1. Consider the ellipsoid with implicit equation
\[ \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1. \]

(a) Parametrize this ellipsoid.

**Solution.** One could use the parametrization
\[ x = a \sin \phi \cos \theta, \quad y = b \sin \phi \sin \theta, \quad z = c \cos \phi, \quad 0 \leq \phi \leq \pi, \quad 0 \leq \theta \leq 2\pi. \]

(b) Set up, but do not evaluate, a double integral that computes its surface area.

**Solution.** Since \( \mathbf{r}(\phi, \theta) = (a \sin \phi \cos \theta, b \sin \phi \sin \theta, c \cos \phi), \) one has
\[ \mathbf{r}_\phi = (a \cos \phi \cos \theta, b \cos \phi \sin \theta, -c \sin \phi), \quad \mathbf{r}_\theta = (-a \sin \phi \sin \theta, b \sin \phi \cos \theta, 0), \]
so
\[ \mathbf{r}_\phi \times \mathbf{r}_\theta = (bc \sin^2 \phi \cos \theta, ac \sin^2 \phi \sin \theta, ab \sin \phi \cos \theta). \]

Therefore
\[ |\mathbf{r}_\phi \times \mathbf{r}_\theta| = \sqrt{b^2 c^2 \sin^4 \phi \cos^2 \theta + a^2 c^2 \sin^4 \phi \sin^2 \theta + a^2 b^2 \sin^2 \phi \cos^2 \phi}, \]
and the surface area is computed by
\[ \text{Area} = \int_0^{2\pi} \int_0^\pi |\mathbf{r}_\phi \times \mathbf{r}_\theta| d\phi d\theta \]
\[ = \int_0^{2\pi} \int_0^\pi \sqrt{b^2 c^2 \sin^4 \phi \cos^2 \theta + a^2 c^2 \sin^4 \phi \sin^2 \theta + a^2 b^2 \sin^2 \phi \cos^2 \phi} \ d\phi d\theta. \]

2. Let
\[ \mathbf{r}(u, v) = ((2 + \cos u) \cos v, (2 + \cos u) \sin v, \sin u), \]
where \( 0 \leq u \leq 2\pi \) and \( 0 \leq v \leq 2\pi. \)

(a) Sketch the surface parametrized by this function.

**Solution.** The sketch of the surface is as follows.
(b) Compute its surface area.

**Solution.** By the parametrization, one has

\[ \mathbf{r}_u = (-\sin u \cos v, -\sin u \sin v, \cos u), \]
\[ \mathbf{r}_v = (-2 + \cos u) \sin v, (2 + \cos u) \cos v, 0), \]

and so

\[ \mathbf{r}_u \times \mathbf{r}_v = (-2 + \cos u) \cos u \cos v, -(2 + \cos u) \cos u \sin v, -(2 + \cos u) \sin v. \]

Therefore \( |\mathbf{r}_u \times \mathbf{r}_v| = 2 + \cos u \), and the surface area is computed by

\[ \text{Area} = \int_0^{2\pi} \int_0^{2\pi} |\mathbf{r}_u \times \mathbf{r}_v| \, du \, dv = \int_0^{2\pi} \int_0^{2\pi} (2 + \cos u) \, du \, dv = 8\pi^2. \]

3. Consider the surface integral

\[ \iint_{\Sigma} z \, dS \]

where \( \Sigma \) is the surface with sides \( S_1 \) given by the cylinder \( x^2 + y^2 = 1 \), \( S_2 \) given by the unit disk in the \( xy \)-plane, and \( S_3 \) given by the plane \( z = x + 1 \). Evaluate this integral as follows:

(a) Parametrize \( S_1 \) using \((\theta, z)\) coordinates.

**Solution.** One can parametrize \( S_1 \) by

\[ x = \cos \theta, \ y = \sin \theta, \ z = z, \ 0 \leq \theta \leq 2\pi, \ 0 \leq z \leq \cos \theta + 1. \]

(b) Evaluate the integral over the surface \( S_2 \) without parametrizing.

**Solution.** Since \( z = 0 \) on \( S_2 \), we know \( \iint_{S_2} z \, dS = 0. \)
(c) Parametrize $S_3$ in Cartesian coordinates and evaluate the resulting integral using polar coordinates.

**Solution.** One can parametrize $S_3$ in Cartesian coordinates

$$x = x, \ y = y, \ z = x + 1, \ -1 \leq x \leq 1, \ -\sqrt{1-x^2} \leq y \leq \sqrt{1-x^2}.$$ 

Now we move to evaluate the integral $\iint_S z \, dS$. Obviously

$$\iint_S z \, dS = \iint_{S_1} z \, dS + \iint_{S_2} z \, dS + \iint_{S_3} z \, dS := I_1 + I_2 + I_3.$$ 

To estimate $I_1$, using the parametrization in (a), one has

$$r(\theta, z) = (\cos \theta, \sin \theta, z).$$ 

Then

$$r_\theta = (-\sin \theta, \cos \theta, 0), \quad r_z = (0, 0, 1),$$

and

$$r_\theta \times r_z = (\cos \theta, \sin \theta, 0).$$

So $|r_\theta \times r_z| = 1$, and

$$I_1 = \int_0^{2\pi} \int_0^{\cos \theta + 1} z \, dz \, d\theta = \int_0^{2\pi} \frac{(\cos \theta + 1)^2}{2} \, d\theta = \int_0^{2\pi} \frac{\cos^2 \theta + 2 \cos \theta + 1}{2} \, d\theta = \frac{3\pi}{2}.$$ 

In (b) we know $I_2 = 0$. To evaluate $I_3$, by the parametrization in (c), one has

$$r(x, y) = (x, y, x + 1), \ -1 \leq x \leq 1, \ -\sqrt{1-x^2} \leq y \leq \sqrt{1-x^2},$$

and so

$$r_x = (1, 0, 1), \quad r_y = (0, 1, 0), \quad r_x \times r_y = (-1, 0, 1).$$

Thus $|r_x \times r_y| = \sqrt{2}$, and the surface integral is

$$I_3 = \int_{-1}^{1} \int_{-\sqrt{1-x^2}}^{\sqrt{1-x^2}} (x + 1) \sqrt{2} \, dy \, dx = \int_{x^2+y^2 \leq 1} (x + 1) \sqrt{2} \, dy \, dx.$$ 

To evaluate this integral, one can use the polar coordinates

$$x = r \cos \theta, \ y = r \sin \theta, \ 0 \leq r \leq 1, \ 0 \leq \theta \leq 2\pi.$$ 

Therefore,

$$I_3 = \int_0^{2\pi} \int_0^1 (r \cos \theta + 1) \sqrt{2} \, r \, dr \, d\theta = \sqrt{2}\pi.$$ 

Adding up all three integrals, one gets

$$\iint_S z \, dS = I_1 + I_2 + I_3 = \frac{3\pi}{2} + \sqrt{2}\pi.$$
4. Let $C$ be the circle in the plane with equation $x^2 + y^2 - 2x = 0$.

(a) Parametrize $C$ as follows. For each choice of a slope $t$, consider the line $L_t$ whose equation is $y = tx$. Then the intersection $L_t \cap C$ of $L_t$ and $C$ contains two points, one of which is $(0, 0)$. Find the other point of intersection, and call its $x-$ and $y-$coordinates $x(t)$ and $y(t)$. Compute a formula for $r(t) = \langle x(t), y(t) \rangle$. Check your answer with your TA.

**Solution.** Bring $y = tx$ into $x^2 + y^2 - 2x = 0$, then one has $x^2 + t^2x^2 - 2x = 0$, and it is easy to get $x = \frac{2}{1+t^2}$, and then $y = \frac{2t}{1+t^2}$. Thus $r(t) = \langle \frac{2}{1+t^2}, \frac{2t}{1+t^2} \rangle$.

(b) Suppose that $t = \frac{p}{q}$ is a rational number. Show that $x(p/q)$ and $y(p/q)$ are also rational numbers. Explain how, by clearing denominators in $x(p/q) - 1$ and $y(p/q)$, you can find a triple of integers $U, V, W$ for which $U^2 + V^2 = W^2$.

**Solution.** Plug $t = \frac{p}{q}$ into the the parametrization, one gets

$$x(p/q) = \frac{2q^2}{p^2 + q^2}, \quad y(p/q) = \frac{2pq}{p^2 + q^2},$$

and both of them are rational numbers. Since $(x - 1)^2 + y^2 = 1$, and $x(p/q) - 1 = \frac{q^2 - p^2}{p^2 + q^2}$, then one has

$$\left( \frac{q^2 - p^2}{p^2 + q^2} \right)^2 + \left( \frac{2pq}{p^2 + q^2} \right)^2 = 1.$$

By setting

$$U = q^2 - p^2, \quad V = 2pq, \quad W = p^2 + q^2,$$

one has $U^2 + V^2 = W^2$.

(c) Compute $\int_C \frac{1}{2} \langle -y, x \rangle \cdot dr$ using your parametrization above.

**Solution.** Since $r = \langle \frac{-2}{1+t^2}, \frac{2t}{1+t^2} \rangle$, one has $r' = \langle -\frac{4t}{(1+t^2)^2}, \frac{2-2t^2}{(1+t^2)^2} \rangle$. Then

$$\int_C \frac{1}{2} \langle -y, x \rangle \cdot dr = \int_0^\infty \frac{1}{2} \langle -\frac{2t}{1+t^2}, \frac{2}{1+t^2} \rangle \cdot \langle -\frac{4t}{(1+t^2)^2}, \frac{2-2t^2}{(1+t^2)^2} \rangle \ dt$$

$$= \int_0^\infty \frac{2}{(1+t^2)^2} \ dt = \pi.$$