

MATB41 - Multivariable Calculus

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Tutorials: TUT0007 (Wed. 11am-12pm)

TUT0006 (Thu. 10am-11am)

TUT0014 (Thu. 11am-12pm)

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Week 1 (Sep 14th)

* No tutorials *

Week 2 (Sep 21st)

Curved Lines

Parabola: (with vertex) at the origin

- $y = ax^2$ → open up when $a > 0$ and down when $a < 0$
- $x = by^2$ → open right when $b > 0$ and left when $b < 0$

* Remember: We can replace x with $x-m$ to shift right and y with $y+n$ to shift up!

Ellipse: (with center) at the origin

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1 \quad \text{intersections } (\pm a, 0) \text{ and } (0, \pm b)$$

When $a=b$, the curve is a circle of radius $a=b$.

Hyperbola: (with center) at the origin

$$\cdot \left(\frac{x}{a}\right)^2 - \left(\frac{y}{b}\right)^2 = 1 \quad \text{It has two curves that goes in opposite directions and do not touch the slant asymptote}$$

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

Ex ① - Sketch the following curves:

a) $x^2 + 3y^2 + 2x - 12y + 10 = 0$

$$\begin{aligned} (x^2 + 2x) + 3(y^2 - 4y) + 10 &= 0 \\ (x^2 + 2x + 1) - 1 + 3(y^2 - 4y + 4) - 12 + 10 &= 0 \\ (x+1)^2 + 3(y-2)^2 &= 3 \end{aligned}$$

$$\Rightarrow \left(\frac{x+1}{\sqrt{3}}\right)^2 + (y-2)^2 = 1 \quad \Rightarrow \left(\frac{x+1}{\sqrt{3}}\right)^2 + (y-2)^2 = 1$$

Okie, now what?! Another way to write the ellipse equation would be:

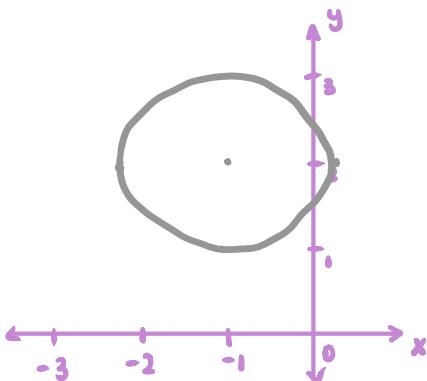
$$\left(\frac{x-m}{a}\right)^2 + \left(\frac{y-n}{b}\right)^2 = 1 \rightarrow \text{we just combined it with *}$$

So the new origin will be $(-1, 2)$ as the ellipse will be shifted left by one and up by 2.

Now, let's find the end points

→ The horizontal max/min will be $(-1 \pm \sqrt{3}, 2)$

→ The vertical max/min will be $(-1, 2 \pm 1)$



b) $\left(\frac{x-2}{4}\right)^2 - \left(\frac{y+2}{9}\right)^2 = 1$

$$\left(\frac{x-2}{2}\right)^2 - \left(\frac{y+2}{3}\right)^2 = 1$$

The origin will be $(2, -2)$, we are shifting right 2 and 2 down.

Check the x-int : $(y=0)$

$$\left(\frac{x-2}{2}\right)^2 - \frac{4}{9} = 1$$

$$\left(\frac{x-2}{2}\right)^2 = \frac{13}{9}$$

$$(x-2)^2 = \frac{52}{9}$$

$$x-2 = \pm \frac{2\sqrt{13}}{3}$$

$$x = 2 \pm \frac{2\sqrt{13}}{3}$$

Check the y-int : $(x=0)$

$$1 - \left(\frac{y+2}{3}\right)^2 = 1$$

$$y = -2$$

Find the slant asymptote:

$$\left(\frac{x-2}{2}\right)^2 - \left(\frac{y+2}{3}\right)^2 = 0$$

$$\frac{x-2}{2} = \frac{y+2}{3}$$

$$3x-6 = 2y+4$$

$$2y = 3x - 10$$

$$y = \frac{3x - 10}{2}$$

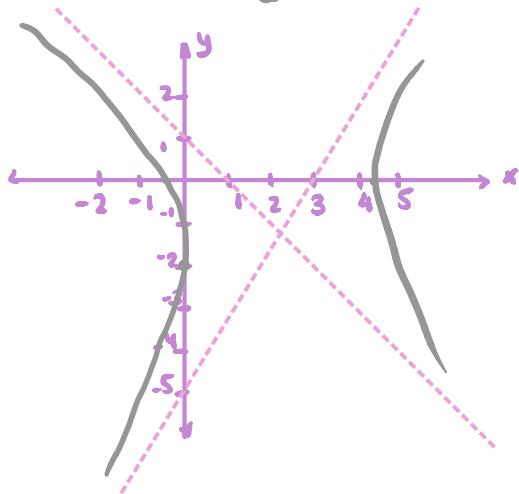
or

$$\frac{-x+2}{2} = \frac{y+2}{3}$$

$$-3x+6 = 2y+4$$

$$2y = -3x + 2$$

$$y = \frac{-3x + 2}{2}$$



Curved Surfaces

3D Sphere: (with center) at the origin of radius R

$$x^2 + y^2 + z^2 = R^2$$

3D Ellipsoid: (with center) at the origin

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 + \left(\frac{z}{c}\right)^2 = 1 \quad \text{3 points } (a, 0, 0), (0, b, 0), (0, 0, c)$$

We can replace $x^2 + y^2$ with r^2 to indicate the rotation.

Ex② - Sketch the following surfaces:

a) $x^2 + y^2 + \frac{z^2}{4} = 1$

$$r^2 + \frac{z^2}{4} = 1$$

$$4r^2 + z^2 = 4$$

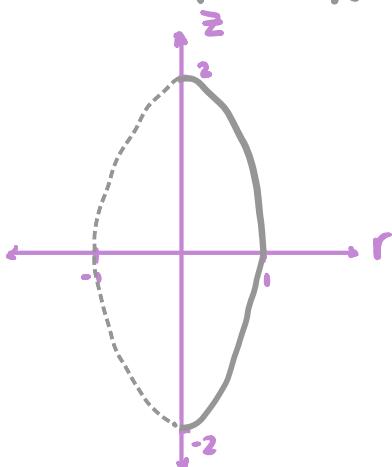
$$r^2 + \frac{z^2}{4} = 1$$

(center at $(0, 0)$)

r -int: $(\pm 1, 0)$

z -int: $(0, \pm 2)$

* Use the ellipsoid formula



$r \geq 0$ because
 $r = \sqrt{x^2 + y^2}$

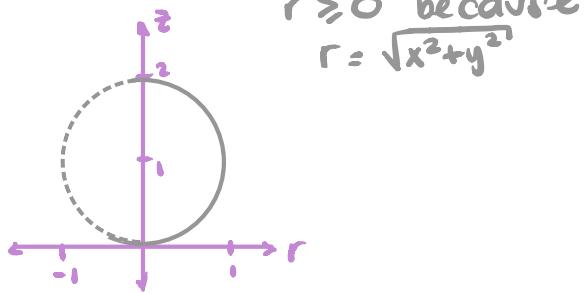
b) $x^2 + y^2 + z^2 = 2z$

$$r^2 + z^2 - 2z = 0$$

$$r^2 + z^2 - 2z + 1 - 1 = 0$$

$$r^2 + (z-1)^2 = 1 \rightarrow \text{circle!}$$

Center $(0, 1)$



$r \geq 0$ because
 $r = \sqrt{x^2 + y^2}$

Dot and Cross Product

let $\vec{u} \cdot \vec{v} = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ v_2 \\ \vdots \end{bmatrix} = u_1v_1 + u_2v_2 + \dots$

let $\vec{u} \times \vec{v} = \begin{vmatrix} i & j & k \\ u_1 & u_2 & u_3 \\ v_1 & v_2 & v_3 \end{vmatrix} = \left(\begin{vmatrix} u_2 & u_3 \\ v_2 & v_3 \end{vmatrix}, -\begin{vmatrix} u_1 & u_3 \\ v_1 & v_3 \end{vmatrix}, \begin{vmatrix} u_1 & u_2 \\ v_1 & v_2 \end{vmatrix} \right)$
 $= (u_2v_3 - u_3v_2, u_3v_1 - u_1v_3, u_1v_2 - u_2v_1)$

You can find the angle between two vectors using dot product:

Let the angle be called θ , then $\cos \theta = \frac{\vec{u} \cdot \vec{v}}{\|\vec{u}\| \|\vec{v}\|}$

Ex ③ - Find the angle between $\vec{u} = (1, -3, 1)$ and $\vec{v} = (2, 1, 2)$ in \mathbb{R}^3

First, we need the dot product and lengths:

$$\vec{u} \cdot \vec{v} = (1, -3, 1) \cdot (2, 1, 2) = 2 - 3 + 2 = 1$$

$$\|\vec{u}\| = \sqrt{1^2 + (-3)^2 + 1^2} = \sqrt{11}$$

$$\|\vec{v}\| = \sqrt{2^2 + 1^2 + 2^2} = \sqrt{9} = 3$$

$$\Rightarrow \cos \theta = \frac{1}{3\sqrt{11}} \quad \therefore \quad \theta = \cos^{-1}\left(\frac{1}{3\sqrt{11}}\right)$$

Line and Planes

Vector equation of a line in \mathbb{R}^3 : $\vec{l} = (a_1, a_2, a_3) + t[v_1, v_2, v_3]$
 $\vec{l} = \vec{a} + t\vec{v}$

Parametric equation of a line in \mathbb{R}^3 : $x = a_1 + t v_1$
 $y = a_2 + t v_2$
 $z = a_3 + t v_3$

Ex ④ - Find the equation of the line or plane

a) The line through $(1, -1, 2)$ and $(3, 1, 9)$

The direction vector for the line is $(3, 1, 9) - (1, -1, 2) = (2, 2, 7)$

$$\rightarrow \text{v. eq. } \vec{l} = (1, -1, 2) + t(2, 2, 7), t \in \mathbb{R}$$

$$\rightarrow \text{P. eq. } x = 1 + 2t, y = -1 + 2t, z = 2 + 7t, t \in \mathbb{R}$$

b) The plane through $(1, -3, 1)$, $(2, 1, 1)$, $(1, 4, 0)$

let's find a pair of directional vectors \vec{v}_1 and \vec{v}_2

$$\vec{v}_1 = (2, 1, 1) - (1, -3, 1) = (1, 4, 0)$$

$$\vec{v}_2 = (1, 4, 0) - (1, -3, 1) = (0, 7, -1)$$

To get the equation of the plane, we need to find the normal which is $\vec{v}_1 \times \vec{v}_2$

$$\vec{n} = \vec{v}_1 \times \vec{v}_2 = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ 1 & 4 & 0 \\ 0 & 7 & -1 \end{vmatrix} = (-4, 1, 7)$$

The plane then is $-4x + y + 7z = d$

$$\text{Let's plug a point: } -4(2) + (1) + 7(1) = -8 + 1 + 7 = 0 = d$$

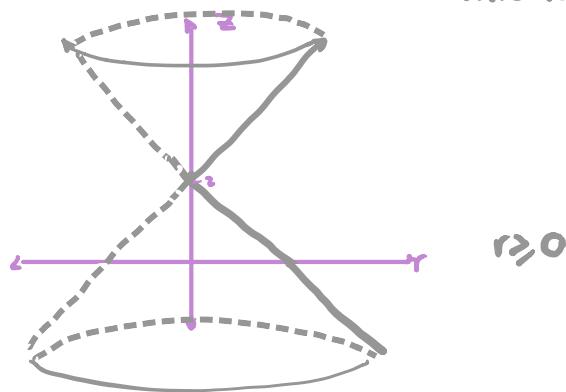
\rightarrow The plane is $-4x + y + 7z = 0$

Level Set

Ex ⑤ - Draw the level set of $f(x, y, z) = z^2 - x^2 - y^2 - 4z$ for $f = -4$

\hookrightarrow this is in 4D though

$$\begin{aligned} -4 &= z^2 - x^2 - y^2 - 4z \\ x^2 + y^2 &= z^2 - 4z + 4 \\ r^2 &= (z-2)^2 \\ r &= |z-2| \end{aligned}$$



Week 3 (Sep 28th)

Limits and Continuity

$f(x, y)$ is continuous at the 2D point \vec{a} if $\lim_{(x,y) \rightarrow \vec{a}} f(x, y) = f(\vec{a})$

$(x,y) \rightarrow \vec{a}$

It's not too hard to show when a limit DNE in \mathbb{R}^2 at $(0,0)$:
 Try different curves in terms of x or y , if they approach to different values at $(0,0)$

To show that the limit exists we can use the Squeeze Theorem:

To attain $\lim_{(x,y) \rightarrow \vec{a}} f(x,y)$, can try to find $g(x,y)$ and $h(x,y)$ so that:

$$1. g(x,y) \leq f(x,y) \leq h(x,y) \text{ near the point } \vec{a}$$

$$2. \lim_{(x,y) \rightarrow \vec{a}} g(x,y) = L = \lim_{(x,y) \rightarrow \vec{a}} h(x,y)$$

Then we conclude $\lim_{(x,y) \rightarrow \vec{a}} f(x,y) = L$

Ex ② - Decide whether the function has a limit at $(0,0)$

$$a) \lim_{(x,y) \rightarrow (0,0)} \frac{x^2 - y^2}{x^2 + y^2} = \text{DNE}$$

$$\text{Restrict to } x=0, \lim_{(0,y) \rightarrow (0,0)} \frac{-y^2}{y^2} = -1$$

$$\text{Restrict to } y=0, \lim_{(x,0) \rightarrow (0,0)} \frac{x^2}{x^2} = 1$$

$$b) \lim_{(x,y) \rightarrow (0,0)} \frac{|x|}{\sqrt{x^2+y^2}} = \text{DNE}$$

$$\text{Restrict to } y=0, \lim_{(x,0) \rightarrow (0,0)} \frac{|x|}{\sqrt{x^2}} = 1$$

$$\text{Restrict to } x=0, \lim_{(0,y) \rightarrow (0,0)} \frac{|x|}{\sqrt{y}} = \frac{0}{\sqrt{y}} = 0$$

$$c) \lim_{(x,y) \rightarrow (0,0)} \frac{x^3 - y^3}{x^2 + y^2} = \lim_{(x,y) \rightarrow (0,0)} \frac{\underset{\textcircled{1}}{x^3}}{\underset{\textcircled{2}}{x^2 + y^2}} - \frac{\underset{\textcircled{2}}{y^3}}{\underset{\textcircled{2}}{x^2 + y^2}} = 0$$

$$\textcircled{1} \quad x^2 \leq x^2 + y^2 \rightarrow 0 \leq \frac{x^2}{x^2 + y^2} \leq 1$$

$$\rightarrow 0 \cdot x \leq \frac{x^3}{x^2 + y^2} \leq x$$

$$\rightarrow \lim_{(x,y) \rightarrow (0,0)} 0 \leq \lim_{(x,y) \rightarrow (0,0)} \frac{x^3}{x^2+y^2} \leq \lim_{(x,y) \rightarrow (0,0)} x$$

$$\rightarrow 0 \leq \lim_{(x,y) \rightarrow (0,0)} \frac{x^3}{x^2+y^2} \leq 0 \\ \Rightarrow 0$$

② Same as ①

$$y^2 \leq x^2+y^2 \rightarrow 0 \leq \frac{y^2}{x^2+y^2} \leq 1$$

$$\rightarrow 0 \cdot \leq \frac{y^3}{x^2+y^2} \leq$$

$$\rightarrow \lim_{(x,y) \rightarrow (0,0)} y \cdot 0 \leq \lim_{(x,y) \rightarrow (0,0)} \frac{y^3}{x^2+y^2} \leq \lim_{(x,y) \rightarrow (0,0)} y$$

$$\rightarrow 0 \leq \lim_{(x,y) \rightarrow (0,0)} \frac{y^3}{x^2+y^2} \leq 0 \\ \Rightarrow 0$$

d) $\lim_{(x,y) \rightarrow (0,0)} \frac{\sin(x^2+y^2)}{x^2+y^2}$

We know $|\sin \theta| \leq 1$ and we saw in class $|\sin \theta| \leq \theta$

$$\Rightarrow |\frac{\sin(x^2+y^2)}{x^2+y^2}| \leq \frac{x^2+y^2}{x^2+y^2} = 1$$

Recall $\lim_{t \rightarrow 0} \frac{\sin t}{t} = 1$, what if we let $t = x^2+y^2$

$$\Rightarrow \lim_{t \rightarrow 0} \frac{\sin t}{t} = 1 = \lim_{(x,y) \rightarrow (0,0)} \frac{\sin(x^2+y^2)}{x^2+y^2}$$

Ex③ - Find if the limit of f exists at $(0,0)$, if it does, find $f(0,0)$ for f to be continuous.

$$f(x,y) = \frac{x^3-x^2-2x^2y+xy^2-y^2-2y^3}{x^2+y^2}$$

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

$$= \lim_{(x,y) \rightarrow (0,0)} x-1-2y \\ = -1$$

$$\Rightarrow f(0,0) = -1$$

$f(\vec{x})$ is homogeneous of degree k if for every $\vec{x} \in \mathbb{R}^n$ and every scalar $c > 0$ we have:

$$f(cx) = c^k f(x)$$

Ex ④ - Show if f is homogeneous

a) $f(x, y) = 8x^2y^2 - 9x^4$

$$\begin{aligned} f(cx, cy) &= 8(cx)^2(cy)^2 - 9(cx)^4 \\ &= 8c^2x^2c^2y^2 - 9c^4x^4 \\ &= 8c^4x^2y^2 - 9c^4x^4 \\ &= c^4(8x^2y^2 - 9x^4) \\ &= c^4 f(x, y) \end{aligned}$$

$\Rightarrow f$ is homogeneous of degree 4.

b) $f(x, y) = \frac{x^2}{y^2} + xy + \frac{y^2}{x^2}$

$$\begin{aligned} f(cx, cy) &= \frac{(cx)^2}{(cy)^2} + (cx)(cy) + \frac{(cy)^2}{(cx)^2} \\ &= \frac{c^2x^2}{c^2y^2} + c^2xy + \frac{c^2y^2}{c^2x^2} \\ &= \frac{x^2}{y^2} + c^2xy + \frac{y^2}{x^2} \quad \Rightarrow \text{cannot factor } c. \end{aligned}$$

$\Rightarrow f$ is not homogeneous.

Week 4 (Oct. 5th)

Partial derivatives

Ex ① - Find the partial derivatives of $f(x, y) = y \sin(xy) + xe^{-y^2}$

$$\frac{\partial f}{\partial x} = y^2 \cos(xy) + e^{-y^2}$$

$$\frac{\partial f}{\partial y} = \sin(xy) + xy \cos(xy) - 2xye^{-y^2}$$

A function, whose partial derivatives exist and are continuous, is said to be of class C^1 .

Directional Derivative

The directional derivative towards the direction \vec{u} at the point \vec{a} :

$$D_{\vec{u}} f(\vec{a}) = \lim_{h \rightarrow 0} \frac{f(\vec{a} + h\vec{u}) - f(\vec{a})}{h} \quad \text{where } \vec{u} \text{ is a unit vector.}$$

If f is differentiable, then all directional derivatives exist and

$$D_{\vec{u}} f = \nabla f \cdot \vec{u} \quad \text{where } \vec{u} \text{ is a unit vector.}$$

* If f is C^1 at \vec{a} , then f is differentiable at \vec{a} (∇f exists)

Ex ② - At the point $(3, 1, 2)$, find the directional derivative of $f(x, y, z) = xy^3z^2$ along the vector $\vec{u} = (1, 3, 4)$

f is $C^1 \rightarrow$ its partial derivatives exist and are continuous.

$$\nabla f(x, y, z) = (y^3z^2, 3xy^2z^2, 2xy^3z)$$

$$\nabla f(3, 1, 2) = (4, 36, 12)$$

$$\Rightarrow D_{\vec{u}} f(p) = \frac{(4, 36, 12)(1, 3, 4)}{\sqrt{1+9+16}} = \frac{4+108+48}{\sqrt{26}} = \frac{160}{\sqrt{26}}$$

Tangent Planes

A tangent plane is given by $\nabla g(a, b, c) \cdot ((x, y, z) - (a, b, c)) = 0$

Ex ③ - Compute an equation for the tangent plane at the point p to the graph of the function $z = f(x, y)$

$$p = (1, 1, 1) \text{ and } xy + yz + zx = 3$$

$$g(x, y, z) = xy + yz + zx - 3$$

$$\nabla g(x, y, z) = (y+z, x+z, y+x)$$

$$\nabla g(1, 1, 1) = (2, 2, 2)$$

$$\Rightarrow (2, 2, 2)((x, y, z) - (1, 1, 1)) = 0$$

$$(2, 2, 2)(x-1, y-1, z-1) = 0$$

$$2x-2 + 2y-2 + 2z-2 = 0$$

$$x+y+z = 3$$

Differentiation

f is differentiable if the gradient vector $\nabla f(\vec{a})$ satisfies

$$\lim_{\vec{h} \rightarrow 0} \frac{f(\vec{a} + \vec{h}) - f(\vec{a}) - \nabla f(\vec{a}) \cdot \vec{h}}{|\vec{h}|}$$

Ex ④ - Find all directional derivatives and show whether the function is differentiable at $(0, 0)$

$$f(x, y) = \begin{cases} \frac{3x^2y + 5xy^2}{x^2 + y^2} & (x, y) \neq (0, 0) \\ 0 & (x, y) = (0, 0) \end{cases}$$

$$\vec{a} = (0, 0)$$

$$\begin{aligned} D_{\vec{u}} f &= \lim_{h \rightarrow 0} \frac{f(\vec{a} + h\vec{u}) - f(\vec{a})}{h} \\ &= \lim_{h \rightarrow 0} \frac{f(ha, hb) - 0}{h} \\ &= \lim_{h \rightarrow 0} \frac{1}{h} \frac{3(ha)^2(hb) + 5(ha)(hb)^2}{(ha)^2 + (hb)^2} \\ &= \lim_{h \rightarrow 0} \frac{1}{h} \cdot h^3 \frac{3a^2b + 5ab^2}{h^2(a^2 + b^2)} \\ &= \lim_{h \rightarrow 0} \frac{3a^2b + 5ab^2}{a^2 + b^2} \end{aligned}$$

$$\rightarrow \vec{u} = (1, 0), D_{\vec{u}} f = \frac{3(1)(0) + 5(1)(0)}{(1)^2 + (0)^2} = 0 \rightarrow \frac{\partial f}{\partial x} = 0$$

$$\rightarrow \vec{u} = (0, 1), D_{\vec{u}} f = \frac{3(0)(1) + 5(0)(1)}{(0)^2 + (1)^2} = 0 \rightarrow \frac{\partial f}{\partial y} = 0$$

$$\nabla f(\vec{a}) = \left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y} \right) = (0, 0)$$

Now, let's apply the definition of differentiability

$$\begin{aligned} \lim_{\vec{h} \rightarrow 0} \frac{f(\vec{a} + \vec{h}) - f(\vec{a}) - \nabla f(\vec{a}) \cdot \vec{h}}{|\vec{h}|} &= \lim_{\vec{h} \rightarrow 0} \frac{f(\vec{h})}{|\vec{h}|}, \text{ let } \vec{h} = (h_1, h_2) \\ &= \lim_{(h_1, h_2) \rightarrow (0, 0)} \frac{1}{\sqrt{h_1^2 + h_2^2}} \cdot \frac{3h_1^2h_2 + 5h_1h_2^2}{h_1^2 + h_2^2} \end{aligned}$$

Restrict $h_1 = 0$

$$\lim_{h_2 \rightarrow 0} \frac{1}{\sqrt{h_2^2}} \cdot \frac{3(0)h_2 + 5(0)h_2^2}{h_2^2} = 0$$

Restrict $h_1 = h_2$

$$\lim_{h_2 \rightarrow 0} \frac{1}{\sqrt{2h_2^2}} \cdot \frac{3h_2^3 + 5h_2^3}{2h_2^2} = \lim_{h_2 \rightarrow 0} \frac{8h_2^3}{2\sqrt{2}h_2^3} = \frac{4}{\sqrt{2}}$$

$\therefore f$ is not differentiable at $(0, 0)$

Week 5 (Oct. 19th)

If f is C^2 , then $f_{xy} = f_{yx}$ $\left[\frac{\partial}{\partial y} \left(\frac{\partial f}{\partial x} \right) = \frac{\partial}{\partial x} \left(\frac{\partial f}{\partial y} \right) \right]$

Ex① - At $(x,y) = (0,0)$, find $\frac{\partial}{\partial y} \left(\frac{\partial f}{\partial x} \right)$ and $\frac{\partial}{\partial x} \left(\frac{\partial f}{\partial y} \right)$. Are they equal?

Is $f(x,y)$ C^2 ?

$$f(x,y) = \begin{cases} \frac{ax^4}{x^2+y^2}, & (x,y) \neq (0,0) \\ 0, & (x,y) = (0,0) \end{cases}$$

Time to find directional derivatives?

$$\begin{aligned} \vec{a} &= (0,0) \\ \vec{u} &= (a,b) \end{aligned}$$

$$\begin{aligned} D_{\vec{u}} f &= \lim_{h \rightarrow 0} \frac{f(\vec{a} + h\vec{u}) - f(\vec{a})}{h} \\ &= \lim_{h \rightarrow 0} \frac{1}{h} f(ha, hb) \\ &= \lim_{h \rightarrow 0} \frac{1}{h} \frac{2(ha)^4}{(ha)^2 + (hb)^2} \\ &= \lim_{h \rightarrow 0} \frac{2h^4a^4}{h(n^2a^2 + b^2)} \\ &= \lim_{h \rightarrow 0} \frac{2h^4a^4}{h^2(a^2 + b^2)} \\ &= 0 \end{aligned}$$

$$\Rightarrow \frac{\partial f}{\partial x}(0,0) = 0 = \frac{\partial f}{\partial y}(0,0)$$

Now, let's find the partial derivatives.

$$\begin{aligned} * \frac{\partial f}{\partial x}(x,y) &= \frac{8x^3(x^2+y^2) - 2x(2x^4)}{(x^2+y^2)^2} = \frac{8x^5 + 8x^3y^2 - 4x^5}{(x^2+y^2)^2} = \frac{4x^5 + 8x^3y^2}{(x^2+y^2)^2} \\ &= \frac{4x^3(x^2+2y^2)}{(x^2+y^2)^2} \end{aligned}$$

$$\Rightarrow g(x,y) = \frac{\partial f}{\partial x}(x,y) = \begin{cases} \frac{4x^3(x^2+2y^2)}{(x^2+y^2)^2}, & (x,y) \neq (0,0) \\ 0, & (x,y) = (0,0) \end{cases}$$

$$* \frac{\partial f}{\partial y}(x,y) = \frac{0(x^2+y^2) - 2y(2x^4)}{(x^2+y^2)^2} = \frac{-4x^4y}{(x^2+y^2)^2}$$

$$\Rightarrow h(x,y) = \frac{\partial f}{\partial y}(x,y) = \begin{cases} \frac{-4x^4y}{(x^2+y^2)^2}, & (x,y) \neq (0,0) \\ 0, & (x,y) = (0,0) \end{cases}$$

$$\left\{ \begin{array}{l} \frac{\partial f}{\partial y}(x,y) \\ 0 \end{array} \right. , \quad (x,y) = (0,0)$$

Time to finally find f_{xy} and f_{yx} at $(0,0)$

* We need to find $\frac{\partial f}{\partial y}\left(\frac{\partial f}{\partial x}(0,0)\right)$, aka $\frac{\partial g}{\partial y}(0,0)$

We can find the directional derivative at $(0,0)$ where $\vec{u} = (0,1)$

$$\begin{aligned} \frac{\partial g}{\partial y}(0,0) &= \lim_{h \rightarrow 0} \frac{g(\vec{a} + h\vec{u}) - g(\vec{a})}{h} \\ &= \lim_{h \rightarrow 0} \frac{1}{h} g(0,h) \\ &= \lim_{h \rightarrow 0} \frac{1}{h} \times 0 \\ &= 0 \end{aligned}$$

* We need to find $\frac{\partial f}{\partial x}\left(\frac{\partial f}{\partial y}(0,0)\right)$, aka $\frac{\partial k}{\partial x}(0,0)$

We can find the directional derivative at $(0,0)$ where $\vec{u} = (1,0)$

$$\begin{aligned} \frac{\partial k}{\partial x}(0,0) &= \lim_{h \rightarrow 0} \frac{k(\vec{a} + h\vec{u}) - k(\vec{a})}{h} \\ &= \lim_{h \rightarrow 0} \frac{1}{h} k(h,0) \\ &= \lim_{h \rightarrow 0} \frac{1}{h} \times 0 \\ &= 0 \end{aligned}$$

$$\therefore \frac{\partial}{\partial y}\left(\frac{\partial f}{\partial x}(0,0)\right) = 0 = \frac{\partial}{\partial x}\left(\frac{\partial f}{\partial y}(0,0)\right)$$

But, is it C^2 ? At $(0,0)$, yes!

$$\begin{aligned} * \frac{\partial}{\partial y}\left(\frac{\partial f}{\partial x}(x,y)\right) &= \frac{[0(x^2+2y^2) + 4y(4x^3)](x^2+y^2)^2 - 2(2y)(x^2+y^2)4x^3(x^2+2y^2)}{(x^2+y^2)^4} \\ &= \frac{16x^3y(x^2+y^2) - 16x^3y(x^2+2y^2)}{(x^2+y^2)^3} \\ &= \frac{16x^3y(x^2+y^2 - x^2 - 2y^2)}{(x^2+y^2)^3} = \frac{-16x^3y^3}{(x^2+y^2)^3} \end{aligned}$$

$$\Rightarrow \frac{\partial}{\partial y}\left(\frac{\partial f}{\partial x}(x,y)\right) = \begin{cases} \frac{-16x^3y^3}{(x^2+y^2)^3}, & (x,y) \neq (0,0) \\ 0, & (x,y) = (0,0) \end{cases}$$

$$* \frac{\partial}{\partial x} \left(\frac{\partial f}{\partial y}(x,y) \right) = -16x^3y \frac{(x^2+y^2)^2 + 4x^4y(2)(2x)(x^2+y^2)}{(x^2+y^2)^4}$$

$$= -16x^3y \frac{(x^2+y^2) + 16x^5y}{(x^2+y^2)^4} = \frac{-16x^3y^3}{(x^2+y^2)^4}$$

$$\Rightarrow \frac{\partial}{\partial y} \left(\frac{\partial f}{\partial x}(x,y) \right) = \begin{cases} \frac{-16x^3y^3}{(x^2+y^2)^4}, & (x,y) \neq (0,0) \\ 0, & (x,y) = (0,0) \end{cases}$$

So $f(x,y)$ is not C^2

Critical Points

Hessian form: (H_f)

$$H = \begin{bmatrix} f_{xx} & f_{xy} \\ f_{yx} & f_{yy} \end{bmatrix} = \begin{bmatrix} \frac{\partial}{\partial x} \left(\frac{\partial f}{\partial x} \right) & \frac{\partial}{\partial x} \left(\frac{\partial f}{\partial y} \right) \\ \frac{\partial}{\partial y} \left(\frac{\partial f}{\partial x} \right) & \frac{\partial}{\partial y} \left(\frac{\partial f}{\partial y} \right) \end{bmatrix}$$

- * If H_f is positive definite, then the Critical Point is a local minimum
- * If H_f is negative definite, then the Critical Point is a local maximum
- * Otherwise, the Critical Point is a saddle point.

Let A be $n \times n$ and symmetric:

- * A is positive definite iff $\det(A_k) > 0$ for $k=1, 2, \dots, n$.
- * A is negative definite iff $(-1)^k \det(A_k) > 0$ for $k=1, 2, \dots, n$

Ex ② - Find the critical points of $f(x,y) = x^3 - 12xy + 8y^3$

$$\frac{\partial f}{\partial x}(x,y) = 3x^2 - 12y$$

$$\frac{\partial f}{\partial y}(x,y) = -12x + 24y^2$$

$$\begin{cases} 3x^2 - 12y = 0 \rightarrow 3x^2 = 12y \\ -12x + 24y^2 = 0 \end{cases} \quad y = \frac{x^2}{4}$$

$$\rightarrow -12x + 24 \left(\frac{x^2}{4} \right)^2 = 0$$

$$-12x + 24x^4 = 0$$

$$x\left(\frac{3}{2}x^3 - 12\right) = 0 \rightarrow x=0 \text{ or } \frac{3}{2}x^3 = 12 \\ \Rightarrow x^3 = 8 \rightarrow x=2$$

\therefore CPs are $(0,0)$ and $(2,1)$

$$\frac{\partial f}{\partial x}\left(\frac{\partial f}{\partial x}(x,y)\right) = 6x$$

$$\frac{\partial f}{\partial x}\left(\frac{\partial f}{\partial y}(x,y)\right) = -12$$

$$\frac{\partial f}{\partial y}\left(\frac{\partial f}{\partial x}(x,y)\right) = -12$$

$$\frac{\partial f}{\partial y}\left(\frac{\partial f}{\partial y}(x,y)\right) = 48y$$

$$\Rightarrow H_f(x,y) = \begin{bmatrix} 6x & -12 \\ -12 & 48y \end{bmatrix}$$

① For $(0,0)$

$$H_f(0,0) = \begin{bmatrix} 0 & -12 \\ -12 & 0 \end{bmatrix}$$

$$\rightarrow \det(A_1) = \det([0]) = 0$$

$$\rightarrow \det(A_2) = \det\left(\begin{bmatrix} 0 & -12 \\ -12 & 0 \end{bmatrix}\right) = -144 < 0$$

\therefore saddle point

② For $(2,1)$

$$H_f(2,1) = \begin{bmatrix} 12 & -12 \\ -12 & 48 \end{bmatrix}$$

$$\rightarrow \det(A_1) = \det([12]) = 12 > 0$$

$$\rightarrow \det(A_2) = \det\left(\begin{bmatrix} 12 & -12 \\ -12 & 48 \end{bmatrix}\right) = 576 - 144 = 432 > 0$$

\therefore local min.

Ex ③- Find the global extrema for $f(x,y) = 6x^2 - 8x + 2y^2 - 5$ on the closed disk $x^2 + y^2 \leq 1$.

The extrema can be at the interior or boundary.

$$\text{Interior: } \frac{\partial f}{\partial x}(x,y) = 12x - 8 \quad \frac{\partial f}{\partial y}(x,y) = 4y$$

$$\begin{cases} 12x - 8 = 0 \\ 4y = 0 \end{cases} \rightarrow \left(\frac{2}{3}, 0\right) \text{ is the only CP.}$$

Since $\left(\frac{2}{3}\right)^2 + (0)^2 = \frac{4}{9} \leq 1$, the point is inside the disk.

Boundary: it happens when $x^2 + y^2 = 1$. and $-1 \leq x \leq 1$
 $y^2 = 1 - x^2$, let's substitute this

$$\begin{aligned} g(x) &= 6x^2 - 8x + 2(1 - x^2) - 5 \\ &= 6x^2 - 8x + 2 - 2x^2 - 5 \\ &= 4x^2 - 8x - 3 \end{aligned}$$

$$\begin{aligned} g'(x) &= 8x - 8 = 0 \\ 8x &= 8 \\ x &= 1 \quad \rightarrow \quad y^2 = 1 - 1 = 0, \quad (1, 0) \\ &\rightarrow y = 0, \quad 0 = 1 - x^2 \rightarrow (-1, 0) \end{aligned}$$

$$\begin{aligned} \therefore f\left(\frac{2}{3}, 0\right) &= -\frac{23}{2}, \text{ global min} \\ f(-1, 0) &= 9, \text{ global max} \\ f(1, 0) &= -7 \end{aligned}$$

Lagrange Multipliers

Ex①-Use Lagrange multipliers to find the constrained critical points of f subject to the given constraints.

$$(a) f(x, y) = xy, \quad 4x^2 + 9y^2 = 32 \rightarrow g(x, y) = 4x^2 + 9y^2 - 32$$

$$h(x, y, \lambda) = xy - \lambda(4x^2 + 9y^2 - 32)$$

$$\begin{cases} h_x = y - 8x\lambda = 0 \rightarrow \lambda = \frac{y}{8x} \\ h_y = x - 18y\lambda = 0 \rightarrow \lambda = \frac{x}{18y} \end{cases} \quad \left[\begin{array}{l} \frac{y}{8x} = \frac{x}{18y} \rightarrow 18y^2 = 8x^2 \rightarrow 4x^2 = 9y^2 \\ \text{or } \lambda = 0 \text{ (contradiction)} \end{array} \right]$$

$$h_\lambda = 32 - 4x^2 - 9y^2 \quad \longrightarrow \quad 32 - 4x^2 - 9y^2 = 0$$

$$8x^2 = 32$$

$$x^2 = 4 \quad \longrightarrow \quad 16 = 9y^2$$

$$x = \pm 2 \quad y = \pm \frac{4}{3}$$

$$\therefore \text{CPs are } \left(2, \frac{4}{3}\right), \left(2, -\frac{4}{3}\right), \left(-2, \frac{4}{3}\right), \left(-2, -\frac{4}{3}\right)$$

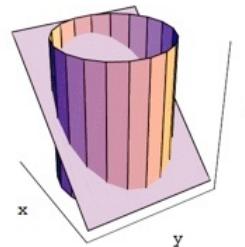
Week 6 (Oct 29th)

(b) The cylinder $x^2 + y^2 = 1$ intersects the plane $x+z=1$ in an ellipse. Find the point on that ellipse that is the furthest from the origin.

We need to maximize the distance function (aka $f(x,y,z) = x^2 + y^2 + z^2$) subject to 2 constraints.

$$h(x,y,z, \lambda, \mu) = x^2 + y^2 + z^2 - \lambda(x^2 + y^2 - 1) - \mu(x + z - 1)$$

$$\begin{cases} h_x = 2x - 2x\lambda - \mu & ① \\ h_y = 2y - 2y\lambda & ② \\ h_z = 2z - \mu & ③ \\ h_\lambda = 1 - x^2 - y^2 & ④ \\ h_\mu = 1 - x - z & ⑤ \end{cases}$$



$$\begin{aligned} ② \quad 2y &= 2y\lambda \\ \Rightarrow 2y(1-\lambda) &= 0 \\ y &= 0, \lambda = 1 \end{aligned}$$

* If $\lambda = 1$:

$$\begin{aligned} ① \quad \mu &= 2x(1-\lambda) = 0 \\ ③ \quad 2z &= \mu = 0 \rightarrow z = 0 \\ ⑤ \quad x &= 1 \\ ④ \quad 1+y^2 &= 1 \rightarrow y = 0 \end{aligned}$$

* If $y = 0$:

$$\begin{aligned} ④ \quad x^2 &= 1 \rightarrow x = \pm 1 \\ ⑤ \quad -1+z &= 1 \rightarrow z = 2 \quad (x=-1) \\ 1+z &= 1 \rightarrow z = 0 \quad (x=1) \quad (\text{We know}) \end{aligned}$$

$$\therefore \text{CPs } (1, 0, 0) \text{ and } (-1, 0, 2)$$

Based on the distance function:

$$(1, 0, 0) \rightarrow \sqrt{1^2} = 1$$

$$(-1, 0, 2) \rightarrow \sqrt{(-1)^2 + (0)^2 + (2)^2} = \sqrt{5}$$

\therefore The furthest point from the origin is $(-1, 0, 2)$.

Since the distance function is continuous and the intersection is compact in \mathbb{R}^3 , the Extreme Value Theorem (EVT) ensures the existence of extreme.

Chain Rule

$$(f(g(x)))' = f'(g(x)) g'(x)$$

Now, let's say $y = y(t)$ and $t = t(x)$

$$\stackrel{1D}{=} \frac{dy}{dx} = \frac{dy}{dt} \cdot \frac{dt}{dx}$$

$$\stackrel{2D}{=} \frac{d^2y}{dx^2} = \frac{d}{dx} \left(\frac{dy}{dx} \right) = \frac{d}{dx} \left(\frac{dy}{dt} \cdot \frac{dt}{dx} \right) \quad \text{product rule!}$$

$$= \frac{d}{dx} \left(\frac{dy}{dt} \right) \frac{dt}{dx} + \frac{dy}{dt} \cdot \frac{d}{dx} \left(\frac{dt}{dx} \right) = \frac{d^2t}{dx^2}$$

ODEs - Euler Equation

Second Order differential equations:

Homogeneous with constant coefficients

$$ay'' + by' + cy = 0 \quad \text{where } a, b, c \text{ are constants.}$$

Characteristic equation $ar^2 + br + c = 0$, find roots r_1 and r_2

Then $y = c_1 e^{r_1 t} + c_2 e^{r_2 t}$ is a general solution

Ex ② - Let $y'' + 5y' + 6y = 0$

(a) Find the general solution of the equation

$$r^2 + 5r + 6 = 0 = (r+2)(r+3) = 0$$

$$r_1 = -2 \text{ and } r_2 = -3$$

$$\text{Then } y = c_1 e^{-2t} + c_2 e^{-3t}, c_1, c_2 \in \mathbb{R}$$

(b) Find the solution of the initial value problem $y(0)=2, y'(0)=3$

$$t=0, y(0) = c_1 + c_2 = 2$$

$$y' = -2c_1 e^{-2t} - 3c_2 e^{-3t} \rightarrow y'(0) = -2c_1 - 3c_2 = 3$$

$$\begin{cases} c_1 + c_2 = 2 \\ -2c_1 - 3c_2 = 3 \end{cases} \rightarrow c_2 = 7 \rightarrow c_2 = -7 \text{ and } c_1 = 9$$

$$\therefore y = 9e^{-2t} - 7e^{-3t}$$

Ex ③ - Find the solution of the initial value problem $4y'' - 8y' + 3y = 0,$

$$y(0) = 2, y'(0) = \frac{1}{2}$$

$$4r^2 - 8r + 3 = 0 = (2r-1)(2r-3)$$

$$r_1 = \frac{1}{2}, r_2 = \frac{3}{2}$$

$$\text{General sol: } y = c_1 e^{t/2} + c_2 e^{3t/2}$$

$$y' = \frac{c_1}{2} e^{t/2} + \frac{3c_2}{2} e^{3t/2}$$

$$y(0) = c_1 + c_2 = 2$$

$$y'(0) = \frac{c_1}{2} + \frac{3c_2}{2} = \frac{1}{2}$$

$$\left. \begin{array}{l} c_1 = 2 - c_2 \\ c_1 = 1 - 3c_2 \end{array} \right\}$$

$$c_2 = -\frac{1}{2}, c_1 = \frac{5}{2}$$

$$\therefore y = \frac{5}{2} e^{t/2} - \frac{1}{2} e^{3t/2}$$

Week 7 (Nov 2nd)

Ex ① - Consider $u=u(x,y)$. Find the general solution to the PDE $\partial u_x - u_y = 10$
with the initial condition $u(x,0) = 5x$

$$a=2, b=-1$$

$$\begin{aligned} \text{Let } s &= ax+by, t = bx-ay \\ s &= 2x-y \quad t = -x-2y \end{aligned}$$

$$\begin{cases} \frac{\partial s}{\partial x} = 2 & \frac{\partial s}{\partial y} = -1 \\ \frac{\partial t}{\partial x} = -1 & \frac{\partial t}{\partial y} = -2 \end{cases}$$

$$u_x = \frac{\partial u}{\partial x} = \frac{\partial u}{\partial s} \cdot \frac{\partial s}{\partial x} + \frac{\partial u}{\partial t} \cdot \frac{\partial t}{\partial x} = 2 \frac{\partial u}{\partial s} - \frac{\partial u}{\partial t}$$

$$u_y = \frac{\partial u}{\partial y} = \frac{\partial u}{\partial s} \cdot \frac{\partial s}{\partial y} + \frac{\partial u}{\partial t} \cdot \frac{\partial t}{\partial y} = - \frac{\partial u}{\partial s} - 2 \frac{\partial u}{\partial t}$$

$$\Rightarrow \partial u_x - u_y = 10$$

$$2 \left(2 \frac{\partial u}{\partial s} - \frac{\partial u}{\partial t} \right) - \left(- \frac{\partial u}{\partial s} - 2 \frac{\partial u}{\partial t} \right) = 10$$

$$5 \frac{\partial u}{\partial s} = 10$$

$$\frac{\partial u}{\partial s} = 2$$

$$\int \partial u = \int 2 \partial s$$

$$u = 2s + f(t)$$

$$\Rightarrow u(x,y) = 2(2x-y) + f(-x-2y) \quad \text{G.S.}$$

$$\text{I.V.P. Let } u(x,0) = 5x$$

$$\Rightarrow u(x,0) = 4x + f(-x) = 5x$$

$$f(-x) = x \rightarrow f(-x-2y) = x+2y$$

$$\therefore u(x,y) = 2(2x-y) + x+2y = 5x$$

Ex ② - Consider $u=u(x,y)$. Find the general solution to the PDE $u_x - u_y + u^2 = 0$
with the initial condition $u(x,0) = \frac{1}{3x}$

$$a=1, b=-1$$

$$\text{Let } s = x-y, t = -x-y$$

$$\begin{cases} \frac{\partial s}{\partial x} = 1 & \frac{\partial s}{\partial y} = -1 \\ \frac{\partial t}{\partial x} = -1 & \frac{\partial t}{\partial y} = -1 \end{cases}$$

$$u_x : \frac{\partial u}{\partial x} = \frac{\partial u}{\partial s} \cdot \frac{\partial s}{\partial x} + \frac{\partial u}{\partial t} \frac{\partial t}{\partial x} = \frac{\partial u}{\partial s} - \frac{\partial u}{\partial t}$$

$$u_y : \frac{\partial u}{\partial y} = \frac{\partial u}{\partial s} \cdot \frac{\partial s}{\partial y} + \frac{\partial u}{\partial t} \frac{\partial t}{\partial y} = -\frac{\partial u}{\partial s} - \frac{\partial u}{\partial t}$$

$$\Rightarrow u_x - u_y + u^2 = 0$$

$$\left(\frac{\partial u}{\partial s} - \frac{\partial u}{\partial t} \right) - \left(-\frac{\partial u}{\partial s} - \frac{\partial u}{\partial t} \right) + u^2 = 0$$

$$2 \frac{\partial u}{\partial s} = -u^2$$

$$\int -2 \frac{\partial u}{u^2} = \int ds$$

$$\frac{2}{u} = s + f(t)$$

$$u = \frac{2}{s + f(t)}$$

$$\Rightarrow u(x, y) = \frac{2}{(x-y) + f(-x-y)} \quad \text{G.S.}$$

IVP. Let $u(x, 0) = \frac{1}{3x}$

$$\begin{aligned} u(x, 0) &= \frac{2}{x + f(-x)} = \frac{1}{3x} \\ 6x &= x + f(-x) \\ f(-x) &= 5x \\ f(x) &= -5x \end{aligned}$$

$$u(x, y) = \frac{2}{x-y-5(-x-y)} = \frac{2}{6x+4y} = \frac{1}{3x+2y}$$

Ex@- Let $u = u(x, y)$, $x = s^2 + 3t$, $y = s^2t$. Find $\frac{\partial u}{\partial s^2}$

$$\frac{\partial u}{\partial s} = \frac{\partial u}{\partial x} \cdot \frac{\partial x}{\partial s} + \frac{\partial u}{\partial y} \cdot \frac{\partial y}{\partial s}$$

$$\left\{ \begin{array}{l} \frac{\partial x}{\partial s} = 2s \\ \frac{\partial y}{\partial s} = 2st \\ \frac{\partial x}{\partial t} = 3 \\ \frac{\partial y}{\partial t} = s^2 \end{array} \right.$$

$$\begin{aligned}\frac{\partial}{\partial s} \left(\frac{\partial u}{\partial s} \right) &= \frac{\partial}{\partial s} \left(\frac{\partial u}{\partial x} \cdot \frac{\partial x}{\partial s} + \frac{\partial u}{\partial y} \cdot \frac{\partial y}{\partial s} \right) \\ &= \frac{\partial}{\partial s} \left(\frac{\partial u}{\partial x} \right) \frac{\partial x}{\partial s} + \frac{\partial u}{\partial x} \cdot \frac{\partial}{\partial s} \left(\frac{\partial x}{\partial s} \right) + \frac{\partial}{\partial s} \left(\frac{\partial u}{\partial y} \right) \frac{\partial y}{\partial s} + \frac{\partial u}{\partial y} \cdot \frac{\partial}{\partial s} \left(\frac{\partial y}{\partial s} \right)\end{aligned}$$

* $\frac{\partial}{\partial s} \left(\frac{\partial u}{\partial x} \right) = \frac{\partial}{\partial x} \left(\frac{\partial u}{\partial x} \right) \frac{\partial x}{\partial s} + \frac{\partial}{\partial y} \left(\frac{\partial u}{\partial x} \right) \frac{\partial y}{\partial s} = 2s u_{xx} + 2st u_{xy}$

* $\frac{\partial}{\partial s} \left(\frac{\partial u}{\partial y} \right) = \frac{\partial}{\partial x} \left(\frac{\partial u}{\partial y} \right) \frac{\partial x}{\partial s} + \frac{\partial}{\partial y} \left(\frac{\partial u}{\partial y} \right) \frac{\partial y}{\partial s} = 2s u_{xy} + 2st u_{yy}$

$$\begin{aligned}\Rightarrow \frac{\partial}{\partial s} \left(\frac{\partial u}{\partial s} \right) &= (2s u_{xx} + 2st u_{xy}) (2s) + u_x (2) + (2s u_{xy} + 2st u_{yy}) (2st) + u_y (2t) \\ &= 4s^2 u_{xx} + 4st u_{xy} + 2u_x + 4s^2 t u_{xy} + 4s^2 t^2 u_{yy} + 2t u_y \\ &= 4s^2 u_{xx} + 4st u_{xy} (1+s) + 4s^2 t^2 u_{yy} + 2u_x + 2t u_y\end{aligned}$$