W12 Notes

Parametric curves

01 Theory

Parametric curves are curves traced by the path of a 'moving' point. An independent parameter, such as t for 'time', controls *both x and y* values through **Cartesian coordinate functions** $x(t)$ and $y(t)$. The coordinates of the moving point are $\big(x(t),\, y(t)\big)$.

Parametric curve

A **parametric curve** is a function from parameter space $\mathbb{R}$ to the plane $\mathbb{R}^2$ given in terms of coordinate functions:

$$t \longmapsto \big(\, x(t),\, y(t) \,\big)$$

⚠ Other notations

Be aware that sometimes the coordinate functions are written with f and g (or yet other letters) like this: $(x, y) = \big(\, f(t),\, g(t) \,\big)$

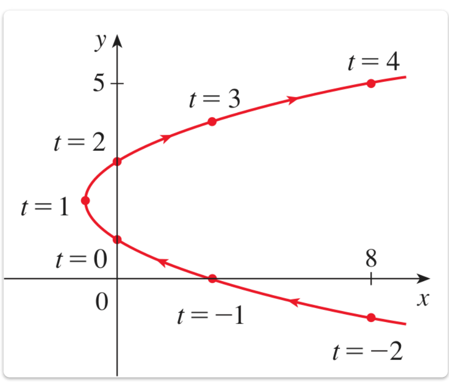
Or simply equating coordinate letters with functions: $x = f(t), \quad y = g(t)$

Sometimes a different parameter is used, like s or u.

For example, suppose:

$$x = t^2 - 2t, \qquad y = t + 1$$

The curve traced out is a parabola that opens horizontally:



Given a parametric curve, we can create an equation satisfied by x and y variables by solving for t in either coordinate function (inverting either f or g) and plugging the result into the other function.

In the example:

$$y = t + 1 \quad \gg\gg \quad t = y - 1$$

$$\gg\gg \quad x = t^2 - 2t \quad \gg\gg \quad x = (y-1)^2 - 2(y-1)$$

$$\gg\gg \quad x = y^2 - 4y + 3 \quad \gg\gg \quad \boxed{x = (y-2)^2 - 1}$$

This is the equation of a parabola centered at $(-1, 2)$ that opens to the right.

Image of a parametric curve

The **image** of a parametric curve is the *set* of output points $\big(x(t), y(t)\big)$ that are traversed by the moving point.

A parametric curve has *hidden information* that isn't contained in the image:

- The *time values* t when the moving point is found in various locations.
- The *speed* at which the curve is traversed.
- The *direction* in which the curve is traversed.

We can **reparametrize** a parametric curve to use a different parameter or different coordinate functions while leaving the *image unchanged*.

In the previous example, shift t by 1:

$$x = (t+1)^2 - 2(t+1), \qquad y = (t+1) + 1$$

$$\gg\gg \qquad x = t^2 - 1, \qquad y = t + 2$$

Since the parameter t and the parameter $t+1$ both cover the same values for $t \in (-\infty, \infty)$, the same curve is traversed. But the moving point in the second, shifted version reaches any given location *one unit earlier* in time. (When $t = -1$ in the second version, the input to $x(t)$ and $y(t)$ is the same as when $t = 0$ in the first one.)

02 Illustration

Example - Parametric circles

The standard equation of a circle of radius R centered at the point (h, k):

$$(x-h)^2 + (y-k)^2 = R^2$$

This equation says that the *distance* from a point (x, y) on the circle to the center point (h, k) equals R. This fact defines the circle.

Parametric coordinates for the circle:

$$x = h + R\cos t, \qquad y = k + R\sin t, \qquad t \in [0, 2\pi)$$

For example, the unit circle $x^2 + y^2 = 1$ is parametrized by $x = \cos t$ and $y = \sin t$.

Example - Parametric lines

A line is the set of points satisfying:

$$y = mx + b \qquad \text{some } a, b$$

Vertical lines cannot be described in this way, we must use equations like $x = a$.

Parametric coordinates for a line:

$$x = a + rt, \qquad y = b + st, \qquad t \in (-\infty, +\infty)$$

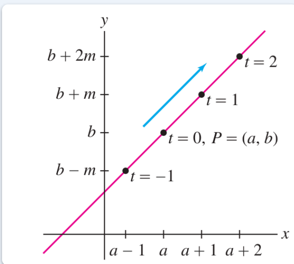
By choosing a, b, c, d appropriately, any line may be described.

For example, a vertical line $x = a$ is given by setting $a = a$ and $b, r, s = 0$.

A non-vertical line $y = mx + b$ is given by setting $b = b,\ s = m$ and $a = 0,\ r = 1$.

For another example, the line $y - a = m(x - b)$ which passes through $P = (a, b)$ with slope m is given by:

$$(x, y) = (a + t, b + mt)$$



Example - Parametric ellipses

The general equation of an ellipse centered at (h, k) with half-axes a and b is:

$$\left(\frac{x - h}{a}\right)^2 + \left(\frac{y - k}{b}\right)^2 = 1$$

This equation represents a *stretched unit circle*:

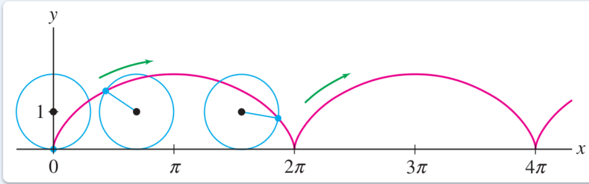
- by a in the x-axis
- by b in the y-axis

Parametric coordinate functions for the general ellipse:

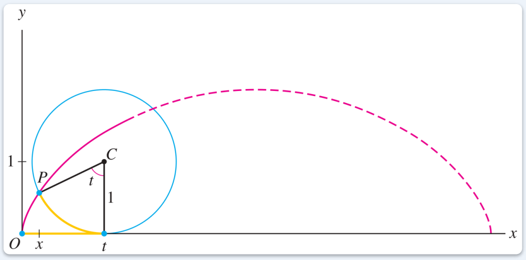
$$x = h + a\cos t, \qquad y = k + b\sin t, \qquad t \in [0, 2\pi)$$

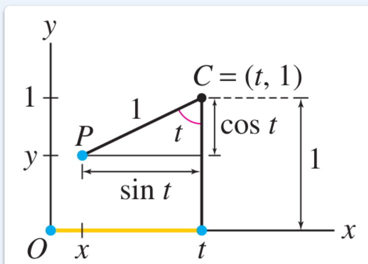
Example - Parametric cycloids

The cycloid is the curve traced by a pen attached to the rim of a wheel as it rolls.



It is easy to describe the cycloid parametrically. Consider the geometry of the situation:





The center C of the wheel is moving rightwards at a constant speed of 1, so its position is $(t, 1)$. The angle is revolving at the same constant rate of 1 (in *radians*) because the *radius* is 1.

The triangle shown has base $\sin t$, so the x coordinate is $t - \sin t$. The y coordinate is $1 - \cos t$.

So the coordinates of the point $P = (x, y)$ are given parametrically by:

$$x = t - \sin t, \qquad y = 1 - \cos t, \qquad t > 0$$

If the circle has another radius, say R, then the parametric formulas change to:

$$x = Rt - R\sin t, \qquad y = R - R\cos t, \qquad t > 0$$

Calculus with parametric curves

03 Theory - Slope, concavity

We can use $x(t)$ and $y(t)$ data to compute the slope of a parametric curve in terms of t.

Slope formula

Given a parametric curve $\big(x(t),\, y(t)\big)$, its slope satisfies:

$$\frac{dy}{dx} \;=\; \frac{y'(t)}{x'(t)} \qquad (\text{where } x'(t) \neq 0)$$

Concavity formula

Given a parametric curve $\big(x(t),\, y(t)\big)$, its concavity satisfies the formula:

$$\frac{d^2y}{dx^2} = \frac{d}{dt}\left(\frac{y'(t)}{x'(t)}\right) \cdot \frac{1}{x'(t)} \qquad (\text{where } x'(t) \neq 0)$$

Extra - Derivation of slope and concavity formulas

For both derivations, it is necessary to view t as a function of x through the inverse parameter function. For example if $x = f(t)$ is the parametrization, then $t = f^{-1}(x)$ is the inverse parameter function.

We will need the derivative $\frac{dt}{dx}$ in terms of t. For this we use the formula for derivative of inverse functions:

$$\frac{dt}{dx} = \frac{1}{dx/dt}$$

Given all this, both formulas are simple applications of the chain rule.

For the slope:

$$\frac{dy}{dx} = \frac{dy}{dt} \cdot \frac{dt}{dx} \qquad \gg\gg \qquad y'(t) \cdot \frac{1}{dx/dt}$$

$$\gg\gg \qquad \frac{y'(t)}{x'(t)}$$

For the concavity:

$$\frac{d^2y}{dx^2} = \frac{d}{dx}\left(\frac{dy}{dx}\right) \qquad \gg\gg \qquad \frac{d}{dt}\left(\frac{dy}{dx}\right) \cdot \frac{dt}{dx}$$

$$\gg\gg \qquad \frac{d}{dt}\left(\frac{y'(t)}{x'(t)}\right) \cdot \frac{1}{x'(t)}$$

(In the second step we inserted the formula for $\frac{dy}{dx}$ from the slope.)

Pure vertical, Pure horizontal movement

In view of the formula $\frac{dy}{dx} = \frac{y'(t)}{x'(t)}$, we see:

- Pure vertical: when $x'(t) = 0$ and yet $y'(t) \neq 0$

- Pure horizontal: when $y'(t) = 0$ and yet $x'(t) \neq 0$

When $x'(t_0) = y'(t_0) = 0$ for the same $t = t_0$, we have a **stationary point**, which might subsequently progress into pure vertical, pure horizontal, or neither.

04 Illustration

Example - Tangent to a cycloid

Find the equation of the tangent line to the cycloid $(4t - 4\sin t,\, 4 - 4\cos t)$ when $t = \frac{\pi}{4}$.

Solution

Compute $x'(\pi/4) = 4 - 2\sqrt{2}$.

- Derivative of $x(t)$:

$$x'(t) = 4 - 4\cos t$$

- Plug in $t = \pi/4$:

$$\begin{aligned} x'(\pi/4) &= 4 - 4\cos(\pi/4) \\ &= 4 - 2\sqrt{2} \end{aligned}$$

Compute $y'(\pi/4) = 4\sin t = 2\sqrt{2}$.

- Derivative of $y(t)$:

$$y'(t) = 4\sin t$$

- Plug in $t = \pi/4$:

$$\begin{aligned} y'(\pi/4) &= 4\sin(\pi/4) \\ &= 2\sqrt{2} \end{aligned}$$

Apply formula $\frac{dy}{dx} = \frac{y'}{x'}$.

- Calculate $\frac{dy}{dx}$ at $t = \pi/4$:

$$\begin{aligned} \frac{dy}{dx}(\pi/4) = \frac{y'(\pi/4)}{x'(\pi/4)} \quad &\gg\gg \quad \frac{2\sqrt{2}}{4 - 2\sqrt{2}} \\ &\gg\gg \quad \frac{2\sqrt{2}}{4 - 2\sqrt{2}} \cdot \frac{4 + 2\sqrt{2}}{4 + 2\sqrt{2}} \\ &\gg\gg \quad \frac{8\sqrt{2} + 8}{16 - 8} \quad \gg\gg \quad \sqrt{2} + 1 \end{aligned}$$

- Slope of tangent line is $m = \sqrt{2} + 1$

A point on the tangent line: $\left(\pi - 2\sqrt{2}, 4 - 2\sqrt{2}\right)$ at $t = \pi/4$.

- Plug $t = \pi/4$ into $\big(x(t), y(t)\big) = (4t - 4\sin t, 4 - 4\cos t)$:

$$\left(4\frac{\pi}{4} - 4\sin(\pi/4), 4 - 4\cos(\pi/4)\right) \qquad \gg\gg \qquad \left(\pi - 2\sqrt{2}, 4 - 2\sqrt{2}\right)$$

Equation of tangent line: $y = mx + b$.

- Point-slope formulation:

$$y - \left(4 - 2\sqrt{2}\right) = \left(\sqrt{2} + 1\right)\left(x - \left(\pi - 2\sqrt{2}\right)\right)$$

- Simplify:

$$\gg\gg \qquad y = \left(\sqrt{2} + 1\right)\left(x - \pi + 2\sqrt{2}\right) + 4 - 2\sqrt{2}$$

$$\gg\gg \qquad y = \left(\sqrt{2} + 1\right)x + 8 - \left(\sqrt{2} + 1\right)\pi$$

This is our final answer.

Example - Vertical and horizontal tangents of the circle

Consider the circle parametrized by $x = \cos t$ and $y = \sin t$. Find the points where the tangent lines are vertical or horizontal.

Solution

For the points with vertical tangent line, we find where the moving point has $x'(t) = 0$ (purely vertical motion):

$$x'(t) = -\sin t,$$

$$x'(t) = 0 \qquad \gg\gg \qquad -\sin t = 0 \qquad \gg\gg \qquad t = 0, \pi$$

For the points with horizontal tangent line, we find where the moving point has $y'(t) = 0$ (purely horizontal motion):

$$y'(t) = \cos t,$$

$$y'(t) = 0 \qquad \gg\gg \qquad \cos t = 0 \qquad \gg\gg \qquad t = \frac{\pi}{2}, \; \frac{3\pi}{2}$$

05 Theory - Arclength

Arclength formula

The **arclength** of a parametric curve with coordinate functions $x(t)$ and $y(t)$ is:

$$L = \int_a^b \sqrt{(x')^2 + (y')^2}\, dt$$

This formula assumes the curve is traversed one time as t increases from a to b.

Counts total traversal

This formula applies when the curve image is traversed *one time* by the moving point.

Sometimes a parametric curve traverses its image with repetitions. The arclength formula would add length from each repetition!

Extra - Derivation of arclength formula

The arclength of a parametric curve is calculated by integrating the infinitesimal arc element:

$$ds = \sqrt{dx^2 + dy^2}$$

$$L = \int_a^b ds$$

In order to integrate ds in the t variable, as we must for parametric curves, we convert ds to a function of t:

$$ds = \sqrt{dx^2 + dy^2} \qquad \gg\gg \qquad \sqrt{\frac{1}{dt^2} \cdot (dx^2 + dy^2) \cdot dt^2}$$

$$\gg\gg \qquad \sqrt{\frac{dx^2}{dt^2} + \frac{dy^2}{dt^2}} \cdot \sqrt{dt^2} \qquad \gg\gg \qquad \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2}\, dt$$

$$\gg\gg \qquad ds = \sqrt{x'(t)^2 + y'(t)^2}\, dt$$

So we obtain $ds = \sqrt{(x')^2 + (y')^2}\, dt$ and the arclength formula follows from this:

$$L = \int_a^b \sqrt{(x')^2 + (y')^2}\, dt$$

06 Illustration

Example - Perimeter of a circle

The perimeter of the circle $(R\cos t, R\sin t)$ is easily found. We have $(x', y') = (-R\sin t, R\cos t)$, and therefore:

$$(x')^2 + (y')^2 = (-R\sin t)^2 + (R\cos t)^2$$

$$\gg\gg \qquad R^2\sin^2 t + R^2\cos^2 t \qquad \gg\gg \qquad R^2$$

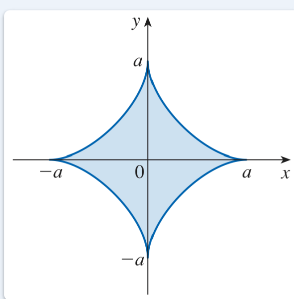
$$ds = \sqrt{(x')^2 + (y')^2}\,dt = R\,dt$$

Integrate around the circle:

$$\text{Perimeter} = \int_0^{2\pi} ds \qquad \gg\gg \qquad \int_0^{2\pi} R\,dt \qquad \gg\gg \qquad Rt\Big|_0^{2\pi} = 2\pi R$$

Example - Perimeter of an asteroid

Find the perimeter length of the 'asteroid' given parametrically by $(x, y) = \big(a\cos^3\theta,\, a\sin^3\theta\big)$ for $a = 2$.



Solution

Notice: Throughout this problem we use the parameter θ instead of t. This does *not* mean we are using polar coordinates!

Compute the derivatives in θ:

$$\big(x', y'\big) = \big(3a\cos^2\theta\sin\theta,\, 3a\sin^2\theta\cos\theta\big)$$

Compute the infinitesimal arc element:

- Compute the sums of squares:

$$(x')^2 + (y')^2 = 9a^2 \cos^4\theta \sin^2\theta + 9a^2 \sin^4\theta \cos^2\theta$$

$$\gg\gg \qquad 9a^2 \sin^2\theta \cos^2\theta \left(\cos^2\theta + \sin^2\theta\right)$$

$$\gg\gg \qquad 9a^2 \sin^2\theta \cos^2\theta$$

- Plug into the arc element, simplify:

$$ds = \sqrt{(x')^2 + (y')^2}\, d\theta = \sqrt{9a^2 \sin^2\theta \cos^2\theta}\, d\theta$$

$$\gg\gg \qquad ds = 3a \big| \sin\theta \cos\theta \big|\, d\theta$$

Determine the bounds: $\int_0^{\pi/2} ds$ for $1/4$ of the asteroid perimeter.

- The full asteroid requires $4\times$ the length of one edge.
- Notice: The term $\sin\theta\cos\theta$ in the ds formula becomes negative after $\pi/2$!
- Instead we integrate $\int_0^{\pi/2} ds$ and multiply by 4.
- On this interval $[0, \pi/2]$ we have $ds = 3a \sin\theta \cos\theta\, d\theta$.

Integrate the arc element:

$$\int_0^{\pi/2} ds = \int_0^{\pi/2} 3a \sin\theta \cos\theta\, d\theta$$

$$\gg\gg \qquad \frac{3a}{2} \int_0^{\pi/2} 2 \sin\theta \cos\theta\, d\theta \qquad \gg\gg \qquad \frac{3a}{2} \int_0^{\pi/2} \sin(2\theta)\, d\theta$$

$$\gg\gg \qquad -\frac{3a}{4} \cos(2\theta) \Big|_0^{\pi/2} \qquad \gg\gg \qquad -\frac{3a}{4}\big(\cos(\pi/2) - \cos(0)\big) \qquad \gg\gg \qquad \frac{3a}{4}$$

Multiply by 4:

$$\text{arclength} = L = 3a$$

07 Theory - Distance, speed

Distance function

The **distance function** $s(t)$ returns the total distance traveled by the particle from a chosen starting time t_0 up to the (input) time t:

$$s(t) \;=\; \int_{t_0}^{t} ds \quad = \quad \int_{t_0}^{t} \sqrt{x'(u)^2 + y'(u)^2}\, du$$

We need the dummy variable u so that the integration process does not conflict with t in the upper bound.

Speed function

The **speed** of a moving particle is the *rate of change of distance*:

$$v(t) \;=\; s'(t) \quad = \quad \sqrt{x'(t)^2 + y'(t)^2}$$

This formula can be explained in either of two ways:

1. Apply the Fundamental Theorem of Calculus to the integral formula for $s(t)$.
2. Consider $ds = \sqrt{x'(t)^2 + y'(t)^2}\,dt$ for a small change dt: so the *rate of change* of arclength is $\frac{ds}{dt}$, in other words $s'(t)$.

08 Illustration

Example - Speed, distance, displacement

The parametric curve $\left(t,\, \frac{2}{3}t^{3/2}\right)$ describes the position of a moving particle (t measuring seconds).

- (a) What is the speed function?

Suppose the particle travels for 8 seconds starting at $t = 0$.

- (b) What is the total distance traveled?
- (c) What is the total displacement?

Solution

(a)
Compute *derivatives*:

$$(x',\, y') = \left(1,\, t^{1/2}\right)$$

Compute the *speed*.

- Find sum of squares:

$$(x')^2 + (y')^2 = 1 + (t^{1/2})^2 = 1 + t$$

- Get the speed function:

$$v(t) = \sqrt{(x')^2 + (y')^2} = \sqrt{1+t}$$

(b)

Distance traveled by using *speed*.

- Compute total distance traveled function:

$$s(t) = \int_{u=0}^{t} \sqrt{1+u}\, du$$

Integrate.

- Substitute $w = 1 + u$ and $dw = du$.
- New bounds are 1 and $1 + t$.
- Calculate:

$$\gg\gg \quad \int_{1}^{1+t} \sqrt{w}\, dw \quad \gg\gg \quad \frac{2}{3} w^{3/2} \Big|_{1}^{1+t} \quad \gg\gg \quad \frac{2}{3}\left((1+t)^{3/2} - 1\right)$$

Insert $t = 8$ for the answer.

- The distance traveled up to $t = 8$ is:

$$s(8) = \frac{2}{3}\left(9^{3/2} - 1\right) \quad \gg\gg \quad \frac{2}{3}(27 - 1) \quad \gg\gg \quad \frac{52}{3}$$

- This is our final answer.

(c)

Displacement formula: $d = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2}$
- Pythagorean formula for distance between given points.

Compute starting and ending points.
- For starting point, insert $t = 0$:

$$\big(x(t), y(t)\big)\Big|_{t=0} \quad \gg\gg \quad \left(t, \frac{2}{3} t^{3/2}\right)\Big|_{t=0} \quad \gg\gg \quad (0, 0)$$

- For ending point, insert $t = 8$:

$$\big(x(t), y(t)\big)\Big|_{t=8} \quad \gg\gg \quad \left(t, \frac{2}{3} t^{3/2}\right)\Big|_{t=8} \quad \gg\gg \quad \left(8, \frac{2}{3} 8^{3/2}\right) \quad \gg\gg \quad \left(8, \frac{32\sqrt{2}}{3}\right)$$

Plug points into distance formula.

- Insert $(0,0)$ and $\left(8, 32\sqrt{2}/3\right)$:

$$\sqrt{8^2 + \left(\frac{32\sqrt{2}}{3}\right)^2} \quad \gg\gg \quad \sqrt{64 + \frac{2048}{9}} \quad \gg\gg \quad \frac{\sqrt{2624}}{3}$$

- This is our final answer.

09 Theory - Surface area of revolutions

Surface area of a surface of revolution: thin bands

Suppose a parametric curve $\big(x(t),\, y(t)\big)$ is revolved around the x-axis or the y-axis.

The surface area is:

$$A \quad = \quad \int_a^b 2\pi R(t)\sqrt{(x')^2 + (y')^2}\,dt$$

The radius $R(t)$ should be the distance to the axis:

$$\begin{aligned} R(t) &= y(t) \qquad \text{revolution about } x\text{-axis} \\ R(t) &= x(t) \qquad \text{revolution about } y\text{-axis} \end{aligned}$$

This formulas adds the areas of thin bands, but the bands are demarcated using parametric functions instead of input values of a graphed function.

The formula assumes that the curve is traversed one time as t increases from a to b.

10 Illustration

Example - Surface of revolution - parametric circle

By revolving the unit upper semicircle about the x-axis, we can compute the surface area of the unit sphere.

The parametrization of the unit upper semicircle is: $(x,y) = (\cos t,\, \sin t)$.

The derivative is: $(x', y') = (-\sin t,\, \cos t)$.

Therefore, the arc element:

$$ds = \sqrt{(x')^2 + (y')^2}\,dt \quad \gg\gg \quad \sqrt{(-\sin t)^2 + (\cos t)^2}\,dt \quad \gg\gg \quad dt$$

Now for R we choose $R = y(t) = \sin t$ because we are revolving about the x-axis.

Plugging all this into the integral formula and evaluating gives:

$$A = \int_0^{\pi} 2\pi \sin t\, dt \quad \gg\gg \quad -2\pi \cos t\Big|_0^{\pi} \quad \gg\gg \quad 4\pi$$

Notice: This method is a little easier than the method using the graph $y = \sqrt{1-x^2}$.

Example - Surface of revolution - parametric curve

Set up the integral which computes the surface area of the surface generated by revolving about the x-axis the curve (t^3, t^2-1) for $0 \leq t \leq 1$.

Solution

For revolution about the x-axis, we set $R = y(t) = t^2 - 1$.

Then compute ds:

$$ds = \sqrt{(x')^2 + (y')^2} \quad \gg\gg \quad \sqrt{(3t^2)^2 + (2t)^2} \quad \gg\gg \quad \sqrt{9t^4 + 4t^2}$$

$$\gg\gg \quad \sqrt{t^2(9t^2+4)} \quad \gg\gg \quad t\sqrt{9t^2+4}$$

Therefore the desired integral is:

$$A = \int_0^1 2\pi R\, ds \quad \gg\gg \quad \int_0^1 2\pi(t^2-1)t\sqrt{9t^2+4}\, dt$$