

# Calculus III

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# Contents

<b>1</b>	<b>Introduction</b>	<b>5</b>
<b>2</b>	<b>Linear Algebra Fundamentals</b>	<b>7</b>
<b>2.1</b>	<b>Vectors</b>	<b>7</b>
2.1.1	Important operations . . . . .	7
2.1.2	Properties . . . . .	10
<b>2.2</b>	<b>Lines</b>	<b>10</b>
2.2.1	Lines in $\mathbb{R}^n$ . . . . .	11
<b>2.3</b>	<b>Planes</b>	<b>12</b>
<b>3</b>	<b>Non-Linear Fundamentals</b>	<b>15</b>
<b>3.1</b>	<b>Polar and Cylindrical Coordinates</b>	<b>15</b>
3.1.1	Cylindrical coordinates . . . . .	15
3.1.2	Spherical coordinates . . . . .	16
<b>3.2</b>	<b>Scalar Functions</b>	<b>17</b>
<b>3.3</b>	<b>Surface Curves</b>	<b>17</b>
<b>3.4</b>	<b>Limits and Continuity</b>	<b>18</b>
3.4.1	Polar Coordinates for limits . . . . .	19





# 1. Introduction

This is the persons i took the course with, they speak mostly spanish but they might help you!

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## 2. Linear Algebra Fundamentals

In order to understand the concepts present in this module of calculus, a few preliminary concepts in the realm of Linear Algebra are necessary, in order to not leave anybody lost, we'll be reviewing those topics.

### 2.1 Vectors

#### 2.1.1 Important operations

##### Addition and Subtraction

Not much mystery to it, you can add and subtract the components in two different vectors:

$$\begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} + \begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix} = \begin{pmatrix} x_1 + x_2 \\ y_1 + y_2 \\ z_1 + z_2 \end{pmatrix}$$

##### Dot Product

We can get a scalar product from the multiplication of the elements two vectors have

$$\begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} \cdot \begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix} = x_1x_2 + y_1y_2 + z_1z_2$$

This can also be written as:

$$\langle \vec{u}, \vec{v} \rangle \tag{2.1}$$

##### Properties

- Dot product is commutative:  $\vec{u} \cdot \vec{v} = \vec{v} \cdot \vec{u}$
- $\vec{u} \cdot \vec{v} = 0 \iff \vec{u} \perp \vec{v}$

- $\vec{u} \cdot \vec{v} = ||\vec{u}|| ||\vec{v}|| \cos \theta$
- Cauchy Schwartz inequality:  $|\vec{u} \cdot \vec{v}| \leq ||\vec{u}|| ||\vec{v}||$
- $\vec{u} \cdot \vec{u} = ||\vec{u}||^2$

### Cross product

Another form to multiply vectors, while getting another vector, is the cross product which we define as:

$$\begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} \times \begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix} = \begin{pmatrix} y_1 z_2 - z_1 y_2 \\ -(x_1 z_2 - z_1 x_2) \\ x_1 y_2 - y_1 x_2 \end{pmatrix}$$

This specific operation cannot be done in dimensions that exceed  $\mathbb{R}^3$  and can't be considered formally the multiplication of two vectors when the system is managed in  $\mathbb{R}^n | n > 4$ . This course, however, is mostly managed for systems at most in 3 dimensions, hyperplanes will probably be tangentially asked about depending on the professor, but I wouldn't count on it.

### Properties

Cross product operations have a few specific things that can happen.

- $\vec{u} \times \vec{v} = -\vec{v} \times \vec{u}$
- $\vec{u} \times \vec{v} \perp \vec{u} \wedge \vec{u} \times \vec{v} \perp \vec{v}$
- $\vec{v} \times \vec{u} = 0 \implies \vec{u} / \vec{v}$
- $||\vec{u} \times \vec{v}|| = \text{Surface}$

### Example

Calculate the plane equation that includes the points:

$$\vec{P} = (2, 0, 0) \tag{2.2}$$

$$\vec{Q} = (0, 1, 0) \tag{2.3}$$

$$\vec{R} = (0, 0, 3) \tag{2.4}$$

### Solution

First of all, we'll do a normal vector via the cross product. First, we'll need two vectors  $\vec{PQ}$  and  $\vec{PR}$  via vector subtraction:

$$\vec{PR} = \begin{pmatrix} 0 \\ 0 \\ 3 \end{pmatrix} - \begin{pmatrix} 2 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} -2 \\ 0 \\ 3 \end{pmatrix} \tag{2.5}$$

$$\vec{PQ} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} - \begin{pmatrix} 2 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} -2 \\ 1 \\ 0 \end{pmatrix} \tag{2.6}$$

And now, we can generate a cross product for these two mathematical objects, this should give us a vector normal to both:

$$\vec{PQ} \times \vec{PR} = \begin{pmatrix} -2 \\ 1 \\ 0 \end{pmatrix} \times \begin{pmatrix} -2 \\ 0 \\ 3 \end{pmatrix} = \quad (2.7)$$

### Example 2

Find the Area of the triangle generated by the points:

$$\vec{P} = (2, 0, 0) \quad (2.8)$$

$$\vec{Q} = (0, 1, 0) \quad (2.9)$$

$$\vec{R} = (0, 0, 3) \quad (2.10)$$

For this, we can use the property of cross products being able to calculate a surface area to assume the way we can calculate a triangle from it:

$$A_{\triangle} = \frac{||\vec{PQ} \times \vec{PR}||}{2} \quad (2.11)$$

As given by our last example, then:

$$A_{\triangle} = \frac{||(3, 6, 2)||}{2} = \frac{\sqrt{3^2 + 6^2 + 2^2}}{2} = \frac{\sqrt{9 + 36 + 4}}{2} = \frac{7}{2} \quad (2.12)$$

### Projection

A projection is the vector that can be found from making

$$Proj_{\vec{u}}(\vec{v}) = \alpha \vec{u} \quad (2.13)$$

This has the following properties:

- $\vec{v} - \alpha \vec{u} \perp \vec{u}$
- $\frac{\vec{u} \cdot \vec{v}}{||\vec{u}||^2} = \alpha$

We can also imagine the projection as:

$$Proj_{\vec{u}}(\vec{v}) = \left( \frac{\vec{u} \cdot \vec{v}}{||\vec{u}||^2} \right) \vec{u} \quad (2.14)$$

### Example

Given:

$$\vec{u} = x + y = 3 \quad (2.15)$$

$$\vec{v} = x + y = 1 \quad (2.16)$$

What is the distance between both lines?

**Solution**

For this we can check for the smallest distance between points, and since they are perpendicular to each other:

$$\min d(\vec{v}, \vec{u}) = d(\vec{v}, \vec{u}) \quad (2.17)$$

lets instantiate the lines in a moment in time where they are both crossing the x axis:

$$P = (0, 1) \quad (2.18)$$

$$Q = (0, 3) \quad (2.19)$$

### 2.1.2 Properties

- two vectors are parallel if one is a multiple of the other, such as:

$$\vec{v} = d\vec{w}; d \in \mathbb{R}$$

- The angle between two vectors can be defined as such:

$$\vec{v} \cdot \vec{w} = ||\vec{v}|| ||\vec{w}|| \cos \theta$$

If this operation is 0, then the two vectors are orthogonal (parallel) to each other.

- The cross product of two vectors is perpendicular to both vectors that generated it.

## 2.2 Lines

A line is simply a mathematical object of the form  $y = mx + b$  that unites two points in the space we're using, through a straight path, where  $b$  is the cutting point in  $x=0$ . and  $m$  is  $\tan \alpha$ , or the slope of this line. We can imagine it as:

$$m = \frac{y_1 - y_0}{x_1 - x_0} \quad (2.20)$$

$$(2.21)$$

another equation of this object is, when working on  $\mathbb{R}^2$  is defined as:

$$ax + by = c \quad (2.22)$$

The reason this sort of expression is so useful, is because this **is a general form**. In other words, we can define with this system every single possible line in  $\mathbb{R}^2$ . For example, let's imagine a line that is perfectly vertical. Such as it can be explained, intuitively, as  $x = 1$ :

This vector can't be expressed through formula 1,1 or  $y = mx + b$ , because it wouldn't cross the '0' axis, and it would have an infinite slope. But if we arrange it through (1,2), we can say:

$$ax + by = c \quad (2.23)$$

$$by = c - ax \quad (2.24)$$

$$y = \frac{c}{b} + \frac{a}{b}x \quad (2.25)$$

We can suppose  $\frac{c}{b}$  as the cutting point with y, and then imagine  $\frac{a}{b}$  as 'm', we can then, use an example where we set 'b' to be 0 and define a situation where  $x = 1$ .

### 2.2.1 Lines in $\mathbb{R}^n$

We can define lines in more dimensions than  $\mathbb{R}^2$  through different forms. For example, we can imagine it as a parametric equation of the form:

$$p = t\vec{v} \quad (2.26)$$

#### Example 2.2.1

Find the parametric equation that passes through  $p = (1,2,3)$  and is parallel to the vector  $(1,0,-1)$

*Solution*

$$\begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} + t \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} \quad (2.27)$$

With this form, we can imagine that the solution actually is producing 3 different equations, and every single one defines how this object will behave in a different dimension.

therefore:

$$x(t) = 1 + t \quad (2.28)$$

$$y(t) = 2 \quad (2.29)$$

$$z(t) = 3 - t \quad (2.30)$$

Pretty neat, huh?

We can define such an equation in 'n' dimensions that can define a line going through be it a plane or a hyperplane like this. We only need two vectors of the same 'n' dimension. So, taking this form, can we express it in other ways? Well, yeah! ...and we just did. The before introduced equations can be called **the parametric equation of a line**. the equation we generated

From here, we can also imagine that instead of using such a form, we can also equate everything to 't' and from here, we'll start defining a **Symmetrical form of the line**.

In the previous example, we can imagine:

$$x - 1 = y - 2 = \frac{z - 3}{-1} = t \quad (2.31)$$

### 2.3 Planes

The plane can be defined as:

$$ax + by + cz = d \quad (2.32)$$

This plane can be defined with a point and a vector, for example:

**Example 2.3.1**

given  $\vec{PQ} = (x, y, z)$  and  $\vec{R} = (a, b, c)$ , define a plane.

*Solution*

$$\begin{pmatrix} x - x_0 \\ y - y_0 \\ z - z_0 \end{pmatrix} \cdot \begin{pmatrix} a \\ b \\ c \end{pmatrix} = 0 \quad (2.33)$$

$$a(x - x_0) + b(y - y_0) + c(z - z_0) = 0 \quad (2.34)$$

$$ax - ax_0 + by - by_0 + cz - cz_0 = 0 \quad (2.35)$$

$$ax + by + cz = ax_0 + by_0 + cz_0 \quad (2.36)$$

$$< d = ax_0 + by_0 + cz_0 > \quad (2.37)$$

$$ax + by + cz = d \quad (2.38)$$

And from there we can define basically every plane in  $\mathbb{R}^3$ , as you can see, we arrived to the way we defined a plane in this dimension, and we could in theory, decide in a random point, a random vector, and start working from there into defining a plane. But now, can we define a parametric equation of a plane, as we did with a line?

Well, the answer is yes.

the parametric form of a plane is actually pretty simple, as it is supremely similar to the one that defines a line, and is defined as:

$$p + s\vec{v}_1 + t\vec{v}_2 \quad (2.39)$$

if we generalize this into a system where  $R = (1,2,3)$ ,  $v_1 = (1,0,1)$  and  $v_2 = (1,1,0)$  we can do a little example, written as:

$$\begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} + s \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} + t \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} \quad (2.40)$$

**Example 2.3.2**

Determine if the line

$$x = 9 + 5t \quad (2.41)$$

$$y = -3 + t \quad (2.42)$$

$$z = 4t \quad (2.43)$$

Intersects with the plane

$$3x + 10y - 2z + 53 \quad (2.44)$$

If so, determine where.

**Solution**

We can begin by replacing. Remember the line's equation and how it has x, y and z values. **These values are equivalent to x, y and z in a plane**, and how you can replace it in the plane's equation.

If we can solve the equation for 't', that means we can intersect that line with the plane and that it will intersect in that specific 't' point

$$3(9 + 5t) + 10(-3 + t) - 2(4t) = 53 \quad (2.45)$$

$$27 + 15t - 30 + 10t - 8t = 53 \quad (2.46)$$

$$t = \frac{56}{16} \quad (2.47)$$

### Plane from 3 points in the space

#### Example 2.3.3

Find the line normal to the plane that crosses the points:

$$P = (0, -3, -3) \quad (2.48)$$

$$Q = (-3, 0, -3) \quad (2.49)$$

$$R = (-3, 3, 0) \quad (2.50)$$

**Solution** We'll begin by getting two vectors from these lines, we can get them by subtracting one point from the other:

$$\vec{PQ} = (-3, 3, 0) \quad (2.51)$$

$$\vec{QR} = (0, -3, 3) \quad (2.52)$$

And now, we'll make a cross product between the two, so we can get a normal vector:

$$\vec{PQ} \times \vec{QR} = \begin{pmatrix} -3 \\ 3 \\ 0 \end{pmatrix} \times \begin{pmatrix} 0 \\ -3 \\ 3 \end{pmatrix} = \begin{pmatrix} 9 \\ 9 \\ 9 \end{pmatrix} = \vec{n} \quad (2.53)$$

Now, we can get from that normal vector, the direction vector for the line:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} 0 \\ -3 \\ -3 \end{pmatrix} + t \begin{pmatrix} 9 \\ 9 \\ 9 \end{pmatrix} \quad (2.54)$$



## 3. Non-Linear Fundamentals

### 3.1 Polar and Cylindrical Coordinates

During the course, we'll be managing non-linear systems and such systems will require managing reference systems that are non-cartesian. When trying to define parts of a line in algebra, we'll usually be looking at coordinates, be them polar or cartesian. In either case, their information can be converted to the other system through the following formulas.

$$\begin{cases} \rho = \sqrt{x^2 + y^2} \\ \theta = \arctan\left(\frac{y}{x}\right) \end{cases} \quad \text{cartesian to polar} \quad (3.1)$$

$$\begin{cases} x = \rho \cos \theta \\ y = \rho \sin \theta \end{cases} \quad \text{polar to cartesian} \quad (3.2)$$

Cartesian coordinates generally translate well to other dimensional spaces, such as would be the case for  $\mathbb{R}^3$ , however, polar coordinates as we know them usually aren't as translatable in a direct manner, and expressing them in three-dimensional spaces might be better suited to be expressed on a cylindrical or spherical condition.

#### 3.1.1 Cylindrical coordinates

In the case of cylindrical coordinates, the translation is probably the most intuitive, by computing a cylinder with polar coordinates that indicate an (x,y) position, and a 'Z' variable indicating height that allows us to project the vector on a third dimension, this 'z' variable is exactly the same as it would be on a cartesian model. We can express it like such:

$$\vec{v} = (\rho, \theta, Z)$$

conversion to a cartesian model can be expressed as:

$$\vec{\alpha} = \begin{cases} \alpha_x = \rho \cos \theta \\ \alpha_y = \rho \sin \theta \\ \alpha_z = Z \end{cases} \quad \text{Cylindrical to cartesian} \quad (3.3)$$

$$\vec{\alpha} = \begin{cases} \rho = \sqrt{x^2 + y^2} \\ \theta = \arctan(\frac{y}{x}) \\ Z = Z \end{cases} \quad \text{Cartesian to Cylindrical} \quad (3.4)$$

These coordinates might be useful to visualize circular functions, such as curves that take a cylindrical, spring-like form.

### 3.1.2 Spherical coordinates

A spherical coordinate is formed by a tuple:

$$(\rho, \theta, \phi); \begin{cases} \rho \geq 0 \\ 0 \leq \theta \leq 2\pi \\ 0 \leq \phi \leq \pi \end{cases} \quad (3.5)$$

Where  $\rho$  is the magnitude of the vector,  $\theta$  is the (x,y) coordinates, and  $\phi$  is the (y,z) angle. They must adhere to the following for it to be geometrically coherent:

$$\begin{cases} \rho > 0 \\ 0 \leq \phi \leq \pi \\ 0 \leq \theta \leq 2\pi \end{cases} \quad (3.6)$$

this tuple can generate two vectors:

$$\begin{cases} \rho \sin \phi \\ \rho \end{cases} \quad (3.7)$$

And can be converted to a cartesian model as such:

$$\vec{\alpha} = \begin{cases} \alpha_x = \rho \sin \phi \cos \theta \\ \alpha_y = \rho \sin \phi \sin \theta \\ \alpha_z = \rho \cos \phi \end{cases} \quad \text{Spherical to cartesian} \quad (3.8)$$

$$\vec{\alpha} = \begin{cases} \rho = \sqrt{x^2 + y^2 + z^2} \\ \theta = \arctan(\frac{y}{x}) \\ \phi = \arccos(\frac{z}{\sqrt{x^2 + y^2 + z^2}}) \end{cases} \quad \text{Cartesian to Spherical} \quad (3.9)$$

These are, of course, pretty useful to visualize spherical objects, but conic objects can also be easily expressed with this reference system.

### 3.2 Scalar Functions

For this course, there are moments in which we might manage more than a single variable on a single mathematical expression. We can imagine that there are functions can be defined as:

$$f(x_1, \dots, x_n) \underset{\text{Domain}}{\underbrace{U}} : \mathbb{R}^n \rightarrow \mathbb{R} \quad (3.10)$$

This basically means, they project from a specific dimension to a point in  $\mathbb{R}$ .

Examples for this sort of function in  $\mathbb{R}^2$  include:

$$f(x, y) = x + y \quad (3.11)$$

$$f(x, y) = x^2 + y^2 \quad (3.12)$$

$$f(x, y) = e^{x^2 y + y} \quad (3.13)$$

We're going to like  $\mathbb{R}^2$  expressions on this course because they allow us to think of those functions in terms of a graphical representation on  $\mathbb{R}^3$ .  $z$  will depend on both variables. We write this formally as:

$$\{(x, y, z) \in \mathbb{R}^3 | z = f(x, y)\} \quad (3.14)$$

### 3.3 Surface Curves

A surface curve, as defined for  $\mathbb{R}^3$ , can be defined as sets of the form:

$$\{(x, y) \in \mathbb{R}^2 | f(x, y) = \text{constant}\} \quad (3.15)$$

A surface curve can be defined with the value 'k' as:

$$\{(x, y) \in \mathbb{R}^2 | f(x, y) = k\} \quad (3.16)$$

generally, we can say for the definition of these level curves:

- If  $k < 0$ , there's no solution
- If  $k = 0$ , then it's a point
- If  $k > 0$ , it's an elliptic form

#### Example 3.3.1

Find the curves of  $f(x, y) = 1 - x - y$

*Solution*

$$1 - k = x + y \text{ Lines in } \mathbb{R}^2 \quad (3.17)$$

#### Intersection of a Surface with a plane

We can make a surface intersect with a plane by replacing one of the variables for the plane with

**Example**

for  $f(x,y) = x^2 + y^2$  make an intersection with  $x^2 + y^2 = k$

**Solution**

For this, we can think on the function as circles centered on the origin, whose radius will be 'k'. Now, we can decide that 'x = 0' and we can try and check for values on which this is true for both expressions. This

### 3.4 Limits and Continuity

For this course, limits will be a fairly important mathematical operation. We can imagine that limits can be described as:

$$\lim_{x \rightarrow x_0} = L \implies \forall \varepsilon > 0 \exists \delta > 0 \text{ if } 0 < |x - x_0| < \delta \implies |f(x) - L| < \varepsilon \quad (3.18)$$

This means that for every number  $\varepsilon > 0$ , there exists a  $\delta > 0$ . this will allow us to define ranges on which a function exists. epsilon and delta are but mathematical definitions of vertical and horizontal values for us to make a limit valid or invalid.

this definition is valid for limits with a single component, for multiple variables, we can assume:

$$\lim_{x \rightarrow x_0} = L \implies \forall \varepsilon > 0 \exists \delta > 0 \text{ if } 0 < \|(x, y) - (x_0, y_0)\| < \delta \implies |f(x, y) - L| < \varepsilon \quad (3.19)$$

There are cases in which a limit exists and some others for which it doesn't.

$$\lim f(x, y) \rightarrow L \implies (x, y) \rightarrow (a, b)$$

A limit doesn't exist if there is two ways of approaching the same point for which the value of the limit is different. This can be seen when

**Example**

Solve:

$$\frac{xy}{x^2 + y^2}$$

**Solution**

If we try to separate the values, we might get this

$$\lim_{x \rightarrow 0} \frac{x \cdot 0}{x^2 + 0^2} = \lim_{x \rightarrow 0} \frac{0}{x^2} = 0 \quad (3.20)$$

$$\lim_{y \rightarrow 0} \frac{y \cdot 0}{0^2 + y^2} = \lim_{y \rightarrow 0} \frac{0}{y^2} = 0 \quad (3.21)$$

It would appear as if the limit existed, but if we take them as a line of the form  $x=y$ , then we might get:

$$\lim_{x \rightarrow 0} \frac{x \cdot x}{x^2 + x^2} = \lim_{x \rightarrow 0} \frac{x^2}{2x^2} = \frac{1}{2} \quad (3.22)$$

This doesn't exist, because 0 is different to  $\frac{1}{2}$

Given the last example, how can we approach a function on infinite ways? for this, we can imagine a line  $y = mx$  that can generalize all the possible lines in the plane. However, this can also be done as explained in section 3.4.1, where we can establish a conversion to polar coordinates that will help our calculations.

### Example

Determine if the following limit exists:

$$\lim_{(x,y) \rightarrow (0,0)} \frac{y^4}{x^4 + 3y^4}$$

### Solution

$$< Y AXIS > \quad (3.23)$$

$$\lim_{y \rightarrow 0} \frac{y^4}{3y^4} \quad (3.24)$$

$$\lim_{y \rightarrow 0} \frac{1}{3} \quad (3.25)$$

So the limit approaches  $\frac{1}{3}$  when the value approaches zero

$$< X AXIS > \quad (3.26)$$

$$\lim_{x \rightarrow 0} \frac{0}{x^4} = \lim_{x \rightarrow 0} 0 = 0 \quad (3.27)$$

You can approach the point from two different places when doing these limits, Therefore the limit DOES NOT EXIST. The limit is going to approach two different points

#### 3.4.1 Polar Coordinates for limits

You can use polar coordinates for making a limit in two variables into one that only uses one. so for example, you could pass a limit as such:

$$\lim_{(x,y) \rightarrow (0,0)} F(x,y) = \lim_{\rho \rightarrow 0} f(\rho \cos \theta, \rho \sin \phi) \quad (3.28)$$

Then, we can evaluate rho as a single coordinate. This will also allow us to say that a limit exists with certainty.

### Example

Determine if the following limit exists:

$$\lim_{(x,y) \rightarrow (0,0)} \frac{e^{x^2+y^2} - 1}{x^2 + y^2}$$

### Solution

it doesn't exist, for it doesn't tend to the values we expected. This is a process that would've been a lot more tedious if we did the separation that we applied for our previous example.

**Example**

evaluate the following limit in its polar form:

$$\frac{x^2}{x^2 + y^2}$$

**Solution**

$$\lim_{r \rightarrow 0} \frac{(r^2 \cos^2 \theta)}{r^2} \quad (3.29)$$

$$\lim_{r \rightarrow 0} = \cos^2 \theta \quad (3.30)$$

Since it depends on  $\theta$ , then the limit does not exist. This is because theta might vary to values different from what we want.

**The limits of polar coordinates as a method**

It is possible that some limits, especially but not uniquely those that have targets different to (0,0), might break when trying to evaluate them through polar coordinates. A limit might break under a bunch of circumstances