10
Polar Coordinates, Parametric Equations

10.1 Polar Coordinates

Coordinate systems are tools that let us use algebraic methods to understand geometry. While the rectangular (also called Cartesian) coordinates that we have been using are the most common, some problems are easier to analyze in alternate coordinate systems.

A coordinate system is a scheme that allows us to identify any point in the plane or in three-dimensional space by a set of numbers. In rectangular coordinates these numbers are interpreted, roughly speaking, as the lengths of the sides of a rectangle. In polar coordinates a point in the plane is identified by a pair of numbers (r, θ). The number r measures the distance from the origin to the point. Figure 10.1.1 shows the point with rectangular coordinates (1, √3); the number r measures the distance from the origin to the point.

Figure 10.1.1 Polar coordinates of the point (1, √3).

Example 10.1.1 Graph the curve given by

\[ r = 2 \sin \theta \].

Just as we describe curves in the plane using equations involving x and y, so can we describe curves using equations involving r and θ. Most common are equations of the form \( r = f(\theta) \).

Example 10.1.1 Graph the curve given by \( r = 2 \). All points with \( r = 2 \) are at distance 2 from the origin, so \( r = 2 \) describes the circle of radius 2 with center at the origin.

Example 10.1.2 Graph the curve given by \( r = 1 + \cos \theta \). We first consider \( y = 1 + \cos x \), as in Figure 10.1.2. As \( \theta \) goes through the values in [0, 2π], the value of r tracks the value of y, forming the “cardioid” shape of Figure 10.1.2. For example, when \( \theta = \pi/2 \), \( r = 1 + \cos(\pi/2) = 1 \), so we graph the point at distance 1 from the origin along the positive y-axis, which is at an angle of \( \pi/2 \) from the positive x-axis. When \( \theta = 3\pi/4 \), \( r = 1 + \cos(3\pi/4) = 1 + \sqrt{2}/2 \approx 1.71 \), and the corresponding point appears in the fourth quadrant. This illustrates one of the potential benefits of using polar coordinates: the equation for this curve in rectangular coordinates would be quite complicated.

Each point in the plane is associated with exactly one pair of numbers in the rectangular coordinate system; each point is associated with an infinite number of pairs in polar coordinates. In the cardioid example, we considered only the range 0 ≤ θ ≤ 2π, and already there was a duplicate: (2, 0) and (2, 2π) are the same point. Indeed, every value of θ outside the interval [0, 2π) duplicates a point on the curve \( r = 1 + \cos \theta \) when 0 ≤ θ < 2π. We can even make sense of polar coordinates like (–2, π/4), (2, –π/4), etc., by going to the direction π/4 and then moving a distance 2 in the opposite direction; see Figure 10.1.3. As usual, a negative angle θ means an angle measured clockwise from the positive x-axis. The point on the right in Figure 10.1.3 also has coordinates (2, 5π/4) and (2, –3π/4).

The relationship between rectangular and polar coordinates is quite easy to understand. The point with polar coordinates (r, θ) has rectangular coordinates \( x = r \cos \theta \) and \( y = r \sin \theta \); this follows immediately from the definition of the sine and cosine functions. Using Figure 10.1.3 as an example, the point shown has rectangular coordinates (1, 2).

Example 10.1.3 The point (–2, π/4) = (2, 5π/4) = (2, –3π/4) in polar coordinates:

\[ x = –(–2) \cos(\pi/4) = –\sqrt{2} \approx 1.4142 \]  and \[ y = –(–2) \sin(\pi/4) = –\sqrt{2} \]. This makes it very easy to convert equations from rectangular to polar coordinates.

Example 10.1.4 Find the equation of the circle \( x^2 + y^2 = 1 \) in polar coordinates. Again substituting \( \sqrt{x^2 + y^2} = r \sin \theta = r \theta = 1/4 \). A bit of algebra turns this into \( r = \cos(\theta) \). You should try plotting a few \( r(\theta) \) values to convince yourself that this makes sense.

Example 10.1.5 Graph the polar equation \( r = \theta \). Here the distance from the origin exactly matches the angle, so a bit of thought makes it clear that when \( \theta \geq 0 \) we get the spiral of Archimedes in Figure 10.1.4.

Converting polar equations to rectangular equations can be somewhat trickier, and graphing polar equations directly is also not always easy.

Exercises 10.1

1. Plot these polar coordinate points on one graph: (2, π/3), (–3, π/2), (–2, –π/4), (1/2, π), (1, 4π/3), (0, 3π/2).

2. Find an equation in polar coordinates that has the same graph as the given equation in rectangular coordinates.

3. \( y = x \)

4. \( y = x^2 \)

5. \( x^2 + y^2 = 9 \)

6. \( y = x^2 \)

7. \( y = \sin x \)

8. \( y = 5x \)

9. \( x = 2 \)

10. \( y = x^2 + 1 \)

11. \( y = x^2 - 2x \)

12. \( y = x^2 + y^2 \)

Sketch the curve.

13. \( r = \cos \theta \)
14. \( r = \sin(\theta + \pi/4) \)
15. \( r = -\sec \theta \)
16. \( r = 0/2, \theta \geq 0 \)
17. \( r = 1 - \theta^2 \)
18. \( r = \cos \theta \cos \theta \)
19. \( r = \frac{1}{\sin^2 \theta + \cos \theta} \)
20. \( r^2 = 2 \sin \theta \cos \theta \)

In the exercises below, find an equation in rectangular coordinates that has the same graph as the given equation in polar coordinates.

21. \( r = \sin(3\theta) \)
22. \( r = \sin^3 \theta \)
23. \( r = \sec \theta \cos \theta \)
24. \( r = \tan \theta \)

10.2 Slopes in polar coordinates

When we describe a curve using polar coordinates, it is still a curve in the \( x-y \) plane. We would like to be able to compute slopes and areas for these curves using polar coordinates.

We have seen that \( x = r \cos \theta \) and \( y = r \sin \theta \) describe the relationship between polar and rectangular coordinates. If in turn we are interested in a curve given by \( r = f(\theta) \), then we can write \( x = f(\theta) \cos \theta \) and \( y = f(\theta) \sin \theta \), describing \( x \) and \( y \) in terms of \( \theta \) alone.

The first of these equations describes \( \theta \) implicitly in terms of \( x \), so using the chain rule we may compute

\[
\frac{dy}{dx} = \frac{dy/d\theta}{dx/d\theta}.
\]

Since \( dr/d\theta = 1/(dx/d\theta) \), we can instead compute

\[
\frac{dy}{dx} = \frac{dy/d\theta}{dx/d\theta} = \frac{f(\theta) \cos \theta + f'(\theta) \sin \theta}{-f(\theta) \sin \theta + f'(\theta) \cos \theta}.
\]

**EXAMPLE 10.2.1** Find the points at which the curve given by \( r = 1 + \cos \theta \) has a vertical or horizontal tangent line. Since this function has period \( 2\pi \), we may restrict our attention to the interval \([0, 2\pi]\) or \([\pi, 3\pi]\), as convenience dictates. First, we compute the slope:

\[
\frac{dy}{dx} = \frac{(1 + \cos \theta) \cos \theta - \sin \theta \sin \theta}{-1 + \sin \theta + \cos \theta}.
\]

Sketch the curves over the interval \([0, 2\pi]\) unless otherwise stated.

2. \( r = 1 + \sin \theta \Rightarrow \)
3. \( r = \cos \theta \Rightarrow \)
4. \( r = \sin \theta \Rightarrow \)
5. \( r = \sec \theta \Rightarrow \)
6. \( r = \sin(2\theta) \Rightarrow \)

**10.3 Areas in polar coordinates**

We can use the equation of a curve in polar coordinates to compute some areas bounded by such curves. The basic approach is the same as with any application of integration: find an approximation that approaches the true value. For areas in rectangular coordinates, we approximated the region using rectangles; in polar coordinates, we use sectors of circles, as depicted in figure 10.3.1. Recall that the area of a sector of a circle is \( \alpha r^2/2 \), where \( \alpha \) is the angle subtended by the sector. If the curve is given by \( r = f(\theta) \), and the angle subtended by a small sector is \( d\theta \), the area is \( f(\theta)^2 d\theta/2 \). Thus we approximate the total area as

\[
\sum_{\theta = \alpha}^{\beta} \frac{1}{2} f(\theta)^2 d\theta.
\]

In the limit this becomes

\[
\int_{\alpha}^{\beta} \frac{1}{2} f(\theta)^2 d\theta.
\]

This fraction is zero when the numerator is zero (and the denominator is not zero). The numerator is \( 2 \cos^2 \theta + 1 \) so by the quadratic formula

\[
\cos \theta = -\frac{1 \pm \sqrt{4 + 4/4}}{2} = -1 \text{ or } 1/2
\]

This means \( \theta = \pi \) or \( \pm \pi/3 \). However, when \( \theta = \pi \), the denominator is also 0, so we cannot conclude that the tangent line is horizontal.

Setting the denominator to zero we get

\[
\cos \theta - 2 \sin \theta \cos \theta = 0
\]

so either \( \sin \theta = 0 \) or \( \cos \theta = -1/2 \). The first is true when \( \theta = 0 \) or \( \pi \), the second when \( \theta = 2\pi/3 \) or \( 4\pi/3 \). However, as above, when \( \theta = \pi \), the numerator is also 0, so we cannot conclude that the tangent line is vertical. Figure 10.2.1 shows points corresponding to \( \theta \) equal to 0, \( \pm \pi/3 \), \( 2\pi/3 \) and \( 4\pi/3 \) on the graph of the function. Note that when \( \theta = \pi \) the curve hits the origin and does not have a tangent line.

![Figure 10.2.1 Points of vertical and horizontal tangents for \( r = 1 + \cos \theta \)](image)

**EXAMPLE 10.2.2** We find the second derivative for the cardioid \( r = 1 + \cos \theta \):

\[
d \frac{dr}{d\theta} = \frac{\cos \theta - \sin \theta}{1 + \cos \theta} \quad \frac{d^2 r}{d\theta^2} = \frac{1}{1 + \cos \theta}
\]

The ellipse here represents a rather substantial amount of algebra. We know from above that the cardioid has horizontal tangents at \( \pm \pi/3 \); substituting these values into the second derivative we get \( y'(\pi/3) = -\sqrt{3}/2 \) and \( y'(4\pi/3) = \sqrt{3}/2 \), indicating concave down and concave up respectively. This agrees with the graph of the function.

**10.4 Areas in polar coordinates**

We can compute the area inside and outside the cardioid \( r = 1 + \cos \theta \), using the procedure of integration by parts.

\[
\int_{\alpha}^{\beta} (1 + \cos \theta)^2 d\theta = \frac{1}{2} \int_{\alpha}^{\beta} 1 + 2 \cos \theta + \cos^2 \theta d\theta = \frac{1}{2} \left[ \theta + 2 \sin \theta \right]_{\alpha}^{\beta} = \frac{1}{2} \left[ \beta - \alpha \right]
\]

**EXAMPLE 10.3.1** We find the area inside the cardioid \( r = 1 + \cos \theta \).

\[
\int_{\alpha}^{\beta} (1 + \cos \theta)^2 d\theta = \frac{1}{2} \int_{\alpha}^{\beta} 1 + 2 \cos \theta + \cos^2 \theta d\theta = \frac{1}{2} \left[ \frac{1}{2} \theta + \sin \theta \right]_{\alpha}^{\beta} = \frac{1}{4} \left[ \beta - \alpha \right]
\]

**EXAMPLE 10.3.2** We find the area between the circles \( r = 2 \) and \( r = 4 \sin \theta \), as shown in figure 10.3.2. The two curves intersect where \( 2 = 4 \sin \theta \), or \( \theta = \pi/6 \) or \( 5\pi/6 \). The area we want is then

\[
\int_{\alpha}^{\beta} (1 + \cos \theta)^2 d\theta = \frac{1}{2} \int_{\alpha}^{\beta} 1 + 2 \cos \theta + \cos^2 \theta d\theta = \frac{1}{2} \left[ \theta + 2 \sin \theta \right]_{\alpha}^{\beta} = \frac{1}{2} \left[ \beta - \alpha \right]
\]

**Figure 10.3.1 Approximating area by sectors of circles.**

**Figure 10.3.2 An area between curves.**

This example makes the process appear more straightforward than it is. Because points have many different representations in polar coordinates, it is not always so easy to identify points of intersection.
EXAMPLE 10.3.3 We find the shaded area in the first graph of figure 10.3.3 as the difference of the other two shaded areas. The cardioid is \( r = 1 + \sin \theta \) and the circle is \( r = 3 \sin \theta \). We attempt to find points of intersection:
\[
1 + \sin \theta = 3 \sin \theta \\
1 = 2 \sin \theta \\
1/2 = \sin \theta.
\]
This has solutions \( \theta = \pi/6 \) and \( 5\pi/6 \). \( \pi/6 \) corresponds to the intersection in the first quadrant that we need.
Note that no solution of this equation corresponds to the intersection point at the origin, but fortunately one that is obvious. The cardioid goes through the origin when \( \theta = -\pi/2 \); the circle goes through the origin at multiples of \( \pi \), starting with 0.

Now the larger region has area
\[
\int_{\pi/6}^{5\pi/6} 2\pi(1 + \sin \theta)^2 \, d\theta = \frac{\pi}{2} \sqrt{3}
\]
and the smaller has area
\[
\int_{\pi/6}^{5\pi/6} 2\pi(3\sin \theta)^2 \, d\theta = \frac{2\pi}{3} \sqrt{3}
\]
so the area we seek is \( \pi/8 \).

10.4 Parametric Equations

When we computed the derivative \( dy/dx \) using polar coordinates, we used the expressions
\[
x = f(\theta) \cos \theta \quad \text{and} \quad y = f(\theta) \sin \theta.
\]
These two equations completely specify the curve, though the form \( r = f(\theta) \) is simpler. The expanded form has the virtue that it can easily be generalized to describe a wider range of curves than can be specified in rectangular or polar coordinates.

Suppose \( f(\theta) \) and \( g(\theta) \) are functions. Then the equations \( x = f(t) \) and \( y = g(t) \) describe a curve in the plane. In the case of the polar coordinates equations, the variable \( t \) is replaced by \( \theta \) which has a natural geometric interpretation. But \( t \) in general is simply an arbitrary variable, often called in this case a parameter, and this method of specifying a curve is known as parametric equations.

One important interpretation of \( t \) is time. In this interpretation, the equations \( x = f(t) \) and \( y = g(t) \) give the position of an object at time \( t \).

EXAMPLE 10.4.1 Describe the path of an object that moves so that its position at time \( t \) is given by \( x = \cos t \), \( y = \cos^2 t \). We see immediately that \( y = 1 - x \), so the path lies on this parabola. The path is not the entire parabola, however, since \( x = \cos t \) is always between -1 and 1. It is now easy to see that the object oscillates back and forth on the parabola between the endpoints \((1, 1) \) and \((-1, 1) \), and at point \((1, 1) \) at time \( t = 0 \).

It is sometimes quite easy to describe a complicated path in parametric equations when rectangular and polar coordinate expressions are difficult or impossible to devise.

EXAMPLE 10.4.2 A wheel of radius 1 rolls along a straight line, say the \( x \)-axis. A point on the rim of the wheel will trace out a curve, called a cycloid. Assume the point starts at the origin; find parametric equations for the curve.

Figure 10.4.1 illustrates the generation of the curve (click on the AP link to see an animation). The wheel is shown at its starting point, and again after it has rolled through about 490 degrees. We take as our parameter \( t \) the angle through which the wheel has turned, measured as shown clockwise from the line connecting the center of the wheel to the ground. Because the radius is 1, the center of the wheel has coordinates \((t, 1)\). We seek to write the coordinates of the point on the rim as \((t + \Delta x, 1 + \Delta y)\), where \( \Delta x \) and \( \Delta y \) are as shown in figure 10.4.2. These values are nearly the sine and cosine of the angle \( t \), from the unit circle definition of sine and cosine. However, some care is required because we are measuring \( t \) from a nonstandard starting line and in a clockwise direction, as opposed to the usual counterclockwise direction. A bit of thought reveals that \( \Delta x = -\sin t \) and \( \Delta y = -\cos t \). Thus the parametric equations for the cycloid are \( x = t - \sin t \), \( y = 1 - \cos t \).
10.5 Calculus with Parametric Equations

We have already seen how to compute slopes of curves given by parametric equations—it is how we computed slopes in polar coordinates.

EXAMPLE 10.5.1  Find the slope of the cycloid $x = t - \sin t$, $y = 1 - \cos t$.

We compute $y' = 1 - \cos t$, $y' = \sin t$, so

$$\frac{dy}{dx} = \frac{\sin t}{1 - \cos t}.$$  
Note that when $t$ is an odd multiple of $\pi$, like $\pi$ or $3\pi$, this is $0$, so there is a horizontal tangent line, in agreement with figure 10.4.1. At even multiples of $\pi$, the fraction is undefined. The figure shows that there is no tangent line at such points.

EXAMPLE 10.5.2  Find the length of one arch of the cycloid.

From EXAMPLE 10.5.1

$$\frac{dy}{dt} = \sin t, \quad \frac{dx}{dt} = 1 - \cos t,$$
so the length is

$$\int_0^{2\pi} \sqrt{(1 - \cos t)^2 + \sin^2 t} \, dt = \int_0^{2\pi} \sqrt{2 - 2\cos t} \, dt.$$  
We use the formula $\sin^2(t/2) = (1 - \cos(t))/2$ or $4 \sin^2(t/2) = 2 - 2\cos t$ to get

$$\int_0^{2\pi} \sqrt{2 \sin^2(t/2)} \, dt.$$  
Since $0 \leq t \leq 2\pi$, $\sin(t/2) \geq 0$, so we can rewrite this as

$$\int_0^{2\pi} 2\sin(t/2) \, dt = 8.$$  

EXAMPLE 10.5.3  Find the length of one arch of the cycloid.

From $x = t - \sin t$, $y = 1 - \cos t$, we get the derivatives $\frac{dx}{dt} = 1 - \cos t$ and $\frac{dy}{dt} = \sin t$, so the length is

$$\int_0^{2\pi} \sqrt{(1 - \cos t)^2 + \sin^2 t} \, dt = \int_0^{2\pi} \sqrt{2 - 2\cos t} \, dt.$$  
Now we use the formula $\sin^2(t/2) = (1 - \cos(t))/2$ or $4 \sin^2(t/2) = 2 - 2\cos t$ to get

$$\int_0^{2\pi} \sqrt{2 \sin^2(t/2)} \, dt.$$  
Since $0 \leq t \leq 2\pi$, $\sin(t/2) \geq 0$, so we can rewrite this as

$$\int_0^{2\pi} 2\sin(t/2) \, dt = 8.$$  

Exercises 10.5.

1. Consider the curve of exercise 6 in section 10.4. Find all values of $t$ for which the curve has a horizontal tangent line.

2. Consider the curve of exercise 6 in section 10.4. Find the area under one arch of the curve.

3. Consider the curve of exercise 6 in section 10.4. Set up an integral for the length of one arch of the curve.

4. Consider the cycloid of exercise 7 in section 10.4. Find all points at which the curve has a horizontal tangent line.

5. Consider the cycloid of exercise 7 in section 10.4. Find the area between the large circle and one arch of the curve.

6. Consider the cycloid of exercise 7 in section 10.4. Find the length of one arch of the curve.

7. Consider the cycloid of exercise 8 in section 10.4. Find the area inside the curve.

8. Consider the cycloid of exercise 8 in section 10.4. Find the length of one arch of the curve.

9. Recall the involute of a circle from exercise 9 in section 10.4. Find the point in the first quadrant in figure 10.4.4 at which the tangent line is vertical.

10. Recall the involute of a circle from exercise 9 in section 10.4. Instead of an infinite string, suppose we have a string of length $\pi$ attached to the unit circle at $(1, 0)$, and initially laid around the top of the circle with its end at $(0, 0)$. If we grasp the end of the string and begin to unwind it, we get a piece of the involute, until the string is vertical. If we then keep the string taut and continue to rotate it counterclockwise, the end traces out a semi-circle with center at $(1, 0)$, until the string is vertical again. Continuing, the end of the string traces out the mirror image of the initial portion of the curve; see figure 10.5.1. Find the area of the region inside this curve and outside the unit circle.

Areas can be a bit trickier with parametric equations, depending on the curve and the area desired. We can potentially compute areas between the curve and the $x$-axis quite easily.

EXAMPLE 10.5.2  Find the area under one arch of the cycloid $x = t - \sin t$, $y = 1 - \cos t$. We would like to compute

$$\int_0^{2\pi} y \, dx,$$
but we do not know $y$ in terms of $x$. However, the parametric equations allow us to make a substitution: use $x = 1 - \cos t$ to replace $y$, and compute $dx = (1 - \cos t) \, dt$. Then the integral becomes

$$\int_0^{2\pi} (1 - \cos t)(1 - \cos t) \, dt = 2\pi.$$
Note that we need to convert the original $x$ limits to $t$ limits using $x = t - \sin t$. When $x = 0$, $t = \sin t$, which happens only when $t = 0$. Likewise, when $x = 2\pi$, $t = 2\pi$. Alternately, because we understand how the cycloid is produced, we can see directly that one arch is generated by $0 \leq t \leq 2\pi$. In general, of course, the $t$ limits will be different than the $x$ limits.

This technique will allow us to compute some quite interesting areas, as illustrated by the exercises.

As a final example, we see how to compute the length of a curve given by parametric equations. Section 9.9 investigates arc length for functions given as $y = f(x)$, but we do not know $y = f(t)$.

Using some properties of derivatives, including the chain rule, we can convert this to use parametric equations $x = f(t)$, $y = g(t)$:

$$\int_a^b \sqrt{1 + \left( \frac{dy}{dx} \right)^2} \, dx = \int_a^b \sqrt{1 + \left( \frac{dy}{dt} \right)^2 \left( \frac{dx}{dt} \right)^2} \, dt \, ds,$$
which reduces to

$$\int_a^b \sqrt{\left( f'(t) \right)^2 + \left( g'(t) \right)^2} \, dt.$$  
Here $u$ and $v$ are the $t$ limits corresponding to the $x$ limits $a$ and $b$.  

FIGURE 10.5.1  A region formed by the end of a string.

11. Find the length of the curve from the previous exercise, shown in figure 10.5.1.  
12. Find the length of the spiral of Archimedes (figure 10.3.4) for $0 \leq \theta \leq 2\pi$.  

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