

1. (a) Find an equation of the tangent plane to the surface S defined parametrically by $\Phi(u, v) = (u^2 + v, v, u + v^2)$ at the point $(9, 0, 3)$.

$$v = 0$$

$$u + v^2 = 3 \implies u = 3$$

$$\phi_u = (2(3), 0, 1)$$

$$\phi_v = (1, 1, 2(0))$$

$$\phi_u \times \phi_v = (-1, 1, 6)$$

So the tangent plane can be given by

$$0 = ((x - 9, y, z - 3) \cdot (-1, 1, 6))$$

$$0 = (9 - x + y + 6z - 18)$$

$$9 = -x + y + 6z$$

- (b) Use symbolic algebra software to sketch the surface S and its tangent plane from part (a).



2. Use a surface integral to find the area of the triangle in \mathbb{R}^3 with vertices $(1,1,0)$, $(1,2,1)$ and $(3,3,2)$.

Since the surface is a plane, the tangent plane is just parallel to the plane, so tangent vectors can be given by taking vectors in the plane i.e. $\phi_u = (3,3,2) - (1,1,0) = (2,2,2)$ and $\phi_v = (1,2,1) - (1,1,0) = (0,1,1)$. Now this is a triangle with side lengths of equal magnitude to the tangents, so the integral is given as.

$$\begin{aligned}\|\phi_u \times \phi_v\| &= \|(0, -2, 2)\| = \sqrt{4 + 4} = 2\sqrt{2} \\ \int_0^1 \int_0^v \|\phi_u \times \phi_v\| \, du \, dv &= \int_0^1 \int_0^v 2\sqrt{2} \, du \, dv \\ &= \int_0^1 2\sqrt{2}v \, dv \\ &= \sqrt{2}\end{aligned}$$

3. Calculate the surface area of the piece of the cone $x^2 + y^2 - z^2 = 0$ which lies inside the cylinder $x^2 + y^2 = 4$.

We can see the radius of the cylinder is 2, so the cone portion that's cut out is the part which has radius less than or equal to 2 $\implies 0 \leq z \leq 2$. Using polar for the cone, $0 \leq \theta \leq 2\pi$.

$$\begin{aligned}
 \Phi(\theta, z) &= (z \cos \theta, z \sin \theta, z) \\
 \phi_\theta &= (-z \sin \theta, z \cos \theta, 0) \\
 \phi_z &= (\cos \theta, \sin \theta, 1) \\
 \phi_\theta \times \phi_z &= (z \cos \theta, z \sin \theta, -z \sin^2 \theta - z \cos^2 \theta) \\
 &= (z \cos \theta, z \sin \theta, -z) \\
 \|\phi_\theta \times \phi_z\| &= z^2 \cos^2 \theta + z^2 \sin^2 \theta + z^2 = 2z^2
 \end{aligned}$$

$$\begin{aligned}
 \int_{\Phi} f \, dS &= \int_0^{2\pi} \int_0^2 2z^2 \, dz \, d\theta \\
 &= \int_0^{2\pi} \left[\frac{2}{3} z^3 \right]_0^2 d\theta \\
 &= \int_0^{2\pi} \frac{16}{3} d\theta = \frac{32\pi}{3}
 \end{aligned}$$

4. (a) Find the area of the portion of the unit sphere that is cut out by the cone $z = \sqrt{x^2 + y^2}$.
(cf. page 391, #10)

$$\begin{aligned}
0 &\leq \varphi \leq \pi, \quad 0 \leq \theta \leq 2\pi \\
\Phi_{\text{sphere}}(\theta, \varphi) &= (\cos \theta \sin \varphi, \sin \theta \sin \varphi, \cos \varphi) \\
\phi_\theta &= (-\sin \theta \sin \varphi, \cos \theta \sin \varphi, 0) \\
\phi_\varphi &= (\cos \theta \cos \varphi, \sin \theta \cos \varphi, -\sin \varphi) \\
\phi_\theta \times \phi_\varphi &= (-\cos \theta \sin^2 \varphi, -\sin \theta \sin^2 \varphi, -\sin^2 \theta \sin \varphi \cos \varphi - \cos^2 \theta \sin \varphi \cos \varphi) \\
&= (-\cos \theta \sin^2 \varphi, -\sin \theta \sin^2 \varphi, -\sin \varphi \cos \varphi) \\
\|\phi_\theta \times \phi_\varphi\| &= \sqrt{\cos^2 \theta \sin^4 \varphi + \sin^2 \theta \sin^4 \varphi + \sin^2 \varphi \cos^2 \varphi} \\
&= \sqrt{\sin^2 \varphi} = \sin \varphi
\end{aligned}$$

$$\begin{aligned}
z &> 0, \quad 0 \leq \theta \leq 2\pi \\
\Phi_{\text{cone}}(\theta, z) &= (z \cos \theta, z \sin \theta, z) \\
\phi_z &= (\cos \theta, \sin \theta, 1) \\
\phi_\theta &= (-z \sin \theta, z \cos \theta, 0) \\
\phi_z \times \phi_\theta &= (-z \cos \theta, -z \sin \theta, z) \\
\|\phi_z \times \phi_\theta\| &= 2z^2
\end{aligned}$$

For the unit sphere $x^2 + y^2 + z^2 = 1$, but the cone is $x^2 + y^2 = z^2 \implies$ sub z into sphere gives $2x^2 + 2y^2 = 1$ So the exact intersection of the surfaces is a circle of radius $2/\sqrt{2}$ centered at the origin. so the surface cut out is the section of the top of the sphere where $z \geq 2\sqrt{2} \implies \varphi \leq \frac{\pi}{4}$ from the $z = \cos \varphi$ portion of the parametrization. So the ranges are $0 \leq \theta \leq 2\pi, 0 \leq \varphi \leq \frac{\pi}{4}$. The area is therefore

$$\begin{aligned}
\int_0^{2\pi} \int_0^{\frac{\pi}{4}} \sin \varphi \, d\varphi \, d\theta &= \int_0^{2\pi} \left[-\cos \varphi \right]_0^{\frac{\pi}{4}} d\theta \\
&= 2\pi \left[-\left(\cos\left(\frac{\pi}{4}\right)\right) - (-\cos(0)) \right] \\
&= 2\pi \left[-\frac{\sqrt{2}}{2} + 1 \right] \\
&= \pi(2 - \sqrt{2})
\end{aligned}$$

- (b) Find the area of the portion of the cone $z = \sqrt{x^2 + y^2}$ that is cut out by the unit sphere.
Plugging in $x^2 + y^2 = 1/2$ to the cone equation again gives $z^2 = 1/2 \implies z = \pm \frac{\sqrt{2}}{2}$ but $z \geq 0$ by the cone definition so $0 \leq z \leq \frac{\sqrt{2}}{2}$.

$$\begin{aligned}
A(\Phi_{\text{cone}}) &= \int_0^{2\pi} \int_0^{\frac{1}{4}} 2z^2 \, dz \, d\theta \\
&= \int_0^{2\pi} \frac{2}{3} \cdot \frac{1}{4^3} \, d\theta \\
&= \frac{\pi}{3(16)} \\
&= \frac{\pi}{48}
\end{aligned}$$

5. Let $\Phi : D \subset \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be a parametrization of a 2-dim surface S in \mathbb{R}^3 .

(a) Set

$$E = \|\phi_u\|^2, \quad F = \phi_u \cdot \phi_v, \quad G = \|\phi_v\|^2,$$

Show that the surface area of S is

$$A(S) = \iint_D \sqrt{EG - F^2} dA$$

$$\begin{aligned} \iint_D \sqrt{EG - F^2} dA &= \iint_D \sqrt{\|\phi_u\|^2 \|\phi_v\|^2 - (\phi_u \cdot \phi_v)^2} dA \\ &= \iint_D \sqrt{(\|\phi_u\| \|\phi_v\|)^2 - (\|\phi_u\| \|\phi_v\|)^2 \cos^2 \theta} dA \quad \text{Where } \theta \text{ is the angle between } \phi_u \text{ and } \phi_v. \\ &= \iint_D \sqrt{(\|\phi_u\| \|\phi_v\|)^2 (1 - \cos^2 \theta)} dA \\ &= \iint_D \sqrt{(\|\phi_u\| \|\phi_v\|)^2 (\sin^2 \theta)} dA \\ &= \iint_D \sqrt{\|\phi_u \times \phi_v\|^2} dA \\ &= \iint_D \|\phi_u \times \phi_v\| dA \\ &= \int_{\Phi} 1 dS \end{aligned}$$

(b) What does the formula for $A(S)$ become if the vectors ϕ_u and ϕ_v are orthogonal?
If the vectors are orthogonal, then the dot product is 0, so the equation reduces to

$$A(S) = \iint_D \|\phi_u\| \|\phi_v\| dA$$

(c) Use parts (a) and (b) to compute the surface area of a sphere of radius a .
(cf. Marsden & Tromba, page 399, # 23.)

$$\begin{aligned} 0 &\leq \varphi \leq \pi, \quad 0 \leq \theta \leq 2\pi \\ \Phi(\theta, \varphi) &= a(\cos \theta \sin \varphi, \sin \theta \sin \varphi, \cos \varphi) \\ \phi_\theta &= a(-\sin \theta \sin \varphi, \cos \theta \sin \varphi, 0) \\ \phi_\varphi &= a(\cos \theta \cos \varphi, \sin \theta \cos \varphi, -\sin \varphi) \\ \|\phi_\theta\| &= a \sin \varphi, \quad \|\phi_\varphi\| = a \\ \implies A(S) &= a^2 \int_0^{2\pi} \int_0^\pi \sin \varphi d\varphi d\theta \\ &= a^2 \int_0^{2\pi} \left[-\cos \varphi \right]_0^\pi d\theta \\ &= a^2 \int_0^{2\pi} -(-1 - 1) d\theta \\ &= a^2 2 \int_0^{2\pi} 1 d\theta \\ &= 4\pi a^2 \end{aligned}$$

6. For each of the following surfaces S , sketch S (using symbolic software) and evaluate the surface integral $\int_S f dS$, where $f(x, y, z) = x$.

(a) S is that part of the surface $y = 4 - x^2$ between $z = 0$ and $z = 1$, with $y \geq 0$.

$$y \geq 0 \implies 4 - x^2 \geq 0 \implies x^2 \leq 4 \implies |x| < 2$$

$$\Phi(x, z) = (x, 4 - x^2, z)$$

$$\phi_x = (1, -2x, 0), \phi_z = (0, 0, 1)$$

$$\phi_x \times \phi_z = (-2x, -1, 0) \implies \|\phi_x \times \phi_z\| = \sqrt{4x^2 + 1}$$

$$\int_S f dS = \int_0^1 \int_{-2}^2 x \sqrt{4x^2 + 1} dx dz$$

The integrand is odd since x odd and $\sqrt{4x^2 + 1}$ even, so the integral over x is 0, making the entire integral 0.

(b) S is the upper half of the unit sphere centered at the origin.

Only the upper half so $0 \leq \theta \leq 2\pi$ and $0 \leq \varphi \leq \pi/2$.

$$\Phi(\theta, \varphi) = (\cos \theta \sin \varphi, \sin \theta \sin \varphi, \cos \varphi)$$

$$\phi_\theta = (-\sin \theta \sin \varphi, \cos \theta \sin \varphi, 0)$$

$$\phi_\varphi = (\cos \theta \cos \varphi, \sin \theta \cos \varphi, -\sin \varphi)$$

$$\begin{aligned} \phi_\theta \times \phi_\varphi &= (-\cos \theta \sin^2 \varphi, -\sin \theta \sin^2 \varphi, -\sin^2 \theta \sin \varphi \cos \varphi - \cos^2 \theta \sin \varphi \cos \varphi) \\ &= (-\cos \theta \sin^2 \varphi, -\sin \theta \sin^2 \varphi, -\sin \varphi \cos \varphi) \end{aligned}$$

$$\|\phi_\theta \times \phi_\varphi\| = \sqrt{\cos^2 \theta \sin^4 \varphi + \sin^2 \theta \sin^4 \varphi + \sin^2 \varphi \cos^2 \varphi}$$

$$= \sqrt{\sin^4 \varphi + \sin^2 \varphi \cos^2 \varphi}$$

$$= \sqrt{\sin^2 \varphi} = \sin \varphi$$

$$\int_{\Phi} f dS = \int_0^{\pi/2} \int_0^{2\pi} \cos \theta \sin^2 \varphi d\theta d\varphi = 0$$

The integral is zero again since integrating $\cos \theta$ over a whole period is 0.

(c) S is that part of the surface $x = \sin y$ with $0 \leq y \leq \pi$ and $0 \leq z \leq 2$.

$$\begin{aligned}
\Phi(y, z) &= (\sin y, y, z) \\
\phi_y &= (\cos y, 1, 0) \\
\phi_z &= (0, 0, 1) \\
\phi_y \times \phi_z &= (1, -\cos y, 0) \\
\|\phi_y \times \phi_z\| &= \sqrt{1 + \cos^2 y} \\
\int_{\Phi} f \, dS &= \int_0^2 \int_0^\pi \sin y \sqrt{1 + \cos^2 y} \, dy \, dz
\end{aligned}$$

$$\text{Let } u = \cos y, \, du = -\sin y \, dy$$

$$= 2 \int_{-1}^1 \sqrt{1 + u^2} \, du$$

$$\text{Let } u = \tan \theta, \, du = \sec^2(\theta) \, d\theta$$

$$= 2 \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \sqrt{\frac{1}{\cos^2 \theta}} \sec^2 \theta \, du$$

$$= 2 \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \sec^3 \theta \, d\theta$$

$$\text{Let } u = \sec \theta, \, du = \sec \theta \tan \theta \, d\theta, \, dv = \sec^2 \theta \, d\theta, \, v = \tan \theta$$

$$= 2 \left(\left[\sec \theta \tan \theta \right]_{-\frac{\pi}{4}}^{\frac{\pi}{4}} - \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \tan^2 \theta \sec \theta \, d\theta \right)$$

$$= 2 \left(\left[\sec \theta \tan \theta \right]_{-\frac{\pi}{4}}^{\frac{\pi}{4}} - \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} (\sec^2 \theta - 1) \sec \theta \, d\theta \right)$$

$$2 \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \sec^3 \theta \, d\theta = 2 \left(\left[\sec \theta \tan \theta \right]_{-\frac{\pi}{4}}^{\frac{\pi}{4}} - \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \sec^3 \theta \, d\theta + \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \sec \theta \, d\theta \right)$$

$$4 \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \sec^3 \theta \, d\theta = 2 \left(\left[\sec \theta \tan \theta \right]_{-\frac{\pi}{4}}^{\frac{\pi}{4}} + \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \sec \theta \, d\theta \right)$$

$$2 \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \sec^3 \theta \, d\theta = \left(\left[\sec \theta \tan \theta \right]_{-\frac{\pi}{4}}^{\frac{\pi}{4}} + \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \sec \theta \, d\theta \right)$$

$$= \left(\left[\sec \theta \tan \theta \right]_{-\frac{\pi}{4}}^{\frac{\pi}{4}} + \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \sec \theta \left(\frac{\sec \theta + \tan \theta}{\sec \theta + \tan \theta} \right) d\theta \right)$$

$$= \left(\left[\sec \theta \tan \theta \right]_{-\frac{\pi}{4}}^{\frac{\pi}{4}} + \left[\ln |\sec \theta + \tan \theta| \right]_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \right)$$

$$= 2\sqrt{2} + \ln |1 + \sqrt{2}| - \ln |\sqrt{2} - 1|$$

7. Find the mass of the metallic surface S given by $z = 1 - \frac{x^2 + y^2}{2}$ with $0 \leq x \leq 1$, $0 \leq y \leq 1$, if the mass density at $(x, y, z) \in S$ is given by $m(x, y, z) = xy$.

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

$$\phi_x = (1, 0, -x)$$

$$\phi_y = (0, 1, -y)$$

$$\|\phi_x \times \phi_y\| = \sqrt{x^2 + y^2 + 1}$$

$$\int_{\Phi} f dS = \int_0^1 \int_0^1 xy \sqrt{x^2 + y^2 + 1} dx dy$$

$$\text{Let } u = x^2 + y^2 + 1, du = 2x dx$$

$$= \frac{1}{2} \int_0^1 \int_{y^2+1}^{y^2+2} y \sqrt{u} du dy$$

$$= \frac{1}{3} \int_0^1 y \left[u^{\frac{3}{2}} \right]_{y^2+1}^{y^2+2} dy$$

$$= \frac{1}{3} \int_0^1 y \left[(y^2 + 2)^{\frac{3}{2}} - (y^2 + 1)^{\frac{3}{2}} \right] dy$$

$$\text{Let } u = y^2 + 1, du = 2y dy$$

$$= \frac{1}{6} \int_1^2 (u + 1)^{\frac{3}{2}} - (u)^{\frac{3}{2}} du$$

$$= \frac{1}{15} \left[(u + 1)^{\frac{5}{2}} - (u)^{\frac{5}{2}} \right]_1^2$$

$$= \frac{1}{15} \left[(3^{\frac{5}{2}} - 2^{\frac{5}{2}}) - (2^{\frac{5}{2}} - 1) \right]$$

$$= \frac{1}{15} \left[3^{\frac{5}{2}} - 2^{\frac{7}{2}} - 1 \right]$$

$$= \frac{1}{15} \left[9\sqrt{3} - 8\sqrt{2} + 1 \right]$$

Bonus

- (i) Calculate the surface area of S , the piece of the cone $x^2 + y^2 = z^2$ lying over the disk $x^2 + y^2 \leq 4$, $z = 0$

Then calculate $\int_S x^2 z dS$

Parametrize the surface as

$$\begin{aligned}\Phi(\theta, r) &= (r \cos \theta, r \sin \theta, \sqrt{r^2 \cos^2 \theta + r^2 \sin^2 \theta}) \\ &= (r \cos \theta, r \sin \theta, r)\end{aligned}$$

Where: $0 \leq \theta \leq 2\pi$, $0 \leq r \leq 2$