The Book of Math (Notes)

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November 10, 2020

Forward and Disclaimer

These are math notes made by a student (with a physics major and math minor) based off text books. It may contain misconceptions and misinterpretations, thus should not be viewed in the same light of a text book. Use at your own risk and mental sanity.

Symbols

Logic

Name	Symbol	Comment
Exists	$\exists$	There exists at least one
For all	$\forall$	
Not exists	$\nexists$	There does not exist
Exists one	$\exists!$	There only exists one and only one
And	$\wedge$	
Or	$\vee$	Inclusive or
Not	$\neg$	
Logically implies	$\implies$	If
Logically implied by	$\impliedby$	Only if
Logically equivalent	$\iff$	If and only if
Implies	$\longrightarrow$	
Implied by	$\longleftarrow$	
Double Implication	$\longleftrightarrow$	

Set Notation

Name	Symbol	Comment
Empty Set	$\varnothing$	The set that is empty
Natural Numbers	$\mathbb{N}$	Set of natural numbers not containing 0, equivalent to the set of positive integers
Integers	$\mathbb{Z}$	Set of integers
Rational Numbers	$\mathbb{Q}$	
Algebraic Numbers	$\mathbb{A}$	
Real Numbers	$\mathbb{R}$	
Complex Numbers	$\mathbb{C}$	
In	$\in$	
Not in	$\notin$	
Owns	$\ni$	Has an element
Proper Subset	$\subset$	Subset that is not itself
Subset	$\subseteq$	
Superset	$\supset$	Superset that is not itself
Proper Superset	$\supseteq$	

Power set	$\wp$	
Union	$\cup$	
Intersection	$\cap$	
Difference	$\setminus$	

Relationships

Name	Symbol	Comment
Defined	$\doteq$	
Approximate	$\approx$	
Equivalent	$\equiv$	Isomorphic (Group Theory)
Congruent	$\cong$	Homomorphic (Group Theory)
Proportional	$\propto$	

Operators

Name	Symbol	Comment
	$\oplus$	
	$\otimes$	
	$\odot$	
	$\circ$	Convolution
Dagger	$\dagger$	Complex conjugate transpose of a matrix

Arrows

Name	Symbol	Comment
Maps to	$\mapsto$	

Hebrew

Name	Symbol	Comment
Aleph	$\aleph$	Carnality of infinite sets that can be well ordered

Other

Name	Symbol	Comment
Real part	Re	Real part of a number
Imaginary part	Im	Imaginary part of a number

Book Constitution

Intents and Purpose

The goal of this book is to organize mathematical knowledge of topics related to the study of physics or the author's interest. It is meant to be used as a source of for future reference, not as a textbook for students new to the topics. It is a notebook of a student, thus should be treated as one and not as a textbook. At most, it could be used as a study guide along side a textbook. Definitely not as the main source for acquiring knowledge.

Layout and Organization

The book is split into parts each containing a field of study mathematics, or a topic large enough to justify giving it its own part. Each part contains chapters that focuses on a particular topic required to understand the field, with sections dedicated to describing a particular knowledge required for the topic.

As axioms, definitions, theorems, corollary, and proofs are integral and abundant to the study of mathematics, each will have a unique style. Each environment and its styles are displayed as follows:

Axiom 0.1: Axiom name
Example Axiom Axioms are the "ground rules" of the set.

Theorem 0.0.1: Theorem name or citation
Example Theorem An important logical result from the axioms, with proof.

Conjecture 0.0.1: Name of conjecture or citation
Example Conjecture A hypothesis, without proof.

Corollary 0.0.1.1:
Example Corollary An implication as a result of a theorem.

Lemma 0.0.1.1:
Example Lemma Small theorems that build up to a larger theorem.

Proposition 0.0.1.1:
Example Proposition Example proposition.

Proof: Logical deductions that results in a theorem. Proofs I've written will be in grey, which may or may not be correct. □

Definition 0.0.1: Word
Example Definition The definition of a word.

Example 0.0.1 *An example.*

Remark. *Remark A comment by the author in the textbooks used.*

Observation. *Example Observation A remark by me.*

Question. *Example Question A question from me for a mystery to be answered later.*

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Resources used in part III

1. Kenneth A. Ross - Elementary Analysis (2nd Ed.) [1]

Chapter 9

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Corollary 9.0.0.1:
Absolutely convergent series are convergent.

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9.1.1 Limit Theorems

9.2 Monotone and Cauchy Sequences

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Part IV

Complex Analysis

Resources used in part IV

Primary:

1. Brown and Churchill - Complex Variables and Applications [2]

Supplement:

1. A. David Wunsch - Complex Variables with Applications [3]

Chapter 12

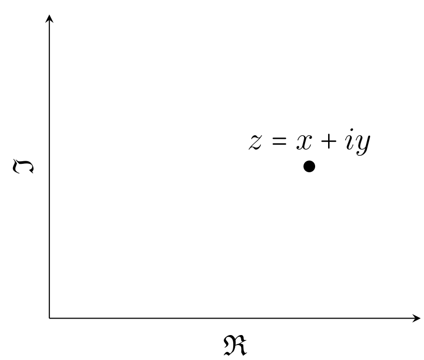
Basics

12.1 Complex Numbers

$$\mathbb{C} = \{x + iy \mid x, y \in \mathbb{R}, i = \sqrt{-1}\}$$

Complex numbers are elements of the complex field ($\mathbb{C}$), therefore, they obey all the properties of a field.

We will denote complex numbers by $z = x + iy$ with $x, y \in \mathbb{R}$, and refer the real part as $\mathrm{Re}(z) = \mathrm{Re}(z) = x$ and imaginary part as $\mathrm{Im}(z) = \mathrm{Im}(z) = y$. Complex numbers can also be defined as an ordered pair $z = (x, y)$ which is interpreted as points in the complex plane. $(x, 0)$ are points on the real axis while $(0, y)$ are points in the imaginary axis. This expression is often called a Couple, and was presented in 1833 by mathematician William Rowan Hamilton (1805 - 1865).



Like numbers in $\mathbb{R}$, numbers in $\mathbb{C}$ obey the commutative, distributive, and associative laws. We add and multiply complex numbers in the usual way:

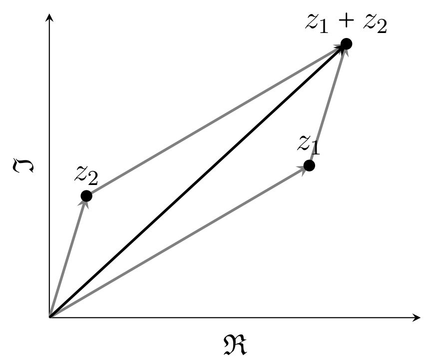
$$\begin{aligned} z_1 + z_2 &= (x_1 + iy_1) + (x_2 + iy_2) \\ &= (x_1 + x_2) + i(y_1 + y_2) \end{aligned} \qquad \begin{aligned} z_1 z_2 &= (x_1 + iy_1)(x_2 + iy_2) \\ &= (x_1 x_2 - y_1 y_2) + i(x_1 y_2 + x_2 y_1) \end{aligned}$$

$\forall z \in \mathbb{C}$, there is an unique additive inverse $(-z)$ and $\forall z \in \mathbb{C} \setminus \{0\}$, there is an unique multiplicative inverse (z^{-1}) such that

$$\begin{aligned} & z + (-z) = 0 && zz^{-1} = 1 \\ & \implies -z = -x - iy && \implies (x_1x_2 - y_1y_2) = 1 \wedge (x_1y_2 + x_2y_1) = 0 \\ & && \implies z^{-1} = \frac{x_1}{x_1^2 + y_1^2} - i\frac{y_1}{x_1^2 + y_1^2} \end{aligned}$$

The existence and uniqueness of the inverses can be easily proven.

The addition of complex numbers may also be interpreted as akin to vector addition.



Note: As a group with addition, $\mathbb{R}^2 \cong \mathbb{C}$, however this is not the case for rings. $\mathbb{C}$ is a field, but $\mathbb{R}^2$ is not. $\mathbb{R}^2$ have non-zero divisors (ie. Take any $a, b \in \mathbb{R}$, $(a, 0) \cdot (0, b) = 0$).

12.2 Triangle Inequality

It is not analysis without a section dedicated to the triangle inequality. For any given number $z_1, z_2 \in \mathbb{C}$ it makes no sense to write an inequality $z_1 = a_1 + ib_1 < a_2 + ib_2 = z_2$. Thus, we need have a different notion of size.

Definition 12.2.1: Modulus

The modulus of a complex number is a function $\mathbb{C} \to \mathbb{R}_{>0}$:

$$|z| = \sqrt{x^2 + y^2} = \sqrt{z\bar{z}}$$

It is obvious why the definition is not $|z| = \sqrt{x^2 + (iy)^2}$ as problems arise when $x = y$. The modulus is the distance of z from $(0, 0)$. $\bar{z}$ is the complex conjugate of z, which is explored in section 12.5

Theorem 12.2.1: Triangle Inequality

$\forall z_1, z_2 \in \mathbb{C}[|z_1 + z_2| \leq |z_1| + |z_2|]$

From the theorem, we can derive a similar inequality:

$$|z_1| = |z_1 + z_2 - z_2| \leq |z_1 + z_2| + |-z_2| \implies |z_1| - |z_2| \leq |z_1 + z_2|$$

An important property of polynomials is observed when theorem 12.2.1 is applied to polynomials.

Corollary 12.2.1.1:

Consider the polynomial $P(z)$ where $a_n \in \mathbb{C}$, $n \in \mathbb{N}$, $a_0 \neq 0$, and $z \in \mathbb{C}$.

$$P(z) = a_0 + a_1 z + a_2 z^2 + \ldots + a_n z^n$$

Then $\forall z, \exists R \in \mathbb{R}_{>0}, |z| < R$ such that

$$\left|\frac{1}{P(z)}\right| < \frac{2}{|a_n| R^n}$$

Proof: Consider

$$\begin{aligned}
w = \frac{P(z)}{z_n} - a_n = \frac{a_0}{z^n} + \frac{a_1}{z^{n-1}} + \ldots + \frac{a_{n-1}}{z} & & z \neq 0 \\
\implies wz^n = a_0 + a_1 z + \ldots + a_{n-1} z^{n-1} & & \\
\implies |w||z|^n \leq |a_0| + |a_1||z| + \ldots + |a_{n-1}||z|^{n-1} & & \\
\implies |w| \leq \frac{|a_0|}{|z|^n} + \frac{|a_1|}{|z|^{n-1}} + \ldots + \frac{|a_{n-1}|}{|z|} & & \\
\implies |w| < n\frac{|a_n|}{2n} = \frac{|a_n|}{2} & & \exists \text{ sufficiently large } R < |z| \text{ s.t.} \\
& & \forall m,\ 0 \leq m \leq n-1,\ \frac{|a_m|}{|z|^{n-m}} < \frac{|a_n|}{2n} \\
\implies |a_n + w| \geq ||a_n| - |w|| > \frac{|a_n|}{2} & & R < |z| \\
\implies |P_n(z)| = |a_n + w||z|^n > \frac{|a_n|}{2}|z|^n > \frac{|a_n|}{2}R^n & & R < |z| \\
\implies \left|\frac{1}{P(z)}\right| < \frac{2}{|a_n| R^n} & &
\end{aligned}$$

□

This tells us that if z is a solution to a polynomial $P(z)$, then the reciprocal of the polynomial $1/P(z)$ is bounded above by $R = |z|$. (i.e. It is bounded by a circle of radius $|z|$.)

12.3 Polar and Exponential Form

Definition 12.3.1: Argument of z

Consider any $z \in \mathbb{C}$ where $z \neq 0$. Let θ be the angle in radians between z and the real axis . Then $\forall n \in \mathbb{N}$, $-\pi < \theta \leq \pi$, the argument of z:

$$\arg(z) = \theta + 2n\pi$$

We know $\forall n \in \mathbb{N}$, $\theta + 2\pi n = \theta$. This leads us to the definition of the principal argument of z.

Definition 12.3.2: Principal Argument of z

Consider any $z \in \mathbb{C}$ where $z \neq 0$. Let θ be the angle in radians between z and the real axis. Then for $-pi < \theta \leq \pi$, the principal argument of z:

$$\text{Arg}(z) = \theta$$

It is clear that $\arg(z) = \text{Arg}(z) + 2n\pi$. It is common for the principal argument to be defined $-\pi < \theta \leq \pi$, although other definitions use $0 \leq \theta < 2\pi$.

Definition 12.3.3: Polar Form of z

Consider $z \in \mathbb{C}$. Let $r = |z|$, and $\theta = \arg(z)$. Then $\forall z \in \mathbb{C}, z \neq 0$:

$$z = x + iy = r(\cos(\theta) + i\sin(\theta))$$

Notice that all three definitions require that $z \neq 0$ as θ is undefined at $z = 0$.

Theorem 12.3.1: Euler's Formula

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

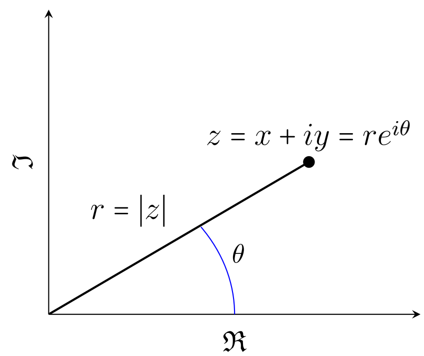
Combining definition 12.3.3 with theorem 12.3.1, we obtain the Exponential Form of z:

Definition 12.3.4: Exponential Form of z

Consider any $z \in \mathbb{C}$, and let $r = |z|$ and $\theta = \text{Arg}(z)$. Then the exponential form of z:

$$z = re^{i\theta}$$

Note: $\theta = \tan^{-1}(y/x)$ and $r = \sqrt{x^2 + y^2}$.



12.3.1 Properties of Polar and Exponential Form

It would be easier to work with the exponential form of z then convert it to the polar form later. The exponential form of a complex number is part of the exponential family of functions, thus possess all the properties of the family. Consider any complex number $z_1 = r_1 e^{i\theta_1}$ and $z_2 = r_2 e^{i\theta_2}$.

$$z_1 z_2 = r_1 r_2 e^{i(\theta_1+\theta_2)} \qquad\qquad z^n = r^n e^{in\theta} \quad \forall n \in \mathbb{Z}$$

A special case arrives for integer exponential of z on the unit circle.

Theorem 12.3.2: de Moivre's Formula

Consider any $z = e^{i\theta} \in \mathbb{C}$ on the unit circle, and let $n \in \mathbb{Z}$.

$$\forall z \in \mathbb{C}\ \forall n \in \mathbb{Z}\,[|z| = 1 \implies (\cos(\theta) + i\sin(\theta))^n = \cos(n\theta) + i\sin(n\theta)]$$

Proof: Consider $z = e^{i\theta}$ and let $n \in \mathbb{Z}$.

$$z^n = (e^{i\theta})^n = e^{in\theta} = \cos(n\theta) + i\sin(n\theta)$$

□

The proof hints that theorem 12.3.2 can be generalized to $\forall n \in \mathbb{R}$, which we will see shortly in **??**. Using theorem 12.3.2, we can obtain the double angle identities.

Corollary 12.3.2.1: Double Angle Identities

$$\cos(2\theta) = \cos^2(\theta) - \sin^2(\theta) \qquad\qquad \sin(2\theta) = 2\sin(\theta)\cos(\theta)$$

Proof: Consider any z on the unit circle, that is $z = e^{i\theta}$.

$$(\cos(\theta) + i\sin(\theta))^2 = \cos(2\theta) + i\sin(2\theta) \qquad \text{Theorem 12.3.2}$$
$$\implies \cos^2(\theta) - \sin^2(\theta) + i2\sin(\theta)\cos(\theta) = cos(2\theta) + i\sin(2\theta)$$

Equating the real and imaginary parts yield the desired results. □

12.3.2 Properties of Arguments

Recall from section 12.3.1:

$$z_1 z_2 = r_1 r_2 e^{i(\theta_1+\theta_2)} \qquad\qquad z^n = r^n e^{in\theta} \qquad \forall n \in \mathbb{Z}$$

The arguments for the arguments of products of any $z_1, z_2 \in \mathbb{C}$ follows immediately from the properties of the exponential.

Corollary 12.3.2.2: Arguments of Products

$$\arg(z_1 z_2) = \arg(z_1) + \arg(z_2) \qquad\qquad \operatorname{Arg}(z_1 z_2) = \operatorname{Arg}(z_1) + \operatorname{Arg}(z_2)$$
$$\arg(z^n) = n \arg(z) \qquad\qquad \operatorname{Arg}(z^n) = n \operatorname{Arg}(z)$$

Proof:

$$\begin{aligned} z_1 z_2 &= r_1 r_2 e^{i(\theta_1+\theta_2)} \\ &\implies \arg(z_1 z_2) = \arg(z_1) + 2n_1\pi + \arg(z_2) + 2n_2\pi && n_1, n_2 \in \mathbb{Z} \\ &\implies \arg(z_1 z_2) = \arg(z_1) + \arg(z_2) \\ &\implies \operatorname{Arg}(z_1 z_2) = \operatorname{Arg}(z_1) = \operatorname{Arg}(z_2) \end{aligned}$$

$$\begin{aligned} z^n &= r^n e^{in\theta} \\ &\implies \arg(z^n) = n \arg(z) + 2n\pi && n \in \mathbb{Z} \\ &\implies \arg(z^n) = n \arg(z) \\ &\implies \mathrm{z}^{\mathrm{n}} = n \operatorname{Arg}(z) \end{aligned}$$

□

It is clear that:

$$\arg\left(\frac{z_1}{z_2}\right) = \arg(z_1) - \arg(z_2) \qquad\qquad \operatorname{Arg}\left(\frac{z_1}{z_2}\right) = \operatorname{Arg}(z_1) - \operatorname{Arg}(z_2)$$

12.4 Roots of z

In definition 12.3.4, you might be wondering why $z^n = r^n e^{in\theta}$ is not for $n \in \mathbb{R}$. That is because there is more things to consider, which we will explore in this section. Recall that $z = re^(i\theta) = re^{i(\theta+2n\pi)}$ for $n \in \mathbb{Z}$.

Definition 12.4.1: Exponential of z

Consider any $z \in \mathbb{C}$ and any $x \in \mathbb{R}$

$$z^x = \left(re^{i(\theta+2n\pi)}\right)^x = r^x e^{ix(\theta+2n\pi)}$$

For $x \notin \mathbb{Z}$, it is clear that $z^x = r^x e^{ix(\theta+2n\pi)} \neq r^x e^{ix\theta}$, since $2nx\pi = 0 \iff nx \in \mathbb{Z}$. In order to define the roots of z we must need a more general and proper definition of z.

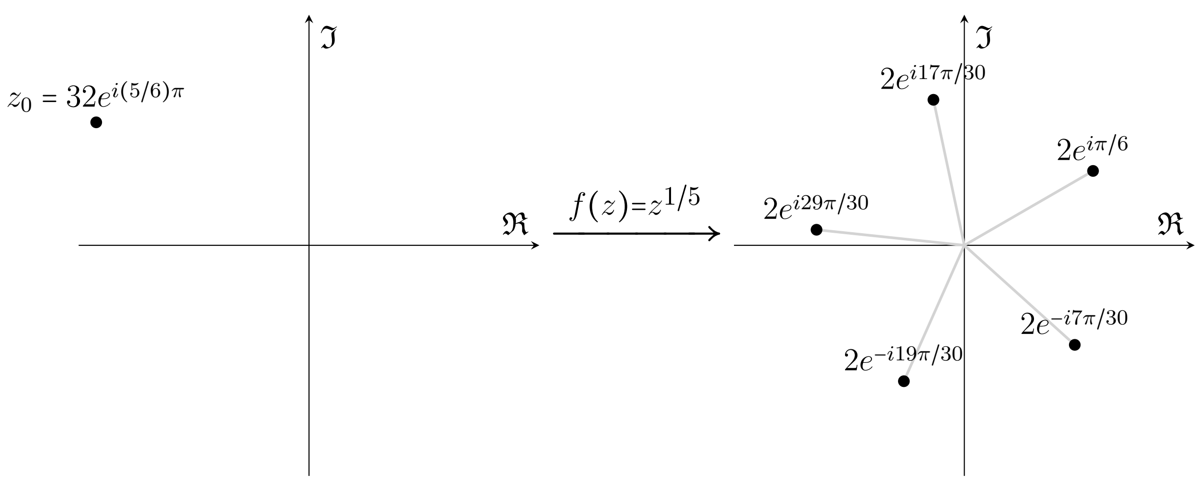
Definition 12.4.2: Roots of z_0

Consider any $z_0 \in \mathbb{C}$ and any $m \in \mathbb{N}$.

$$z_0^{\frac{1}{m}} = r_0^{\frac{1}{m}} e^{i\left(\frac{\theta_0+2n\pi}{m}\right)} = r_0^{\frac{1}{m}} e^{i\left(\frac{\theta_0}{m}+\frac{2n\pi}{m}\right)}$$

Taking the m-th root of $z_0 \in C$ scales θ_0 by $1/m$, and provides solutions at equally spaced by $2\pi/m$ on a circle of radius $r^{1/m}$. That is, the roots lie on the vertices of a regular n-sided polygon inscribed in a circle of radius $|z|^{1/m}$.

Example 12.4.1 *Consider $z_0 = 32e^{i(5/6)\pi}$, then $z_0^{(1/5)} = 3e^{i(\pi/6)+i(2/5)n\pi}$ for $n \in \mathbb{Z}$. The radius went from 35 to $35^{(1/5)} = 2$, and five roots appear equally spaced with distance of $(2/5)\pi$ on a circle with radius 2. Before and after graphs are as follows, note graph on right is zoomed in:*



We can see that the roots of z_0 form a set:

Definition 12.4.3: Set of roots of z_0

Consider the m-th root of any $z_0 \in \mathbb{C}$. Let:

$$z_0 = r_0 e^{i\theta_0} \qquad c_0 = r_0^{1/m} e^{i\theta_0/m} \qquad \omega_n = e^{\frac{i2\pi}{m}} \qquad m \in \mathbb{N}$$

Then the set of roots of z_0:

$$z_0^{1/m} = \left\{c_k = c_0\omega_m^k \mid k \in \mathbb{N},\ 0 \le k < m\right\}$$

c_0 is the principal root. The root corresponding to the principal argument of z.

Definition 12.4.4: Principal Root

Consider the m-th root of any $z_0 \in \mathbb{C}$. The principal root of z_0 is defined as:

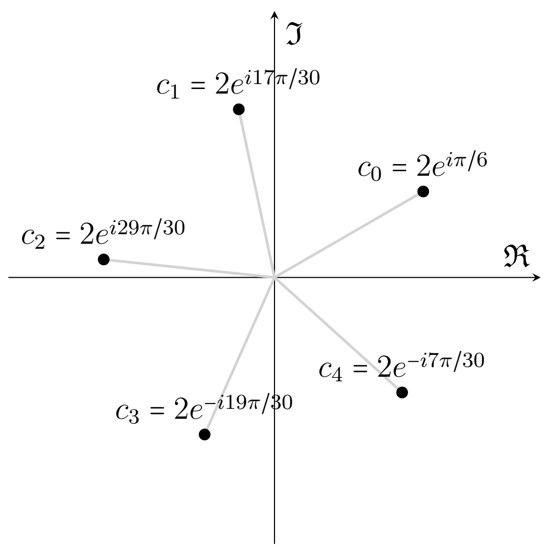
$$c_0 = r_0^{\frac{1}{m}} e^{i\frac{\theta_0}{m}}$$

Example 12.4.2 *Recall from the previous example: $z_0 = 32e^{i(5/6)\pi}$. This gives us*

$$c_0 = 32^{1/5}e^{i\pi/6} = 2e^{i\pi/6} \qquad \omega_5 = e^{i2\pi/5}$$

Then

$$\begin{aligned}
c_0 &= c_0\omega_5^0 = 2e^{i\pi/6} \\
c_1 &= c_0\omega_5^1 = 2e^{i\pi/6}e^{i2\pi/5} = 2e^{i17\pi/30} \\
c_2 &= c_0\omega_5^1 = 2e^{i\pi/6}e^{i4\pi/5} = 2e^{i29\pi/30} \\
c_3 &= c_0\omega_5^1 = 2e^{i\pi/6}e^{i6\pi/5} = 2e^{i41\pi/30} = 2e^{-i19\pi/30} \\
c_4 &= c_0\omega_5^1 = 2e^{i\pi/6}e^{i8\pi/5} = 2e^{i53\pi/30} = 2e^{-i7\pi/30}
\end{aligned}$$



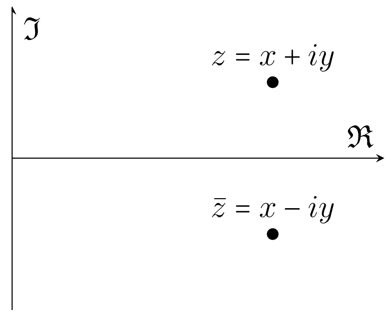
12.5 Complex Conjugate

Definition 12.5.1: Complex Conjugate

The complex conjugate of $z \in \mathbb{C}$ is denoted $\bar{z}$.

$$\bar{z} = x - iy = r(\cos(\theta) - i\sin(\theta)) = re^{-i\theta}$$

Graphically, it is the reflection of z across the real axis.



It is then easy to see

$$\mathrm{Re}(z) = \frac{z + \bar{z}}{2} \qquad \mathrm{Im}(z) = \frac{z - \bar{z}}{2i} \qquad |z|^2 = z\bar{z}$$

As $\mathrm{Re}(z) = x = r\cos(\theta)$ and $\mathrm{Im}(z) = y = r\sin(\theta)$ and using definition 12.3.4, we can obtain the complex forms of sine and cosine:

Definition 12.5.2: Complex Sine and Cosine

$$\cos(\theta) = \frac{e^{i\theta} + e^{-i\theta}}{2} \qquad \sin(\theta) = \frac{e^{i\theta} - e^{-i\theta}}{2i}$$

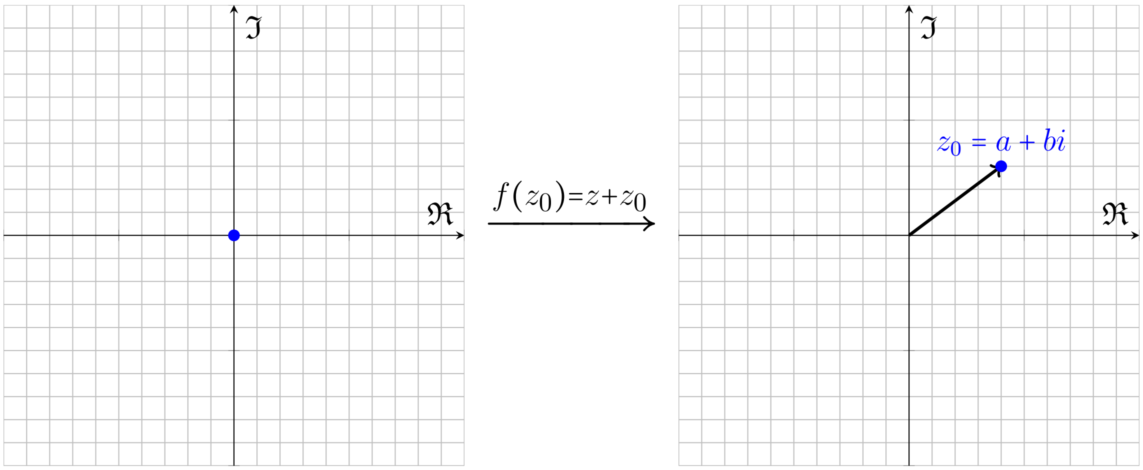
It is easy to prove $\forall z_1, z_2 \in \mathbb{C}$:

$$\overline{z_1 + z_2} = \overline{z_1} + \overline{z_2} \qquad \overline{z_1 \cdot z_2} = \overline{z_1} \cdot \overline{z_2}$$

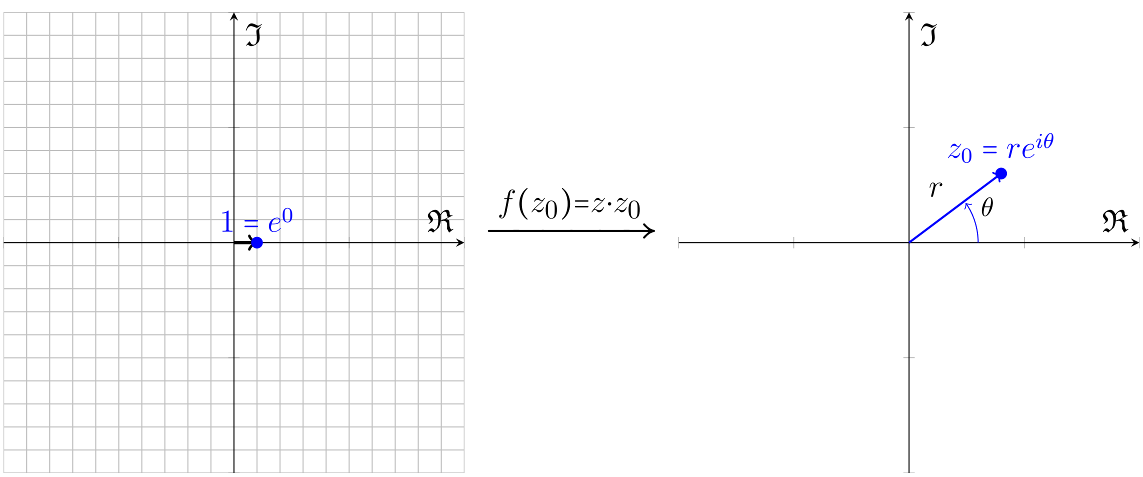
12.6 Operations as Transformations

Consider any $z \in \mathbb{C}$. A function $f : \mathbb{C} \to \mathbb{C}$ can be viewed as transformations of the complex plane.

Example 12.6.1 (Addition as translation) *Consider any $z_0 \in \mathbb{C}$, $z_0 = a + ib$ for $a, b \in \mathbb{R}$. Addition by z_0 can be seen as a shift in the complex plane by $a + bi$. (i.e. It takes the origin and shifts it by z_0.)*



Example 12.6.2 (Multiplication as scaling and rotation) *Consider any $z_0 \in \mathbb{C}$, $z_0 = re^{i\theta}$. Multiplication by z_0 scales the entire complex plane by r and rotates it by θ. (Imagine rotating and stretching out a net.)*



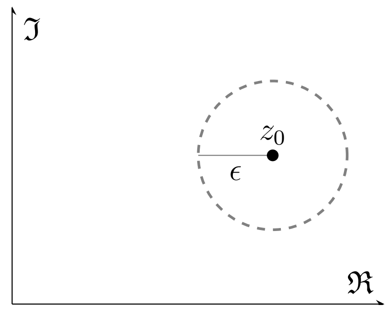
12.7 Complex Analysis Definitions

Definition 12.7.1: Neighbourhood

A neighbourhood of a point z_0 is the set of all points z with distance less than ϵ.

$$\{z : |z - z_0| < \epsilon\}$$

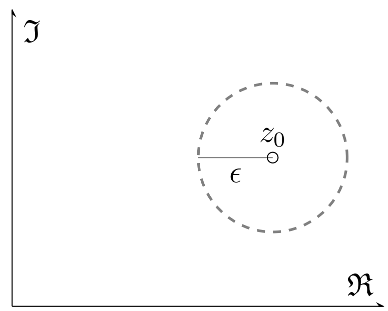
i.e. It is the set of all points that lie within a circle centred at z_0 with radius ϵ. Points on the circumference not included.



Definition 12.7.2: Deleted Neighbourhood

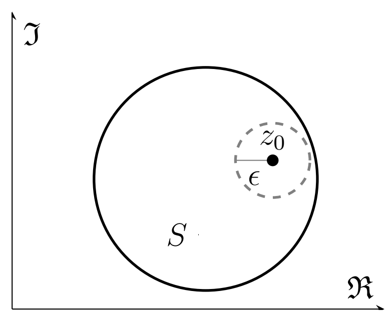
A deleted neighbourhood is the set of all points z with distance less than ϵ from a point z_0, not including z_0. That is, it is a neighbourhood of z_0 without z_0.

$$\{z : |z - z_0| < \epsilon,\ \ z \neq z_0\}$$



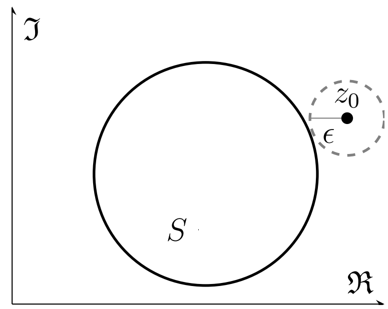
Definition 12.7.3: Interior Point

Let S be a set. A point z_0 is an interior point of S if $\exists \epsilon$ such that $\forall z$, $|z - z_0| < \epsilon \implies z \in S$. That is, z_0 is an interior point of S if it has a neighbourhood where all points in the neighbourhood is an element of S.



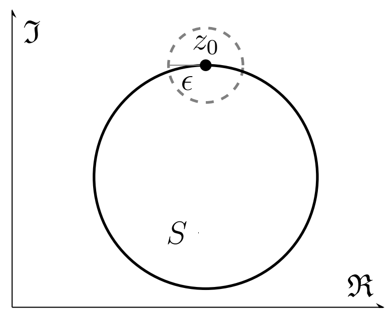
Definition 12.7.4: Exterior Point

Let S be a set. A point z_0 is an exterior point of S if $\exists \epsilon$ such that $\forall z$, $|z - z_0| < \epsilon \implies z \notin S$. That is, $z_0$is an exterior point of S if it has neighbourhood that does not contain any element of S.



Definition 12.7.5: Boundary Point

Let S be a set. A point z_0 is a boundary point of S if $\forall \epsilon$, $\exists z \in S, z' \notin S$, such that $|z - z_0| \epsilon$ and $|z' - z_0| < \epsilon$. That is, for all neighbourhoods of z_0 there exists a point that is in S and a point not in S.



Note: A boundary point of S may or may not be in S.

Definition 12.7.6: Boundary of a Set

A boundary of a set S is the set of all boundary points of S. The set containing all boundary points of S.

$$\{z_0 : \forall \epsilon \exists z \in S, z' \notin S(|z - z_0| < \epsilon \land |z' - z_0| < \epsilon)\}$$

Definition 12.7.7: Open Set

A set that does not contain any boundary points.

Theorem 12.7.1:

Set S is open $\iff$ $\forall s \in S$, s is an interior point of S

Proof: $\underline{\implies}$: Suppose S is open $\not\Rightarrow$ $\forall s \in S$, s is an interior point of S, for contradiction. That is, $\exists s \in S$ that is either a boundary point or an exterior point. $s \in S$ implies s is not an exterior point of S, so s has to be a boundary point of S. This contradicts that S is an open set.

$$S \text{ is open } \implies \forall s \in S(s \text{ is an interioir point of } S)$$

$\Longleftarrow$:

$$\begin{aligned}
&\forall s \in S(s \text{ is an interior point of S}) \\
&\implies \forall s' \forall \epsilon (|s' - s| < \epsilon \implies s' \in S) \\
&\implies S \text{ does not contain boundary points} \implies S \text{ is open}
\end{aligned}$$

□

A set can be neither open or closed. Consider the set $S = \{z : 0 < |z| \leq 1\}$. S is not closed since it does not contain the boundary point 0, and it is not open since it contains boundary points where $|z| = 1$. The set $\mathbb{C}$ is both open and closed since it has no boundary points.

Definition 12.7.8: Closed Set

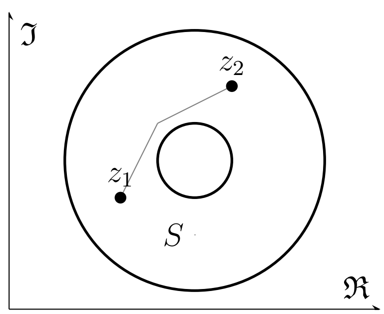
A set that contains all of its boundary points.

Definition 12.7.9: Closure of a Set

Let S be a set. The closure of S is a closed set containing all points of S and all boundary points of S.

Definition 12.7.10: Connected Set

An opens set S is connected if $\forall z_1, z_2 \in S$, z_1 and z_2 can be connected by a polygonal line lying within S.



Definition 12.7.11: Polygonal Line

A finite set of line segments joined end to end.

Definition 12.7.12: Domain

A nonempty connected set.

Note: All neighbourhoods are domains.

Definition 12.7.13: Region

A domain with none, some, or all of its boundary points.

Definition 12.7.14: Bounded Set/Region

A set S is bounded if $\exists R = |z| > 0$ such that $\forall s \in S$, $|s| < R$. That is, S is bounded if $\forall s \in S$, s is contained in some circle of radius R centred at the origin.

Definition 12.7.15: Closed Region

A domain with all its boundary points. A bounded and closed region.

Definition 12.7.16: Accumulation/Limit Point

A point z_0 is a accumulation point of a set S if all deleted neighbourhood of z_0 contains an element of S.

$$\forall \epsilon \exists s \in S(s \neq z_0 \wedge |z - s| < \epsilon)$$

Note: Unlike a boundary point, an accumulation point does not require that all neighbourhood of z_0 contain an element not in S.

Theorem 12.7.2:

Set S is closed $\iff$ $\forall$ accumulation points z_0 of S, $z_0 \in S$

Proof: $\underline{\implies:}$ Let S is closed and z_0 is an accumulation point of a set S where $z_0 \notin S$ for contradiction. If $\exists z_0 \notin S$, then z_0 is a boundary point of S. Contradicts closed set contains all boundary points.

$\underline{\impliedby:}$ Suppose all accumulation points of S are elements of S but S is not closed for contradiction. Then S does not contain one or more boundary points. Suppose z_0 is a boundary point of S that is not in S. Then $\forall \epsilon$ $\exists s \in S$ where $|s - z_0| < \epsilon$, so by considering the deleted neighbourhood of z_0, this makes z_0 an accumulation point of S. This contradicts that all accumulation points of S is in S. $\square$

Chapter 13

Analytic Functions

13.1 Functions as mappings

A function $f : S \to S'$ is a function that maps elements from S to elements on S'. The value of f at z is denoted $f(z)$ and the set S is the domain of f while S' is the image of f. Recall section 12.6, a function can likewise be viewed as a transformation or mapping, that maps $z \in \text{dom}(f) = S$ to values $z' \in \text{img}(f) = S'$.

Definition 13.1.1: Range

Let f be a function with domain S and image S'. The range of f is the entire image of S.

Note: Image is a subset of range, and can be a single point or a set of points.

Definition 13.1.2: Inverse Range

The set of all points $s \in S$ with the value $f(s) = s'$ for some $s' \in S'$.

$$\{s : f(s) = s',\ s' \in S'\}$$

Note: The domain of a function is often a domain, but it does not need to be a domain.

We will consider functions $f : S \to S'$ where both $S, S' \subseteq \mathbb{C}$. For such functions we can break it into a two real valued functions:

$$\begin{aligned} f(z) &= u(x,y) + iv(x,y) \qquad\qquad \text{dom}(u) \subseteq \mathbb{R}, \text{dom}(v) \subseteq \mathbb{R} \\ &= u(r,\theta) + iv(r,\theta) \end{aligned}$$

Recall that a real-valued function is a function with a domain that is a subset of $\mathbb{R}$ (**??**). If $\forall z,\ v(x,y) = 0$, then f is called a real-valued function of a complex variable.

Definition 13.1.3: Polynomial

Let $a_i \in \mathbb{C}$, $0 \le i \le n$ where $i, n \in \mathbb{N} \cup \{0\}$. If $a_n \neq 0$, then a polynomial of degree n is

$$P(z) = a_0 + a_1 z + a_2 z^2 + \ldots + a_n z^n = \sum_{i=0}^{n} a_i z^i$$

Definition 13.1.4: Rational Functions

Let $P(z)$ and $Q(z)$ are polynomials, then rational functions are quotients:

$$\frac{P(z)}{Q(z)}$$

Defined for all z where $Q(z) \neq 0$.

Definition 13.1.5: Multiple-Valued Function

Let f be a function and $z \in \mathrm{dom}(f)$. f is a multiple-valued function if it assigns more than one value to a point z.

"When multiple-valued functions are studied, usually just one of the possible values assigned at each point is taken, in a systematic manner and a (single-valued) function is constructed from the multiple-valued one" - Brown and Churchill [2]

What this means that for $z \in \mathbb{C}$ a function f assigns $u(z)$ and $v(z)$ to to z. By taking just u or v, we create a single-valued function from a multiple-valued function.

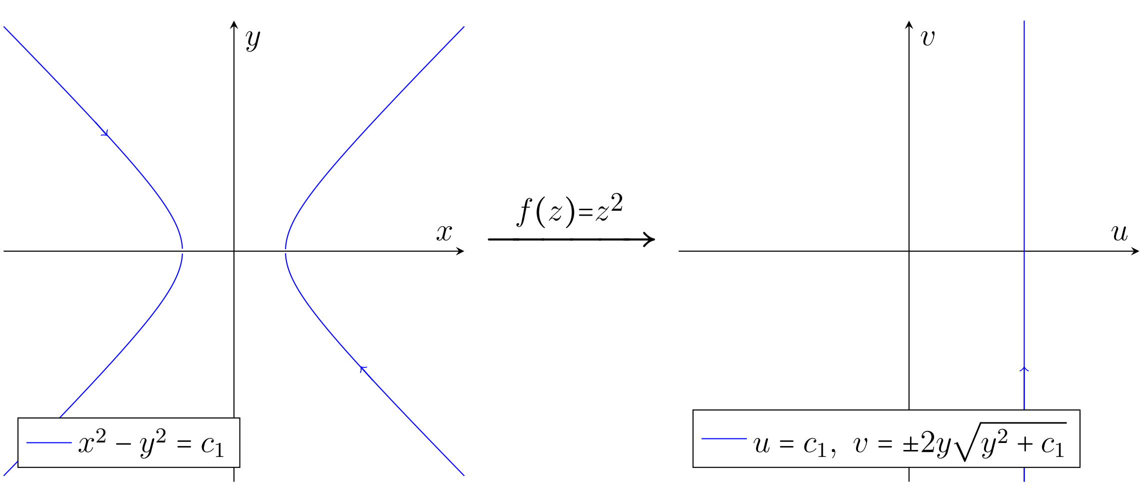
Example 13.1.1 ($f(z) = z^2$)

$$\begin{aligned} f(z) = z^2 = x^2 - y^2 + i2xy \\ \implies u(x,y) = x^2 - y^2 \qquad v(x,y) = 2xy \end{aligned}$$

By setting $u = x^2 - y^2 = c_1$ where $c_1 \in \mathbb{R}_{>0}$ we can see that

$$u = x^2 - y^2 = c_1 \qquad\qquad v = 2xy = \pm 2y\sqrt{y^2 + c_1}$$

This tells us that in the complex plane of u and v, if we fix u to a constant c_1 and move along $v = \pm 2y\sqrt{y^2 + c_1}$ by incrementing y we draw out two hyperbolas in the complex plane of x and y. This means that the function $f(z) = z^2$ takes points on hyperbolas the complex plane of x and y and translates them onto a vertical line in the complex plane of u and v where u is a constant.



Likewise if we set $v = c_2$ where $c_2 \in \mathbb{R}_{>0}$, we get:

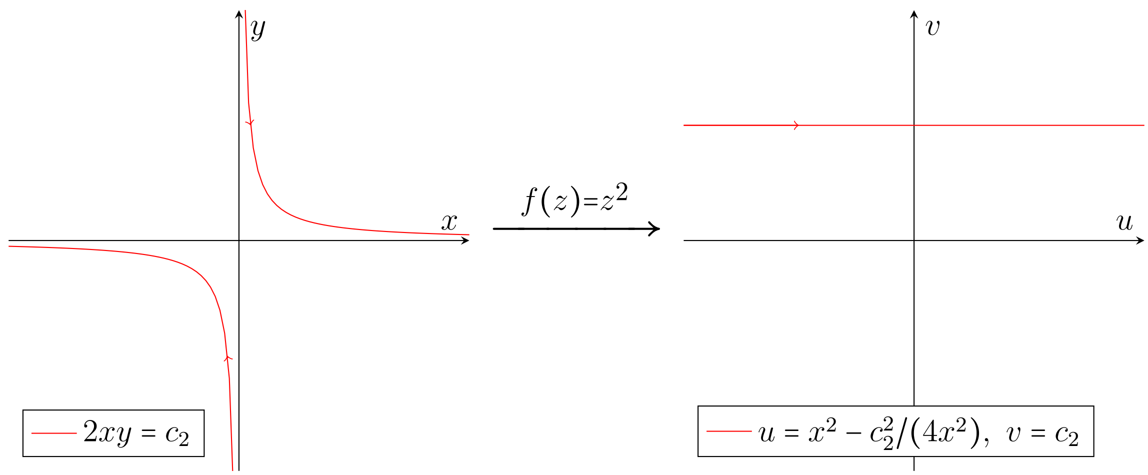
$$u = x^2 - \frac{c_2^2}{4x^2} \qquad\qquad v = 2xy = c_2$$

Taking the limits:

$$\lim_{x\to 0^+} u = -\infty \qquad\qquad \lim_{x\to\infty, x>0} u = \infty \tag{13.1}$$

$$\lim_{x\to -\infty, x<0} u = \infty \qquad\qquad \lim_{x\to 0^-} u = -\infty \tag{13.2}$$

Equation 11.1 tells us as x goes from 0 to ∞, u moves from $-\infty$ to ∞, which corresponds to the hyperbola in the first quadrant of the xy complex plane. Similarly for equations 11.2.



If we look at f using the polar representation, we get $f(z) = r^2 e^{i2\theta}$. This tells us $\forall r \geq 0$, $r \mapsto r^2 = \rho \geq 0$, and $\forall \theta$, $\theta \mapsto \phi = 2\theta$. It is worth noting that mapping of points between $0 \leq 0 < 2\pi$ is not one-to-one, since points in $0 \leq \theta < \pi$ and points in $\pi \leq \theta < 2\pi$ both get mapped to $0 \leq \phi < 2\pi$.

13.2 Limits

Definition 13.2.1: Limit

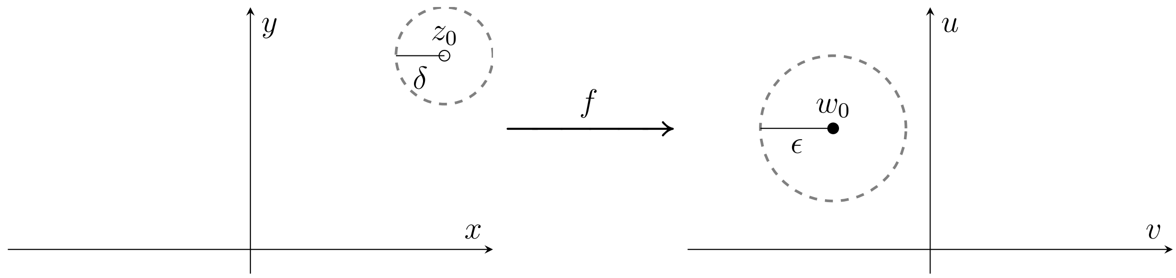
Let $z, z_0, w_0 \in \mathbb{C}$ and f be a function. We say $f(z)$ has limit w_0 as z approaches z_0 if:

$$\forall \epsilon \exists \delta [0 < |z - z_0| < \delta \implies |f(z) - w_0| < \epsilon]$$

We then denote: $\lim_{z\to z_0} f(z) = w_0$

This tells us that $\lim_{z\to z_0} f(z) = w_0$ if some deleted neighbourhood $|z - z_0| < \delta$ corresponds to a neighbourhood $|f(z) - w_0| < \epsilon$. Note that the mapping of all points z in $|z - z_0| < \delta$ to $|f(z) - w_0| < \epsilon$ need not be subjective. It just needs to be mapped less than distance ϵ from w_0.

Note: Definition 13.2.1 allows us to verify if a limit exists, but it is not a method for determining a limit.



Theorem 13.2.1: Uniqueness of Limits
Suppose the limit of f at z_0 exists, then it is unique.

Proof: Suppose two limits of f at z_0 exists for contradiction.

$$[\lim_{z\to z_0} f(z) = w_0] \wedge [\lim_{z\to z_0} f(z) = w_1]$$
$$\implies [0 < |z - z_0| < \delta_0 \implies |f(z) - w_0| < \epsilon] \wedge [0 < |z - z_0| < \delta_0 \implies |f(z) - w_0| < \epsilon]$$

$$w_1 - w_0 = [f(z) - w_0] + [w_1 - f(z)]$$
$$\implies |w_1 - w_0| = |[f(z) - w_0] + [w_1 - f(z)]| \le |f(z) - w_0| + |f(z) - w_1|$$

Now choosing $\delta = \min\{\delta_1, \delta_2\}$, we get:

$$|w_1 - w_0| < \epsilon + \epsilon = 2\epsilon$$

Choosing ϵ to be arbitrary small, we end up with:

$$w_1 - w_0 = 0 \implies w_1 = w_0$$

□

Definition 13.2.1 requires that f be defined at all points in the deleted neighbourhood of z_0. That is, z_0 is interior to the region which f is defined. We can extend the definition by agreeing that $0 < |z - z_0| < \delta \implies |f(z) - w_0| < \epsilon$ also holds for z that lie in the region where f is defined and the deleted neighbourhood of z_0. That is $f(z_0)$ need not be defined for a limit at z_0 to exist.

Example 13.2.1 *Show* $(f(z) = iz/2) \wedge (|z| < 1) \implies \lim_{z\to 1} f(z) = i/2$.

We can see that we have restricted the domain of f to the region $|z| < 1$, this puts $z = 1$ right at the boundary of the domain of definition of f.

$$|z| < 1 \implies \left|f(z) - \frac{i}{2}\right| = \left|\frac{iz}{2} - \frac{i}{2}\right| = \frac{|z-1|}{2}$$
$$\implies \forall z \forall \epsilon \exists \delta \left[0 < |z - 1| < \delta = 2\epsilon \implies \left|f(z) - \frac{i}{2}\right| < \epsilon\right]$$
$$\implies \lim_{z\to 1} f(z) = \frac{i}{2}$$

This highlights the fact that if the limit exists, then z is allowed to approach z_0 from any arbitrary direction.

Example 13.2.2 *Limit of $f(z) = z/\bar{z}$ does not exist at $z = 0$*

Consider $\lim_{z\to 0} f(z)$. *Let us approach the limit from the x-axis and the y-axis.*

$$\lim_{z=(x,0)\to 0} f(z) = \frac{x+i0}{x-i0} = 1 \qquad\qquad \lim_{z=(0,y)\to 0} f(z) = \frac{0+iy}{0-iy} = -1$$

We end up with two different limits. As limits are unique, we conclude that $\lim_{z\to 0} f(z)$ *does not exist.*

13.2.1 Limit Theorems

Theorem 13.2.2:

Consider $f(z) = u(x,y) + iv(x,y)$. Let $z_0 = x_0 + iy_0$ and $w_0 = u_0 + iv_0$.

$$\left[\lim_{(x,y)\to(x_0,y_0)} u(x,y) = u_0\right] \wedge \left[\lim_{(x,y)\to(x_0,y_0)} v(x,y) = v_0\right] \iff \lim_{z\to z_0} f(z) = w_0$$

Proof: $\underline{\implies:}$

By definition:

$$\begin{aligned} &\left[\lim_{(x,y)\to(x_0,y_0)} u(x,y) = u_0\right] \wedge \left[\lim_{(x,y)\to(x_0,y_0)} v(x,y) = v_0\right] \\ &\implies \forall\epsilon\exists\delta_1,\delta_2\left[\left(0 < \sqrt{(x-x_0)^2+(y-y_0)^2} < \delta_1 \implies |u-u_0| < \frac{\epsilon}{2}\right)\right. \\ &\qquad\qquad \left.\wedge \left(0 < \sqrt{(x-x_0)^2+(y-y_0)^2} < \delta_2 \implies |v-v_0| < \frac{\epsilon}{2}\right)\right] \end{aligned} \tag{13.3}$$

Triangle inequality for the distance between points:

$$\begin{aligned} |(u+iv)-(u_0-iv_0)| &= |(u-u_0)+i(v-v_0)| \leq |u-u_0| + |v-v_0| \\ \sqrt{(x-x_0)^2+(y-y_0)^2} &= |(x-x_0)+i(v-v_0)| = |(x+iy)-(x_0-iy_0)| \end{aligned}$$

Let $\delta = \min\{\delta_1,\delta_2\}$, it follows from eq. (13.3):

$$0 < |(x+iy)-(x_0+iy_0)| < \delta \implies |(u+iv)-(u_0-iv_0)| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon$$

Thus, $\lim_{z\to z_0} f(z) = w_0$.

$\underline{\impliedby:}$

Suppose $\lim_{z\to z_0} f(z) = w_0$.

$$\begin{aligned} &\lim_{z\to z_0} f(z) = w_0 \\ &\implies \forall\epsilon\exists\delta > 0[|(x+iy)-(x_0-iy_0)| < \delta \implies |(u+iv)-(u_0+iv_0)| < \epsilon] \end{aligned} \tag{13.4}$$

By the triangle inequality:

$$\begin{aligned}|u-u_0| &\leq |(u-u_0)+i(v-v_0)| = |(u+iv)-(u_0+iv_0)| \\ |v-v_0| &\leq |(u-u_0)+i(v-v_0)| = |(u+iv)-(u_0+iv_0)|\end{aligned}$$

$$|(x+iy)-(x_0+iy_0)| = |(x-x_0)+i(y-y_0)| = \sqrt{(x-x_0)^2+(y-y_0)^2}$$

Thus, it follows from the inequalities in eq. (13.4):

$$\begin{aligned}&0 < \sqrt{(x-x_0)^2+(y-y_0)^2} < \delta \\ &\implies [|u-u_0| < \epsilon] \wedge [|v-v_0| < \epsilon] \\ &\implies \left[\lim_{(x,y)\to(x_0,y_0)} u(x,y) = u_0\right] \wedge \left[\lim_{(x,y)\to(x_0,y_0)} v(x,y) = v_0\right]\end{aligned}$$

□

Theorem 13.2.3:

Suppose

$$\left[\lim_{z\to z_0} f(z) = w_0\right] \wedge \left[\lim_{z\to z_0} F(z) = W_0\right]$$

Then

$$\begin{aligned}\lim_{z\to z_0}[f(z)+F(z)] &= w_0+W_0 \\ \lim_{z\to z_0}[f(z)F(z)] &= w_0W_0 \\ \lim_{z\to z_0}\frac{f(z)}{F(z)} &= \frac{w_0}{W_0} \qquad W_0 \neq 0\end{aligned}$$

Proof: Let:

$$f(z) = u(x,y)+iv(x,y) \qquad F(z) = U(x,y)+iV(x,y)$$

$$z_0 = x_0+iy_0 \qquad w_0 = u_0+iv_0 \qquad W_0 = U_0+iV_0$$

$\underline{\lim_{z\to z_0}[f(z)+F(z)] = w_0+W_0}$

From Theorem 13.2.2:

$$\begin{aligned}&f(z)+F(z) = (u+U)+i(v+V) \\ &\implies \lim_{(x,y)\to(x_0,y_0)} f(z)F(Z) = (u_0+U_0)+i(v_0+V_0) = w_0+W_0\end{aligned}$$

$\underline{\lim_{z\to z_0}[f(z)F(z)] = w_0W_0}$

From Theorem 13.2.2:

$$f(z)F(z) = (uU - vV) + i(vU + uV)$$
$$\implies \lim_{(x,y)\to(x_0,y_0)} f(z)F(Z) = (u_0U_0 - v_0V_0) + i(v_0U_0 + u_0V_0) = w_0W_0$$

$\lim_{z\to z_0} \frac{f(z)}{F(z)} = \frac{w_0}{W_0}$ if $W_0 \neq 0$

From Theorem 13.2.2:

$$\frac{f(z)}{F(z)} = \frac{u + iv}{U + iV} \implies \lim_{(x,y)\to(x_0,y_0)} \frac{f(z)}{F(z_0)} = \frac{u_0 + v_0}{U_0 + iV_0} = \frac{w_0}{W_0}$$

□

Corollary 13.2.3.1:

Let c be a constant, $z, z_0 \in \mathbb{C}$, and $P(z)$ be a polynomial. Then

$$\lim_{z\to z_0} c = c \qquad \lim_{z\to z_0} z = z_0 \qquad \lim_{z\to z_0} z^n = z_0^n \qquad n \in \mathbb{N}$$

$$\lim_{z\to z_0} P(z) = P(z_0)$$

Observation. *It is surprisingly quick that Brown and Churchill went from ϵ−δ proofs straight to proving with limits. This is different to the approach in Sequences of Limits Theorem for Sequences Section by Kennith A. Ross. [1]. (Section 9.1.1)*

Question. *It might be possible use a series approach to prove limit theorems for $z \in \mathbb{C}$ by having separate series for x and y (real and imaginary components of z), or a series in the form of $s_n = (x_n, y_n)$. Which would be the proper approach?*

13.2.2 Limits of Points at Infinity

Definition 13.2.2: Extended Complex Plane

The complex plane union with the points at infinity:

$$\mathbb{C} \cup \{\pm\infty, \pm i\infty\}$$

Definition 13.2.3: Riemann Sphere

A unit sphere centred at the origin of the complex plane, which is consequently bisected by the complex plane.

Definition 13.2.4: Stereographic Projection

Consider the Riemann Sphere. Let N be the northern point of the sphere (the point on the sphere above the origin of the complex plane) and z be any point in the complex plane. Let l be a line that goes through N and z, then l will intersect the Riemann Sphere. Let P be the point where l intersects the Riemann Sphere. If we let N correspond to the points at infinity, then there is a one-to-one correspondence between points on the sphere and the points on the extended complex plane. This correspondence is called the Stereographic Projection. (Figure 13.1)

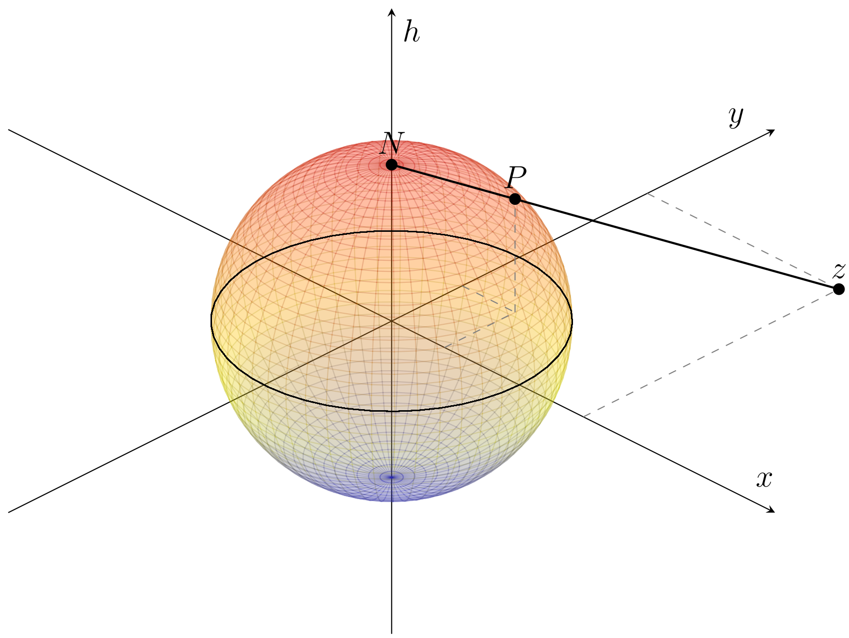


Figure 13.1: Riemann Sphere and Stereographic Projection

The region outside the unit circle enveloped by the Riemann sphere corresponds to the upper hemisphere of the Riemann sphere, with the point N deleted. N corresponds to the points at infinity, since l will be parallel to the complex plane.

Note: In some texts, the Riemann Sphere is a sphere of unit diameter (not a unit sphere, which is of unit radius) sitting on top of the Complex Plane. That is, with the south pole sitting at $(0, 0)$. The definitions for line L, and points N, P, and z remains the same. In either case, the Stereographic Projection maps to a unique point P on the sphere, and the definition of the point at infinity remains unchanged.

Definition 13.2.5: Neighbourhood of ∞

The set: $\{|z| > 1/\epsilon : \epsilon \in \mathbb{R}_{>0}\}$

Note that since ϵ is a small positive number, $|z| > 1/\epsilon$ corresponds to points far away from the unit circle, hence P is close to N.

Note: When referring to any point z, it is referring to a point in the finite plane. Points at infinity will be specifically mentioned.

Definition 13.2.6: Limit at Infinity
Let $f(z)$ be a function, and $z, z_0 \in \mathbb{C}$.

$$\forall \epsilon \in \mathbb{R}_{>0}, \exists r \in \mathbb{R}_{>0}[|z| > r \implies |f(z) - z_0| < \epsilon] \iff \lim_{z\to\infty} f(z) = z_0$$

That is, if $\forall z$ in the neighbourhood of infinity implies $|f(z) - z_0| < \epsilon$, then $\lim_{z\to\infty} f(z) = z_0$.

Theorem 13.2.4:
Let $z_0, w_0 \in \mathbb{C}$, then

$$\lim_{z\to z_0} \frac{1}{f(z)} = 0 \implies \lim_{z\to z_0} f(z) = \infty$$
$$\lim_{z\to 0} f\left(\frac{1}{z}\right) = w_0 \implies \lim_{z\to\infty} f(z) = w_0$$
$$\lim_{z\to 0} \frac{1}{f(1/z)} = 0 \implies \lim_{z\to\infty} f(z) = \infty$$

Proof: $\underline{\lim_{z\to z_0} \frac{1}{f(z)} = 0 \implies \lim_{z\to z_0} f(z) = \infty}$

$$\begin{aligned}\lim_{z\to z_0} \frac{1}{f(z)} = 0 &\implies \forall\epsilon\exists\delta > 0\left[|z - z_0| < \delta \implies \left|\frac{1}{fz} - 0\right| < \epsilon\right]\\ &\implies \forall\epsilon\exists\delta > 0\left[|z - z_0| < \delta \implies |f(z)| > \frac{1}{\epsilon}\right]\\ &\implies \lim_{z\to z_0} f(z) = \infty\end{aligned}$$

$\underline{\lim_{z\to 0} f\left(\frac{1}{z}\right) = w_0 \implies \lim_{z\to\infty} f(z) = w_0}$

$$\begin{aligned}\lim_{z\to 0} f\left(\frac{1}{z}\right) = w_0 &\implies \forall\epsilon\exists\delta > 0\left[|z - 0| < \delta \implies \left|f\left(\frac{1}{z}\right) - w_0\right| < \epsilon\right]\\ &\implies \forall\epsilon\exists\delta > 0\left[|z| > \frac{1}{\delta} \implies |f(z) - w_0| < \epsilon\right]\\ &\implies \lim_{z\to\infty} f(z) = w_0\end{aligned}$$

$\underline{\lim_{z\to 0} \frac{1}{f(1/z)} = 0 \implies \lim_{z\to\infty} f(z) = \infty}$

$$\begin{aligned}\lim_{z\to 0} \frac{1}{f(1/z)} = 0 &\implies \forall\epsilon\exists\delta > 0\left[|z - 0| < \delta \implies \left|\frac{1}{f(1/z)} - 0\right| < \epsilon\right]\\ &\implies \forall\epsilon\exists\delta > 0\left[|z| > \frac{1}{\delta} \implies |f(z)| > \frac{1}{\epsilon}\right]\\ &\implies \lim_{z\to\infty} f(z) = \infty\end{aligned}$$

□

Note: As δ goes to 0, $1/\delta$ goes to ∞, hence $|z|$ goes to ∞ if $|z| > 1/\delta$.

Observation. *As expected, theorem 13.2.4 is consistent if $z \in \mathbb{R}$. (Check: Section 9.1.1).*

13.3 Continuity

Definition 13.3.1: Continuous

Let f be a function. We say f is continuous at all point $z_0 \in \mathbb{C}$ if it satisfies the following:

$$\lim_{z \to z_0} f(z) \text{ exists } \wedge f(z_0) \text{ exists } \wedge \lim_{z \to z_0} f(z) = f(z_0)$$

Note:

$$\lim_{z \to z_0} f(z) = f(z_0) \implies \lim_{z \to z_0} f(z) \text{ exists } \wedge f(z_0) \text{ exists}$$
$$\forall \epsilon \exists \delta > 0 \left[|z - z_0| < \delta \implies |f(z) - f(z_0)| < \epsilon \right] \iff \lim_{z \to z_0} f(z) = f(z_0)$$

Definition 13.3.2: Continuous at a Region

Let f be a function, $R \subset \mathbb{C}$ be a region, and $z \in R$:

$$f \text{ is continuous in } R \iff \forall z \in R (f \text{ is continuous})$$

Theorem 13.3.1:

Let $f(z)$ and $g(z)$ be continuous functions at $z_0 \in \mathbb{C}$. Then the following are also continuous at z_0:

$$f(z_0) + g(z_0) \qquad f(z_0)g(z_0) \qquad \frac{f(z_0)}{g(z_0)} \qquad g(z_0) \neq 0$$

Proof: Consequence of theorem 13.2.3. □

Corollary 13.3.1.1:

Let $P(z)$ be a polynomial, then $P(z)$ is continuous $\forall z \in \mathbb{C}$. That is $P(z)$ is continuous in the entire plane of $\mathbb{C}$.

Proof: Consequence of corollary 13.2.3.1. □

Observation. *Both theorem 13.3.1 and corollary 13.3.1.1 rely on definition 13.3.1, which state for a function f and point $z_0 \in \mathbb{C}$:*

$$\lim_{z \to z_0} f(z) \text{ exists} \implies f(z) \text{ is continuous at } z_0$$

This is why the proofs cite the results of theorem 13.2.3 and corollary 13.2.3.1.

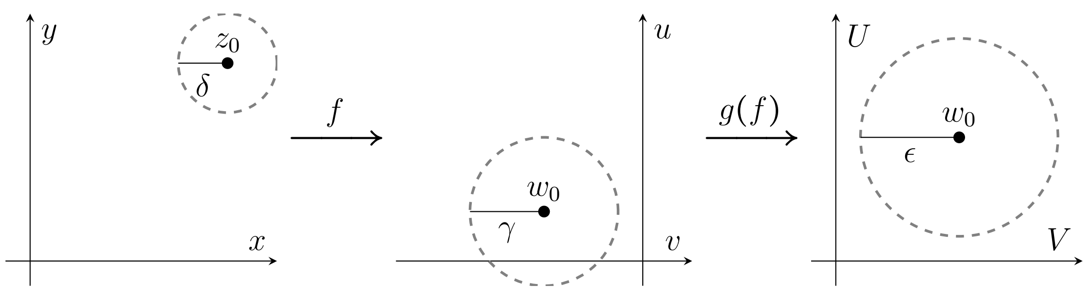
Theorem 13.3.2:
Let $f(z)$ and $g(z)$ be functions.

$$f(z) \text{ and } g(z) \text{ continuous} \implies g(f(z)) \text{ continuous}$$

Proof: Let $f(z) = w$ be defined in the neighbourhood $\forall z[|z - z - 0| < \delta]$, and $g(w) = W$ where $\text{dom}(g) = \text{img}(f)$. Suppose that f is continuous at z_0 and g is continuous at $f(z_0)$.

$$\begin{aligned} f \text{ continuous at } z_0 &\iff \forall\gamma\exists\delta > 0\,[|z - z_0| < \delta \implies |f(z) - f(z_0)| < \gamma] \\ &\implies \forall\epsilon\exists\gamma > 0\,[|f(z) - f(z_0)| < \gamma \implies |g(f(z)) - g(f(z_0))| < \epsilon] \end{aligned}$$

We can always find a small enough δ for γ to satisfy $|g(f(z)) - g(f(z_0))| < \epsilon$. □



Theorem 13.3.3:
Let $f(z)$ be a function and $f(z_0) \neq 0$.

$$f(z_0) \neq 0 \implies \exists\epsilon\forall z[|f(z) - f(z_0)| < \epsilon \implies f(z) \neq 0]$$

That is, if $f(z_0) \neq 0$ then it has a neighbourhood where $f(z) \neq 0$.

Proof: Suppose $f(z)$ is continuous and non-zero at z_0, and let $\epsilon = |f(z_0)|/2$:

$$\exists z[f(z) = 0] \wedge \forall\epsilon\exists\delta > 0\left[|z - z_0| < \delta \implies |f(z) - f(z_0)| < \frac{|f(z_0)|}{2}\right]$$

$$\implies |f(z_0)| < \frac{|f(z_0)|}{2} \qquad \text{Contradiction!}$$

□

Theorem 13.3.4:
Let $f(z) = u(x, y) + iv(x, y)$ be a function, and $z = x + iy$, $z \in \mathbb{C}$.

$$f \text{ continuous at } z_0 \iff [u \text{ continuous at } z_0] \wedge [v \text{ continuous at } z_0]$$

Proof: Direct consequence of theorem 13.2.2 □

Theorem 13.3.5:
Let f be continuous in a closed and bounded region R, then

$$\forall z \in R, \exists M \in \mathbb{R}_{>0}\left[|f(z) \leq M|\right] \wedge |\{z : f(z) = M\}| \geq 1$$

That is, for $\forall z \in R$, $|f(z)| \leq M$ and there is at least one point z where $|f(z)| = M$. $f(z)$ is bounded in R.

Proof: Let $f(z) = u(x, y) + iv(x, y)$ be continuous, then

$$|f(z)| = \sqrt{[u(x,y)]^2 + [v(x,y)]^2} \text{ is continuous in } R \implies \exists M \in \mathbb{R}_{>0}[|f(z)| \leq M]$$

□

13.3.1 Exercises

Example 13.3.1 *Prove:*

$$\lim_{z \to z_0} f(z) = w_0 \implies \lim_{z \to z_0} |f(z)| = |w_0|$$

Note: $||f(z_0)| - |w_0|| \leq |f(z) - w_0|$

Proof: Use definition of limit, then plug and chug. □

Example 13.3.2 *Prove: Limits involving points at infinity are unique.*

Proof: Suppose that limit of the point at infinity is not unique, that is there is two neighbourhoods of infinity. Using he definition of the limit, we will arrive at a contradiction where the two neighbourhoods are the same. □

Example 13.3.3 *Prove:*

$$S \text{ is unbounded} \iff \forall \epsilon \exists z \left[z \in S : |z| > \frac{1}{\epsilon} \right]$$

That is, S is unbounded $\iff$ every neighbourhood of the point at infinity contains at least one point in S

Proof: Proof Sketch: Recall the Riemann Sphere. (Definition 13.2.3). The set $|z| > 1/\epsilon$ corresponds to the points close to N, which is the neighbourhood of the point at infinity. If we let $\gamma = 2\epsilon$, $\exists z$ where $|z| > 1/\gamma$ holds. This along with $z \in \mathbb{C}$ (which is S in our case), implies the direction $\impliedby$ is true. That is, we can still find elements in S as we shrink the circle around N.

S is unbounded implies that for all circle with radius R centred at the origin there is at least one element of $s \in S$ where $|s| > R$. Suppose for contradiction that there is a neighbourhood of the point at infinity that does not contain any points in S. We will arrive at a contradiction, where there is $M \in \mathbb{R}_{>0}$ such that $\forall s \in S[|s| < M]$. Thus S is bounded, a contradiction. This implies that the direction $\implies$ is true. □

13.4 Differentiation

Definition 13.4.1: Derivative

Let f be a function where $|z - z_0| < \epsilon$ and $z \in \operatorname{dom}(f)$. Then the derivative of f at point z_0:

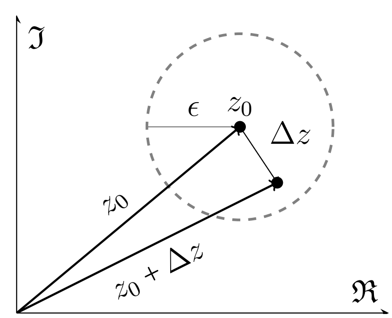
$$f'(z_0) = \lim_{z \to z_0} \frac{f(z) - f(z_0)}{z - z_0}$$

Definition 13.4.2: Differentiable

A function f is differentiable at $z_0 \in \mathbb{C}$ if $f'(z_0)$ exists.

If we let $\Delta z = z - z_0$ where $z \neq z_0$:

$$f'(z_0) = \lim_{\Delta z \to 0} \frac{f(z_0 + \Delta z) - f(z_0)}{\Delta z}$$



There's another notation by letting $\Delta w = f(z + \Delta z) - f(z)$:

$$f'(z) = \frac{\mathrm{d}w}{\mathrm{d}z} = \lim_{\Delta z \to 0} \frac{\Delta w}{\Delta z}$$

Observation. *The definition of a derivative in definition 13.4.1 looks similar to that of a derivative for the real numbers:*

$$F'(x_0) = \lim_{x \to x_0} \frac{f(x) - f(x_0)}{x - x_0}$$

However, the existence of $f'(z)$ possesses a much stronger requirement than the existence of $F'(z)$. That is, let $f(z) = u(x,y) + iv(x,y)$. The existence of $f'(z)$ at point z_0 requires the existence of both $u'(x,y)$ and $v'(x,y)$.

$$f'(z_0) = \lim_{(x,y) \to (x_0,y_0)} \frac{f(z) - f(z_0)}{z - z_0} = \lim_{(x,y) \to (x_0,y_0)} \frac{u(z) - u(z_0)}{z - z_0} + i\frac{v(z) - v(z_0)}{z - z_0}$$

and that

$$\lim_{(x,y_0)\to(x_0,y_0)} \frac{u(x,y_0)-u(x_0,y_0)}{x-x_0} + i\frac{v(x_0,y_0)-v(x_0,y_0)}{x-x_0}$$
$$= \lim_{(x_0,y)\to(x_0,y_0)} \frac{u(x_0,y)-u(x_0,y_0)}{x-x_0} + i\frac{v(x_0,y)-v(x_0,y_0)}{x-x_0}$$

That is

$$\lim_{(\Delta x,0)\to(0,0)} \frac{u(x_0+\Delta x,y_0)-u(x_0,y_0)}{\Delta x} = \lim_{(0,\Delta y)\to(0,0)} \frac{u(x_0,y_0+\Delta y)-u(x_0,y_0)}{\Delta y}$$
$$\lim_{(\Delta x,0)\to(0,0)} \frac{v(x+\Delta x,y_0)-v(x_0,y_0)}{\Delta x} = \lim_{(0,\Delta y)\to(0,0)} \frac{v(x_0,y+\Delta y)-v(x_0,y_0)}{\Delta y}$$

This tells us that the existence of a derivative for a real valued function $F(x)$ does not imply the existence of a derivative for a similar function $f(z)$ in the complex plane, which we will see later. (i.e. Take $f(z) = |z|^2$ and $F(x) = |x|^2$.) We are dealing with a two-dimensional limit instead of a one dimensional limit.

Question. *Under what conditions will differentiability in$\mathbb{C}$ imply differentiability in $\mathbb{R}$, and vice versa?*

Example 13.4.1 *Let $f(z) = \bar{z}$:*

$$\frac{\Delta w}{\Delta z} = \frac{\overline{z+\Delta z} - \bar{z}}{\Delta z} = \frac{\bar{z} + \overline{\Delta z} - \bar{z}}{\Delta z} = \frac{\overline{\Delta z}}{\Delta z}$$

Consider $\Delta z = (\Delta x, \Delta y) \to (0,0)$. If we move on the real axis, that is $(\Delta x, 0)$:

$$\overline{\Delta z} = \overline{\Delta x + i0} = \Delta x - i0 = \Delta x + i0 = \Delta z \implies \frac{\Delta w}{\Delta z} = \frac{\overline{\Delta z}}{\Delta z} = \frac{\Delta z}{\Delta z} = 1$$

If we move on the imaginary axis, that is $(0, \Delta y)$:

$$\overline{\Delta z} = \overline{0 + i\Delta y} = 0 - i\Delta y = -\Delta z \implies \frac{\Delta w}{\Delta z} = \frac{\overline{\Delta z}}{\Delta y} = \frac{-\Delta z}{\Delta z} = -1$$

Limits are unique, so the limit of $\mathrm{d}w/\mathrm{d}z$ does not exist anywhere.

Example 13.4.2 *Consider $f(z) = |z|^2$:*

$$\frac{\Delta w}{\Delta z} = \frac{|z+\Delta z|^2 - |z|^2}{\Delta z} = \frac{(z+\Delta z)(\overline{z+\Delta z}) - z\bar{z}}{\Delta z}$$
$$= \frac{(z+\Delta z)(\bar{z}+\overline{\Delta z}) - z\bar{z}}{\Delta z} = \frac{z\bar{z} + \Delta z\bar{z} + \overline{\Delta z}z + \overline{\Delta z}\Delta z - z\bar{z}}{\Delta z} = \bar{z} + \overline{\Delta z} + z\frac{\overline{\Delta z}}{\Delta z}$$

As in the previous example, as $(\Delta x, \Delta y) \to (0,0)$:

$$\overline{\Delta z} = \Delta z \qquad \text{From the real axis}$$
$$\overline{\Delta z} = -\Delta z \qquad \text{From the imaginary axis}$$

Thus

$$\frac{\Delta w}{\Delta z} = \bar{z} + \Delta z + z \qquad \Delta z = (\Delta x, 0)$$
$$\frac{\Delta w}{\Delta z} = \bar{z} - \Delta z - z \qquad \Delta z = (0, \Delta y)$$

Therefore, by uniqueness of limits as $\Delta z \to 0$:

$$\lim_{\Delta z \to 0}(\bar{z} + \Delta z + z) = \lim_{\Delta z \to 0}(\bar{z} - \Delta z - z) \implies z = -z \implies z = 0$$

Hence, $\mathrm{d}w/\mathrm{d}z$ *does not exist for* $z \neq 0$*. We can also see that:*

$$\frac{\Delta w}{\Delta z} = \bar{z} + \overline{\Delta z} + z\frac{\overline{\Delta z}}{\Delta z} = \overline{\Delta z} \qquad z = 0$$

Thus, $\mathrm{d}w/\mathrm{d}z$ *only exists at* $z = 0$*:*

$$\left.\frac{\mathrm{d}w}{\mathrm{d}z}\right|_{z=0} = 0$$

Remark. *The following are facts:*

(1) A function $f(z)$ can be differentiable at a point z_0, but nowhere else in the neighbourhood of z_0.

(2) $f(z) = |z|^2 \implies u(x,y) = x^2 + y^2 \wedge v(x,y) = 0$, hence $u(x,y)$ and $v(x,y)$ can have continuous partial derivatives of all orders at a point z_0, even though f may not be differentiable at z_0.

(3) $f(z)$ differentiable at $z_0 \implies f(z)$ continuous at z_0

Proof: Assume $f'(z_0)$ exists:

$$\lim_{z \to z_0}[f(z) - f(z_0)] = \lim_{z \to z_0}\frac{f(z) - f(z_0)}{z - z_0}\lim_{z \to z_0}(z - z_0) = f'(z_0) \cdot 0 = 0$$
$$\implies \lim_{z \to z_0} f(z) = f(z_0)$$

So, f is differentiable at $z_0 \implies f$ is continuous at z_0. □

Note: Continuity of a function at $z_0 \in \mathbb{C} \nRightarrow$ existence of derivative at point z_0.

Ex: $f(z) = |z|^2$ is continuous everywhere in $\mathbb{C}$ for $z_0 \neq 0$, but $f(z_0)$ does not exist at z_0.

13.4.1 Differentiation Rules

Definition of derivative in $\mathbb{C}$ (definition 13.4.1) is the same of that in $\mathbb{R}$, so rules remain the same.

Let $c \in \mathbb{C}$ be a constant and functions f and g be differentiable at point z. Then

$$\frac{\mathrm{d}}{\mathrm{d}z}c = 0 \qquad \frac{\mathrm{d}}{\mathrm{d}z}z = 1 \qquad \frac{\mathrm{d}}{\mathrm{d}z}[cf(z)] = cf'(z) \qquad \frac{\mathrm{d}}{\mathrm{d}z}z^n = nz^{n-1} \qquad n \in \mathbb{Z} \setminus \{0\}$$

Let functions f and g be differentiable at point z. Then

$$\frac{\mathrm{d}}{\mathrm{d}z}[f(z) + g(z)] = f'(z) + g'(z) \qquad \frac{\mathrm{d}}{\mathrm{d}z}[f(z)g(z)] = f(z)g'(z) + f'(z)g(z)$$

$$\frac{\mathrm{d}}{\mathrm{d}z}\left[\frac{f(z)}{g(z)}\right] = \frac{g(z)f'(z) - f(z)g'(z)}{[g(z)]^2}$$

Proof: Deriving: $\frac{\mathrm{d}}{\mathrm{d}z}[f(z)g(z)] = f(z)g'(z) + f'(z)g(z)$

Let $w = f(z)g(z)$:

$$\begin{aligned}\Delta w &= f(z + \Delta z)g(z + \Delta z) - f(z)g(z) \\ &= f(z)[g(z + \Delta z) - g(z)] + [f(z + \Delta z) - f(z)]g(z + \Delta z)\end{aligned}$$

Thus

$$\frac{\Delta w}{\Delta z} = f(z)\frac{g(z + \Delta z) - g(z)}{\Delta z} + \frac{f(z + \Delta z) - f(z)}{\Delta z}g(z + \Delta z)$$

Hence

$$\frac{\mathrm{d}w}{\mathrm{d}z} = \lim_{\Delta z \to 0}\frac{\Delta w}{\Delta z} = f(z)g'(z) + f'(z)g(z)$$

□

Theorem 13.4.1: Chain Rule for Composite Functions

Let function f be differentiable at z_0 and function g be differentiable at $f(z_0)$. Then $F(z) = g[f(z)]$ is differentiable at z_0.

$$F'(z_0) = g'[f(z_0)]f'(z_0)$$

Proof: Suppose f is differentiable at z_0. Let $w_0 = f(z_0)$ and assume that $g'(w_0)$ exists. Then

$$\forall w \exists \epsilon [|w - w_0| < \epsilon \implies \Phi(w_0) = 0]$$

Where

$$\Phi(w) = \frac{g(w) - g(w_0)}{w - w_0} - g'(w_0) \qquad w \neq w_0$$

Note: $\lim_{w \to w_0}\Phi(w) = 0$, so Φ is continuous at w_0. Then

$$g(w) - g(w_0) = [g'(w_0) + \Phi(w)](w - w_0) \qquad |w - w_0| < \epsilon$$

Note: This is valid for $w = w_0$.

$$\begin{aligned} f'(z_0) \text{ exists} &\implies f \text{ continuous at } z_0 \\ &\implies \forall \epsilon \exists \delta > 0[|z - z_0| < \delta \implies |w - w_0| < \epsilon] \end{aligned}$$

Hence, we can replace w by $f(z)$ when $|z - z_0| < \delta$. Subbing $w = f(z)$ and $w_0 = f(z_0)$:

$$\frac{g[f(z)] - g[f(z_0)]}{z - z_0} = \{g'[f(z_0)] + \Phi[f(z)]\}\frac{f(z) - f(z_0)}{z - z_0} \qquad 0 < |z - z_0| < \delta,\ z \neq z_0$$

Then

$$(f \text{ continous at } z_0) \land (\Phi \text{ continuoust at } w_0 = f(z_0)) \implies \Phi[f(z)] \text{ continuous at } z_0$$

$$\Phi(w_0) = 0 \implies \lim_{z \to z_0} \Phi[f(z) = 0]$$

Thus

$$\begin{aligned} \lim_{z \to z_0} \frac{g[f(z)] - g[f(z_0)]}{z - z_0} &= \lim_{z \to z_0} \{g'[f(z_0)] + \Phi[f(z)]\}\frac{f(z) - f(z_0)}{z - z_0} \\ &= g'[f(z_0)]f'(z_0) \end{aligned}$$

We then get

$$F'(z_0) = g'[f(z_0)]f'(z_0)$$

□

Alternatively, if we let $w = f(z)$ and $W = F(z)$, then the Chain Rule becomes:

$$\frac{\mathrm{d}W}{\mathrm{d}z} = \frac{\mathrm{d}W}{\mathrm{d}w}\frac{\mathrm{d}w}{\mathrm{d}z}$$

Note: Although this looks like a fraction, it is not a fraction and should not be treated as such! (Logical inconsistency when infinitesimals when viewed as ratios.)

Theorem 13.4.2: L'Hopital's Rule

Suppose $f(z_0) = 0$ and $g(z_0) = 0$, $f'(z_0)$ and $g(z_0)$ exists, with $g'(z_0) \neq 0$. Then

$$\lim_{z \to z_0} \frac{f(z)}{g(z)} = \frac{f'(z_0)}{g'(z_0)}$$

Proof: Let $f(z_0) = 0$, $g(z_0) = 0$, and $z \neq z_0$.

$$\lim_{z \to z_0} \frac{f(z)}{g(z)} = \lim_{z \to z_0} \frac{\frac{f(z) - f(z_0)}{z - z_0}}{\frac{g(z) - g(z_0)}{z - z_0}} = \lim_{\Delta z \to 0} \frac{\frac{f(z_0 + \Delta z) - f(z_0)}{\Delta z}}{\frac{g(z_0 + \Delta z) - g(z_0)}{\Delta z}} = \frac{f'(z_0)}{g'(z_0)}$$

□

13.4.2 Exercises

Example 13.4.3 *Show that $f'(z)$ does not exist for all points $z \in \mathbb{C}$ when:*

(a) $f(z) = \mathrm{Re}\{z\}$

(b) $f(z) = \mathrm{Im}\{z\}$

Proof: Let $f(z) = u(x,y) + iv(x,y)$, $\Delta w = f(x + \Delta x, y + \Delta y) - f(x,y)$.

$\underline{f(z) = \mathrm{Re}\{z\}}$

Recall $\mathrm{Re}\{z\} = x + i0$.

$$\frac{\Delta w}{\Delta z} = \frac{\mathrm{Re}\{z + \Delta z\} - \mathrm{Re}\{z\}}{\Delta z} = \frac{x + \Delta x - x}{\Delta z} = \frac{\Delta x}{\Delta x + \Delta y}$$

Now as $(\Delta x, 0) \to (0,0)$:

$$\lim_{(\Delta x,0)\to(0,0)} \frac{\Delta w}{\Delta z} = \lim_{(\Delta x,0)\to(0,0)} \frac{\Delta x}{\Delta x} = 1$$

Now as $(0, \Delta y) \to (0,0)$:

$$\lim_{(0,\Delta y)\to(0,0)} \frac{\Delta w}{\Delta z} = \lim_{(0,\Delta y)\to(0,0)} \frac{0}{\Delta y} = 0$$

Limits are unique, but this isn't the case, so we conclude that $f'(z)$ when $f(z) = \mathrm{Re}\{z\}$ does not exist.

$\underline{f(z) = \mathrm{Im}\{z\}}$

Recall $\mathrm{Im}\{z\} = 0 + iy$.

$$\frac{\Delta w}{\Delta z} = \frac{\mathrm{Im}\{z + \Delta z\} - \mathrm{Im}\{z\}}{\Delta z} = \frac{y + \Delta y - y}{\Delta z} = \frac{\Delta y}{\Delta x + \Delta y}$$

Now as $(\Delta x, 0) \to (0,0)$:

$$\lim_{(\Delta x,0)\to(0,0)} \frac{\Delta w}{\Delta z} = \lim_{(\Delta x,0)\to(0,0)} \frac{0}{\Delta x} = 0$$

Now as $(0, \Delta y) \to (0,0)$:

$$\lim_{(0,\Delta y)\to(0,0)} \frac{\Delta w}{\Delta z} = \lim_{(0,\Delta y)\to(0,0)} \frac{\Delta y}{\Delta y} = 1$$

Limits are unique, but this isn't the case, so we conclude that $f'(z)$ when $f(z) = \mathrm{Im}\{z\}$ does not exist. $\square$

13.5 Cauchy-Riemann Equations

Theorem 13.5.1: Cauchy-Riemann Equations (Cartesian)
Let $f(z) = u(x, y) + iv(x, y)$. If $f'(z)$ exists at a point $z_0 = x_0 + iy_0$, then $u'(x_0, y_0)$ and $v'(x_0, y_0)$ exists and satisfy Cauchy-Riemann equations:

$$u_x = v_y \qquad\qquad u_y = -v_x$$

Also, as a result of evaluating $f'(z)$ from the horizontal and vertical direction:

$$f'(z_0) = [u_x + iv_x]\Big|_{(x_0,y_0)} = [v_y - iu_y]\Big|_{(x_0,y_0)}$$

Proof: Let $f(z) = u(x, y) + iv(x, y)$, and suppose $f'(z)$ exists at z_0. Then

$$z_0 = x_0 + iy_0 \qquad \Delta z = \Delta x + i\Delta y \qquad \Delta w = f(z_0 + \Delta z) - f(z_0)$$

So that

$$\Delta w = [u(x_0 + \Delta x, y_0 + \Delta y) + iv(x_0 + \Delta x, y_0 + \Delta y)] - [u(x_0, y_0) + iv(x_0, y_0)]$$

Therefore

$$\frac{\Delta w}{\Delta z} = \frac{u(x_0 + \Delta x, y_0 + \Delta y) - u(x_0, y_0)}{\Delta x + i\Delta y} + i\frac{v(x_0 + \Delta x, y_0 + \Delta y) - v(x_0, y_0)}{\Delta x + i\Delta y}$$

Note: This equation remains valid as $(\Delta x, \Delta y) \to (0, 0)$.

Horizontal Approach:

Let $(\Delta x, 0) \to (0, 0)$ in the horizontal direction, then

$$\begin{aligned} f'(z_0) &= \lim_{\Delta x\to 0} \frac{u(x_0 + \Delta x, y_0) - u(x_0, y_0)}{\Delta x} + i \lim_{\Delta x\to 0} \frac{v(x_0 + \Delta x, y_0) - v(x_0, y_0)}{\Delta x} \\ &\Longrightarrow f'(z_0) = u_x(x_0, y_0) + iv_x(x_0, y_0) \end{aligned}$$

Vertical Approach:

Let $(0, \Delta y) \to (0, 0)$ in the vertical direction, then

$$\begin{aligned} f'(z_0) &= \lim_{\Delta y\to 0} \frac{u(x_0, y_0 + \Delta y) - u(x_0, y_0)}{i\Delta y} + i \lim_{\Delta x\to 0} \frac{v(x_0, y_0 + \Delta y) - v(x_0, y_0)}{i\Delta y} \\ &= -i \lim_{\Delta y\to 0} \frac{u(x_0, y_0 + \Delta y) - u(x_0, y_0)}{\Delta y} + \lim_{\Delta x\to 0} \frac{v(x_0, y_0 + \Delta y) - v(x_0, y_0)}{\Delta y} \\ &\Longrightarrow f'(z_0) = v_y(x_0, y_0) - iu_y(x_0, y_0) \end{aligned}$$

Putting it together:

For $f'(z)$ to exists at z_0, $f(z_0)$ from the horizontal approach must equal that of the vertical approach. By equating the real and imaginary parts:

$$\begin{aligned} &u_x(x_0, y_0) + iv_x(x_0, y_0) = v_y(x_0, y_0) - iu_y(x_0, y_0) \\ &\implies (u_x = v_y) \wedge (u_y = -v_x) \end{aligned}$$

□

Theorem 13.5.2: Cauchy-Riemann Equations (Polar)

Let $f(z) = u(r, \theta) + iv(r, \theta)$ be defined in some neighbourhood ϵ of $z_0 = r_0 e^{i\theta_0}$, $z_0 \neq 0$. If the first order partials derivatives of u and v with respect to r and θ exists and are continuous at z_0, and satisfies the polar form of the Cauchy-Riemann equations:

$$ru_r = v_\theta \qquad\qquad u_\theta = -rv_r$$

Then $f'(z_0)$ exists:

$$f'(z_0) = e^{-i\theta}(u_r + iv_r)\Big|_{(r_0, \theta_0)} = \frac{-i}{z_0}(u_\theta + iv_\theta)\Big|_{(r_0, \theta_0)}$$

Proof: Let $f(z) = u(r, \theta) + iv(r, \theta)$. Suppose that the first order partial derivatives of u and v exists in some neighbourhood ϵ of z_0 and is continuous at z_0. By differentiating u with respect to x and y:

$$\frac{\partial u}{\partial r} = \frac{\partial u}{\partial x}\frac{\partial x}{\partial r} + \frac{\partial u}{\partial y}\frac{\partial y}{\partial r} \qquad\qquad \frac{\partial u}{\partial \theta} = \frac{\partial u}{\partial x}\frac{\partial x}{\partial \theta} + \frac{\partial u}{\partial y}\frac{\partial y}{\partial \theta}$$

Likewise for v. As $x = r\cos\theta$ and $y = r\sin\theta$:

$$\begin{aligned} u_r &= u_x \cos\theta + u_y \sin\theta & u_\theta &= -u_x r \sin\theta + u_y r \cos\theta \\ v_r &= v_x \cos\theta + v_y \sin\theta & v_\theta &= -v_x r \sin\theta + v_y r \cos\theta \end{aligned}$$

From theorem 13.5.1 we have:

$$u_x = v_y \qquad\qquad u_y = -v_x$$

Subbing the Cauchy-Riemann equations into v_r and v_θ:

$$\begin{aligned} u_r &= u_x \cos\theta + u_y \sin\theta & u_\theta &= -u_x r \sin\theta + u_y r \cos\theta \\ v_r &= -u_y \cos\theta + u_x \sin\theta & v_\theta &= u_y r \sin\theta + u_x r \cos\theta \end{aligned}$$

We can see that:

$$ru_r = v_\theta \qquad\qquad u_\theta = -rv_r$$

Which are the Cauchy Riemann equations in polar form. Let's verify it without relying on the Cauchy-Riemann equations in Cartesian form:

Recall:

$$u_r = u_x \cos\theta + u_y \sin\theta \qquad u_\theta = -u_x r \sin\theta + u_y r \cos\theta$$
$$v_r = v_x \cos\theta + v_y \sin\theta \qquad v_\theta = -v_x r \sin\theta + v_y r \cos\theta$$

Writing u_r and v_r in matrix notation:

$$\begin{bmatrix} u_r \\ u_\theta \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -r\sin\theta & r\cos\theta \end{bmatrix} \begin{bmatrix} u_x \\ u_y \end{bmatrix}$$

Solving for u_x and u_y:

$$\begin{aligned} \begin{bmatrix} u_x \\ u_y \end{bmatrix} &= \begin{bmatrix} \cos\theta & \sin\theta \\ -r\sin\theta & r\cos\theta \end{bmatrix}^{-1} \begin{bmatrix} u_r \\ u_\theta \end{bmatrix} \\ &= \frac{1}{r\cos^2\theta + r\sin^2\theta} \begin{bmatrix} r\cos\theta & -\sin\theta \\ -r\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u_r \\ u_\theta \end{bmatrix} \qquad \begin{bmatrix} a & b \\ c & d \end{bmatrix}^{-1} = \frac{1}{ad-cb} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix} \\ &= \frac{1}{r} \begin{bmatrix} r\cos\theta & -\sin\theta \\ r\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u_r \\ u_\theta \end{bmatrix} \end{aligned}$$

It is clear that for u_x and u_y, and likewise for v_x and v_y:

$$u_x = u_r \cos\theta - \frac{1}{r} u_\theta \sin\theta \qquad u_y = u_r \sin\theta + \frac{1}{r} u_\theta \cos\theta \tag{13.5}$$
$$v_x = v_r \cos\theta - \frac{1}{r} v_\theta \sin\theta \qquad v_y = v_r \sin\theta + \frac{1}{r} v_\theta \cos\theta \tag{13.6}$$

Using the Cauchy-Riemann equations $u_x = v_y$ and $u_y = -v_x$, we see:

$$u_r \cos\theta - \frac{1}{r} u_\theta \sin\theta = v_r \sin\theta + \frac{1}{r} v_\theta \cos\theta$$
$$u_r \sin\theta + \frac{1}{r} u_\theta \cos\theta = -v_r \cos\theta + \frac{1}{r} v_\theta \sin\theta$$

Clearly, the equations are equal only if

$$r u_r = v_\theta \qquad u_\theta = -r v_r$$

Which are the polar forms of the Cauchy-Riemann equations.

Show $f'(z_0) = e^{-i\theta}(u_r + i v_r)$:

Recall from theorem 13.5.1:

$$f'(z_0) = u_x + i v_y$$

Using eq. (13.5) and eq. (13.6) from before and substituting them into $f'(z_0)$:

$$
\begin{aligned}
f'(z_0) &= \left(u_r\cos\theta - \frac{1}{r}u_\theta\sin\theta + iv_r\cos\theta - \frac{i}{r}v_\theta\sin\theta\right)\bigg|_{(r_0,\theta_0)} \\
&= \left(u_r\cos\theta + v_r\sin\theta + iv_r\cos\theta - iu_r\sin\theta\right)\Big|_{(r_0,\theta_0)} \\
&= \left[u_r(\cos\theta - i\sin\theta) + v_r(\sin\theta + i\cos\theta)\right]\Big|_{(r_0,\theta_0)} \\
&= \left[u_r(\cos\theta - i\sin\theta) + iv_r(\cos\theta - i\sin\theta)\right]\Big|_{(r_0,\theta_0)} \\
&= \left[\left(\frac{e^{i\theta}+e^{-i\theta}}{2} - \frac{e^{i\theta}-e^{-i\theta}}{2}\right)(u_r + iv_r)\right]\bigg|_{(r_0,\theta_0)} \\
&= e^{-i\theta}(u_r + iv_r)\Big|_{(r_0,\theta_0)} \\
&= \frac{-i}{re^{i\theta}}(u_\theta + iv_\theta)\bigg|_{(r_0,\theta_0)} = \frac{-i}{z_0}(u_\theta + iv_\theta)\bigg|_{(r_0,\theta_0)} \qquad (ru_r = v_\theta) \wedge (u_\theta = -rv_r)
\end{aligned}
$$

Thus

$$f'(z_0) = e^{-i\theta}(u_r + iv_r)\Big|_{(r_0,\theta_0)} = \frac{-i}{z_0}(u_\theta + iv_\theta)\bigg|_{(r_0,\theta_0)}$$

$\square$

Question. *When comparing the Cartesian form to the polar form of the Cauchy-Riemann equations:*

$$
\begin{aligned}
&f'(z_0)\ \textit{exists} \implies \forall z_0[(u_x = v_y) \wedge (u_y = -v_x)] \\
&(z_0 \neq 0) \wedge \forall z_0[(ru_r = v_\theta) \wedge (u_\theta = -rv_r)] \implies f'(z_0)\ \textit{exists}
\end{aligned}
$$

Should both be $\iff$ *instead of* $\implies$*? No, satisfying Cauchy-Riemann equations does not guarantee differentiability at a point as we will see in example 13.5.3. However, satisfying certain conditions allows allows differentiability to exist (theorem 13.5.4).*

Example 13.5.1 (Solving the $f'(z)$ using the partial derivative with respect to one variable) *Recall in theorem 13.5.1:*

$$f'(z_0) = [u_x + iv_x]\Big|_{(x_0,y_0)} = [v_y - iu_y]\Big|_{(x_0,y_0)}$$

This implies we can solve $\mathrm{d}f(z)/\mathrm{d}z$ *by taking the partial of* $f(z)$ *with respect to* x *or* y*. Consider* $f(z) = z^2$*:*

$$f(z) = z^2 = x^2 - y^2 + i2xy$$

We then have:

$$u(x,y) = x^2 - y^2 \qquad\qquad v(x,y) = 2xy$$

Hence

$$u_x = 2x = v_y \qquad\qquad u_y = -2y = -v_x$$

Thus

$$f'(z) = 2x + i2y = 2(x + iy) = 2z$$

Example 13.5.2 (Using Cauchy-Riemann equations to find where $f(z)$ is not differentiable) *Using the contrapositive of $f'(z_0)$ exists $\implies \exists u' \exists v' [(u_x = v_y) \wedge (u_y = -v_x)]$:*

$$\exists z_0 [(u_x \neq v_y) \vee (u_y \neq -v_x)] \implies f(z) \text{ not differentiable at } z_0$$

Consider $f(z) = |z|^2$:

$$u(x,y) = x^2 + y^2 \qquad\qquad v(x,y) = 0$$

By Cauchy-Riemann:

$$2x = 0 \qquad\qquad 2y = 0$$

Therefore, $f'(z)$ only exists at $(0,0)$ and does not exist elsewhere.

Note: Theorem 13.5.1 does not guarantee the existence of $f'(z)$ at z_0.

Example 13.5.3 ($f(z)$ satisfy Cauchy-Riemann equations at (0,0), but $f'(0)$ does not exist) *Consider*

$$f(z) = \begin{cases} \bar{z}^2/z & z \neq 0 \\ 0 & z = 0 \end{cases}$$

Then

$$u(x,y) = \frac{x^3 - 3xy^2}{x^2 + y^2} \qquad v(x,y) = \frac{y^3 - 3x^2 y}{x^2 + y^2} \qquad (x,y) \neq (0,0)$$

Checking differentiability at $(0,0)$, note $u(0,0) = 0$ and $v(0,0) = 0$:

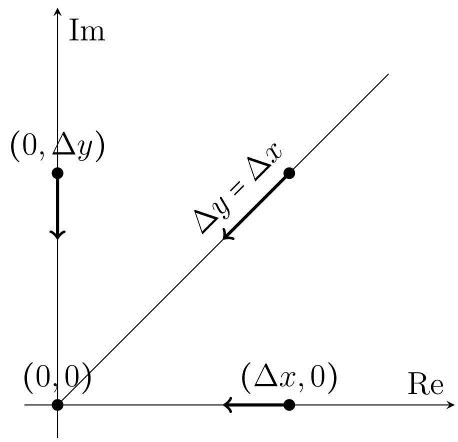
$$\begin{aligned}
u_x(0,0) &= \lim_{\Delta x \to 0} \frac{u(0 + \Delta x, 0) - u(0,0)}{\Delta x} = \lim_{\Delta x \to 0} \frac{\Delta x}{\Delta x} = 1 \\
v_y(0,0) &= \lim_{\Delta y \to 0} \frac{v(0, 0 + \Delta y) - v(0,0)}{\Delta y} = \lim_{\Delta y \to 0} \frac{\Delta y}{\Delta y} = 1 \\
u_y(0,0) &= \lim_{\Delta y \to 0} \frac{u(0, 0 + \Delta y) - u(0,0)}{\Delta y} = \lim_{\Delta y \to 0} \frac{0/(\Delta y)^2}{\Delta y} = 0 \\
v_x(0,0) &= \lim_{\Delta x \to 0} \frac{v(0 + \Delta x, 0) - v(0,0)}{\Delta x} = \lim_{\Delta x \to 0} \frac{0/(\Delta x)^2}{\Delta x} = 0
\end{aligned}$$

We can see that the Cauchy-Riemann equations are satisfied:

$$u_x = v_y = 1 \qquad\qquad u_y = -v_x = 0$$

However, $f'(0)$ does not exist: (Brown and Churchill - Complex Variables and Applications, Section 20, Exercise 9 [2])

Let $\Delta w = f(z+\Delta z) - f(z)$. We need to show for all nonzero points on the real and imaginary axis, $\Delta w/\Delta z = -1$, but for all nonzero points on the line $\Delta x = \Delta y$, $\Delta w/\Delta z = -1$. Hence, a contradiction, so $f('0)$ does not exist.



$$\frac{\Delta w}{\Delta z} = \frac{f(z+\Delta z) - f(z)}{\Delta z} = \frac{u(x+\Delta x, y+\Delta y) + v(x+\Delta x, y+\Delta y)}{\Delta x + \Delta y} - \frac{u(x,y) + v(x,y)}{\Delta x + \Delta y}$$

Along the real axis:

Evaluating along $(\Delta x, 0) \to (0,0)$.

$$\begin{aligned}\lim_{(\Delta x,0)\to(0,0)} \frac{\Delta w}{\Delta z} &= \frac{u(\Delta x, 0) + v(\Delta x, 0)}{\Delta x} - \frac{u(0,0) + v(0,0)}{\Delta x} \\ &= \frac{1}{\Delta x}\left[\frac{(\Delta x)^3}{(\Delta x)^2} + \frac{0}{(\Delta x)^2}\right] - 0 = \frac{\Delta x}{\Delta x} = 1\end{aligned}$$

Along the imaginary axis:

Evaluating along $(0, \Delta y) \to (0,0)$.

$$\begin{aligned}\lim_{(0,\Delta y)\to(0,0)} \frac{\Delta w}{\Delta z} &= \frac{u(0, \Delta y) + v(0, \Delta y)}{\Delta y} - \frac{u(0,0) + v(0,0)}{\Delta y} \\ &= \frac{1}{\Delta y}\left[\frac{0}{(\Delta y)^2} + \frac{(\Delta y)^3}{(\Delta y)^2}\right] - 0 = \frac{\Delta y}{\Delta y} = 1\end{aligned}$$

Along the axis $\Delta x = \Delta y$:

Evaluating along $(\Delta x, \Delta x) \to (0,0)$.

$$\lim_{(\Delta x,\Delta x)\to(0,0)} \frac{\Delta w}{\Delta z} = \frac{u(\Delta x,\Delta x)}{\Delta x + \Delta x} - \frac{u(0,0)+v(0,0)}{\Delta x + \Delta x}$$
$$= \frac{1}{2\Delta x}\left[\frac{(\Delta x)^3 - 3(\Delta x)^3}{2(\Delta x)^2} + \frac{(\Delta x)^3 - 3(\Delta x)^3}{2(\Delta x)^2}\right]$$
$$= \frac{1}{2\Delta x}\left[-\frac{2(\Delta x)^3}{2(\Delta x)^2} - \frac{2(\Delta x)^3}{2(\Delta x)^2}\right] = \frac{1}{2\Delta x}\left[-\Delta x - \Delta x\right] = -\frac{2\Delta x}{2\Delta x} = -1$$

As we can see, the limits are not unique regardless of the path we take to approach $(0,0)$, hence $f'(0)$ does not exist. Therefore, an equation can satisfy the Cauchy-Riemann equations at $0,0$, yet have a derivative that does not exist. The Cauchy-Riemann equations does not guarantee differentiability at z_0.

Example 13.5.4 *(Any branch of $f(z) = z^{1/2}$ is differentiable everywhere in domain of definition) Let*

$$f(z) = z^{1/2} = \sqrt{r}e^{i\theta} \qquad\qquad r > 0,\ \alpha < \theta < \alpha + 2\pi$$

Hence

$$u(r,\theta) = \sqrt{r}\cos\left(\frac{\theta}{2}\right) \qquad\qquad v(r,\theta) = \sqrt{r}\sin\left(\frac{\theta}{2}\right)$$

By Cauchy-Riemann:

$$ru_r = \frac{\sqrt{r}}{2}\cos\left(\frac{\theta}{2}\right) = v_\theta \qquad\qquad u_\theta = -\frac{\sqrt{r}}{2}\sin\left(\frac{\theta}{2}\right) = -rv_r$$

Thus, the derivative exists wherever $f(z)$ is defined. Also, by theorem 13.5.2:

$$f'(z) = e^{i\theta}(u_r + iv_r)\Big|_{(r_0,\theta_0)}$$
$$= e^{-i\theta}\left[\frac{1}{2\sqrt{r}}\cos\left(\frac{\theta}{2}\right) + i\frac{1}{2\sqrt{r}}\sin\left(\frac{\theta}{2}\right)\right] = \frac{1}{2\sqrt{r}}e^{-i\theta}\left[\cos\left(\frac{\theta}{2}\right) + i\sin\left(\frac{\theta}{2}\right)\right]$$
$$= \frac{1}{2\sqrt{r}e^{i\theta/2}} = \frac{1}{2f(z)} = \frac{1}{2}z^{-1/2}$$

13.5.1 Complex Form of the Cauchy-Riemann Equations

Theorem 13.5.3: Cauchy-Riemann Equation (Complex Form)
Let $f(z) = u(x,y) + iv(x,y)$. If the first order partial derivatives of u and v with respect to x and y exists and satisfy the Cauchy-Riemann equations. Then

$$\frac{\partial}{\partial \bar{z}} f(z) = 0$$

Proof: Recall:

$$x = \frac{z + \bar{z}}{2} \qquad\qquad y = \frac{z - \bar{z}}{2i}$$

Let F be a real valued function, that is $x, y \in \mathbb{R}$. Then

$$\frac{\partial F}{\partial \bar{z}} = \frac{\partial F}{\partial x}\frac{\partial x}{\partial \bar{z}} + \frac{\partial F}{\partial y}\frac{\partial y}{\partial \bar{z}}$$

Substituting $\frac{\partial x}{\partial \bar{z}} = 1/2$ and $\frac{\partial y}{\partial \bar{z}} = i/2$:

$$\frac{\partial F}{\partial \bar{z}} = \frac{1}{2}\left(\frac{\partial F}{\partial x} + i\frac{\partial F}{\partial y}\right)$$

Define the operator:

$$\frac{\partial}{\partial \bar{z}} = \frac{1}{2}\left(\frac{\partial}{\partial x} + i\frac{\partial}{\partial y}\right)$$

Then

$$\begin{aligned}\frac{\partial f}{\partial \bar{z}} &= \frac{1}{2}\left(\frac{\partial f}{\partial x} + i\frac{\partial f}{\partial y}\right) = \frac{1}{2}\left(\frac{\partial u}{\partial x} + i\frac{\partial v}{\partial x} + i\frac{\partial u}{\partial y} - \frac{\partial v}{\partial y}\right)\\ &= \frac{1}{2}\left[(u_x - v_y) + i(u_y + v_x)\right]\end{aligned}$$

We can see that if $\frac{\partial f}{\partial \bar{z}}$ satisfies the Cauchy-Riemann equations (theorem 13.5.1):

$$\frac{\partial}{\partial \bar{z}} f(z) = 0 \qquad\qquad \frac{\partial}{\partial x} f = -i\frac{\partial f}{\partial y} \implies i\frac{\partial}{\partial x} f = \frac{\partial f}{\partial y}$$

□

13.5.2 Conditions for Differentiability

Theorem 13.5.4:

Let $f(z) = u(x, y) + iv(x, y)$ be defined in some neighbourhood ϵ of point $z_0 = x_0 + iy_0$. Consider the first order partial derivatives of u and v with respect to x and y. If they

(1) Exist for all z, $|z - z_0| < \epsilon$.

(2) Are continuous at z_0.

(3) Satisfies the Cauchy-Riemann equations at z_0.

Then $f'(z_0)$ exists:

$$f'(z_0) = (u_x + iv_x)\Big|_{(x_0, y_0)}$$

Proof: Assume the first order partial derivatives of u and v with respect to x and y exists $\forall z[|z - z_0| < \epsilon]$, are continuous at z_0, and satisfies the Cauchy-Riemann equations. Let $\Delta z = \Delta x + i\Delta y$, $0 < |\Delta z| < \epsilon$, and $\Delta w = f(z_0 + \Delta z) - f(z_0)$. We then have

$$\Delta w = \Delta u + i\Delta v$$

Where

$$\begin{aligned}\Delta u &= u(x_0 + \Delta x, y_0 + \Delta y) - u(x_0, y_0)\\ \Delta v &= v(x_0 + \Delta x, y_0 + \Delta y) - v(x_0, y_0)\end{aligned}$$

Since first order partials of u and v are continuous at z_0:

$$\begin{aligned}\Delta u &= u_x(x_0, y_0)\Delta x + u_y(x_0, y_0)\Delta y + \epsilon_1\Delta x + \epsilon_2\Delta y\\ \Delta v &= v_x(x_0, y_0)\Delta x + v_y(x_0, y_0)\Delta y + \epsilon_3\Delta x + \epsilon_4\Delta y\end{aligned}$$

$$(\epsilon_1, \epsilon_2, \epsilon_3, \epsilon_4) \to (0, 0, 0, 0) \text{ as } (\Delta x, \Delta y) \to (0, 0)$$

Substituting Δu and Δv into Δw:

$$\begin{aligned}\Delta w =& u_x(x_0, y_0)\Delta x + u_y(x_0, y_0)\Delta y + \epsilon_1\Delta x + \epsilon_2\Delta y\\ &+ i[v_x(x_0, y_0)\Delta x + v_y(x_0, y_0)\Delta y + \epsilon_3\Delta x + \epsilon_4\Delta y]\end{aligned}$$

Using the Cauchy-Riemann equations and dividing by Δz:

$$\frac{\Delta w}{\Delta z} = u_x(x_0, y_0) + iv_x(x_0, y_0) + (\epsilon_1 + i\epsilon_3)\frac{\Delta x}{\Delta z} + (\epsilon_2 + i\epsilon_4)\frac{\Delta y}{\Delta z}$$

From the inequalities $|\Delta x| \leq |\Delta z|$ and $|\Delta y| \leq |\Delta z|$:

$$\left|\frac{\Delta x}{\Delta z}\right| \leq 1 \qquad\qquad \left|\frac{\Delta y}{\Delta z}\right| \leq 1$$

So

$$\begin{aligned}\left|(\epsilon_1 + i\epsilon_3)\frac{\Delta x}{\Delta z}\right| &\leq |\epsilon_1 + i\epsilon_3| \leq |\epsilon_1| + |\epsilon_3|\\ \left|(\epsilon_2 + i\epsilon_4)\frac{\Delta y}{\Delta z}\right| &\leq |\epsilon_2 + i\epsilon_4| \leq |\epsilon_2| + |\epsilon_4|\end{aligned}$$

Then $|\epsilon_2| + |\epsilon_4| \to 0$ and $|\epsilon_1| + |\epsilon_3| \to 0$ as $\Delta z = \Delta x + i\Delta y \to 0$.

$$\implies \frac{\Delta w}{\Delta z} = u_x(x_0, y_0) + iv_x(x_0, y_0) \implies f'(z_0) \text{ exists}$$

$\square$

Example 13.5.5 (All 3 conditions must be satisfied for $f'(z_0)$ to exist) *Do not use expression of $f'(z)$ before existence of $f'(z_0)$ is established. Consider $f(z) = x^3 + i(1 - y)^3$.*

$$u(x, y) = x^3 \qquad\qquad v(x, y) = (1 - y)^3$$

Taking the partial derivatives:

$$u_x = 3x^2 \qquad v_x = 0$$
$$u_y = 0 \qquad v_y = -3(1-y)^2$$

It would be foolish to ignore Cauchy-Riemann and directly use:

$$f'(z) = u_x + iv_x = 3x^2$$

We can see that the Cauchy-Riemann equations are satisfied only if:

$$3x^2 = -3(1-y)^2 \implies x^2 + (1-y)^2 = 0 \implies (x=0) \wedge (y=1)$$

Therefore, $f'(z)$ exists only if $z = i$, and that $f'(i) = 0$

13.6 Analytic Functions

Definition 13.6.1: Analytic/Regular/Holomorphic

Let S be an open set, $S \subset \mathbb{C}$. Let f be a function.

$$f \text{ is analytic in } S \iff \forall z \in S[f'(z) \text{ exists }]$$

We say $f(z)$ is analytic at a point z_0 if it is analytic in some neighbourhood of z_0. If we say that $f(z)$ is analytic in a closed set S' then we mean that it is analytic in an open set S where $S' \subset S$.

Definition 13.6.2: Entire

A function $f(z)$ is entire if it is analytic at all points in the plane.

Example 13.6.1

$$\text{Derivative of polynomial exists everywhere} \implies \text{All polynomials are entire functions}$$

See section 13.5.2 for conditions for a function te be differentiable, hence analytic in a set S.

Corollary 13.6.0.1:

Let $f(z)$ and $g(z)$ be analytic in a domain D. Then the following are analytic in D:

$$f(z) + g(z)$$
$$f(z)g(z)$$
$$\frac{f(z)}{g(z)} \qquad g(z) \neq 0 \forall z \in D$$

Likewise, if $P(z)$ and $Q(z)$ are polynomials, then $P(z)/Q(z)$ is analytic if $\forall z \in D[Q(z) \neq 0]$.

Corollary 13.6.0.2:

Let w be the image of D under $f(z)$ and w be the domain of g. Then $g(f(z))$ is analytic in D and

$$\frac{\mathrm{d}}{\mathrm{d}z} g[f(z)] = g'[f(z)]f'(z)$$

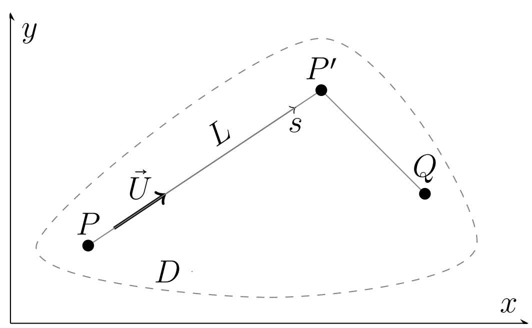
Theorem 13.6.1:

Let D be the domain of a function $f(z)$.

$$\forall z \in D[f'(z) = 0] \implies f(z) \text{ is constant in } D$$

Proof: Let $f(z) = u(x, y) + iv(x, y)$ with domain D, and P, P', and Q be points in D. Let $\vec{U}$ be the unit vector on the line segment L connecting P and P', and s be the distance along L.

$$f'(z) = 0 \implies \forall z \in D[u_x = u_y = v_x = v_y = 0]$$



We know that the directional derivative:

$$\frac{\mathrm{d}u}{\mathrm{d}s} = \nabla u \cdot \vec{U} \qquad\qquad \nabla u = u_x\hat{i} + u_y\hat{j}$$

Previously, $u_x = u_y = 0$, so for all points on L:

$$u_x = u_y = 0 \implies \nabla u = 0 \implies \frac{\mathrm{d}u}{\mathrm{d}s} = 0 \implies u \text{ constant on } L$$

Now, that we have established that u is constant on any given line L in D, we can see that since D is simply connected and there are finitely many lines connecting P and Q, the values of u at P and Q must be equal and constant. Hence, $\exists a \in \mathbb{R}$ such that $u(x, y) = a$ in D. Likewise, $v(x, y) = b$ in D. Thus

$$f(z) = a + bi = c \qquad\qquad c \text{ is constant}$$

□

Definition 13.6.3: Singular Point

Let ϵ be a neighbourhood of point z_0, and $f(z)$ be a function. z_0 is a singular point if $f'(z_0)$ does not exist, but $f(z)$ is differentiable in all neighbourhoods of z_0.

13.6.1 Examples

Example 13.6.2 (Determining analyticity using Cauchy-Riemann equations) *Consider* $f(z) = \sin(x)\cosh(y) + i\cos(x)\sinh(y)$.

$$u(x,y) = \sin(x)\cosh(y) \qquad\qquad v(x,y) = \cos(x)\sinh(y)$$

Cauchy-Riemann:

$$u_x = \cos(x)\cosh(y) = v_y \qquad\qquad u_y = \sin(x)\sinh(y) = -v_x$$

Therefore, it is clear that $f(z)$ *is entire.*

$$f'(z) = u_x + iv_x = \cos(x)\cosh(y) - i\sin(x)\sinh(y)$$

Another application of Cauchy-Riemann see that $f'(z)$ *is also entire.*

Example 13.6.3 ($f(z)$ and $\overline{f(z)}$ is analytic in $D \implies f(z)$ is constant in D) *Let*

$$f(z) = u(x,y) + iv(x,y) \qquad\qquad \overline{f(z)} = u(x,y) - iv(x,y) = U(x,y) + iV(x,y)$$

Because of $f(z)$ *and* $\overline{f(z)}$ *is analytic in* D*, the Cauchy-Riemann equations hold:*

$$\begin{aligned} u_x &= v_y & \qquad\qquad u_y &= -v_x \\ U_x &= V_y & \qquad\qquad U_y &= -V_x \end{aligned}$$

We can see that:

$$u_x = -v_y = v_y \qquad\qquad u_y = v_x = -v_x$$

Hence, $u_x = 0$ *and* $v_x = 0$*, then we can conclude*

$$f'(z) = 0 \implies f(z) \text{ is constant in } D$$

Example 13.6.4 ($f(z)$ is analytic in D and $|f(z)|$ is constant in $D \implies f(z)$ is constant in D) *Let* $\forall z \in D[|f(z)| = c]$*, where* c *is a constant. It is easy to see that* $c = 0 \implies \forall z \in D[f(z) = 0]$*, so consider* $c \neq 0$*. Then*

$$f(z)\overline{f(z)} = c^2 \neq 0 \implies \forall z \in D[f(z) \neq 0]$$

Thus

$$\overline{f(z)} = \frac{c^2}{f(z)} \qquad \forall z \in D$$

Hence $\overline{f(z)}$ *is analytic everywhere in* D*, so* $f(z)$ *is constant in* D*.*

13.7 Harmonic Functions

Harmonic functions are functions where the curvature in each component direction cancels each other out.

Definition 13.7.1: Laplace's Equation

Let $F(x,y)$ be a real-valued function. That is $x, y \in \mathbb{R}$. Laplace's equation:

$$\frac{\partial^2}{\partial x^2}F + \frac{\partial^2}{\partial y^2}F = 0$$

In polar form:

$$r^2 u_{rr}(r,\theta) + r u_r(r,\theta) + u_{\theta\theta}(r,\theta) = 0$$
$$r^2 v_{rr}(r,\theta) + r v_r(r,\theta) + v_{\theta\theta}(r,\theta) = 0$$

See example 13.7.1

Definition 13.7.2: Harmonic

A real-valued function $F(x,y)$ is harmonic in the xy-plane if it satisfies Laplace's equation.

Theorem 13.7.1:

Let D be the domain of a function $f(z) = u(x,y) + iv(x,y)$.

$$f(z) \text{ is analytic in } D \implies u(x,y) \wedge v(x,y) \text{ are harmonic in } D$$

Proof: f is analytic in D, so its component functions must satisfy the Cauchy-Riemann equations:

$$(u_x = v_y) \wedge (u_y = -v_x) \implies (u_{xy} = v_{yy}) \wedge (u_{yx} = -v_{xx})$$
$$(u_x = v_y) \wedge (u_y = -v_x) \implies (u_{xx} = v_{yx}) \wedge (u_{yy} = -v_{xy})$$

Now, we know from calculus that $u_{xy} = u_{yx}$ and $v_{yx} = v_{xy}$, so we conclude

$$u_{xx} + u_{yy} = 0 \qquad\qquad v_{xx} + v_{yy} = 0$$

□

Note: The converse ($\impliedby$) is true for simply connected domains, hence, theorem 13.7.1 becomes $\iff$ in simply connected domains. (R, Boas - Invitation to Complex Analysis. (1987) Section 19.)

Corollary 13.7.1.1:

Let $F(x,y)$ is a real-valued function in a simply connected domain D. Then there exists a function $f(z)$ and $g(z)$ in D such that $f(z) = F(x,y) + iv(x,y)$ and $g(z) = u(x,y) + iF(x,y)$. That is, there exists a function where the real part equals F and a function where the imaginary part equals F.

Definition 13.7.3: Harmonic Conjugate

If $f(z) = u(x,y) + iv(x,y)$ is analytic in a domain D, then $v(x,y)$ is the harmonic conjugate of $v(x,y)$. This is not to be confused with the complex conjugate.

Example 13.7.1 *Let $f(z) = u(r,\theta) + iv(r,\theta)$ be analytic in domain $D' = D \setminus \{0\}$. Show $u(r,\theta)$ and $v(r,\theta)$ satisfies the polar form of Laplace's equation.*

Proof: We know from the Polar form of the Cauchy-Riemann equation:

$$ru_r = v_\theta \qquad\qquad u_\theta = -rv_r$$

Operating by $r\,\partial/\partial r$ and $\partial/\partial\theta$, we obtain:

$$\begin{aligned}
r\frac{\partial}{\partial r}ru_r &= ru_r + r^2u_{rr} = rv_{\theta r} \\
r\frac{\partial}{\partial r}u_\theta &= ru_{\theta r} = r\frac{\partial}{\partial r}(-rv_r) = -rv_r - r^2v_{rr} \\
\frac{\partial}{\partial\theta}ru_r &= ru_{\theta r} = v_{\theta\theta} \\
\frac{\partial}{\partial\theta}u_\theta &= u_{\theta\theta} = -rv_{r\theta}
\end{aligned}$$

We can see that

$$\begin{cases} ru_r + r^2u_{rr} = -u_{\theta\theta} \\ rv_r + r^2v_{rr} = -v_{\theta\theta} \end{cases} \implies \begin{cases} r^2u_{rr} + ru_r + u_{\theta\theta} = 0 \\ r^2v_{rr} + rv_r + v_{\theta\theta} = 0 \end{cases}$$

$\square$

Example 13.7.2 *Let $f(z) = u(x,y)+iv(x,y)$ be analytic in domain D. Consider the families of level curves $u(x,y) = c_1$ and $v(x,y) = c_2$, with $c_1, c_2 \in \mathbb{R}$ being constants. Show for $z_0 = (x_0, y_0) \in \mathbb{C}$ common to $u(x,y) = c_1$ and $v(x,y) = c_2$ and $f'(z_0) \neq 0$, then the lines tangent to $u(x,y) = c_1$ and $v(x,y) = c_2$ at z_0 are orthogonal.*

Note:

$$[u(x,y) = c_1] \wedge [v(x,y) = c_2] \implies \left(\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y}\frac{\mathrm{d}y}{\mathrm{d}x} = 0\right) \wedge \left(\frac{\partial v}{\partial x} + \frac{\partial v}{\partial y}\frac{\mathrm{d}y}{\mathrm{d}x} = 0\right)$$

Proof: The tangent lines of $u(x,y)$ and $v(x,y)$ are

$$\nabla u = \left(\frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}\right) = (u_x, u_y) \qquad\qquad \nabla v = \left(\frac{\partial v}{\partial x}, \frac{\partial v}{\partial y}\right) = (v_x, v_y)$$

Taking the dot product, and applying the Cauchy-Riemann equations:

$$u_xv_x + u_yv_y = u_x(-u_y) + u_y(u_x) = 0$$

Hence, $u(x,y)$ and $v(x,y)$ are orthogonal.

Note:

$$f'(z_0) = 0 \implies u_x + iv_x = 0 \implies v_y - iu_y = 0$$
$$\implies u_x = u_y = v_x = v_y = 0$$

Hence, we can see that $f'(z_0) = 0$ is required for $u(x,y)$ and $v(x,y)$ to exist and be orthogonal. □

13.8 Uniquely Determined Analytic Functions

Lemma 13.8.0.1:
Suppose a function f is analytic throughout domain D, and $f(z) = 0$ $\forall z \in D' \subset D$ or line segment contained in D. Then $f(z) \equiv 0$ throughout D.

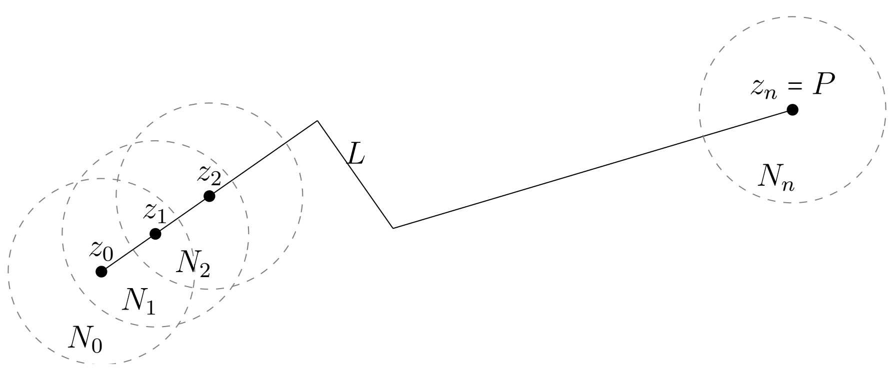
Proof: Let f be a function analytic in domain D and $f(z) = 0$ for all point or line segment in D. Let z_0 in the subdomain of D or on a line segment in D.

D is connected open set, so there is a polygonal line L jointing any point P in D to z_0 lying entirely in D. (Recall: A polygonal line consists of a finite number of lines connected end-to-end.) Let d be the shortest distance from points on L to the boundary on D, so $d > 0$, unless D is the entire plane. Then there is a sequence of points along L:

$$\{z_0, z_1, z_2, \ldots, z_{n-1}, z_n = P\} \qquad |z_k - z_{k+1}| < d \qquad k \in \mathbb{N}$$

That is, each point is sufficiently close to each other. We construct neighbourhoods of each point with radius d, all of which are in D, so points z_{k-1} and z_{k+1} lie in the neighbourhood of z_k, $k \in \mathbb{N}$:

$$\{N_0, N_1, N_2, \ldots, N_{n-1}, N_n\}$$



Now as f is analytic in N_0 and $f(z) = 0$ in a domain or line segment containing z_0, then $f(z) \equiv 0$ in N_0. z_1 is in N_0, so $f(z_0) \equiv 0$ in N_1. Continuing this we can see that $f(z_n) \equiv 0$ in N_n, hence, $f(z) \equiv 0$ in D. □

Theorem 13.8.1:

Let f be analytic in domain D. Then it's uniquely determined over D by its values in D or along a line segment in D.

Proof: Let functions f and g be analytic in some domain D, and $f(z) = g(z)$ $\forall z \in D$. Then $h(z) = f(z) - g(z))$ is also analytic in D, and $h(z) = 0$ in the subdomain or along the line segment, so $h(z) \equiv 0$ throughout D. $\square$

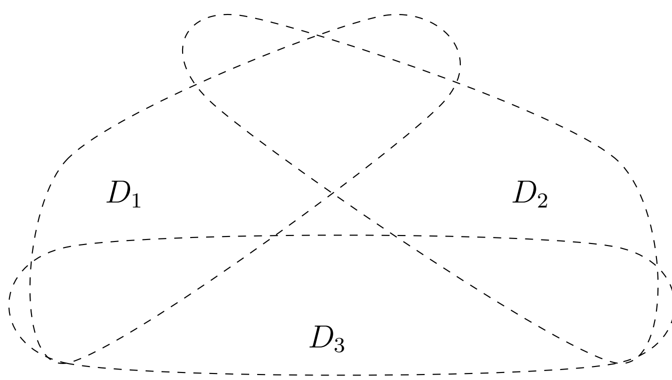
Theorem 13.8.2: Coincidence Principle

If functions f and g are analytic in D and $f(z) = g(z)$ in $D' \subset D$ with limit point $z_0 \in D$, then $f(z) = g(z)$ everywhere in D.

This is a more generalized version of theorem 13.8.1

Definition 13.8.1: Analytic continuation

Consider the domains D_1 and D_2 with intersection $D_1 \cap D_2$, and functions f_1 and f_2. If f_1 is analytic in D_1, and there exists f_2 that is analytic in D_2 such that $f_1(z) = f_2(2)$ for all $z \in D_1 \cap D_2$. Then f_2 is the analytic continuation of f_1.



Theorem 13.8.1 tells us that if such analytic continuation exists, then it is unique. Now if there exists f_3 in D_3 that is an analytic continuation of f_2, then it is not necessarily true that $f_3(z) = f_1(z)$ for all $z \in D_1 \cap D_3$. (See example 13.8.1.)

Definition 13.8.2: Elements of a function

Let f_2 be the analytic continuation of a function f_1 in D_1 into domain D_2, and let $F(z)$ be analytic in $D_1 \cup D_2$.

$$F(z) = \begin{cases} f_1(z) & z \in D_1 \\ f_2(z) & z \in D_2 \end{cases}$$

Then F is the analytic continuation of f_1 and f_2 into $D_1 \cup D_2$, and f_1 and f_2 are elements of F.

13.8.1 Reflection Principle

Generally, $\overline{f(z)} \neq f(\bar{z})$ for all z, but....

Theorem 13.8.3: Reflection Principle

Let f be a function with domain D containing a segment of the real axis $R \subset D$. Then

$$\forall z \in D[\overline{f(z)} = f(\bar{z})] \iff \forall x \in R[f(x) \in \mathbb{R}]$$

See example 13.8.2 for the case when $f(x)$ is purely imaginary.

Proof: Let $f(z)$ and $F(z)$ be analytic functions:

$$f(z) = u(x,y) + iv(x,y) \qquad\qquad F(z) = U(x,y) + iV(x,y)$$

$\underline{(\Longleftarrow):}$

Suppose $\forall x \in R[f(x) \in \mathbb{R}]$, and that $F(z) = \overline{f(\bar{z})}$.

$$f(z) = u(x,y) + iv(x,y) \qquad\qquad F(z) = U(x,y) + iV(x,y)$$

Then

$$\overline{f(\bar{z})} = u(x,-y) - iv(x,-y)$$

Therefore

$$U(x,y) = u(x,t) \qquad\qquad V(x,y) = -v(x,t) \qquad\qquad t = -y$$

$f(x,t)$ is analytic, so it satisfies the Cauchy-Riemann equations:

$$u_x = v_t \qquad\qquad u_t = -v_x$$

Hence

$$U_x = u_x \qquad\qquad V_y = -v_t \frac{\mathrm{d}t}{\mathrm{d}y} = v_t$$

$$U_y = u_t \frac{\mathrm{d}t}{\mathrm{d}y} = -u_t \qquad\qquad V_x = -v_x$$

Thus, we can see that $F(z)$ also satisfies the Cauchy Riemann equations

$$U_x = V_y \qquad\qquad U_y = -V_x$$

Since, the partial derivatives of U and V are continuous in D, we can say hat $F(z)$ is analytic in D. On the segment of the real axis $R \subset D$, $f(z)$ is real, so $v(x,0) = 0$.

$$\begin{aligned} F(x) = U(x,0) + iV(x,0) &= u(x,0) - iv(x,0) = u(x,0) \\ &\Longrightarrow \forall z \in R[F(z) = f(z)] \\ &\Longrightarrow \forall z \in D[\overline{f(\bar{z})} = f(z)] \qquad\qquad \textit{Theorem } 13.8.1 \end{aligned}$$

$\underline{(\implies):}$

Suppose $\overline{f(z)} = f(\bar{z})$. Then

$$u(x,-y) - iv(x,-y) = u(x,y) + iv(x,y)$$

Consider any point $(x,0) \in R \subset D$:

$$u(x,0) - iv(x,0) = u(x,0) + iv(x,0) \implies v(x,0) = 0$$

Hence, $f(x)$ is real $\forall x \in R \subset D$. $\square$

Theorem 13.8.3 tells us that if a complex function is real for all points on the real axis, then it will obey the Reflection Principle, and vice versa.

13.8.2 Examples

Example 13.8.1 *Consider*

$$\begin{aligned}
f_1(z) &= \sqrt{r}e^{i\theta/2} && r > 0,\ 0 < \theta < \pi \\
f_2(z) &= \sqrt{r}e^{i\theta/2} && r > 0,\ \frac{\pi}{2} < \theta < 2\pi \\
f_3(z) &= \sqrt{r}e^{i\theta/2} && r > 0,\ \pi < \theta < \frac{5\pi}{2}
\end{aligned}$$

It is clear that $f_1,\ f_2,\ f_3$ are continuous and satisfies the Cauchy-Riemann equations throughout their domain of definition, since they have a derivative everywhere in their domain of definition. Hence, they are analytic continuations of each other. Let $D_1,\ D_2,$ and D_3 be the domains of $f_1,\ f_2,$ and f_3, respectively. Consider f_1 and f_3 in the domain $D_1 \cap D_3$, and any z in the first quadrant of the complex plane. Then $z = re^{i\theta} = re^{i(\theta+2\pi)}$ and we have

$$\begin{aligned}
f_1(z) &= \sqrt{r}e^{i(\theta/2)} && 0 < \theta < \pi \\
f_3(z) &= \sqrt{r}e^{i(\theta/2+\pi)} && 0 < \theta < \pi
\end{aligned}$$

Hence,

$$\begin{aligned}
f_1(z) &= \sqrt{r}[\cos(\theta/2) + i\sin(\theta/2)] && 0 < \theta < \pi \\
f_3(z) &= \sqrt{r}[\cos(\theta/2+\pi) + i\sin(\theta/2+\pi)] && 0 < \theta < \pi \\
&= -\sqrt{r}[\cos(\theta/2) + i\sin(\theta/2)]
\end{aligned}$$

Thus we can see that $f_1 = -f_3$ in $D_1 \cap D_3$.

Example 13.8.2 *Consider theorem 13.8.3, but $f(x)$ is purely imaginary $\forall x \in \mathbb{R}$. We know that $\impliedby$ holds, and that $F(z) = \overline{f(\bar{z})}$ satisfies the Cauchy-Riemann equations. We have*

$$F(x) = U(x,0) + iV(x,0) = u(x,0) - iv(x,0) = -iv(x,0) = -f(x)$$

Hence

$$\overline{f(\bar{z})} = -f(z) \implies \overline{f(z)} = -f(\bar{z})$$

Chapter 14

Elementary Functions

14.1 Exponential Function

Definition 14.1.1: Exponential Function

Consider $z \in \mathbb{C}$, the exponential function is defined:

$$f(z) = e^z = e^{x+iy} = e^x[\cos(y) + i\sin(y)]$$

Where y is taken in radians.

Note: This is not the same as the polar form of a complex number (definition 12.3.3).

It is clear that the set of n-th roots of e:

$$\{e^{1/n} : n \in \mathbb{N}\}$$

and

$$|e^z| = e^x \qquad \arg(e^z) = y + 2n\pi \qquad n \in \mathbb{N} \cup \{0\}$$

The exponential function follows from the usual properties of exponentials. We also know that

$$\frac{\mathrm{d}}{\mathrm{d}z}e^z = e^z \qquad \forall z \in \mathbb{C}$$

so, e^z is entire. We should also note that e^z is periodic due to e^{iy}.

14.2 Logarithmic Function

Definition 14.2.1: Logarithmic Function

Consider any $z \in \mathbb{C}$ in exponential form:

$$\log(z) = \ln(r) + i(\theta + 2n\pi) = \ln(|z|) + i\arg(z) \qquad n \in \mathbb{Z}$$

Note: This is a multi-valued function.

Definition 14.2.2: Principal Value of the Logarithmic Function

Let $z \in \mathbb{C}$, the principal value of the logarithmic function is denoted by $\text{Log}(z)$*.*

$$\text{Log}(z) = \ln(r) + i\theta$$

It is clear that

$$\log(z) = \text{Log}(z) + 2n\pi \qquad n \in \mathbb{Z}$$

and for any z on the real axis, the logarithmic function reduces to

$$\text{Log}(z) = \ln(x) \qquad x \in \mathbb{R}$$

14.2.1 Branches and Derivatives of Logarithms

$\log(z)$ is a multi-valued function. Let $\alpha \in \mathbb{R}$:

$$\log(z) = \ln(r) + i\theta = u(r,\theta) + iv(r,\theta) \qquad\qquad r > 0, \alpha < \theta < \alpha + 2\pi$$

Note: If $\log(z)$ is defined on $\theta = \alpha$, then it is not continuous there, as there is a discontinuity between points near α and $\alpha + 2\pi$.

The first order partials of u and v are continuous in the domain, and satisfies the Cauchy-Riemann equations:

$$ru_r = v_\theta \qquad\qquad u_\theta = -rv_\theta$$

So its derivative exists everywhere in the domain.

$$\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}z}\log(z) = e^{-i\theta}(u_r + iv_r) = e^{i\theta}\left(\frac{1}{r} + i0\right) = \frac{1}{re^{i\theta}}& \\
\implies \frac{\mathrm{d}}{\mathrm{d}z}\log(z) = \frac{1}{z} \qquad\qquad & |z| > 0,\ \alpha < \arg(z) < \alpha + 2\pi \\
\implies \frac{\mathrm{d}}{\mathrm{d}z}\text{Log}(z) = \frac{1}{z} \qquad\qquad & |z| > 0,\ -\pi < \text{Arg}(z) < \pi
\end{aligned}$$

Definition 14.2.3: Branch

A branch is a single-valued function F of a multi-valued function f. F is analytic throughout some domain of f and assumes the one of the values of f.

Definition 14.2.4: Principal Branch

$$\text{Log}(z) = \ln(r) + i\theta \qquad\qquad r > 0,\ -\pi < \theta < \pi$$

Definition 14.2.5: Branch Cut

A portion of a line or curved introduced to define a branch F of a multi-valued function f. Points on the branch cut of F are singular points of F.

Definition 14.2.6: Branch Point
A singular point common to all branch cuts of a multi-valued function f.

Example 14.2.1 *The branch cut for* $\text{Log}(z) = \ln(r) + i\theta$, $r > 0$, $-\pi < \theta < \pi$, *is the origin and* $\theta = \pi$.

Branch points for all branches of $\log(z)$ *is the origin.*

Different branches may result in different values.

Example 14.2.2 *Consider* $\log(i^2)$ *in the branch:*

$$\log(z) = \ln(r) + i\theta \qquad\qquad r > 0,\ \frac{\pi}{4} < \theta < \frac{9\pi}{4}$$

Then

$$\log\left(i^2\right) = \log(-1) = \ln(1) + i\pi = i\pi$$
$$2\log(i) = 2\left(\ln(1) + i\frac{\pi}{2}\right) = \pi i$$

Therefore

$$\log\left(i^2\right) = 2\log(i) \qquad\qquad r > 0,\ \frac{\pi}{4} < \theta < \frac{9\pi}{4}$$

Now consider the branch:

$$\log(z) = \ln(r) + i\theta \qquad\qquad r > 0,\ \frac{3\pi}{4} < \theta < \frac{11\pi}{4}$$

Then

$$\log\left(i^2\right) = \log(-1) = \ln(1) + i\pi = i\pi$$
$$2\log(i) = 2\left(\ln(1) + i\frac{5\pi}{2}\right) = 5\pi i$$

Therefore,

$$\log\left(i^2\right) \neq 2\log(i) \qquad\qquad r > 0,\ \frac{3\pi}{4} < \theta < \frac{11\pi}{4}$$

14.2.2 Identities of Logarithms

Let $z_1, z_2 \in \mathbb{C}$, then

$$\log(z_1 z_2) = \log(z_1) + \log(z_2)$$

can be interpreted as

$$\arg(z_1 z_2) = \arg(z_1) + \arg(z_2)$$

therefore

$$\ln|z_1 z_2| + i\arg(z_1 z_2) = (\ln|z_1| + i\arg(z_1)) + (\ln|z_2| + i\arg(z_2))$$

Rest of the identities are the same as for elements in $\mathbb{R}$, but beware of branches and arguments.

Example 14.2.3 *Show* $\forall z_1, z_2 \in \mathbb{C}$

$$\mathrm{Log}(z_1 z_2) = \mathrm{Log}(z_1) + \mathrm{Log}(z_2) + 2N\pi i \qquad N \in \{0, \pm 1\}$$

Consider:

$$\begin{aligned} \log(z_1 z_2) &= \ln|z_1 z_2| + i\arg(z_1 z_2) \\ &= \ln(r_1) + \ln(r_2) + i\arg(z_1) + i\arg(z_2) \\ &= \ln(r_1) + \ln(r_2) + i\theta_1 + i\theta_2 + 2n\pi i && n \in \mathbb{Z} \\ &= \ln(r_1) + \ln(r_2) + i\,\mathrm{Arg}(z_1) + i\,\mathrm{Arg}(z_2) + 2n\pi i && n \in \mathbb{Z} \end{aligned}$$

Then, since $-\pi < \mathrm{Arg}(z_1) < \pi$ *and* $-\pi < \mathrm{Arg}(z_2) < \pi$*:*

$$\begin{aligned} \mathrm{Log}(z_1 z_2) &= \ln(r_1) + \ln(r_2) + i\,\mathrm{Arg}(z_1) + i\,\mathrm{Arg}(z_2) + 2N\pi i && N \in \{0, \pm 1\} \\ &= \mathrm{Log}(z_1) + \mathrm{Log}(z_2) + 2N\pi i && N \in \{0, \pm 1\} \end{aligned}$$

14.2.3 Power Function

Definition 14.2.7: Power Function

Let $z, c \in \mathbb{C}$*. The Power Function:*

$$z^c = e^{c\log(z)} \qquad z \neq 0$$

Likewise

$$c^z = e^{z\log(c)} \qquad c \neq 0$$

The logarithm is multi-valued $\implies$ the power function is multi-valued.

The principle branch of the Power Function is log being replaced by Log:

$$\begin{aligned} z^c &= e^{c\,\mathrm{Log}(z)} && z \neq 0 \\ c^z &= e^{z\,\mathrm{Log}(c)} && c \neq 0 \end{aligned}$$

When a branch is specified, $\log(z)$ becomes single-valued and analytic. Hence the derivatives:

$$\frac{\mathrm{d}}{\mathrm{d}z} z^c = \frac{\mathrm{d}}{\mathrm{d}z} e^{c\log(z)} = \frac{c}{z} e^{c\log(z)} = cz^{z-1} \qquad |z| > 0,\ \alpha < \arg(z) < \alpha + 2\pi,\ \alpha \in \mathbb{R}$$

When value of $\log(c)$ is specified, c^z is entire function of z and

$$\frac{\mathrm{d}}{\mathrm{d}z} c^z = \frac{\mathrm{d}}{\mathrm{d}z} e^{z\log(c)} = e^{z\log(c)}\log(c) = c^z\log(c)$$

14.3 Trigonometric Functions

Recall: Definition 12.5.2. Likewise for any $z \in \mathbb{C}$:

Definition 14.3.1: Complex Sine and Cosine Functions

For any $z \in \mathbb{C}$:

$$\cos(z) = \frac{e^{iz} + e^{-iz}}{2} \qquad \sin(z) = \frac{e^{iz} - e^{-iz}}{2i}$$

Sine and cosine are entire functions as e^{iz} and e^{-iz} are entire.

Taking the derivatives:

$$\frac{\mathrm{d}}{\mathrm{d}z} e^{iz} = ie^{iz} \implies \left(\frac{\mathrm{d}}{\mathrm{d}z}\sin(z) = \cos z\right) \wedge \left(\frac{\mathrm{d}}{\mathrm{d}z}\cos(z) = -\sin(z)\right)$$

It's also easy to see that:

$$\sin(-z) = \sin(z) \qquad \cos(-z) = -\cos(z) \qquad e^{iz} = \cos(z) + i\sin(z)$$

The usual trigonometric identities apply, such as:

$$\sin(z_1 + z_2) = \sin(z_1)\cos(z_2) + \cos(z_1)\sin(z_2)$$
$$\cos(z_1 + z_2) = \cos(z_1)\cos(z_2) - \sin(z_2)\sin(z_2)$$

Now suppose $y \in \mathbb{R}$, and take the hyperbolic functions:

$$\sinh(y) = \frac{e^y - e^{-y}}{2} \qquad \cosh(y) = \frac{e^y + e^{-y}}{2}$$

Then we get:

$$\sin(iy) = i\sinh(y) \qquad \cos(iy) = \cosh(y)$$

If we let $z = x + iy$, we can define:

$$\sin(z) = \sin(x)\cosh(y) + i\cos(x)\sinh(y)$$
$$\cos(z) = \cos(x)\cosh(y) - i\sin(x)\sinh(y)$$

and that

$$|\sin(z)|^2 = \sin^2(x) + \sinh^2(y)$$
$$|\cos(z)|^2 = \cos^2(x) + \sinh^2(y)$$

Note: Unlike in $\mathbb{R}$ where sine and cosine are bounded by 1 and -1, it is clear that sine and cosine are not bounded in the complex plane, since sinh is unbounded for all values of y.

14.3.1 Zeros and Singularities

Definition 14.3.2: Zero (function)
Let $f(z)$ be a function. A zero of f is a point z_0 such that

$$f(z_0) = 0$$

Theorem 14.3.1:
The zeros of $\cos(z)$ and $\sin(z)$ for $z \in \mathbb{C}$ is the same as the zeros of $\cos(x)$ and $\sin(x)$ for $x \in \mathbb{R}$, that is

$$\forall x \in \mathbb{R} \forall z \in \mathbb{C} \forall n \in \mathbb{Z}\left[(\cos(x) = 0) \wedge (\cos(z) = 0) \iff z = x = \frac{\pi}{2} + n\pi\right]$$
$$\forall x \in \mathbb{R} \forall z \in \mathbb{C} \forall n \in \mathbb{Z}[(\sin(x) = 0) \wedge (\sin(z) = 0) \iff z = x = n\pi]$$

Proof: Let $z = x + iy$ and consider $\sin(z) = 0$:

$$\begin{aligned}
\sin(z) = 0 &\implies \sin^2(x) + \sinh^2(y) = 0 && |\sin(z)|^2 = \sin^2(x) + \sinh^2(y)\\
&\implies [\sin(x) = 0] \wedge [\sinh(y) = 0]\\
&\implies [x = n\pi] \wedge [y = 0] && n \in \mathbb{Z}\\
&\implies z = x = n\pi && n \in \mathbb{Z}
\end{aligned}$$

As for cosine, we know that:

$$\cos(z) = \sin\left(z + \frac{\pi}{2}\right)$$

Thus

$$\cos(z) = 0 \implies z = x = n\pi + \frac{\pi}{2} \qquad n \in \mathbb{Z}$$

□

Example 14.3.1 *Show* $\forall z \in \mathbb{C}$*:*
The Reflection Principle:

$$\forall z \in D \subset \mathbb{C}[\overline{f(z)} = f(\bar{z})] \iff \forall x \in \mathbb{R}[f(x) \in \mathbb{R}]$$

(a) $\overline{\cos(z)} = \cos(\bar{z})$

Proof: It is clear that $\forall x \in \mathbb{R}$, $\sin(x) \in \mathbb{R}$. The result follows from the Reflection Principle. Also

$$\overline{\sin(z)} = \overline{\frac{z - \bar{z}}{2i}} = \frac{\bar{z} - z}{2i} = \sin(\bar{z})$$

□

(b) $\overline{\sin(z)} = \sin(\bar{z})$

Proof: It is clear that $\forall x \in \mathbb{R}$, $\cos(x) \in \mathbb{R}$. The result follows from the Reflection Principle. Also

$$\overline{\cos(z)} = \overline{\frac{z+\bar{z}}{2}} = \frac{\bar{z}+z}{2} = \cos(\bar{z})$$

□

Example 14.3.2 *Show:*

(a) $\forall z \in \mathbb{C}[\overline{\cos(iz)} = \cos(i\bar{z})]$

Proof:

$$\overline{\cos(iz)} = \overline{\frac{iz+\overline{iz}}{2}} = \frac{\overline{iz}+iz}{2} = \frac{-i\bar{z}+iz}{2} = i\frac{z-\bar{z}}{2} = i\,\mathrm{Im}\{z\}$$
$$\cos(i\bar{z}) = \frac{i\bar{z}+\overline{i\bar{z}}}{2} = \frac{i\bar{z}-iz}{2} = i\frac{\bar{z}-z}{2} = i\,\mathrm{Im}\{z\}$$

Hence $\forall z \in \mathbb{C}$

$$\overline{\cos(iz)} = \cos(i\bar{z})$$

□

(b) $\forall z \in \mathbb{C}\forall n \in \mathbb{Z}[\overline{\sin(iz)} = \sin(i\bar{z}) \iff z = n\pi i]$

Proof:

$$\overline{\sin(iz)} = \overline{\frac{iz-\overline{iz}}{2i}} = \frac{-i\bar{z}-iz}{2i} = -\frac{z+\bar{z}}{2} = -\mathrm{Re}\{z\}$$
$$\sin(i\bar{z}) = \frac{i\bar{z}-\overline{i\bar{z}}}{2i} = \frac{i\bar{z}+iz}{2i} = \frac{z+\bar{z}}{2} = \mathrm{Re}\{z\}$$

We know that

$$\mathrm{Re}\{z\} = -\mathrm{Re}\{z\} \implies \mathrm{Re}\{z\} = 0 \implies \overline{\sin(iz)} = \sin(i\bar{z}) = 0 \iff z = n\pi i$$

□

14.4 Hyperbolic Functions

Definition 14.4.1: Hyperbolic Sine and Cosine Functions
Let $z \in \mathbb{C}$:

$$\sinh(z) = \frac{e^z - e^{-z}}{2} \qquad \cosh(z) = \frac{e^z + e^{-z}}{2}$$

It is clear that the derivatives:

$$\frac{\mathrm{d}}{\mathrm{d}z}\sinh(z) = \cosh(z) \qquad \frac{\mathrm{d}}{\mathrm{d}z}\cosh(z) = \sinh(z)$$

The relationships with sine and cosine:

$$\begin{aligned} -i\sinh(iz) &= \sin(z) & \cosh(iz) &= \cos(z) \\ -i\sin(iz) &= \sinh(z) & \cos(iz) &= \cosh(z) \end{aligned}$$

Hence in the complex plane, sinh and cosh are periodic with period $2\pi i$.

Identities:

$$\sinh(-z) = -\sinh(z) \qquad \cosh(-z) = \cosh(z) \qquad \cosh^2(z) - \sinh^2(z) = 1$$

$$\begin{aligned} \sinh(z_1 + z_2) &= \sinh(z_1)\cosh(z_2) + \cosh(z_1)\sinh(z_2) \\ \cosh(z_1 + z_2) &= \cosh(z_2)\cosh(z_2) + \sinh(z_1)\sinh(z_2) \end{aligned}$$

$$\begin{aligned} \sinh(z) &= \sinh(x)\cos(y) + i\cosh(x)\sin(y) \\ \cosh(z) &= \cosh(x)\cos(y) + i\sinh(x)\sin(y) \end{aligned}$$

$$\begin{aligned} |\sinh(z)|^2 &= \sinh^2(x) + \sin^2(y) \\ |\cosh(z)|^2 &= \sinh^2(x) + \cos^2(y) \end{aligned}$$

Theorem 14.4.1:

The zeros of hyperbolic zine and cosine:

$$\begin{aligned} \sinh(z) = 0 &\iff z = n\pi i & n \in \mathbb{Z} \\ \cosh(z) = 0 &\iff z = \left(\frac{\pi}{2} + n\pi\right)i & n \in \mathbb{Z} \end{aligned}$$

Example 14.4.1 *Show:*

(a) $\sinh(z + \pi i) = -\sinh(z)$

Proof:

$$\sinh(z + \pi i) = \frac{e^{z+\pi i} - e^{-z-\pi i}}{2} = \frac{-e^z + e^{-z}}{2} = -\frac{e^z - e^{-z}}{2} = -\sinh(z)$$

□

(b) $\cosh(z + \pi i) = -\cosh(z)$

Proof:

$$\cosh(z+\pi i) = \frac{e^{z+\pi i}+e^{-z-\pi i}}{2} = -\frac{e^{z}+e^{-z}}{2} = -\cosh(z)$$

□

(c) $\tanh(z+\pi i) = \tanh(z)$

Proof:

$$\tanh(z+\pi i) = \frac{\sinh(z+\pi i)}{\cosh(z+\pi i)} = \frac{-\sinh(z)}{-\cosh(z)} = \tanh(z)$$

□

Example 14.4.2 *Show* $\forall z \in \mathbb{C}$*:*

$$\overline{\sinh(z)} = \sinh(\bar{z}) \qquad \overline{\cosh(z)} = \cosh(\bar{z}) \qquad \forall z \neq 0\left[\overline{\tanh(z)} = \tanh(\bar{z})\right]$$

Proof: We can see that $\forall x \in \mathbb{R}$, $\sinh(x) \in \mathbb{R}$ and $\cosh(x) \in \mathbb{R}$, so we can conclude from the Reflection Principle (theorem 13.8.3) that $\forall z \in \mathbb{C}$:

$$\overline{\sinh(z)} = \sinh(\bar{z}) \qquad \overline{\cosh(z)} = \cosh(\bar{z})$$

Thus it follows that

$$\forall z \neq 0\left[\overline{\tanh(z)} = \tanh(\bar{z})\right]$$

□

14.5 Inverse Trigonometric and Hyperbolic Functions

Definition 14.5.1: Inverse Trigonometric Functions
Let $z \in \mathbb{C}$*:*

$$\sin^{-1}(z) = -i\log[iz + (1-z^2)^{1/2}]$$
$$\cos^{-1}(z) = -i\log[z + i(i-z^2)^{1/2}]$$
$$\tan^{-1}(z) = \frac{i}{2}\log\left(\frac{i+z}{i-z}\right)$$

$\cos^{-1}(z)$ *and* $\tan^{-1}(z)$ *are multi-valued. All inverse trigonometric functions become single-valued and analytic when in specific branches of the square root and logarithmic functions.*

Proof: $\underline{\sin^{-1}(z) = -i\log[iz + (1-z^2)^{1/2}]}$

Let $w = \sin^{-1}(z)$ whenever $z = \sin(w)$

$$z = \sin(w) \implies z = \frac{e^{iw} - e^{-iw}}{2i} \implies (e^{iw})^2 - 2ize^{iw} - 1 = 0$$

Using the quadratic formula to solve for e^{iw}:

$$e^{iw} = iz + (1-z^2)^{1/2} \implies iw = \log\left(iz + (1-z^2)^{1/2}\right)$$
$$\implies \sin^{-1}(z) = -i\log\left[iz + (1-z^2)^{1/2}\right]$$

$\underline{\cos^{-1}(z) = -i\log[z + i(i-z^2)^{1/2}]}$

Likewise, let $w = \cos^{-1}(z)$ whenever $z = \cos(w)$

$$z = \cos(w) \implies z = \frac{e^{iw} + e^{-iw}}{2} \implies (e^{iw})^2 - 2ze^{iw} + 1 = 0$$

Using the quadratic formula to solve for e^{iw}:

$$e^{iw} = \frac{2z \pm \sqrt{4z^2 - 4}}{2} = z \pm \sqrt{z^2 - 1} = z \pm i(1-z^2)^{1/2}$$
$$\implies iw = \log\left[z \pm i(1-z^2)^{i/2}\right]$$
$$\implies w = -i\log\left[z \pm i(1-z^2)^{i/2}\right]$$

$\underline{\tan^{-1}(z) = \frac{i}{2}\log\left(\frac{i+z}{i-z}\right)}$

Again, let $w = \tan^{-1}(z)$ whenever $z = \tan(w)$

$$z = \tan(w) = \frac{e^{iw} - e^{-iw}}{i(e^{iw} + e^{iw})}$$
$$\implies iz = \frac{e^{iw} - e^{-iw}}{e^{iw} + e^{iw}} \implies ize^{iw} + ize^{-iw} = e^{iw} - e^{-iw}$$
$$\implies (iz-1)e^{iw} + (iz+1)e^{-iw} = 0 \implies (iz-1)e^{2iw} + (iz+1) = 0$$
$$\implies e^{iw} = \left(\frac{-iz-1}{iz-1}\right)^{\frac{1}{2}} \implies iw = \frac{1}{2}\log\left(\frac{-iz-1}{iz-1}\right) \implies w = -\frac{i}{2}\log\left(\frac{-(iz+1)}{iz-1}\right)$$
$$\implies w = \tan^{-1}(z) = \frac{i}{2}\log\left(\frac{i+z}{i-z}\right)$$

$\square$

Derivatives:

$$\frac{\mathrm{d}}{\mathrm{d}z}\sin^{-1}(z) = \frac{1}{(1-z^2)^{1/2}}$$ Depends on value coosen for square root

$$\frac{\mathrm{d}}{\mathrm{d}z}\cos^{-1}(z) = -\frac{1}{(1-z^2)^{1/2}}$$ Depends on value chosen for square root

$$\frac{\mathrm{d}}{\mathrm{d}z}\tan^{-1}(z) = \frac{1}{1+z^2}$$ Independent on value chosen for square root

Using the same procedures on the hyperbolic functions, we obtain the inverse hyperbolic functions:

Definition 14.5.2: Inverse Hyperbolic Functions
Let $z \in \mathbb{C}$:

$$\begin{aligned}\sinh^{-1}(z) &= \log\left[z + (z^2+1)^{1/2}\right]\\ \cosh^{-1}(z) &= \log\left[z + (z^2-1)^{1/2}\right]\\ \tanh^{-1}(z) &= \frac{1}{2}\log\left(\frac{1+z}{1-z}\right)\end{aligned}$$

14.6 Phasors

Definition 14.6.1: Phasor
Consider the function

$$f(t) = \mathrm{Re}\{Fe^{st}\} \qquad F = F_0 e^{i\theta} \qquad s = \sigma + i\omega,\ \ \sigma,\omega \in \mathbb{R}$$

F is the phasor associated with $f(t)$.

We can see tha $f(t)$ grows exponentially according to the value of σ, has a phase of θ, and a phase frequency of ω. (It is clear why engineers love this.)

Properties:

1. $$f(t) = \mathrm{Re}\{Fe^{st}\} \implies \begin{cases} F \text{ is unique} & \omega \neq 0 \\ \text{Only } \mathrm{Re}\{F\} \text{ is unique} & \omega = 0 \end{cases}$$

2. $$\forall t \in \mathbb{R}[f(t) = g(t)] \implies \begin{cases} F = G & \omega \neq 0 \\ \mathrm{Re}\{F\} = \mathrm{Re}\{G\} & \omega = 0 \end{cases}$$

3. For any given $s = \sigma + i\omega$, there is only one function of t corresponding to a phasor.

4. Let $f(t)$ and $g(t)$ have the same complex frequency, that is, $\omega_1 = \omega_2$, then the phasor for $f(t) + g(t)$ is $F + G$.

5. $\forall M \in \mathbb{R}$. The phasor for $Mf(t)$ is MF.

6. "For a given complex frequency, the function of t corresponding to the sum of two or more phasors is the sum of the time functions for each." -Wunsch

7. Let $n \in \mathbb{N}$.

$$(f(t) \text{ has phasor } F) \wedge (\mathrm{d}f/\mathrm{d}t \text{ has phasor } sF) \implies \mathrm{d}^n f/\mathrm{d}t^n \text{ has phasor } s^n F$$

8.

$$f(t) \text{ has phasor } F \implies \int^t f(t')dt' \text{ has phasor } \frac{F}{s} \qquad\qquad s \neq 0$$

These properties follow from the properties of e.

Example 14.6.1 *Consider:*

$$R\mathtt{i}(t) + L\frac{\mathrm{d}\mathtt{i}}{\mathrm{d}t} = V_0 \cos(\omega t)$$

Suppose the complex frequency is $s = i\omega$. If I is the phasor for $\mathtt{i}$, then substituting it into the differential equation:

$$RI + iwLI = (R + i\omega L)I = V_0 \qquad\qquad \textit{Phasors on both side must equal}$$

Then solving for the phasor:

$$I = \frac{V_0}{R + i\omega L} = \frac{V_0 e^{i\theta}}{\sqrt{R^2 + \omega^2 L^2}} \qquad\qquad \theta = -\tan^{-1}\left(\frac{\omega L}{R}\right)$$

Using $s = i\omega$ to obtain $\mathtt{i}(t)$, we have

$$\mathtt{i}(t) = \mathrm{Re}\left\{\frac{V_0 e^{i\theta}}{\sqrt{R^2 + (\omega L)^2}} e^{i\omega t}\right\}$$

Chapter 15

Integrals

15.1 Derivatives of Functions

Definition 15.1.1: Derivative of Complex-Valued Function

Consider a complex-valued function $w(t) = u(t) + iv(t)$, with u and v being real-valued functions. If $w(t)$ is differentiable at t, then it's derivative with respect to t:

$$w'(t) = \frac{\mathrm{d}}{\mathrm{d}t} w(t) = u'(t) + iv'(t)$$

The rules for calculus in $\mathbb{R}$ still applies.

Note: The mean value theorem for derivatives no longer apply for complex-valued functions.

Example 15.1.1 *Let $w(t) = e^{it}$ be continuous on $[0, 2\pi]$, so $u(t)$ and $v(t)$ are also continuous on $[0, 2\pi]$. For the mean value theorem to hold, there must exist $a, b, c \in \mathbb{C}$, where $a < c < b$, such that*

$$w'(c) = \frac{w(b) - w(a)}{b - a}$$

We can see that

$$|w'(t)| = \left|ie^{it}\right| = 1 \qquad \frac{w(b) - w(a)}{b - a} = \frac{w(2\pi) - w(0)}{2\pi - 0} = \frac{e^{i2\pi} - e^{i0}}{2\pi} = \frac{1 - 1}{2\pi} = 0$$

So we can see that there does not exist a $c \in \mathbb{C}$ such that the mean value theorem holds.

15.2 Definite Integrals of Functions

Definition 15.2.1: Definite Integral of Complex-Valued Function

Consider a complex-valued function $w(t) = u(t) + iv(t)$, with u and v being real-valued *functions. If u and v are piecewise continuous on interval $[a,b]$, then the definite integral of $w(t)$ over interval $[a,b]$:*

$$\int_a^b w(t)dt = \int_a^b u(t)dt + i\int_a^b v(t)dt$$

The rules for integrals in $\mathbb{R}$ and the Fundamental Theorem of Calculus still applies.

Likewise with derivatives of complex-valued functions, the mean value theorem does not hold for complex-valued integrals.

Example 15.2.1 *Let $w(t) = e^{it}$ be a complex-valued function of t. For $w(t)$ to hold on $[a,b]$, this must hold for some $a < c < b$:*

$$\int_a^b w(t)dt = w(c)(b-a)$$

Consider $w(t)$ on $[0, 2\pi]$. Then

$$\int_a^b w(t)dt = \int_0^{2\pi} e^{it}dt = \frac{e^it}{i}\bigg|_0^{2\pi} = 0 \qquad |w(c)(b-a)| = \left|e^{ic}\right|2\pi = 2\pi$$

We can see there does not exist c, $0 < c < 2\pi$, such that both sides of the equations are equal.

15.3 Contours

Definition 15.3.1: Arc

An arc is a set of points dependent on a parameter $t \in \mathbb{R}$.

$$\{z = (x(t), y(t)) : t \in [a,b]\}$$

Where $x(t)$ and $y(t)$ are continuous functions.

It is convenient in $\mathbb{C}$ to use:

$$z = z(t) = x(t) + iy(t) \qquad a \le t \le b$$

Definition 15.3.2: Simple/Jordan Arc

An arc is simple if it does not cross itself. That is: $t_1 \neq t_2 \implies z(t_1) \neq z(t_2)$

Definition 15.3.3: Simple Closed Curve / Jordan Curve

A simple curve, but endpoints gets mapped to equal values. That is, $z(a) = z(b)$ for $a \le t \le b$. It is positively oriented if it is counterclockwise.

The interval for which the arc is parameterized is not unique. Consider

$$t = \phi(\tau) \qquad \alpha \le \tau \le \beta$$

Then $\phi(\alpha) = a$ and $\phi(\beta) = b$. We have

$$z(t) = Z(\tau) = z[\phi(\tau)] \qquad \alpha \le \tau \le \beta$$

Definition 15.3.4: Differentiable Arc

Suppose $\mathrm{d}/\mathrm{dt}\, z(t) = z'(t) = x'(t) + iy'(t)$ *exists and is continuous. Then* $z'(t)$ *is a differentiable arc.*

We can integrate over the differential arc in the interval $[a, b]$:

$$L = \int_a^b |z'(t)| dt \qquad\qquad |z'(t)| = \sqrt{[x'(t)]^2 + [y'(t)]^2}$$

Note: $|z'(t)|$ is a real-valued function.

Again, due to the curve being invariant under the representation for the arc:

$$L = \int_a^b |z'(t)| dt = \int_\alpha^\beta |z'[\phi(t)]| \phi'(t) dt = \int_\alpha^\beta |Z'(\tau)| d\tau \qquad Z'(\tau) = z'[\phi(\tau)]\phi'(\tau)$$

If the differentiable arc $z'(t) \neq 0$ in the interval $[a, b]$, then the unit tangent vector is defined in said interval:

$$\hat{\mathbf{T}} = \frac{z'(t)}{|z'(t)|}$$

Recall: The gradient of a function is perpendicular to the function, so $\hat{\mathbf{T}}$ is normal to $z(t)$, over the interval $[a, b]$.

Definition 15.3.5: Smooth

An arc $z(t)$ *is smooth in the interval* $[a, b]$ *if* $z'(t)$ *is continuous* $\forall t \in [a, b]$ *and non-zero* $\forall t \in (a, b)$.

Definition 15.3.6: Contour

A piecewise smooth arc.

Definition 15.3.7: Simple Closed Contour

A contour where only $z(a) = z(b)$ *in the interval* $[a, b]$.

Theorem 15.3.1: Jordan Curve Theorem

All points on a simple close curve or simple closed contour $z(t)$ *are boundary points of two distinct domains. One is bounded and interior to* $z(t)$ *and the other is unbounded and exterior to* $z(t)$*. That is,* $z(t)$ *as a boundary line of two domains.*

Proof: Good luck! □

i.e. If $z(t)$ is a circle, then one domain is within the circle and contains the points on the parameter, and one is exterior to the circle.

15.4 Contour Integrals

Evaluating an integral over a contour. It is common to assume that a line integral represents an area under a curve. Generally, this is a far too simplistic approach, even for real-valued functions. Consider the limit definition of the line integral.

Definition 15.4.1: Line Integral (Real)

Let f be a real-valued function.

$$\int_a^b f(z)ds = \lim_{n\to\infty} \sum_{k=1}^{n} f(x_k, y_k)\Delta s_k \qquad \Delta s_k = (x_k - x_{k-1}) + (y_k - y_{k-1})$$

Note: The integral exists only if the limit exists.

We can see that Δs_k acts like a vector, and the definition of the line integral assigns a value according to the weighting function f to each Δs_k. The contour integral is then the weighted sum of these vectors from a to b as $n \to \infty$.

The complex line integral is defined similarly.

Definition 15.4.2: Line Integral (Complex)

Let f be a complex-valued function.

$$\int_a^b f(z)dz = \lim_{n\to\infty} \sum_{k=1}^{n} f(z_k)\Delta z_k \qquad \Delta z = (x_k - x_{k-1}) + i(y_k - y_{k-1})$$

Upon expanding, we can see that:

$$\begin{aligned}\int_a^b f(z)dz &= \lim_{n\to\infty} \sum_{k=1}^{n} f(z_k)\Delta z_k \\ &= \lim_{n\to\infty} \sum_{k=1}^{n} [u(x_k, y_k) + iv(x_k, y_k)](\Delta x_k + i\Delta y_k) \\ &= \int_a^b (u + iv)(dx + idy) = \int_a^b u\ dx - v\ dy + i\int_a^b v\ dx + u\ dy\end{aligned}$$

These are the integrals taken in each direction when evaluating from a to b for $a, b \in \mathbb{C}$.

Note: This reduces to a regular integral $\int_a^b u\ dx$ in the reals when $v = 0$ and $dy = 0$.

A contour integral is a line integral over a contour. Here we define it parameterized by t.

Definition 15.4.3: Contour Integral

Let $z(t)$ in $C = [a, b]$ be a contour, and $f[z(t)]$ be a piecewise continuous function on C. Then the contour integral:

$$\int_C f(z)dz = \int_a^b f[z(t)]z'(t)dt$$

Note: C is contour $\implies$ $z'(t)$ is piecewise continuous on C $\implies$ Existence of integral on C

Notation: Let $f(z)$ be a function evaluated over the contour C.

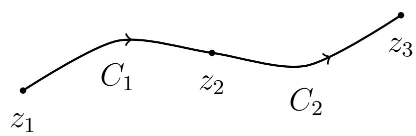
$$\int_C f(z)dz \qquad\qquad \int_{z_1}^{z_2} f(z)dz$$

$\int_{z_1}^{z_2}$ is often used when the integral is independent of the path between end points. $\int_{-C}$ represents the same contour, but in reverse.

Following from the contours, the integral is invariant under change in representation of the contour.

Definition 15.4.4: Sum (Contour)

Let C_1 be contour from z_1 to z_2, and C_2 be from z_2 to z_3, then the sum is contour C from z_1 to z_3.



Some properties (which follows from integrals):

$$\int_C = z_0 f(z)dz = z_0 \int_C f(z)dz \qquad\qquad \int_C f(z) + g(z)dz = \int_C f(z)dz + \int_C g(z)dz$$

$$\begin{aligned}\int_{-C} f(z)dz &= \int_{-b}^{-a} f([z(-t)])\frac{\mathrm{d}}{\mathrm{d}t}z(-t)dt = -\int_{-b}^{-a} f[z(-t)]z'(-t)dt \\ &= -\int_{-b}^{-a} f[z(\tau)]z'(\tau)d\tau \\ &= -\int_C f(z)dz\end{aligned}$$

$$\begin{aligned}\int_a^b f[z(t)]z'(t)dt &= \int_a^c f[z(t)]z'(t)dt + \int_c^b f[z(t)]z'(t)dt \\ \int_C f(z)dz &= \int_{C_1} f(z)dz + \int_{C_2} f(z)dz\end{aligned}$$

15.4.1 Upper Bounds for the Moduli

It is not analysis without inequality involving modulus.

Lemma 15.4.0.1:

Let $w(t)$ be a piecewise smooth function defined on $[a, b]$. Then

$$\left|\int_a^b w(t)dt\right| \leq \int_a^b |w(t)|dt$$

Proof: Assume $\int_a^b w(t)dt$ is non-zero, otherwise the inequality is trivial.

$$\begin{aligned} \int_a^b w(t)dt = r_0 e^{i\theta_0} &\implies r_0 = e^{-i\theta_0}\int_a^b w(t)dt \\ &\implies r_0 = \mathrm{Re}\left\{e^{-i\theta_0}\int_a^b w(t)dt\right\} && r_0 \in \mathbb{R} \\ &\implies r_0 = \int_a^b \mathrm{Re}\left\{e^{i\theta_0}w(t)\right\}dt \end{aligned}$$

Now

$$\begin{aligned} \mathrm{Re}\left\{e^{-i\theta_0}w(t)\right\} &\le \left|e^{-i\theta_0}w(t)\right| = \left|e^{-i\theta_0}\right||w(t)| = |w(t)| \\ &\implies r_0 \le \int_a^b |w(t)|dt \\ &\implies \left|\int_a^b w(t)dt\right| \le \int_a^b |w(t)|dt && r_0 = \left|\int_a^b w(t)dt\right| \end{aligned}$$

□

Theorem 15.4.1: ML Inequality

Let $f(z)$ be piecewise continuous function on contour C with length L.

$$\forall z \in C\ \exists M \in \mathbb{R}\,[|f(z)| \le M] \implies \left|\int_C f(z)dz\right| \le ML$$

That is, if $f(z)$ is bounded on the contour, then the value of it's integral is bounded.

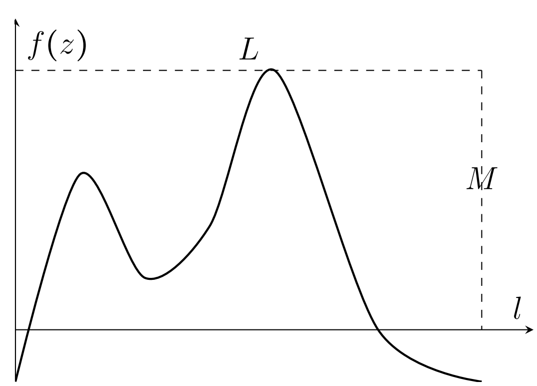
Proof: Let $z = z(t)$ in $[a, b]$ be a parametric representation of C. Then

$$\begin{aligned} \left|\int_C f(z)dz\right| = \left|\int_a^b f[z(t)]z'(t)dt\right| &\le \int_a^b |f[z(t)]z'(t)|dt = \int_a^b |f[z(t)]||z'(t)|dt \\ &\le M\int_a^b |z'(t)|dt = M|z(t)| = ML \end{aligned}$$

□

Note: According to the Extreme Value Theorem, any continuous real-valued function on a closed interval is bounded, so such $M \in \mathbb{R}$ will always exist.

Observation. *Let l be the length along the contour C. Graphically, what this is telling us:*



This is useful in evaluating the size of the integral, and if we are lucky:

Example 15.4.1 *Let C_R be the semicircle:*

$$z = Re^{i\theta} \qquad\qquad 0 \le \theta \le \pi,\ \ R > 3$$

Consider

$$\lim_{r\to\infty} \int_{C_R} \frac{z+1}{(z^2+4)(z^2+9)} dz$$

We know that:

$$\begin{aligned} |z+1| &\le |z| + 1 = R + 1 \\ \left|z^2+4\right| &\ge \left||z|^2 - 4\right| = R^2 - 4 \\ \left|z^2+9\right| &\ge \left|\left|z^2\right| - 9\right| = R^2 - 9 \end{aligned}$$

Then

$$|f(z)| = \left|\frac{z+1}{(z^2+4)(z^2+9)}\right| = \frac{|z+1|}{|z^2+4||z^2+9|} \le \frac{R+1}{(R^2-4)(R^2-9)} = M_R$$

Now we have

$$M_R = \frac{R+1}{(R^2-4)(R^2-9)} \qquad\qquad L = \pi R$$

Since

$$\left|\int_{C_R} \frac{z+1}{(z^2+4)(z^2+9)} dz\right| \le M_R L$$

Hence

$$\lim_{R\to\infty} M_R L = \lim_{R\to\infty} \frac{R^2+R}{(R^2-4)(R^2-9)}\pi = \lim_{R\to\infty} \frac{\frac{1}{R^2} + \frac{1}{R^3}}{\left(1 - \frac{4}{R^2}\right)\left(1 - \frac{9}{R^2}\right)}\pi = 0$$

Thus

$$\lim_{r\to\infty} \int_{C_R} \frac{z+1}{(z^2+4)(z^2+9)} dz = 0$$

15.5 Antiderivatives

Definition 15.5.1: Antiderivative

Let $f(z)$ be a continuous function on domain D, the antiderivative is a function $F(z)$ such that

$$F'(z) = f(z) \qquad\qquad \forall z \in D$$

Note: By definition, $F(z)$ is an analytic function, and an antiderivative is unique up to an additive constant. An indefinite integral is the family of functions that are the antiderivative of a particular function.

Theorem 15.5.1:

Let $f(z)$ be a continuous function on domain D. TFAE:

(a) There is a function $F(z)$ such that

$$\forall z \in D[F'(z) = f(z)]$$

($f(z)$ has an antiderivative throughout D.)

(b) All contours of $f(z)$ in D from any point z_1 to z_2 all have the same value. That is

$$\int_{z_1}^{z_2} f(z)dz = F(z)\Big|_{z_1}^{z_2} = F(z_2) - F(z_1)$$

(c) For all closed contours C lying in D:

$$\oint_C f(z)dz = 0$$

Simply:

$$\forall z \in D[F'(z) = f(z)] \iff \int_{z_1}^{z_2} f(z)dz = F(z)\Big|_{z_1}^{z_2} \iff \oint_C f(z)dz = 0$$

Proof: (a) $\implies$ (b):

Suppose $F'(z)$ exists for $f(z)$ for all $z \in D$. We know:

$$\frac{\mathrm{d}}{\mathrm{d}t}F[z(t)] = F'(z(t))z'(t) = f[z(t)]z'(t) \qquad t \in [a,b]$$

Then

$$\int_C f(z)dz = \int_a^b f[z(t)]z'(t)dt = F[z(t)]\Big|_a^b = F[z(b)] - F[z(a)] = F(z_2) - F(z_1)$$

If C consists of a finite number of smooth arc C_k, $k \in \{1, 2, 3, \dots, n\}$:

$$\int_C f(z)dz = \sum_{k=1}^{n} \int_C f(z)dz = \sum_{k=1}^{n} \int_{z_k}^{z_{k+1}} f(z)dz = \sum_{k=1}^{n} [F(z_{k+1}) - F(z_k)]$$

Then

$$\int_C f(z)dz = F(z_{n+1}) - F(z_1)$$

Thus

$$\forall z \in D[F'(z) = f(z)] \implies \int_{z_1}^{z_2} f(z)dz = F(z)\Big|_{z_1}^{z_2}$$

(b) $\implies$ (c):
Let C_1 and C_2 be contours with endpoints z_1 and z_2. Suppose that integration is path independent, then

$$\int_{C_1} f(z)dz = \int_{C_2} f(z)dz \implies \int_{C_1} f(z)dz + \int_{-C_2} f(z)dz = 0 \implies \int_{C=C_1-C_2} f(z)dz = 0$$

Thus

$$\int_{z_1}^{z_2} f(z)dz = F(z)\Big|_{z_1}^{z_2} \implies \oint_C f(z)dz = 0$$

(c) $\implies$ (a):
Suppose integration around a closed contour C in D is zero. Since integration is path independent in D, we can define the function:

$$F(z) = \int_{z_0}^{z} f(z)ds$$

Let $z + \Delta z$ be any point in the neighbourhood of z contained in D, then

$$F(z+\Delta z) - F(z) = \int_{z_0}^{z+\Delta z} f(z)ds - \int_{z_0}^{z} f(z)ds = \int_{z}^{z+\Delta z} f(s)ds$$

Since

$$\int_{z}^{z+\Delta z} ds = \Delta z \implies f(z) = \frac{1}{\Delta z}\int_{z}^{z+\Delta z} f(z)ds$$

Then

$$\frac{F(z+\Delta z) - F(z)}{\Delta z} - f(z) = \frac{1}{\Delta z}\int_{z}^{z+\Delta z} f(s) - f(z)ds$$

As f is continuous at the point z:

$$\forall \epsilon \exists \delta [|s - z| < \delta \implies |f(s) - f(z)| < \epsilon]$$

If $|\Delta z| < \delta$:

$$\left|\frac{F(z+\Delta z) - F(z)}{\Delta z} - f(z)\right| < \frac{1}{|\Delta z|}\epsilon|\Delta z| = \epsilon$$

Then

$$\lim_{\Delta z \to 0} \frac{F(z+\Delta z) - F(z)}{\Delta z} = f(z) \implies F'(z) = f(z)$$

Thus

$$\oint_C f(z)dz = 0 \implies \forall z \in D[F'(z) = f(z)]$$

$\square$

Example 15.5.1 *Let $f(z) = z^{-2}$. We can see that f is continuous everywhere except at the origin, and has antiderivative $F(z) = -z^{-1}$ in $|z| > 0$. Thus around the unit circle:*

$$\int_C z^{-2} dz = 0 \qquad\qquad z = e^{i\theta},\ \theta \in [-\pi, \pi]$$

Example 15.5.2 *Consider $f(z) = z^{-1}$. It has an antiderivative $F(z) = \log(z)$, which is not differentiable or defined along its branch cut. To evaluate the integral along the unit circle, we can break it up into two domains to avoid this issue. First consider C_1:*

$$z = e^{i\theta} \qquad\qquad -\frac{\pi}{2} \leq \theta \leq \frac{\pi}{2}$$

Then

$$\begin{aligned}\int_{C_1} z^{-1} dz = \int_{-i}^{i} z^{-1} dz &= \operatorname{Log}(z)\Big|_{-i}^{i} = \operatorname{Log}(i) - \operatorname{Log}(-i)\\ &= \left(\ln(1) + i\frac{\pi}{2}\right) - \left(\ln(1) - i\frac{\pi}{2}\right) = \pi i\end{aligned}$$

Now consider C_2:

$$z = e^{i\theta} \qquad\qquad \frac{\pi}{2} \leq \theta \leq \frac{3\pi}{2}$$

Then

$$\begin{aligned}\int_{C_2} = z^{-1} dz = \int_{i}^{-i} z^{-1} dz &= \log(z)\Big|_{i}^{-i} = \log(-i) - \log(i)\\ &= \left(\ln(1) + i\frac{3\pi}{2}\right) - \left(\ln(1) + i\frac{\pi}{2}\right) = \pi i\end{aligned}$$

Thus around the circle $C = C_1 + C_2$:

$$\int_C z^{-1} dz = \int_{C_1} z^{-1} dz + \int_{C_2} z^{-1} dz = \pi i + \pi i = 2\pi i$$

15.6 Cauchy-Goursat Theorem

Previously: A function f that has an antiderivative in any domain D, then the integral of f around any closed contour in D is zero. (Theorem 15.5.1) Now, it's for simple closed contours.

Recall:

$$\begin{aligned}\int f(z) dz = \int (u + iv)(dx + idy) &= \int u\ dx - v\ dy + i \int v\ dx + u\ dy\\ &= \iint -v_x - u_x\ dx\ dy + i \iint u_x - v_y dx\ dy && \textit{Theorem } 17.0.1\\ &= 0 && \textit{Theorem } 13.5.1\end{aligned}$$

This result requires $f'(z)$ be continuous, due to the requirement of Green's Theorem (theorem 17.0.1). The Cauchy-Goursat theorem eliminates this requirement.

Theorem 15.6.1: Cauchy-Goursat Theorem

Let C be a simple closed contour. If a function f is analytic for all set of points z on and in C, then

$$\int_C f(z)dz = 0$$

Proof: First, a lemma:

Lemma 15.6.1.1:

Let C be a closed contour, R denote the region enclosed and on the contour, and f be a function analytic in R. The region R can be covered by a finite number of squares or partial squares, indexed $j = 1, 2, \ldots, n$, such that for some $\epsilon > 0$:

$$\left|\frac{f(z) - f(z_j)}{z - z_j} - f'(z_j)\right| < \epsilon$$

Holds for all points z other than a fixed point z_j in that square or partial square. We let a square denote a region with boundary points included with points interior to it. If a square has points not in R, then we remove those points and it becomes a partial square.

Proof: Suppose there does not exist a z_j where

$$\left|\frac{f(z) - f(z_j)}{z - z_j} - f'(z_j)\right| < \epsilon$$

holds after subdividing a square a finite number of times for contradiction. Let σ_0 denote the original square or the entire square of the partial square, σ_1 denote the squares after subdividing σ_0 into four equal smaller squares, and so on. After subdividing σ_0, one of the σ_1 must contain points of R but still no such z_j exists, so we continue to subdivide such σ_1 since the inequality does not hold. We will then obtain an infinite sequence

$$\sigma_0, \sigma_1, \sigma_2, \ldots, \sigma_{k-1}, \sigma_k, \ldots$$

There is a point z_0 that is common to each of these squares and each of these squares contain points of R other than z_0. As the size of the squares are decreasing, there exists a neighbourhood $\delta > |z - z_0|$ containing the squares with diagonals less than δ, so each neighbourhood δ contains points of R distinct from z_0. Thus z_0 is an accumulation point of R (definition 12.7.16), and since R is a closed set, $z_0 \in R$.

Now, since f is analytic in R and z_0, $f'(z_0)$ exists and according to definition 13.4.1:

$$\forall \epsilon \exists \delta > 0 \left[|z - z_0| < \delta \implies \left|\frac{f(z) - f(z_0)}{z - z_0} - f'(z_0)\right| < \epsilon\right]$$

However, such neighbourhood $|z - z_0| < \delta$ contains σ_K for some sufficiently large K, so z_0 serves as z_j for a the subregion of σ_K or part of σ_K, thus there is no need to subdivide σ_K. We have reached a contradiction. $\square$

Upper bound for modulus of an integral:

Given some ϵ we cover region R with squares such that

$$\left| \frac{f(z) - f(z_j)}{z - z_j} - f'(z_j) \right| < \epsilon$$

We define a neighbourhood $\delta_j(z)$ enclosing the j-th square or partial square by

$$\delta_j(z) = \begin{cases} \frac{f(z)-f(z_j)}{z-z_j} - f'(z_j) & z \neq z_j \\ 0 & z = z_j \end{cases}$$

Then

$$\forall z \in \sigma \subset R[|\delta_j(z)| < \epsilon]$$

As $f(z)$ is continuous throughout subregion σ, $\delta_j(z)$ is continuous in σ and

$$\lim_{z \to z_j} \delta_j(z) = f'(z_j) - f'(z_j) = 0$$

Now, let C_j denote the positively oriented contours on the boundaries of the squares and partial squares covering R. Then on any C_j be definition of $\delta_j(z)$:

$$\begin{aligned} &f(z) = f(z_j) - z_j f'(z_j) + f'(z_j)z + (z - z_j)\delta_j(z) \\ &\implies \int_{C_j} f(z)dz = [f(z_j) - z_j f'(z_j)] \int_{C_j} dz + f'(z_j) \int_{C_j} zdz + \int_{C_j} (z - z_j)\delta_j(z)dz \end{aligned}$$

However, according to theorem 15.5.1:

$$\int_{C_j} dz = 0 \qquad \int_{C_j} zdz = 0$$

So

$$\begin{aligned} &\int_{C_j} f(z)dz = \int_{C_j} (z - z_j)\delta_j(z)dz \qquad j = 1, 2, 3, \ldots, n \\ &\implies \sum_{j=1}^{n} \int_{C_j} f(z)dz = \sum_{j=1}^{n} \int_{C_j} (z - z_j)\delta_j(z)dz \end{aligned}$$

Now as boundaries of adjacent subregions cancel each other out, since they are taken along opposite senses to each other, only those on C remain, so

$$\int_C f(z)dz = \sum_{j=1}^{n} \int_{C_j} (z - z_j)\delta_j(z)dz \implies \left| \int_C f(z)dz \right| \leq \sum_{j=1}^{n} \left| \int_{C_j} (z - z_j)\delta_j(z)dz \right|$$

Endgame:

Let s_j denote the length of the sides of the square or partial square σ_j, since C_j is on the boundary or part of the boundary of the square.

$$|z - z_j| \le \sqrt{2}s_j \qquad\qquad \sqrt{2}s_j \text{ is diagonal of square}$$

Then

$$|\delta_j(z)| < \epsilon \implies |(z - z_j)\delta_j(z)| = |z - z_j||\delta_j(z)| < \sqrt{2}s_j\epsilon$$

Let A_j be the area of the square. If C_j is the boundary of a square, then the length of C_j is $4s_j$ and we have

$$\left|\int_{C_j}(z - z_j)\delta_j(z)dz\right| < \sqrt{2}s_j\epsilon 4s_j = 4\sqrt{2}A_j\epsilon$$

Now, if C_j is the boundary of a partial square, then the length of C_j is less than $4s_j + L_j$, where L_j is the length of C_j that is a part of C. Let S be the length of the sides of some square that entirely encloses C, so sum of A_j is less then S^2. Then we have:

$$\left|\int_{C_j}(z - z_j)\delta_j(z)dz\right| < \sqrt{2}s_j\epsilon(4s_j + L_j) < 4\sqrt{2}A_j\epsilon + \sqrt{2}SL_j\epsilon$$

If L is the length of C, then

$$\begin{aligned}\left|\int_C f(z)dz\right| &\le \sum_{j=1}^{n}\left|\int_{C_j}(z - z_j)\delta_j(z)dz\right| < \sum_{j=1}^{n}\left(4\sqrt{2}A_j\epsilon + \sqrt{2}SL_j\epsilon\right)\\ &< \left(4\sqrt{2}S^2 + \sqrt{2SL}\right)\epsilon\end{aligned}$$

Since ϵ is arbitrary, we can choose it to be as small as we like, so

$$\forall\epsilon > 0\left[\left|\int_C f(z)dz\right| < \left(4\sqrt{2}S^2 + \sqrt{2SL}\right)\epsilon\right] \implies \left|\int_C f(z)dz\right| = 0$$

Hence, if function f is analytic on all $z \in C$ where C is a simple closed contour, then

$$\int_C f(z)dz = 0$$

TLDR:

We found that the upper bound for f around the contour integral C is less than or equal to the sum of all the contours around the squares covering the region bounded by C. Since f is analytic in R, the sum of the contours of the squares in R is a function of the neighbourhood $\delta_j(z)$ surrounding z_j in each square, which is chosen to be less than some ϵ, the error between the derivative of f and the finite difference of f. As ϵ can be made arbitrary small and the inequality must hold for all values of ϵ, we find $\int_C f(z)dz = 0$. $\square$

15.6.1 Morera's Theorem

A converse to the Cauchy-Goursat theorem.

Lemma 15.6.1.2:

Suppose $P(x,y)$, $Q(x,y)$, P_y, and Q_x are continuous in a simply connected domain D. Then for all simple closed contour C in D:

$$\int_C P\ dx + Q\ dy = 0 \implies \frac{\partial}{\partial x} Q = \frac{\partial}{\partial y} P$$

Proof: Suppose $\exists x_0, y_0 \in D$ such that $\partial Q/\partial x - \partial P/\partial y > 0$. Then there exists a circle C in D centred at (x_0, y_0) such that $\partial Q/\partial x - \partial P/\partial y > 0$ in and on C. That is, there exists a neighbourhood that $\partial Q/\partial x - \partial P/\partial y > 0$ holds. Then by Green's Theorem (theorem 17.0.1):

$$\int_C P\ dx + Q\ dy = \iint \left(\frac{\partial}{\partial x} Q - \frac{\partial}{\partial y} P \right)\ dx\ dy$$

Then

$$\iint \left(\frac{\partial}{\partial x} Q - \frac{\partial}{\partial y} P \right)\ dx\ dy > 0 \implies \int_C P\ dx + Q\ dy > 0$$

But by hypothesis

$$\int_C P\ dx + Q\ dy = 0$$

We have a contradiction, so

$$\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \leq 0$$

Using a similar argument, we have $\partial Q/\partial x - \partial P/\partial y \geq 0$ for $\partial Q/\partial x - \partial P/\partial y < 0$, so we have

$$\frac{\partial}{\partial x} Q = \frac{\partial}{\partial y} P$$

□

Theorem 15.6.2: Morera's Theorem

Let $f(x,y) = u(x,y) + iv(x,y)$ where u and v are continuous in a domain D. Then for every simple closed contour C in D:

$$\int_C f(z) dz = 0 \implies f(z) \text{ is analytic in } D$$

Proof:

$$\begin{aligned}\int_C f(z)dz = 0 &\implies \int_C u\ dx - v\ dy + iv\ dx + iu\ dy = 0\\ &\implies \left[\int_C u\ dx - v\ dy = 0\right] \land \left[\int_C v\ dx + u\ dy = 0\right]\\ &\implies \left[\frac{\partial}{\partial y}u = -\frac{\partial}{\partial x}v\right] \land \left[\frac{\partial}{\partial y}v = \frac{\partial}{\partial x}u\right]\end{aligned}$$

These are the Cauchy-Riemann equations (theorem 13.5.1), thus $f(z)$ is analytic in D. □

Note: This proof requires that the partial derivatives to be continuous in D. However, there is a proof that eliminates this requirement.

15.6.2 Simply Connected Domains

Definition 15.6.1: Simply Connected Domain

A domain D which every simple closed contour that lies within it only encloses points in D.

Theorem 15.6.3:

Let f be a function that is analytic throughout a simply connected domain D. Then for every closed contour C lying in D:

$$\int_C f(z)dz = 0$$

We will later learn in theorem 15.7.4 that this is $\iff$, due to theorem 15.5.1.

Proof: Suppose C is simple and lies entirely in D. The result follows from the Cauchy-Goursat theorem (theorem 15.6.1).

Suppose that C is closed, but intersects itself a finite number of times, then it consists of a finite number of simple closed contours. Result again follows from the Cauchy-Goursat Theorem.

Note: There are subtleties for infinite number of self-intersection points. □

Corollary 15.6.3.1:

If f is a function analytic throughout a simply connected domain D, then it has antiderivatives everywhere in D.

Proof: If f is analytic in a simply connected domain D then it is continuous in D. Then

$$\int_C f(z)dz = 0 \iff \forall z \in D\ \exists F(z)[F'(z) = f(z)] \qquad \textit{Theorem } 15.5.1$$

□

Corollary 15.6.3.2:
Entire functions have antideriviatives everywhere in their domain of definition.

Proof: Consequence of previous corollary and that finite plane is simply connected. □

15.6.3 Multiply Connected Domains

Definition 15.6.2: Multiply Connected Domains
A domain that is not simply connected.

Theorem 15.6.4:
Let C be a simple closed contour in the positive direction, and C_k ($k \in \{1, 2, 3, \ldots, n\}$) be simple closed contours in C taken in the negative direction that are disjoint with no common interior points. If a function f is analytic on C and C_k and throughout the multiply connected domain consisting of points inside C but exterior to all C_k, then

$$\int_C f(z)dz + \sum_{k=1}^{n} \int_{C_k} f(z)dz = 0$$

Proof: Let a polygonal path L_1 connect C to the inner contour C_1, L_2 connecting C_1 to C_2, and continue in this manner. Finally, let L_{n+1} connect C_n to C. Then we have two contours Γ_1 and Γ_2. Γ_1 consisting of parts of the contours C, C_k, and L_k. Γ_2 consisting of the remaining parts of contours C, C_k, and $-L_k$. If we apply the Cauchy-Goursat theorem to Γ_1 and Γ_2, then

$$\int_{\Gamma_1} f(z)dz + \int_{\Gamma_2} f(z)dz = 0$$

Now, since the integrals along L_k cancel (due to being taken in the opposite direction), only integrals along C and C_k remain. Hence

$$\begin{aligned}
&\int_{\Gamma_1} f(z)dz + \int_{\Gamma_2} f(z)dz = 0 \\
\implies &\int_C f(z)dz + \sum_{k=1}^{n+1} \int_{L_k} f(z)dz - \sum_{k=1}^{n+1} \int_{L_k} f(z)dz + \sum_{k=1}^{n} \int_{C_k} f(z)dz = 0 \\
\implies &\int_C f(z)dz + \sum_{k=1}^{n} \int_{C_k} f(z)dz = 0
\end{aligned}$$

□

Observation. *Basically, imagine a slice of Swiss cheese. We took a knife and cut a single path though all of the holes in order. Another way of saying it is that we cut through each hole only once. This way we end up with two slices each consisting a part of the outer edge of the original slice, a part of the edge of the holes, and the edges introduced by our cut. Since we have cut through all of the holes, our two slices will not have holes so we can integrate along the outer edge of each of those slices. The Cauchy-Goursat theorem tells us that the value for the sum will be zero, since they are now simply connected domains.*

Question. *We pretty much end up with two simply connected domains, right? If so then shouldn't it be:*

$$\left(\int_{\Gamma_1} f(z)dz = 0\right) \wedge \left(\int_{\Gamma_2} f(z)dz = 0\right) \implies \int_{\Gamma_1} f(z)dz + \int_{\Gamma_2} f(z)dz = 0$$

As apposed to just

$$\int_{\Gamma_1} f(z)dz + \int_{\Gamma_2} f(z)dz = 0$$

which does not imply

$$\left(\int_{\Gamma_1} f(z)dz = 0\right) \wedge \left(\int_{\Gamma_2} f(z)dz = 0\right)$$

Corollary 15.6.4.1: Principle of Deformation of Paths
Let C_1 and C_2 be positively oriented simple closed contours, with C_1 interior to C_2. If a function f is analytic on C_1, C_2, and the regions between them, then

$$\int_{C_1} f(z)dz = \int_{C_2} f(z)dz$$

Proof: It follows from theorem 15.6.4 that

$$\int_{C_1} f(z)dz - \int_{-C_2} f(z)dz = 0 \implies \int_{C_1} f(z)dz = \int_{C_2} f(z)dz$$

□

Observation. *It is easy to see that for any contour C_3 lying between contours C_1 and C_2 and on points on C_1 and C_2:*

$$\int_{C_1} f(z)dz = \int_{C_2} f(z)dz = \int_{C_3} f(z)dz$$

In fact, this theorem more powerful then it seems. It is implying that the contour integrals of a function f over any contour is equal, given that one contour can continuously deform into the other without crossing any singular points of $f(z)$. It is the key to choosing a simpler path for integration.

15.7 Cauchy Integral Formula

The Cauchy-Goursat theorem (theorem 15.6.1) gives us the value of a contour integral without singularities in the interior. What if there is a singularity in the interior? See below.

Theorem 15.7.1: Cauchy Integral Formula

Let a function f be analytic on and inside a simple closed contour C oriented positively. Then for all z_0 interior to C:

$$f(z_0) = \frac{1}{2\pi i} \int_C \frac{f(z)}{z - z_0} dz$$

That is, if f is analytic within and on a simple closed contour C, then values of f interior to C is determined by values of f on C.

Proof: Let C be a positively oriented contour and z_0 be any point interior to C. Let C_ρ be a positively oriented circular contour lying inside C centred at z_0. That is, C_ρ lies on points $|z - z_0| = \rho$. Then from corollary 15.6.4.1, we can write:

$$\begin{aligned} &\int_C \frac{f(z)}{z - z_0} dz = \int_{C_\rho} \frac{f(z)}{z - z_0} dz \\ &\implies \int_C \frac{f(z)}{z - z_0} dz - f(z_0) \int_{C_\rho} \frac{1}{z - z_0} dz = \int_C \frac{f(z) - f(z_0)}{z - z_0} dz \end{aligned}$$

Now

$$\begin{aligned} \int_{C_\rho} \frac{1}{z - z_0} dz &= \int_{C_\rho} \frac{1}{re^{i\theta}} ire^{i\theta} d\theta \qquad\qquad z = z_0 + re^{i\theta} \\ &= \int_{C_\rho} i d\theta = 2\pi i \end{aligned}$$

So

$$\int_C \frac{f(z)}{z - z_0} dz - 2\pi i f(z_0) = \int_{C_\rho} \frac{f(z) - f(z_0)}{z - z_0} dz$$

Since f is analytic, thus continuous:

$$\forall \epsilon > 0, \exists \delta > 0 [|z - z_0| < \delta \implies |f(z) - f(z_0)| < \epsilon]$$

Now, $|z - z_0| = \rho < \delta$ for all z on C_ρ, so according to theorem 15.4.1:

$$\left| \int_{C_\rho} \frac{f(z) - f(z_0)}{z - z_0} dz \right| < \frac{\epsilon}{\rho}(2\pi\rho) = 2\pi\epsilon \qquad\qquad \left| \frac{f(z) - f(z_0)}{z - z_0} \right| < \frac{\epsilon}{\delta}$$

Then

$$\left| \int_C \frac{f(z)}{z - z_0} dz - 2\pi i f(z_0) \right| < 2\pi\epsilon$$

This inequality must hold for all values of $\epsilon > 0$, so

$$\int_C \frac{f(z)}{z - z_0} dz - 2\pi i f(z_0) = 0 \implies \int_C \frac{f(z)}{z - z_0} dz = 2\pi i f(z_0)$$

$\square$

The Cauchy Integral Theorem links $f(z_0)$ to a contour integral. The extension of the Cauchy Integral Formula links the n-th derivative of f, $f^{(n)}(z_0)$, to the contour integral of f at z_0.

Theorem 15.7.2: Cauchy Integral Formula (Extension)

Let a function f be analytic on and inside a simple closed contour C oriented positively. Then for all z_0 interior to C:

$$f^{(n)}(z_0) = \frac{n!}{2\pi i}\int_C \frac{f(z)}{(z-z_0)^{n+1}}dz \qquad n \in \mathbb{N}\cup\{0\}$$

Proof: Proof that is not a proof, but a verification in Brown and Churchill [2].
Taking the original Cauchy Integral formula:

$$f(z) = \frac{1}{2\pi i}\int_C \frac{f(s)}{s-z}ds \implies f'(z) = \frac{1}{2\pi i}\int_C f(z)\frac{\partial}{\partial z}(s-z)^{-1}ds = \frac{1}{2\pi i}\int_C \frac{f(s)}{(s-z)^2}ds$$

Continued differentiation under the integral sign yields the desired result...or does it? Verification is needed.

<u>**Verification**</u>

Let z be any point interior to a simple closed contour C, and d denote the smallest distance from z to points s on C. Assume $0 < |\Delta z| < d$, then

$$\begin{aligned}\frac{f(z+\Delta z)-f(s)}{\Delta z} &= \frac{1}{2\pi i}\int_C\left(\frac{1}{s-z-\Delta z}-\frac{1}{s-z}\right)\frac{f(s)}{\Delta z}ds\\ &= \frac{1}{2\pi i}\int_C \frac{f(s)}{(s-z-\Delta z)(s-z)}ds\end{aligned}$$

Now

$$\frac{1}{(s-z-\Delta z)(s-z)} = \frac{1}{(s-z)^2} + \frac{\Delta z}{(s-z-\Delta z)(s-z)^2}$$

Hence

$$\frac{f(z+\Delta z)-f(s)}{\Delta z} - \frac{1}{2\pi i}\int_C \frac{f(s)}{(s-z)^2}ds = \frac{1}{2\pi i}\int_C \frac{f(s)\Delta z}{(s-z-\Delta z)(s-z)^2}ds$$

Let $M = \max|f(s)|$ on C, since $|s-z| \geq d$ and $|\Delta z| < d$:

$$|s-z-\Delta z| = |(s-z)-\Delta z| \geq ||s-z|-|\Delta z|| \geq d-|\Delta z| > 0$$

Then letting L be the length of C and using theorem 15.4.1:

$$\left|\int_C \frac{f(s)\Delta z}{(s-z-\Delta z)(s-z)^2}\right| \leq \frac{|\Delta z|M}{(d-|\Delta z|)d^2}L$$

Taking the limit $\Delta z \to 0$:

$$\lim_{\Delta z\to 0}\left|\int_C \frac{f(s)\Delta z}{(s-z-\Delta z)(s-z)^2}\right| \leq \lim_{\Delta z\to 0}\frac{|\Delta z|M}{(d-|\Delta z|)d^2}L = 0$$

Hence

$$\lim_{\Delta z \to 0} \frac{f(z+\Delta z) - f(s)}{\Delta z} - \frac{1}{2\pi i}\int_C \frac{f(s)}{(s-z)^2} ds = \lim_{\Delta z \to 0} \frac{1}{2\pi i}\int_C \frac{f(s)\Delta z}{(s-z-\Delta z)(s-z)^2} ds = 0$$

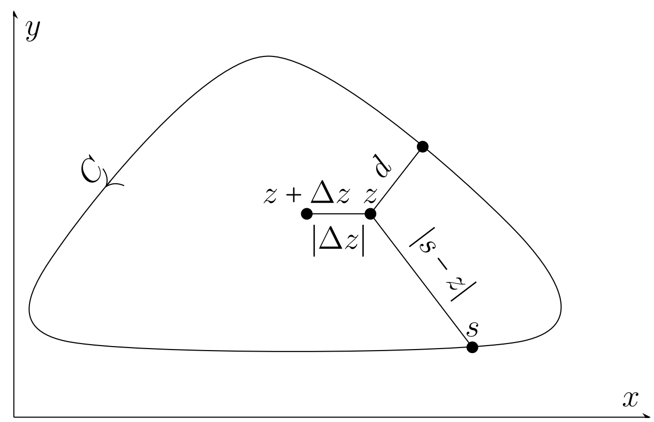
Thus

$$\lim_{\Delta z \to 0} \frac{f(z+\Delta z) - f(s)}{\Delta z} = \frac{1}{2\pi i}\int_C \frac{f(s)}{(s-z)^2} ds$$

By induction, we get:

$$f^{(n)}(z) = \frac{n!}{2\pi i}\int_C \frac{f(s)}{(s-z)^{n+1}} ds \qquad n \in \mathbb{N} \cup \{0\}$$

□



Example 15.7.1 *We can then rewrite the Legendre Polynomials:*

$$P_n(z) = \frac{1}{n!2^n}\frac{\mathrm{d}^n}{\mathrm{d}z^n}\left(z^2-1\right)^2 = \frac{1}{2^{n+1}\pi i}\int_C \frac{(s^2-1)^n}{(s-z)^{n+1}} ds \qquad n \in \mathbb{N} \cup \{0\}$$

15.7.1 Consequences

Theorem 15.7.3:

Let a function f be analytic at a point z_0, then $f^{(n)}$ exists at z_0 for all $n \in \mathbb{N}$. That is, the derivative of f of all orders are analytic at z_0.

Proof: Suppose a function f is analytic at point z_0, then there exists a neighbourhood $\epsilon > |z - z_0|$ where f is analytic. By extension, there is a positively oriented circular contour C_0 centred at z_0 with radius $\epsilon/2$ where f is analytic on and inside C_0. Then by theorem 15.7.2:

$$f''(z) = \frac{1}{\pi i}\int_{C_0} \frac{f(s)}{(s-z)^3} ds \qquad \forall z \text{ interior to } C_0$$

The existence of of $f''(z)$ in $|z - z_0| < \epsilon \implies f'$ is analytic at z_0. The same argument on f' implies f'' is also analytic. □

Note: Suppose $f(z) = u(x,y) + iv(x,y)$ is analytic at $z = (x,y)$. Then it is also continuous:

$$\begin{aligned} f(z) = u(x,y) + iv(x,y) &\implies [f'(z) = u_x + iv_x = v_y - iu_y] \wedge [f' \text{ is continuous }] \\ &\implies [f''(z) = u_{xx} + iv_{xx} = v_{xy} - iu_{yx}] \wedge [f'' \text{ is continuous}] \end{aligned}$$

Corollary 15.7.3.1:

Let a function $f(z) = u(x,y)+iv(x,y)$ be analytic at a point z_0. Then u and v have continuous partial derivatives of all orders at z_0.

Theorem 15.7.4:

Let a function f be continuous on domain D, and C be any closed contour lying in D.

$$\forall C \left[\int_C f(z) dz = 0 \right] \implies f \textit{ is analytic throughout } D$$

If D is simply connected, this is the converse of theorem 15.6.3.

Proof:

$$\begin{aligned} f \text{ is continous in } D &\implies \forall z \in D, \exists F(z)[F'(z) = f(z)] && \textit{Theorem } 15.5.1 \\ &\implies f \text{ is analytic in } D && \textit{Theorem } 15.7.3 \end{aligned}$$

□

Theorem 15.7.5: Cauchy's Inequality

Let a function f be analytic on and inside a positively oriented circular contour C_R centered at z_0 with radius R.

$$M_R = \max |f(z)| \Big|_{C_R} \implies \left| f^{(n)}(z_0) \right| \leq \frac{n! M_R}{R^n} \qquad n \in \mathbb{N}$$

Proof: From theorem 15.4.1:

$$\begin{aligned} f^{(n)}(z_0) &= \frac{n!}{2\pi i} \int_{C_R} \frac{f(z)}{(z - z_0)^{n+1}} && n \in \mathbb{N} \\ \implies \left| f^{(n)}(z_0) \right| &\leq \frac{n!}{2\pi} \cdot \frac{M_R}{R^{n+1}} \cdot 2\pi R = \frac{n! M_R}{R^n} && |z - z_0| \leq R, \; n \in \mathbb{N} \end{aligned}$$

□

15.8 Liouville's Theorem and the Fundamental Theorem of Algebra

Theorem 15.8.1: Liouville's Theorem

Let f be a function in the complex plane

$$f \textit{ is entire and bounded in } \mathbb{C} \implies f(z) \textit{ is constant in } \mathbb{C}$$

Proof: f is entire so $\forall z \in \mathbb{C}$ $f'(z)$ exists. Then From theorem 15.7.5, and f being bounded:

$$|f'(z_0)| \leq \frac{M_R}{R} = \frac{M}{R} \qquad\qquad n = 1, \forall z \in C, \exists M[|f(z)| \leq M]$$

This inequality must hold for all values of R (R can be arbitrarily large), so we find:

$$|f'(z_0)| = 0 \implies f \text{ is constant}$$

□

Observation. *Liouville's Theorem implies that any non-constant function in $\mathbb{C}$ is either not entire or unbounded. See the Maximum Modulus Principle (theorem 15.9.2).*

Question. *Shouldn't Liouville's theorem be $\iff$ since a constant function is also entire and bounded?*

Intuitively, this tells us that if f is bounded by $f(z_0)$, then $f(z_0)$ must either be a maximum or a minimum. This can not be the case since it violates f being a harmonic function, where the sum of curvatures in each component direction is zero.

Theorem 15.8.2: Fundamental Theorem of Algebra

Let $P(z) = \sum_{i=0}^{n} a_i z^i$ be any polynomial, then

$$\forall n \in \mathbb{N}, \exists z_0 \in \mathbb{C}[P(z_0) = 0]$$

Proof: Suppose for contradiction $\nexists z_0 \in \mathbb{C}$ such that $P(z_0) = 0$ Recall from corollary 12.2.1.1 that $\exists R \in \mathbb{R}$ such that

$$\left|\frac{1}{P(z)}\right| < \frac{2}{|a_n|R^n} \qquad\qquad \forall z \in \mathbb{C}[|z| > R]$$

$1/P(z)$ is bounded on for $|z| > R$, but $P(z)$ is continuous on $|z| \leq R$, which implies that $1/P(z)$ is bounded for $|z| \leq R$. Thus $P(z)$ is bounded in the entire complex plane. (Theorem 13.3.5) It follows from theorem 15.8.1 that $1/P(z)$ is constant $\implies$ $P(z)$ is constant, but $P(z)$ is not constant. Contradiction! □

Theorem 15.8.2 tells us that any polynomial of degree $n \geq 1$ can be expressed as a product of linear factors:

$$P(z) = c\prod_{i=1}^{i=n}(z - z_i)$$

Since the existence of a zero z_1 implies

$$P(z) = (z - z_1)Q_1(z) \qquad\qquad \deg(Q_1) = n - 1$$

Result follows from induction.

15.9 Maximum Modulus Principle

Theorem 15.9.1: Gauss's Mean Value Theorem

Let f be a function analytic in and on a circular contour C_ρ centred at z_0, then $f(z_0)$ is the arithmetic mean of the values on the circle:

$$f(z_0) = \frac{1}{2\pi i}\int_0^{2\pi} f(z_0 + \rho e^{i\theta})d\theta \qquad z = z_0 + \rho e^{i\theta},\ 0 \leq \theta \leq 2\pi$$

That is, the value of $f(z_0)$ is the average of the values of $f(z)$ in some neighbourhood with radius ρ around z_0.

Proof: Let C_ρ be a circular contour centred at z_0, and $|z - z_0| = \rho$. Then by the Cauchy Integral formula (theorem 15.7.1):

$$f(z_0) = \frac{1}{2\pi i}\int_{C_\rho} \frac{f(z)}{z - z_0}dz = \frac{1}{2\pi i}\int_0^{2\pi} f(z_0 + \rho e^{i\theta})d\theta \qquad z = z_0 + \rho e^{i\theta},\ 0 \leq \theta \leq 2\pi$$

□

Lemma 15.9.1.1:

Let f be a function analytic in some neighbourhood $|z - z_0| < \epsilon$:

$$\forall z \in \{z : |z - z_0| < \epsilon\}[|f(z)| \leq |f(z_0)|] \implies \forall z \in \{|z - z_0| < \epsilon\}[f(z) = f(z_0)]$$

That is, if f is bounded by its value at z_0 in the neighbourhood of z_0, then it is constant throughout the neighbourhood with value $f(z_0)$.

Proof: Following theorem 15.9.1, we have

$$f(z_0) = \frac{1}{2\pi i}\int_0^{2\pi} f(z_0 + \rho e^{i\theta})d\theta \implies |f(z_0)| \leq \frac{1}{2\pi}\int_0^{2\pi} \left|f(z_0 + \rho e^{i\theta})\right|d\theta$$

However, since we have condition $|f(z)| = |f(z_0 + \rho e^{i\theta})| \leq |f(z_0)|$:

$$\int_0^{2\pi} \left|f(z_0 + \rho e^{i\theta})\right|d\theta \leq \int_0^{2\pi} |f(z_0)|d\theta = 2\pi|f(z_0)| \qquad 0 \leq \theta \leq 2\pi$$
$$\implies |f(z_0)| \geq \frac{1}{2\pi}\int_0^{2\pi} \left|f(z_0 + \rho e^{i\theta})\right|d\theta$$

The inequalities tells us:

$$|f(z_0)| = \frac{1}{2\pi}\int_0^{2\pi} \left|f(z_0 + \rho e^{i\theta})\right|d\theta \implies \int_0^{2\pi} |f(z_0)| - \left|f(z_0 + \rho e^{i\theta})\right|d\theta = 0$$

Our condition $|f(z)| = |f(z_0 + \rho e^{i\theta})| \leq |f(z_0)|$ tells us that

$$\int_0^{2\pi} \left|f(z_0 + \rho e^{i\theta})\right|d\theta \leq \int_0^{2\pi} |f(z_0)|d\theta \implies \int_0^{2\pi} |f(z_0)| - \left|f(z_0 + \rho e^{i\theta})\right|d\theta \geq 0$$

So for $\int_0^{2\pi} |f(z_0)| - |f(z_0 + \rho e^{i\theta})| d\theta = 0$, the integrand must be zero:

$$\begin{aligned} & \left|f(z_0 + \rho e^{i\theta})\right| - |f(z_0)| = 0 && 0 \le \theta \le 2\pi \\ \implies & \forall z \in \{z : |z - z_0| = \rho\}[|f(z)| = |f(z_0)|] \end{aligned}$$

Since $0 < |z - z_0| < \epsilon$ and $|f(z)| = |f(z_0)|$ for all $0 < \rho < \epsilon$, we have $|f(z)| = |f(z_0)|$ for $|z - z_0| < \epsilon$. We know that if a function is analytic in a domain and its modulus is constant in the domain, then the function is constant (example 13.6.4), thus

$$\forall z \in \{z : |z - z_0| < \epsilon\}[f(z) = f(z_0)]$$

That is $f(z)$ is constant in the neighbourhood $|z - z_0| < \epsilon$ with value $f(z_0)$. $\square$

Theorem 15.9.2: Maximum Modulus Principle

Let f be an analytic function in a domain D.

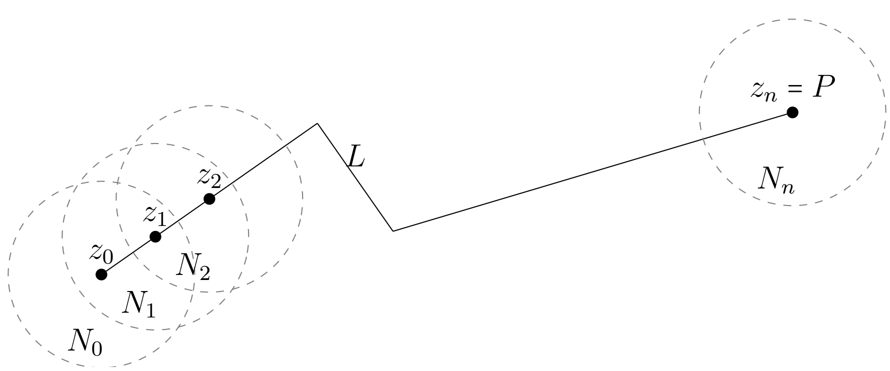
$$f \text{ not constant in } D \implies \forall z \in D, \nexists z_0 \in D[|f(z)| \le |f(z_0)| = M]$$

That is, if an analytic function is not constant in a domain D, then it is not bound.

Proof: Suppose for contradiction f is bounded in domain D. That is $\forall z \in D[|f(z)| \le M]$. Let L be a polygonal line lying in D extending from z_0 to any arbitrary $z_n = P$ in D, and d be the shortest distance from points on L to the boundary of D. Then for each point z_k ($k \in [0, n]$), we have $|z_k - z_{k-1}| < d$ and neighbourhoods N_k.

Each neighbourhood N_k has radius d and the center of each neighbourhood N_k lies in the neighbourhood of N_{k-1}.

Since $\max|f(z)| = |f(z_0)|$, by lemma 15.9.1.1, all points in N_0 has value $f(z_0)$. The neighbourhoods overlap, so by extension $\forall k \in [0, n]$, $f(z_k) = f(z_0)$, and we have $f(z)$ is constant in D with value $f(z_0)$. f is then bounded in D and we have a contradiction! Thus, if an analytic function f is not constant in domain D, then it is not bounded. $\square$



For a closed bounded region R, the Maximum Modulus Principle may seem to contradict theorem 13.3.5. It is important to realize that we are working with a domain and the differences between a domain (definition 12.7.12) and region (definition 12.7.13).

Corollary 15.9.2.1:

Let f be an analytic function on a closed bounded region R that is not constant in the interior of R. Then $\max|f(z)|$ in R is always reached and only reached at some boundary of R, never in the interior of R.

Proof: Consider

$$f(x,y) = u(x,y) + iv(x,y)$$

Then as f as analytic in R, u is harmonic in R and can not assume maximum value in the interior of R. The same logic applies to v. (See Maximum Principle.)

More precisely, consider $g(z) = e^{f(z)}$, then g is analytic, continuous, and non-constant in the interior of R. Hence $|g(z)| = |e^{u(x,y)}|$ must assume its maximum value at the boundary of R, so $f(z)$ must also obtain its maximum at the boundary of R. □

Note: Same is true for $\min|f(z)|$ (Example 15.9.2).

Note: Corollary 15.9.2.1 follows from the properties of $f(z) = u(x,y) + iv(x,y)$ being able to be expressed in terms of real valued functions and that harmonic real valued functions only have maximum and minimum values occurring at the boundaries of a closed and bounded region. We will soon see this in example 15.9.2 and example 15.9.3.

Note: There is a difference between complex-valued functions and real-valued functions. For complex valued functions $f(z)$, the maximums and minimums of the modulus $|f(z)|$ occur at some boundary of R, while for some real-valued function $u(x,y)$ (no modulus) the maximum and minimum occurs only at some boundary of R.

Note: This can be seen a result of Gauss's Mean Value Theorem (theorem 15.9.1).

15.9.1 Examples

Example 15.9.1 *Suppose that $f(z)$ is entire and that the function $u(x,y) = \text{Re}\{f(z)\}$ is harmonic and has upper bound $u_0 \geq u(x,y)$ for all $(x,y) \in \mathbb{R}^2$. Then $u(x,y)$ is constant in $\mathbb{R}^2$.*

Proof: Consider $g(z) = e^{f(z)} = e^{u(x,y)}e^{iv(x,y)}$. $e^{iv(x,y)}$ is a phase, so we ignore it and focus on $e^{u(x,y)}$:

$$\begin{aligned} & e^{u(x,y)} \text{ is entire} \\ \implies & \exists (x_0,y_0) \in \mathbb{R}^2 \left[\left| e^{u(x,y)} \right| \leq u_0 = u(x_0,y_0) \right] && \text{Cauchy's Inequalitey } (\textit{Theorem } 15.7.5) \\ \implies & e^{u(x,y)} \text{ is constant} && \text{Liouville's Theorem } (\textit{Theorem } 15.8.1) \end{aligned}$$

□

Example 15.9.2 *Let a function f be continuous on a closed bounded region R, and be analytic and not constant throughout the interior of R. Also, let $f(z) \neq 0$ for all $z \in \mathbb{R}$. Prove* $\min|f(z)|$ *only occurs at the boundaries and never in the interiors of R.*

Proof: Consider $g(z) = 1/f(z)$.

$$\begin{aligned}
& f \text{ is continuous, analytic, non-constant, and } \forall z/inR[f(z) \neq 0] \\
& \implies g \text{ is continuous, analytic, non-constant} \\
& \implies \max|g(z)| \text{ only occurs at boundary of } R && \textit{Corollary } 15.9.2.1 \\
& \implies \min|f(z)| \text{ occurs only at some boundary of } R
\end{aligned}$$

As for why $f(z) \neq 0$ for all $z \in R$ is required:
Suppose $f(z_0) = 0$ for some z_0 in the interior of R.

$$\begin{aligned}
& \implies g(z) = 1/f(z) \text{ is not countinuous in } R && \textit{Corollary } 15.9.2.1 \\
& \implies \max|g(z)| \text{ does not occur only some boundary of } R \\
& \implies \min|f(z)| \text{ exists in the interior of } R
\end{aligned}$$

□

Question. *If $f(z_0) = 0$ for some z_0 in the interior of R, then does that mean* $\min|f(z_0)| = 0$ *for all $z_0 \in \{z : f(z) = 0\}$?*

Example 15.9.3 *Let $f(z) = u(x,y) + iv(x,y)$ be a function continuous on a closed bounded region R be analytic and not constant in the interior of R. Prove* $\min u(x,y)$ *occurs only at some boundary of R.*

Proof: Let $f(z) = u_1(x,y) + iv_1(x,y)$ and $g(z) = e^{1/f(z)} = e^{u_2(x,y)+iv_2(x,y)}$, which is continuous, analytic, and not constant in the interior of R. Then $|g(z)| = e^{u_2(x,y)}$ is continuous in R must have a maximum at the some boundary of R. Hence, $f(z)$ has a minimum at some boundary of R. □

15.10 Poisson Integral Formula

We are looking to solve the Dirichlet Problem (definition 17.0.1). Finding a function in a harmonic domain that assumes preassigned values at the boundary.

Definition 15.10.1: Poisson Integral Formula (Circle Interior)

Let f be a complex-valued function on a circular simple closed domain with radius R, and C be a circular contour an the boundary of the domain. Then the Dirichlet Problem is solved in the domain by

$$u(r,\theta) = \frac{1}{2\pi}\int_0^{2\pi} \frac{u(R,\phi)(R^2 - r^2)}{R^2 + r^2 - 2Rr\cos(\phi - \theta)} d\phi$$

Proof: Let z be any point inside a circular domain with radius R, f be an analytic function throughout the interior of the domain, and C be a circular contour on the boundary of the domain. Consider the Cauchy Integral Formula (theorem 15.7.1):

$$f(z) = \frac{1}{2\pi i}\int_C \frac{f(w)}{w-z}dw$$

Define a point that lies outside the circle: $z_1 = R^2/\bar{z}$

Where

$$|z_1| = \frac{R^2}{|\bar{z}|} = \frac{R^2}{|z|} > R \qquad\qquad |z| < R$$
$$\arg(z_1) = \arg(z)$$

Then by Cauchy-Goursat (theorem 15.6.1)

$$\frac{1}{2\pi i}\int_C \frac{f(w)}{w-z_1}dw = \frac{1}{2\pi i}\int_C \frac{f(w)}{w-(R^2/\bar{z})}dw = 0$$

Subtracting the two equations:

$$\begin{aligned}
f(z) &= \frac{1}{2\pi i}\int_C f(w)\left[\frac{1}{w-z} - \frac{1}{w-(R^2/\bar{z})}\right]dw \\
&= \frac{1}{2\pi i}\int_C f(w)\left[\frac{z-(R^2/\bar{z})}{(w-z)[w-(R^2/\bar{z})]}\right]dw \\
&= \frac{1}{2\pi i}\int_C f(R,\phi)\left[\frac{re^{i\theta} - [R^2/(re^{-i\theta})]}{(Re^{i\phi}-re^{i\theta})\{Re^{i\phi}-[R^2/(re^{-i\theta})]\}}\right]Re^{i\phi}i\ d\phi \qquad w = Re^{i\phi} \\
&= \frac{1}{2\pi}\int_0^{2\pi} \frac{f(R,\phi)(R^2-r^2)}{R^2+r^2-2Rr\cos(\phi-\theta)}d\phi
\end{aligned}$$

Separating into real and imaginary parts:

$$u(r,\theta) + iv(r,\theta) = \frac{1}{2\pi}\int_0^{2\pi} \frac{[u(R,\phi)+iv(R,\phi)][R^2-r^2]}{R^2+r^2-2Rr\cos(\phi-\theta)}d\phi$$

Taking the real part yields the desired result. $\square$

Definition 15.10.2: Poisson Integral Formula (Upper Half Plane)

Consider the Dirichlet problem for the upper half of the complex plane ($y > 0$) which satisfies the boundary condition $U(X,0)$ on $Y = 0$. Then the Dirichlet Problem is solved by

$$v(x,y) = \frac{y}{\pi}\int_{-\infty}^{\infty} \frac{u(X,0)}{(X-x)^2+y^2}dX$$

Proof: Let $f(w) = U(X,Y) + iV(X,Y)$ be analytic for $Y > 0$, and C be the contour comprised of the semi-circular arc from R to $-R$ on the upper half of the complex, and the line from $-R$ to R on the real axis. Then from the Cauchy Integral Formula (theorem 15.7.1):

$$f(z) = \frac{1}{2\pi i}\int_C \frac{f(w)}{w-z}dw$$

Then for all z with $\mathrm{Im}\{z\} > 0$ and by the Cauchy-Goursat theorem (theorem 15.6.1):

$$\frac{1}{2\pi i}\int_C \frac{f(w)}{(w-\bar{z})}dw = 0$$

Subtracting the two equations:

$$f(z) = \frac{1}{2\pi i}\int_C f(w)\left[\frac{1}{w-z} - \frac{1}{w-\bar{z}}\right]dw = \frac{1}{2\pi i}\int_C \frac{z-\bar{z})}{(w-z)(w-\bar{z})}dw$$

By breaking up C into the line L and arc A components:

$$\begin{aligned} f(z) &= \frac{1}{2\pi i}\int_L \frac{(z-\bar{z})f(w)}{(w-z)(w-\bar{z})}dw + \frac{1}{2\pi i}\int_C \frac{(z-\bar{z})f(w)}{(w-z)(w-\bar{z})}dw \\ &= \frac{y}{\pi}\int_{-R}^{R} \frac{f(X)}{(X-x)^2+y^2}dX + \frac{y}{\pi}\int_A \frac{f(w)}{(w-z)(w-\bar{z})}dw \qquad w = X + iY \end{aligned}$$

Taking the limit as $R \to \infty$, letting $z = x + iy$ and $M = \max|f(w)|$ on A, and knowing $y \le R$ and $r \le R$ (since $z = re^{i\theta}$ is within the semi-circle):

$$\begin{aligned} &\lim_{R\to\infty}\left|\int_A \frac{f(w)}{(w-z)(w-\bar{z})}dw\right| \\ &\le \lim_{R\to\infty}\left|\frac{M}{(Re^{i\phi}-re^{i\theta})(Re^{i\phi}-re^{-i\theta})}\right||\pi R| \qquad \textit{Theorem } 15.4.1 \\ &= \lim_{R\to\infty}|\pi R|\left|\frac{M}{R^2e^{2i\phi} - Rre^{i(\phi-\theta)} - Rre^{i(\phi+\theta)} + r^2}\right| \\ &\le \lim_{R\to\infty}|\pi R|\frac{|M|}{|R^2+r^2|} = 0 \end{aligned}$$

Hence, the contour integral on the arc disappears and we are left with:

$$f(z) = \frac{y}{\pi}\int_{-\infty}^{\infty} \frac{f(X)}{(X-x)^2+y^2}dX$$

Thus

$$U(x,y) + iV(x,y) = \frac{y}{\pi}\int_{-\infty}^{\infty} \frac{U(X,0)+iV(X,0)}{(X-x)^2+y^2}dX$$

Taking the real part yields the desired results. □

Chapter 16

Series

16.1 Convergence

Definition 16.1.1: Limit
Let $z_1, z_2, z_3, \dots$ be an infinite sequence of complex numbers. We say a limit exists for the sequence if

$$\forall \epsilon > 0, \exists n_0 \in \mathbb{N}[n > n_0 \implies |z_n - z| < \epsilon]$$

Definition 16.1.2: Converge (Series)
If such limit exists, we say the sequence converges to z and that

$$\lim_{n\to\infty} z_n = z$$

Definition 16.1.3: Diverge (Series)
If a limit does not exists for a series.

Theorem 16.1.1:
Let $z_n = x_n + iy_n$ for $n \in \mathbb{N}$ and $z = x + iy$. Then

$$\lim_{n\to\infty} z_n = z \iff \left[\lim_{n\to\infty} x_n = x\right] \wedge \left[\lim_{n\to\infty} y_n = y\right]$$

Proof: $\underline{\impliedby:}$

$$\left[\lim_{n\to\infty} x_n = x\right] \wedge \left[\lim_{n\to\infty} y_n = y\right]$$
$$\implies \forall \epsilon > 0, \exists n_1, n_2 \in \mathbb{N}\left[\left(n > n_1 \implies |x_n - x| < \frac{\epsilon}{2}\right) \wedge \left(n > n_2 \implies |y_n - y| < \frac{\epsilon}{2}\right)\right]$$

Let $n_0 = \max(n_1, n_2)$, then:

$$n > n_0 \implies \left[|x_n - x| < \frac{\epsilon}{2}\right] \wedge \left[|y_n - y| < \frac{\epsilon}{2}\right]$$

Since

$$|(x_n - iy_n) - (x + iy)| = |(x_n - x) + i(y_n - y)| \le |x_n - x| + |y_n - y|$$

Thus

$$n > n_0 \implies |z_n - z| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon$$

$\underline{\implies:}$

$$\lim_{n\to\infty} z_n = z \implies [n > n_0 \implies |(x_n + iy_n) - (x + iy)| < \epsilon]$$

However,

$$|x_n - x| \le |(x_n - x) + i(y_n - y)| = |(x_n + iy_n) - (x + iy)|$$
$$|y_n - y| \le |(x_n - x) + i(y_n - y)| = |(x_n + iy_n) - (x + iy)|$$

Hence

$$[n > n_0 \implies (|x_n - x| < \epsilon) \wedge (|y_n - y| < \epsilon)] \implies \left(\lim_{n\to\infty} x_n = x\right) \wedge \left(\lim_{n\to\infty} y_n = y\right)$$

Thus

$$\lim_{n\to\infty} z_n = z \iff \left[\lim_{n\to\infty} x_n = x\right] \wedge \left[\lim_{n\to\infty} y_n = y\right]$$

□

Be extra careful when converting to polar coordinates:

Example 16.1.1 *It is easy to see that*

$$\lim_{n\to\infty} z_n = -1 + i\frac{(-1)^n}{n^2} = -1 \qquad\qquad n \in \mathbb{N}$$

Converting to polar:

$$r_n = |z_n| \qquad\qquad \Theta_n = \operatorname{Arg}(z_n) \qquad\qquad n \in \mathbb{N},\ -\pi < \Theta_n \le \pi$$

Then

$$\lim_{n\to\infty} r_n = \lim_{n\to\infty} \sqrt{1 + \frac{1}{n^4}} = 1$$

But

$$\lim_{n\to\infty} \Theta_{2n} = \pi \qquad\qquad \lim_{n\to\infty} \Theta_{2n-1} = -\pi \qquad\qquad n \in \mathbb{N}$$

The limit of Θ_n does not exist as $n \to \infty$.

Definition 16.1.4: Partial Sum (Series)

Consider a infinite series

$$\sum_{n=1}^{\infty} z_n$$

A partial sum is a finite sum of of the first N terms of the infinite series, that is:

$$S_N = \sum_{n=1}^{N} z_n \qquad\qquad N \in \mathbb{N}$$

Definition 16.1.5: Converge (Series)

We say a series converge to sum S if the sequence of partial sums converges to S.

Definition 16.1.6: Divergence (Series)

A series diverge if its sequence of partial sums does not converge to sum S.

Theorem 16.1.2:

Let $z_n = x_n + iy_n$ for $n \in \mathbb{N}$ and $S = X + iY$, then

$$\sum_{n=1}^{\infty} z_n = S \iff \left[\sum_{n=1}^{\infty} x_n = X\right] \wedge \left[\sum_{n=1}^{\infty} y_n = Y\right]$$

Proof:

$$S_N = X_N + iY_N = \sum_{n=1}^{N} x_n + i\sum_{n=1}^{\infty} y_n$$

Then

$$\lim_{N\leftarrow\infty} S_N = S \iff \left[\lim_{N\to\infty} X_N = X\right] \wedge \left[\lim_{N\to\infty} Y_N = Y\right]$$

□

Corollary 16.1.2.1:

Let $z_1, z_2, z_3, \ldots$ be an infinite sequence of complex numbers. Then $z_n \to 0$ as $n \to \infty$.

Proof: Follows from the n-th term of a convergent series of real number tends to zero as $n \to \infty$. □

Corollary 16.1.2.2:

Convergent series are bounded, that is:

$$\forall n \in \mathbb{N}, \exists M \in \mathbb{R}_{>0}[|z_n| \leq M]$$

Definition 16.1.7: Absolutely Convergent (Series)
A series is absolutely convergent if

$$\sum_{n=1}^{\infty} |z_n| = \sum_{n=1}^{\infty} \sqrt{x_n^2 + y_n^2} \qquad\qquad z_n = x_n + iy_n$$

converges to some real number.

Corollary 16.1.2.3:
Absolute Convergence $\implies$ *Convergence*

Proof: Assume a complex series converges absolutely.

$$|x_n| \le \sqrt{x_n^2 + y_n^2} \qquad\qquad |y_n| \le \sqrt{x_n^2 + y_n^2}$$

Then by comparison test, the following must converge

$$\sum_{n=1}^{\infty} |x_n| \qquad\qquad \sum_{n=1}^{\infty} |y_n|$$

Result follows from the absolute convergence of real series implies convergence of real series (corollary 9.0.0.1). ☐

Definition 16.1.8: Remainder (Series Definition - Complex)
Let S be an infinite series, the remainder after N terms:

$$\rho_N = S - S_N$$

Corollary 16.1.2.4:
Series tend to S $\iff$ *Sequence of ρ_N tends to 0*

Example 16.1.2 *Verify following using remainders:*

$$\sum_{n=0}^{\infty} z^n = \frac{1}{1-z} \qquad\qquad |z| < 1$$

Consider the series:

$$Z = \sum_{n=0}^{N} z^n \qquad\qquad z \ne 1$$

Then

$$Z - Zz = \sum_{n=0}^{N} z^n - \sum_{n=1}^{N+1} z^n = 1 - z^{N+1} \implies Z = \sum_{n=0}^{N} z^n = \frac{1 - z^{N+1}}{1-z}$$

Now, we can use this to write the partial sum:

$$S_N(z) = \sum_{n=0}^{N-1} z^n = \frac{1 - z^n}{1 - z}$$

If we let:

$$S(z) = \frac{1}{1-z} \implies \rho_N(z) = S(z) - S_N(z) = \frac{z^N}{1-z}$$
$$\implies |\rho_N(z)| = \frac{|z|^N}{|1-z|}$$

It is clear that $\rho_N(z) \to 0$ *for* $z < 1$*, so* $\sum_{n=0}^{\infty} z^n = 1/(1-z)$ *is established.*

16.2 Taylor Series

Definition 16.2.1: Power Series

Let R *be a region containing a point* z_0*. A power series is a series of the form*

$$\sum_{n=0}^{\infty} a_n(z - z_0)^n \qquad\qquad z_0, a_n \in \mathbb{C}, \;\; z \in R$$

Theorem 16.2.1: Taylor's Theorem

Let f *be a function analytic throughout a disk* $|z - z_0| < R_0$ *with radius* R_0*. Then* $f(z)$ *has the power series representation:*

$$f(z) = \sum_{n=0}^{\infty} a_n(z - z_0)^n \qquad a_n = \frac{f^{(n)}(z_0)}{n!} \qquad |z - z_0| < R_0, \;\; n \in \mathbb{N} \cup \{0\}$$

Note: By extension, f *must also be analytic at* z_0*.*

Proof: Let C_0 be a circular contour with radius $|s| = r_0$ and z be any point inside the circle, so $|z| = r$. Now suppose there is a bigger circle enveloping C_0 with radius R_0 such that $r < r_0 < R_0$. Let f be analytic in and on C_0.

$\underline{z_0 = 0}$:
f is analytic in and on C_0, we can use the Cauchy-Integral formula (theorem 15.7.1):

$$f(z) = \frac{1}{2\pi i} \int_{C_0} \frac{f(s)}{s - z} ds$$

Recall from example 16.1.2:

$$\frac{1}{1-z} = \sum_{n=0}^{N-1} z^n + \frac{z^n}{1-z} \implies \frac{1}{s-z} = \sum_{n=0}^{N-1} \frac{1}{s^{n+1}} z^n + \frac{z^N}{(s-z)s^N}$$

We can then write the Cauchy Integral formula:

$$f(z) = \frac{1}{2\pi i}\left[\sum_{n=0}^{N-1}\left(\int_{C_0}\frac{f(s)}{s^{n+1}}ds\right)z^n + z^N\int_{C_0}\frac{f(s)}{(s-z)s^N}ds\right]$$

Using the theorem 15.7.2:

$$\frac{1}{2\pi i}\int_{C_0}\frac{f(z)}{s^{n+1}}ds = \frac{f^{(n)}(0)}{n!} \qquad\qquad n\in\mathbb{N}\cup\{0\}$$

We get

$$f(z) = \sum_{n=0}^{N-1}\frac{f^{(n)}(0)}{n!}z^n + \rho_N(z) \qquad\qquad \rho_N(z) = \frac{z^N}{2\pi i}\int_{C_0}\frac{f(s)}{(s-z)s^N}ds$$

This is the Maclaurin series (definition 16.2.2) if we let $N\to\infty$. To prove it:

$$|s-z| \geq ||s|-|z|| = r_0 - r$$

Letting $M = \max|f(s)|$ on C_0:

$$|\rho_N(z)| \leq \frac{r^N}{2\pi}\cdot\frac{M}{(r_0-r)r_0^N}2\pi r_0 = \frac{Mr_0}{r_0-r}\left(\frac{r}{r_0}\right)^N$$

Thus

$$\frac{r}{r_0} < 1 \implies \lim_{N\to\infty}\left(\frac{r}{r_0}\right)^N = 0 \implies \lim_{N\to\infty}\rho_N(z) = 0$$

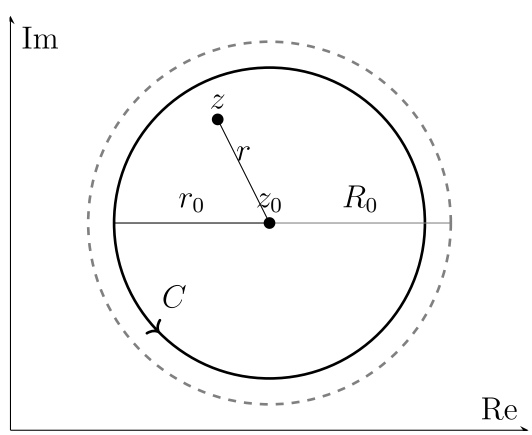
<u>$z_0 \neq 0$:</u>
Suppose f is analytic in $|z-z_0| < R_0$, then $f(z+z_0)$ must be analytic in $|(z+z_0)-z_0| < R_0$. Then

$$f(z+z_0) = g(z) = \sum_{n=0}^{\infty}\frac{g^{(n)}(0)}{n!}z^n \qquad\qquad |z| < R_0$$

$$\implies f(z+z_0) = \sum_{n=0}^{\infty}\frac{f^{(n)}(z_0)}{n!}z^n \qquad\qquad |z| < R_0$$

$$\implies f(z) = \sum_{n=0}^{\infty}\frac{f^{(n)}(z_0)}{n!}(z-z_0)^n \qquad\qquad |z| < R_0$$

□



Definition 16.2.2: Maclaurin Series

A Taylor series with $z_0 = 0$:

$$f(z) = \sum_{n=0}^{\infty} \frac{f^{(n)}(0)}{n!} z^n \qquad |z| < R_0$$

Useful identities:

$$\begin{aligned}
\frac{1}{1-z} &= \sum_{n=0}^{\infty} z^n & & & |z| < 1 \\
e^z &= \sum_{n=0}^{\infty} \frac{z^n}{n!} & & & |z| < \infty \\
\sin(z) &= \sum_{n=0}^{\infty} \frac{(-1)^n z^{2n+1}}{(2n+1)!} & \cos(z) &= \sum_{n=0}^{\infty} \frac{(-1)^n z^{2n}}{(2n)!} & |z| < \infty \\
\sinh(z) &= \sum_{n=0}^{\infty} \frac{z^{2n+1}}{(2n+1)!} & \cosh(z) &= \sum_{n=0}^{\infty} \frac{z^{2n}}{(2n)!} & |z| < \infty
\end{aligned}$$

16.3 Laurent Series

In Taylor's theorem (theorem 16.2.1), f is required to be analytic at z_0. What about the case where f does not need to be analytic at z_0? Well...

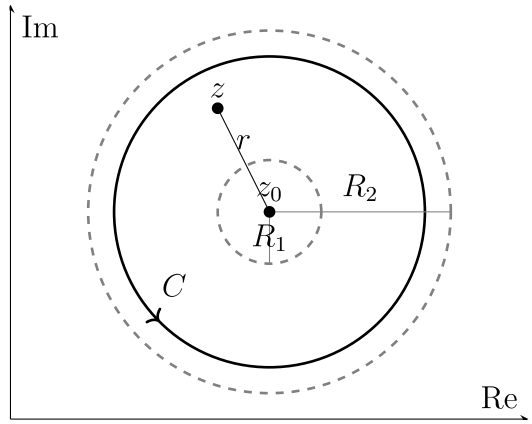
Theorem 16.3.1: Laurent's Theorem

Let f be analytic throughout an annular domain $R_1 < |z - z_0| < R_2$ centred at z_0, and C be any positively oriented simple closed contour in said domain. Then at any z in the domain:

$$\begin{aligned}
f(z) &= \sum_{n=0}^{\infty} a_n (z - z_0)^n + \sum_{n=0}^{\infty} \frac{b_n}{(z - z_0)^n} & & R_1 < |z - z_0| < R_2 \\
a_n &= \frac{1}{2\pi i} \int_C \frac{f(z)}{(z - z_0)^{n+1}} dz = \frac{f^{(n)}(z_0)}{n!} & & n \in \mathbb{N} \cup \{0\} \\
b_n &= \frac{1}{2\pi i} \int_C \frac{f(z)}{(z - z_0)^{-n+1}} dz & & n \in \mathbb{N}
\end{aligned}$$

Or (by replacing n by $-n$ in b_n):

$$f(z) = \sum_{n=-\infty}^{\infty} c_n (z - z_0)^n \qquad c_n = \frac{1}{2\pi i} \int_C \frac{f(z)}{(z - z_0)^{n+1}} \qquad R_1 < |z - z_0| < R_2, \ n \in \mathbb{Z}$$



Proof: Consider the annular regions $R_1 < r_1 \le |z| \le r_2 < R_2$ containing the point z and simple closed contour C. Let C_1 and C_2 denote the circular contours with radius r_1 and r_2, respectively. All the contours are positively oriented. Let f be an analytic function between the region enclosed by C_1 and C_2 and on C_1 and C_2.

$\underline{z_0 = 0:}$
Let γ be a circular contour centred at z and small enough to fit in the annular region $r_1 \le |z| \le r_2$. Using the Cauchy-Goursat theorem (theorem 15.6.1) on multiply connected domains (section 15.6.3):

$$\int_{C_2} \frac{f(s)}{s-z} ds - \int_{C_1} \frac{f(s)}{s-z} ds - \int_{\gamma} \frac{f(s)}{s-z} ds = 0$$

By Cauchy Integral formula (theorem 15.7.1):

$$\int_{\gamma} \frac{f(z)}{s-z} ds = 2\pi i f(z)$$

Hence

$$2\pi i f(z) = \int_{C_2} \frac{f(s)}{s-z} ds - \int_{C_1} \frac{f(s)}{s-z} ds = \int_{C_2} \frac{f(s)}{s-z} ds + \int_{C_1} \frac{f(s)}{z-s} ds$$

Using example 16.1.2:

$$\begin{aligned}
\frac{1}{s-z} &= \sum_{n=0}^{N-1} \frac{z^n}{s^{n+1}} + \frac{z^N}{(s-z)s^N} \\
\frac{1}{z-s} &= \sum_{n=0}^{N-1} \frac{1}{s^{-n}} \cdot \frac{1}{z^{n+1}} + \frac{1}{z^N} \cdot \frac{s^N}{z-s} = \sum_{n=1}^{N} \frac{1}{s^{-n+1}} \cdot \frac{1}{z^n} + \frac{1}{z^N} \cdot \frac{s^N}{z-s}
\end{aligned}$$

This implies

$$2\pi i f(z) = \int_{C_2} f(s) \left[\sum_{n=0}^{N-1} \frac{z^n}{s^{n+1}} + \frac{z^N}{(s-z)s^N} \right] ds + \int_{C_1} f(s) \left[\sum_{n=1}^{N} \frac{1}{s^{-n+1}} \cdot \frac{1}{z^n} + \frac{1}{z^N} \cdot \frac{s^N}{z-s} \right] ds$$

Interchanging the integral and summation, and dividing by $2\pi i$:

$$f(z) = \sum_{n=0}^{N-1} a_n z^n + \rho_N(z) + \sum_{n=1}^{N} \frac{b_n}{z^n} + \sigma_N(z)$$

Where

$$a_n = \frac{1}{2\pi i}\int_{C_2} \frac{f(s)}{s^{n+1}} ds \qquad \rho_N(z) = \frac{z^N}{2\pi i}\int_{C_2} \frac{f(s)}{(s-z)s^N} ds$$

$$b_n = \frac{1}{2\pi i}\int_{C_1} \frac{f(s)}{s^{-n+1}} ds \qquad \sigma_N(z) = \frac{1}{2\pi i z^N}\int_{C_1} \frac{s^N f(s)}{z-s} ds$$

This gives us the Laurent series in $R_1 \leq |z| \leq R_2$ given that

$$\lim_{N\to\infty} \rho_N(z) = 0 \qquad \lim_{N\to\infty} \sigma_N(z) = 0$$

Which we can prove by letting $|z| = r$, $r_1 < r < r_2$, and $M = \max|f(S)|$ on C_1 and C_2. Then

$$|\rho_N(z)| \leq \frac{Mr_2}{r_2 - r}\left(\frac{r}{r_2}\right)^N \qquad |s - z| \geq r_2 - r \text{ for } s \in C_2$$

$$|\sigma_N(z)| \leq \frac{Mr_1}{r - r_1}\left(\frac{r_1}{r}\right)^N \qquad |z - s| \geq r - r_1 \text{ for } s \in C_1$$

Since $r_1 < r < r_2$, we can see that

$$\lim_{N\to\infty}\left(\frac{r}{r_2}\right)^N = 0 \qquad \lim_{N\to\infty}\left(\frac{r_1}{r}\right)^N = 0$$

By corollary 15.6.4.1, we can replace C_1 and C_2 by a positively oriented closed contour C, giving us the desired expression for the Laurent series.

$z_0 \neq 0$:
Let f be analytic in $R_1 < |z - z_0| < R_2$, then $g(z) = f(z + z_0)$ is analytic in $R_1 < |(z + z_0) - z_0| = |z| < R_2$. Now let t parameterize the path Γ on C so that:

$$z = z(t) - z_0 \qquad R_1 < |z(t) - z_0| = |z| < R_2 \qquad a \leq t \leq b$$

Then g has the Laurent series representation:

$$g(z) = \sum_{n=0}^{\infty} a_n z^n + \sum_{n=1}^{\infty} \frac{b^n}{z^n} \qquad R_2 < |z| < R_2$$

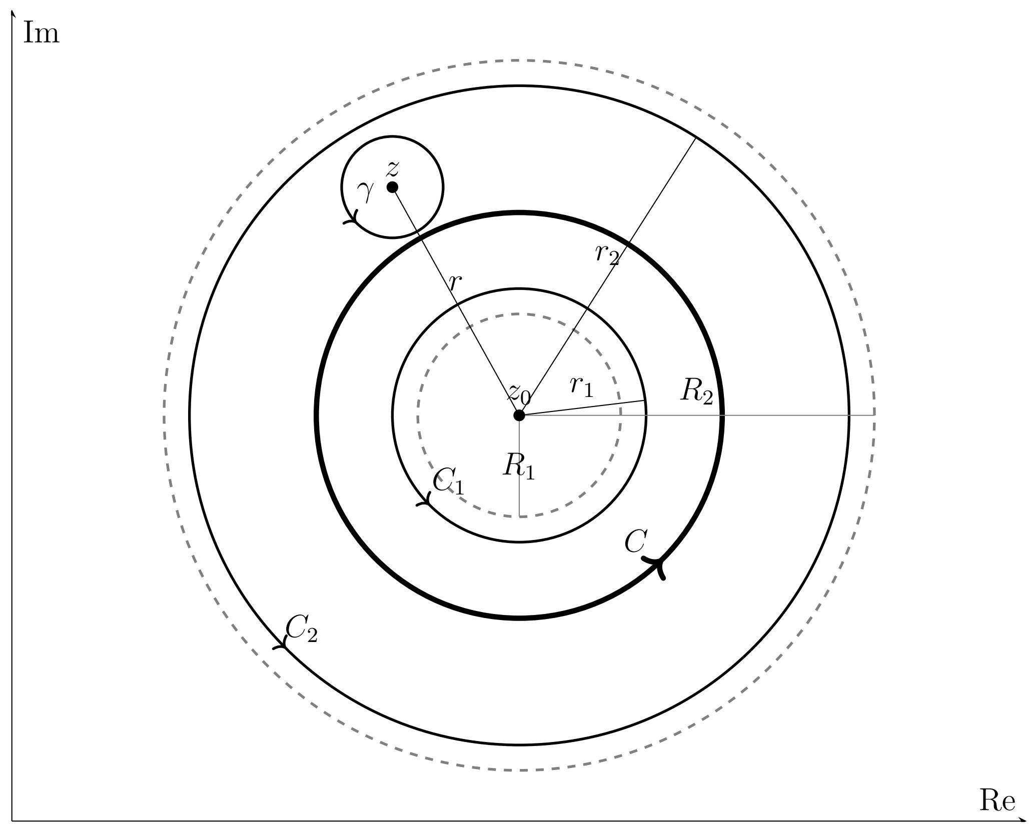
$$a_n = \frac{1}{2\pi i}\int_{\Gamma} \frac{g(z)}{z^{n+1}} dz \qquad n \in \mathbb{N} \cup \{0\}$$

$$b_n = \frac{1}{2\pi i}\int_{\Gamma} \frac{g(z)}{z^{-n+1}} dz \qquad n \in \mathbb{N}$$

Replacing z by $z - z_0$ and using corollary 15.6.4.1 to replace Γ by C yields the desired result. Note that:

$$2\pi i a_n = \int_{\Gamma} \frac{g(z)}{z^{n+1}} dz = \int_C \frac{f[z(t)]z'(t)}{[z(t) - z_0]^{n+1}} dt = \int_C \frac{f(z)}{(z - z_0)^{n+1}} dz \qquad z(t) = z$$

Similarly for b_n. $\square$



Note: If f is analytic throughout the disk $|z - z_0| < R_2$, $b_n = (2\pi i)^{-1} \int_C f(z)(z - z_0)^{n-1} dz$ becomes analytic, so $b_n = 0$ due to Cauchy-Goursat theorem (theorem 15.6.1). The Laurent series then becomes a Taylor series about z_0.

Note: In the case where f is not analytic at z_0, then R_1 can become arbitrarily small, so the Laurent series is valid for the punctured disk $0 < |z - z_0| < R_2$. Likewise, if f is only analytic for points outside R_1, then the Laurent series is valid for the region $R_1 < |z - z_0| < \infty$.

16.3.1 Examples

Example 16.3.1 (Finding Laurent Series via Known Series) *Find series representation of*

$$f(z) = \frac{1}{z(1 + z^2)}$$

We have singularities at $z = 0, \pi 1$, *and since* $|-z^2| < 1 \implies |z| < 1$, *we may use*

$$\frac{1}{1 - z} = \sum_{n=0}^{\infty} z^n \qquad |z| < 1$$

Substituting $-z^2$ *for* z*:*

$$f(z) = \frac{1}{z}\sum_{n=0}^{\infty}(-1)^n z^{2n} = \sum_{n=0}^{\infty}(-1)^n z^{2n-1} \qquad |z| < 1$$
$$= \frac{1}{z} + \sum_{n=1}^{\infty}(-1)^n z^{2n-1}$$
$$= \sum_{n=0}^{\infty}(-1)^{n+1} z^{2n+1} + \frac{1}{z} \qquad \textit{(Standard form)}$$

Note: This is valid in the region $|z| < 1$*, there is another representation for* $|z-i| < 1$ *and* $|z+1| < 1$*.*

Example 16.3.2 (z-transform) *Suppose*

$$X(z) = \sum_{n=-\infty}^{\infty} x[n]z^{-n} \qquad R_1 < |z| < R_2,\ n \in \mathbb{Z}$$

Show that if the Laurent series contains the unit circle $|z| = 1$ *then*

$$X^{-1}(z) = x[n] = \frac{1}{2\pi}\int_{-\pi}^{\pi} X(e^{i\theta})e^{in\theta}d\theta \qquad n \in \mathbb{Z}$$

Proof: We can write:

$$\sum_{n=-\infty}^{\infty} x[n]z^{-n} = \sum_{n=-\infty}^{\infty} x[n](z-z_0)^{-n} \qquad z_0 = 0$$

It is clear that

$$x[n] = b_n = \frac{1}{2\pi i}\int_C \frac{X(z)}{(z-z_0)^{-n+1}}dz \qquad |z| < 1$$
$$= \frac{1}{2\pi i}\int_C \frac{X(z)}{z^{-n+1}}dz \qquad z_0 = 0$$
$$= \frac{1}{2\pi i}\int_{-\pi}^{\pi} \frac{X(e^{i\theta})}{e^{i\theta(-n+1)}}\frac{\mathrm{d}}{\mathrm{d}\theta}e^{i\theta}d\theta \qquad z = e^{i\theta}$$
$$= \frac{1}{2\pi i}\int_{-\pi}^{\pi} X(e^{i\theta})e^{in\theta - i\theta}ie^{i\theta}d\theta = \frac{1}{2\pi}\int_{-\pi}^{\pi} X(e^{i\theta})e^{in\theta}d\theta$$

□

Example 16.3.3 (Bessel Functions of the First Kind) *Let* $z \in \mathbb{C}$ *and* C *be the unit circle* $w = e^{i\phi}$*,* $-\pi < \phi < \pi$*, in the* w*-plane. Show for the Laurent series about the origin in the* w*-plane:*

$$\exp\left[\frac{z}{2}\left(w - \frac{1}{w}\right)\right] = \sum_{n=-\infty}^{\infty} J_n(z)w^n \qquad 0 < |w| < \infty$$
$$J_n(z) = \frac{1}{2\pi}\int_{-\pi}^{\pi} \exp[-i(n\phi - z\sin(\phi))]d\phi \qquad n \in \mathbb{Z}$$

And that

$$\mathrm{Re}\{J_n(z)\} = \frac{1}{\pi}\int_0^{\infty} \cos[n\phi - z\sin(\phi)]d\phi \qquad n \in \mathbb{Z} \qquad (16.1)$$

Proof: We know for a Laurent series

$$f(z) = \sum_{n=-\infty}^{\infty} c_n (z - z_0)^n \qquad R_1 < |z - z_0| < R_2$$

$$c_n = \frac{1}{2\pi i} \int_C \frac{f(z)}{(z - z_0)^{n+1}} dz \qquad n \in \mathbb{Z}$$

For $z_0 = 0$ (since we are taking the series about the origin), we can write

$$\begin{aligned} J_n(z) = c_n &= \frac{1}{2\pi i} \int_C \frac{\exp[z2^{-1}(w - w^{-1})]}{w^{n+1}} dw & n \in \mathbb{Z} \\ &= \frac{1}{2\pi i} \int_{-\pi}^{\pi} \frac{\exp[z2^{-1}(e^{i\phi} - e^{-i\phi})]}{e^{i\phi(n+1)}} (ie^{i\phi}) d\phi & w = e^{i\phi} \\ &= \frac{1}{2\pi} \int_{-\pi}^{\pi} \exp[zi \sin(\phi)](e^{-in\phi}) d\phi \\ &= \frac{1}{2\pi} \int_{-\pi}^{\pi} \exp[-i(n\phi - z\sin(\phi))] d\phi \end{aligned}$$

Which is what we are looking for. As for $\text{Re}\{J_n(z)\}$:

$$J_n(z) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \cos[-i(n\phi - z\sin(\phi))] + i\sin[-i(n\phi - z\sin(\phi))] d\phi$$

This implies

$$\begin{aligned} \text{Re}\{J_n(z)\} &= \frac{1}{2\pi} \int_{-\pi}^{\pi} \cos[-i(n\phi - z\sin(\phi))] d\phi \\ &= \frac{1}{\pi} \int_{0}^{\pi} \cos[-i(n\phi - z\sin(\phi))] d\phi & \text{Cosine is an even function} \end{aligned}$$

□

Example 16.3.4 (Fourier Series) *Let $f(z)$ be a function in some annular domain about the origin that includes the unit circle $z = e^{i\phi}$, $-\pi \le \phi \le \pi$. Show that in the Laurent series representation for any $z \in \mathbb{C}$:*

$$f(z) = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(e^{i\phi}) d\phi + \frac{1}{2\pi} \sum_{n=1}^{\infty} \int_{-\pi}^{\pi} f(e^{i\phi}) \left[\left(\frac{z}{e^{i\phi}}\right)^n + \left(\frac{e^{i\phi}}{z}\right)^n \right] \qquad -\pi \le \phi \le \pi$$

and that for $u(\theta) = \text{Re}\{f(e^{i\phi})\}$:

$$u(\theta) = \frac{1}{2\pi} \int_{-\pi}^{\pi} u(\phi) d\phi + \frac{1}{\pi} \sum_{n=1}^{\infty} \int_{-\pi}^{\pi} u(\phi) \cos[n(\theta - \phi)] d\phi \qquad -\pi \le \theta \le \pi$$

which is the Fourier Series of $u(\theta)$ about $-\pi \le \phi \le \pi$. Restrictions on $u(\theta)$ is more severe than necessary in order for it to be represented by a Fourier series, because it needs to be piecewise continuous on $[-\pi, \pi]$, and periodic with period of 2π and be everywhere differentiable in $\mathbb{R} \cup \{-\infty, \infty\}$ (theorem 17.0.2).

Proof: We know that for the Laurent series representation of a function:

$$\begin{aligned} f(z) &= \sum_{n=0}^{\infty} a_n (z-z_0)^n + \sum_{n=1}^{\infty} \frac{b_n}{(z-z_0)^n} && R_1 < |z| < R_2 \\ a_n &= \frac{1}{2\pi i} \int_C \frac{f(z)}{(z-z_0)^{n+1}} dz && n \in \mathbb{N} \cup \{0\} \\ b_n &= \frac{1}{2\pi i} \int_C \frac{f(z)}{(z-z_0)^{-n+1}} dz && n \in \mathbb{N} \end{aligned}$$

This tells us that

$$f(z) = \frac{1}{2\pi i} \sum_{n=0}^{\infty} \left(\int_C \frac{f(z)}{(z-z_0)^{n+1}} dz \right) (z-z_0)^n + \frac{1}{2\pi i} \sum_{n=1}^{\infty} \left(\int_C \frac{f(z)}{(z-z_0)^{-n+1}} dz \right) (z-z_0)^{-n}$$

Let $z_0 = 0$ since we are in an annular domain about the origin:

$$\begin{aligned} 2\pi i f(z) &= \left[\int_C \frac{f(z)}{z^{n+1}} dz \right] + \sum_{n=1}^{\infty} \left(\int_C \frac{f(z)}{z^{n+1}} dz \right) z^n + \sum_{n=1}^{\infty} \left(\int_C \frac{f(z)}{z^{-n+1}} dz \right) z^{-n} \\ &= \left[\int_C \frac{f(z)}{z^{n+1}} dz \right] + \sum_{n=1}^{\infty} \left[\left(\int_C \frac{f(z)}{z^{n+1}} dz \right) z^n + \left(\int_C \frac{f(z)}{z^{-n+1}} dz \right) z^{-n} \right] \end{aligned}$$

We know that

$$\begin{aligned} \int_C \frac{f(z)}{z^{n+1}} dz &= \int_{-\pi}^{\pi} \frac{f(e^{i\phi})}{e^{i\phi(n+1)}} (ie^{i\phi}) d\phi = i \int_{-\pi}^{\pi} f(e^{i\phi}) d\phi \\ \int_C \frac{f(z)}{z^{n+1}} dz &= \int_{-\pi}^{\pi} \frac{f(e^{i\phi})}{e^{i\phi(n+1)}} (ie^{i\phi}) d\phi = i \int_{-\pi}^{\pi} \frac{f(e^{i\phi})}{e^{in\phi}} d\phi \\ \int_C \frac{f(z)}{z^{-n+1}} dz &= \int_{-\pi}^{\pi} \frac{f(e^{i\phi})}{e^{i\phi(-n+1)}} (ie^{i\phi}) d\phi = i \int_{-\pi}^{\pi} f(e^{i\phi}) e^{in\phi} d\phi \end{aligned}$$

This gives us

$$2\pi i f(z) = i \int_{-\pi}^{\pi} f(e^{i\phi}) d\phi + \sum_{n=1}^{\infty} \left[\left(i \int_{-\pi}^{\pi} \frac{f(e^{i\phi})}{e^{in\phi}} d\phi \right) z^n + \left(i \int_{-\pi}^{\pi} f(e^{i\phi}) e^{in\phi} d\phi \right) z^{-n} \right]$$

Bringing z into the integral (we can do this since z is any point in the domain, while the z in the integral is any on C. They represent two different sets of points. Bad notation.)

$$\begin{aligned} 2\pi f(z) &= \int_{-\pi}^{\pi} f(e^{i\phi}) d\phi + \sum_{n=1}^{\infty} \left[\left(\int_{-\pi}^{\pi} f(e^{i\phi}) \frac{e^{in\phi}}{z^n} d\phi \right) + \left(\int_{-\pi}^{\pi} f(e^{i\phi}) \frac{e^{in\phi}}{z^{-n}} d\phi \right) \right] \\ &= \int_{-\pi}^{\pi} f(e^{i\phi}) d\phi + \sum_{n=1}^{\infty} \int_{-\pi}^{\pi} f(e^{i\phi}) \left[\left(\frac{z}{e^{i\phi}} \right)^n + \left(\frac{e^{i\phi}}{z} \right)^n \right] d\phi \end{aligned}$$

Giving us our desired equation. Now let $u(\theta) = \text{Re}\{f(e^{i\theta})\}$:

$$\begin{aligned} 2\pi f(e^{i\theta}) &= \int_{-\pi}^{\pi} f(e^{i\phi})d\phi + \sum_{n=1}^{\infty} \int_{-\pi}^{\pi} f(e^{i\phi})\left[\left(e^{in(\theta-\phi)}\right) + \left(e^{-in(\theta-\phi)}\right)\right] d\phi \\ &= \int_{-\pi}^{\pi} f(e^{i\phi})d\phi + \sum_{n=1}^{\infty} \int_{-\pi}^{\pi} f(e^{i\phi})\left[2\cos[n(\theta-\phi)]\right] d\phi \end{aligned}$$

$\theta, \phi \in \mathbb{R} \implies$ Cosine is real-valued function:

$$\begin{aligned} \text{Re}\left\{2\pi f(e^{i\phi})\right\} &= \int_{-\pi}^{\pi} u(e^{i\phi})d\phi + \sum_{n=1}^{\infty} \int_{-\pi}^{\pi} u(e^{i\phi})\left[2\cos[n(\theta-\phi)]\right] d\phi \\ \text{Re}\left\{f(e^{i\phi})\right\} &= \frac{1}{2\pi}\int_{-\pi}^{\pi} u(\phi)d\phi + \frac{1}{\pi}\sum_{n=1}^{\infty} \int_{-\pi}^{\pi} u(\phi)\cos[n(\theta-\phi)]d\phi \end{aligned}$$

□

16.4 Absolute and Uniform Convergence of Power Series

Definition 16.4.1: Circle of Convergence

The greatest circle centred at z_0 for which the power series $\sum_{n=0}^{\infty} a_n(z-z_0)^n$ converges for all points interior to the circle. That is, if the circle has radius R and is centred at z_0, then the power series converges $\forall z$ where $|z-z_0| < R$.

Theorem 16.4.1: Absolute Convergence of Power Series

Consider a power series $\sum_{n=0}^{\infty} a_n(z-z_0)^n$

$$\begin{aligned} &\sum_{n=0}^{\infty} a_n(z_1-z_0)^n \text{ converges for } z_1 \neq z_0 \\ &\implies \sum_{n=0}^{\infty} a_n(z-z_0)^n \text{ converges absolutely } \forall z \in \{z : |z-z_0| < R_1 = |z_1-z_0|\} \end{aligned}$$

That is if $\sum_{n=0}^{\infty} a_n(z-z_0)^n$ converges for some z_1, then it converges absolutely for all points interior to the neighbourhood $|z_1-z_0|$.

Proof: content □

Definition 16.4.2: Uniform Convergence of Power Series Definition - Complex

environment-name

Theorem 16.4.2:

content

Chapter 17

Conformal Mapping

Part V

Ordinary Differential Equations

Theorem 17.0.1: Green's Theorem

Let $F = P(x,y)\hat{i} + Q(x,y)\hat{j}$ be a vector field on a simple closed contour C, R be the region enclosed and on C, and s be the path along C.

$$\int_C F \cdot ds = \iint_R \nabla \times F \; dx \; dy$$

Part VI

Nonlinear Dynamics

Part VII

Partial Differential Equations

Definition 17.0.1: Dirichlet Problem

Finding a function in an harmonic domain that assumes preassigned values at the boundary of the domain.

Theorem 17.0.2: Fourier Theorem

Let a function f:

1. *Piecewise continuous on $[-\pi, \pi]$*
2. *Periodic with period 2π $\forall x \in \mathbb{R} \cup \{-\infty, \infty\}$*
3. *$\forall x \in \mathbb{R} \cup \{-\infty, \infty\}$, $f'_+(x)$ and $f'_-(x)$ both exist*

Then the Fourier series converges to the mean value

$$\frac{f(x+) + f(x-)}{2}$$

of one-sided limit of f at x

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