

Green's Theorem

C : a simple closed curve

$\vec{F} = (M, N)$, M, N and

their first derivatives are cont.

in $R = \text{interior of } C$

Then

$$(i) \oint_C \vec{F} \cdot \vec{n} ds = \oint_C M dy - N dx = \iint_R (M_x + N_y) dA$$

(normal form) $\vec{n} ds = (dy, -dx) = \left(\frac{dy}{dt}, \frac{-dx}{dt} \right) dt$

$$(ii) \oint_C \vec{F} \cdot \vec{T} ds = \oint_C M dx + N dy = \iint_R (N_x - M_y) dA$$

(tangential form) $\vec{T} ds = \left(\frac{dx}{dt}, \frac{dy}{dt} \right) dt$

Rm $\vec{F} = (M, N) \leftrightarrow \vec{G} = (N, -M)$

normal form for \vec{F} = tangential form for \vec{G}
(tangential) (normal)

Rm They are special cases of

(Gauss) $\iiint_D \nabla \cdot \vec{F} \, dV = \iint_{\partial D} \vec{F} \cdot \vec{n} \, d\sigma$
(div \vec{F})

(Stokes) $\iint_S (\nabla \times \vec{F}) \cdot \vec{n} \, d\sigma = \int_{\partial S} \vec{F} \cdot \vec{T} \, ds$

$d\sigma$: surface integral

∂D : boundary of D (domain)

∂S : boundary of S (surface)

dt

where

$$\begin{aligned}\operatorname{div} \vec{F} &= \nabla \cdot \vec{F} = (\partial_x, \partial_y, \partial_z) \cdot (F_1, F_2, F_3) \\ &= \partial_x F_1 + \partial_y F_2 + \partial_z F_3\end{aligned}$$

$$\operatorname{curl} \vec{F} = \nabla \times \vec{F} = (\partial_x, \partial_y, \partial_z) \times (F_1, F_2, F_3)$$

$$= \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ \partial_x & \partial_y & \partial_z \\ F_1 & F_2 & F_3 \end{vmatrix}$$

$$= (\partial_y F_3 - \partial_z F_2, \partial_z F_1 - \partial_x F_3, \partial_x F_2 - \partial_y F_1)$$

Special case of Stokes': Take $S = R$. $\partial S = C$

$$\vec{F} = \begin{pmatrix} F_1 & F_2 \\ M & N & 0 \end{pmatrix}, \quad \vec{n} = (0, 0, 1) \Leftrightarrow C = \odot$$

$$\iint_S (\nabla \times \vec{F}) \cdot \vec{n} \, dS = \iint_R \underbrace{\partial_x F_2 - \partial_y F_1}_{N_x - M_y} \, dA = \oint_C \vec{F} \cdot \vec{T} \, ds$$

Eg 3 Verify both forms
of Green's Thm for

$$\vec{F}(x,y) = (x-y, x) \text{ and}$$

$$C: \vec{r}(t) = (\cos t, \sin t), \quad 0 \leq t \leq 2\pi$$

Sol normal form

$$\iint_{x^2+y^2 \leq 1} M_x + N_y \, dA = \oint_C \vec{F} \cdot \vec{n} \, ds$$

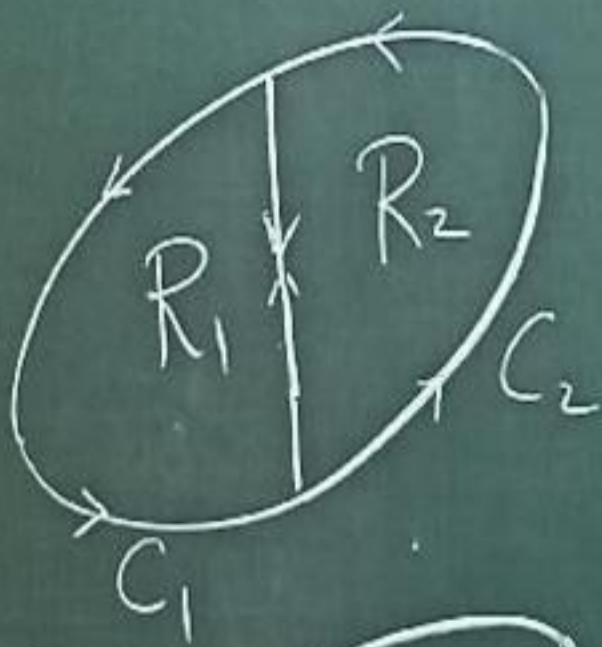
$$\text{LHS} = \iint_{x^2+y^2 \leq 1} 1 \, dA = \pi$$

$$\text{RHS} = \oint_C \vec{F} \cdot \left(\frac{dy}{dt}, -\frac{dx}{dt} \right) dt = \int_0^{2\pi} \begin{pmatrix} \cos t - \sin t \\ \cos t \end{pmatrix} \cdot \begin{pmatrix} \cos t \\ \sin t \end{pmatrix} dt = \pi$$

pf of Green's Theorem (tangential form)

$$(i) \oint_C \vec{F} \cdot \vec{T} ds = \oint_C M dx + N dy = \iint_R (N_x - M_y) dA$$

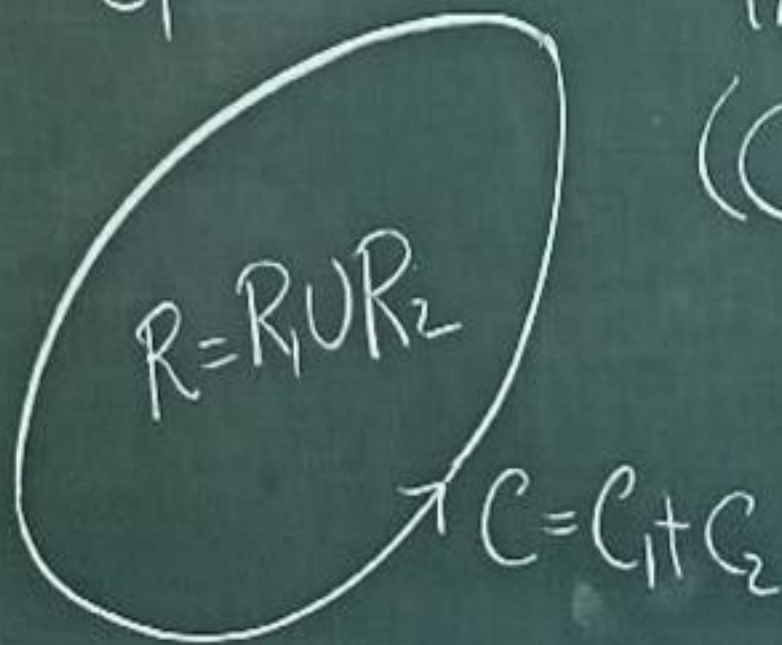
(pf for normal form is similar)



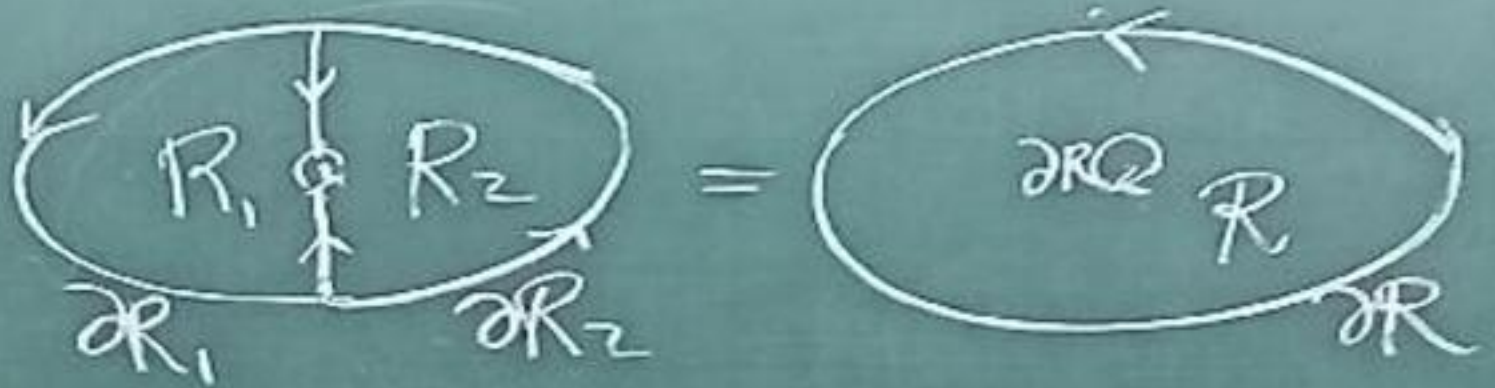
If (i) is true for (C_1, R_1) , (C_2, R_2) then it is true for (C, R) where

$$C = C_1 + C_2$$

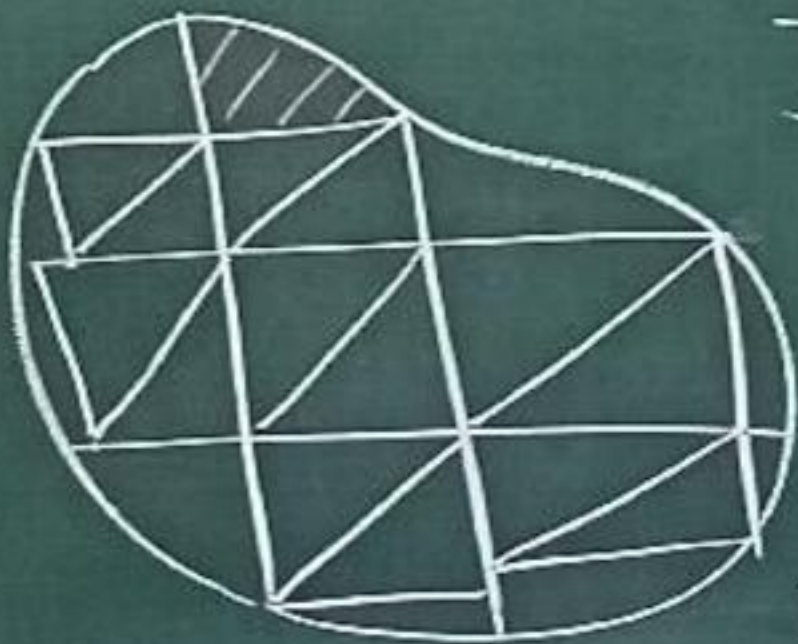
$$R = R_1 \cup R_2$$




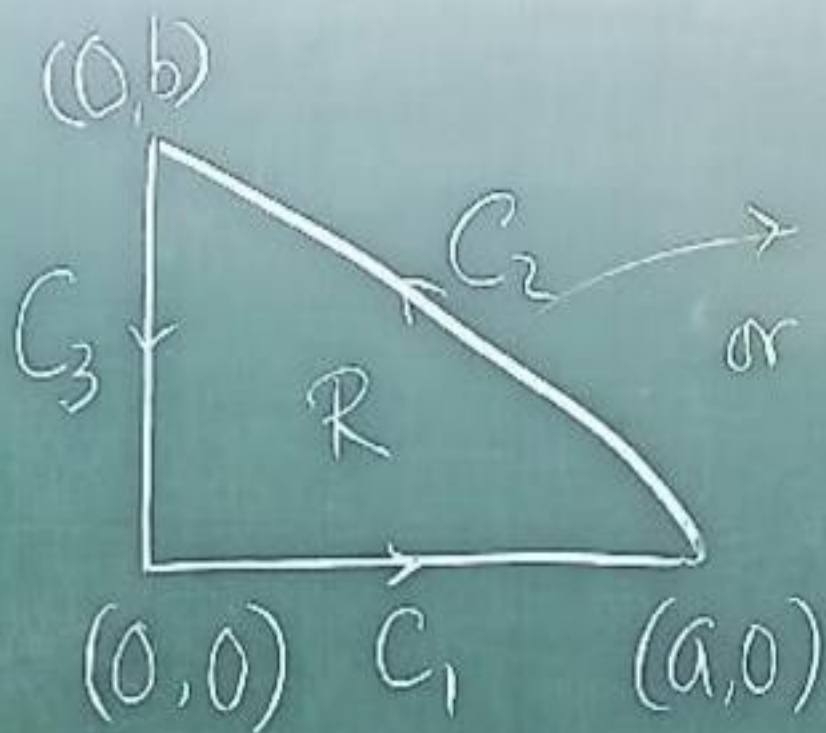
R_m in previous example



Similarly



In general,
it suffices to
verify R
of the form 



$$y = f(x) \quad 0 \leq x \leq a$$

$$\text{or } x = g(y) \quad 0 \leq y \leq b$$

$$C_2 = \{(x, f(x)), 0 \leq x \leq a\}$$

$$= \{(g(y), y), 0 \leq y \leq b\}$$

Check tangential form, line integrals:

$$\int_{C_1} \vec{F} \cdot \vec{T} dt = \int_{t=0}^a \vec{F} \cdot (1, 0) dt = \int_0^a M(t, 0) dt = \int_0^a M(x, 0) dx \quad \text{(I)}$$

$$\int_{C_3} \vec{F} \cdot \vec{T} dt = \int_{t=0}^b \vec{F} \cdot (0, -1) dt = - \int_{y=b}^0 N(0, y) (-dy)$$

$$\text{or } \int_{C_3 \downarrow} \vec{F} \cdot \vec{T} ds = - \int_{s=0}^b N(0, s) ds = - \int_{y=0}^b N(0, y) dy \quad \text{(III)}$$

$$\int_{C_2} \left(M \frac{dx}{dt} + N \frac{dy}{dt} \right) dt = \int_0^b \left(M(g(t), t) g'(t) + N(g(t), t) \right) dt$$

$$C_2 = \{y=t, x=g(t), 0 \leq t \leq b\} \quad \dot{x} = g'(t), \dot{y} = 1$$

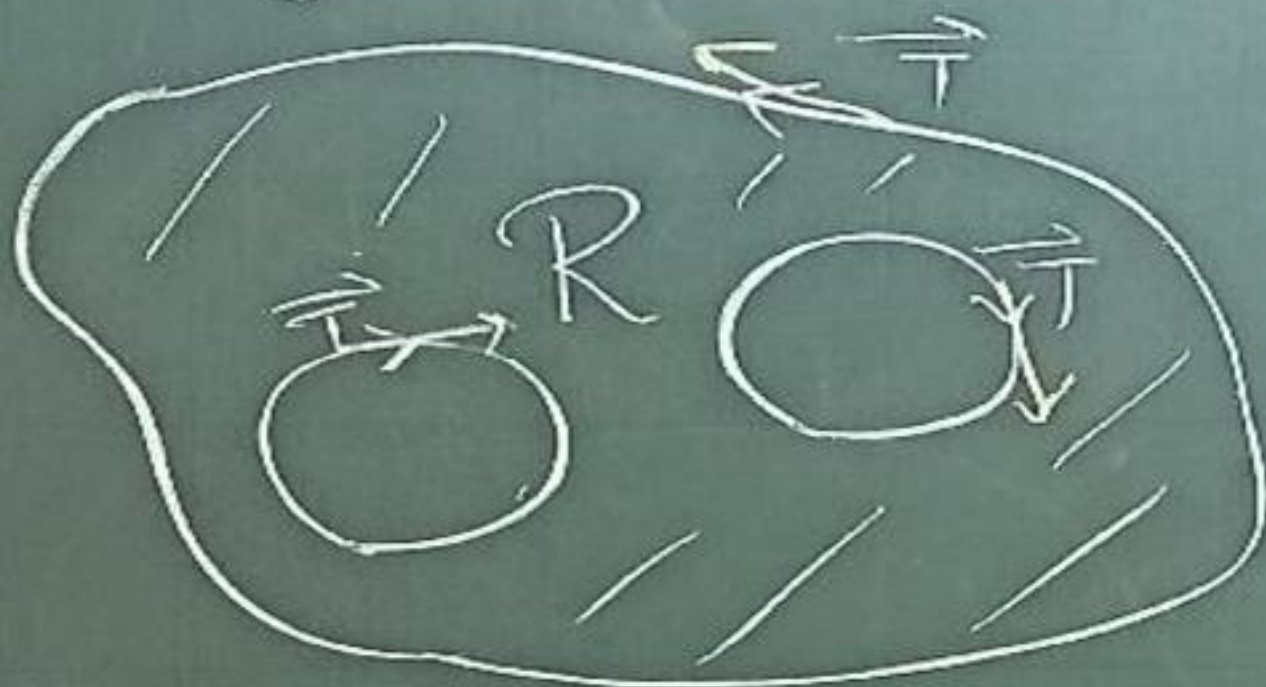
Double integrals $\iint (N_x - M_y) dA$

$$\iint_R N_x dA = \int_0^b \int_0^{g(y)} N_x dx dy = \int_0^b (N(g(y), y) - N(0, y)) dy$$

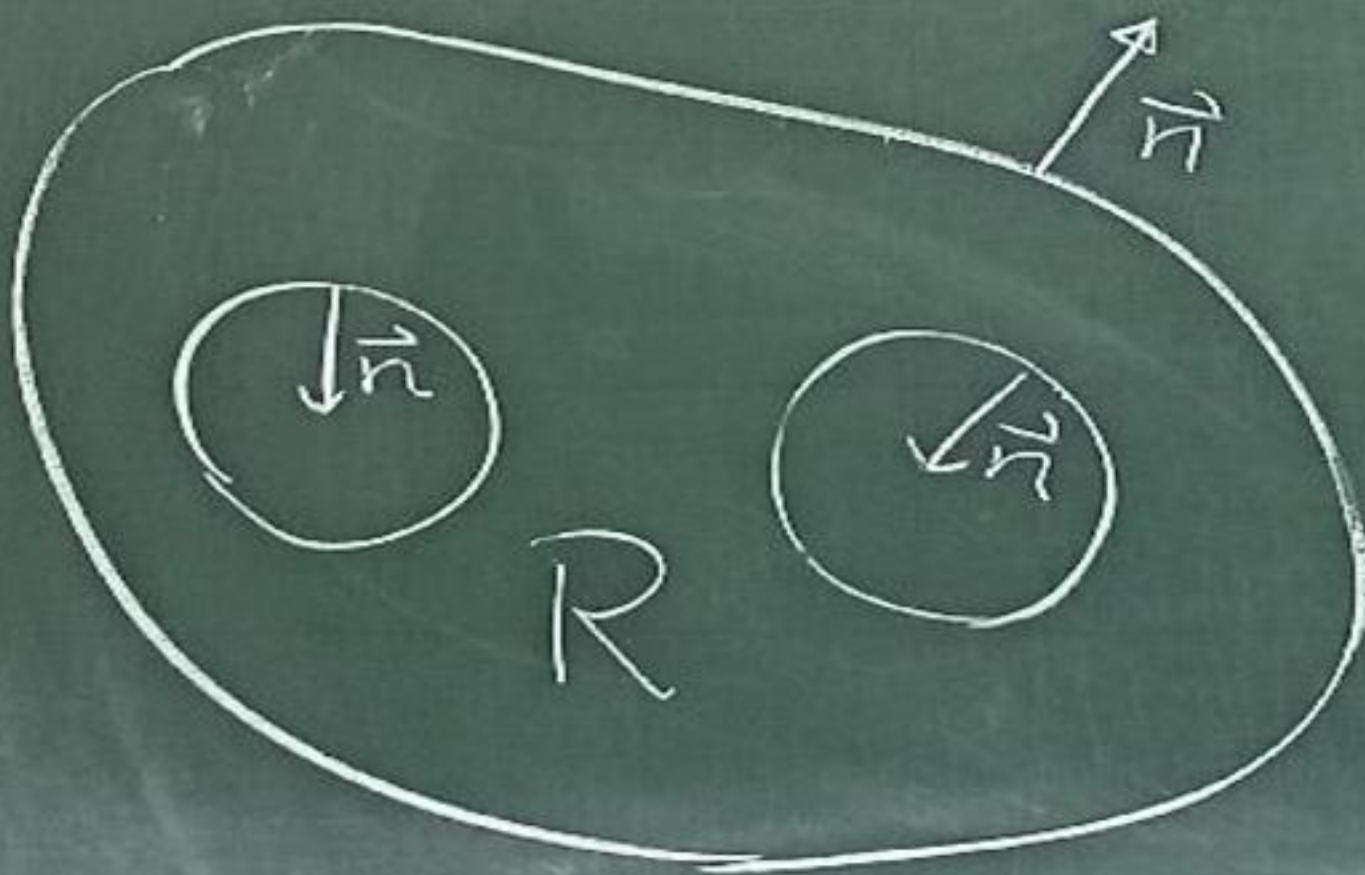
$$- \iint_R M_y dA = - \int_0^a \int_0^{f(x)} M_y dy dx = - \int_0^a (M(x, f(x)) - M(x, 0)) dx$$

$$(IV) = - \int_0^a M(x, f(x)) dx \quad y = f(x) \\ x = f^{-1}(y) \equiv g(y) \\ = - \int_{y=b}^0 M(g(y), y) g'(y) dy \quad dx = g'(y) dy \quad \therefore (i) \text{ verified}$$

Tangential form



Normal form



$$\underline{\underline{Rm}} \quad \text{For } \vec{F} = \frac{(-y, x)}{x^2 + y^2}$$

$$\oint_C \vec{F} \cdot \vec{T} ds = \begin{cases} 2\pi, & (0,0) \in R \\ 0, & (0,0) \notin R \end{cases}$$

$R =$ inside of C

$$\underline{\underline{Rm}} \quad \frac{(-y, x)}{x^2 + y^2} = \nabla \tan^{-1}\left(\frac{y}{x}\right)$$

But $\theta = \tan^{-1}\left(\frac{y}{x}\right)$ is NOT

everywhere defined on $x^2 + y^2 \neq 0$