

# Multivariable Calculus Unit 3 Study Guide

## 1 Continuity

$$\lim_{(x,y) \rightarrow (0,0)} \frac{x^2 y}{x^4 + y^2}$$

Test the following:

$$\lim_{\text{along } x\text{-axis}} \frac{x^2 * 0}{x^4 + 0^2} = \lim_{x \rightarrow 0} \frac{0}{x^4} = 0$$

$$\lim_{\text{along } y\text{-axis}} \frac{0^2 * y}{0^4 + y^2} = \lim_{y \rightarrow 0} \frac{0}{y^2} = 0$$

$$\lim_{\text{along } y=x} \frac{x^2 * x}{x^4 + x^2} = \lim_{x \rightarrow 0} \frac{x^3}{x^4 + x^2} = 0$$

$$\lim_{\text{along } y=x^2} \frac{x^2 * x^2}{x^4 + (x^2)^2} = \lim_{x \rightarrow 0} \frac{x^4}{2x^4} = \frac{1}{2}$$

## 2 Total Differential and Linear Approximation

$$df = \frac{\partial f}{\partial x} dx + \frac{\partial f}{\partial y} dy$$

$$\Delta f \approx \frac{\partial f}{\partial x} \Delta x + \frac{\partial f}{\partial y} \Delta y$$

Let  $f(x, y) = \sqrt{x^2 + y^2}$ , use the total differential to approximate  $f(1.02, 1.99)$ .

$$\frac{\partial f}{\partial x} = \frac{1}{2\sqrt{x^2 + y^2}} \frac{\partial}{\partial x} (x^2 + y^2) = \frac{x}{\sqrt{x^2 + y^2}}$$

$$\frac{\partial f}{\partial y} = \frac{1}{2\sqrt{x^2 + y^2}} \frac{\partial}{\partial y} (x^2 + y^2) = \frac{y}{\sqrt{x^2 + y^2}}$$

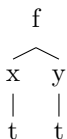
$$f(1, 2) = \sqrt{5} \quad \Delta x = 0.02 \quad \Delta y = -0.01$$

$$\Delta f = \frac{1}{\sqrt{1^2 + 2^2}} (0.02) + \frac{2}{\sqrt{1^2 + 2^2}} (-0.01) = 0$$

$$f(1.02, 1.99) = f(1, 2) + \Delta f = \sqrt{5}$$

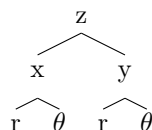
### 3 Chain Rule

$$f(x(t), y(t))$$



$$\frac{df}{dt} = \frac{\partial f}{\partial x} \frac{dx}{dt} + \frac{\partial f}{\partial y} \frac{dy}{dt}$$

Let  $z^2x - zy^2 + 2 = 0$  where  $x = r\cos\theta$  and  $y = r\sin\theta$ . Find  $\frac{\partial z}{\partial r}$  when  $r = 2$  and  $\theta = \frac{\pi}{2}$ .



$$\frac{\partial z}{\partial r} = \frac{\partial z}{\partial x} \frac{\partial x}{\partial r} + \frac{\partial z}{\partial y} \frac{\partial y}{\partial r}$$

Let  $f(x, y, z) = z^2x - zy^2 + 2$

$$\frac{\partial z}{\partial x} = -\frac{\frac{\partial f}{\partial x}}{\frac{\partial f}{\partial z}} = -\frac{z^2}{2xz - y^2}$$

$$\frac{\partial z}{\partial y} = -\frac{\frac{\partial f}{\partial y}}{\frac{\partial f}{\partial z}} = -\frac{-2yz}{2xz - y^2}$$

$$\frac{\partial x}{\partial r} = \cos\theta$$

$$\frac{\partial y}{\partial r} = \sin\theta$$

$$\frac{\partial z}{\partial r} = \frac{-z^2}{2xz - y^2} \cos\theta + \frac{2yz}{2xz - y^2} \sin\theta$$

Calculate  $x, y, z$  when  $r = 2$  and  $\theta = \frac{\pi}{2}$

$$x = 2\cos\frac{\pi}{2} = 0$$

$$y = 2\sin\frac{\pi}{2} = 2$$

$$z^2 * 0 - z * 2^2 + 2 = 0, z = \frac{1}{2}$$

$$\frac{\partial z}{\partial r} = \frac{-(\frac{1}{2})^2}{(2)(0)(\frac{1}{2}) - (2)^2} \cos(\frac{\pi}{2}) + \frac{(2)(2)(\frac{1}{2})}{(2)(0)(\frac{1}{2}) - (2)^2} \sin(\frac{\pi}{2}) = -\frac{1}{2}$$

## 4 Directional Derivative

The directional derivative in the given direction  $\vec{u}$  at point  $P : (x_0, y_0, z_0)$

$$D_{\vec{u}}f = \nabla f \cdot \vec{u}$$

$$\nabla f(x_0, y_0, z_0) = \left\langle \frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z} \right\rangle$$

ex. Find  $D_{\vec{u}}f$  of  $f(x, y) = x^2 + 2y^2$  in the direction  $\langle 3, 4 \rangle$  at  $(1, 2)$

$$\nabla f = \langle 2x, 4y \rangle \rightarrow \langle 2, 8 \rangle$$

$$\vec{u} = \left\langle \frac{3}{5}, \frac{4}{5} \right\rangle$$

$$D_{\vec{u}}f = \langle 2, 8 \rangle \cdot \left\langle \frac{3}{5}, \frac{4}{5} \right\rangle = \frac{38}{5}$$

The unit vector  $\vec{u}$  in the direction of fastest increase or maximum  $D_{\vec{u}}f$  given a point  $P : (x_0, y_0, z_0)$

$$\vec{u} = \frac{\nabla f(x_0, y_0, z_0)}{\|\nabla f(x_0, y_0, z_0)\|}$$

ex. Find a unit vector in the direction in which  $f(x, y) = (x^2 + y^2)^{\frac{3}{2}}$  increases most rapidly at the point  $(5, -13)$

$$\vec{u} = \left\langle \frac{3}{2}(x^2 + y^2)^{\frac{1}{2}}(2x), \frac{3}{2}(x^2 + y^2)^{\frac{1}{2}}(2y) \right\rangle \rightarrow \langle 15\sqrt{194}, -39\sqrt{194} \rangle$$

$$\vec{u} = \left\langle \frac{15\sqrt{194}}{582}, \frac{-39\sqrt{194}}{582} \right\rangle = \left\langle \frac{5\sqrt{194}}{194}, \frac{-13\sqrt{194}}{194} \right\rangle$$

## 5 Tangent Planes and Normal Vectors

Normal vector  $\vec{n}$  to the tangent plane at point  $P : (x_0, y_0, z_0)$

$$\vec{n} = \nabla f(x_0, y_0, z_0)$$

Tangent plane equation at point  $P$

$$T = \nabla f(x_0, y_0, z_0) \cdot \langle x - x_0, y - y_0, z - z_0 \rangle = 0$$

Line normal to the surface at point  $P$

$$\vec{r}(t) = \langle x_0, y_0, z_0 \rangle + t\nabla f(x_0, y_0, z_0)$$

Given surface  $2z^2 \cos(xy) + \frac{z}{x} + 2$  find the normal vector  $\vec{n}$  and the tangent plane at the point  $(\frac{1}{3}, \pi, -1)$ .

$$w(x, y, z) = 2z^2 \cos(xy) + \frac{z}{x} + 2$$

$$\nabla w = \langle -2yz^2 \sin(xy) - \frac{z}{x^2}, -2xz^2 \sin(xy), 4z \cos(xy) + \frac{1}{x} \rangle$$

$$\vec{n} = \nabla w(\frac{1}{3}, \pi, -1) = \langle -\sqrt{3}\pi + 9, -\frac{\sqrt{3}}{3}, 1 \rangle$$

$$T = \langle -\sqrt{3}\pi + 9, -\frac{\sqrt{3}}{3}, 1 \rangle \cdot \langle x - \frac{1}{3}, y - \pi, z + 1 \rangle = (9 - \sqrt{3}\pi)x + \frac{2\pi - y}{\sqrt{3}} + z - 2$$

$$\vec{r}(t) = \langle \frac{1}{3}, \pi, -1 \rangle + t \langle -\sqrt{3}\pi + 9, -\frac{\sqrt{3}}{3}, 1 \rangle$$

## 6 Optimization and 2nd Derivative Test

Second derivative in the direction  $\vec{u} = \langle u_1, u_2 \rangle$

$$D_{\vec{u}}^2 f = f_{xx}(u_1 + \frac{u_2 f_{xy}}{f_{xx}})^2 + \frac{u_2^2}{f_{xx}}(f_{xx} f_{yy} - f_{xy}^2)$$

Find critical points

$$\nabla f = \langle \frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z} \rangle = 0$$

Second derivative test

$$D = f_{xx} f_{yy} - f_{xy}^2$$

Local minimum if  $D > 0$  and  $f_{xx} > 0$

Local maximum if  $D > 0$  and  $f_{xx} < 0$

Saddle point if  $D < 0$

Optimization given constraints using Lagrange Multipliers

$$f(x, y) = xye^{-\frac{(x^2+y^2)}{2}} \quad x^2 + y^2 \leq 4$$

$$g(x, y) = x^2 + y^2$$

$$\nabla f = \langle ye^{-\frac{(x^2+y^2)}{2}}(1-x^2), xe^{-\frac{(x^2+y^2)}{2}}(1-y^2) \rangle \quad \nabla g = \langle 2x, 2y \rangle$$

$$\nabla f = \lambda \nabla g$$

$$ye^{-\frac{(x^2+y^2)}{2}}(1-x^2) = 2x\lambda$$

$$xe^{-\frac{(x^2+y^2)}{2}}(1-y^2) = 2y\lambda$$

$$x^2 + y^2 = 4$$

$$\frac{y(1-x^2)}{x(1-y^2)} = \frac{x}{y}$$

$$y^2(1-x^2) = x^2(1-y^2)$$

$$y^2 - x^2 y^2 = x^2 - x^2 y^2$$

$$y^2 = x^2$$

$$x^2 + x^2 = 4 \rightarrow (x, y) = (\pm\sqrt{2}, \pm\sqrt{2})$$

$$f(\sqrt{2}, \sqrt{2}) = f(-\sqrt{2}, -\sqrt{2}) = 2e^{-2}$$

$$f(\sqrt{2}, -\sqrt{2}) = f(-\sqrt{2}, \sqrt{2}) = -2e^{-2}$$

Absolute maximum at  $(\sqrt{2}, \sqrt{2})$  and  $(-\sqrt{2}, -\sqrt{2})$

Absolute minimum at  $(\sqrt{2}, -\sqrt{2})$  and  $(-\sqrt{2}, \sqrt{2})$