

Math Diversion Problem 175

P. Reany

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You cannot read mathematics the way you read a novel. If you zip through a page in less than an hour, you are probably going too fast.

— Sheldon Axler
(from *Linear Algebra Done Right*)

The YouTube video is found at:

Source: https://www.youtube.com/watch?v=GnE_6Jt0pio

Title: A Quatrodcecic Equation | Problem 290

Presenter: aplusbi

1 The Problem

Given the relations $z = a + bi = re^{i\theta}$ and

$$z^{14} = \bar{z}, \quad (1)$$

find the values of z . (Skip down to the solution if you wish.)

2 Basics of Complex Numbers

Typically, we find a generic complex number denoted by the letter z , but one is free to choose other letters, as well. So, if z is a complex number, in general it has both real and imaginary parts:

$$z = a + bi, \quad (2)$$

where a, b are real components of basis vectors $1, i$. But they are also expressed as, respectively, the ‘real’ and ‘imaginary’ components of z .

Complex conjugation of complex number z is an operation that leaves real numbers alone but replaces the unit imaginary i with its negative, i.e., $-i$. The

symbols most often used to represent complex conjugation are the $*$ and the overbar. I'll usually use the overbar. Thus, the complex conjugate of z in (2) is

$$\bar{z} = a - bi. \quad (3)$$

Obviously, the complex conjugation of a pure real number has no effect.

A funny thing happens when we multiply a complex number by its conjugate:

$$z\bar{z} = (a + bi)(a - bi) = a^2 + b^2. \quad (4)$$

So, $z\bar{z}$ is zero if and only if $z = 0$, otherwise, it's a positive real number.

Another funny thing happens when we add a complex number and its conjugate: we also get a real number. Let's see.

$$z + \bar{z} = (a + bi) + (a - bi) = 2a. \quad (5)$$

Why do we care about this? Because sometimes we need to map complex numbers into the real numbers to get information on the complex numbers. This problem will show you that.

I'm not going to prove this here, but every complex number can be expressed in exponential (or polar) form:

$$z = a + bi = \sqrt{a^2 + b^2}e^{i\theta} = (z\bar{z})^{1/2}e^{i\theta} = re^{i\theta}, \quad (6)$$

where we can think of r as the length of the complex numbers z or \bar{z} .

$$r \equiv (z\bar{z})^{1/2} \quad \text{or} \quad r^2 = z\bar{z} = |z|^2. \quad (7)$$

So, it will be good to know all this stuff in this section before you attempt to follow my solutions to these complex variables problems.

By the way, the complex numbers are what's called a *field*, so they can be added, subtracted, multiplied, and divided by each other (except you can't divide by zero, as usual). And, therefore, you can apply the quadratic formula to them! (Yay!)

Lemma 1: If a complex number z is equal to its own conjugate $z = \bar{z}$, it's real.

Lemma 2: If a complex number z is complex conjugated twice then there's no change: $\bar{\bar{z}} = z$.

Lemma 3: The complex conjugated of a product or a sum is the product or sum of the complex conjugates: $\overline{z_1 z_2} = \bar{z}_1 \bar{z}_2$ and $\overline{z_1 + z_2} = \bar{z}_1 + \bar{z}_2$.

Lemma 4: If $s, t \in \mathbb{R}$ and $z = s + ti$ then

$$i\bar{z} = t + si. \quad (8)$$

3 Basics of Complex Numbers with Trig Functions

Let's begin with the Euler relations:

$$\cos \theta + i \sin \theta = e^{i\theta}, \quad (9a)$$

$$\cos \theta - i \sin \theta = e^{-i\theta}, \quad (9b)$$

Next, let's invert them:

$$\cos \theta = \frac{1}{2}(e^{i\theta} + e^{-i\theta}), \quad (10a)$$

$$\sin \theta = \frac{1}{2i}(e^{i\theta} - e^{-i\theta}), \quad (10b)$$

where, in the above cases, I used the usually understood real variable θ , but that can be replaced by the complex variable z . In fact, soon we will do so.

Okay, how to represent $\tan z$ by exponentials?

$$\tan z = \frac{\sin z}{\cos z} = \frac{1}{i} \frac{e^{iz} - e^{-iz}}{e^{iz} + e^{-iz}}. \quad (11)$$

4 The Solution

If you put the Given relation (1) into Wolfram Alpha, you'll get back

$$z = 0, \quad 1, \quad -\frac{1}{2} \pm \frac{i\sqrt{3}}{2}, \quad z = \frac{1}{4}(-1 - \sqrt{5}) - \frac{1}{2}i\sqrt{\frac{1}{2}(5 - \sqrt{5})}. \quad (12)$$

The first two of these are the 'trivial' solutions. From here on, I'm interested only in the nontrivial solutions.

Now, if we multiply (1) through by z , we get

$$z^{15} = z\bar{z} = r^2. \quad (13)$$

The next thing we should try to do is to determine r . So, multiply (13) through by its conjugate to get

$$z^{15}\bar{z}^{15} = (z\bar{z})^{15} = r^4, \quad (14)$$

but this implies that $r^{30} = r^4$, which is only possible for real, positive r , if $r = 1$.

Thus, we go back to (13) to write

$$z^{15} = 1 = e^{2\pi i}. \quad (15)$$

I included the term $e^{2\pi i}$ because we are about to take roots, and that's what you need to do most of the time when using complex numbers. Thus,

$$z = e^{2\pi ik/15}, \quad (k = 0, 1, 2, \dots, 14), \quad (16)$$

which gives us 15 roots, which are apparently not all distinct. However, I won't investigate each case for various k , just the special ones.

Case $k = 5$:

$$z = e^{2\pi i/3} = -\frac{1}{2} + \frac{i\sqrt{3}}{2}. \quad (17)$$

Case $k = 10$:

$$z = e^{4\pi i/3} = -\frac{1}{2} - \frac{i\sqrt{3}}{2}. \quad (18)$$

Case $k = 8$ gives us another third-quadrant value:

$$z = e^{16i\pi/15}. \quad (19)$$