Calc in 3d Notes

saffron_

Contents

Chapter 2: Vectors in Space

Graphing
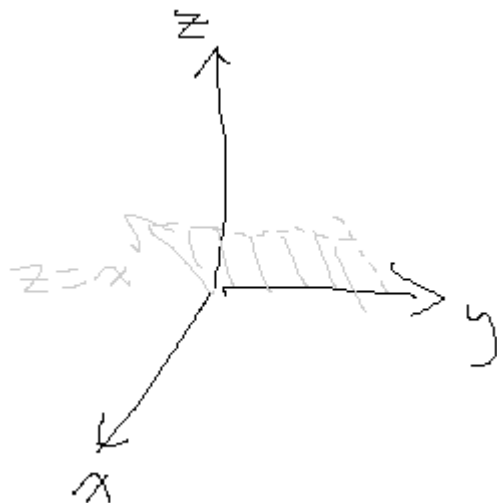
convention

sphere: $(x-1)^2 + (y-2)^2 + (z+3)^2 = 9$

The Vector

$\vec{v} = \langle -3, 4 \rangle$ $\|\vec{v}\| = 5$

$\theta \approx 127°$

$\hat{u} = \langle -\frac{3}{5}, \frac{4}{5} \rangle$

- a quantity with a magnitude and direction

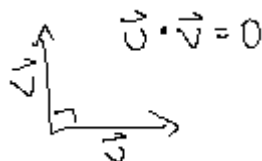- unit vector $\hat{u} = \dfrac{\vec{v}}{\|\vec{v}\|}$

Vector Operations

- Addition

  - $\vec{a} = \langle 1, 2 \rangle$, $\vec{b} = \langle 3, 4 \rangle$
  - $\vec{a} + \vec{b} = \langle 4, 6 \rangle$

- Scalar Multiplication

  - $\vec{v} = \langle 1, 3 \rangle$, $c = 2$
  - $c\vec{v} = \langle 2, 6 \rangle$

simple inverses for subtraction and scalar division exist.

- Dot Product (also 2d!)

  - geom.:

  $$\vec{u} \cdot \vec{v} = \|\vec{u}\| \, \|\vec{v}\| \cos \theta$$

  - alg.:
    $\vec{u} = \langle u_1, u_2, u_3 \rangle$, $\vec{v} = \langle v_1, v_2, v_3 \rangle$
    $\vec{u} \cdot \vec{v} = \sum u_i v_i$
  - $\vec{v} \cdot \vec{v} = \|\vec{v}\|^2$
  - two vectors are orthogonal aka $\perp$ iff their dot product is 0
  - $\cos \theta = \dfrac{\vec{u} \cdot \vec{v}}{\|u\| \, \|v\|}$ wtf is equation 2.5 "unique over this range" on abt
  - work $= \vec{F} \cdot \vec{D}$
  - comp (scalar projection)

  $$\operatorname{comp}_{\vec{u}} \vec{v} = \|\vec{v}\| \cos \theta$$
  $$= \frac{\vec{u} \cdot \vec{v}}{\|\vec{u}\|}$$

  - proj (vector projection)

  $$\operatorname{proj}_{\vec{u}} \vec{v} = \operatorname{comp}_{\vec{u}} \vec{v} \cdot \frac{\vec{u}}{\|\vec{u}\|}$$
  $$= \frac{\vec{u} \cdot \vec{v}}{\|\vec{u}\|^2} \vec{u}$$

- Cross Product (3d)

  - geom.:

  $$\|\vec{u} \times \vec{v}\| = \|\vec{u}\| \, \|\vec{v}\| \sin \theta$$

  - alg.:

  - $\vec{u} \times \vec{v} = \det \begin{vmatrix} \hat{\imath} & \hat{\jmath} & \hat{k} \\ u_1 & u_2 & u_3 \\ v_1 & v_2 & v_3 \end{vmatrix}$

  - result is $\perp$ to both input vectors, direction by right hand rule
  - triple scalar product:
    $\vec{u} \cdot (\vec{v} \times \vec{w})$
    $= (\vec{u} \times \vec{v}) \cdot \vec{w}$
    $= \det \begin{vmatrix} u_1 & u_2 & u_3 \\ v_1 & v_2 & v_3 \\ w_1 & w_2 & w_3 \end{vmatrix}$
  - if $\vec{u}$ and $\vec{v}$ are the sides of a parallelogram, then its area is $\|\vec{u} \times \vec{v}\|$
  - if a parallelepiped has edges $\vec{u}, \vec{v}, \vec{w}$, its volume is the absolute value of its triple scalar product
  - torque $= \vec{\tau} = \vec{r} \times \vec{F}$

Lines

(1) Vector Equation Form

$\vec{r} = \vec{r_0} + t\vec{v}$
eg $\langle x, y, z \rangle = \langle 1, 2, -5 \rangle + t \langle 3, -4, -1 \rangle$

(2) Parametric Equation Form

$$x = 1 + 3t$$
$$y = 2 - 4t$$
$$z = -5 - t$$

(3) Symmetric Equation Form

solve for t

$$\frac{x-1}{3} = \frac{y-2}{-4} = \frac{z+5}{-1}$$

(4) Edge Case: 0-component

Let a line be defined by the point and vector $(1, -2, 6)$ and $\langle 3, 7, 0 \rangle$. We say the line is:

$$\frac{x-1}{3} = \frac{y+2}{7}, z = 6$$

- point to line distance: use paralleogram area trick

Planes

(1) Vector Equation Form

$(\vec{r} - \vec{r_0}) \cdot \vec{n} = 0$
eg $(\langle x, y, z \rangle - \langle 1, 0, 1 \rangle) \cdot \langle 1, 2, -3 \rangle = 0$

(2) Scalar Equation, "General" Form

$ax + by + cz + d = 0$

- point to plane distance: use $\text{comp}_{\vec{u}} \vec{v}$ trick

- angle between planes: same as angle between their normal vectors

Quadric Surfaces

- cylinder: 3d shape consisting of all parallel lines (eg $y = 3x^2$)

- see `quadric_surfaces.pdf`

Chapter 3: Vector-Valued Functions

Vector-Valued Function

$$\vec{r}(t) = \langle f(t), g(t), h(t) \rangle, i < t < j$$

Unit Circle Parameterization
temp

Limits of VVFs

- pass them into the vec. pretty intuitive

- a VVF $\vec{r}(a)$ is cont. at a iff $\lim_{t \to a} \vec{r}(t) = \vec{r}(a)$ (and both are defined)

Calc with VVFs

- derivatives are intuitive. use the corresponding dot/cross/scalar in deriving $\vec{u} \cdot \vec{v}$

- unit tangent vector is the derivative's unit vector

- integrals are intuitive. consider constant vector C instead of scalar constant

Consult exam 1 cheatsheet for notes on the rest of the chapter

Chapter 4: Differentiation

Functions of Multiple Variables

- domain: analyze what values are invalid

- range: image of domain

- level planes/level surfaces/contour maps: setting the function to some constant and drawing out the resulting shape

Limits and Continuity

- limit rules are identical to 2d, including

- limits must be unique. ie, the δ disk around a point must only contain one value. (disprove limit by finding different values through different "paths" to the limit)

- as in 2d, $f(x, y)$ is continuous at (a, b) iff

$$\lim_{(x,y)\to(a,b)} f(x, y) = f(a, b)$$

  with both defined.

- sum, product, comp of cont functions: cont

Partial Derivatives

- slope of line in a direction, at a point

- Limit definition:

$$\frac{\partial f}{\partial x} = \lim_{h\to 0} \frac{f(x + h, y) - f(x, y)}{h}$$

- four second order partials exist

$$\frac{\partial^2 f}{\partial x^2} = \frac{\partial}{\partial x}\left[\frac{\partial f}{\partial x}\right] = f_{xx}$$

$$\frac{\partial^2 f}{\partial x \partial y} = \frac{\partial}{\partial x}\left[\frac{\partial f}{\partial y}\right] = f_{yx}$$

$$\frac{\partial^2 f}{\partial y \partial x} = \frac{\partial}{\partial y}\left[\frac{\partial f}{\partial x}\right] = f_{xy}$$

$$\frac{\partial^2 f}{\partial y^2} = \frac{\partial}{\partial y}\left[\frac{\partial f}{\partial y}\right] = f_{yy}$$

- Clairaut's Thrm: if f_{xy} and f_{yx} are cont near a point, they are equal

Tangent Planes

- if all tangent lines to a point are in the same plane, call that the tangent plane

  - (not true if there is a point)

  - maybe theres a correlation somewhere with differentiability? (p393)

- the tangent plane to $z = f(x, y)$ at (a, b) is

$$z = f(a, b) + f_x(a, b)(x - a) + f_y(a, b)(y - b)$$

- find an approx at (a, b) via the linear approximation plane $L(x, y) = \text{RHS}$ (above)

- a function is differentiable at (a, b) iff

$$f(x, y) = \text{RHS} + E(x, y)$$

  where the error term E satisfies

$$\lim_{(x,y)\to(a,b)} \frac{E(x, y)}{\sqrt{(x - a)^2 + (y - b)^2}} = 0.$$

  alternatively, if f, f_x, and f_y exist near (a, b) and are cont. at (a, b), then f is differentiable there.

- let $z = f(x, y)$ with (a, b) in the domain of f, and let Δx and Δy be chosen such that $(a + \Delta x, b + \Delta y)$ is also in the domain of f. then

$$dx = \Delta x$$
$$dy = \Delta y$$
$$dz = f_x(a, b)dx + f_y(a, b)dy.$$

  dx and dy are differentials, dz the "total differential," and we estimate error with it.

  notice the similarity to the tangent plane equation.
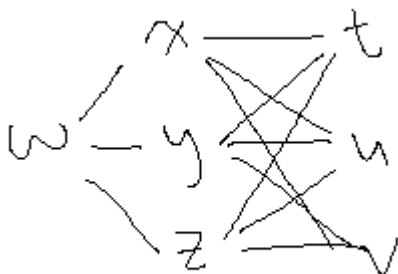
5

The Chain Rule

- consider

$$w = f(x, y, z)$$
$$x = x(t, u, v)$$
$$y = y(t, u, v)$$
$$z = z(t, u, v)$$

.

then,

$$\frac{\partial w}{\partial t} = \frac{\partial w}{\partial w}\frac{\partial x}{\partial t} + \frac{\partial w}{\partial y}\frac{\partial y}{\partial t} + \frac{\partial w}{\partial z}\frac{\partial z}{\partial t}.$$

others are left as an exercise to the reader.

Implicit Differentiation

- consider $x^2 + 3y^2 + 4y - 4 = 0$.

  to find $\frac{dy}{dx}$, we may implicitly differentiate this by taking $\frac{d}{dx}$ of both sides and solving.

  but we may also define

  $$f(x, y) = x^2 + 3y^2 + 4y - 4, f(x, y) = 0.$$

  with this in mind, suppose $f(x, y) = 0$. then,

  $$\frac{dy}{dx} = -\frac{\partial f/\partial x}{\partial f/\partial y}$$

  and if $f(x, y, z) = 0$,

  $$\frac{\partial z}{\partial x} = -\frac{\partial f/\partial x}{\partial f/\partial z}, \frac{\partial z}{\partial y} = -\frac{\partial f/\partial y}{\partial f/\partial z}.$$

  these can be derived from the chain rule.

Directional Derivatives and the Gradient

- the directional derivative of $f(x, y)$ in the direction $\hat{u} = \langle \cos\theta, \sin\theta \rangle$ is

  $$D_{\hat{u}}f(a, b) = \lim_{h \to 0} \frac{f(a + h\cos\theta, b + h\sin\theta) - f(a, b)}{h}$$

  alternatively, if the partials exist,

  $$D_{\hat{u}}f(x, y) = f_x(x, y)\cos\theta + f_y(x, y)\sin\theta$$
  $$= \langle f_x(x, y), f_y(x, y) \rangle \cdot \hat{u}$$
  $$= \nabla f(x, y) \cdot \hat{u}.$$

- $\nabla f(x, y)$ is called the gradient and points toward the greatest increase of a function. it's perpendicular to the graph's level curves (if the partials are cont. near the points)

- suppose $z = f(x, y)$ diffbl at (a, b).

  – if $\nabla f(a, b) = \vec{0}$, then $D_{\hat{u}}f(a, b) = 0$ for any $\hat{u}$

  – if $\nabla f(a, b) \neq \vec{0}$, then $D_{\hat{u}}f(a, b)$ is max when $\hat{u}$ is in the same direction as $\nabla f(a, b)$.
    max of $D_{\hat{u}}f(a, b)$ is $\|\nabla f(a, b)\|$

  – if $\nabla f(a, b) \neq \vec{0}$, then $D_{\hat{u}}f(a, b)$ is min when $\hat{u}$ is in the opposite direction as $\nabla f(a, b)$.
    min of $D_{\hat{u}}f(a, b)$ is $-\|\nabla f(a, b)\|$

- yes, these work for multivar funcs.

TODO do example 4.34-5 on page 429 and onwards

Finding Maxima/Minima

- like 2d, critical points (a, b) exist iff
  - $f_x(a, b) = f_y(a, b) = 0$
  - or the partials there don't exist
- local extrema are crit points
- Second Derivative Test (for 3d calc)

  let $z = f(x, y)$ where the first and second order partials are cont near a point (a, b)

  $$D = f_{xx}(a, b)f_{yy}(a, b) - (f_{xy}(a, b))^2$$

  - $D > 0$ and $f_{xx}(a, b) > 0$
    $\Rightarrow f$ has a local min at (a, b)
  - $D > 0$ and $f_{xx}(a, b) < 0$
    $\Rightarrow f$ has a local max at (a, b)
  - $D < 0$
    $\Rightarrow f$ has a saddle point at (a, b)
  - $D = 0$
    $\Rightarrow$ the test is inconclusive
- to find local extrema:

  1. find crit points. discard if a partial DNE
  2. find discriminant D for each point
  3. apply 2nd derivative test
- Extreme Value Theorem

  a cont function on a closed and bounded set has an abs min and abs max in the set
- the abs max and abs min will be either at a critical point or on a boundry
- to analyze the boundry, consider parameterizing line segments/ellipses or using Lagrange multipliers

Lagrange Multipliers

- Theory: consider an objective function and a constraint function. when they are tangent, their gradients must be in the same direction. so, we say they are different by λ, the Lagrange multiplier.
- Let $f(x, y)$ and $g(x, y)$ have cont partials along $g(x, y) = 0$. if f has a local extrema on $g(x, y) = 0$ at (a, b) and $\nabla g(a, b) \neq 0$, then
  $$\nabla f(a, b) = \lambda \nabla g(a, b)$$
- to use λ (yes, f and g may be fn of 3 vars):

  1. find the objective function $f(x, y)$, constraint function $g(x, y)$.
  2. solve for a and b using
     $$\nabla f(a, b) = \lambda \nabla g(a, b)$$
     $$g(a, b) = 0$$
  3. largest value of f will be largest among all $f(a, b)$ found. similar for smallest.
- alternatively, with two constraints:

  let obj fn be $w = f(x, y, z)$, and constraint fns $g(x, y, z) = 0$, $h(x, y, z) = 0$. solve for
  $$\nabla f(a, b, c) = \lambda_1 \nabla g(a, b, c) + \lambda_2 \nabla h(a, b, c)$$
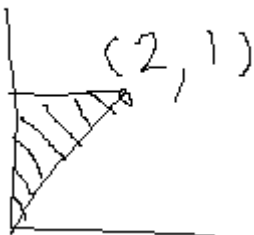 $$g(a, b, c) = 0$$
  $$h(a, b, c) = 0.$$

TODO CLOSED/OPEN SETS AND STUFF

Chapter 5: Multiple Integration

Double Integration

- Consider

.

- its area via a double integral:

$$\int_{x=0}^{x=2}\int_{y=\frac{1}{2}x}^{2}1\,dy\,dx.$$

- notice the order of bounds variables.

- to change order of integration, graph the region to get the bounds ($x=$, $y=$) correct

- for improper integrals that come from unbounded functions, adapting the above is fine.

- but for improper integrals that come from unbounded regions, consider $\iint xye^{-x^2-y^2}\,dA$ for the first quadrant. then we set up and solve

$$\lim_{(b,d)\to(\infty,\infty)}\int_0^b\int_0^d xye^{-x^2-y^2}\,dy\,dx$$

$$=\lim_{(b,d)\to(\infty,\infty)}\int_0^b\int_0^d xe^{-x^2}ye^{-y^2}\,dy\,dx$$

$$=\lim_{(b,d)\to(\infty,\infty)}\int_0^b xe^{-x^2}\,dx\int_0^b ye^{-y^2}\,dy$$

$$=\dots$$

$$=\frac{1}{4}$$

- converting to polar from rectangular? use

$$x = r\cos\theta$$
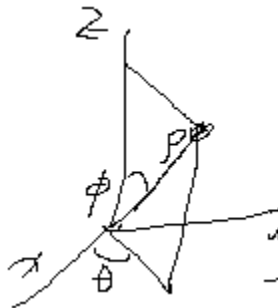$$y = r\sin\theta$$
$$dA = r\,dr\,d\theta$$

Triple Integration

- six orderings exist for bounds. one ex:

$$\iiint\limits_E f(x,y,z)\,dV$$

$$=\int_{x=a}^{x=b}\int_{y=g_1(x)}^{y=g_2(x)}\int_{z=h_1(x,y)}^{z=h_2(x,y)} f(x,y,z)\,dz\,dy\,dx.$$

- think: fix x with first bound. now we can use x in the second bound. etc.

- avg value of f on region E:

$$\text{Avg}(f) = \frac{1}{\text{Vol}(E)}\iiint\limits_E f\,dV$$

- rect to cylindrical? just polar, but keep z. $dV = r\,dz\,dr\,d\theta$ is usually best.

- cyl to rect? $r = \sqrt{x^2+y^2}, \tan\theta = y/x$, keep z. careful: $\forall\theta, \tan^{-1}(\theta)\in(-\frac{\pi}{2},\frac{\pi}{2})$

- consider spherical:

- rect to spherical: $\rho^2 = x^2+y^2+z^2$, $\tan\theta = \frac{y}{x}, \phi = \cos^{-1}\left(\frac{z}{\sqrt{x^2+y^2+z^2}}\right)$

  $dV = \rho^2\sin\phi\,d\rho\,d\theta\,d\phi$ usually best?

- cyl to spherical: $\rho^2 = r^2+z^2$, $\theta = \theta, \phi = \cos^{-1}\left(\frac{z}{\sqrt{r^2+z^2}}\right)$

- spherical to rect: $x = \rho\sin\phi\cos\theta$, $y = \rho\sin\phi\sin\theta, z = \rho\cos\phi$

- spherical to cyl: $r = \rho\sin\phi$, $\theta = \theta, z = \rho\cos\phi$

Appendix

Sorted newest first

double integral properties

for most properties, just feel it out from single integrals.

but some more esoteric ones (even if in notation only) exist:

- if $m \leq f(x,y) \leq M$, then

$$m \times A(R) \leq \iint_R f(x,y)dA \leq M \times A(R).$$

- if $f(x,y)$ is factorable as a product of $g(x)$ (of x only) and $h(y)$ (of y only), then over $R = \{(x,y) \mid a \leq x \leq b, c \leq y \leq d\}$,

$$\iint_R f(x,y)dA = \left(\int_a^b g(x)dx \right) \left(\int_c^d h(y)dy \right).$$

  I think this is because of that property where you can factor out numbers, applied creatively several times?

cross/dot products

- see:
  - `media/cross_prod_area_ex.png`
  - `media/scalar_projection_composition_ex.png`
  - `media/scalar_triple_prod_parallelepiped_ex.png`

matrices, 3x3 determinants

In depth lesson:

- `https://www.mathcentre.ac.uk/resources/uploaded/sigma-matrices9-2009-1.pdf`

Recall that a elements of a matrix are enumerated a_{ij} where i is column and j is row, both 1-indexed.

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix}$$

Recall that the minor of the matrix element here is the 2 by 2 determinant when you take away the row and column of the element in a 3 by 3 matrix. Picking an arbitrary row (or even column), with a_{ij} being an element and M_{ij} being a minor, a 3 by 3 determinant is calculated by

$$\sum_{j=1}^{3}(-1)^{i+j}a_{ij}M_{ij}$$

In the figure `media/3x3determinant.png`, $(-1)^{i+j}$ is in green, a_{ij} in orange, and M_{ij} in blue.