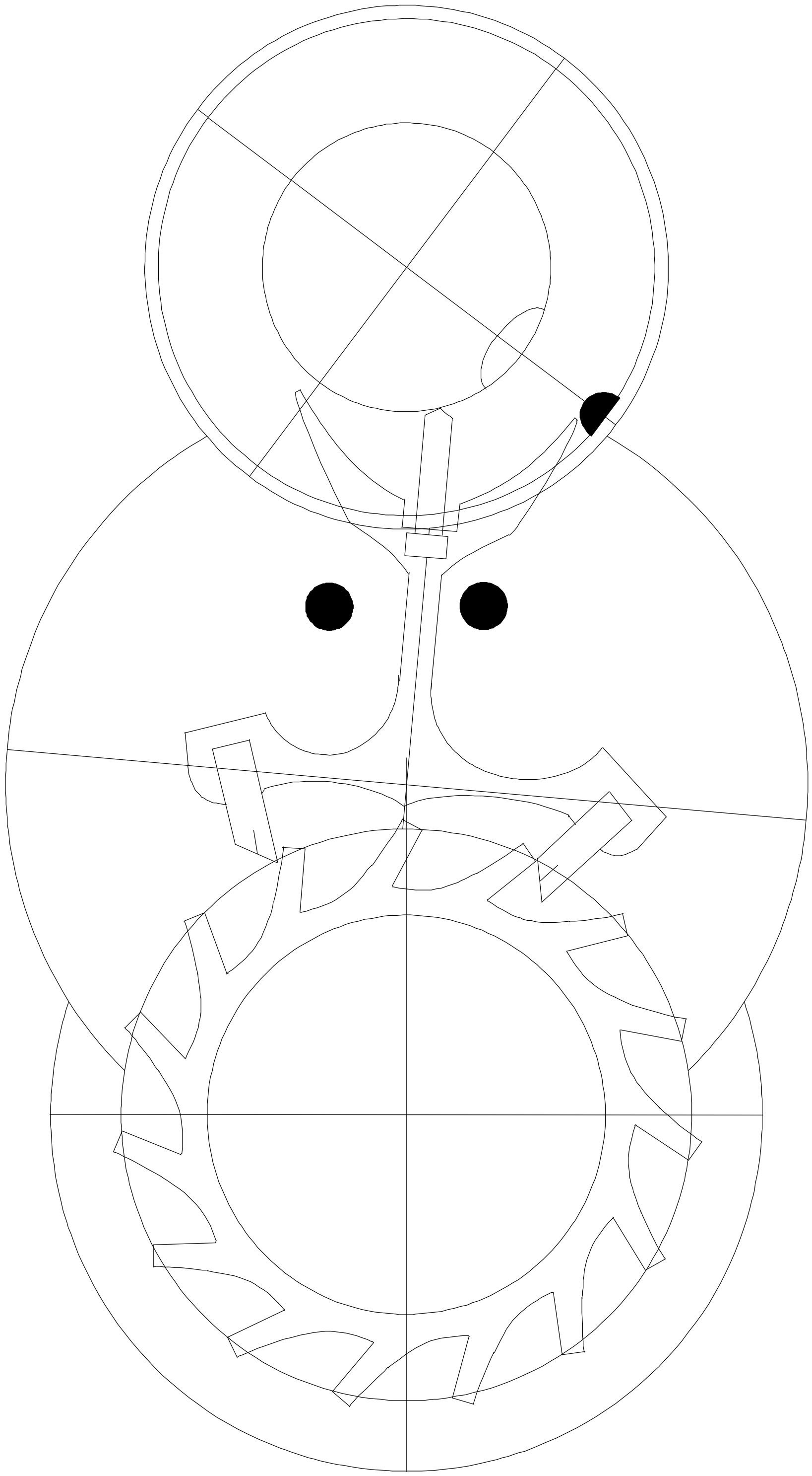
There is also a small gap between the fork and the banking pin. This slide is necessary to keep the guard finger away from the roller table. It also creates "fork horn freedom," which is the freedom of movement the fork has between the roller jewel and the banking pin in this position, but notice that the guard finger prevents the fork horn from touching the roller jewel at this point.

Rotate the pallets by 2º further, until the fork is pressed against the banking pin. By increasing the angle that the fork is in contact with the roller jewel during rotation from 18º to 26º, you create depthing to make sure that, when the roller jewel returns to unlock the pallets, the roller jewel would engage the fork below its entrance corner. This is the same as making the fork longer: if the fork were too short, there may not be enough depth-ing.

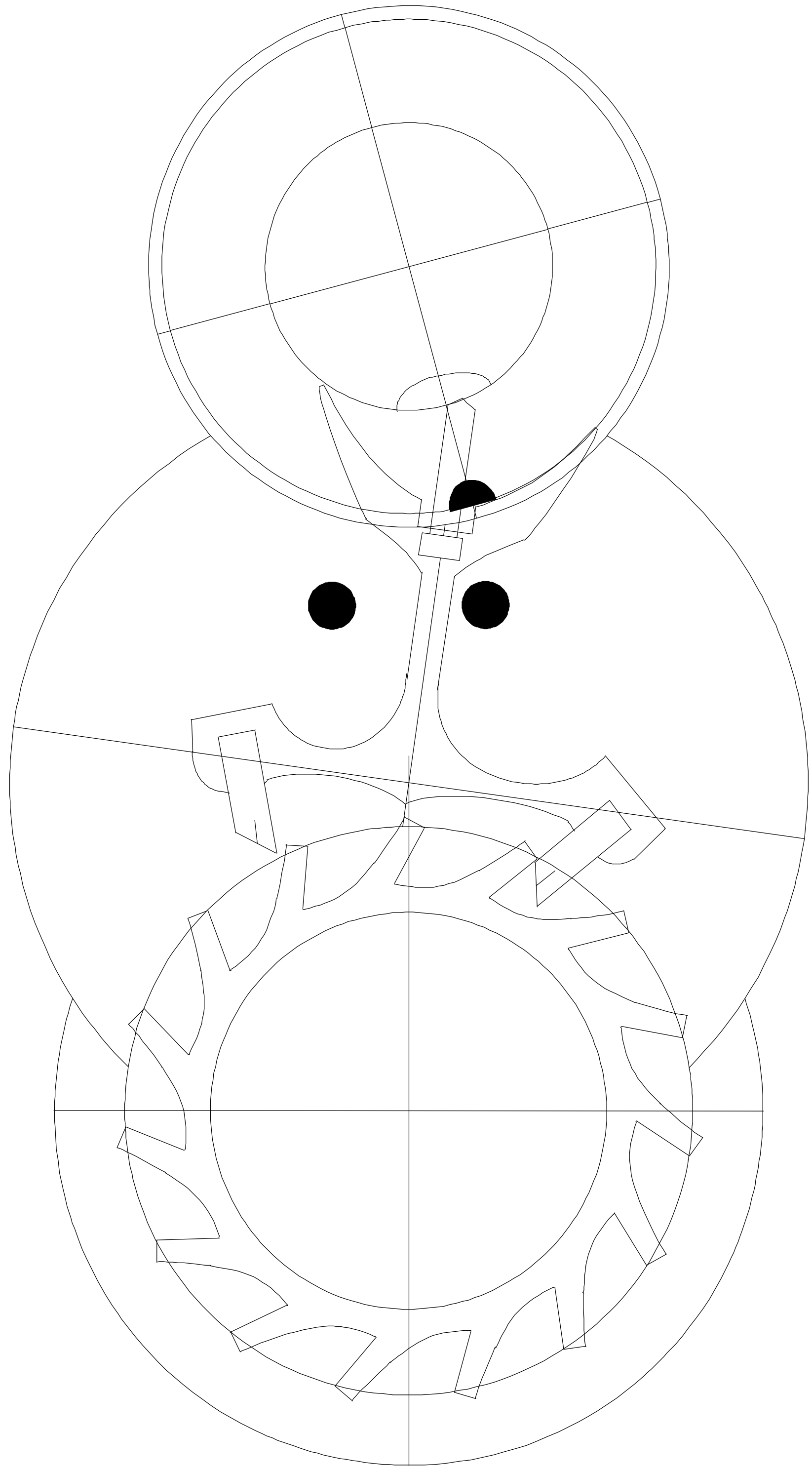


If the guard finger were too short, the fork horn may get in the way of the roller jewel, and overbanking may occur. Guard finger freedom would be increased, and if it increased to the point where the pallet were allowed to unlock the tooth, there would be binding because the guard pin would be pressed against the roller table as the escape tooth pushes on the pallet's impulse face. Conversely, if the guard finger were too long, there would be no gap between the guard finger and the safety roller when the fork is pressed against the banking pin. This gap is called "guard finger freedom."

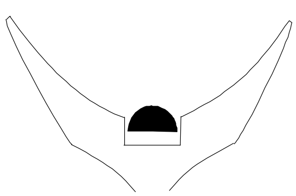
In this drawing, the guard pin is too short. The escape tooth is pressing on the pallet's impulse face as the guard pin is pressed against the safety roller, causing severe frictional losses. The fork horn is blocking the path of the roller jewel.



If the pallet unlocked prematurely, just before the roller jewel were to begin to unlock it, binding might occur. There needs to be enough lock so that when the fork horn is pressed against the roller jewel before it could completely enter the fork slot, the pallet does not unlock the escape tooth. There also needs to be some slot corner freedom, or the shake of the fork between the banking pin and the roller jewel in this position: here the guard finger could enter the safety notch and so could not prevent premature unlocking, so this position must be checked very carefully.



The fork slot must be slightly wider than the width of the roller jewel:

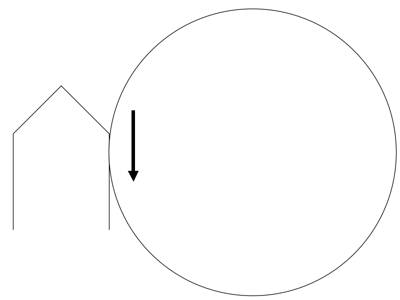


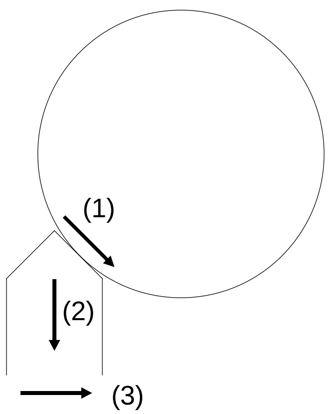
It should be clear that with the freedom of the roller jewel, the slot corner freedom, the fork horn freedom, the guard finger freedom, and the side-shake of the pivots in the jewels of the escape wheel, the pallet fork and the balance wheel, there needs to be enough lock in the drop-lock position to prevent unlocking while the parameters of these variables are tested. There also needs to be enough depthing of the roller jewel in the fork slot in case the slide needs to be increased to ensure enough guard pin shake.

The most important advantage of the double roller over the single roller is the ability to increase the depth of engagement of the guard finger into the safety roller. Increasing the depth reduces the likelihood that the pallet fork might accidentally move across to the wrong side.

Lock and slide and the angle of the locking face together result in the small binding action that keeps the guard finger away from the safety roller after each beat, a binding action that is referred to as "draw." If the design had insufficient draw, consider what would happen if the guard pin rubbed against the roller table.

If the guard pin rubbed against the safety roller on the side, the oscillation of the balance wheel would be interfered with, and the symmetry of the action of the balance wheel would be altered, affecting the timekeeping.





The power loss increases dramatically if the guard pin rubs the safety roller from a different angle. Here, the safety roller exerts a force (1) upon the guard pin that could be seen as pushing the pin towards the pallets, shown by arrow (2), and as pushing the pin towards the other side, shown by arrow (3). Arrow (3) shows that this arrangement has a binding effect when the guard pin is pressed against the roller table. The drawings on pages 82 and 84 reveal a similar binding effect, and the latter is compounded by the escape tooth pushing on the pallet's impulse face. The banking pins are adjusted wide enough to create enough draw to keep the guard finger away from the safety roller, and far enough away to reduce the likelihood that the finger might touch the roller if the watch were jolted.

Look back at the chapter concerning the Duplex escapement to see how the relationship between the escape wheel's locking tooth and the locking jewel would result in a similar binding effect. The same binding effect could be found in the Cylinder escapement.

It is naturally assumed that the timepiece should be adjusted to maximize efficiency, but there is one criterion that is more important than efficiency and for which some efficiency *should* be compromised: **symmetry of action**. A fine watch might be adjusted for maximum efficiency by adjusting for only a very small amount of drop-lock and a very small amount of run to the banking, in order to minimize the power losses caused by draw. The watch may run very well on the timing machine, keeping consistent time in all positions. However, when worn on the wrist, this watch would become erratic, particularly if the owner were very active. This is because the movements on the wrist would cause the fork to interfere with the movement of the balance wheel, even if only occasionally and only momentarily. The watch may otherwise appear to run well. If the lock and slide were increased slightly to ensure better action, the watch would be a more consistent time-keeper, even though a small amount of efficiency may be compromised in the adjustments. The power lost in unlocking (caused by draw) should not be seen as wasted because draw serves such an important function. The locking angle, the drop-lock and the run to the banking should be the same on both sides, in order for the forces of action and reaction to be symmetrical on both sides.

You could use computer simulations to see the effects of problems caused not only by maladjustment but also by design defects. For example, you could observe the action of an eccentric escape wheel, or what would happen if you installed an escape wheel that is over or undersized. You could observe the effects of having the wrong pallets, too thick or too thin, or the effect of having one jewel set further out than the other, resulting in the fork being "out of angle." What would happen to the adjustments if the temperature changed and the metals in the watch expanded or contracted slightly? By creating your own drawings and experimenting with changes in the variables, you will increase your understanding of escapements considerably, and this knowledge will add to your skills at the bench.

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http://www.angelfire.com/ut/horology/watchesa.html
The watch website has information about what to look out for as a collector of watches and clocks, and a large photo gallery of watch mechanisms. If you have any difficulties with the main website, you could try one of the others, which all have the same content.