From the beginning of last week:
Remember from calculus the addition and scalar multiplication of polynomials:

e.g $(2t^2+1)+(-t^2+3t+2)=t^2+3t+3$.

e.g $(-3)(-t^2+3t+2)=3t^2-9t-6$.

We want to represent abstract vectors as column vectors so we can do calculations (e.g. row-reduction) to study linear systems (e.g. week 6 p20) and linear transformations (e.g. week 6 p43).

Is this really different from $\mathbb{R}^3$?

$$\begin{bmatrix}1\\0\\2\end{bmatrix}+\begin{bmatrix}2\\3\\-1\end{bmatrix}=\begin{bmatrix}3\\3\\1\end{bmatrix}. \qquad (-3)\begin{bmatrix}2\\3\\-1\end{bmatrix}=\begin{bmatrix}-6\\-9\\3\end{bmatrix}. \quad \begin{matrix}\leftarrow \text{coefficient of } 1\\ \leftarrow \text{coefficient of } t\\ \leftarrow \text{coefficient of } t^2\end{matrix}$$

We want to represent abstract vectors as column vectors so we can do calculations (e.g. row-reduction) to study linear systems and linear transformations.

In $\mathbb{R}^n$, $\begin{bmatrix}x_1\\ \vdots\\ x_n\end{bmatrix}=x_1\mathbf{e}_1+\cdots+x_n\mathbf{e}_n$.

$\{\mathbf{b}_1,\dots,\mathbf{b}_n\}$ must span V

We can copy this idea: in V, pick a special set of vectors $\{\mathbf{b}_1,\dots,\mathbf{b}_n\}$, write each $\mathbf{x}$ in V uniquely as $c_1\mathbf{b}_1+\cdots+c_n\mathbf{b}_n$ and represent $\mathbf{x}$ by the column vector $\begin{bmatrix}c_1\\ \vdots\\ c_n\end{bmatrix}$.

$\{\mathbf{b}_1,\dots,\mathbf{b}_n\}$ must be linearly independent

Example: In $\mathbb{P}_2$, let $\mathbf{b}_1=1, \mathbf{b}_2=t, \mathbf{b}_3=t^2$.

Then we represent $a_0+a_1t+a_2t^2$ by $\begin{bmatrix}a_0\\a_1\\a_2\end{bmatrix}$ (see previous page).

§4.3: Bases

Definition: Let W be a subspace of a vector space V. An indexed set of vectors $\mathcal{B}=\{\mathbf{b}_1,\dots,\mathbf{b}_p\}$ in V is a *basis for W* if

i $\mathcal{B}$ is a linearly independent set, and

ii Span $\{\mathbf{b}_1,\dots,\mathbf{b}_p\}=W$.

The order matters: $\{\mathbf{b}_1,\mathbf{b}_2\}$ and $\{\mathbf{b}_2,\mathbf{b}_1\}$ are different bases.

i means: The only solution to $x_1\mathbf{b}_1+\cdots+x_p\mathbf{b}_p=\mathbf{0}$ is $x_1=\cdots=x_p=0$.

ii means: W is the set of vectors of the form $c_1\mathbf{b}_1+\cdots+c_p\mathbf{b}_p$ where $c_1,\dots,c_p$ can take any value.

Condition ii implies that $\mathbf{b}_1,\dots,\mathbf{b}_p$ must be in W, because Span $\{\mathbf{b}_1,\dots,\mathbf{b}_p\}$ contains each of $\mathbf{b}_1,\dots,\mathbf{b}_p$.

Every vector space V is a subspace of itself, so we can take $W=V$ in the definition and talk about bases for V.

Definition: Let W be a subspace of a vector space V. An indexed set of vectors $\mathcal{B}=\{\mathbf{b}_1,\dots,\mathbf{b}_p\}$ in V is a *basis for W* if

i $\mathcal{B}$ is a linearly independent set, and

ii Span $\{\mathbf{b}_1,\dots,\mathbf{b}_p\}=W$.

Example: The standard basis for $\mathbb{R}^3$ is $\{\mathbf{e}_1,\mathbf{e}_2,\mathbf{e}_3\}$, where

$$\mathbf{e}_1=\begin{bmatrix}1\\0\\0\end{bmatrix}, \mathbf{e}_2=\begin{bmatrix}0\\1\\0\end{bmatrix}, \mathbf{e}_3=\begin{bmatrix}0\\0\\1\end{bmatrix}.$$

To check that this is a basis: $\begin{bmatrix}| & | & |\\ \mathbf{e}_1 & \mathbf{e}_2 & \mathbf{e}_3\\ | & | & |\end{bmatrix}=\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$ is in reduced echelon form.

The matrix has a pivot in every column, so its columns are linearly independent.
The matrix has a pivot in every row, so its columns span $\mathbb{R}^3$.

Definition: Let W be a subspace of a vector space V. An indexed set of vectors $\mathcal{B} = \{\mathbf{b}_1, \dots, \mathbf{b}_p\}$ in V is a *basis for W* if

i. $\mathcal{B}$ is a linearly independent set, and
ii. $\text{Span}\{\mathbf{b}_1, \dots, \mathbf{b}_p\} = W$.

A basis for W is not unique: (different bases are useful in different situations, see next week).
Let's look for a different basis for $\mathbb{R}^3$.

Example: Let $\mathbf{v}_1 = \begin{bmatrix}1\\2\\0\end{bmatrix}, \mathbf{v}_2 = \begin{bmatrix}0\\1\\1\end{bmatrix}$. Is $\{\mathbf{v}_1, \mathbf{v}_2\}$ a basis for $\mathbb{R}^3$?

Answer: No, because two vectors cannot span $\mathbb{R}^3$: $\begin{bmatrix}| & | \\ \mathbf{v}_1 & \mathbf{v}_2 \\ | & |\end{bmatrix} = \begin{bmatrix}1 & 0\\2 & 1\\0 & 1\end{bmatrix}$ cannot have a pivot in every row.

Definition: Let W be a subspace of a vector space V. An indexed set of vectors $\mathcal{B} = \{\mathbf{b}_1, \dots, \mathbf{b}_p\}$ in V is a *basis for W* if

i. $\mathcal{B}$ is a linearly independent set, and
ii. $\text{Span}\{\mathbf{b}_1, \dots, \mathbf{b}_p\} = W$.

A basis for W is not unique: (different bases are useful in different situations, see next week).
Let's look for a different basis for $\mathbb{R}^3$.

Example: Let $\mathbf{v}_1 = \begin{bmatrix}1\\2\\0\end{bmatrix}, \mathbf{v}_2 = \begin{bmatrix}0\\1\\1\end{bmatrix}, \mathbf{v}_3 = \begin{bmatrix}-1\\0\\3\end{bmatrix}$. Is $\{\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3\}$ a basis for $\mathbb{R}^3$?

Answer: Form the matrix $A = \begin{bmatrix}| & | & | \\ \mathbf{v}_1 & \mathbf{v}_2 & \mathbf{v}_3 \\ | & | & |\end{bmatrix} = \begin{bmatrix}1 & 0 & -1\\2 & 1 & 0\\0 & 1 & 3\end{bmatrix}$. Because $\det A = 1 \neq 0$, the matrix A is invertible, so (by Invertible Matrix Theorem) its columns are linearly independent and its columns span $\mathbb{R}^3$.

Definition: Let W be a subspace of a vector space V. An indexed set of vectors $\mathcal{B} = \{\mathbf{b}_1, \dots, \mathbf{b}_p\}$ in V is a *basis for W* if

i. $\mathcal{B}$ is a linearly independent set, and
ii. $\text{Span}\{\mathbf{b}_1, \dots, \mathbf{b}_p\} = W$.

A basis for W is not unique: (different bases are useful in different situations, see next week).
Let's look for a different basis for $\mathbb{R}^3$.

Example: Let $\mathbf{v}_1 = \begin{bmatrix}1\\2\\0\end{bmatrix}, \mathbf{v}_2 = \begin{bmatrix}0\\1\\1\end{bmatrix}, \mathbf{v}_3 = \begin{bmatrix}1\\1\\0\end{bmatrix}, \mathbf{v}_4 = \begin{bmatrix}0\\0\\1\end{bmatrix}$. Is $\{\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3, \mathbf{v}_4\}$ a basis for $\mathbb{R}^3$?

Answer: No, because four vectors in $\mathbb{R}^3$ must be linearly dependent:
$\begin{bmatrix}| & | & | & | \\ \mathbf{v}_1 & \mathbf{v}_2 & \mathbf{v}_3 & \mathbf{v}_4 \\ | & | & | & |\end{bmatrix} = \begin{bmatrix}1 & 0 & 1 & 0\\2 & 1 & 1 & 0\\0 & 1 & 0 & 1\end{bmatrix}$ cannot have a pivot in every column.

By the same logic as in the above examples:
Fact: $\{\mathbf{v}_1, \dots \mathbf{v}_p\}$ is a basis for $\mathbb{R}^n$ if and only if:

- $p = n$ (i.e. the set has exactly n vectors), and
- $\det \begin{bmatrix}| & & | \\ \mathbf{v}_1 & \dots & \mathbf{v}_n \\ | & & |\end{bmatrix} \neq 0$.

Fewer than n vectors: not enough vectors, can't span $\mathbb{R}^n$.
More than n vectors: too many vectors, linearly dependent.

Example: The standard basis for $\mathbb{P}_n$ is $\mathcal{B} = \{1, t, t^2, \ldots, t^n\}$.

To check that this is a basis:

ii By definition of $\mathbb{P}_n$, every element of $\mathbb{P}_n$ has the form $a_0 + a_1 t + a_2 t^2 + \cdots + a_n t^n$, so $\mathcal{B}$ spans $\mathbb{P}_n$.

i To see that $\mathcal{B}$ is linearly independent, we show that $c_0 = c_1 = \cdots = c_n = 0$ is the only solution to

$$c_0 + c_1 t + c_2 t^2 + \cdots + c_n t^n = 0. \text{ (the zero function)}$$

Substitute $t = 0$: we find $c_0 = 0$.

Differentiate, then substitute $t = 0$: we find $c_1 = 0$.

Differentiate again, then substitute $t = 0$: we find $c_2 = 0$.

Repeating many times, we find $c_0 = c_1 = \cdots = c_n = 0$.

Once we have the standard basis of $\mathbb{P}_n$, it will be easier to check if other sets are bases of $\mathbb{P}_n$, using coordinates (later, p14).

Advanced exercise: what do you think is the standard basis for $M_{m\times n}$?

One way to make a basis for V is to start with a set that spans V.

Theorem 5: Spanning Set Theorem: If $V = \text{Span}\{\mathbf{v}_1, \ldots, \mathbf{v}_p\}$, then some subset of $\{\mathbf{v}_1, \ldots, \mathbf{v}_p\}$ is a basis for V.

Proof: basically, the idea of the casting-out algorithm (week 6 p28-34) works in abstract vector spaces too.

- If $\{\mathbf{v}_1, \ldots, \mathbf{v}_p\}$ is linearly independent, it is a basis for V.
- If $\{\mathbf{v}_1, \ldots, \mathbf{v}_p\}$ is linearly dependent, then one of the $\mathbf{v}_i$s is a linear combination of the others. Removing this $\mathbf{v}_i$ from the set still gives a set that spans V. Continue removing vectors in this way until the remaining vectors are linearly independent.

Example: $\mathbb{P}_2 = \text{Span}\{5, 3+t, 1+2t^2, 4+2t-4t^2\}$, but this set is not linearly independent because $4+2t-4t^2$ is a linear combination of the other polynomials: $4+2t-4t^2 = 2(3+t) - 2(1+2t^2)$. So remove $4+2t-4t^2$ to get the set $\{5, 3+t, 1+2t^2\}$, which is in fact a basis (we can show this with coordinates, p14-15).

PP 234, 238-240 (§4.4), 307-308 (§5.4): Coordinates

Recall (p2) that our motivation for finding a basis is because we want to write each vector $\mathbf{x}$ as $c_1\mathbf{b}_1 + \cdots + c_p\mathbf{b}_p$ in a unique way. Let's show that this is indeed possible

Theorem 7: Unique Representation Theorem: Let $\mathcal{B} = \{\mathbf{b}_1, \ldots, \mathbf{b}_n\}$ be a basis for a vector space V. Then for each $\mathbf{x}$ in V, there exists a unique set of scalars $c_1, \ldots, c_n$ such that

$$\mathbf{x} = c_1\mathbf{b}_1 + \cdots + c_n\mathbf{b}_n.$$

Proof:

Since $\mathcal{B}$ spans V, there exists scalars $c_1, \ldots, c_n$ such that the above equation holds.

Suppose $\mathbf{x}$ has another representation

$$\mathbf{x} = d_1\mathbf{b}_1 + \cdots + d_n\mathbf{b}_n.$$

for some scalars $d_1, \ldots, d_n$. Then

$$\mathbf{0} = \mathbf{x} - \mathbf{x} = (c_1 - d_1)\mathbf{b}_1 + \cdots + (c_n - d_n)\mathbf{b}_n.$$

Because $\mathcal{B}$ is linearly independent, all the weights in this equation must be zero, i.e. $(c_1 - d_1) = \cdots = (c_n - d_n) = 0$. So $c_1 = d_1, \ldots, c_n = d_n$.

Because of the Unique Representation Theorem, we can make the following definition:

Definition: Let $\mathcal{B} = \{\mathbf{b}_1, \ldots, \mathbf{b}_n\}$ be a basis for V. Then, for any $\mathbf{x}$ in V, the *coordinates of $\mathbf{x}$ relative to $\mathcal{B}$*, or the *$\mathcal{B}$-coordinates of $\mathbf{x}$*, are the unique weights $c_1, \ldots, c_n$ such that

$$\mathbf{x} = c_1\mathbf{b}_1 + \cdots + c_n\mathbf{b}_n.$$

The vector in $\mathbb{R}^n$

$$[\mathbf{x}]_\mathcal{B} = \begin{bmatrix} c_1 \\ \vdots \\ c_n \end{bmatrix}$$

is the *coordinate vector of $\mathbf{x}$ relative to $\mathcal{B}$*, or the *$\mathcal{B}$-coordinate vector of $\mathbf{x}$*.

Example: Let $\mathcal{B} = \{1, t, t^2, t^3\}$ be the standard basis for $\mathbb{P}_3$. Then the coordinate vector of an arbitrary polynomial is $[a_0 + a_1 t + a_2 t^2 + a_3 t^3]_\mathcal{B} = \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix}$.

Why are coordinate vectors useful?

Because of the Unique Representation Theorem, the function V to $\mathbb{R}^n$ given by

$\mathbf{x} \mapsto [\mathbf{x}]_\mathcal{B}$ (e.g. $a_0 + a_1t + a_2t^2 + a_3t^3 \mapsto \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix}$) is linear, one-to-one and onto.

Definition: A linear transformation $T : V \to W$ that is both one-to-one and onto is called an *isomorphism*. We say V and W are isomorphic.

This means that, although the notation and terminology for V and W are different, the two spaces behave the same as vector spaces. Every vector space calculation in V is accurately reproduced in W, and vice versa.

Important consequence: if V has a basis of n vectors, then V and $\mathbb{R}^n$ are isomorphic, so we can solve problems about V (e.g. span, linear independence) by working in $\mathbb{R}^n$.

If V has a basis of n vectors, then V and $\mathbb{R}^n$ are isomorphic, so we can solve problems about V (e.g. span, linear independence) by working in $\mathbb{R}^n$.

Example: Is the set of polynomials $\left\{1, 2-t, (2-t)^2, (2-t)^3\right\}$ linearly independent?

Answer: The coordinates of these polynomials relative to the standard basis of $\mathbb{P}_3$ are

$$[1]_\mathcal{B} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \qquad [(2-t)^2]_\mathcal{B} = [4 - 4t + t^2]_\mathcal{B} = \begin{bmatrix} 4 \\ -4 \\ 1 \\ 0 \end{bmatrix},$$

$$[2-t]_\mathcal{B} = \begin{bmatrix} 2 \\ -1 \\ 0 \\ 0 \end{bmatrix}, \quad [(2-t)^3]_\mathcal{B} = [(8 - 12t + 6t^2 - t^3]_\mathcal{B} = \begin{bmatrix} 8 \\ -12 \\ 6 \\ -1 \end{bmatrix}$$

The set of polynomials is linearly independent if and only if their coordinate vectors are linearly independent (continued on next page).

Example: Is the set of polynomials $\left\{1, 2-t, (2-t)^2, (2-t)^3\right\}$ linearly independent?

Answer: (continued). The matrix

$$\begin{bmatrix} 1 & 2 & 4 & 8 \\ 0 & -1 & -4 & -12 \\ 0 & 0 & 1 & 6 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

has determinant $1 \neq 0$ (it is upper triangular so its determinant is the product of the diagonal entries), so it is invertible, and by the Invertible Matrix Theorem, its columns are linearly independent in $\mathbb{R}^4$. So the polynomials are linearly independent. (In fact they form a basis, because IMT says they also span $\mathbb{R}^4$.)

Advanced exericse: if $\mathbf{p}_i$ has degree exactly i, then $\{\mathbf{p}_0, \mathbf{p}_1, \dots, \mathbf{p}_n\}$ is a basis for $\mathbb{P}_n$. (This idea is how I usually prove that a set is a basis in my research work.)

Harder example: (in preparation for week 9, change of coordinates) Let $\mathcal{F} = \left\{1, 2-t, (2-t)^2, (2-t)^3\right\}$. We just showed that $\mathcal{F}$ is a basis. So if the $\mathcal{F}$-coordinates of a polynomial $\mathbf{p}$ is $[\mathbf{p}]_\mathcal{F} = \begin{bmatrix} 2 \\ 4 \\ 0 \\ -1 \end{bmatrix}$, then what is $\mathbf{p}$?

Answer:

$[\mathbf{p}]_\mathcal{F} = \begin{bmatrix} 2 \\ 4 \\ 0 \\ -1 \end{bmatrix}$ means $\mathbf{p} = 2 + 4(2-t) + 0(2-t)^2 - 1(2-t)^3 = 2 + 8t - 6t^2 + t^3$.

If V has a basis of n vectors, then V and $\mathbb{R}^n$ are isomorphic, so we can solve problems about V (e.g. span, linear independence) by working in $\mathbb{R}^n$.

What about problems concerning linear transformations $T : V \to W$?

Remember from week 3 §1.9: Every linear transformation $T : \mathbb{R}^n \to \mathbb{R}^m$ is a matrix transformation $T(\mathbf{x}) = A\mathbf{x}$, where

apply T to ith basis vector, put the coordinates of the result into column i

$$A = \begin{bmatrix} | & | & | \\ T(\mathbf{e}_1) & \dots & T(\mathbf{e}_n) \\ | & | & | \end{bmatrix} \quad \text{(standard matrix of } T\text{)}.$$

The standard matrix is useful because we can solve $T(\mathbf{x}) = \mathbf{y}$ by row-reducing $[A|\mathbf{y}]$.

Definition: If V is a vector space with basis $\mathcal{B} = \{\mathbf{b}_1, \dots, \mathbf{b}_n\}$ and $T : V \to V$ is a linear transformation, then the *matrix for T relative to $\mathcal{B}$* is

$$[T]_{\mathcal{B}} = \begin{bmatrix} | & | & | \\ [T(\mathbf{b}_1)]_{\mathcal{B}} & \dots & [T(\mathbf{b}_n)]_{\mathcal{B}} \\ | & | & | \end{bmatrix}.$$

(so the standard matrix of T is the matrix for T relative to the standard basis of $\mathbb{R}^n$.)

DEFINITION:If V is a vector space with basis $\mathcal{B} = \{\mathbf{b}_1, \dots, \mathbf{b}_n\}$ and $T : V \to V$ is a linear transformation, then the matrix for T relative to $\mathcal{B}$ is

$$[T]_{\mathcal{B}} = \begin{bmatrix} | & | & | \\ [T(\mathbf{b}_1)]_{\mathcal{B}} & \dots & [T(\mathbf{b}_n)]_{\mathcal{B}} \\ | & | & | \end{bmatrix}.$$

EXAMPLE:(p308 of textbook) Let $T : \mathbb{P}_2 \to \mathbb{P}_2$ be the differentiation function

$$T(a_0 + a_1 t + a_2 t^2) = \frac{d}{dt}(a_0 + a_1 t + a_2 t^2) = a_1 + 2a_2 t.$$

Work in the standard basis of $\mathbb{P}_2$: $\mathbf{b}_1 = 1, \mathbf{b}_2 = t, \mathbf{b}_3 = t^2$.

$T(\mathbf{b_1}) =$ $\quad$ $T(\mathbf{b_2}) =$ $\quad$ $T(\mathbf{b_3}) =$

$[T(\mathbf{b_1})]_{\mathcal{B}} = \begin{bmatrix} \\ \\ \end{bmatrix}$ $\quad$ $[T(\mathbf{b_2})]_{\mathcal{B}} = \begin{bmatrix} \\ \\ \end{bmatrix}$ $\quad$ $[T(\mathbf{b_3})]_{\mathcal{B}} = \begin{bmatrix} \\ \\ \end{bmatrix}$

So

$$[T]_{\mathcal{B}} =$$

The matrix $[T]_{\mathcal{B}}$ is useful because

$$[T(\mathbf{x})]_{\mathcal{B}} = [T]_{\mathcal{B}}[\mathbf{x}]_{\mathcal{B}}, \qquad (*)$$

so we can solve $T(\mathbf{x}) = \mathbf{y}$ by row-reducing $\left[[T]_{\mathcal{B}} \middle| [\mathbf{y}]_{\mathcal{B}}\right]$.

Example: Let $T : \mathbb{P}_2 \to \mathbb{P}_2$ be the differentiation function $T(\mathbf{p}) = \frac{d}{dt}\mathbf{p}$ as on the previous page. Here is an example of equation $(*)$ for $\mathbf{x} = 2 + 3t - t^2$.

$$T(2+3t-t^2) = \frac{d}{dt}(2+3t-t^2) \qquad = 3 - 2t$$

$$[T]_{\mathcal{B}}\begin{bmatrix}2\\3\\-1\end{bmatrix} = \begin{bmatrix}0&1&0\\0&0&2\\0&0&0\end{bmatrix}\begin{bmatrix}2\\3\\-1\end{bmatrix} = \begin{bmatrix}3\\-2\\0\end{bmatrix}.$$

Some other things about T that we can learn from the matrix $[T]_{\mathcal{B}}$:

- We can solve the differential equation $\frac{d}{dt}\mathbf{p} = 1 - 3t$ by row-reducing $\left[\begin{array}{ccc|c}0&1&0&1\\0&0&2&-3\\0&0&0&0\end{array}\right]$.
- $[T]_{\mathcal{B}}$ is in echelon form, and it does not have a pivot in every column, so T is not one-to-one (which you know from calculus - this is why indefinite integrals have $+C$).

Basis and coordinates for subspaces:

Example: Let W be the set of vectors of the form $\begin{bmatrix}a\\0\\b\end{bmatrix}$, where a, b can take any value.

We showed (week 6 p14) that W is a subspace of $\mathbb{R}^3$ because $W = \text{Span}\left\{\begin{bmatrix}1\\0\\0\end{bmatrix}, \begin{bmatrix}0\\0\\1\end{bmatrix}\right\}$.

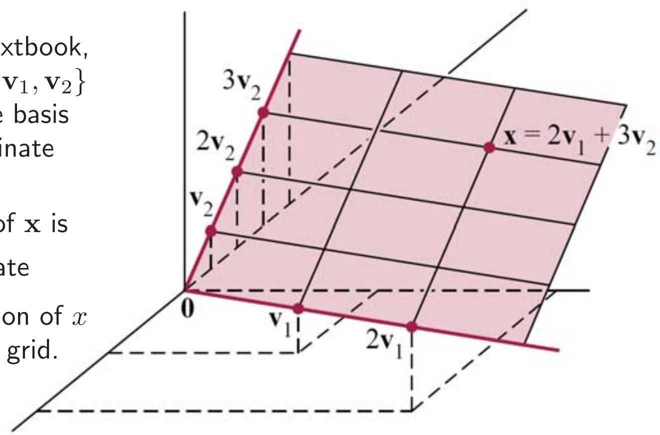
Since $\left\{\begin{bmatrix}1\\0\\0\end{bmatrix}, \begin{bmatrix}0\\0\\1\end{bmatrix}\right\}$ is furthermore linearly independent, it is a basis for W.

Because $\begin{bmatrix}a\\0\\b\end{bmatrix} = a\begin{bmatrix}1\\0\\0\end{bmatrix} + b\begin{bmatrix}0\\0\\1\end{bmatrix}$, the coordinate vector of $\begin{bmatrix}a\\0\\b\end{bmatrix}$, relative to the basis $\left\{\begin{bmatrix}1\\0\\0\end{bmatrix}, \begin{bmatrix}0\\0\\1\end{bmatrix}\right\}$, is $\begin{bmatrix}a\\b\end{bmatrix}$. So $\begin{bmatrix}a\\0\\b\end{bmatrix} \mapsto \begin{bmatrix}a\\b\end{bmatrix}$ is an ismorphism from W to $\mathbb{R}^2$.

Coordinates for subspaces (e.g. planes in $\mathbb{R}^3$) are useful as they allow us to represent points in the subspace with fewer numbers (e.g. with 2 numbers instead of 3 numbers).

In this picture (p239 of textbook, example 7 in §4.4), $\mathcal{B} = \{\mathbf{v}_1, \mathbf{v}_2\}$ is a basis for a plane. The basis allows us to draw a coordinate grid on the plane.

The $\mathcal{B}$-coordinate vector of $\mathbf{x}$ is $[\mathbf{x}]_{\mathcal{B}} = \begin{bmatrix}2\\3\end{bmatrix}$. This coordinate vector describes the location of x relative to this coordinate grid.



An "abstract" example of coordinates:
EXAMPLE: Let $\mathcal{B} = \{\mathbf{b_1}, \mathbf{b_2}, \mathbf{b_3}\}$ be a basis for V.

1. What is the $\mathcal{B}$-coordinate vector of $\mathbf{b_1} + \mathbf{b_2}$?

Suppose $T : V \to V$ is a linear transformation satisfying

$$T(\mathbf{b_1}) = \mathbf{b_1} + \mathbf{b_2}, \quad T(\mathbf{b_2}) = \mathbf{b_1} - 2\mathbf{b_3}, \quad T(\mathbf{b_3}) = \mathbf{b_3}.$$

2. Find the matrix $[T]_{\mathcal{B}}$ for T relative to $\mathcal{B}$.

3. Find $T(\mathbf{b_1} + \mathbf{b_2})$.