1. Consider the set $\mathbb{R}^2$ consisting of pairs of real numbers. For $(x, y) \in \mathbb{R}^2$, define scalar multiplication by: $c(x, y) = (cx, cy)$ for any real number c, and define vector addition and multiplication as follows:

$$(x_1, y_1) + (x_2, y_2) = (x_1 + x_2, y_1 + y_2)\,, \tag{1}$$
$$(x_1, y_1) \cdot (x_2, y_2) = (x_1 x_2, y_1 y_2)\,. \tag{2}$$

(a) Is $\mathbb{R}^2$ a group?

It is straightforward to check the group axioms and show that $\mathbb{R}^2$ is a group under addition [as defined in eq. (1)]. $\mathbb{R}^2$ is not a group under multiplication. For example, $(0, 0)$ does not possess a multiplicative inverse.

(b) Is $\mathbb{R}^2$ a field?

$\mathbb{R}^2$ is not a field. Recall that all elements of a field, excluding the additive inverse, must possess a multiplicative inverse. In the case of $\mathbb{R}^2$, the additive inverse is $(0, 0)$. However, for any $x \neq 0$ and $y \neq 0$, $(x, 0)$ and $(0, y)$ also do not possess multiplicative inverses.

(c) Is $\mathbb{R}^2$ a linear vector space (over $\mathbb{R}$)?

It is straightforward to check the axioms that define a linear vector space and show that $\mathbb{R}^2$ is a linear vector space over $\mathbb{R}$.

(d) Is $\mathbb{R}^2$ a linear algebra (over $\mathbb{R}$)?

It is straightforward to check the axioms that define a linear algebra and show that $\mathbb{R}^2$ is a linear algebra, where the vector multiplication law is given by eq. (2).

2. Consider the following two groups:

$$T = \big\{\text{proper rotations that map a regular tetrahedron into itself}\big\}\,,$$

$$T_d = \big\{\text{proper rotations and reflections that map a regular tetrahedron into itself}\big\}\,.$$

Show that the following isomorphisms are valid: $T \cong A_4$ and $T_d \cong S_4$.

A regular tetrahedron consists of four equilateral triangles with four vertices (labeled by the integers 1,2,3,4) as shown in Figure 1(a). The symmetry operations, consisting of proper rotations [shown in Figure 1(b) and (c)] and reflections through planes that pass through two of the four tetrahedron vertices, have the effect of permuting the four vertices.

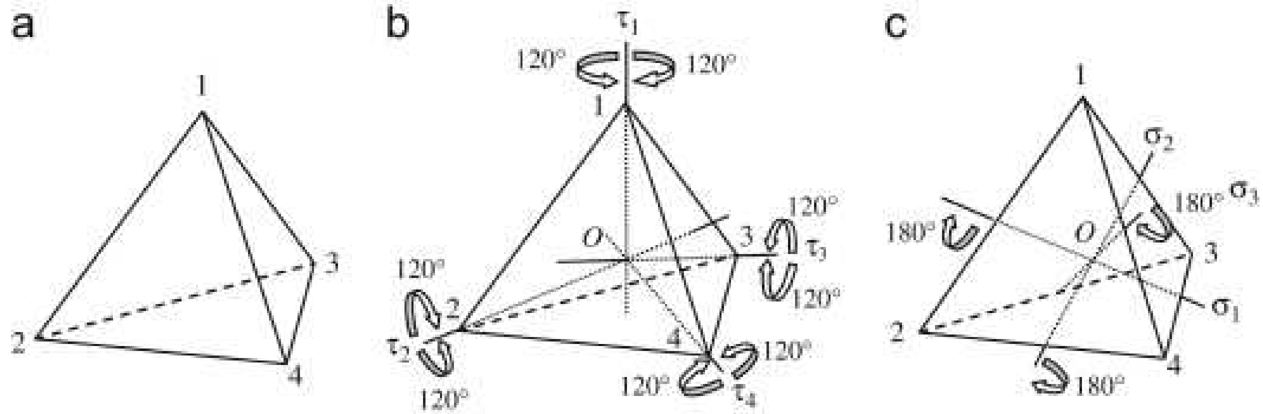

Figure 1: Proper rotations that map a regular tetrahedron into itself.

Consider first the proper rotations. One can rotate by 120° in a clockwise or counterclockwise fashion about an axis through vertex 1, denoted by τ_1 in Figure 1(b). This has the effect of permuting the vertices 2,3,4. All in all, one can perform clockwise or counterclockwise rotations about any one of the four axes [denoted by τ_i, $i = 1, 2, 3, 4$ in Figure 1(b)]. In each case, three of the four vertices are permuted. One can describe each rotation by an element of the permutation group. Using cycle notation, the eight rotation operations described above correspond to the three-cycles of the permutation group S_4. In cycle notation, these are:

$$(123), (132), (124), (142), (134), (143), (234), (243)\,. \tag{3}$$

In addition, one can rotate by 180° about the axes that are denoted by σ_i, $i = 1, 2, 3$ in Figure 1(c). For example, performing a 180° about σ_1 interchanges vertices 1 and 2 and likewise interchanges vertices 3 and 4. Thus, the three possible rotation operations described above correspond to permutations that are the product of two disjoint transpositions. In cycle notation, these are:

$$(12)(34), (13)(24), (14)(23) \tag{4}$$

Finally, the identity element corresponds to performing no rotation (or reflection). This completes the enumeration of all possible proper rotations that map a regular tetrahedron into itself. We conclude that

$$T = \{e, (123), (132), (124), (142), (134), (143), (234), (243), (12)(34), (13)(24), (14)(23)\}\,. \tag{5}$$

These twelve elements correspond to the even permutations of the four vertices.[1] Therefore, it follows that

$$T \cong A_4\,,$$

where A_4, the alternating group of four objects, is the subgroup of the permutation group S_4 that consists of the even permutations of four objects.

[1]Even permutations can be expressed as the product of an even number of transpositions. Moreover, as shown in class, an n-cycle can be written as the product of $n-1$ transpositions. Hence, it follows that 3-cycles must be even permutations. Thus, eq. (5) exhausts all the possible even permutations of four objects.

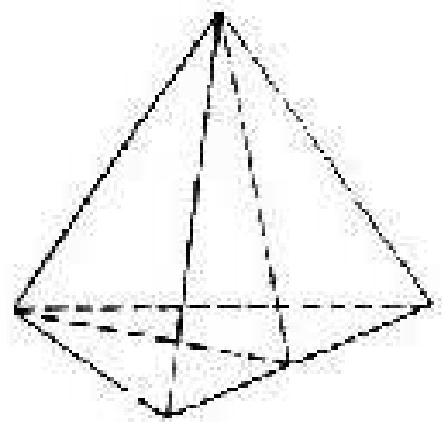

Figure 2: Consider the bisectors of two of the equilateral triangles that are faces of the tetrahedron. The two bisectors meet at a point. The other ends of the two bisectors are connected by one of the tetrahedron edges. This defines one of six possible reflection planes that pass through two of the four vertices of the tetrahedron.

One can also consider six possible reflection planes, one of which is illustrated in Figure 2. Note that each reflection plane passes through two of the four possible tetrahedron vertices. There are $4!/(2!\,2!) = 6$ ways of choosing the two vertices. When a reflection through one of these planes is carried out, the tetrahedron is mapped into itself. The two vertices that are located on the reflection plane are unaffected by the reflection, whereas the other two vertices are interchanged. These correspond to the transpositions of S_4,

$$(12), (13), (14), (23), (24), (34)\,. \tag{6}$$

One can also combine any one of these reflections with a proper rotation. It is sufficient to consider one reflection (e.g., the reflection that interchanges vertices 1 and 2). There are six new permutations that can be produced:

$$(1\;\;3\;\;4)(1\;\;2) = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 3 & 2 & 4 & 1 \end{pmatrix}\begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 1 & 3 & 4 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 3 & 4 & 1 \end{pmatrix} = (1\;\;2\;\;3\;\;4)\,,$$

$$(1\;\;4\;\;3)(1\;\;2) = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 4 & 2 & 1 & 3 \end{pmatrix}\begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 1 & 3 & 4 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 4 & 1 & 3 \end{pmatrix} = (1\;\;2\;\;4\;\;3)\,,$$

$$(2\;\;3\;\;4)(1\;\;2) = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 1 & 3 & 4 & 2 \end{pmatrix}\begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 1 & 3 & 4 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 3 & 1 & 4 & 2 \end{pmatrix} = (1\;\;3\;\;4\;\;2)\,,$$

$$(2\;\;4\;\;3)(1\;\;2) = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 1 & 4 & 3 & 2 \end{pmatrix}\begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 1 & 3 & 4 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 4 & 1 & 2 & 3 \end{pmatrix} = (1\;\;4\;\;3\;\;2)\,,$$

$$(1\;\;3)(2\;\;4)(1\;\;2) = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 3 & 4 & 1 & 2 \end{pmatrix}\begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 1 & 3 & 4 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 4 & 3 & 1 & 2 \end{pmatrix} = (1\;\;4\;\;2\;\;3)\,,$$

$$(1\;\;4)(2\;\;3)(1\;\;2) = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 4 & 3 & 2 & 1 \end{pmatrix}\begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 1 & 3 & 4 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 3 & 4 & 2 & 1 \end{pmatrix} = (1\;\;3\;\;2\;\;4)\,.$$

Combining the reflection that interchanges vertices 1 and 2 with the five remaining rotations listed in eqs. (3) and (4) yields the five remaining transpositions,

$$(1\ 2\ 3)(1\ 2) = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 3 & 1 & 4 \end{pmatrix} \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 1 & 3 & 4 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 3 & 2 & 1 & 4 \end{pmatrix} = (1\ 3)\,,$$

$$(1\ 3\ 2)(1\ 2) = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 3 & 1 & 2 & 4 \end{pmatrix} \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 1 & 3 & 4 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 1 & 3 & 2 & 4 \end{pmatrix} = (2\ 3)\,,$$

$$(1\ 2\ 4)(1\ 2) = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 4 & 3 & 1 \end{pmatrix} \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 1 & 3 & 4 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 4 & 2 & 3 & 1 \end{pmatrix} = (1\ 4)\,,$$

$$(1\ 4\ 2)(1\ 2) = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 4 & 1 & 3 & 2 \end{pmatrix} \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 1 & 3 & 4 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 1 & 4 & 3 & 2 \end{pmatrix} = (2\ 4)\,,$$

$$(1\ 2)(3\ 4)(1\ 2) = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 1 & 4 & 3 \end{pmatrix} \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 1 & 3 & 4 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 1 & 2 & 4 & 3 \end{pmatrix} = (3\ 4)\,.$$

Thus, all the odd permutations of the four tetrahedron vertices can be realized by either a single reflection or a reflection followed by a rotation. One can easily check that two successive symmetry operations of the tetrahedron are in one-to-one correspondence with the multiplication table of S_4. Thus, we conclude that

$$T_d \cong S_4\,.$$

3. Consider the possibility that a set G of $n \times n$ matrices forms a group with respect to matrix multiplication.

(a) Prove that if G is a group and if one of the elements of G is a non-singular matrix then all of the elements of G must be non-singular matrices. Conclude that all the elements of G are either non-singular matrices or singular matrices.

Let $G = \{A_0, A_1, A_2, \ldots\}$ be a group of $n \times n$ matrices, where $e \equiv A_0$ is the group identity element.[2] First, suppose that the identity element A_0 is a non-singular matrix, in which case $\det A_0 \neq 0$. Then consider

$$A_i B_i = A_0\,, \qquad \text{for } i \neq 0 \text{ (no sum over } i)\,, \tag{7}$$

where B_i is the group inverse of A_i. Taking the determinant of both sides of eq. (7), it follows that $\det A_i \neq 0$ and $\det B_i \neq 0$. That is, A_i is a non-singular matrix for all i. Hence, if the identity element is a non-singular matrix, then all the elements of G are non-singular matrices.

Next, suppose that the identity element A_0 is a singular matrix, in which case $\det A_0 = 0$. Since A_0 is the group identity element, it follows that

$$A_i A_0 = A_i\,, \qquad \text{for any } i \neq 0\,. \tag{8}$$

Taking the determinant of both sides of eq. (8), it follows that $\det A_i = 0$ for all i. Hence, if the identity element is a singular matrix, then all the elements of G are singular matrices.

[2]The group G may be a discrete or continuous group of matrices.

REMARKS:

1. In the case where all elements of G are non-singular matrices, then we can multiply both sides of eq. (8) by the matrix inverse A_i^{-1} to conclude that $A_0 = \mathbb{1}_{n\times n}$, where $\mathbb{1}_{n\times n}$ is the $n \times n$ identity matrix. In the case where all the elements of G are singular matrices, then A_0 *cannot* be the identity matrix (since $\mathbb{1}_{n\times n}$ is non-singular).

2. One can shorten the above proof by proving directly that if *any* element of G is singular then all elements of G are singular. Suppose $x \in G$ is a singular matrix, in which case $\det x = 0$. Consider any other element $y \in G$ where $y \neq x$. Then by writing

$$y = x(x^{-1}y)\,, \tag{9}$$

and taking the determinant of both sides of eq. (9), it follows that

$$\det y = \det x \, \det(x^{-1}y) = 0\,.$$

Hence, if any element of G is a singular matrix then all elements of G are singular matrices. An immediate consequence of this result is that if any element of G is a non-singular matrix then all elements of G must be non-singular matrices.

(b) Consider the set of 2×2 singular matrices G of the form

$$\begin{pmatrix} x & x \\ x & x \end{pmatrix}, \tag{10}$$

where $x \in \mathbb{R}$ and $x \neq 0$. Prove that G is a group with respect to matrix multiplication. Determine the matrix corresponding to the identity element of G. Determine the inverse of the element specified in eq. (10).

Observe that

$$\begin{pmatrix} x & x \\ x & x \end{pmatrix}\begin{pmatrix} y & y \\ y & y \end{pmatrix} = \begin{pmatrix} z & z \\ z & z \end{pmatrix}, \qquad \text{where } z = 2xy\,.$$

This demonstrates that the elements of G satisfy closure on matrix multiplication. Next, we note that

$$\begin{pmatrix} x & x \\ x & x \end{pmatrix}\begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{pmatrix} = \begin{pmatrix} x & x \\ x & x \end{pmatrix},$$

which implies that

$$e = \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{pmatrix}, \tag{11}$$

is the identity element. Finally,

$$\begin{pmatrix} x & x \\ x & x \end{pmatrix}\begin{pmatrix} \frac{1}{4x} & \frac{1}{4x} \\ \frac{1}{4x} & \frac{1}{4x} \end{pmatrix} = \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{pmatrix},$$

which implies that the group inverse of the element specified in eq. (10) is

$$\begin{pmatrix} \frac{1}{4x} & \frac{1}{4x} \\ \frac{1}{4x} & \frac{1}{4x} \end{pmatrix} . \tag{12}$$

(c) The group defined in part (b) is isomorphic to a well known group. Identify this group.

Consider the function from $G \to \mathbb{R}^*$ that maps the elements

$$\begin{pmatrix} x & x \\ x & x \end{pmatrix} \quad \longmapsto \quad 2x\,, \qquad \text{for all } x \in \mathbb{R}^*\,, \tag{13}$$

where $\mathbb{R}^* \equiv \mathbb{R}^0 - \{0\}$ is the group of non-zero real numbers with respect to multiplication. This map is an isomorphism. It is easy to check that the group multiplication law is preserved, since

$$\begin{pmatrix} \frac{1}{2}x & \frac{1}{2}x \\ \frac{1}{2}x & \frac{1}{2}x \end{pmatrix} \begin{pmatrix} \frac{1}{2}y & \frac{1}{2}y \\ \frac{1}{2}y & \frac{1}{2}y \end{pmatrix} = \begin{pmatrix} \frac{1}{2}xy & \frac{1}{2}xy \\ \frac{1}{2}xy & \frac{1}{2}xy \end{pmatrix} \quad \longmapsto \quad (x)(y) = xy\,,$$

is in one-to-one correspondence with multiplication in $\mathbb{R}^*$. Moreover, the identity [eq. (11)] maps to 1, which is the identity of $\mathbb{R}^*$. Finally, the inverse given in eq. (12) is mapped by eq. (13) to $1/(2x)$, which is the inverse of $2x$ in $\mathbb{R}^*$. We conclude that $G \cong \mathbb{R}^*$.

We can see the isomorphism more explicitly by considering the equivalent representation,

$$S^{-1}\begin{pmatrix} x & x \\ x & x \end{pmatrix} S\,, \qquad \text{where } S = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix}\,,$$

A straightforward computation yields

$$\frac{1}{2}\begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}\begin{pmatrix} x & x \\ x & x \end{pmatrix}\begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} = \begin{pmatrix} 2x & 0 \\ 0 & 0 \end{pmatrix} .$$

Thus, the matrix representation given in eq. (10) is completely reducible and is the direct sum of two one dimensional representations. We can simply discard the zeros, which leaves a one-dimensional representation that is isomorphic to $\mathbb{R}^*$ with the map given by eq. (13).

4. Consider the dihedral group D_4.

(a) Write down the group multiplication table.

The elements of D_4 are defined by:

$$D_4 = \{1, r, r^2, r^3, d, rd, r^2d, r^3d\}\,,$$

where the elements satisfy the relations,

$$r^4 = d^2 = 1 \quad \text{and} \quad dr = r^3 d\,. \tag{14}$$

We have used the notation $e \equiv 1$ to define the identity element of D_4.

Using eq. (14), the group multiplication table is immediately obtained:

	1	r	r^2	r^3	d	rd	r^2d	r^3d
1	1	r	r^2	r^3	d	rd	r^2d	r^3d
r	r	r^2	r^3	1	rd	r^2d	r^3d	d
r^2	r^2	r^3	1	r	r^2d	r^3d	d	rd
r^3	r^3	1	r	r^2	r^3d	d	rd	r^2d
d	d	r^3d	r^2d	rd	1	r^3	r^2	r
rd	rd	d	r^3d	r^2d	r	1	r^3	r^2
r^2d	r^2d	rd	d	r^3d	r^2	r	1	r^3
r^3d	r^3d	r^2d	rd	d	r^3	r^2	r	1

(b) Enumerate the subgroups, the normal subgroups and the conjugacy classes.

There are eight proper subgroups of D_4:

$$\begin{aligned} \{1,r^2\}\cong\{1,d\}\cong\{1,rd\}\cong\{1,r^2d\}\cong\{1,r^3d\}&\cong\mathbb{Z}_2\,,\\ \{1,r,r^2,r^3\}&\cong\mathbb{Z}_4\,,\\ \{1,r^2,d,r^2d\}\cong\{1,r^2,rd,r^3d\}&\cong D_2\,. \end{aligned}$$

Among these subgroups, four are normal subgroups:[3]

$$\{1,r^2\}\cong\mathbb{Z}_2\,,\quad \{1,r,r^2,r^3\}\cong\mathbb{Z}_4\,,\quad\text{and}\quad \{1,r^2,d,r^2d\}\cong\{1,r^2,rd,r^3d\}\cong D_2\,.$$

Finally, we enumerate the classes:

$$\mathcal{C}_1=\{1\}\,,\quad \mathcal{C}_2=\{r,r^3\}\,,\quad \mathcal{C}_3=\{r^2\}\,,\quad \mathcal{C}_4=\{d,r^2d\}\quad\text{and}\quad \mathcal{C}_5=\{rd,r^3d\}\,. \tag{15}$$

(c) Identify the factor groups. Is the full group the direct product of some of its subgroups?

Using the results of part (b), the possible factor groups are:

$$D_4/\mathbb{Z}_2\cong D_2\,,\qquad D_4/\mathbb{Z}_4\cong\mathbb{Z}_2\,,\qquad D_4/D_2\cong\mathbb{Z}_2\,. \tag{16}$$

The last two factor groups are identified uniquely as $\mathbb{Z}_2$, since this is the only group of two elements. The identification of the first factor group is non-trivial, since there are two possible groups of order four—D_2 and $\mathbb{Z}_4$. Note that D_2 is *not* a cyclic group, whereas $\mathbb{Z}_4$ is a cyclic group. However, it is clear that $D_4/\mathbb{Z}_2$ is not a cyclic group. In particular, writing out the left cosets,

$$D_4/\mathbb{Z}_2=\Big\{\{1,r^2\}\,,\,\{r,r^3\}\,,\,\{d,r^2d\}\,,\,\{rd,r^3d\}\Big\}\,,$$

[3] One can prove that if a finite group G possesses a subgroup H that contains exactly half the number of elements of G, then H is a normal subgroup of G.

and identifying $\{1, r^2\}$ as the identity element of $D_4/\mathbb{Z}_2$, it is straightforward to check that the squares of all the other elements of $D_4/\mathbb{Z}_2$ yields the identity element, which is *not* in general satisfied by the elements of $\mathbb{Z}_4$.

In light of eq. (16), the only possible candidates for writing D_4 as a direct product of its subgroups are $\mathbb{Z}_2 \otimes D_2$ or $\mathbb{Z}_2 \otimes \mathbb{Z}_4$. But the latter two are direct products of abelian groups, which imply that the corresponding direct product groups are abelian, whereas D_4 is a non-abelian group. Hence, D_4 is *not* a direct product of some of its subgroups. On the other hand, D_4 can be expressed as a semi-direct product of its subgroups in two different ways,

$$D_4 \cong \mathbb{Z}_4 \rtimes \mathbb{Z}_2 \cong D_2 \rtimes \mathbb{Z}_2 \,. \tag{17}$$

If we take $D_2 = \{1, r^2, rd, r^3 d\}$, then we identify $\mathbb{Z}_2 = \{1, d\}$ in both semi-direct products of eq. (17).[4] Note that D_4 cannot be written as $\mathbb{Z}_2 \rtimes D_2$, since the first group of the semi-direct product is the normal subgroup. But, with $\mathbb{Z}_2 = \{1, r^2\}$, we see that one does not obtain all elements of D_4 in the form of $g_1 g_2$, with $g_1 \in \mathbb{Z}_2 = \{1, r^2\}$ and $g_2 \in D_2$.

5. The *center* of a group G, denoted by $Z(G)$, is defined as the set of elements $z \in G$ that commute with all elements of the group. That is,

$$Z(G) = \{z \in G \,|\, zg = gz \,, \forall\, g \in G\} \,.$$

(a) Show that $Z(G)$ is an abelian subgroup of G.

To prove that $Z(G)$ is a subgroup of G, we must prove that:

$$\begin{array}{lll} \text{(i)} & z_1,\, z_2 \in Z(G) \quad \Longrightarrow \quad z_1 z_2 \in Z(G), \\ \text{(ii)} & e \in Z(G), \quad \text{where } e \text{ is the identity}, \\ \text{(iii)} & z \in Z(G) \quad \Longrightarrow \quad z^{-1} \in Z(G). \end{array}$$

To prove (i), we note that $z_1,\, z_2 \in Z(G)$ means that

$$z_1 g = g z_1 \,, \qquad \text{for all } g \in G, \tag{18}$$

$$z_2 g = g z_2 \,, \qquad \text{for all } g \in G. \tag{19}$$

Multiply eq. (18) on the right by z_2 to obtain

$$z_1 g z_2 = g z_1 z_2 \,. \tag{20}$$

Then, use eq. (19) to write $z_1 g z_2 = z_1 z_2 g$. Then, eq. (20) can be rewritten as

$$z_1 z_2 g = g z_1 z_2 \,,$$

which means that $z_1 z_2$ commutes with any element $g \in G$. Hence, $z_1 z_2 \in Z(G)$.

[4] If $D_2 = \{1, r^2, d, r^2 d\}$ then we identify $\mathbb{Z}_2 = \{1, rd\}$ in the second semi-direct product in eq. (17).

The proof of (ii) is trivial since e commutes with all elements of G. Finally to prove (iii) we note that $z \in Z(G)$ means that $zg = gz$ for all $g \in G$. Multiplying this equation on the left by g^{-1} and on the right by g^{-1} yields

$$g^{-1}z = zg^{-1}\,, \quad \text{for all } g \in G\,. \tag{21}$$

Taking the inverse of eq. (21) yields

$$z^{-1}g = gz^{-1}\,, \quad \text{for all } g \in G\,.$$

Hence, $z^{-1} \in Z(G)$. Thus, we have succeeded in showing $Z(G)$ is a subgroup of G.

Finally, it should be clear that $Z(G)$ is an abelian subgroup. As previously noted, for any $z_1,\ z_2 \in Z(G)$, eq. (18) is satisfied. In particular, choosing $g = z_2$ in eq. (18), it follows that $z_1z_2 = z_2z_1$. This arguments continues to hold for any choice of z_1,$z_2 \in Z(G)$. Thus, we conclude that $Z(G)$ is an *abelian* subgroup of G.

(b) Show that $Z(G)$ is a normal subgroup of G.

To show that $Z(G)$ is a normal subgroup, one must show that for any $z \in Z(G)$ and $g \in G$, we have $gzg^{-1} \in Z(G)$. By definition, if $z \in Z(G)$ then $gz = zg$ for all $g \in G$. Hence, for any $z \in Z(G)$, we have $gzg^{-1} = zgg^{-1} = z \in Z(G)$ for all $g \in G$, as required for a normal subgroup.

(c) Find the center of D_4 and construct the group $D_4/Z(D_4)$. Determine whether the isomorphism $D_4 \cong [D_4/Z(D_4)] \otimes Z(D_4)$ is valid.

The multiplication table for D_4 was given in part (a) of problem 4. Inspection of the multiplication table reveals that:

$$Z(D_4) = \{e, r^2\} \cong \mathbb{Z}_2\,,$$

where the identification of the center follows from the fact that any finite group of two elements must be isomorphic to $\mathbb{Z}_2$.

The left cosets of D_4 with respect to the $\mathbb{Z}_2$ subgroup are:

$$\begin{aligned} \mathbb{Z}_2 &= \{e, r^2\}\,, \\ r\mathbb{Z}_2 &= \{r, r^3\}\,, \\ d\mathbb{Z}_2 &= \{d, r^2d\}\,, \\ rd\mathbb{Z}_2 &= \{rd, r^3d\}\,, \end{aligned}$$

which exhausts all the elements of D_4. We identify the quotient group

$$D_4/\mathbb{Z}_2 = \Big\{\{e, r^2\}\,,\ \{r, r^3\}\,,\ \{d, r^2d\}\,,\ \{rd, r^3d\}\Big\}\,.$$

From the multiplication table for D_4, one can construct the multiplication table for $D_4/\mathbb{Z}_2$,

	$\{e,r^2\}$	$\{r,r^3\}$	$\{d,r^2d\}$	$\{rd,r^3d\}$
$\{e,r^2\}$	$\{e,r^2\}$	$\{r,r^3\}$	$\{d,r^2d\}$	$\{rd,r^3d\}$
$\{r,r^3\}$	$\{r,r^3\}$	$\{e,r^2\}$	$\{rd,r^3d\}$	$\{d,r^2d\}$
$\{d,r^2d\}$	$\{d,r^2d\}$	$\{rd,r^3d\}$	$\{e,r^2\}$	$\{r,r^3\}$
$\{rd,r^3d\}$	$\{rd,r^3d\}$	$\{d,r^2d\}$	$\{r,r^3\}$	$\{e,r^2\}$

This is clearly not a cyclic group with one generator. Hence, it is not isomorphic to the cyclic group $\mathbb{Z}_4$, which leave only one remaining possibility, D_2. Indeed, one can check that the multiplication table above is equivalent to that of D_2. Hence,

$$D_4/\mathbb{Z}_2 \cong D_2 \,.$$

Finally, if the isomorphism $D_4 \cong [D_4/Z(D_4)] \otimes Z(D_4)$ were valid, then

$$D_4 \overset{?}{\cong} D_2 \otimes \mathbb{Z}_2 \,.$$

But this identification is incorrect. In particular, D_4 is a nonabelian group, whereas both D_2 and $\mathbb{Z}_2$ are abelian groups. Thus, it follows that $D_2 \otimes \mathbb{Z}_2$ is abelian, which means that this group cannot be isomorphic to the nonabelian group D_4.

6. An automorphism is defined as an isomorphism of a group G onto itself.

(a) Show that for any $g \in G$, the mapping $T_g(x) = gxg^{-1}$ is an automorphism (called an *inner automorphism*), where $x \in G$.

To show that $T_g(x) = gxg^{-1}$ is an automorphism, we must show that it is a homomorphism from the group G to itself that is one-to-one and onto. To prove that T_g is a homomorphism, one must verify that

$$T_g(x)T_g(y) = T_g(xy)\,, \qquad \text{for all } x, y \in G\,. \tag{22}$$

That is, $T_g(x)$ preserves the group multiplication table. The computation is straightforward:

$$T_g(x)T_g(y) = (gxg^{-1})(gyg^{-1}) = gxyg^{-1} = T_g(xy)\,.$$

To see that $T_g(x) = gxg^{-1}$ is one-to-one and onto (i.e. it is an isomorphism), we can invoke the rearrangement lemma. Multiplication on the left and/or on the right by a fixed element of G simply reorders the group multiplication table.[5] Hence, we conclude that T_g is an isomorphism from $G \longrightarrow G$. That is, T_g is an automorphism of the group G.

[5]One can also prove the one-to-one and onto properties directly. To prove that the homomorphism is one-to-one, one must show that

$$T_g(x) = T_g(y) \quad \Longrightarrow \quad x = y\,.$$

But, $T_g(x) = T_g(y)$ implies that $gxg^{-1} = gyg^{-1}$. Multiplying this equation on the left by g^{-1} and on the right by g then yields $x = y$. To prove that the homomorphism is onto, one must show that for all $y \in G$, there exists an $x \in G$ such that $T_g(x) = y$. In this case, it is sufficient to choose $x = g^{-1}yg$. Evaluating $T_g(x)$ for this choice,

$$T_g(g^{-1}yg) = g(g^{-1}yg)g^{-1} = y\,,$$

as required. Thus, for any choice of $y \in G$, we have explicitly determined the required x, namely $x = g^{-1}yg$, such that $T_g(x) = y$. That is, the homomorphism maps G *onto* itself.

(b) Show that the set of all inner automorphisms of G, denoted by $\mathcal{I}(G)$, is a group.

Define $\mathcal{I}(G) = \{T_g \,|\, g \in G\}$. Since T_g is an automorphism, we can introduce a group multiplication law that consists of the composition of two maps. In particular,

$$T_{g_1}T_{g_2}(x) = T_{g_1}(g_2 x g_2^{-1}) = g_1 g_2 x g_2^{-1} g_1^{-1} = (g_1 g_2)x(g_1 g_2)^{-1} = T_{g_1 g_2}(x)\,,$$

which holds for any $x \in G$. Hence, the composition of two maps is given by:

$$T_{g_1}T_{g_2} = T_{g_1 g_2}\,. \tag{23}$$

It follows that $\mathcal{I}(G)$ satisfies the axioms of a group by virtue of the fact that the group G satisfies the group axioms. In particular, eq. (23) implies that $\mathcal{I}(G)$ is closed with respect to the group multiplication law. Moreover, associativity is guaranteed because $g_1(g_2 g_3) = (g_1 g_2)g_3$ implies that

$$T_{g_1}(T_{g_2}T_{g_3}) = (T_{g_1}T_{g_2})T_{g_3} = T_{g_1 g_2 g_3}\,.$$

The identity of $\mathcal{I}(G)$ is T_e (where e is the identity element of the group G) since

$$T_g T_e = T_e T_g = T_{ge} = T_{eg} = T_g\,.$$

The inverse of T_g is $T_{g^{-1}}$, since

$$T_g T_{g^{-1}} = T_{g^{-1}} T_g = T_{gg^{-1}} = T_{g^{-1}g} = T_e\,.$$

Thus, the group axioms are satisfied, which implies that $\mathcal{I}(G)$ is a group.

(c) Show that $\mathcal{I}(G) \simeq G/Z(G)$, where $Z(G)$ is the center of G.

The kernel of the map $f : G \longrightarrow G'$ is defined by

$$K \equiv \ker\, f = \{g \in G \,|\, f(g) = e'\}\,,$$

where G' is the image of f and e' is the identity element of G'. Introduce the two homomorphisms,

$$\begin{aligned} &\phi : G \longrightarrow G/K \quad && \text{given by } \phi(g) = gK\,, \\ &\psi : G/K \longrightarrow G' \quad && \text{given by } \psi(gK) = f(g)\,. \end{aligned}$$

It follows that $\psi{\cdot}\phi(g) = f(g)$. It is straightforward to show that ψ is an isomorphism, in which case we can identify

$$G' \cong G/K\,. \tag{24}$$

This result can be represented diagrammatically by:

$$\begin{tikzcd} G \arrow[rr, "f"] \arrow[dr, "\phi"'] & & G' \arrow[dl, "\psi"] \\ & G/K & \end{tikzcd}$$

Consider the homomorphism, $f : G \longrightarrow \mathcal{I}(G)$, given by $f(g) = T_g$. Note that f is onto, i.e. $\mathcal{I}(G)$ is the image of f. The kernel of f is

$$K = \{g \in G\} \mid f(g) = T_e\} \,,$$

where T_e is the identity element of $\mathcal{I}(G)$, i.e. $T_e(x) = x$. Thus, K consists of all elements of G satisfying $T_g = T_e$, or equivalently, $gxg^{-1} = x$, which implies that $gx = xg$ for all $x \in G$. We recognize this as the center of G, denoted by $Z(G)$ in problem 4. Using eq. (24), it follows that

$$\mathcal{I}(G) \cong G/Z(G) \,. \tag{25}$$

(d) Show that the set of all automorphisms of G, denoted by $\mathcal{A}(G)$, is a group and that $\mathcal{I}(G)$ is a normal subgroup. (The factor group $\mathcal{A}(G)/\mathcal{I}(G)$ is called the group of *outer automorphisms* of G.)

Let $\mathcal{A}(G)$ be the set of all automorphisms of G. To show that this is a group, we must define the group multiplication law. As in the case of part (b), we define

$$A_1A_2(g) = A_1(A_2(g)) \,, \quad \text{for } A_1, A_2 \in \mathcal{A} \text{ and } g \in G \,.$$

That is the multiplication law is simply the composition of maps. It is straightforward to verify that the group axioms are satisfied. Note that since an automorphism is one-to-one and onto, each element of $\mathcal{A}(G)$ possesses a unique inverse. Next, we demonstrate that the set of inner automorphisms, $\{T_g \mid g \in G\}$, is a normal subgroup of $\mathcal{A}(G)$. To do this, one must show that $AT_gA^{-1} \in \mathcal{I}(G)$, for all $A \in \mathcal{A}(G)$. Consider,

$$\begin{aligned} AT_gA^{-1}(x) &= AT_g(A^{-1}(x)) = A(gA^{-1}(x)g^{-1}) \\ &= A(g)A(A^{-1}(x))A(g^{-1}) = A(g)xA^{-1}(g) \\ &= T_{A(g)}(x) \,, \end{aligned} \tag{26}$$

where we have used the fact that A is a homomorphism, which therefore satisfies

$$A(g_1g_2) = A(g_1)A(g_2) \quad \text{and} \quad A(g^{-1}) = A^{-1}(g) \,, \qquad \text{for any } g, g_1, g_2 \in G \,. \tag{27}$$

It follows that

$$AT_gA^{-1} = T_{A(g)} \in \mathcal{I}(G) \,.$$

7. Consider an arbitrary orthogonal matrix R, which satisfies $RR^{\mathsf{T}} = \mathbb{1}$ (where $\mathbb{1}$ is the identity matrix).

(a) Prove that the possible values of $\det R$ are ± 1.

Using the fact that $\det R^{\mathsf{T}} = \det R$, it follows that

$$\det(RR^{\mathsf{T}}) = (\det R)(\det R^{\mathsf{T}}) = [\det R]^2 = 1 \,, \tag{28}$$

since $RR^{\mathsf{T}} = \mathbb{1}$ implies that $\det(RR^{\mathsf{T}}) = \det \mathbb{1} = 1$. Taking the square root of eq. (28) yields $\det R = \pm 1$.

(b) The group SO(2) consists of all 2×2 orthogonal matrices with unit determinant. Prove that SO(2) is an abelian group.

Suppose that $Q \in \mathrm{SO}(2)$. If we parameterize

$$Q = \begin{pmatrix} a & b \\ c & d \end{pmatrix},$$

then we can find relations among the parameters a, b, c and d by imposing the conditions $Q^{\mathsf{T}}Q = \mathbb{1}$ and $\det Q = 1$. That is,

$$\begin{pmatrix} a & c \\ b & d \end{pmatrix}\begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} a^2+c^2 & ab+cd \\ ab+cd & b^2+d^2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix},$$

and $\det Q = ad - bc = 1$. Hence, the relations among the parameters a, b, c and d are determined by the following conditions,

$$a^2 + c^2 = b^2 + d^2 = 1\,, \qquad ab + cd = 0\,, \qquad ad - bc = 1\,. \tag{29}$$

We now consider two cases. First if $c \neq 0$, it follows that $d = -ab/c$. Inserting this result back into eq. (29) yields

$$1 = ad - bc = -\frac{a^2 b}{c} - bc = -\frac{b}{c}\left(a^2 + c^2\right) = -\frac{b}{c}\,,$$

after using eq. (29). That is, $c = -b$. It immediately follows that $d = -ab/c = a$, and we conclude that the most general SO(2) matrix is given by

$$Q = \begin{pmatrix} a & b \\ -b & a \end{pmatrix}.$$

In light of eq. (29), $c = -b$ yields $a^2 + b^2 = 1$, which implies that $-1 \leq a, b \leq 1$. Thus, it is convenient to parameterize a and b by defining $a = \cos\theta$ and $b = \sin\theta$. Hence, the most general SO(2) matrix is given by

$$Q = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \tag{30}$$

where $0 \leq \theta < 2\pi$.

Next, we examine the case of $c = 0$. In this case, eq. (29) yields $a^2 = 1$, $ab = 0$, and $ad = 1$. It follows that $b = 0$ and $a = d = \pm 1$. Hence the form for Q in this case (where $a = d = \pm 1$ and $b = c = 0$) is consistent with eq. (30).

It is now a simple matter to show that SO(2) is a group and any two elements of SO(2) of the form given in eq. (30) commute. In particular,

$$\begin{aligned}
&\begin{pmatrix} \cos\theta_1 & \sin\theta_1 \\ -\sin\theta_1 & \cos\theta_1 \end{pmatrix}\begin{pmatrix} \cos\theta_2 & \sin\theta_2 \\ -\sin\theta_2 & \cos\theta_2 \end{pmatrix} \\
&\qquad = \begin{pmatrix} \cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2 & \sin\theta_1\cos\theta_2 + \cos\theta_1\sin\theta_2 \\ -\sin\theta_1\cos\theta_2 - \cos\theta_1\sin\theta_2 & \cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2 \end{pmatrix} \\
&\qquad = \begin{pmatrix} \cos(\theta_1+\theta_2) & \sin(\theta_1+\theta_2 \\ -\sin(\theta_1+\theta_2) & \cos(\theta_1+\theta_2) \end{pmatrix}.
\end{aligned} \tag{31}$$

The form of the group multiplication law given above exhibits closure. The identity corresponds to taking $\theta = 0$ in eq. (30), and the inverse of Q is obtained by taking $\theta \to -\theta$. Finally, if we interchange θ_1 and θ_2 in eq. (31), we recover the same result. Hence, all products of SO(2) elements are commutative (which implies associativity), and we conclude that SO(2) is an abelian group.

(c) The group O(2) consists of all 2×2 orthogonal matrices, with no restriction on the sign of its determinant. Is O(2) abelian or non-abelian? (If the latter, exhibit two O(2) matrices that do not commute.)

The matrix Q given in eq. (30) is also an element of O(2). An element of O(2) that is not an element of SO(2) is

$$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} .$$

But this matrix does not commute with Q. In particular,

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ -\sin\theta & -\cos\theta \end{pmatrix} ,$$

whereas

$$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix} .$$

Hence, we conclude that O(2) is a non-abelian group.

<u>*REMARK*</u>:

Note that SO(2) is a normal subgroup of O(2). To prove this result, consider the homomorphism, $f : \mathrm{O}(2) \longrightarrow \{+1\,, -1\}$, which is defined by $f(A) = \det A$, for $A \in \mathrm{O}(2)$. The kernel of f is SO(2), since the latter corresponds to the set of all elements of O(2) with determinant equal to one. Hence, $\mathrm{O}(2)/\mathrm{kef}\ f \cong \{+1\,, -1\}$. Since we can identify $\mathbb{Z}_2 = \{+1\,, -1\}$ where the group operation is ordinary multiplication, we can conclude that $\mathrm{O}(2)/\mathrm{SO}(2) \cong \mathbb{Z}_2$.

However, it does *not* follow that $\mathrm{O}(2) \cong \mathrm{SO}(2) \otimes \mathbb{Z}_2$. Indeed, O(2) is a nonabelian group whereas $\mathrm{SO}(2) \otimes \mathbb{Z}_2$ is an abelian group. Nevertheless, it is true that O(2) is a semi-direct product,

$$\mathrm{O}(2) \cong \mathrm{SO}(2) \rtimes \mathbb{Z}_2 \,.$$

To show this, we simply need to exhibit a $\mathbb{Z}_2$ subgroup of O(2) such that $\mathrm{SO}(2) \cap \mathbb{Z}_2 = \{e\}$, where e is the identity element of O(2). A possible choice for the $\mathbb{Z}_2$ subgroup of O(2) that satisfies this requirement is,

$$\mathbb{Z}_2 = \left\{ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} , \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \right\} .$$

One can easily verify that this $\mathbb{Z}_2$ subgroup is not a normal subgroup of O(2). In particular, $g\mathbb{Z}_2 g^{-1} \neq \mathbb{Z}_2$ for all $g \in$O(2), as one can easily check.