15 Vector Functions

15.1 Space Curves

We have already seen that a convenient way to describe a line in three dimensions is to provide a vector that "points to" every point on the line as a parameter t varies, like

\[(1,2,3) + t([-1, -2, 2]) = (1 + t, 2 - 2t, 3 + 2t).\]

Except that this gives a particularly simple geometric object, there is nothing special about the individual functions of t that make up the coordinates of this vector—any vector with a parameter, like \((f(t), g(t), h(t))\), will describe some curve in three dimensions as t varies through all possible values.

**EXAMPLE 15.1.1** Describe the curves \((\cos t, \sin t, 0)\), \((\cos t, \sin t, t)\), and \((\cos t, \sin t, 2t)\).

As t varies, the first two coordinates in all three functions trace out the points on the unit circle, starting with \((1,0)\) when \(t = 0\) and proceeding counterclockwise around the circle as t increases. In the first case, the z coordinate is always 0, so this describes precisely the unit circle in the x-y plane. In the second case, the x and y coordinates still describe a circle, but now the z coordinate varies, so that the height of the circle matches the value of t. When t = \(\pi\), for example, the resulting vector is \((-1,0,\pi)\). A bit of thought should convince you that the result is a helix. In the third vector, the z coordinate varies twice as fast as the parameter t, so we get a stretched out helix. Both are shown in figure 15.1.1. On the left is the first helix, shown for t between 0 and 4\(\pi\); on the right is the second helix, shown for t between 0 and 2\(\pi\). Both start and end at the same point, but the first helix takes two full "turns" to get there, because its z coordinate grows more slowly.

![Figure 15.1.1 Two helixes. (AP)](image)

A vector expression of the form \(f(t), g(t), h(t)\) is called a vector function; it is a function from the real numbers \(R\) to the set of all three-dimensional vectors. We can alternately think of it as three separate functions, \(x = f(t)\), \(y = g(t)\), and \(z = h(t)\), that describe points in space. In this case we usually refer to the set of equations as parametric equations for the curve, just as for a line. While the parameter t in a vector function might represent any one of a number of physical quantities, or be simply a "pure number", it is often convenient and useful to think of t as representing time. The vector function then tells you where in space a particular object is at any time.

Vector functions can be difficult to understand, that is, difficult to picture. When available, computer software can be very helpful. When working by hand, one useful approach is to consider the "projections" of the curve onto the three standard coordinate planes. We have already done this in part: in example 15.1.1 we noted that all three curves project to a circle in the x-y plane, since \((\cos t, \sin t)\) is a two-dimensional vector function for the unit circle.

**EXAMPLE 15.1.2** Graph the projections of \((\cos t, \sin t, 2t)\) onto the x-z plane and the y-z plane. The two dimensional vector function for the projection onto the x-z plane is \((\cos t, 2t)\), or in parametric form, \(x = \cos t, y = 2t\). By eliminating t we get the equation \(x = \cos z/2\), the familiar curve shown on the left in figure 15.1.2. For the projection onto the y-z plane, we start with the vector function \((\sin t, 2t)\), which is the same as \(y = \sin t, z = 2t\). Eliminating t gives \(y = \sin(z/2)\), as shown on the right in figure 15.1.2.

![Figure 15.1.2 The projections of \((\cos t, \sin t, 2t)\) onto the x-z and y-z planes.](image)

**Exercises 15.1.**

1. Describe the curve \(r(t) = \langle \cos t, \cos t, \cos t \rangle\).
2. Describe the curve \(r(t) = \langle \cos t, \sin t, t \rangle\).
3. Describe the curve \(r(t) = \langle t, t^2, \cos t \rangle\).
4. Describe the curve \(r(t) = \langle \cos(2t)/\sqrt{1 + \sin^2(2t)}, \sin(2t)/\sqrt{1 + \cos^2(2t)} \rangle\).
5. Find a vector function for the curve of intersection of \(x^2 + y^2 = 9\) and \(y + z = 2\).
6. A bug is crawling outward along the spokes of a wheel that lies along a radius of the wheel. The bug is crawling at 1 unit per second and the wheel is rotating at 1 radian per second. Suppose the wheel lies in the y-z plane with center at the origin, and at time \(t = 0\) the bug is at the origin. Find a vector function \(r(t)\) for the position of the bug at time \(t\).
7. What is the difference between the parametric curves \(f(t) = \langle t, t^2, t \rangle\) and \(g(t) = \langle t^2, t^3, t^4 \rangle\)?
8. Plot each of the curves below in two dimensions, projected onto each of the three standard planes (the x-y, x-z, and y-z planes).
   a. \(r(t) = \langle t, t^2, t^3 \rangle\); t ranges over all real numbers
   b. \(r(t) = \langle t^2, t, t^2 \rangle\); t ranges over all real numbers
9. Given points \(A = (a_1, a_2, a_3)\) and \(B = (b_1, b_2, b_3)\), give parametric equations for the line segment connecting A and B. Be sure to give appropriate \(t\) values.
10. With a parametric plot and a set of \(t\) values, we can associate a "direction". For example, the curve \((\cos t, \sin t)\) is the unit circle traced counterclockwise. How can we assign a set of given parametric equations and \(t\) values to get the same curve, only traced backwards?

15.2 Calculus with vector functions

A vector function \(r(t) = \langle f(t), g(t), h(t) \rangle\) is a function of one variable—that is, there is only one "input" value. What makes vector functions more complicated than the functions shown for \(t\) between 0 and 2\(\pi\). Both start and end at the same point, but the first helix takes two full "turns" to get there, because its z coordinate grows more slowly.
Unfortunately, the vector $\Delta r$ approaches 0 in length, the vector $(0, 0, 0)$ is not very informative. By dividing by $\Delta t$, when it is small, we effectively keep magnifying the length of $\Delta r$ so that in the limit it doesn’t disappear. Thus the limiting vector $(f'(t), g'(t), h'(t))$ will (usually) be a good, non-zero vector that is tangent to the curve.

What about the length of this vector? It’s nice that we’ve kept it away from zero, so that in the limit it doesn’t disappear. Thus the limiting vector

\[
\frac{r(t + \Delta t) - r(t)}{\Delta t}
\]

The numerator is the length of the vector that points from one position of the object to a “nearby” position; this length is approximately the distance traveled by the object between times $t$ and $t + \Delta t$. Dividing this distance by the length of time it takes to travel that distance gives the average speed. As $\Delta t$ approaches zero, this average speed approaches the actual, instantaneous speed of the object at time $t$.

So by performing a “obvious” calculation to get something that looks like the derivative of $r(t)$, we get precisely what we would want from such a derivative: the vector $r'(t)$ points in the direction of travel of the object and its length tells us the speed of travel. In some cases, we can still work with a unit vector in the same direction as $r'(t)$, as when we find the angle between two curves. On other occasions it will be useful to work with a unit vector that is tangent to the curve. In a sense, when we computed the angle between two tangent vectors we have already made use of the unit tangent vector.

**EXAMPLE 15.2.1** We have seen that $r = (\cos t, \sin t, t)$ is a helix. We compute $r' = (\cos t, \sin t, 1)$, and $|r'| = \sqrt{\sin^2 t + \cos^2 t + 1} = \sqrt{2}$. Thus the point of intersection is $t = \pi$. At $t = \pi$, we get precisely what we would want from such a derivative: the vector $r'(t)$ points in the direction of travel of the object and its length tells us the speed of travel. In the case that $t$ is time, then, we call $v(t) = r'(t)$ the velocity vector. Even if $t$ is not time, $r'(t)$ is useful—it is a vector tangent to the curve.

![Figure 15.2.2](image)

**Figure 15.2.2** A tangent vector on the helix. (AP)

**EXAMPLE 15.2.4** Find the angle between the curves $(1, t, t^2)$ and $(-1, -t, t^2)$ where they meet.

The angle between two curves at a point is the angle between their tangent vectors—any tangent vectors will do, so we can use the derivatives. We need to find the point of intersection, evaluate the two derivatives there, and finally find the angle between them.

To find the point of intersection, we need to solve the equations

\[
\begin{align*}
t &= 3 - u \\
1 - t &= u - 2 \\
3 + t^2 &= u^2
\end{align*}
\]

Solving either of the first two equations for $u$ and substituting in the third gives $3 + t^2 = (3 - t)^2$, which means $t = 1$. This together with $u = 2$ satisfies all three equations. Thus the two curves meet at $(1, 0, 0)$, the first when $t = 1$ and the second when $t = 2$.

The derivatives are $(1, -1, 2t)$ and $(-1, 1, 2t)$; at the intersection point these are $(1, -1, 2)$ and $(-1, 1, 4)$. The cosine of the angle between them is then

\[
\cos \theta = \frac{-1 - 1 + 8}{\sqrt{3} \sqrt{3}} = \frac{4}{3};
\]

so $\theta = \arccos(1/\sqrt{3}) \approx 0.96$.

The derivatives of vector functions obey some familiar looking rules, which we will occasionally need.

**THEOREM 15.2.5** Suppose $r(t)$ and $s(t)$ are differentiable functions, $f(t)$ is a differentiable function, and $a$ is a real number.

\[
\begin{align*}
a. \quad & \frac{d}{dt} (ar(t)) = ar'(t) \\
b. \quad & \frac{d}{dt} (r(t) + s(t)) = r'(t) + s'(t) \\
c. \quad & \frac{d}{dt} f(r(t)) = f'(r(t))r'(t) \\
d. \quad & \frac{d}{dt} (r(t) \cdot s(t)) = r'(t) \cdot s(t) + r(t) \cdot s'(t) \\
e. \quad & \frac{d}{dt} (r(t) \times s(t)) = r'(t) \times s(t) + r(t) \times s'(t) \\
f. \quad & \frac{d}{dt} (f(t)) = f'(f(t))f'(t)
\end{align*}
\]

**EXAMPLE 15.2.2 The velocity vector for $(\cos t, \sin t, \cos t)$ is $(-\sin t, \cos t, -\sin t)$. As before, the first two coordinates mean that from above this curve looks like a circle. The $z$ coordinate is now also periodic, so that as the object moves around the curve its height oscillates up and down. In fact it turns out that the curve is a tilted ellipse, as shown in figure 15.2.3.**

![Figure 15.2.3](image)

**EXAMPLE 15.2.3 The velocity vector for $(\cos t, \sin t, \sin 2t)$ is $(-\sin t, \cos t, -2\sin 2t)$. The $z$ coordinate is now oscillating twice as fast as in the previous example, so the graph is not surprising, see figure 15.2.4.**

![Figure 15.2.4](image)

**EXAMPLE 15.2.6 Suppose that $r(t) = (1 + t^2, t^2, 1)$, so $r'(t) = (2t^2, 2t, 0)$. This is $\mathbf{0}$ at $t = 0$, and there is indeed a cusp at the point $(1, 0, 1)$, as shown in figure 15.2.5.**

![Figure 15.2.5](image)

The angle between $r'(t)$ and $s'(t)$ is $\pi$ but not its length. In some cases, we can still work with $r'$, as when we find the angle between two curves. On other occasions, it will be useful to work with a unit vector in the same direction as $r'$; of course, we can compute such a vector by dividing $r'$ by its own length. This standard unit tangent vector is usually denoted by $T$.

\[
T = \frac{r'}{|r'|}
\]

In a sense, when we computed the angle between two tangent vectors we have already made use of the unit tangent, since

\[
\cos \theta = \frac{v \cdot u}{|v||u|} = \frac{v' \cdot u'}{|v'||u'|} = \frac{v' \cdot u'}{|v'|^2|u'|^2}
\]
Now that we know how to make sense of \( \mathbf{r}' \), we immediately know what an antiderivative must be, namely
\[
\int \mathbf{r}(t) \, dt = \int f(t) \, dt + \int g(t) \, dt + \int h(t) \, dt,
\]
if \( \mathbf{r} = (f(t), g(t), h(t)) \). What about definite integrals? Suppose that \( \mathbf{v}(t) \) gives the velocity of an object at time \( t \). Then \( \mathbf{v}(t) \, dt \) is a vector that approximates the displacement of the object over the time \( \Delta t \); \( \mathbf{v}(t) \, dt \) points in the direction of travel, and \( |\mathbf{v}(t) \, dt| = |\mathbf{v}(t)| \Delta t \) is the speed of the object times \( \Delta t \), which is approximately the distance traveled. Thus, if we sum up these tiny vectors:
\[
\sum_{i=0}^{n-1} \mathbf{v}(t_i) \Delta t
\]
we get an approximation to the displacement vector over the time interval \([t_0, t_n] \). If we take the limit we get the exact value of the displacement vector:
\[
\lim_{n \to \infty} \sum_{i=0}^{n-1} \mathbf{v}(t_i) \Delta t = \int_{t_0}^{t_n} \mathbf{v}(t) \, dt = \mathbf{r}(t_n) - \mathbf{r}(t_0).
\]

Denote \( \mathbf{r}(t_0) \) by \( \mathbf{a} \). Then given the velocity vector we can compute the vector function \( \mathbf{r} \) giving the location of the object:
\[
\mathbf{a} + \int_{t_0}^{t} \mathbf{v}(u) \, du.
\]

**EXAMPLE 15.2.7** An object moves with velocity vector \( \langle \cos t, \sin t, \cos t \rangle \), starting at \((1, 1, 1)\) at time 0. Find the function \( \mathbf{r} \) giving its location.

\[
\mathbf{r}(t) = \mathbf{a} + \int_{t_0}^{t} \mathbf{v}(u) \, du = (1 + \sin t, -
\cos u, \sin u) \du = (1, 1, 1) + \cos t, \sin t, \cos t \rangle \rightarrow (0, -1, 0) \rightarrow (1 + \sin t, 2 - \cos t, 1 + \sin t)\]

See figure 15.2.6.

13. Arc length and curvature

Sometimes it is useful to compute the length of a curve in space; for example, if the curve represents the path of a moving object, the length of the curve between two points may be the distance traveled by the object between those points.

Recall that if the curve is given by the vector function \( \mathbf{r} \) then the vector \( \Delta \mathbf{r} = \mathbf{r}(t + \Delta t) - \mathbf{r}(t) \) points from one position on the curve to another, as depicted in figure 15.2.1. If the points are close together, the length of \( \Delta \mathbf{r} \) is close to the length of the curve between the two points. If we add up the lengths of many such tiny vectors, placed head to tail along a segment of the curve, we get an approximation to the length of the curve over that segment. In the limit, as usual, this sum turns into an integral that computes precisely the length of the curve. First, note that,
\[
|\Delta \mathbf{r}| = |\Delta \mathbf{r}| = |\mathbf{r}'(t)| \Delta t,
\]
when \( \Delta t \) is small. Then the length of the curve between \( \mathbf{a} \) and \( \mathbf{b} \) is
\[
\lim_{n \to \infty} \sum_{i=0}^{n-1} |\Delta \mathbf{r}| = \lim_{n \to \infty} \sum_{i=0}^{n-1} |\mathbf{r}'(t)| \Delta t = \int_{a}^{b} |\mathbf{r}'(t)| \, dt.
\]
(Well, sometimes. This works if between \( a \) and \( b \) the segment of curve is traced out exactly once.)
EXAMPLE 15.3.4 Suppose $r(t) = (\cos t, \sin t, t)$. We know that this curve is a helix. The distance along the helix from (1, 0, 0) to (cos t, sin t, t) is

$$s = \int_0^t |r'(u)|\,du = \int_0^1 \sqrt{\cos^2 u + \sin^2 u + 1}\,du = \int_0^1 \sqrt{2}\,du = \sqrt{2}.$$ 

Thus, the value of $t$ that gives us distance $s$ along the helix is $t = s/\sqrt{2}$, and so the same curve is given by $r(s) = (\cos(s/\sqrt{2}), \sin(s/\sqrt{2}), s/\sqrt{2})$.

In general, if we have a vector function $r(t)$, to convert it to a vector function in terms of arc length we compute

$$s = \int_0^t |r'(u)|\,du = \int f(t).$$

solve $s = f(t)$ for $t$, getting $t = g(s)$, and substitute this back into $r(t)$ to get $r(s) = r(g(s))$.

Suppose that $t$ is time. By the Fundamental Theorem of Calculus, if we start with arc length

$$s(t) = \int_0^t |r'(u)|\,du$$

and take the derivative, we get

$$s'(t) = |r'(t)|.$$ 

Here $s'(t)$ is the rate at which the arc length is changing, and we have seen that $|r'(t)|$ is the speed of a moving object; these are of course the same.

Suppose that $r(s)$ is given in terms of arc length; what is $|r'(s)|$? It is the rate at which arc length is changing relative to arc length, it must be $1$. In the case of the helix, for example, the arc length parameterization is $r(s) = (\cos(s/\sqrt{2}), \sin(s/\sqrt{2}), s/\sqrt{2})$, the derivative is $(-\sin(s/\sqrt{2})/\sqrt{2}, \cos(s/\sqrt{2})/\sqrt{2}, 1/\sqrt{2})$, and the length of this is

$$\sqrt{\frac{\sin^2(s/\sqrt{2})}{2} + \frac{\cos^2(s/\sqrt{2})}{2} + \frac{1}{2}} = 1.$$ 

So in general, $r'$ is a unit tangent vector.

Given a curve $r(t)$, we would like to be able to measure, at various points, how sharply curved it is. Clearly this is related to how "fast" a tangent vector is changing direction, so a first guess might be that we can measure curvature with $|r''(t)|$. A little thought shows that this is flawed; if we think of $t$ as time, for example, we could be tracing out the curve more or less quickly as time passes. The second derivative $|r''(t)|$ incorporates this notion of time, so it depends not simply on the geometric properties of the curve but on how quickly we move along the curve.

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everywhere the inverse of the radius. It is sometimes useful to think of curvature as describing what a circle a curve most resembles at a point. The curvature of the helix in the previous example is $1/2$; this means that a small piece of the helix looks very much like a circle of radius 2, as shown in figure 15.3.1.

Figure 15.3.1. A circle with the same curvature as the helix. (AP)

EXAMPLE 15.3.9 Consider $r(t) = (\cos t, \sin t, 2t)$, as shown in figure 15.2.4. $r'(t) = (-\sin t, \cos t, 2)$, and $|r'(t)| = \sqrt{1 + 4\sin^2(2t)}$, so

$$T(t) = \frac{-\sin t}{\sqrt{1 + 4\sin^2(2t)}} \frac{\cos t}{\sqrt{1 + 4\sin^2(2t)}} \frac{2}{\sqrt{1 + 4\sin^2(2t)}}.$$

Computing the derivative of this and then the length of the resulting vector is possible but unpleasant.

Fortunately, there is an alternate formula for the curvature that is often simpler than the one we have

$$\kappa = \frac{|r'(t) \times r''(t)|}{|r'(t)|^3}.$$ 

EXAMPLE 15.3.10 Returning to the previous example, we compute the second derivative $r''(t) = (-\cos t, -\sin t, -4\cos(2t))$. Then the cross product $r'(t) \times r''(t)$ is

$$\{-4 \cos t \cos 2t - 2 \sin t \sin 2t, 2 \cos t \sin 2t - 4 \sin t \cos 2t, 1\}.$$ 

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EXAMPLE 15.3.5 Consider $r(t) = (\cos t, \sin t, 0)$ and $r(t) = (\cos 2t, \sin 2t, 0)$. Both of these vector functions represent the unit circle in the $x$-$y$ plane, but if $t$ is interpreted as time, the second describes an object moving twice as fast as the first. Computing the second derivatives, we find $|r'(t)| = 1$, $|r''(t)| = 4$.

To remove the dependence on time, we use the arc length parameterization. If a curve is given by $r(t)$, then the first derivative $r'(t)$ is a unit vector, that is, $r'(t) = T(t)$. We now compute the second derivative $r''(t) = T'(t)$ and use $|T'(t)|$ as the "official" measure of curvature, usually denoted $\kappa$.

EXAMPLE 15.3.6 We have seen that the arc length parameterization of a particular helix is $r(s) = (\cos(s/\sqrt{2}), \sin(s/\sqrt{2}), s/\sqrt{2})$. Computing the second derivative gives $r''(s) = (-\cos(s/\sqrt{2})/\sqrt{2}, -\sin(s/\sqrt{2})/\sqrt{2}, 1/\sqrt{2})$ with length $1/2$.

What if we are given a curve as a vector function $r(t)$, where $t$ is not arc length? We have seen that arc length can be difficult to compute; fortunately, we do not need to convert to the arc length parameterization to compute curvature. Instead, let us imagine that we have done this, so we have found $s = g(t)$ and then formed $r(s) = r(g(t))$. The first derivative $r'(s)$ is a unit tangent vector, so it is the same as the unit tangent vector $T(t) = T(g(t))$. Taking the derivative of this we get

$$\frac{dT}{ds} = T'(g(t)) = T'(t)|g'(t)|.$$ 

The curvature is the length of this vector:

$$\kappa = \frac{|dT|}{ds} = \frac{|T'(g(t))|}{|g'(t)|}.$$ 

(Recall that we have seen that $ds/dt = |r'(t)|$.) Thus we can compute the curvature by computing only derivatives with respect to $t$; we do not need to do the conversion to arc length.

EXAMPLE 15.3.7 Returning to the helix, suppose we start with the parameterization $r(t) = (\cos t, \sin t, t)$. Then $r'(t) = (-\sin t, \cos t, 1)$, $|r'(t)| = \sqrt{2}$, and $T(t) = (-\sin t, \cos t, 1)/\sqrt{2}$. Then $T'(t) = (-\cos t, -\sin t, 0)/\sqrt{2}$ and $|T'(t)| = 1/\sqrt{2}$. Finally, $\kappa = 1/\sqrt{2}$. We know that this curve is a helix.

EXAMPLE 15.3.8 Consider this circle of radius $a$: $r(t) = (a \cos t, a \sin t, 1)$. Then $r'(t) = (-a \sin t, a \cos t, 0)$, $|r'(t)| = a$, and $T(t) = (-a \sin t, a \cos t, 0)/a$. Now $T'(t) = (-a \cos t, -a \sin t, 0)/a$ and $|T'(t)| = 1$. Finally, $\kappa = 1/a$; the curvature of a circle is

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Computing the length of this vector and dividing by $|r'(t)|$ is still a bit tedious. With the aid of a computer we get

$$\kappa = \frac{\sqrt{4 \cos^2 t + 4 \sin^2 t}}{\sqrt{4 \cos^4 t + 16 \cos^2 t + 1}}.$$ 

Graphing this we get

Compare this to figure 15.2.4— you may want to load the Java applet there so that you can see it from different angles. The highest curvature occurs where the curve has its highest and lowest points, and indeed in the picture these appear to be the most sharply curved portions of the curve, while the curve is almost a straight line midway between those points.

Here’s a way to simplify the equation for curvature. Starting with the definition of $T$, $r' = |r'|T$ so by the product rule $r'' = |r'|'T + |r'|T'$. Then by Theorem 14.4.1 the cross product is

$$r' \times r'' = |r'|T \times (|r'|T') = |r'|^2 (T \times T') = |r'|^2 (T \times T') = 0,$$

because $T \times T = 0$, since $T$ is parallel to itself. Then

$$y' = \frac{r''}{r'} = \frac{|r'|^2 (T \times T')}{|r'|^2} = \frac{|r'|^2 T \times T'}{\sin \theta} = \frac{|r'|^2 T}{\sin \theta},$$

where $\theta = \arccos(|r'|)$. Dividing both sides by $|r'|$ then gives the desired formula.

We used the fact here that $T'$ is perpendicular to $T$; the vector $N = T'/(|T'|)$ is thus a unit vector perpendicular to $T$, called the unit normal to the curve. Occasionally of use is the unit binormal $B = T \times N$, a unit vector perpendicular to both $T$ and $N$. 

Exercises 15.3.
1. Find the length of \( \langle 3 \cos t, 2t, 3 \sin t \rangle \), \( t \in [0, 2\pi] \).
2. Find the length of \( \langle t^2, 2t, t^3 \rangle \), \( t \in [0, 1] \).
3. Find the length of \( \langle t^2, \sin t, \cos t \rangle \), \( t \in [0, 1] \).
4. Find the length of the curve \( y = x^3 \), \( x \in [1, 2] \).
5. Set up an integral to compute the length of \( \langle \cos t, \sin t, t^2 \rangle \), \( t \in [0, 2] \). (It is tedious but not too difficult to compute this integral.)
6. Find the curvature of \( \langle x^2, t \rangle \).
7. Find the curvature of \( \langle x^2, t \rangle \).
8. Find the curvature of \( \langle x^2, t \rangle \).
9. Find the curvature of \( y = x^4 \) at \( (1, 1) \).

15.4 Motion along a Curve

We have already seen that if \( t \) is time and an object’s location is given by \( \mathbf{r}(t) \), then the derivative \( \mathbf{r}'(t) \) is the velocity vector \( \mathbf{v}(t) \). Just as \( \mathbf{v}(t) \) is a vector describing how \( \mathbf{r}(t) \) changes, so is \( \mathbf{v}'(t) \) a vector describing how \( \mathbf{v}(t) \) changes, namely, \( \mathbf{a}(t) = \mathbf{v}'(t) = \mathbf{r}''(t) \) is the acceleration vector.

Example 15.4.1 Suppose \( \mathbf{r}(t) = \langle \cos t, \sin t, 1 \rangle \). Then \( \mathbf{v}(t) = \langle -\sin t, \cos t, 0 \rangle \) and \( \mathbf{a}(t) = \langle -\cos t, -\sin t, 0 \rangle \). This describes the motion of an object traveling on a circle of radius 1, with constant \( z \) coordinate 1. The velocity vector is of course tangent to the curve; note that \( \mathbf{a} = 0 \), so \( \mathbf{v} \) and \( \mathbf{a} \) are perpendicular. In fact, it is not hard to see that \( \mathbf{a} \) points from the location of the object to the center of the circular path at \( (0, 0, 1) \).

Recall that the unit tangent vector is given by \( \mathbf{T}(t) = \mathbf{v}(t)/|\mathbf{v}(t)| \), \( \mathbf{v} = |\mathbf{T}| \). If we take the derivative of both sides of this equation we get

\[
a = \frac{|\mathbf{v}|}{|\mathbf{T}|} \mathbf{v} \times \mathbf{T}.
\]

(15.4.1)

Also recall the definition of the curvature, \( \kappa = |\mathbf{T}'|/|\mathbf{v}| \), or \( |\mathbf{T}'| = \kappa |\mathbf{v}| \). Finally, recall that we defined the unit normal vector as \( \mathbf{N} = \mathbf{T}'/|\mathbf{T}'| \), so \( \mathbf{T}' = |\mathbf{N}| = \kappa |\mathbf{v}| \mathbf{N} \). Substituting into equation 15.4.1 we get

\[
a = |\mathbf{v}| \mathbf{T} + \kappa |\mathbf{v}| \mathbf{N} \cdot a = \mathbf{T}' + \kappa \mathbf{N}.
\]

(15.4.2)

The quantity \( |\mathbf{v}| \) is the speed of the object, often written as \( s(t) \); \( |\mathbf{v}'(t)| \) is the rate at which the speed is changing, or the scalar acceleration of the object, \( a(t) \). Rewriting equation 15.4.2 with these gives us

\[
a = s \mathbf{T} + \kappa |\mathbf{v}| \mathbf{N} = s \mathbf{T} + \kappa \mathbf{N}.
\]

\( s \mathbf{T} \) is the tangential component of acceleration and \( \kappa \mathbf{N} \) is the normal component of acceleration. We have already seen that \( s \mathbf{T} \) measures how the speed is changing; if you are riding in a vehicle with large \( s \mathbf{T} \) you will feel a force pulling you into your seat. The other component, \( \kappa \mathbf{N} \), measures how sharply your direction is changing with respect to time. So it naturally is related to how sharply the path is curved, measured by \( \kappa \), and also to how fast you are going. Because \( \kappa \mathbf{N} \) includes \( v^2 \), note that the effect of speed is magnified, doubling your speed around a curve quadruples the value of \( \kappa \mathbf{N} \). You feel the effect of this as a force pushing you toward the outside of the curve, the “centripetal force.”

In practice, if want \( \kappa \mathbf{N} \) we would use the formula for \( \kappa \):

\[
a_N = \kappa |\mathbf{v}|^2 = \frac{|\mathbf{v}' \times \mathbf{v}''|}{|\mathbf{v}'|^2} \cdot |\mathbf{v}'| = \frac{|\mathbf{v}' \times \mathbf{v}''|}{|\mathbf{v}'|^3}.
\]

To compute \( s \mathbf{T} \) we can project \( a \) onto \( \mathbf{v} \):

\[
s_T = \frac{\mathbf{v} \cdot a}{|\mathbf{v}|} = \frac{\mathbf{v}' \cdot \mathbf{v}''}{|\mathbf{v}'|^2}.
\]

Example 15.4.2 Suppose \( \mathbf{r} = \langle t^3, t^2, t^4 \rangle \). Compute \( a \), \( a_T \), and \( a_N \).

Taking derivatives we get \( \mathbf{v} = \langle 3t^2, 2t, 4t^3 \rangle \) and \( \mathbf{a} = \langle 6t, 2, 12t^2 \rangle \). Then

\[
a_T = \frac{36t^3 + 6t^2}{\sqrt{1 + 4t^2 + 36t^4}} \quad \text{and} \quad a_N = \frac{\sqrt{1 + 4t^2 + 36t^4}}{\sqrt{1 + 4t^2 + 36t^4}}.
\]

Exercises 15.4.

1. Let \( \mathbf{r} = \langle \cos t, \sin t, t \rangle \). Compute \( \mathbf{v} \), \( a \), \( a_T \), and \( a_N \).
2. Let \( \mathbf{r} = \langle \cos t, \sin t, t^2 \rangle \). Compute \( \mathbf{v} \), \( a \), \( a_T \), and \( a_N \).
3. Let \( \mathbf{r} = \langle \cos t, \sin t, t^3 \rangle \). Compute \( \mathbf{v} \), \( a \), \( a_T \), and \( a_N \).
4. Let \( \mathbf{r} = \langle t^4, t^2, t^5 \rangle \). Compute \( \mathbf{v} \), \( a \), \( a_T \), and \( a_N \).
5. Suppose an object moves so that its acceleration is given by \( a = \langle -1 - 3 \cos t, -2 \sin t, 0 \rangle \). At time \( t = 0 \) the object is at \( (3, 0, 0) \) and its velocity vector is \( (0, 2, 0) \). Find \( \mathbf{v}(t) \) and \( \mathbf{r}(t) \) for the object.
6. Suppose an object moves so that its acceleration is given by \( a = \langle -1 - 3 \cos t, -2 \sin t, 0 \rangle \). At time \( t = 0 \) the object is at \( (3, 0, 0) \) and its velocity vector is \( (0, 2, 1) \). Find \( \mathbf{v}(t) \) and \( \mathbf{r}(t) \) for the object.
7. Suppose an object moves so that its acceleration is given by \( a = \langle -1 - 3 \cos t, -2 \sin t, 0 \rangle \). At time \( t = 0 \) the object is at \( (3, 0, 0) \) and its velocity vector is \( (0, 2, 1) \). Find \( \mathbf{v}(t) \) and \( \mathbf{r}(t) \) for the object.
8. Suppose an object moves so that its acceleration is given by \( a = \langle -1 - 3 \cos t, -2 \sin t, 0 \rangle \). At time \( t = 0 \) the object is at \( (3, 0, 0) \) and its velocity vector is \( (0, 2, 1) \). Find \( \mathbf{v}(t) \) and \( \mathbf{r}(t) \) for the object.

9. Describe a situation in which the normal component of acceleration is 0 and the tangential component of acceleration is non-zero. Is it possible for the tangential component of acceleration to be 0 while the normal component of acceleration is non-zero? Explain. Finally, is it possible for an object to move (not be stationary) so that both the tangential and normal components of acceleration are 0°? Explain.