

Math 101 - Calculus II

Euler's relation and complex numbers

Complex numbers are numbers that are constructed to solve equations where square roots of negative numbers occur. These numbers look like

$$1 + i, \quad 2i, \quad 1 - i$$

They are added, subtracted, multiplied and divided with the normal rules of algebra with the additional condition that $i^2 = -1$. The symbol i is treated just like any other algebraic variable. So,

$$(2 + i)^2 = (2 + i)(2 + i) = 2 \cdot 2 + 2 \cdot i + 2 \cdot i + i^2 = 4 + 4i - 1 = 3 + 4i$$

and

$$(x - i)(x + i) = x^2 + x \cdot i - x \cdot i - i^2 = x^2 + 1.$$

This last example shows that when complex numbers are used, we are able to factor more expressions than we can with real numbers. These numbers are also useful with the quadratic formula

$$x^2 + x + 1 = 0 \quad \Rightarrow \quad x = \frac{-1 \pm \sqrt{1 - 4}}{2} = \frac{-1 \pm i\sqrt{3}}{2}. \quad (1)$$

The real and imaginary parts of a complex number are given by

$$\operatorname{Re}(3 - 4i) = 3 \quad \text{and} \quad \operatorname{Im}(3 - 4i) = -4.$$

This means that if two complex numbers are equal, their real and imaginary parts must be equal.

Next we investigate the values of the exponential function with complex arguments. This will lead to the well-known Euler formula for complex numbers. We start with the power series for e^x and substitute $x = i\theta$. Therefore

$$\begin{aligned} e^x &= \sum_{n=0}^{\infty} \frac{x^n}{n!} = \sum_{n=0}^{\infty} \frac{(i\theta)^n}{n!} \\ &= e^{i\theta} = \sum_{n=0}^{\infty} \frac{i^n \theta^n}{n!} = \underbrace{\left(1 - \frac{\theta^2}{2!} + \frac{\theta^4}{4!} - \frac{\theta^6}{6!} + \dots\right)}_{\text{for } n \text{ even}} + \underbrace{\left(i\theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \frac{\theta^7}{7!} + \dots\right)}_{\text{for } n \text{ odd}} i \end{aligned}$$

where we used $i^2 = -1$ and arranged the terms into real and imaginary parts. Now if we recall the power series for sine and cosine,

$$\begin{aligned} \sin \theta &= \sum_{n=0}^{\infty} \frac{(-1)^n \theta^{2n+1}}{(2n+1)!} = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \frac{\theta^7}{7!} + \dots \\ \cos \theta &= \sum_{n=0}^{\infty} \frac{(-1)^n \theta^{2n}}{(2n)!} = 1 - \frac{\theta^2}{2!} + \frac{\theta^4}{4!} - \frac{\theta^6}{6!} + \dots \end{aligned}$$

we see that

$$e^{i\theta} = \cos \theta + i \sin \theta$$

which is Euler's formula and has extensive uses in physics, electronics, electrical engineering and mathematics. For example, if we substitute $\theta = \pi$, we obtain

$$e^{i\pi} + 1 = 0$$

which combines five of the most important mathematical constants: 0, 1, i , π and e .

Course Policies Math 101 Calculus 1

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