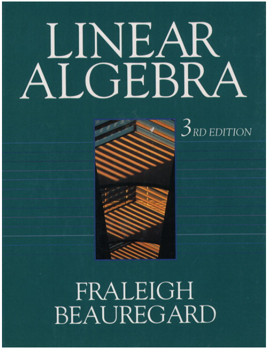
Linear Algebra

Chapter 1. Vectors, Matrices, and Linear Systems

Section 1.2. The Norm and Dot Product—Proofs of Theorems



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Solution. If we divide $\vec{w}$ by the scalar $\|\vec{w}\| > 0$, we get a vector of length 1 (i.e., a unit vector; this process is called *normalizing* a vector). Such a vector is in the same direction as $\vec{w}$ (by Definition 1.2 of "parallel and same direction").

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Solution. We have by definition that the desired angle is $\cos^{-1} \dfrac{\vec{u} \cdot \vec{v}}{\|\vec{u}\| \|\vec{v}\|}$.

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Now by Definition 1.5, "Vector Norm," $\|\vec{u}\| = \sqrt{(-1)^2 + (3)^2 + (4)^2} = \sqrt{1 + 9 + 16} = \sqrt{26}$ and $\|\vec{v}\| = \sqrt{(2)^2 + (1)^2 + (-1)^2} = \sqrt{4 + 1 + 1} = \sqrt{6}$. Also, by Definition 1.6, "Dot Product," $\vec{u} \cdot \vec{v} = [-1, 3, 4] \cdot [2, 1, -1] = (-1)(2) + (3)(1) + (4)(-1) = -2 + 3 - 4 = -3$.

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So the angle between $\vec{u}$ and $\vec{v}$ is $\cos^{-1} \dfrac{\vec{u} \cdot \vec{v}}{\|\vec{u}\| \|\vec{v}\|} = \cos^{-1} \dfrac{-3}{\sqrt{26}\sqrt{6}} =$

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We can use a calculator to approximate the true answer to find that the angle is roughly 103.90°.

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Page 33 Number 42(b). Let $\vec{u}, \vec{v}, \vec{w} \in \mathbb{R}^n$. Prove the Distributive Law: $\vec{u} \cdot (\vec{v} + \vec{w}) = \vec{u} \cdot \vec{v} + \vec{u} \cdot \vec{w}$.

Proof. Since $\vec{u}, \vec{v}, \vec{w} \in \mathbb{R}^n$, then by our first definition in Section 1.1, we have that $\vec{u} = [u_1, u_2, \ldots, u_n]$, $\vec{v} = [v_1, v_2, \ldots, v_n]$, and $\vec{w} = [w_1, w_2, \ldots, w_n]$ where all u_i, v_i, w_i are real numbers.

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$$\begin{aligned}\vec{u} \cdot (\vec{v} + \vec{w}) &= [u_1, u_2, \ldots, u_n] \cdot ([v_1, v_2, \ldots, v_n] + [w_1, w_2, \ldots, w_n]) \\ &= [u_1, u_2, \ldots, u_n] \cdot [v_1 + w_1, v_2 + w_2, \ldots, v_n + w_n] \\ &\quad \text{by Definition 1.1.(1), “Vector Addition”}\end{aligned}$$

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&= [u_1, u_2, \ldots, u_n] \cdot [v_1 + w_1, v_2 + w_2, \ldots, v_n + w_n] \\
&\quad \text{by Definition 1.1.(1), ``Vector Addition''} \\
&= u_1(v_1 + w_1) + u_2(v_2 + w_2) + \cdots + u_n(v_n + w_n) \\
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&= (u_1 v_1 + u_2 v_2 + \cdots + u_n v_n) + (u_1 w_1 + u_2 w_2 + \cdots + u_n w_n) \\
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&= [u_1, u_2, \ldots, u_n] \cdot [v_1, v_2, \ldots, v_n] \\
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&= \vec{u} \cdot \vec{v} + \vec{u} \cdot \vec{w}.
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Solution. By the definition of perpendicular (see page 4 of the class notes) we want x such that $[x, -3, 5] \cdot [-1, 3, 4] = 0$.

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$$[x, -3, 5] \cdot [-1, 3, 4] = (x)(-1) + (-3)(3) + (5)(4) = -x - 9 + 20 = -x + 11.$$

So to get a dot product of 0 we must have $\boxed{x = 11.}$ □

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Page 31 Number 16. Find a nonzero vector in $\mathbb{R}^3$ which is perpendicular to both $\vec{u} = [-1, 3, 4]$ and $\vec{v} = [2, 1, -1]$.

Solution. Let the desired vector be $\vec{w} = [w_1, w_2, w_3]$. By the definition of perpendicular (see page 4 of the class notes) we need $\vec{w} \cdot \vec{u} = 0$ and $\vec{w} \cdot \vec{v} = 0$.

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$$\vec{w} \cdot \vec{u} = [w_1, w_2, w_3] \cdot [-1, 3, 4]$$
$$= (w_1)(-1) + (w_2)(3) + (w_3)(4) = -w_1 + 3w_2 + 4w_3 = 0$$

and

$$\vec{w} \cdot \vec{v} = [w_1, w_2, w_3] \cdot [2, 1, -1]$$
$$= (w_1)(2) + (w_2)(1) + (w_3)(-1) = 2w_1 + w_2 - w_3 = 0.$$

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So we need $w_1, w_2, w_3 \in \mathbb{R}$ that satisfy both:

$$\begin{aligned} -w_1 + 3w_2 + 4w_3 &= 0 \qquad (1) \\ 2w_1 + w_2 - w_3 &= 0. \qquad (2) \end{aligned}$$

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$$\vec{w} \cdot \vec{u} = [w_1, w_2, w_3] \cdot [-1, 3, 4]$$

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$$\begin{array}{rcll} -w_1 + 3w_2 + 4w_3 & = & 0 & \quad (1) \\ 2w_1 + w_2 - w_3 & = & 0. & \quad (2) \end{array}$$

. . .

Page 31 Number 16 (continued)

Solution (continued). . . .

$$\begin{aligned} -w_1 + 3w_2 + 4w_3 &= 0 \qquad (1)\\ 2w_1 + w_2 - w_3 &= 0. \qquad (2)\end{aligned}$$

Adding 2 times equation (1) to equation (2) gives $0w_1 + 7w_2 + 7w_3 = 0$. So we *can* take $w_2 = 1$ and $w_3 = -1$. Plugging these values into equation (1) gives $-w_1 + 3(1) + 4(-1) = 0$ and so $-w_1 - 1 = 0$ or $w_1 = -1$.

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Page 31 Number 16 (continued)

Solution (continued). . . .

$$\begin{aligned} -w_1 + 3w_2 + 4w_3 &= 0 \qquad (1) \\ 2w_1 + w_2 - w_3 &= 0. \qquad (2) \end{aligned}$$

Adding 2 times equation (1) to equation (2) gives $0w_1 + 7w_2 + 7w_3 = 0$. So we *can* take $w_2 = 1$ and $w_3 = -1$. Plugging these values into equation (1) gives $-w_1 + 3(1) + 4(-1) = 0$ and so $-w_1 - 1 = 0$ or $w_1 = -1$. So *a* choice for w_1, w_2, w_3 is $w_1 = -1$, $w_2 = 1$, and $w_3 = -1$. That is, we can choose $\boxed{\vec{w} = [w_1, w_2, w_3] = [-1, 1, -1].}$ (In fact, any nonzero multiple of this choice of $\vec{w}$ is also correct.)

Let's check the orthogonality:

$\vec{w} \cdot \vec{u} = [-1, 1, -1] \cdot [-1, 3, 4] = (-1)(-1) + (1)(3) + (-1)(4) = 1 + 3 - 4 = 0$

and

$\vec{w} \cdot \vec{v} = [-1, 1, -1] \cdot [2, 1, -1] = (-1)(2) + (1)(1) + (-1)(-1) = -2 + 1 + 1 = 0.$

So, by the definition of perpendicular, $\vec{w}$ is perpendicular to both $\vec{u}$ and $\vec{v}$, as required. □

Page 31 Number 16 (continued)

Solution (continued). ...

$$\begin{array}{rcll} -w_1 + 3w_2 + 4w_3 & = & 0 & (1) \\ 2w_1 + w_2 - w_3 & = & 0. & (2) \end{array}$$

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Page 26 Example 7

Page 26 Example 7. Prove that the sum of the squares of the lengths of the diagonals of a parallelogram in $\mathbb{R}^n$ is equal to the sum of the squares of the lengths of the sides. This is the *parallelogram relation* or the *parallelogram law*.

Proof. Let two of the sides of the parallelogram be determined by vectors $\vec{v}$ and $\vec{w}$ in standard position:

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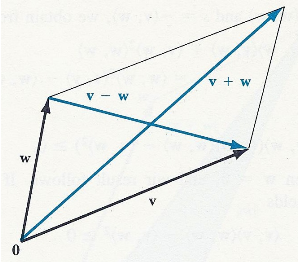

Then the lengths of the sides of the parallelogram are $\|\vec{v}\|$, $\|\vec{v}\|$, $\|\vec{w}\|$, and $\|\vec{w}\|$; the lengths of the diagonals are $\|\vec{v}+\vec{w}\|$ and $\|\vec{v}-\vec{w}\|$.

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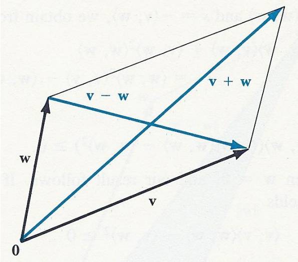

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Page 26 Example 7 (continued)

Proof (continued). Expressing the squares of norms using dot products as in Note 1.2.A:

$$\begin{aligned}
\|\vec{v}+\vec{w}\|^2+\|\vec{v}-\vec{w}\|^2 &= (\vec{v}+\vec{w})\cdot(\vec{v}+\vec{w})+(\vec{v}-\vec{w})\cdot(\vec{v}-\vec{w}) \\
&= (\vec{v}\cdot\vec{v}+2\vec{v}\cdot\vec{w}+\vec{w}\cdot\vec{w}) \\
&\quad +(\vec{v}\cdot\vec{v}-2\vec{v}\cdot\vec{w}+\vec{w}\cdot\vec{w}) \\
&\quad \text{ by Theorem 1.3(D1) and (D2),} \\
&\quad \text{“Commutivity and Distribution of Dot Product”} \\
&= 2\vec{v}\cdot\vec{v}+2\vec{w}\cdot\vec{w}=2\|\vec{v}\|^2+2\|\vec{w}\|^2.
\end{aligned}$$

Page 26 Example 7 (continued)

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&\quad +(\vec{v}\cdot\vec{v}-2\vec{v}\cdot\vec{w}+\vec{w}\cdot\vec{w}) \\
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&= 2\vec{v}\cdot\vec{v}+2\vec{w}\cdot\vec{w}=2\|\vec{v}\|^2+2\|\vec{w}\|^2.
\end{aligned}$$

So the sum of the squares of the lengths of the diagonals, $\|\vec{v}+\vec{w}\|^2+\|\vec{v}-\vec{w}\|^2$, equals the sum of the squares of the lengths of the sides, $\|\vec{v}\|^2+\|\vec{v}\|^2+\|\vec{w}\|^2+\|\vec{w}\|^2=2\|\vec{v}\|^2+2\|\vec{w}\|^2$. □

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Theorem 1.4

Theorem 1.4. Schwarz's Inequality.
Let $\vec{v}, \vec{w} \in \mathbb{R}^n$. Then

$$|\vec{v} \cdot \vec{w}| \leq \|\vec{v}\| \|\vec{w}\|.$$

Proof. Let $\vec{v}, \vec{w} \in \mathbb{R}^n$ and let r and s be any scalars in $\mathbb{R}$. Then $\|r\vec{v} + s\vec{w}\| \geq 0$ by Theorem 1.2(1), "Positivity of the Norm," and so

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$$\begin{aligned} 0 &\leq \|r\vec{v} + s\vec{w}\|^2 = (r\vec{v} + s\vec{w}) \cdot (r\vec{v} + s\vec{w}) \text{ by Note 1.2.A} \\ &= (r\vec{v}) \cdot (r\vec{v}) + 2(r\vec{v}) \cdot (s\vec{w}) + (s\vec{w}) \cdot (s\vec{w}) \\ &\quad \text{by Theorem 1.3(D1) and (D2), "Commutivity and} \\ &\quad \text{Distribution of Dot Products"} \end{aligned}$$

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Theorem 1.4 (continued)

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Proof (continued). Since this holds for all scalars $r, s \in \mathbb{R}$, we can let $r = \|\vec{w}\|^2$ and $s = -\vec{v} \cdot \vec{w}$ and hence

$$\begin{aligned} 0 &\leq r^2\|\vec{v}\|^2 + 2rs\vec{v} \cdot \vec{w} + s^2\|\vec{w}\|^2 \\ &= \|\vec{w}\|^4\|\vec{v}\|^2 - 2\|\vec{w}\|^2(\vec{v} \cdot \vec{w})^2 + (\vec{v} \cdot \vec{w})^2\|\vec{w}\|^2 \\ &= \|\vec{w}\|^4\|\vec{v}\|^2 - \|\vec{w}\|^2(\vec{v} \cdot \vec{w})^2 \\ &= \|\vec{w}\|^2(\|\vec{w}\|^2\|\vec{v}\|^2 - (\vec{v} \cdot \vec{w})^2). \quad (*) \end{aligned}$$

If $\|\vec{w}\| = 0$ then $\vec{w} = \vec{0}$ by Theorem 1.3(D4), "Positivity of the Dot Product," and then $\vec{v} \cdot \vec{w} = \vec{v} \cdot \vec{0} = 0$ so that $0 = |\vec{v} \cdot \vec{w}| \leq \|\vec{v}\|\|\vec{w}\| = \|\vec{v}\|0 = 0$ and Schwarz's Inequality holds.

Theorem 1.4 (continued)

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$$\begin{aligned} 0 &\leq r^2\|\vec{v}\|^2 + 2rs\vec{v} \cdot \vec{w} + s^2\|\vec{w}\|^2 \\ &= \|\vec{w}\|^4\|\vec{v}\|^2 - 2\|\vec{w}\|^2(\vec{v} \cdot \vec{w})^2 + (\vec{v} \cdot \vec{w})^2\|\vec{w}\|^2 \\ &= \|\vec{w}\|^4\|\vec{v}\|^2 - \|\vec{w}\|^2(\vec{v} \cdot \vec{w})^2 \\ &= \|\vec{w}\|^2(\|\vec{w}\|^2\|\vec{v}\|^2 - (\vec{v} \cdot \vec{w})^2). \quad (*) \end{aligned}$$

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Theorem 1.4 (continued)

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Let $\vec{v}, \vec{w} \in \mathbb{R}^n$. Then $|\vec{v} \cdot \vec{w}| \leq \|\vec{v}\| \|\vec{w}\|$.

Proof (continued). Since this holds for all scalars $r, s \in \mathbb{R}$, we can let $r = \|\vec{w}\|^2$ and $s = -\vec{v} \cdot \vec{w}$ and hence

$$\begin{aligned} 0 &\leq r^2\|\vec{v}\|^2 + 2rs\vec{v} \cdot \vec{w} + s^2\|\vec{w}\|^2 \\ &= \|\vec{w}\|^4\|\vec{v}\|^2 - 2\|\vec{w}\|^2(\vec{v} \cdot \vec{w})^2 + (\vec{v} \cdot \vec{w})^2\|\vec{w}\|^2 \\ &= \|\vec{w}\|^4\|\vec{v}\|^2 - \|\vec{w}\|^2(\vec{v} \cdot \vec{w})^2 \\ &= \|\vec{w}\|^2(\|\vec{w}\|^2\|\vec{v}\|^2 - (\vec{v} \cdot \vec{w})^2). \quad (*) \end{aligned}$$

If $\|\vec{w}\| = 0$ then $\vec{w} = \vec{0}$ by Theorem 1.3(D4), "Positivity of the Dot Product," and then $\vec{v} \cdot \vec{w} = \vec{v} \cdot \vec{0} = 0$ so that $0 = |\vec{v} \cdot \vec{w}| \leq \|\vec{v}\| \|\vec{w}\| = \|\vec{v}\| 0 = 0$ and Schwarz's Inequality holds. If $\|\vec{w}\| \neq 0$ then from $(*)$, dividing both sides by $\|\vec{w}\|^2$, we have that $\|\vec{v}\|^2\|\vec{w}\|^2 - (\vec{v} \cdot \vec{w})^2 \geq 0$. That is, $(\vec{v} \cdot \vec{w})^2 \leq \|\vec{v}\|^2\|\vec{w}\|^2$ and so $\sqrt{(\vec{v} \cdot \vec{w})^2} \leq \sqrt{\|\vec{v}\|^2\|\vec{w}\|^2}$ or $|\vec{v} \cdot \vec{w}| \leq \|\vec{v}\| \|\vec{w}\|$, as claimed. □

Page 31 Number 36

Page 31 Number 36. The captain of a barge wishes to get to a point directly across a straight river that runs north to south. If the current flows directly downstream at 5 knots and the barge steams at 13 knots, in what direction should the captain steer the barge?

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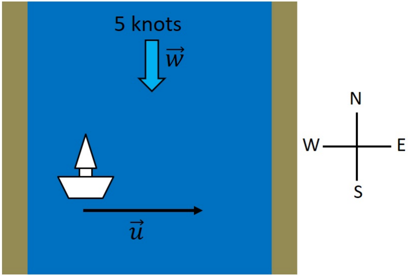

We need the barge to have a velocity $\vec{v}$ such that $\vec{v} + \vec{w}$ results in a vector $\vec{u}$ that runs east-west.

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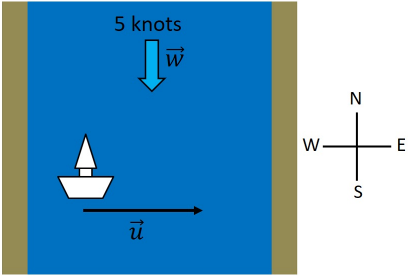
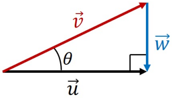


We need the barge to have a velocity $\vec{v}$ such that $\vec{v} + \vec{w}$ results in a vector $\vec{u}$ that runs east-west.

Page 31 Number 36 (continued)

Solution (continued). By the parallelogram property of the addition of vectors (see Figure 1.1.5, page 5) we have:



where $\vec{w} = [0, -5]$ knots and $\vec{u} = [u_1, u_2] = [u_1, 0]$ knots. So with $\vec{v} = [v_1, v_2]$, we have $\vec{v} + \vec{w} = \vec{u}$ or $[v_1, v_2] + [0, -5] = [u_1, 0]$ or $[v_1, v_2 - 5] = [u_1, 0]$. Hence $v_2 = 5$ knots.

Page 31 Number 36 (continued)

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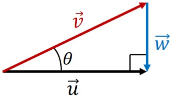

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Page 31 Number 36 (continued)

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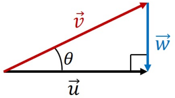

where $\vec{w} = [0, -5]$ knots and $\vec{u} = [u_1, u_2] = [u_1, 0]$ knots. So with $\vec{v} = [v_1, v_2]$, we have $\vec{v} + \vec{w} = \vec{u}$ or $[v_1, v_2] + [0, -5] = [u_1, 0]$ or $[v_1, v_2 - 5] = [u_1, 0]$. Hence $v_2 = 5$ knots. Since $\|\vec{v}\| = \sqrt{v_1^2 + v_2^2} = \sqrt{v_1^2 + (5)^2} = 13$ knots then $\sqrt{v_1^2 + 25} = 13$ and $v_1^2 + 25 = 169$ or $v_1^2 = 144$ (knots^2) or $v_1 = 12$ knots. Then $u_1 = v_1 = 12$ knots and so $\vec{u} = [12, 0]$ knots. Notice from the right triangle determined by $\vec{u}$, $\vec{w}$, and $\vec{v}$ we have $\cos\theta = \|\vec{u}\|/\|\vec{v}\| = 12/13$ and so $\theta = \cos^{-1}(12/13)$. So

the captain should steer the barge $\theta = \cos^{-1}(12/13)$ upstream. □

Page 31 Number 36 (continued)

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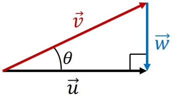

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