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Student Learning Objectives SLOs: Linear Transformations in Geometry
Challenge Questions :: Going Deeper

SLOs 2.2 Linear Transformations in Geometry

After this lecture you should:

- Know the Matrix Forms for scaling, rotation, reflection, shear.
- Be the Inter-Galactic Grand Emperor of Orthogonal Projections: know the formula for projection onto a line, and the geometric interpretations.
- Be able to perform Reflections Across a Line: know the formula and relation to orthogonal projections onto a line

Challenge Question Just for “fun” 1 of 2

Last time we defined

Theorem (Linear Transforms)
A transformation \( T : \mathbb{R}^m \to \mathbb{R}^n \) is linear if and only if

- **Vector Addition** —
  \[ T(\mathbf{v} + \mathbf{w}) = T(\mathbf{v}) + T(\mathbf{w}), \quad \forall \mathbf{v}, \mathbf{w} \in \mathbb{R}^m, \text{ and} \]

- **Scalar Multiplication** —
  \[ T(k\mathbf{v}) = kT(\mathbf{v}), \quad \forall \mathbf{v} \in \mathbb{R}^m, \text{ and } \forall k \in \mathbb{R}. \]

by it is not necessary to restrict this definition to vectors. We can say:

Theorem (Linear Transforms (Generalized))
A transformation \( T : V \to W \) is linear if and only if

- **Addition** —
  \[ T(\mathbf{v}_1 + \mathbf{v}_2) = T(\mathbf{v}_1) + T(\mathbf{v}_2), \quad \forall \mathbf{v}_1, \mathbf{v}_2 \in V, \text{ and} \]

- **Scalar Multiplication** —
  \[ T(k\mathbf{v}) = kT(\mathbf{v}), \quad \forall \mathbf{v} \in V, \text{ and } \forall k \in \mathbb{R}. \]
Challenge Question

Keeping the generalized linear transform in mind, can you think of an example where $V$ and $W$ are NOT vector spaces ($\mathbb{R}^n$, $\mathbb{R}^m$)?

What is a “Challenge Question?”

It is a question which stretches beyond what we “know” at this stage in the class. Some challenge questions will be “answered” later in the semester, and some in future class(es), e.g. Math 524 and Math 543.

Will “Challenge Questions” show up on the midterm/final?

No... Well, if a question is answered later in the semester, it is fair game. (but not until then)

The Geometry of Linear Transforms

Rotations

We have seen [PREVIOUS LECTURE; ASSOCIATED MOVIES] that the matrix $\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ gives a counter-clockwise rotation by $\pi/2$ ($90^\circ$); in general, let

$$A(\theta) = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}, \quad A(\theta) \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} x \cos \theta - y \sin \theta \\ x \sin \theta + y \cos \theta \end{bmatrix}$$

defines a counter-clockwise rotation by $\theta$.

When $A \in \mathbb{R}^{n \times n}$, and $\text{rank}(A) < n$; the linear transformation $Ax$ is a projection onto a subspace of $\mathbb{R}^n$. Here $n = 2$ and $\text{rank}(A) = 1$:

- (i) $\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$ projects onto the $x$-axis: $\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} x \\ 0 \end{bmatrix}$;
- (ii) $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ projects onto the $y$-axis: $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 0 \\ y \end{bmatrix}$.

The Geometry of Linear Transforms

Scaling

The Geometry of Linear Transforms

Projection

When $A$ is a multiple of the identity matrix, $\alpha \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, then all vectors are scaled by the factor $\alpha$. 

<table>
<thead>
<tr>
<th>$A$</th>
<th>$A = \begin{bmatrix} 2 &amp; 0 \ 0 &amp; 2 \end{bmatrix}$</th>
<th>$A = \begin{bmatrix} 2 &amp; 0 \ 0 &amp; 2 \end{bmatrix}$</th>
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<tbody>
<tr>
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<td>Rotating with $A(1)$</td>
<td>$w$-axis</td>
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<tr>
<td>$x$</td>
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- (i) $\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$ projects onto the $x$-axis: $\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} x \\ 0 \end{bmatrix}$;
- (ii) $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ projects onto the $y$-axis: $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 0 \\ y \end{bmatrix}$.
Here we see examples of reflections;

- (i) \[
\begin{pmatrix}
-1 & 0 \\
0 & 1
\end{pmatrix}
\] reflects about the y-axis; and

- (ii) \[
\begin{pmatrix}
1 & 0 \\
0 & -1
\end{pmatrix}
\] reflects about the x-axis; and

- (iii) \[
\begin{pmatrix}
0 & -1 \\
-1 & 0
\end{pmatrix}
\] reflects about the line \( y = -x \).

The scaling and rotation matrices commute.

All these operations (+ clock-wise rotation) can be combined in a multitude of ways; the most commonly appearing combination being scaling+rotation, e.g.

\[
\begin{pmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
0.5 & 0 \\
0 & 0.5
\end{pmatrix}
\begin{pmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{pmatrix}
= \begin{pmatrix}0.5 \cos \theta & -0.5 \sin \theta \\
0.5 \sin \theta & 0.5 \cos \theta\end{pmatrix}
\]

In this case, order does not matter; we can rotate-then-scale, or scale-then-rotate, or scale-and-rotate-at-the-same-time

Scaling

\( \forall k > 0 \), the matrix \( M = \begin{pmatrix} k & 0 \\ 0 & k \end{pmatrix} \) defines a scaling by \( k \):

\[
M\vec{x} = \begin{pmatrix} k & 0 \\ 0 & k \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} kx_1 \\ kx_2 \end{pmatrix} = k \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = k\vec{x}.
\]

We call this a dilation (enlargement) when \( k > 1 \), and a contraction when \( 0 < k < 1 \); when \( k = 0 \) you get a contraction to a point \( \vec{0} \); when \( k < 0 \) you get a reflection in each coordinate plane followed by a scaling by \( |k| \).

Scaling generalizes to \( \mathbb{R}^n \) in the most straight-forward way; scaling matrices are of the form \( kI_n \), where \( I_n \) is the identity matrix of size \( n \).
**Rotations**

Theorem (Rotations)

The matrix of a counter-clockwise rotation in $\mathbb{R}^2$ through an angle $\theta$ is

$$\begin{bmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{bmatrix}.$$ 

Note that this is a matrix of the form $$\begin{bmatrix} a & -b \\ b & a \end{bmatrix}, \text{ where } a^2 + b^2 = 1.$$ Conversely, any matrix of this form represents a rotation.

For clockwise rotations, change $\theta \rightarrow -\theta$.

**Shear**

Theorem (Horizontal and Vertical Shears)

The matrix of a horizontal shear is of the form $$\begin{bmatrix} 1 & k \\ 0 & 1 \end{bmatrix}, \text{ and the matrix of a vertical shear is of the form } \begin{bmatrix} 1 & 0 \\
k & 1 \end{bmatrix}, \text{ where } k \text{ is any constant.}$$

"[Mechanical shear is] a strain in the structure of a substance produced by pressure, when its layers are laterally shifted in relation to each other." — Google.

More info: — Math, Engineering, Physics, Geology (Earthquakes), Aviation...
https://en.wikipedia.org/wiki/Shear
https://en.wikipedia.org/wiki/Shear_matrix

**Orthogonal Projections**

Ponder a line $L$ (described by the equation $c_1x + c_2y = 0$) in the plane ($\mathbb{R}^2$); any vector $\vec{x} \in \mathbb{R}^2$ can we written uniquely as $\vec{x} = \vec{x}^\parallel + \vec{x}^\perp$, where $\vec{x}^\parallel$ is parallel to the line $L$, and $\vec{x}^\perp$ is orthogonal (perpendicular) to $L$.

The transformation $T(\vec{x}) = \vec{x}^\parallel$ from $\mathbb{R}^2$ to $\mathbb{R}^2$ is called the **orthogonal projection of $\vec{x}$ onto $L$**; sometimes denoted by $\text{proj}_L(\vec{x})$.

The projection is essentially, the **shadow** $\vec{x}$ casts on $L$ if we shine a light on $L$ (where are the light-rays are perfectly orthogonal to $L$).
Orthogonal Projections

We can describe the Orthogonal Projection using the dot product...

First, let \( \vec{w} \neq \vec{0} \) be any vector parallel to \( L \). We must have

\[
\vec{x}^\parallel = k\vec{w},
\]

for some \( k \in \mathbb{R} \). The “leftovers” are

\[
\vec{x}^\perp = \vec{x} - \vec{x}^\parallel = \vec{x} - k\vec{w},
\]

but \( \vec{x}^\perp \) must be perpendicular to \( L \); so that [Definition of Orthogonality]

\[
(\vec{x} - k\vec{w}) \cdot \vec{w} = 0.
\]

Let’s digest that for \( 10^{-9} \) seconds...

Using the [Distributive Property] of the dot product:

\[
(\vec{x} - k\vec{w}) \cdot \vec{w} = 0 \quad \iff \quad \vec{x} \cdot \vec{w} - k(\vec{w} \cdot \vec{w}) = 0,
\]

which leads to an expression for \( k \):

\[
k = \frac{\vec{x} \cdot \vec{w}}{\vec{w} \cdot \vec{w}}.
\]

We conclude with the

Formulas for the Orthogonal Projection onto a line, \( L \)

\[
\vec{x}^\parallel = \operatorname{proj}_L(\vec{x}) = k\vec{w} = \left( \frac{\vec{x} \cdot \vec{w}}{\vec{w} \cdot \vec{w}} \right) \vec{w}, \quad \text{where } \vec{w} \text{ is any point on } L.
\]

Note that \( \vec{w} \cdot \vec{w} \) is [Definition of Vector Length] just \( \| \vec{w} \|^2 \).

If we build the projection with a vector of length 1 (unit vector, \( \| \vec{u} \| = 1 \)), the projection formula simplifies to

\[
\vec{x}^\parallel = \operatorname{proj}_L(\vec{x}) = k\vec{u} = (\vec{x} \cdot \vec{u}) \vec{u}.
\]

You can always “make” a unit vector for this purpose, by re-scaling \( \vec{w} \) to be length 1:

\[
\vec{u} = \frac{1}{\| \vec{w} \|} \vec{w}
\]
Linear Transformations in Geometry — (21/28)

Orthogonal Projections

We can express the projection as a matrix-vector multiplication; therefore it is a linear transformation.

\[ \vec{x}^\parallel = \text{proj}_L(\vec{x}) = k\vec{u} = (\vec{x} \cdot \vec{u}) \vec{u} = (x_1u_1 + x_2u_2) \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \]

\[ = \begin{bmatrix} x_1u_1^2 + x_2u_1u_2 \\ x_1u_1u_2 + x_2u_2^2 \end{bmatrix} = \begin{bmatrix} u_1^2 \\ u_1u_2 \\ u_2^2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}. \]

Orthogonal Projections, and Reflections

Hey, Reflections are “Easy” if we know Projections!

We realize that

\[ \vec{x} = \vec{x}^\parallel + \vec{x}^\perp \iff \vec{x}^\parallel = \vec{x} - \vec{x}^\perp \iff -\vec{x}^\perp = \vec{x}^\parallel - \vec{x}; \]

where

- \( \vec{x}^\parallel \) is the part of \( \vec{x} \) in the direction of \( L \)
- \( \vec{x}^\perp \) is the part of \( \vec{x} \) in the direction orthogonal to \( L \).

\( \vec{x} \) reflected in \( L \) must be the same distance “on the other side” of \( L \), that is

\[ \text{ref}_L(\vec{x}) = \vec{x}^\parallel - 2\vec{x}^\perp = \vec{x} - 2\vec{x}^\perp = 2\vec{x}^\parallel - \vec{x}. \]
Reflections

Definition (Reflections)
Consider a line \( L \) (\( c_1x + c_2y = 0 \)) in the plane (\( \mathbb{R}^2 \)), and let \( \vec{x} = \vec{x}^\parallel + \vec{x}^\perp \) be a vector in \( \mathbb{R}^2 \). The linear transformation \( T(\vec{x}) = \vec{x}^\parallel - \vec{x}^\perp \) is called the reflection of \( \vec{x} \) about \( L \), denoted by
\[
\text{ref}_L(\vec{x}) = \vec{x}^\parallel - \vec{x}^\perp.
\]

We can relate \( \text{ref}_L(\vec{x}) \) to \( \text{proj}_L(\vec{x}) \):
\[
\text{ref}_L(\vec{x}) = 2\text{proj}_L(\vec{x}) - \vec{x} = 2(\vec{x} \cdot \vec{u})\vec{u} - \vec{x}.
\]

The Reflection matrix
\[
S = \begin{bmatrix}
2u_1^2 - 1 & 2u_1u_2 \\
2u_1u_2 & 2u_2^2 - 1
\end{bmatrix}
\]
is of the form \( \begin{bmatrix} a & b \\ b & -a \end{bmatrix} \), where \( a^2 + b^2 = 1 \). Conversely, any matrix of this form represents a reflection about a line.

Projections and Reflections in 3D, and Beyond...

Nothing strange happens when you go to higher dimensions...

Let \( L \) be a line in \( \mathbb{R}^3 \), and let \( \vec{u} \) be a unit vector parallel to \( L \); again we can write \( \vec{x} = \vec{x}^\parallel + \vec{x}^\perp \); and
\[
\text{proj}_L(\vec{x}) = \vec{x}^\parallel = (\vec{x} \cdot \vec{u})\vec{u}
\]

Now, \( V = L^\perp \) is the plane thru the origin which is orthogonal to \( L \). Writing down the projections to, and reflections across \( V \) is fairly straight-forward
\[
\begin{align*}
\text{proj}_V(\vec{x}) &= \vec{x} - \text{proj}_L(\vec{x}) = \vec{x} - (\vec{x} \cdot \vec{u})\vec{u} \\
\text{ref}_V(\vec{x}) &= \text{proj}_L(\vec{x}) - \text{proj}_V(\vec{x}) = 2\text{proj}_L(\vec{x}) - \vec{x} = 2(\vec{x} \cdot \vec{u})\vec{u} - \vec{x} \\
\text{ref}_V(\vec{x}) &= \text{proj}_V(\vec{x}) - \text{proj}_L(\vec{x}) = -\text{ref}_L(\vec{x}) = \vec{x} - 2(\vec{x} \cdot \vec{u})\vec{u}
\end{align*}
\]

Suggested Problems 2.2

Available on Learning Glass videos:
2.2 — 1, 6, 7, 9, 12, 13, 17, 26

Lecture – Book Roadmap

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<tr>
<td>1.2</td>
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<td>1.3</td>
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<td>§1.1–§1.3, §2.1–§2.3</td>
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<td>§8.1, §8.2*, §2.5*</td>
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<tr>
<td>2.2</td>
<td>§8.1, §8.2*, §4.2*, §4.4*</td>
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</table>

§2.5* (p.86–88) “Calculating \( A^{-1} \) by Gauss-Jordan Elimination”
§4.2* (p.207) “Projection Onto a Line” – (p.210) end of “Example 2”
§4.4* Example 1, Example 3
§8.2* We will talk about “Basis” / “Bases” soon... don’t worry about those concepts... yet.