

The Elements of Linear Algebra
Volume One: Livre des Lignes Droites

Theron J Hitchman

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CONTENTS

To the Student:

So. I am writing this book. (Let's not pretend I am done. You can see the state it is in.) There are dozens (hundreds?) of introductory linear algebra books, so it is pretty reasonable to ask why I am putting in the effort, and in the meantime, causing this much pain. I should explain.

I have taught linear algebra many times and I have liked some books, but never loved one. The closest match for what I wanted to teach is Strang's *Introduction to Linear Algebra*, and I am sure that people who have read that will see some influences here. But my students never seemed to connect with Prof. Strang's enthusiastic, stream-of-consciousness prose. And over time, I found that the things I need to emphasize for my students just don't match with that text, or any other.

In addition, most textbooks assume a certain class structure: lectures accompanied by weekly homework, with some exams. I don't want to run our course that way.

So this book is my solution. It is my attempt to make a thing which matches how I want our class to run.

Here is what you should expect. This book has the basics of linear algebra, done thoroughly. I want this to help you see why some very basic, important things are done the way they are. It is amazing how much of the subject of linear algebra can be done by focusing on small examples, that is, in small dimensions. (We'll learn about *dimension* later on.) We'll sort out other things through assignments and class discussions.

It is important to read this book actively. If you haven't learned how to read a math text before, there are some key ideas:

TO THE STUDENT:

Time Mathematics is often technical and tricky. It takes time to absorb. Plan to give yourself lots of time to read and think. And don't be surprised if you have to read some section more than once. (This is not a novel. As much as I see it as a story, it won't sweep you away.)

Examples In the interest of brevity, I have streamlined the exposition. In particular, there are no examples. **The point is that you should make your own.** This is so important a skill that it is basically a mathematical super-power. Whenever you come across an idea, if you understand it or not, you should make some very explicit examples and consider them carefully.

Questions As part of your *active* engagement with the text, you will find things that don't quite make sense, yet. This is normal. The mathematician's best approach then is to (1) write down a specific question or two about the confusing bit, and (2) talk to other people about it. You are fortunate that you have an instructor and classmates to talk to. Make lists of questions and try to get them answered!

The real beauty in linear algebra is the tight set of connections between algebra and geometry. I hope you enjoy it.

The Equation of a Line in the Plane

Let's recall the idea of *the plane* from classical geometry: the plane is like a flat sheet of drawing paper, which extends indefinitely in all directions without bound. It is the playground for lots of serious considerations from high school: points, lines, circles, triangles, rectangles, and various other doodles live in it. I say *in* it rather than *on* it, because all of those objects really have their existence inside the plane. If we were to say "on the plane" then one might think of them as sitting on top of the paper, where a light breeze might move them about. No, those things live inside the plane just as sure as you and I live inside the universe.

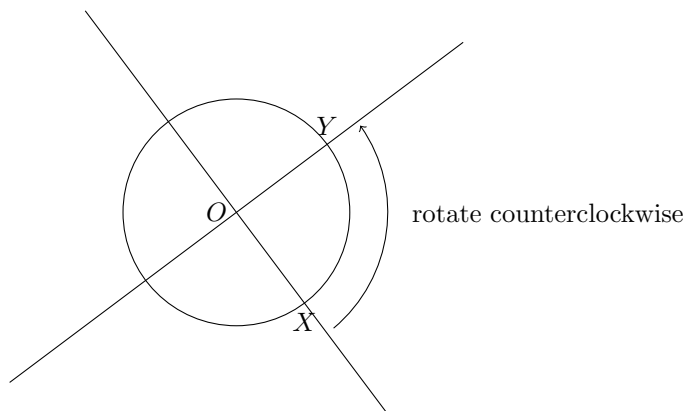
And while all of that is evocative and romantic, it doesn't make doing mathematics any easier. Our aim in this first chapter is to do some concrete mathematics: we want to figure out how to describe a single line in the plane very carefully. To do this, we will use tools that René Descartes taught us: coordinates. Better yet, we will use an update of the idea and introduce *vectors*. Our work has to rely on something, so at some points we will make use of geometry facts you learned in high school. But for all of the points and vectors, angles and dot products, we will go straight to the heart of a single important question:

**How can we clearly describe a single
line in the plane with an equation?**

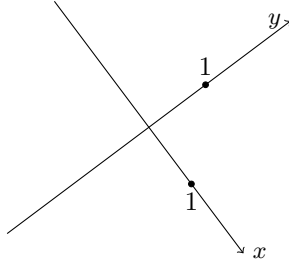
THE EQUATION OF A LINE IN THE PLANE

POINTS, VECTORS, AND VECTORS

You have likely seen the idea of *Cartesian coordinates* on the plane before. To be clear, let's set things down carefully. In the plane, we choose a pair of perpendicular lines which meet at a point O . This special point is called the *origin*. Then, we choose a point X on one of the lines and draw the circle centered at O which passes through X . Note that this circle meets our two lines in two points each, four points total, one of which is the point X . Then, from X , we rotate around the circle by a quarter turn counterclockwise until we hit one of the points on the other line. This new point we will call Y . Are you drawing with me? Here is my picture so far.



We call the line OX the *x-axis* and the line containing Y the *y-axis*. Here comes the amazing part: we declare the circle we used to be of *unit size*, and make the lines OX and OY into number lines! The important part is that the point O should represent 0 on both number lines, and the points X and Y should each represent 1 on their lines. So, instead of marking things with O , X , and Y , we put down marks where X and Y are and label them with 1's, and add little arrows marked with x and y near the positive "ends" of the lines OX and OY , respectively.



Note that above I have done something a bit silly and let the picture just fall on the paper in an unusual way. I really mean unusual as “not usual.” The usual way arranges the lines on the paper to match our expected horizontal (x) and vertical (y) directions. This isn’t actually required, but it is what everyone always does. The typical picture looks like Figure 1.

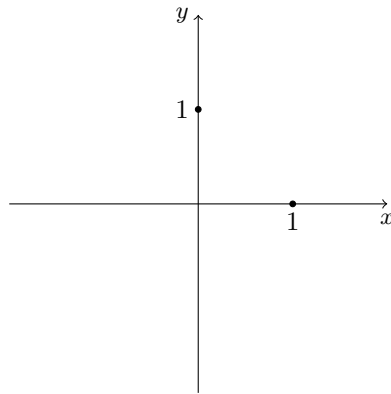


Figure 1: The Standard Cartesian Coordinate System

Now suppose we have some point in the plane, let’s call it P . We can describe the location of P relative to our two lines in a simple way. First, we draw a line through P which is parallel to the y -axis and perpendicular to the x -axis. The foot of this

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perpendicular hits the x -axis at some point A . But this point A is part of the number line OX , so it has an associated real number, which we will call a . So the point A is instead marked with the label a from this number line.

Similarly, we draw a line through P parallel to the x -axis and perpendicular to the y -axis. The foot of this perpendicular hits the y -axis at some point B , which is part of the number line OY . We denote the number associated to B by b . Again, the point is labeled with the number b from the number line.

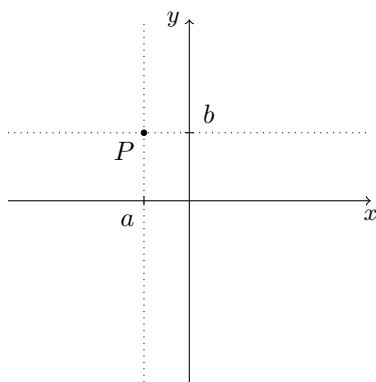


Figure 2: A point P and its coordinates (a, b) .

So, to identify the point P , we can instead give the pair of numbers a and b . These numbers are called the *coordinates* of P . Of course, the order of the coordinates matters, so we make what we call an *ordered pair* (a, b) to keep things straight, where the x -coordinate comes first, and the y -coordinate comes second. Note that in Figure 2 the x -coordinate a is negative, but the y -coordinate b is positive.

This whole process is reversible, too. If we pick a pair of numbers c and d , in order, then we can find a point in the plane which corresponds, and we can do it unambiguously. Find the spot labeled c on the x -axis number line and construct a line perpendicular to the x -axis through this point. Similarly, find the

spot labeled d on the y -axis and construct a line perpendicular to the y -axis through this point. The two lines you just drew will meet in exactly one point Q , and Q will have coordinates (c, d) .

This setup of coordinates on the plane allows us to formalize a wonderful and useful idea from physics, too. Physicists use the concept of a *vector* to describe something (like the wind) which has both magnitude or size (like how fast the air is moving) and direction (which way the air is going). Usually, vectors are drawn as little arrows: the arrow has a direction, and it has a length which represents its magnitude. It is possible to draw vectors which have the same direction but different lengths, and vice versa.

We can use coordinates to describe vectors in the plane, too. Here's how: A physicist's vector v is some arrow in the plane. That arrow has an initial point P , called its *tail*, and a final point Q , called its *head*. We can write the coordinates of these points as $P = (a, b)$ and $Q = (c, d)$.

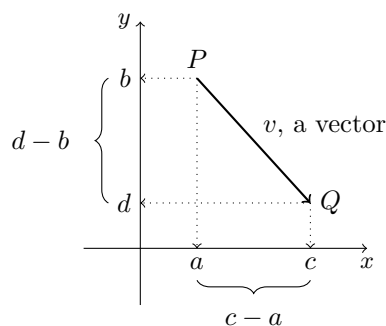


Figure 3: Coordinates for a physicist's vector v .

Then the coordinates of v are taken to be the numbers $c - a$ and $d - b$, which we interpret how much v acts in the directions parallel to the x -axis and the y -axis, respectively. Note that in Figure 3, the y -coordinate is negative, since $b > d$.

These coordinates have a hint of algebraic manipulation in them. Those subtractions line up almost like we could write

THE EQUATION OF A LINE IN THE PLANE

$v = (c - a, d - b) = (c, d) - (a, b) = Q - P$. But v is a vector, and if we write it like $(c - a, d - b)$, it looks like the notation for a point. We should not do that because it could get confusing. Furthermore, that “equation” would mean that we are subtracting points and creating a vector, which is also weird. Still, there is something to it. We will return to this idea soon.

For now, let’s focus on a bit of ambiguity in the physicist’s idea of a vector. Where should that vector be? That is, given the coordinates of a vector in the plane, it is not clear where to draw it! I can slide a vector around the plane, and as long as I keep it parallel to the original, the coordinates won’t change. So, unlike with the coordinates of a point, the coordinates of a vector do not uniquely specify the vector.

The mathematician’s special fix is this: we simply declare all our vectors to have their initial points, their tails, at the origin O , of our coordinate system. That curtails some of the (admittedly useful) freedom in the physics notion, but it also lets us be more clear.

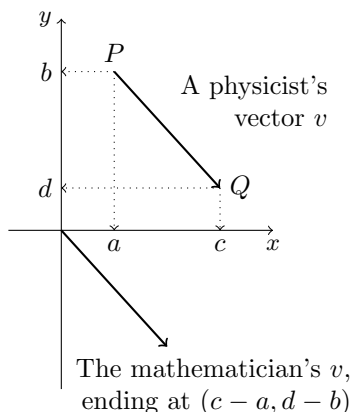


Figure 4: The physicist’s vector vs. the mathematician’s vector.

But it pays to keep in mind that the physicists conception of the vector V with coordinates $c - a$ and $d - b$ could be one of

many different arrows, while the mathematician's vector v is the arrow from the point $O = (0, 0)$ to the point $(c - a, d - b)$.

Now we have circled back around to a muddle. If a mathematician's vector is always based at O , we only need to specify where the head of the vector is... which is just a point. So, how is a vector supposed to be different from a point, again?

This confusion of three different, shifting, partially-overlapping interpretations causes some trouble to the new learner. Professionals tend to pass back and forth between these and use them flexibly to get results. Once you have gotten used to the ideas, you will, too. You should watch out for these instances where the words point and vector get interchanged. If they cause you trouble, remember that we have three different things, which are closely related.

For now, the simplest way to handle things is like this:

- Ignore the physicist's version of the word vector as much as possible.
- A point is a location in the plane, and represented by coordinates in the form of an ordered pair of numbers (a, b) .
- A vector is an arrow based at the origin, which can be specified by the coordinates of its head. To keep this separate from the idea of a point, we will write it differently, with the numbers stacked vertically like this: $\begin{pmatrix} a \\ b \end{pmatrix}$.
- Always remember that for each point in the plane, there is a unique mathematician's vector which corresponds, and vice versa.

With this in mind, we make our first official definition.

Definition 1. *A 2-vector is a vertical stack of 2 real numbers, like so:*

$$v = \begin{pmatrix} a \\ b \end{pmatrix}.$$

The collection of all such 2-vectors is called the plane, and written with this notation: \mathbb{R}^2 .

The notation \mathbb{R}^2 is often read “arr-two,” and many people use that language interchangeably with “the plane.”

THE EQUATION OF A LINE IN THE PLANE

VECTOR ALGEBRA

Let's return to that glimpse of subtraction we saw in Figure 3. We saw there that for points $P = (a, b)$ and $Q = (c, d)$, the vector v from P to Q has coordinates $c - a$ and $d - b$. This looks almost like we subtracted the points to get $Q - P = v$. Can we use that? The weird part is that it mixes up points and vectors. So, we will just change viewpoints, and instead think of P and Q as (mathematician's) vectors. To keep things clear, let's introduce new labels.

$$p = \begin{pmatrix} a \\ b \end{pmatrix}, \quad q = \begin{pmatrix} c \\ d \end{pmatrix}$$

If we put these together on the plane with the physicist's vector v from p to q and the mathematician's v we see a wonderful triangle, and an extra vector. So we see a way to talk about subtracting

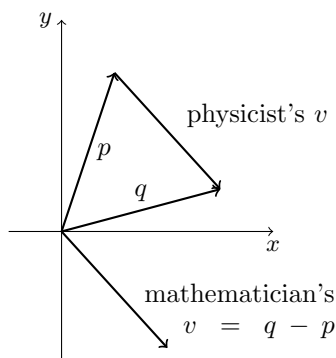


Figure 5: Subtraction of vectors

vectors: Given two vectors p and q as above, their *difference* is the vector

$$V = Q - P = \begin{pmatrix} c \\ d \end{pmatrix} - \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} c - a \\ d - b \end{pmatrix}.$$

Geometrically, we draw the arrow from p to q and then translate it down so that its tail is at the origin $O = (0, 0)$. Of course, the order of p and q in this operation matters. If we switch them, we get an arrow pointing in the opposite direction.

If we can subtract vectors, surely we can add vectors. How would that work? Algebraically, if $v = q - p$, then we expect $q = v + p$ by rearranging. That would mean

$$q = \begin{pmatrix} c \\ d \end{pmatrix} = v + p = \begin{pmatrix} c - a \\ d - b \end{pmatrix} + \begin{pmatrix} a \\ b \end{pmatrix},$$

which all fits. It looks like addition should be defined coordinate-by-coordinate.

Definition 2 (Addition of Vectors). *Let $p = \begin{pmatrix} a \\ b \end{pmatrix}$ and $q = \begin{pmatrix} c \\ d \end{pmatrix}$ be two vectors in \mathbb{R}^2 . Their sum is the vector*

$$p + q = \begin{pmatrix} a + c \\ b + d \end{pmatrix}.$$

Theorem 3. *Addition of vectors satisfies the same rules as addition of real numbers:*

- *when adding more than two vectors, it doesn't matter which operations you do first: $(p + q) + r = p + (q + r)$;*
- *one can add in either order $P + Q = Q + P$;*
- *the vector o corresponding to the origin O is a “zero” since $p + o = o + p = p$;*
- *for each vector p , there is an opposite vector $-p$ so that $p + (-p) = o$.*

Remember that you are supposed to read actively. You can draw all of these pictures and try out all of these things with specific examples that you invent. You should check these by making examples and working out the details. Can you also draw the pictures which go with your examples?

But what about subtracting geometrically? In Figure 5, I have a strong desire to complete the figure by joining the loose end of v to the rest of the figure. If we draw the arrow from the head of v to the head of q , we get this:

THE EQUATION OF A LINE IN THE PLANE

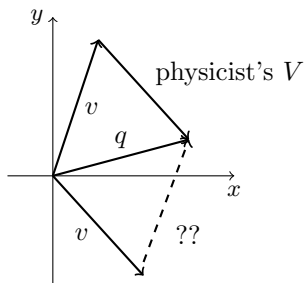


Figure 6: Subtraction of vectors

What should the label on the dashed vector in Figure 6 be? Just as the physicist's v and the mathematician's v are parallel, this new vector is parallel to the mathematician's vector p . So the dashed vector must be a physicist's version of p . Then we see $q = v + p$.

Now we know how to add geometrically: to add two vectors u and v , translate B until its tail is on the head of A , then draw a new vector $u + v$ as the vector from the tail of u to the head of this translated v . It just repurposes the structure of Figure 6.

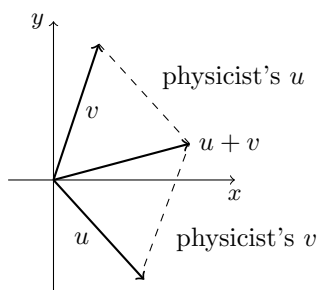


Figure 7: Geometric Addition of Vectors

This is sometimes called the *parallelogram rule* for addition of vectors.

There is another useful operation on vectors called *scalar multiplication*. The terminology comes from physics (again) where a *scalar* quantity is just a number, and not a vector. So “scalar multiplication” means to multiply a vector by a scalar.

Definition 4 (Scalar Multiplication for vectors). *Let $p = \begin{pmatrix} a \\ b \end{pmatrix}$ be a vector in \mathbb{R}^2 , and let λ be a real number. Then the scalar multiple λp is defined to be*

$$\lambda p = \begin{pmatrix} \lambda a \\ \lambda b \end{pmatrix}$$

If you have never seen the symbol λ before, it is an old Greek letter pronounced “lamb-duh.” It is traditional to use it in linear algebra in lots of places. Welcome to the λ -club. Oh, there are others, too, like μ , which is pronounced “mew.”

Again, this operation has some important similarities to the familiar multiplication of numbers, but because it combines a scalar (a number) with a vector (not a number, exactly) to produce another vector (again, not a number) things are a little different.

Theorem 5. *Suppose that p and q are vectors, and λ and μ are numbers. Scalar multiplication has the following properties:*

- *Scalar multiplication distributes over vector addition:*
 $\lambda(P + Q) = \lambda p + \lambda q$;
- *Scalar multiplication distributes over scalar addition:*
 $(\lambda + \mu)P = \lambda p + \mu q$;
- *Scalar multiplication and regular multiplication can be done in either order: $\lambda(\mu p) = (\lambda\mu)p$;*
- *if $\lambda = 0$, then $\lambda p = 0p = o$ is the zero vector.*
- *if n is a counting number, then np is the same thing as adding together n copies of p . In particular, $1p = p$.*

This Theorem, like the last one, just says that a bunch of natural things you expect to happen really do happen. When you study **Modern Algebra**, making lists of these kinds of properties will be really useful. So far, we have collected up the properties that describe a *vector space*.

THE EQUATION OF A LINE IN THE PLANE

What is the geometry of scalar multiplication? It corresponds to stretching (or shrinking) a vector, without changing its direction. Let λ be a non-zero number. Since

$$\lambda p = \lambda \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} \lambda a \\ \lambda b \end{pmatrix},$$

we see that the ratio of the two coordinates of a vector doesn't change under scalar multiplication. This means that p and λp point in the same direction. One can see this by considering similar triangles with sides parallel to the x -axis, the y -axis, and p .

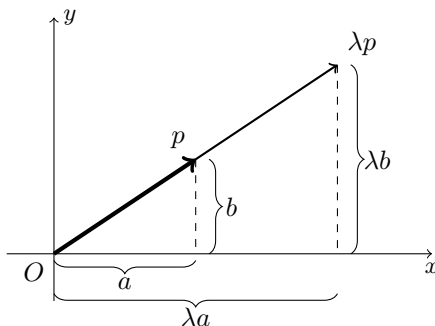


Figure 8: Similar triangles and scalar multiplication, $\lambda > 1$

The triangles in Figure 8 are similar: their corresponding horizontal and vertical sides are parallel, and those pairs of sides have a common ratio. We learn that p and λp lie in the same line.

Now we are getting somewhere! We want to understand lines in the plane, and we have just discovered how scalar multiplication relates to lines which pass through the origin, O .

By the way, this picture helps explain the terminology. The vector λp is a rescaled version of p . A *scalar* is a thing which *scales* vectors.

LINES AS PARAMETRIC OBJECTS

We see that for a non-zero vector p , and a non-zero number λ , the vectors p and λp lie on the same line through the origin, O . But this doesn't depend on which number λ we choose. So if we vary λ , we will get lots of different points on that line. The picture looks something like this one:

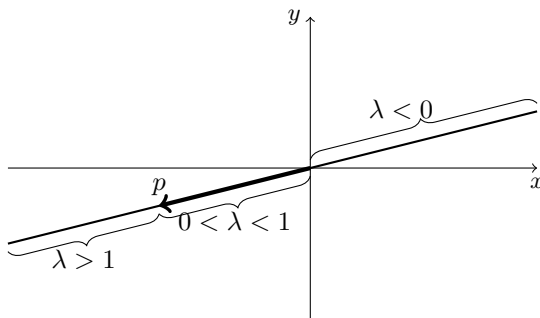


Figure 9: The points on a line: λp for different λ

This leads us to what is called a *parametric description* of the line. We think of some variable, say t , as a parameter. (I chose t here so that we think of it as “time.”) As we change the value of t , the vectors tp trace out the line which goes through the origin and the point which is the head of the vector p .

Theorem 6 (parametric lines through the origin). *Suppose that $P = (a, b)$ is some point in the plane. The line which passes through the origin O and the point P consists of the heads of all the vectors*

$$tp = t \begin{pmatrix} a \\ b \end{pmatrix},$$

where t varies over all real numbers. That is, this line is the set of the heads of all scalar multiples of the vector p corresponding to P .

This, is fantastic. We can use simple vector algebra to describe

THE EQUATION OF A LINE IN THE PLANE

any line through the origin. What about lines that are not through the origin? Suppose we just have two random points P and Q , neither of which is the origin, and we want to describe the line ℓ through P and Q ?

Again, let's think of the points on this line ℓ as the heads of mathematics-style vectors. If we put in the vectors p and q which correspond to the points P and Q , we get a good picture like this one.

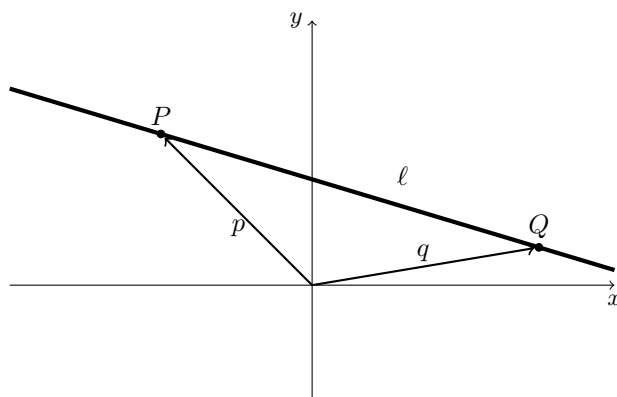


Figure 10: Working toward a parametric line, part 1

Each point in Figure 10 is the head of a vector from the origin to that point. In particular, the point P is the head of the vector p . So if we add $-p$ to every single one of these vectors, we will move the whole line ℓ in the direction of $-p$ and with the same distance as $-p$. That will make a new line, ℓ' , and the point which comes from P will land on the origin.

Since q is one of the vectors with its head on the original line, the vector $q - p$ will have its head on the new line, too. But $q - p$ has its tail at the origin! So, our new line passes through the origin and the head of the vector $q - p$, and we are in a situation to apply Theorem 6.

By Theorem 6, the line ℓ' is described as all of the points which

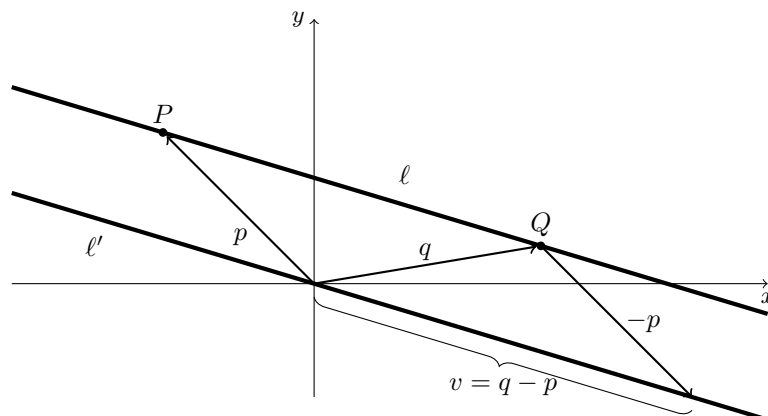


Figure 11: Working toward a parametric line, part 2

are heads of vectors of the form $t(q - p)$, where t is a parameter which is allowed to vary over all real numbers. But we get from ℓ' back to ℓ by simply adding the vector p back in. So, our original line ℓ , which goes through the heads of vectors p and q , is described as the set heads of the vectors

$$p + t(q - p),$$

where t is a parameter which is allowed to vary over all real numbers. Now, let's sum up what we have learned.

Theorem 7 (parametric line). *Let $P = (a, b)$ and $Q = (c, d)$ be two points in the plane. The line which passes through these two points can be described as the heads of all vectors of the form*

$$p + t(q - p) = \begin{pmatrix} a \\ b \end{pmatrix} + t \begin{pmatrix} c - a \\ d - b \end{pmatrix},$$

where t is a parameter which is allowed to vary over all real numbers.

THE EQUATION OF A LINE IN THE PLANE

Note that this theorem actually includes the previous one as a special case. If one of our points happens to be the origin, we simply use $P = O$, which corresponds to the zero vector, and this description collapses back into the one we found earlier. In either case, the vector $v = q - p$ is called a *direction vector* for the line.

As a bit of a palate cleanser, let's answer this: Suppose you are given a line described as in the last theorem. How would you sketch it in the plane? The simplest method is to choose two different values of t , use them to generate two points on the line, plot those points, and trace the line through them. Which values of t should you choose? It is often convenient to use $t = 0$ and $t = 1$.

LENGTHS AND ANGLES IN THE PLANE

- lengths, angles, and the dot product in \mathbb{R}^2
- normal vector to a line in \mathbb{R}^2
- duality

LINES AND EQUATIONS

- equation of a line, three methods: elimination, from two pts via similar triangles, from geometry of dot product
- families of parallel lines
- sketching a line from an equation

CONCLUSION: THE BIG THEOREM

The Equations of a Line in Space

Outline

- points, vectors in space
- \mathbb{R}^3
- vector algebra
- planes in \mathbb{R}^3 parametrically: through the origin, not
- dot product in \mathbb{R}^3
- normal vector to a plane
- the equation of a plane: by elimination, by dot product
- families of parallel planes
- sketching from an equation
- big theorem with duality for planes
- LINES in \mathbb{R}^3 as intersection of two planes

THE EQUATIONS OF A LINE IN SPACE

Systems of Lines in the Plane

Outline

- note about how we understand one line in the plane, what about two?
- idea of three possible outcomes
- translations into matrix algebra equation: matrix-vector multiplication
- idea of a solution to a system
- questions: how can we characterize the three options in terms of the matrix
- use normals to answer, linear independence...
- characterization of column space bit??
- write "solution" as parametric form of the line, or as just point
- algorithmic solution stuff

SYSTEMS OF LINES IN THE PLANE

Systems of Planes in Space

Outline

- to-do

SYSTEMS OF PLANES IN SPACE

The Algebra of Square Matrices

THE ALGEBRA OF SQUARE MATRICES

Approximate Solutions to Unsolvable Systems

APPROXIMATE SOLUTIONS TO UNSOLVABLE SYSTEMS

Matrices as Transformations