

MATB42: Assignment #10

1. Let \mathbf{F} be a vector field on \mathbb{R}^3 given by $\mathbf{F} = (F_1, F_2, F_3)$ where F_1 , F_2 , and F_3 are C^1 -functions from $\mathbb{R}^3 \rightarrow \mathbb{R}$

- (a) Let η be the 2-form given by

$$\eta = F_3 dx dy + F_1 dy dz + F_2 dz dx$$

Show that $d\eta = (\operatorname{div} \mathbf{F}) dx dy dz$

(page 489, #6)

$$\begin{aligned}
 \eta &= F_3 dx dy + F_1 dy dz + F_2 dz dx \\
 d\eta &= d(F_3 dx dy + F_1 dy dz + F_2 dz dx) \\
 &= (dF_3) dx dy + (dF_1) dy dz + (dF_2) dz dx \\
 &= \left(\frac{\partial}{\partial x} F_3 dx + \frac{\partial}{\partial y} F_3 dy + \frac{\partial}{\partial z} F_3 dz \right) dx dy + (dF_1) dy dz + (dF_2) dz dx \\
 &= \frac{\partial}{\partial z} F_3 dz dx dy + (dF_1) dy dz + (dF_2) dz dx \\
 &= \frac{\partial}{\partial z} F_3 dx dy dz + \left(\frac{\partial}{\partial x} F_1 dx + \frac{\partial}{\partial y} F_1 dy + \frac{\partial}{\partial z} F_1 dz \right) dy dz + (dF_2) dz dx \\
 &= \frac{\partial}{\partial z} F_3 dx dy dz + \frac{\partial}{\partial x} F_1 dx dy dz + (dF_2) dz dx \\
 &= \frac{\partial}{\partial z} F_3 dx dy dz + \frac{\partial}{\partial x} F_1 dx dy dz + \left(\frac{\partial}{\partial x} F_2 dx + \frac{\partial}{\partial y} F_2 dy + \frac{\partial}{\partial z} F_2 dz \right) dz dx \\
 &= \frac{\partial}{\partial z} F_3 dx dy dz + \frac{\partial}{\partial x} F_1 dx dy dz + \frac{\partial}{\partial y} F_2 dy dz dx \\
 &= \frac{\partial}{\partial z} F_3 dx dy dz + \frac{\partial}{\partial x} F_1 dx dy dz + \frac{\partial}{\partial y} F_2 dx dy dz \\
 &= \frac{\partial}{\partial x} F_1 + \frac{\partial}{\partial y} F_2 + \frac{\partial}{\partial z} F_3 dx dy dz = (\operatorname{div} \mathbf{F}) dx dy dz
 \end{aligned}$$

(b) Show that $dF_1 \wedge dF_2 \wedge dF_3 = (\det D\mathbf{F}) dx dy dz$

$$df = \sum_{i=0}^n \frac{\partial f}{\partial x_i} dx_i$$

$$\begin{aligned}
dF_1 \wedge dF_2 \wedge dF_3 &= \left(\frac{\partial F_1}{\partial x} dx + \frac{\partial F_1}{\partial y} dy + \frac{\partial F_1}{\partial z} dz \right) \wedge \left(\frac{\partial F_2}{\partial x} dx + \frac{\partial F_2}{\partial y} dy + \frac{\partial F_2}{\partial z} dz \right) \wedge dF_3 \\
&= \left(\frac{\partial F_1}{\partial x} dx \wedge \left(\frac{\partial F_2}{\partial x} dx + \frac{\partial F_2}{\partial y} dy + \frac{\partial F_2}{\partial z} dz \right) \right. \\
&\quad + \frac{\partial F_1}{\partial y} dy \wedge \left(\frac{\partial F_2}{\partial x} dx + \frac{\partial F_2}{\partial y} dy + \frac{\partial F_2}{\partial z} dz \right) \\
&\quad \left. + \frac{\partial F_1}{\partial z} dz \wedge \left(\frac{\partial F_2}{\partial x} dx + \frac{\partial F_2}{\partial y} dy + \frac{\partial F_2}{\partial z} dz \right) \right) \wedge dF_3 \\
&= \left(\left(\frac{\partial F_1}{\partial x} \frac{\partial F_2}{\partial y} dx dy + \frac{\partial F_1}{\partial x} \frac{\partial F_2}{\partial z} dx dz \right) \right. \\
&\quad + \left(\frac{\partial F_1}{\partial y} \frac{\partial F_2}{\partial x} dy dx + \frac{\partial F_1}{\partial y} \frac{\partial F_2}{\partial z} dy dz \right) \\
&\quad \left. + \left(\frac{\partial F_1}{\partial z} \frac{\partial F_2}{\partial x} dz dx + \frac{\partial F_1}{\partial z} \frac{\partial F_2}{\partial y} dz dy \right) \right) \wedge dF_3 \\
&= \left(\left(\frac{\partial F_1}{\partial x} \frac{\partial F_2}{\partial y} - \frac{\partial F_1}{\partial y} \frac{\partial F_2}{\partial x} \right) dx dy \right. \\
&\quad + \left(\frac{\partial F_1}{\partial y} \frac{\partial F_2}{\partial z} - \frac{\partial F_1}{\partial z} \frac{\partial F_2}{\partial y} \right) dy dz \\
&\quad \left. + \left(\frac{\partial F_1}{\partial z} \frac{\partial F_2}{\partial x} - \frac{\partial F_1}{\partial x} \frac{\partial F_2}{\partial z} \right) dz dx \right) \wedge \left(\frac{\partial F_3}{\partial x} dx + \frac{\partial F_3}{\partial y} dy + \frac{\partial F_3}{\partial z} dz \right) \\
&= \left(\frac{\partial F_3}{\partial z} \left(\frac{\partial F_1}{\partial x} \frac{\partial F_2}{\partial y} - \frac{\partial F_1}{\partial y} \frac{\partial F_2}{\partial x} \right) dx dy \right. \\
&\quad + \frac{\partial F_3}{\partial x} \left(\frac{\partial F_1}{\partial y} \frac{\partial F_2}{\partial z} - \frac{\partial F_1}{\partial z} \frac{\partial F_2}{\partial y} \right) dy dz \\
&\quad \left. + \frac{\partial F_3}{\partial y} \left(\frac{\partial F_1}{\partial z} \frac{\partial F_2}{\partial x} - \frac{\partial F_1}{\partial x} \frac{\partial F_2}{\partial z} \right) dz dx \right) \\
&= \frac{\partial F_3}{\partial x} \left(\frac{\partial F_1}{\partial y} \frac{\partial F_2}{\partial z} - \frac{\partial F_1}{\partial z} \frac{\partial F_2}{\partial y} \right) dx dy dz \\
&\quad - \frac{\partial F_3}{\partial y} \left(\frac{\partial F_1}{\partial x} \frac{\partial F_2}{\partial z} - \frac{\partial F_1}{\partial z} \frac{\partial F_2}{\partial x} \right) dx dy dz \\
&\quad + \frac{\partial F_3}{\partial z} \left(\frac{\partial F_1}{\partial x} \frac{\partial F_2}{\partial y} - \frac{\partial F_1}{\partial y} \frac{\partial F_2}{\partial x} \right) dx dy dz \\
&= \frac{\partial F_3}{\partial x} \begin{vmatrix} \frac{\partial F_1}{\partial y} & \frac{\partial F_1}{\partial z} \\ \frac{\partial F_2}{\partial y} & \frac{\partial F_2}{\partial z} \end{vmatrix} - \frac{\partial F_3}{\partial y} \begin{vmatrix} \frac{\partial F_1}{\partial x} & \frac{\partial F_1}{\partial z} \\ \frac{\partial F_2}{\partial x} & \frac{\partial F_2}{\partial z} \end{vmatrix} + \frac{\partial F_3}{\partial z} \begin{vmatrix} \frac{\partial F_1}{\partial x} & \frac{\partial F_1}{\partial y} \\ \frac{\partial F_2}{\partial x} & \frac{\partial F_2}{\partial y} \end{vmatrix} dx dy dz \\
&= \begin{vmatrix} \frac{\partial F_1}{\partial x} & \frac{\partial F_1}{\partial y} & \frac{\partial F_1}{\partial z} \\ \frac{\partial F_2}{\partial x} & \frac{\partial F_2}{\partial y} & \frac{\partial F_2}{\partial z} \\ \frac{\partial F_3}{\partial x} & \frac{\partial F_3}{\partial y} & \frac{\partial F_3}{\partial z} \end{vmatrix} dx dy dz
\end{aligned}$$

2. Let ω be a k -form and let η be a ℓ -form. Find $d(d\omega \wedge \eta - \omega \wedge d\eta)$.

$$\begin{aligned}
 d(d\omega \wedge \eta - \omega \wedge d\eta) &= d(d\omega \wedge \eta) - d(\omega \wedge d\eta) \\
 &= (d^2\omega \wedge \eta + (-1)^{k+1}(d\omega \wedge d\eta)) - (d\omega \wedge d\eta + (-1)^k(\omega \wedge d^2\eta)) \\
 &= (-1)^{k+1}d\omega \wedge d\eta - d\omega \wedge d\eta \\
 &= ((-1)^{k+1} - 1)d\omega \wedge d\eta
 \end{aligned}$$

3. Determine if $\eta = y \, dx \, dy + xz \, dy \, dz - yz \, dz \, dx$ is exact. If η is exact find a 1-form ω with $d\omega = \eta$. Check if $d\eta = \mathcal{O}$ to see if η closed.

(compare with page 461, # 22)

$$\begin{aligned}
 d\eta &= d(y \, dx \, dy + xz \, dy \, dz - yz \, dz \, dx) \\
 &= (dy \, dx \, dy + d(xz) \wedge dy \, dz - d(yz) \wedge dz \, dx) \\
 &= ((z \, dx + x \, dz) \wedge dy \, dz - (z \, dy + y \, dz) \wedge dz \, dx) \\
 &= (z \, dx) \wedge dy \, dz - (z \, dy) \wedge dz \, dx \\
 &= z \, dx \, dy \, dz - z \, dx \, dy \, dz = \mathcal{O}
 \end{aligned}$$

Since the polynomials of x , y and z defined throughout \mathbb{R}^3 and η closed, it is exact. By inspection,

$$\omega = xy \, dy + xyz \, dz$$

4. Evaluate $\iint_S \omega$, where $\omega = z dx dy + x dy dz + y dz dx$ and S is the unit sphere, directly and by the Divergence Theorem.

(page 489, #12)

Directly:

Parametrize the sphere S as

$$\Phi(\varphi, \theta) = (\cos \theta \sin \varphi, \sin \theta \sin \varphi, \cos \varphi) \text{ with } \theta \in [0, 2\pi], \varphi \in [0, \pi]$$

$$\begin{aligned} \iint_S \omega &= \iint_{\Phi} z dx dy + \iint_{\Phi} x dy dz + \iint_{\Phi} y dz dx \\ &= \int_0^{2\pi} \int_0^{\pi} \cos \varphi \begin{vmatrix} \frac{\partial \cos \theta \sin \varphi}{\partial \varphi} & \frac{\partial \cos \theta \sin \varphi}{\partial \theta} \\ \frac{\partial \sin \theta \sin \varphi}{\partial \varphi} & \frac{\partial \sin \theta \sin \varphi}{\partial \theta} \end{vmatrix} d\varphi d\theta + \int_0^{2\pi} \int_0^{\pi} \cos \theta \sin \varphi \begin{vmatrix} \frac{\partial \sin \theta \sin \varphi}{\partial \varphi} & \frac{\partial \sin \theta \sin \varphi}{\partial \theta} \\ \frac{\partial \cos \varphi}{\partial \varphi} & \frac{\partial \cos \varphi}{\partial \theta} \end{vmatrix} d\varphi d\theta \\ &\quad + \int_0^{2\pi} \int_0^{\pi} \sin \theta \sin \varphi \begin{vmatrix} \frac{\partial \cos \varphi}{\partial \varphi} & \frac{\partial \cos \varphi}{\partial \theta} \\ \frac{\partial \cos \theta \sin \varphi}{\partial \varphi} & \frac{\partial \cos \theta \sin \varphi}{\partial \theta} \end{vmatrix} d\varphi d\theta \\ &= \int_0^{2\pi} \int_0^{\pi} \cos \varphi \begin{vmatrix} \cos \theta \cos \varphi & -\sin \theta \sin \varphi \\ \sin \theta \cos \varphi & \cos \theta \sin \varphi \end{vmatrix} d\varphi d\theta + \int_0^{2\pi} \int_0^{\pi} \cos \theta \sin \varphi \begin{vmatrix} \sin \theta \cos \varphi & \cos \theta \sin \varphi \\ -\sin \varphi & 0 \end{vmatrix} d\varphi d\theta \\ &\quad + \int_0^{2\pi} \int_0^{\pi} \sin \theta \sin \varphi \begin{vmatrix} -\sin \varphi & 0 \\ \cos \theta \cos \varphi & -\sin \theta \sin \varphi \end{vmatrix} d\varphi d\theta \\ &= \int_0^{2\pi} \int_0^{\pi} \sin \varphi \cos^2 \varphi d\varphi d\theta + \int_0^{2\pi} \int_0^{\pi} \cos^2 \theta \sin^3 \varphi + \sin^2 \theta \sin^3 \varphi d\varphi d\theta \\ &= \int_0^{2\pi} \int_0^{\pi} \sin \varphi (\cos^2 \varphi + \sin^2 \varphi) d\varphi d\theta \\ &= \int_0^{2\pi} \int_0^{\pi} \sin \varphi d\varphi d\theta \\ &= 2\pi \left[-\cos \varphi \right]_0^{\pi} = 2\pi \end{aligned}$$

Divergence Theorem:

$$d\omega = dz dy dx + dx dy dz + dy dz dx = 3 dx dy dz$$

$$\begin{aligned} \iint_S \omega &= \iiint_R d\omega \\ &= 3 \int_0^{2\pi} \int_0^{\pi} \int_0^1 \rho^2 \sin(\varphi) d\rho d\varphi d\theta \\ &= \int_0^{2\pi} \int_0^{\pi} \sin(\varphi) d\varphi d\theta \\ &= 2\pi \left[-\cos \varphi \right]_0^{\pi} = 2\pi \end{aligned}$$

5. Compute $\int_S \omega$ and use symbolic algebra software to sketch S in each of the following.

(a) $\omega = xz \, dx \, dy + x^2 \, dy \, dz + dy \, dz \, dx$

S is the upper hemisphere $x^2 + y^2 + z^2 = 4, z \geq 0$ with \mathbf{n} pointing upward.

Close it with the disk of radius 2 on the xy -plane to apply divergence theorem

$$\Phi(\theta, r) = (r \cos \theta, r \sin \theta, 0), \quad r \in [0, 2], \quad \theta \in [0, 2\pi]$$

$$dx \, dy = \begin{vmatrix} -r \sin \theta & \cos \theta \\ r \cos \theta & \sin \theta \end{vmatrix} = -2r$$

Which is negative, so correct orientation for normal pointing down.

$$dy \, dz = 0 \quad \text{Since } z \text{ is } 0$$

$$dz \, dx = 0$$

$$\stackrel{\text{Div Thm}}{\implies} \iint_S \omega = \iiint_R d\omega - \iint_{\Phi} \omega$$

$$\text{But } z = 0 \implies xz \, dx \, dy = 0 \implies \iint_{\Phi} \omega = 0$$

$$d\omega = x \, dx \, dy \, dz + 2x \, dx \, dy \, dz = 3x \, dx \, dy \, dz$$

$$\iiint_R d\omega = \int_0^2 \int_0^{2\pi} \int_0^{\frac{\pi}{2}} 3(\rho \sin \varphi \cos \theta) \rho^2 \sin \varphi \, d\varphi \, d\theta \, d\rho$$

$$= 0 \quad \text{Since integrating } \cos \text{ over full period}$$

$$\implies \int_S \omega = 0$$



(b) $\omega = z \, dx \, dy + x \, dy \, dz + y \, dz \, dx$

S is the part of the plane $x + y + z = 1$ which lies in the first octant oriented by the unit normal which points upward.

Use the natural parametrization for S :

$$\Phi(x, y) = (x, y, 1 - x - y), \quad x \in [0, 1], \quad y \in [0, 1 - x]$$

$$dx \, dy = \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} > 0 \, \forall x, y \implies \text{Correct orientation}$$

$$\begin{aligned} \int_S \omega &= \int_0^1 \int_0^{1-x} (1 - x - y) + x \begin{vmatrix} 0 & 1 \\ -1 & -1 \end{vmatrix} + y \begin{vmatrix} -1 & -1 \\ 1 & 0 \end{vmatrix} dy \, dx \\ &= \int_0^1 \int_0^{1-x} 1 \, dy \, dx = \int_0^1 1 - x \, dx \\ &= 1 - \frac{1}{2} = \frac{1}{2} \end{aligned}$$

(c) $\omega = xz \, dx \, dy + y \, dx \, dz + z^2 \, dy \, dz$

S is the part of the cone $z = \sqrt{x^2 + y^2}$ between $z = 1$ and $z = 3$, oriented by the unit normal with negative z -component.

$$\Phi(\theta, r) = (r \cos \theta, r \sin \theta, r), \quad r \in [1, 3], \quad \theta \in [0, 2\pi]$$

$$dx \, dy = \begin{vmatrix} -r \sin \theta & \cos \theta \\ r \cos \theta & \sin \theta \end{vmatrix} = -r < 0 \text{ for } r > 1$$

$$dy \, dz = \begin{vmatrix} r \cos \theta & \sin \theta \\ 0 & 1 \end{vmatrix} = r \cos \theta$$

$$dz \, dx = \begin{vmatrix} 0 & 1 \\ -r \sin \theta & \cos \theta \end{vmatrix} = r \sin \theta$$

$$\implies \omega = (r \cos \theta)(r)(-r) - (r \sin \theta)(r \sin \theta) + (r)^2(r \cos \theta)$$

$$= -r^2 \sin^2 \theta = -r^2 \left(\frac{1}{2} - \frac{\cos(2\theta)}{2} \right)$$

$$\begin{aligned} \implies \int_S \omega &= \int_1^3 \int_0^{2\pi} -r^2 \left(\frac{1}{2} - \frac{\cos(2\theta)}{2} \right) d\theta \, dr \\ &= \int_1^3 -r^2 \pi \, dr = -\pi \left[\frac{r^3}{3} \right]_1^3 = -\frac{26\pi}{3} \end{aligned}$$

(d) $\omega = z \, dx \, dy + y \, dy \, dz$

S is the oriented surface given by the parametrization

$$\Phi(u, v) = (u + v, uv^2, u^2 + v^2), \quad 0 \leq u \leq 1, \quad 0 \leq v \leq 1.$$

$$dx \, dy = \begin{vmatrix} 1 & 1 \\ v^2 & 2uv \end{vmatrix} = 2uv - v^2, \quad dy \, dz = \begin{vmatrix} v^2 & 2uv \\ 2u & 2v \end{vmatrix} = 2v^3 - 4u^2v$$

$$\begin{aligned} \iint_S \omega &= \int_0^1 \int_0^1 (u^2 + v^2)(2uv - v^2) + (uv^2)(2v^3 - 4u^2v) \, du \, dv \\ &= \int_0^1 \int_0^1 (2u^3v - u^2v^2) + (2uv^3 - v^4) + (2uv^5 - 4u^3v^3) \, du \, dv \\ &= \int_0^1 \frac{v}{2} - \frac{v^2}{3} + v^3 - v^4 + v^5 - v^3 \, dv \end{aligned}$$

6. Verify Stokes' theorem by direct calculation of both sides when the surface S is the piece of the paraboloid $z = x^2 + y^2 - 4$ with $z \leq 0$, oriented by the downward pointing unit normal, and $\omega = (2y - z) dx + (x + y^2 - z) dy + (4y - 3x) dz$.

As part of your solution, provide a sketch showing the appropriate orientations. (For this question you may draw the sketch by hand or use symbolic algebra software.)

7. Let $\omega = yz\,dx - xz\,dy + xy\,dz$ and let $\gamma(t) = (2\cos t, 2\sin t, 4)$, $0 \leq t \leq 2\pi$.

- (a) Let S be the piece of the surface $z = x^2 + y^2$ with $z \leq 4$. Use Stokes' theorem to give an integral over S which is equivalent to $\int_{\gamma} \omega$. Verify by directly computing both integrals.
- (b) Let S' be the part of the plane $z = 4$ with $x^2 + y^2 \leq 4$. Use Stokes' theorem to give an integral over S' which is equivalent to $\int_{\gamma} \omega$. Verify by direct computation.
- (c) Can you give another explanation as to why the integrals you get over S and S' should have the same value?

8. Let $\mathbf{F}(x, y, z) = (e^{z^2}, 4z - y, 8x \sin y)$. Find $\int_S (\nabla \times \mathbf{F}) \cdot d\mathbf{S}$ where S is the unit sphere oriented with the outward normal.

9. (a) Marsden & Tromba, page 451, # 13.
(b) Marsden & Tromba, page 451, # 15.
(c) Use symbolic algebra software to sketch the surfaces in parts (a) and (b).

10. (a) Let \mathbf{F} and \mathbf{G} be vector fields on \mathbb{R}^3 and let $f : \mathbb{R}^3 \rightarrow \mathbb{R}$. Verify the following identities.
- (i) $\operatorname{div}(\mathbf{F} \times \mathbf{G}) = \mathbf{G} \cdot \operatorname{curl} \mathbf{F} - \mathbf{F} \cdot \operatorname{curl} \mathbf{G}$.
 - (ii) $\operatorname{curl}(f\mathbf{F}) = f\operatorname{curl} \mathbf{F} + (\operatorname{grad} f) \times \mathbf{F}$.
- (b) Let R be a closed region in \mathbb{R}^3 with boundary ∂R . Prove the identity

$$\int_{\partial R} (\mathbf{F} \times \operatorname{curl} \mathbf{G}) \cdot d\mathbf{S} = \int_R (\operatorname{curl} \mathbf{F}) \cdot (\operatorname{curl} \mathbf{G}) dV - \int_R \mathbf{F} \cdot \operatorname{curl}(\operatorname{curl} \mathbf{G}) dV$$

(page 490, #2)