AMATH / PMATH 332 Course Notes

Applied Complex Analysis

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Contents

Chapter 1 Complex Numbers

1.1 Intro, Properties of Complex Numbers

Intro:

- What it's about: not like real analysis; some of intro to calculus on $\mathbb{C}$
- Goal: extend calculus on $\mathbb{R}$ to $\mathbb{C}$ - many results become simpler! (more complete picture here)
- Can be used to solve some $\mathbb{R}$ problems.

The Fundamentals:

- Basic idea: define solutions to $x^2 + 1 = 0$
- Early Mathematicians: $x = \pm\sqrt{-1}$. For $\sqrt{-1}$, should we call it i?
- Note: "$\sqrt{}$" always denotes positive root, e.g. $\sqrt{4} = 2$
- Problem:

$$\begin{aligned}\sqrt{-1}\sqrt{-1} &= -1 \quad \text{by definition of } \sqrt{} \\ \sqrt{-1}\sqrt{-1} &= \sqrt{(-1)(-1)} = \sqrt{1} = 1 \quad \text{since } \sqrt{ab} = \sqrt{a}\sqrt{b}\end{aligned}$$

- Fix: intepret "$\sqrt{}$" differently for complex numbers - it must be multivalued, and define the imaginary unit i by $i^2 = 1$

Definition 1.1. Complex number:

$$z = \underbrace{a}_{\text{"real part" } Re(z)} + i \underbrace{b}_{\text{"imaginary part" } Im(z) \text{ which is real!}} \quad \text{where } a, b \in \mathbb{R}$$

$\mathbb{C}$ = set of complex numbers. Note that $\mathbb{R} \subset \mathbb{C}$

Definition 1.2. Let $z = a + bi$, and $w = c + di$. Then:

- $z = w$ if and only if $a = c$ and $b = d$
- $z + w = (a + bi) + (c + di) = a + c + (b + d)i$
- $z - w = z + (-w) = (a + bi) + (-c - di) = a - c + (b - d)i$
- $zw = (a + bi)(c + di) = ac + bdi^2 + adi + bci = ac - bd + (ad + bc)i$
- $\dfrac{z}{w} = \dfrac{a + bi}{c + di} \cdot \dfrac{c - di}{c - di} = \dfrac{ac + bd}{c^2 + d^2} + i \cdot \dfrac{bc - ad}{c^2 + d^2}$

Example 1.3.

$$\frac{2+i}{1+2i} = \frac{2+i}{1+2i} \cdot \frac{1-2i}{1-2i} = \frac{4}{5} - \frac{3}{5}i$$

$$\frac{1}{i} = \frac{1}{i} \cdot \frac{-i}{-i} = \frac{-i}{-i^2} = -i$$

Theorem 1.4. $z + w = w + z$, $k(z + w) = kz + kw$ apply as usual. $zw = wz$

Note: We can't classify complex numbers as "positive" or "negative", and can't use inequalities, e.g. $z > w$ doesn't make sense.

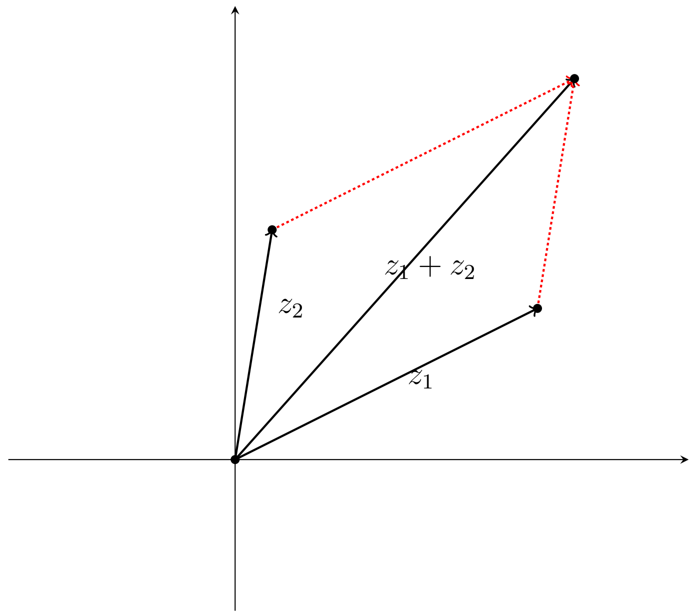
Definition 1.5. Conjugate of $z = a + bi$ is

$$\overline{z} = a - bi$$

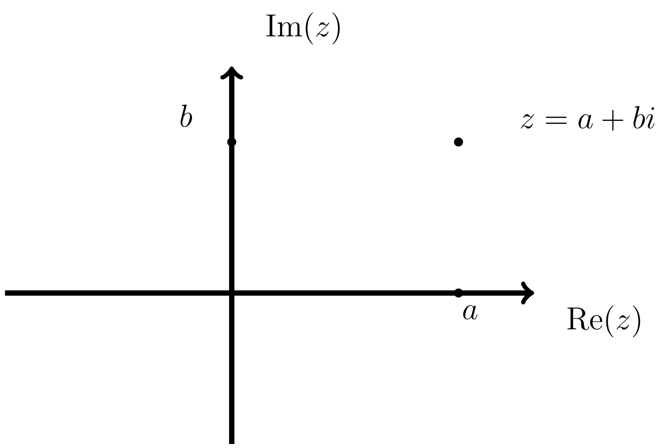
(Sometimes written as z^* as well)

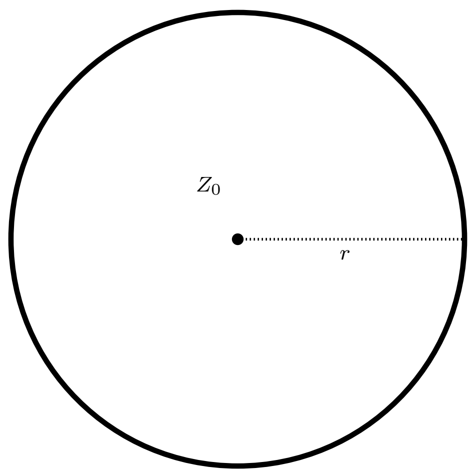
Proposition 1.6. The following rules apply:

1. $\overline{\overline{z}} = z$
2. $\overline{z \pm w} = \overline{z} \pm \overline{w}$
3. $\overline{zw} = \overline{z}\,\overline{w}$ and $\overline{\left(\dfrac{z}{w}\right)} = \dfrac{(\overline{z})}{(\overline{w})}$
4. $z + \overline{z} = 2Re(z) \quad \Rightarrow \quad Re(z) = \frac{1}{2}(z + \overline{z})$
5. $z - \overline{z} = 2iIm(z) \quad \Rightarrow \quad Im(z) = \frac{1}{2i}(z - \overline{z})$
6. $z\overline{z} = a^2 + b^2$ which is real!



1.2 The Complex Plane, Polar form





Definition 1.7. The **modulus** of $z = a + bi$ is $|z| = \sqrt{a^2 + b^2}$

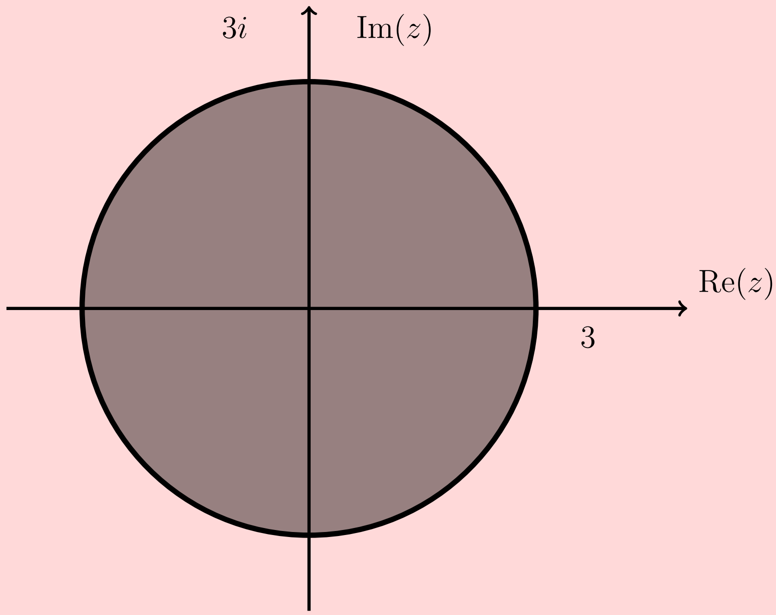
The **distance** between two numbers z and w is $|z - w|$

Notes:

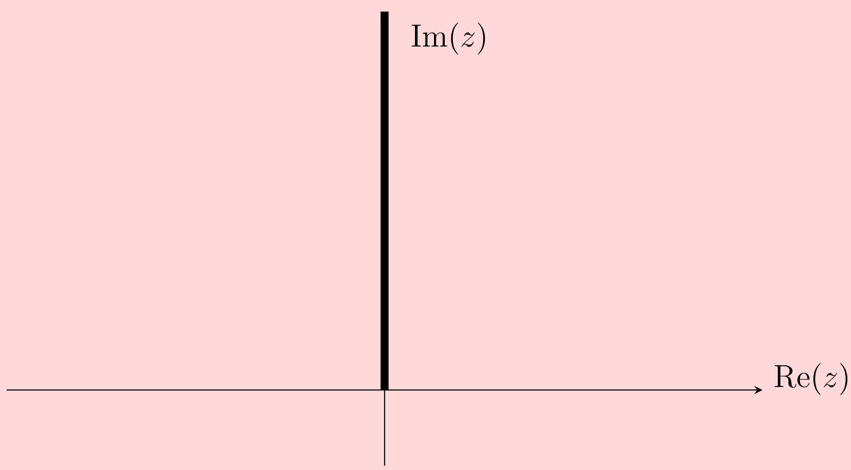
- $|z| \geq 0$ and is real
- $z\overline{z} = a^2 + b^2 = |z|^2$
- $|z - z_0| = r$ describes a circule of radius r centered at z_0

Example 1.8. Sketch the sets:

1. $|z| < 3$



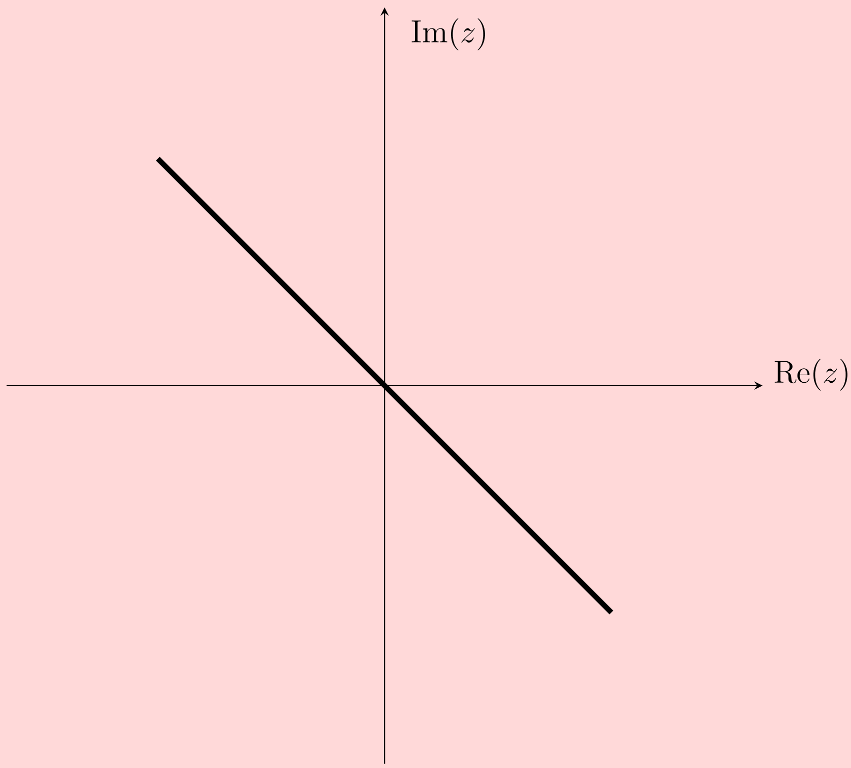
2. $|z| = Im(z)$. Let $z = a + ib$. So, $\sqrt{a^2 + b^2} = b$, which gives $a^2 + b^2 = b^2$, so $a = 0, b \geq 0$



3. $|z - 1| = |z + i|$. So

$$\begin{aligned}
\sqrt{(a-1)^2 + b^2} &= \sqrt{a^2 + (b+1)^2} \\
(a-1)^2 + b^2 &= a^2 + (b+1)^2 \\
a^2 - 2a + 1 + b^2 &= a^2 + b^2 + 2b + 1 \\
b &= -a
\end{aligned}$$

This is the set of points that are equidistant from $z = 1$ and $z = -i$



We will often use $z = x + yi$, so we are in the xy-plane, still not called $\mathbb{R}^2$ though.

Useful inequalities:

$$|z_1 + z_2| \leq |z_1| + |z_2|$$

This is known as "Triangle Inequality". This also extends to

$$|z_1 = z_2 + \cdots + z_n| \leq |z_1| + \cdots + |z_n|$$

Corollary 1.9.

$$|z_1 + z_2| \geq \Big||z_1| - |z_2|\Big|$$

Proof 1.10.

$$\begin{aligned} |z_1| &= |z_1 + (z_2 - z_2)| \\ &= |(z_1 + z_2) + (-z_2)| \\ &\leq |z_1 + z_2| + |z_2| \end{aligned}$$

$$\begin{aligned}|z_2| &= |z_2 + (z_1 - z_1)| \\ &= |(z_1 + z_2) + (-z_1)| \\ &\le |z_1 + z_2| + |z_1|\end{aligned}$$

So $|z_1 + z_2| \geq |z_1| - |z_2|$ and $|z_2| - |z_1|$. So

$$|z_1 + z_2| \geq \Big| |z_1| - |z_2| \Big|$$

□

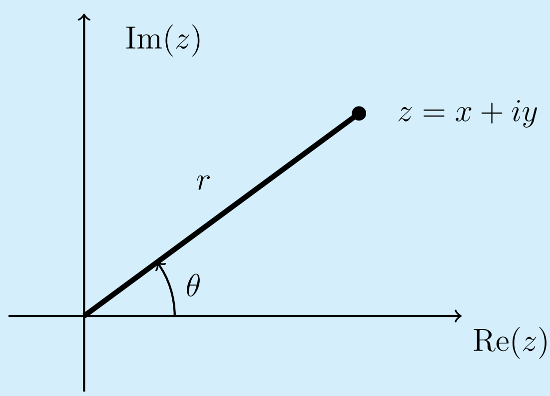
Definition 1.11. <u>**Polar Form**</u>

$$\boxed{x = r\cos\theta,\ y = r\sin\theta}$$

So,

$$\begin{aligned}z &= r\cos\theta + ir\sin\theta \\ &= r(\cos\theta + i\sin\theta) \\ &= r \underbrace{\text{cis}}_{\text{common abreviation}} \theta\end{aligned}$$

$$\boxed{r = \sqrt{x^2 + y^2},\ \tan\theta = \frac{y}{x}}$$



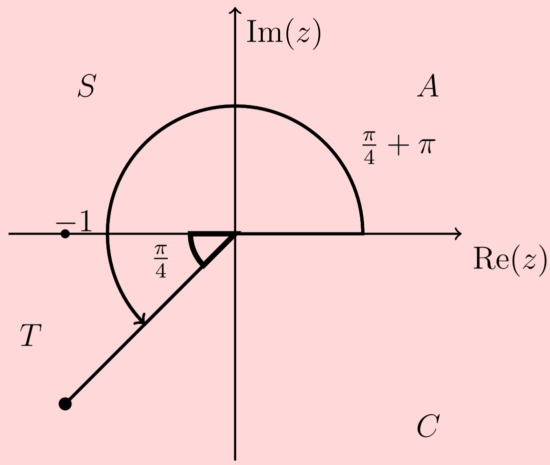
Notes:

- This is not unique. e.g. $z = 2 = 2\,\text{cis}\,0 = 2\,\text{cis}\,2\pi = \cdots$, also $z = 0 = 0\,\text{cis}\,\theta$ for any θ
- $\theta = \tan^{-1}(\frac{y}{x})[\pm 2k\pi]$ if $x > 0$, but must add π if $x < 0$ - Recall principal values

Example 1.12. Say we want to express $z = -1 - i$ in polar form.

We compute $r = \sqrt{(-1)^2 + (-1)^2} = \sqrt{2}$. $\tan\theta = \frac{-1}{-1} = 1$. Note that $\theta \neq \tan^{-1}(1) = \frac{\pi}{4}$, instead, $\theta = \frac{5\pi}{4}$.

So, $z = \sqrt{2}\operatorname{cis}\frac{5\pi}{4}$ or $\sqrt{2}\operatorname{cis}(\frac{5\pi}{4} + 2k\pi)$



Note:

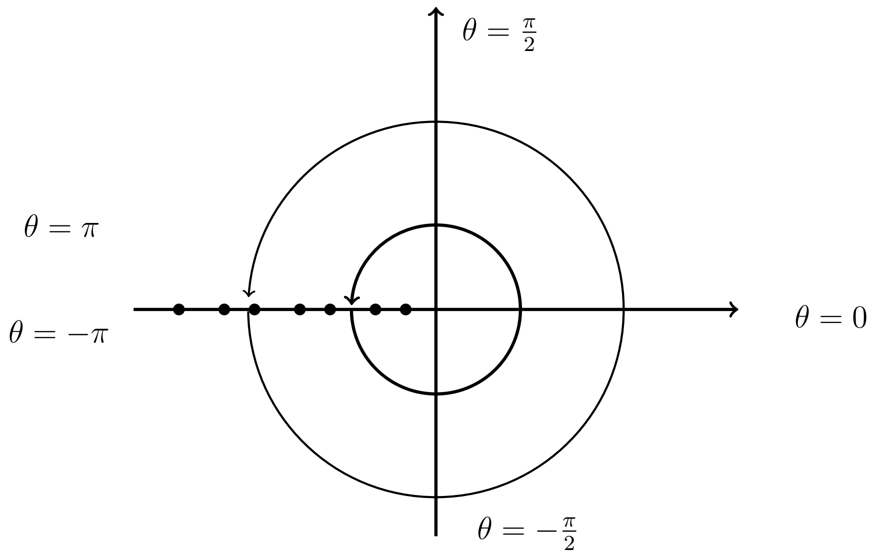
$$z = \underbrace{r}_{=\sqrt{x^2+y^2}, r=|z|, \text{"modulus"}} \operatorname{cis} \underbrace{\theta}_{\text{"argument" of } z}$$

Also, "$\arg z$" = set of all possible values of θ. "$\operatorname{Arg} z$" = principle values of θ, usually in $(\pi, \pi]$

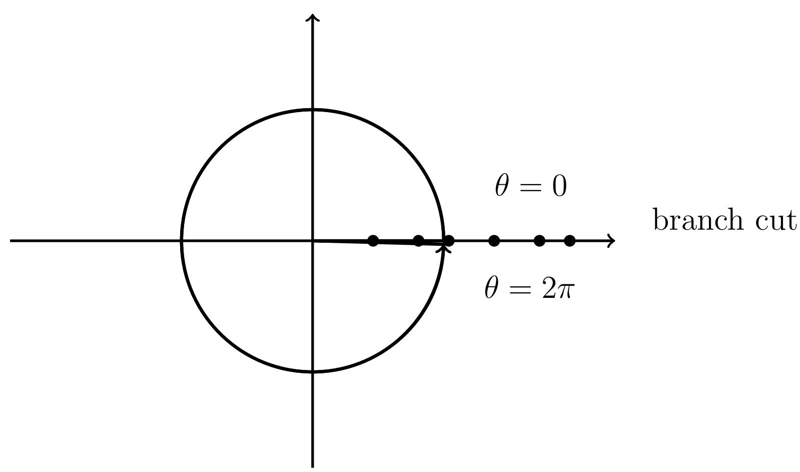
Example 1.13. For $z = -1 + \sqrt{3}i$. $\operatorname{Arg} z = \frac{2\pi}{3}$, $\arg z = \frac{2\pi}{3} + 2k\pi, k \in \mathbb{Z}$

Also, $|z| = 2$, so $-1 + \sqrt{3}i = 2\operatorname{cis}\frac{2\pi}{3}$

We sometimes think of $\arg z$ as a multivalued "function" of z. For a single-valued function, we could use $\operatorname{Arg} z$, but it has discontinuity on negative real axis.



Another way: we can define $\mathrm{Arg}(z)$ to have range $[0, 2\pi)$. In general, $\mathrm{Arg}_{\theta_0} z$ has range $[\theta_0, \theta_0 + 2\pi)$, and usually we use $\mathrm{Arg}\, z = \mathrm{Arg}_{-\pi} z$



1.3 Complex Exponential, Powers and Roots

Reading textbook Section 1.4, 1.5

Definition 1.14. If $z = x + iy$, then e^z is defined to be the complex number

$$e^z := e^x(\cos y + i \sin y)$$

Proposition 1.15. Euler's equation is formally consistent with the usual Taylor series expansions:

$$\begin{aligned} e^x &= 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots \\ \cos x &= 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \cdots \\ \sin x &= x - \frac{x^3}{3!} + \frac{x^5}{5!} - \cdots \end{aligned}$$

Proof 1.16. Let's substitute $x = iy$ into the exponential series:

$$\begin{aligned} e^{iy} &= 1 + iy + \frac{(iy)^2}{2!} + \frac{(iy)^3}{3!} + \cdots \\ &= (1 - \frac{y^2}{2!} + \frac{y^4}{4!} - \cdots) + i(y - \frac{y^3}{3!} + \frac{y^5}{5!} - \cdots) \\ &= \cos y + i \sin y \end{aligned}$$

□

As a result, we may introduce the standard polar representation

$$z = r \operatorname{cis} \theta = r(\cos\theta + i\sin\theta) = re^{i\theta} = |z|e^{i \arg z}$$

Notice that

$$e^{i0} = e^{2\pi i} = e^{-2\pi i} = e^{4\pi i} = e^{-4\pi i} = \cdots = 1$$
$$e^{(\pi/2)i} = i \quad e^{(-\pi/2)i} = -i \quad e^{\pi i} = -1$$

Also notice that

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

Hence,

$$z_1 z_2 = (r_1 e^{i\theta_1})(r_2 e^{i\theta_2}) = (r_1 r_2) e^{i(\theta_1 + \theta_2)}$$
$$\frac{z_1}{z_2} = \frac{r_1 e^{i\theta_1}}{r_2 e^{i\theta_2}} = \frac{r_1}{r_2} e^{i(\theta_1 - \theta_2)}$$
$$\overline{z} = re^{-i\theta}, \text{ given that } z = re^{i\theta}$$

Example 1.17. Compute the following:

1. $(1+i)/(\sqrt{3}-i)$.

   Notice that $1+i = \sqrt{2}\operatorname{cis}(\pi/4) = \sqrt{2}e^{i\pi/4}$, and $\sqrt{3}-i = 2\operatorname{cis}(-\pi/6) = 2e^{-i\pi/6}$. So,

$$\frac{1+i}{\sqrt{3}-i} = \frac{\sqrt{2}e^{i\pi/4}}{2e^{-i\pi/6}} = \frac{\sqrt{2}}{2}e^{i5\pi/12}$$

2. $(1+i)^{24}$

   We have

$$(1+i)^{24} = (\sqrt{2}e^{i\pi/4})^{24} = (\sqrt{2})^{24}e^{i24\pi/4} = 2^{12}e^{i6\pi} = 2^{12}$$

Theorem 1.18.

$$(\cos\theta + i\sin\theta)^n = \cos n\theta + i\sin n\theta \quad n = 1, 2, 3, ...$$

Definition 1.19. There are exactly m distinct m-th **roots of unity**, denoted by $1^{1/m}$, and they are given by

$$1^{1/m} = e^{i2k\pi/m} = \cos\frac{2k\pi}{m} + i\sin\frac{2k\pi}{m} \quad (k = 0, 1, 2, ..., m-1)$$

Take $k = 1$ into the above equation, we can get

$$\omega_m := e^{i2\pi/m} = \cos\frac{2\pi}{m} + i\sin\frac{2\pi}{m}$$

So the complete set of roots can be displayed as

$$\{1, \omega_m, \omega_m^2, \cdots, \omega_m^{m-1}\}$$

Note that a number w is said to be a **primitive** m-th root of unity if $w^m = 1$ but $w^k \neq 1$ for $k = 1, 2, ..., m-1$. Clearly, ω_m is a primitive root.

Theorem 1.20.

$$1 + \omega_m + \omega_m^2 + \cdots + \omega_m^{m-1} = 0$$

Proof 1.21. Note that

$$(\omega_m - 1)(1 + \omega_m + \omega_m^2 + \cdots + \omega_m^{m-1}) = (\omega_m - 1) = 0$$

Since $\omega_m \neq 1$, the result follows. $\square$

To obtain the m-th root of an arbitrary (non-zero) complex number $z = re^{i\theta}$, we can obtain the following generalized result.

Definition 1.22. The m-th distinct roots of z are given by

$$z^{1/m} = \sqrt[m]{|z|}e^{i(\theta+2k\pi)/m}$$

Example 1.23. Find all the cube roots of $\sqrt{2} + i\sqrt{2}$

The polar form for $\sqrt{2} + i\sqrt{2}$ is

$$\sqrt{2} + i\sqrt{2} = 2e^{i\pi/4}$$

Putting $|z| = 2, \theta = \pi/4, m = 3$ into the above definition, we obtain

$$(\sqrt{2} + i\sqrt{2})^{1/3} = \sqrt[3]{2}e^{i(\pi/12+2k\pi/3)}, \quad (k = 0, 1, 2)$$

Hence, the three cube roots of $\sqrt{2} + i\sqrt{2}$ are:

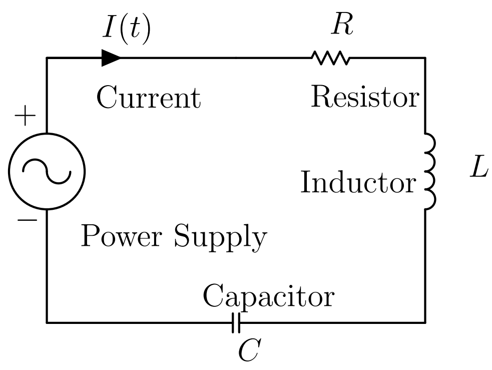
- $\sqrt[3]{2}(\cos \pi/12 + i \sin \pi/12)$
- $\sqrt[3]{2}(\cos 3\pi/4 + i \sin 3\pi/4)$
- $\sqrt[3]{2}(\cos 17\pi/12 + i \sin 17\pi/12)$

1.4 Application to Electrical Circuits

A typical electrical circuits is like the following:

Laws:

1. Resistor: $V = IR$
2. Inductor: $V = L\dfrac{dI}{dt}$
3. Capacitor: $C\dfrac{dV}{dt} = I$



Suppose the current is

$$I(t) = \underbrace{I_0}_{\text{amplitude}} \cos \underbrace{\omega}_{\text{frequency}} t = Re(\underbrace{I_0 e^{i\omega t}}_{\text{call it } \widetilde{I}(t)})$$

Then

1. Law 1 tells us $V = (I_0 \cos \omega t)(R) = Re(\widetilde{I}(t) \cdot R)$. So "complex voltage" is

$$\boxed{\tilde{V} = R\widetilde{I}}$$

2. Law 2 tells us

$$\begin{aligned} V &= L \cdot (-\omega I_0 \sin \omega t) \\ &= -\omega L I_0 \cdot \underbrace{Re(e^{i(\omega t - \frac{\pi}{2})})}_{=\cos(\omega t - \frac{\pi}{2}) = \sin \omega t} \\ &= Re(-\omega L I_0 e^{i\omega t} e^{-i\frac{\pi}{2}}) \\ &= Re(i\omega L I_0 e^{i\omega t}) \end{aligned}$$

So

$$\boxed{\widetilde{V} = i\omega L\widetilde{I}}$$

3. Law 3 tells us

$$\begin{aligned} V &= \frac{1}{C} \int I(t) \\ &= \frac{I_0}{C\omega} \sin \omega t \\ &= Re(\frac{I_0}{C\omega} e^{i(\omega t - \frac{\pi}{2})}) \\ &= Re(\frac{I_0}{iC\omega} e^{i\omega t}) \end{aligned}$$

So

$$\boxed{\widetilde{V} = \frac{1}{iC\omega}\widetilde{I}}$$

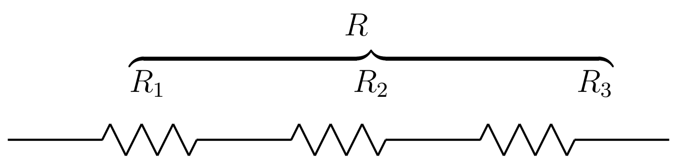
So, with the complex representation, all three circuit elements behave like resistors with a complex "Ohm's Law'

$$\boxed{\widetilde{V} = Z\widetilde{I} \qquad \text{where } Z = \begin{cases} R & \text{for resistors} \\ i\omega L & \text{for inductors} \\ \dfrac{1}{i\omega C} & \text{for inductors} \end{cases}}$$

Moreover, Z is called "impedance"

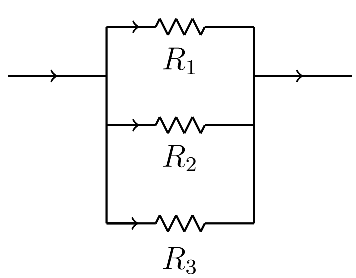
Combining the components:

- In series:



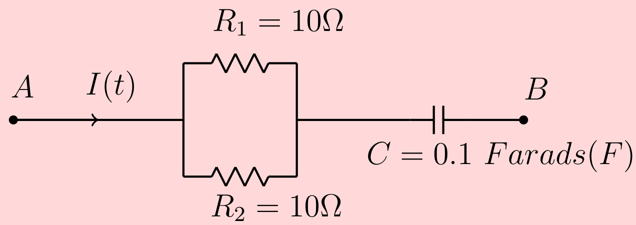
$$\begin{aligned} R &= R_1 + R_2 + R_3 + \cdots \\ L &= L_1 + L_2 + L_3 + \cdots \\ \frac{1}{C} &= \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots \\ Z &= Z_1 + Z_2 + Z_3 + \cdots \end{aligned}$$

- In parallel:



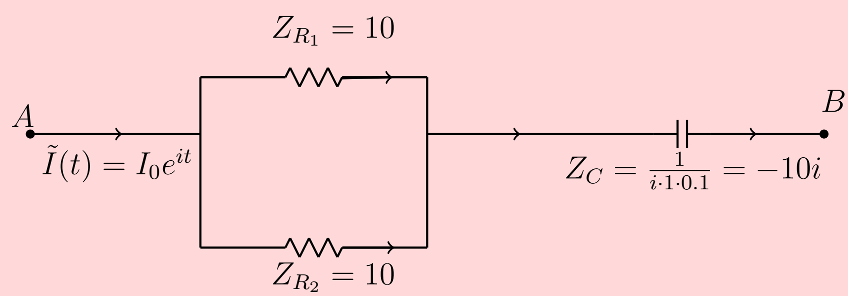
$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$$
$$\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \cdots$$
$$C = C_1 + C_2 + C_3 + \cdots$$
$$\frac{1}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3} + \cdots$$

Example 1.24. Suppose a current $I(t) = I_0 \cos t$, passes through this:



Find $V(t)$, the difference in electrical potential energy between A and B

Solution:



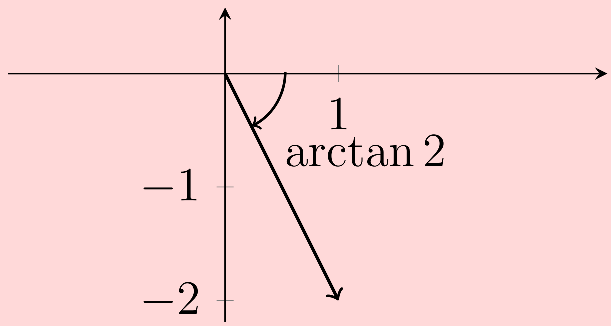
Let's use the complex version of "Ohm's Law". We have $\dfrac{1}{Z_R} = \dfrac{1}{Z_{R_1}} + \dfrac{1}{Z_{R_2}} = \dfrac{1}{10} + \dfrac{1}{10} = \dfrac{1}{5}$, so $Z_R = 5$.

Combine the resistor and capacitor in series: $Z = Z_R + Z_C = 5 - 10i$.

So, the complex voltage is

$$\begin{aligned}\widetilde{V} &= Z\widetilde{I} \\ &= (5 - 10i)I_0 e^{it} \\ &= 5I_0(1 - 2i)e^{it} \\ &= 5I_0\sqrt{5}e^{i \arctan -2}e^{it}\end{aligned}$$

So, $V(t) = Re(\widetilde{V}(t)) \approx 5\sqrt{5}I_0 \cos(t - 1.107)$



1.5 Sets in the Complex Plane

Definition 1.25. **Neighborhood of z_0** is

$$N_\epsilon(z_0) = \{z \in \mathbb{C} : |z - z_0| < \epsilon\}$$

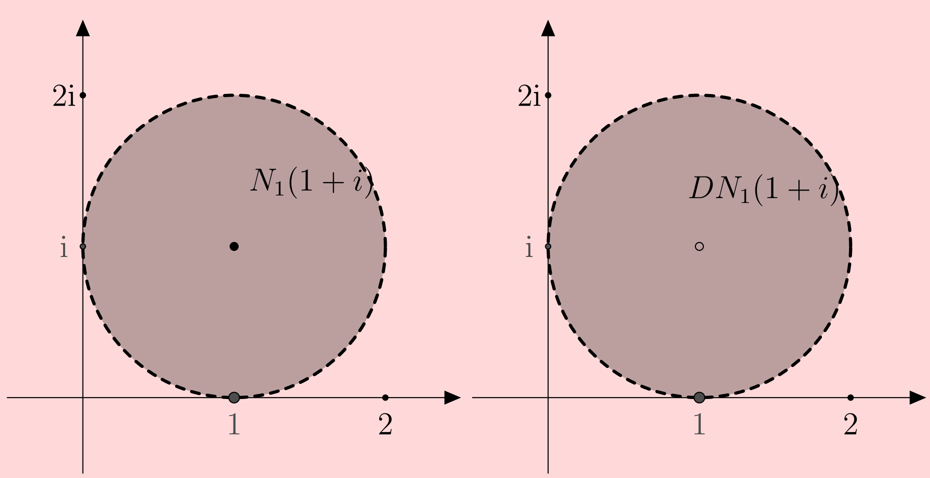
where $\epsilon > 0$ is real

Definition 1.26. **Deleted Neighborhood of z_0** is

$$DN_\epsilon(z_0) = \{z \in \mathbb{C} : 0 < |z - z_0| < \epsilon\}$$

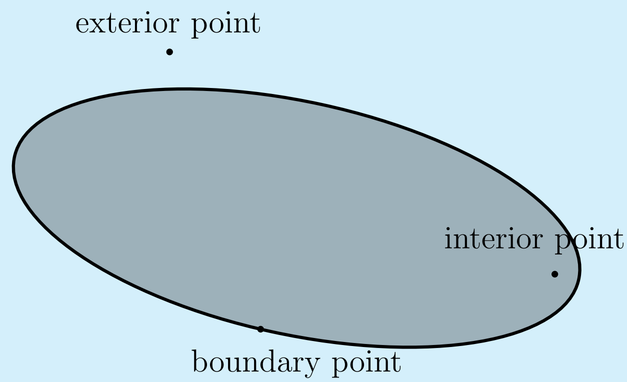
where $\epsilon > 0$ is real

Example 1.27. For $z_0 = 1 + i$, consider $|z - (1 + i)| < 1$. The neighborhood of z_0 and deleted neighborhood of z_0 is as follows:



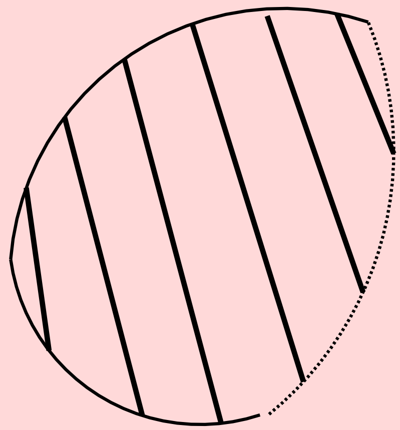
Definition 1.28. Let $S \subseteq \mathbb{C}$:

- z_0 is an **interior point** of S if there exists a neighborhood of z_0 which contains only points in S
- z_0 is an **exterior point** of S if there exists a neighborhood of z_0 which contains no points in S
- z_0 is a **boundary point** of S if every neighborhood of z_0 contains some points in S and some points not.
- **Boundary of S** is the set of all boundary points of S
- S is **open** if it contains none of its boundary points
- S is **closed** if it contains all of its boundary points, equivalently if its complement is open.
- Note that S could be both open and closed, when it does not have any boundary points



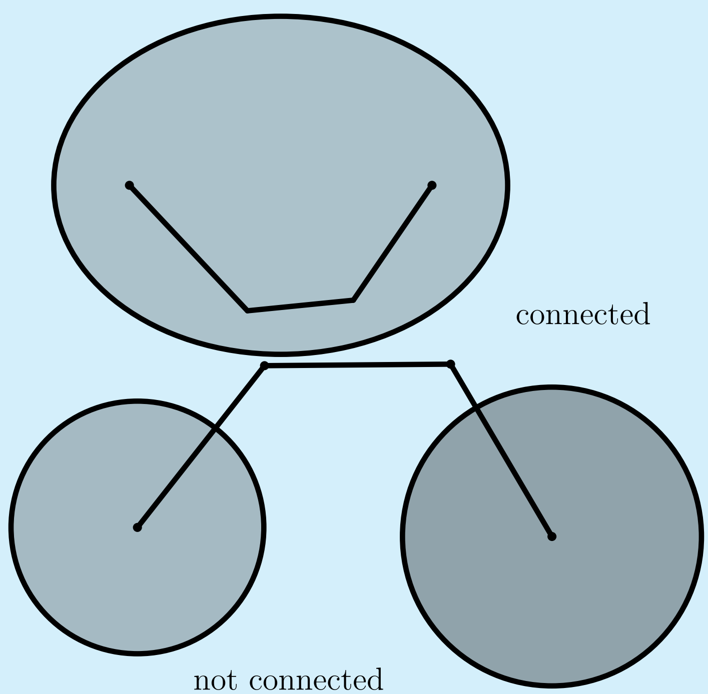
Example 1.29. Note that

- $N_1(1+i)$ is open
- $\mathbb{C}$ is both open and closed
- $|z - z_0| \leq 1$ is closed
- The figure below: it is neither open nor closed.



Definition 1.30. For $S \subseteq \mathbb{C}$:

- **Closure** of S is S plus its boundary.
- An open set S is **connected** if any two points in S can be connected by a polygonal path lying entirely in S
- A **domain** is an open connected set. We should not confuse this with "domain of a function"
- A **region** is a domain plus some, none, or all of its boundary points.
- S is **bounded** if there exists $R \in \mathbb{R}$ such that $|z| < R$ for all $z \in S$

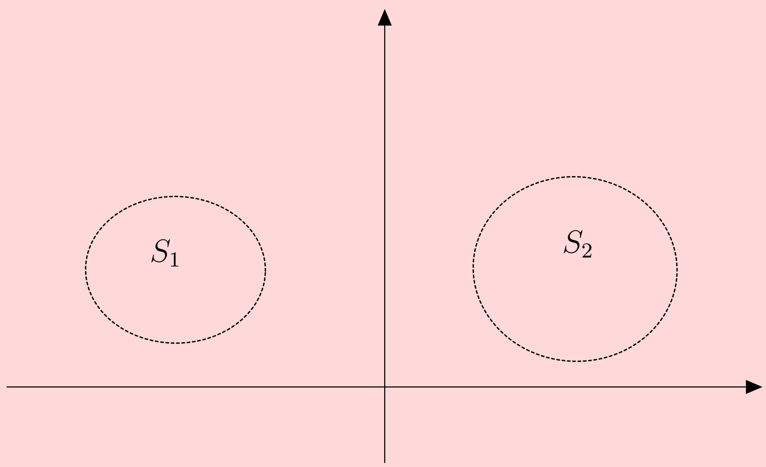


Theorem 1.31. If $u(x, y)$, defined on a domain D, satisfies

$$\frac{\partial u}{\partial x} = \frac{\partial u}{\partial y} = 0$$

for all points in D, then $u(x, y) = \text{constant in } D$.

Example 1.32. Suppose we have S_1 and S_2 like this:



in which we have $u(x, y) = 0$ on S_1 and $u(x, y) = 1$ on S_2.

Then, $\dfrac{\partial u}{\partial x} = \dfrac{\partial u}{\partial y} = 0$ on $S_1 \cup S_2$, but $u(x, y)$ is not constant on $S_1 \cup S_2$.

Why does not the theorem hold? Well this is because $S_1 \cup S_2$ is not connected, so it's not a domain.

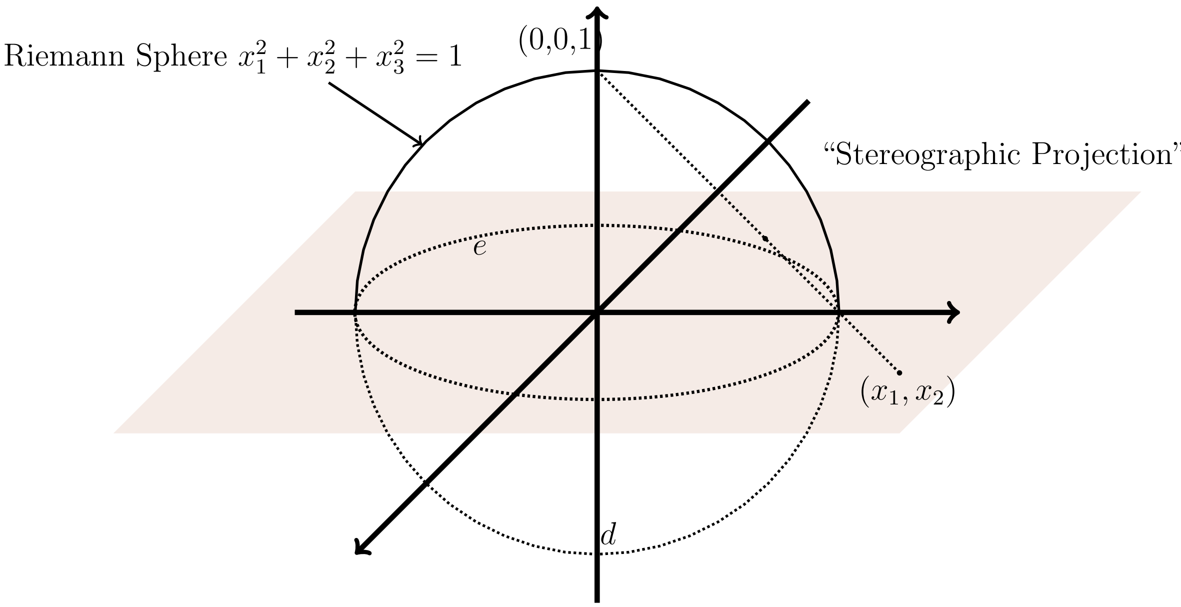
The Extended Complex Plane:

The "neighborhood of ∞" is defined as:

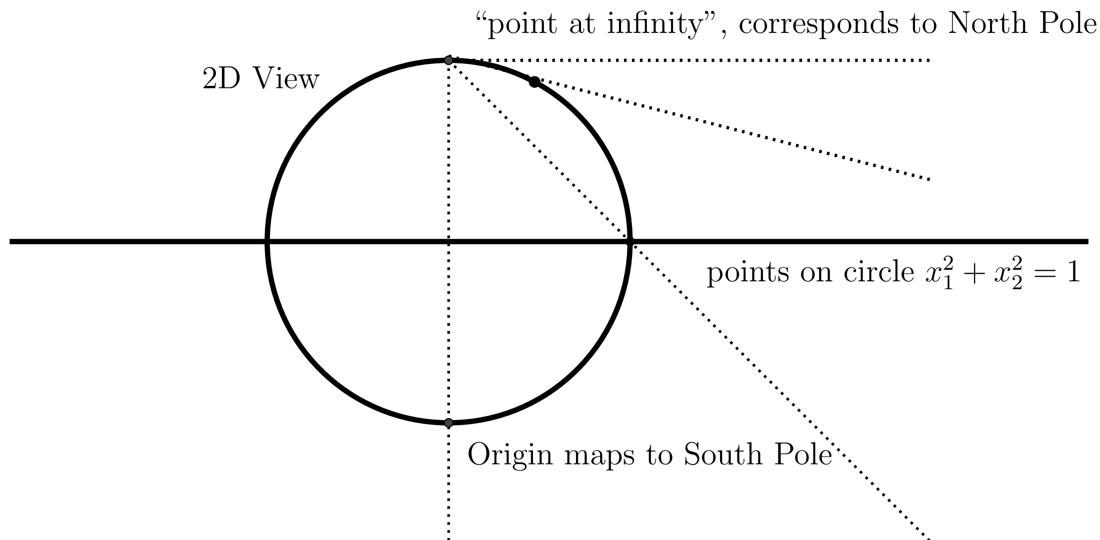
$$N_\epsilon(\infty) = \{z \in \mathbb{C} : |z| > \frac{1}{\epsilon}\}$$

for some real $\epsilon > 0$

The Riemann sphere:



We can define a one-to-one mapping between x_1x_2-plane and the sphere:



See the course text for more detail, in particular:

- Circles and lines all map circles on the sphere
- Lines are just circles which pass through the "point at infinity"

Chapter 2 Analytic Functions

2.1 Functions

For a function on complex numbers:

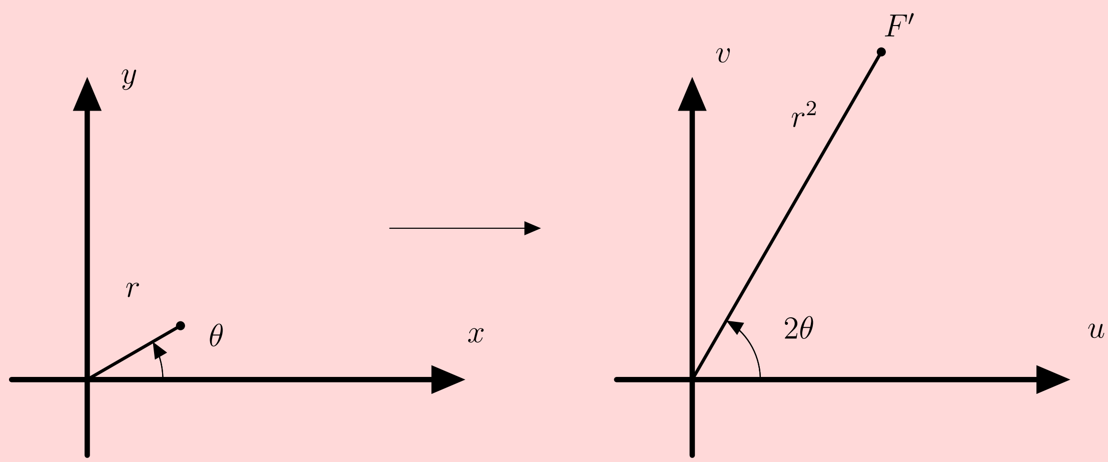
$$\begin{aligned}\omega &= f(z)\\ &= f(x+iy)\\ &= u(x,y)+iv(x,y)\end{aligned}$$

We can think of it as a mapping.

Example 2.1. 1. $f(z)=z^2$. Find the images of

(a) the first quadrant.

$f(z)=(x+iy)^2=\underbrace{(x^2-y^2)}_{u}+i\underbrace{2xy}_{v}$

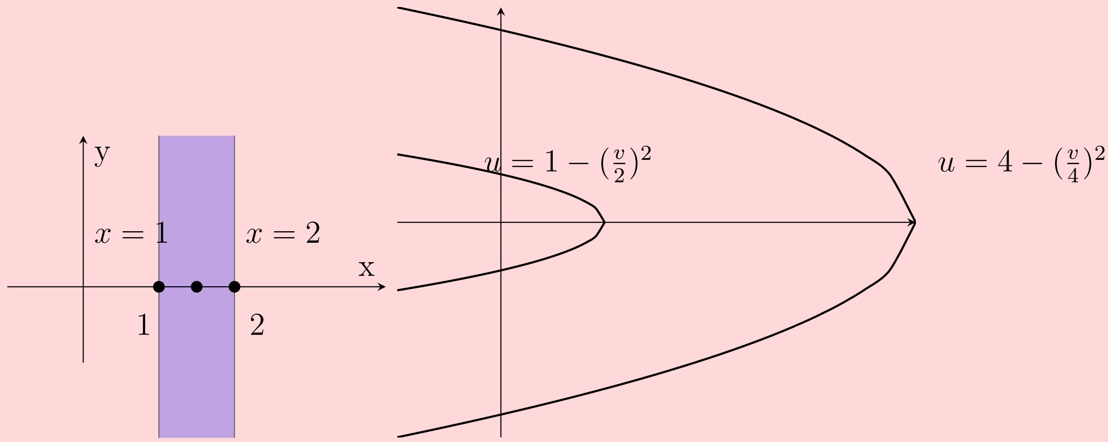


Note that $f(z)=(re^{i\theta})^2=r^2e^{i2\theta}$ (angle is doubled)

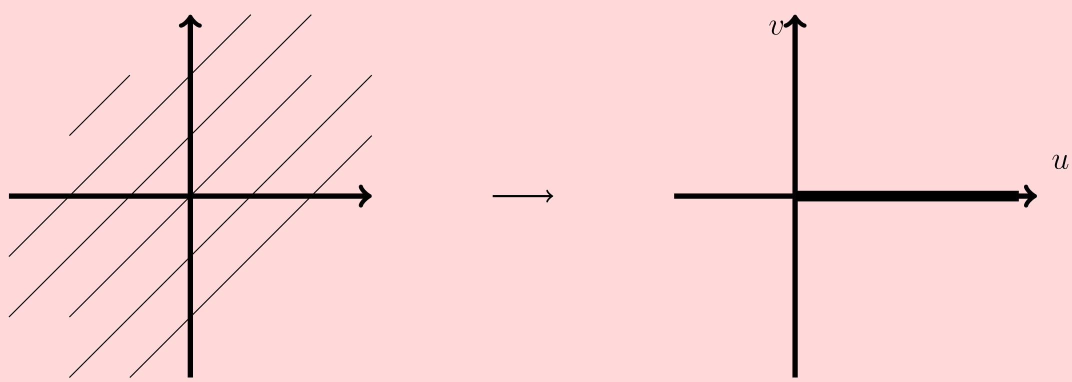
(b) the strip $1\le Re(z)\le 2$

With $1\le x\le 2$, the boundaries become:

- $x=1\Rightarrow\begin{cases}u=1-y^2\\ v=2y\end{cases}\Rightarrow u=1-\big(\frac{v}{2}\big)^2$, which is a parabola
- $x=2\Rightarrow\begin{cases}u=4-y^2\\ v=4y\end{cases}\Rightarrow u=4-\big(\frac{v}{4}\big)^2$, which is a parabola



2. $f(z) = |z|$. This one maps complex plane to non-negative real axis.

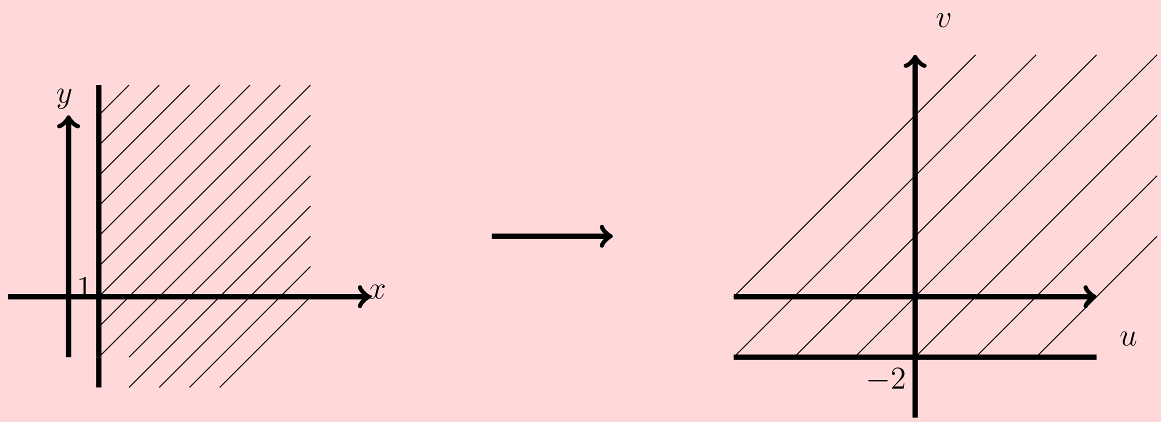


3. $f(z) = z - z_0 = (x + iy) - (x_0 + iy_0) = (x - x_0) + i(y - y_0)$. This is a translation.
4. $f(z) = z_0 z$, so

$$f(z) = r_0 e^{i\theta_0} r e^{i\theta} = \underbrace{r_0}_{\text{magnification}} r e^{i \overbrace{\theta_0}^{\text{rotation}} + \theta} = r_0 r e^{i\theta_0 + \theta}$$

5. $f(z) = \overline{z} = x - iy \to \begin{cases} u = x \\ v = -y \end{cases}$. This is a reflection on y-axis.
6. Find image of half-plane $Re(z) \geq 1$ under the map $\omega = f(z) = iz - 3i$.

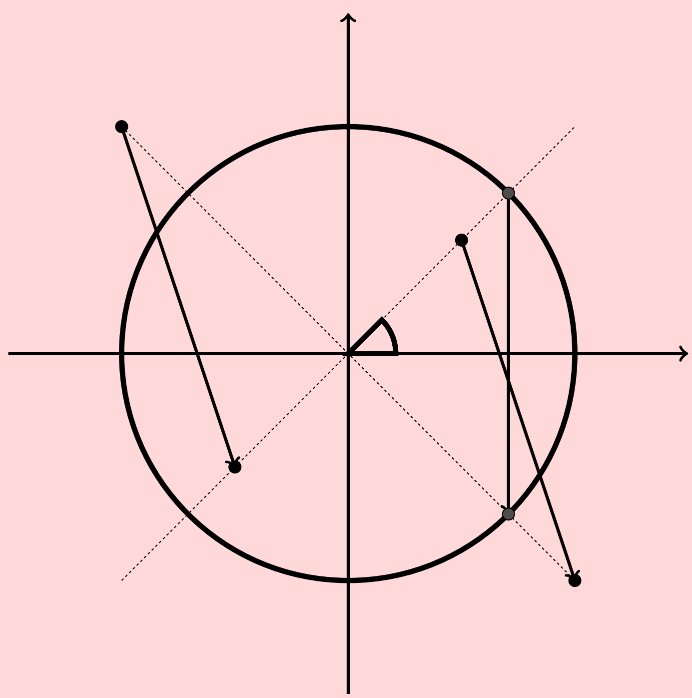
   We can do this step by step. First it's a rotation of $\frac{\pi}{2}$ (comes from the first i), then its a shift down 3 units.



The image is the half-plane $v \geq -2$.

7. Inversion mapping. $f(z) = \dfrac{1}{z} = \dfrac{1}{re^{i\theta}} = \dfrac{1}{r}e^{-i\theta}$. So, it's a scaling by r, and then reflection through the x-axis.

   For this mapping, unit circle maps to the unit circle. Outside points go to inside, and inside points go to outside.



8. Image of circle $(x-1)^2 + y^2 = 1$ under $f(z) = \dfrac{1}{z}$.

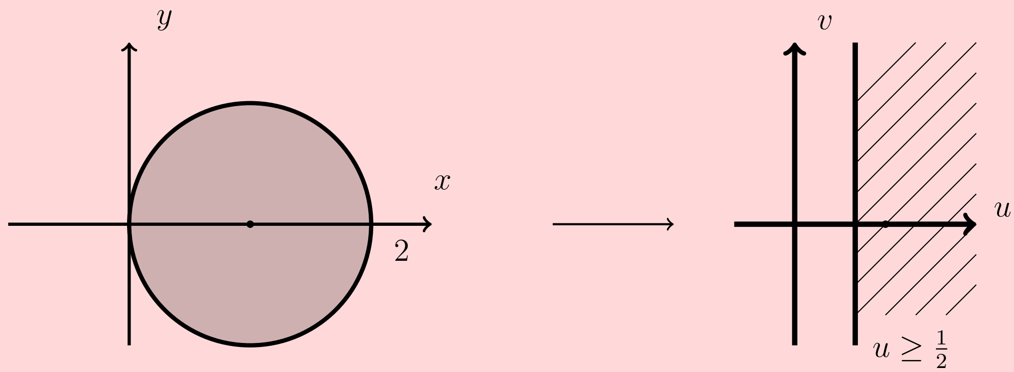
   The trick is to use polar fomulas. Recall $x^2 + y^2 = r^2, x = r\cos\theta, y = r\sin\theta$.

   So, $x^2 - 2x + 1 + y^2 = 1$ yields that $r^2 = 2r\cos\theta$. Since $r \neq 0$, we then have $r = 2\cos\theta$.

To apply the map, replace r with $\dfrac{1}{r}$, and θ with $-\theta$:

$$\frac{1}{r} = 2\cos(-\theta) \Rightarrow r = \frac{1}{2\cos\theta} \Rightarrow r\cos\theta = \frac{1}{2}$$

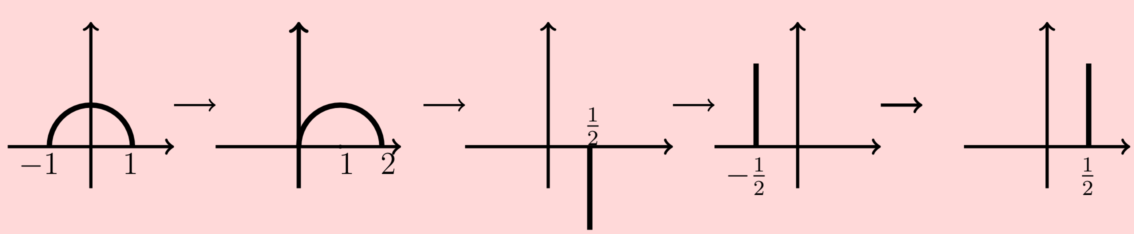
So $u = \dfrac{1}{2}$ since $\begin{cases} u = r\cos\theta \\ v = r\sin\theta \end{cases}$ in the uv plane.



9. $w = f(z) = \dfrac{z}{z+1}$, find the image of upper-half of unit circle.

First, $f(z) = \dfrac{z+1-1}{z+1} = 1 - \dfrac{1}{z+1}$. This is a sequence of transformations:

$$z \to \underbrace{z+1}_{\text{shift right}} \to \underbrace{\frac{1}{z+1}}_{\text{invert}} \to \underbrace{\frac{-1}{z+1}}_{\text{reflect and rotate } \pi} \to \underbrace{1 - \frac{1}{z+1}}_{\text{shift right}}$$



2.2 Limits and Differentiation

Definition 2.2. <u>Limits</u>:

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

means that for any $\epsilon > 0$, there exists $\delta > 0$ such that

$$0 < |z - z_0| < \delta \quad \Rightarrow \quad |f(z) - w_0| < \epsilon$$

Example 2.3. Prove that $\lim_{z \to 1+i} (2+i)z = 1 + 3i$.

Solution: We first do some preliminary work:

$$|(2+i)z - (1+3i)| = |2+i| \cdot |z - \frac{1+3i}{2+i}| = \sqrt{5} \cdot |z - (1+i)|$$

So, let $\epsilon > 0$, with $|z - z_0| < \dfrac{\epsilon}{\sqrt{5}} (= \delta)$, we have

$$\begin{aligned} |(2+i)z - (1+3i)| &= \sqrt{5} \cdot |z - (1+i)| \\ &< \sqrt{5} \cdot \frac{\epsilon}{\sqrt{5}} \\ &= \epsilon \end{aligned}$$

So, $\lim_{z \to 1+i} (2+i)z = 1 + 3i$ □

Note that similar definitions apply when dealing with infinity, e.g. $\lim_{z \to z_0} f(z) = \infty$ means that for any $\epsilon > 0$, there exists $\delta > 0$ such that $0 < |z - z_0| < \delta \quad \Rightarrow \quad |f(z)| > \dfrac{1}{\epsilon}$

Definition 2.4. **Continuity**: f is **continuous** at z_0 means that

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

The usual limit and continuity theorems hold, e.g.

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

Theorem 2.5. Let $f(z) = u + iv, z_0 = x_0 + iy_0, w_0 = u_0 + iv_0$, then

$$\lim_{z \to z_0} f(z) = w_0 \quad \text{if and only if} \quad \begin{cases} \displaystyle\lim_{(x,y) \to (x_0,y_0)} u(x,y) = u_0 \\ \displaystyle\lim_{(x,y) \to (x_0,y_0)} v(x,y) = v_0 \end{cases}$$

Definition 2.6. **Differentiation**:

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

Derivative function is

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

For functions with real analogues (e.g. $f(z) = z^2$ analogous to $f(x) = x^2$), the usual rules (power, quotient, etc.) apply, e.g.

$$f(z) = 3z^2 + z^4 \quad \Rightarrow f'(z) = 6z + 4z^3$$

What about functions without real analogues?

Example 2.7. $f(z) = \overline{z}$. Is it differentiable?

Solution:

$$\begin{aligned} f'(z_0) &= \lim_{z \to z_0} \frac{\overline{z} - \overline{z_0}}{z - z_0} \\ &= \lim_{z \to z_0} \frac{\overline{z - z_0}}{z - z_0} \\ &= \lim_{z \to z_0} \frac{\overline{re^{i\theta}}}{re^{i\theta}} \quad \text{where} \quad z - z_0 = e^{i\theta} \\ &= \lim_{z \to z_0} \frac{e^{-i\theta}}{e^{i\theta}} \\ &= \lim_{z \to z_0} e^{-i2\theta} \end{aligned}$$

which depends on θ! No unique value, so limit DNE. So, f is not differentiable anywhere.

Theorem 2.8. **Cauchy-Riemann Equations**: If $f(z) = u(x, y) + iv(x, y)$ and $f'(z_0)$ exists, then

$$\boxed{u_x = v_y \quad \text{and} \quad v_x = -u_y \qquad \text{at } (x_0, y_0)}$$

Note that for notation,

$$
\begin{aligned}
u_x &= \frac{\partial u}{\partial x} \\
u_y &= \frac{\partial u}{\partial y} \\
v_x &= \frac{\partial v}{\partial x} \\
v_y &= \frac{\partial v}{\partial y}
\end{aligned}
$$

Proof 2.9.

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

Since the limit exists, it must be independent of path, so

- Along $\Delta y = 0$:

$$f'(z_0) = \lim_{\Delta x \to 0} \frac{u(x_0 + \Delta x, y_0) - u(x_0, y_0)}{\Delta x} + i(\cdots) = \frac{\partial u}{\partial x} + i\frac{\partial v}{\partial x}$$

- Along $\Delta x = 0$:

$$f'(z_0) = \lim_{\Delta y \to 0} \frac{u(x_0, y_0 + \Delta y) - u(x_0, y_0)}{i\Delta y} + i(\cdots) = -i\frac{\partial u}{\partial y} + \frac{\partial v}{\partial y}$$

Equating the real and imaginary part yields the result. □

2.3 Differentiability Continued

Example 2.10. Is $f(z) = |z|^2$ differentiable? Where?

<u>**Solution**</u>: $f(z) = \sqrt{x^2 + y^2}^2 = \underbrace{x^2 + y^2}_{u} + \underbrace{0}_{v} i$. So, by CRE, we know that

$$
\begin{cases}
u_x = v_y & \Rightarrow 2x = 0 \\
v_x = -u_y & \Rightarrow 0 = -2y
\end{cases}
$$

It's clear that this is satisfied only at $x = y = 0$.

So, if $(x, y) \neq (0,0)$, i.e. $z \neq 0$, then f is not differentiable.

When $z = 0$, $f'(z) = \lim_{\Delta z \to 0} \dfrac{f(0+\Delta z) - f(0)}{\Delta z} = \lim_{\Delta z \to 0} \dfrac{|\Delta z|^2 - 0}{\Delta z} = 0$. This is because $\left| \dfrac{|\Delta z|^2}{\Delta z} - 0 \right| \leq |\Delta z| \to 0$ as $\Delta z \to 0$ (by applying the squeeze theorem).

Hence, CRE are necessary but not sufficient conditions.

Theorem 2.11. Let f be defined in some neighborhood of z_0. If u_x, u_y, v_x, v_y exist in that neighborhood, satisfying CRE at z_0, and are **continuous** at z_0, then f is differentiable at z_0.

Definition 2.12. $f(z)$ is **analytic at z_0** if $f'(z)$ exists at every point in some neighborhood of z_0.

$f(z)$ is **analytic on an open set S** if it is analytic at every point of S.

Example 2.13. $f(z) = z^3 = \cdots = \underbrace{(x^3 - 3xy^2)}_{u(x,y)} + i\underbrace{(3x^2y - y^2)}_{v(x,y)}$.

We have

$$\begin{aligned} u_x &= 3x^2 - 3y^2 \\ u_y &= -6xy \\ v_x &= 6xy \\ v_y &= 3x^2 - 3y^2 \end{aligned}$$

So, CRE satisfied everywhere. All partial derivatives are continuous. By theorem, f is differentiable everywhere, so is analytic everywhere. We refer to "analytic everywhere" as "entire"

Example 2.14. Where is $f(z) = x^2 + iy^2$ analytic?

We have

$$\begin{aligned} u_x &= 2x \\ u_y &= 0 \\ v_x &= 0 \\ v_y &= 2y \end{aligned}$$

We need $x = y$ to satisfy CRE.

- If $x \neq y$, f is not differentiable, so not analytic.
- If $x = y$, f cannot be analytic because we are not on an open set.

So, f is not analytic nowhere.

Theorem 2.15. Sums, products, and compositions of analytic functions are also analytic, except when $\div 0$

Example 2.16. $f(z) = \dfrac{z^3+2}{z^2+1}$ is analytic everywhere except at $z = \pm i$.

$g(z) = f(z^2)$ is analytic everywhere except wherre $z^2 = \pm i$, i.e. except

$$\begin{aligned} z &= e^{i(\frac{n\pi + \pi/2}{2})} \\ &= e^{i(n\pi/2+\pi/4)} \\ &= e^{i(n\pi/4)}, e^{i(n3\pi/4)}, e^{i(n5\pi/4)}, e^{i(n7\pi/4)} \\ &= \frac{1}{\sqrt{2}} + \frac{i}{\sqrt{2}}, -\frac{1}{\sqrt{2}} + \frac{i}{\sqrt{2}}, -\frac{1}{\sqrt{2}} - \frac{i}{\sqrt{2}}, \frac{1}{\sqrt{2}} - \frac{i}{\sqrt{2}}, \end{aligned}$$

Theorem 2.17. Suppose f is analytic in a domain D. If $f'(z) = 0$ for all $z \in D$, then f is constant in D

Proof 2.18. $f'(z) = u_x + iv_x = v_y - iu_y$. So, $f'(z) = 0 \Rightarrow u_x = v_y = 0 = v_y = u_y$. So, u and v are constant, since D is connected. □

Theorem 2.19. Suppose f is analytic in a domain D. If $|f(z)| = M$ for all $z \in D$, where M is constant, then $f(z)$ is constant in D.

Proof 2.20. $|f(z)|^2 = u^2 + v^2 = M^2$.

We differentiate:

- with respect to x: $2uu_x + 2vv_x = 0 \quad -(1)$

- with respect to y: $2uu_y + 2vv_y = 0 \quad -(2)$

Now $u_x = v_y$, and $v_x = -u_y$, so the (2) gives $-uv_x + vu_x = 0 \quad -(3)$.

Multiply (1) by u_x.

$$\begin{aligned} &uu_x^2 + vu_xv_x = 0 \\ \Rightarrow\ &uux^2 + (uv_x)v_x = 0 \quad \text{by (3)} \\ \Rightarrow\ &u(u_x^2 + v_x^2) = 0 \end{aligned}$$

So, unless $u = 0$ for all $z \in D$, we must have $u_x^2 + v_x^2 = 0$. So, $u_x = v_x = 0$, implying that u, v are constant. Hence, f is constant.

What if $u = 0$ for all $z \in D$? Then, $u_x = u_y = 0$, so $v_x = v_y = 0$ by CRE. f is constant as well. □

2.4 Harmonic Functions

Recap:

$$f'(z) = u_x + iv_x = \frac{u_y + iv_y}{i} = v_y - iu_y$$
$$CRE: \quad u_x = v_y \quad v_x = -u_y$$

Also, "analytic" means differentiable on a open set.

Suppose $f(z) = u(x, y) + iv(x, y)$ is analytic in a domain D. Then u and v satisfy CRE.

Also, which will be shown later, $u, v \in C^2$ (continuous under second partial derivatives), and this implies that $u_{xy} = u_{yx}$, and $v_{xy} = v_{yx}$.

From CRE:

$$\underbrace{u_x - v_y}_{\Rightarrow u_{xx} = v_{yx}} \quad \text{and} \quad \underbrace{v_x = -u_y}_{\Rightarrow u_{yy} = -v_{xy}}$$

Definition 2.21. From the above derivation, we see

$$u_{xx} + u_{yy} = v_{yx} - v_{xy} = 0$$

and

$$v_{xx} + v_{yy} = 0$$

We refer to these as **"Laplace's equation"**

Solution to Laplace's equation are called **"harmonic functions"**

Notes:

- We've shown that if $f(z) = u + iv$ is analytic, then u and v must be harmonic
- Laplace's equation is very useful! We will see that later.
- $u_{xx} + u_{yy} = 0$ is also denoted as $\Delta^2 u = 0$, and we denote Δ as "Laplacian operator".

Example 2.22. Suppose $u(x, y) = e^{-2x} \cos 2y + 2y$. Find $v(x, y)$ such that $f(z) = u + iv$ is analytic.

Solution: u and v must satisfy CRE. So, $v_y = u_x = -2e^{-2x} \cos 2y$. Hence,

$$\begin{aligned} v &= \int -2e^{-2x} \cos 2y dy \\ &= -e^{2x} \sin 2y + C(x) \end{aligned}$$

Note that $C(x)$ is a function of all other variables.

Now we try to make it satisfy other CRE:

$$\begin{aligned} v_x = -u_y \ &\Rightarrow \ 2e^{-2x} \sin 2y + C'(x) = 2e^{-2x} \sin 2y - 2 \\ &\Rightarrow \ C'(x) = -2 \\ &\Rightarrow \ C(x) = -2x + k \end{aligned}$$

Therefore, $v(x, y) = -e^{-2x} \sin 2y - 2x + k$

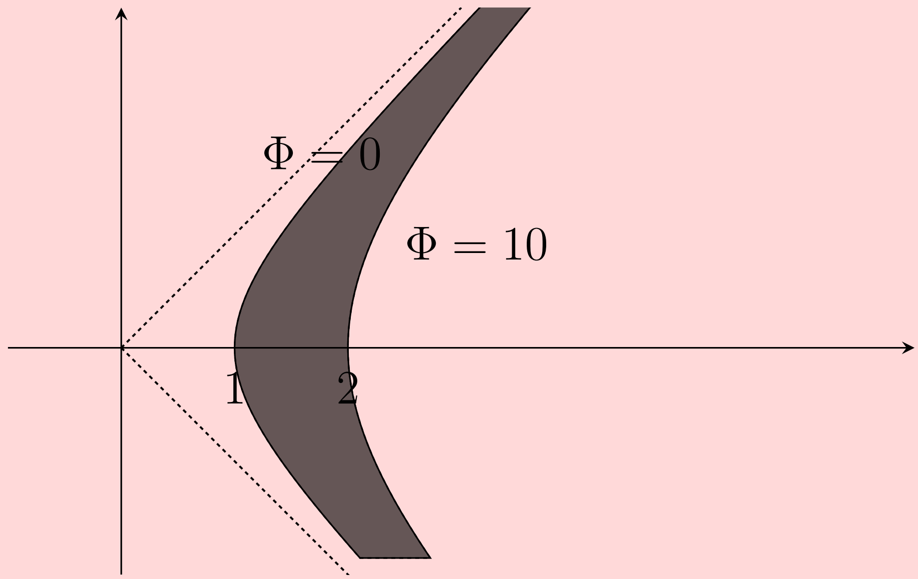
Note that $v(x, y)$ is called the "harmonic conjugate" of u.

Exercise: show that if v is the harmonic conjugate of u, then $-u$ is the harmonic conjugate of v.

Example 2.23. Solve Laplace's equation $\Phi_{xx} + \Phi_{yy} = 0$ on region between hyperbolas $x^2 - y^2 = 1$ and $x^2 - y^2 = 4$, $x > 0$, with "boundary conditions"

$$\begin{cases} \Phi = 0 & \text{on } x^2 - y^2 = 1 \\ \Phi = 10 & \text{on } x^2 - y^2 = 4 \end{cases}$$

i.e. Find $\Phi(x, y)$



Solution: Consider $f(z) = z^2 = (x+yi)^2 = \underbrace{x^2 - y^2}_{u(x,y)} + i\underbrace{2xy}_{v(x,y)}$

Since $f(z)$ is already analytic, we have that $u(x,y) = x^2 - y^2$ is harmonic. Boundary curves of region are level curves of a harmonic function.

Is the solution $\Phi(x,y) = x^2 - y^2$? No.

Try $\Phi(x,y) = A \cdot (x^2 - y^2) + B$ (also harmonic by linearity).

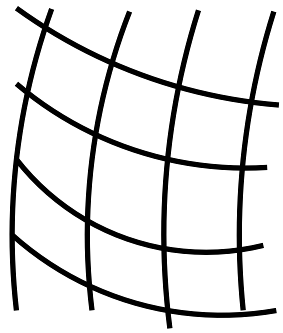
Applying the Boundary Conditions:

$$0 = A \cdot 1 + B \Rightarrow \ B = -A$$
$$10 = A \cdot 4 + B \Rightarrow \ A = \frac{10}{3}, B = -\frac{10}{3}$$

So the solution is $\Phi(x,y) = \dfrac{10}{3}(x^2 - y^2) - \dfrac{10}{3}$

Notes:

- It can be used in temperature distribution
- What about more complicated regions?
- Orthogonal trajectories



- list of harmonic functions

Chapter 3 Elementary Functions

3.1 Elementary Functions

Definition 3.1. Polynomials:

$$p(z) = a_0 + a_1 z + a_2 z^2 + \cdots + a_n z^n \ , \quad a_i \in \mathbb{C}$$

There are obviously **entire**.

The fundamental theorem of algebra guarantees that we can factor this as

$$p(z) = a_n(z - z_1)(z - z_2) \cdots (z - z_n)$$

Note that z_i are not necessarily distinct.

z_0 is a "zero of multiplicity" k if and only if

$$p(z) = (z - z_0)^k q(z)$$

where $q(z)$ is a polynomial such that $q(z_0) \neq 0$

Definition 3.2. Rational Functions:

$$R(z) = \frac{p(z)}{q(z)} = \frac{a_n(z - z_1)(z - z_2) \cdots (z - z_n)}{b_m(z - w_1)(z - w_2) \cdots (z - w_n)}$$

Suppose all common factors have been cancelled, then

- the roots (or zeroes) of $p(z)$ are called the **roots/zeroes** of $R(z)$
- the roots (or zeroes) of $q(z)$ are called the **poles** of $R(z)$

Example 3.3.

$$R(z) = \frac{3i(z - 1)(z - \frac{1}{3}i)^2(z + i)}{(z - i)^3(z - 2 - i)}$$

Zeroes at 1 and $-i$ (order 1 would be a "simple zero"), and $\dfrac{1}{3}i$ (order 2).

Poles at i (order 3) and $2 + i$ (order 1 would be a "simple pole")

Partial Fractions has simpler rules:

Example 3.4. Decompose $R(z) = \dfrac{1}{(z+4)^2(z^2+1)}$

Solution: Factor and expand

$$\frac{1}{(z+4)^2(z^2+1)} = \frac{A}{z+4} + \frac{B}{(z+4)^2} + \frac{C}{z+i} + \frac{D}{z-i}$$

This gives us

$$1 = A\cdot(z+4)(z+i)(z-i) + B(z+i)(z-i) + C(z+4)^2(z-i) + D(z+4)^2(z+i)$$

We can solve this by:

- set $z = -4$, this gives us $1 = 0 + (-4+i)(-4-i)B + 0 + 0$, so $B = \dfrac{1}{17}$
- set $z = -i$, this gives us $1 = 0 + 0 + (-i+4)^2(-2i)C + 0$. Then we conpute $(-2i)(15-8i) = 16-30i$, also $(-16-30i) = \dfrac{(-16-30i)(-16+30i)}{(-16+30i)} = \dfrac{1156}{(-16+30i)} = \dfrac{578}{-8+15i}$.

  Hence, $C = \dfrac{-8+15i}{578}$.
- set $z = -4$, this gives us $1 = 0 + 0 + 0 + (i+4)^2(2i)D$, so $D = \dfrac{-8-15i}{578}$. The trick to compute things here is that, we can replace i with $-i$ from C since the expression is similar to C.

Now what about A? We can try another z, or just compare the coefficients of z^3. By comparing the coefficients of z^3, we get that

$$0 + A + C + D = A + \frac{-8+15i}{578} + \frac{-8-15i}{578}$$

So $A = \dfrac{16}{578} = \dfrac{8}{289}$

Hence,

$$\frac{1}{(z+4)^2(z^2+1)} = \frac{8/289}{z+4} + \frac{1/17}{(z+4)^2} + \frac{\frac{-8+15i}{578}}{z+i} + \frac{\frac{-8-15i}{578}}{z-i}$$

Actually, often we will only need one of the coefficients, and there's a quick way which will be covered later in the course.

Definition 3.5. **Exponential Function**: We already defined that $e^z = e^{x+iy} = e^x(\cos y + i\sin y)$.

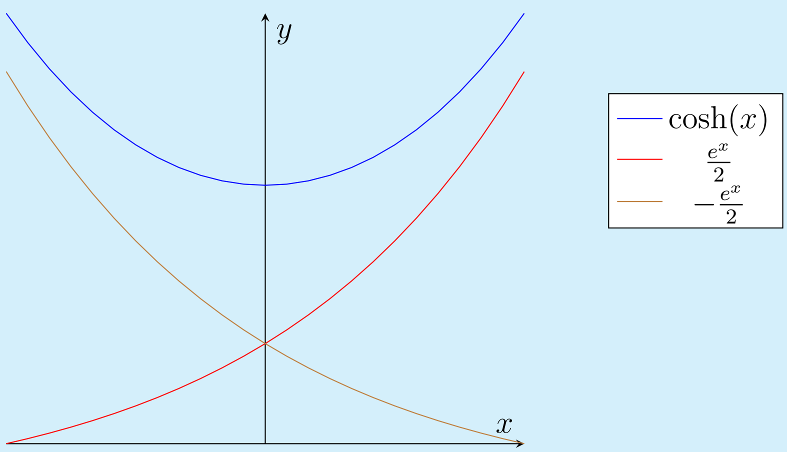
Note that $e^{z_1+z_2} = e^{z_1}e^{z_2}$, $\frac{d}{dz}e^z = e^z$. Also, e^z is **periodic** with period $2\pi i$

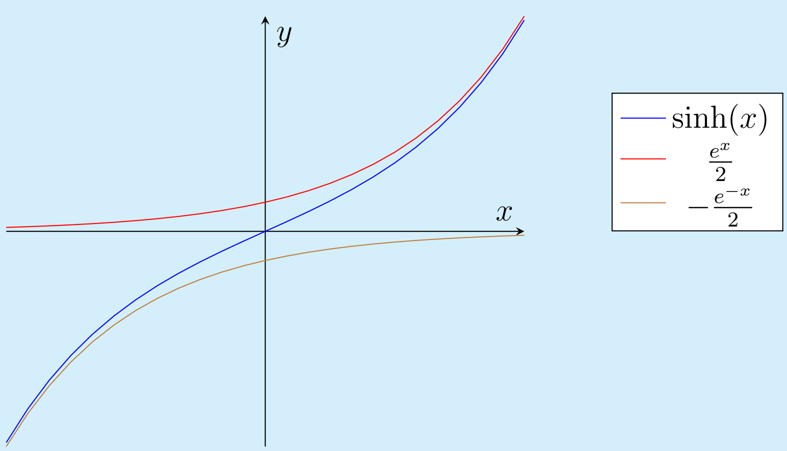
Definition 3.6. Hyperbolic Functions: From real calculus, we seen that

$$\cosh x = \frac{1}{2}(e^x + e^{-x}) \quad \text{this is the even component of } e^x$$
$$\sinh x = \frac{1}{2}(e^x - e^{-x}) \quad \text{this is the odd component of } e^x$$

It can be shown that

$$\cosh x + \sinh x = e^x$$
$$\cosh^2 x - \sinh^2 x = 1$$
$$\frac{d}{dx}\sinh x = \cosh x$$
$$\frac{d}{dx}\cosh x = \sinh x$$





To extend these to $\mathbb{C}$, we define

$$\boxed{\cosh z = \frac{1}{2}(e^z + e^{-z}) \quad \sinh z = \frac{1}{2}(e^z - e^{-z})}$$

3.2 Trigonometric and Logarithmic Function

Definition 3.7. **Trigonometric Functions**: Recall

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

Sum to get $\cos\theta = \dfrac{e^{i\theta} + e^{-i\theta}}{2}$, and $\sin\theta = \dfrac{e^{i\theta} - e^{-i\theta}}{2i}$

We define

$$\boxed{\cos z = \frac{1}{2}(e^{iz} + e^{-iz}) = \cosh(iz) \quad \sin z = \frac{1}{2i}(e^{iz} - e^{-iz}) = \frac{1}{i}\sinh(iz)}$$

Furthermore:

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

$$\text{For real } z, \quad e^z = e^x = \cosh x + \sinh x$$
$$\text{For imaginary } z, \quad e^z = e^{iy} = \cos y + i\sin y$$

The $\cosh x$ and $\cos y$ are the even parts, and $\sinh x$ and $i\sin y$ are the odd parts

Functions	Along Real Axis	Along Imaginary Axis
$e^{iz}, \cos z, \sin z$	periodic	grow exponentially
$e^z, \cosh z, \sinh z$	grow exponentially	periodic

Familiar identities hold true.

Example 3.8.

$$\begin{aligned}\cos^4\theta &= (\frac{e^{i\theta}+e^{-i\theta}}{2})^4\\ &= \frac{1}{16}(e^{i4\theta}+4e^{2\theta}+6+4e^{-i2\theta}+e^{-i4\theta})\\ &= \frac{1}{8}\cos 4\theta+\frac{1}{2}\cos 2\theta+\frac{3}{8}\end{aligned}$$

Example 3.9.

$$\begin{aligned}&\cos^2\theta+\sin^2\theta=1\\ \Rightarrow\ &\cos^2(iy)+\sin^2(iy)=1\\ \Rightarrow\ &\cosh^2 y+i^2\sinh^2 y=1\\ \Rightarrow\ &\cosh^2 y-\sinh^2 y=1\end{aligned}$$

By using the rules $\begin{cases}\cos(iz)=\cosh z\\ \sin(iz)=i\sinh z\end{cases}$.

Notice the "Obsborne's rule" here: Hyperbolic function satisfy the same identities as trigonometric functions except that <u>we must change the sign of every product of two sines</u>.

Derivatives: e^z is entire, and so is $\cos z, \sin z, \cosh z, \sinh z$. Also,

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

Other as expected as well

Note: we can also define $\tan z$, $\sec z$ etc. in the usual ways, and derivatives of them are as expected.

Example 3.10. What is the value of $\sin(\pi+i)$?

<u>Solution</u>:

$$\begin{aligned}\sin(\pi+i)&=\sin\pi\cos(i\cdot 1)+\cos\pi\sin(i\cdot 1)\\ &=\sin\pi\cosh 1+\cos\pi i\sinh(1)\\ &=0+(-1)\cdot i\cdot\sinh(1)\\ &=-\sin i\end{aligned}$$

Example 3.11. Find all solutions of $\sin z = 1000$

<u>**Solution**</u>: We write $\sin(x + yi) = 1000$, and get that

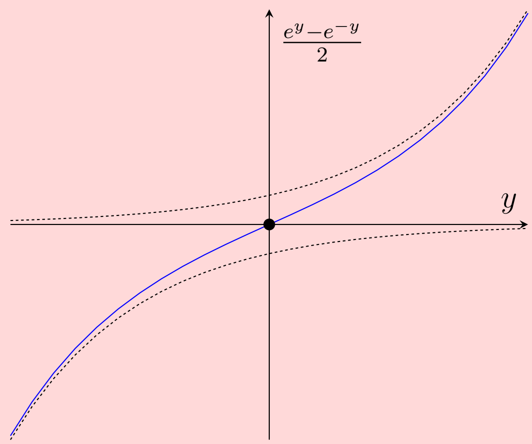
$$\sin x \cosh y + i \cos x \sinh y = 1000$$

So

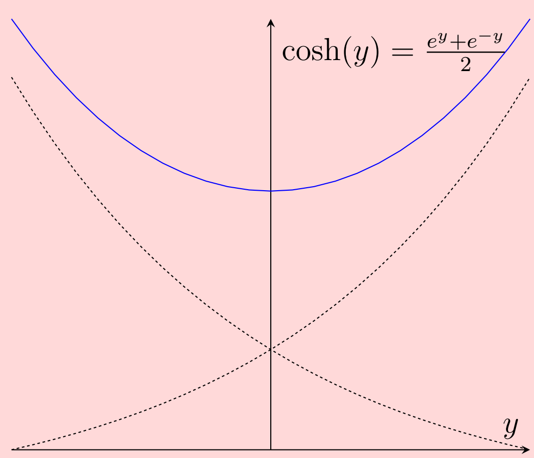
$$\begin{cases} \sin x \cosh y = 1000 & \cdots\cdots(1) \\ \cos x \sinh y = 0 & \cdots\cdots(2) \end{cases}$$

Equation 2 gives that $\cos x = 0$ or $\sinh y = 0$, which yields that $x = (2n+1)\dfrac{\pi}{2}$ or $y = 0$.

The following figure shows that the only x that $\sinh(x) = 0$ is at $x = 0$.



- If $y = 0$, equation 1 gives that $\sin x \cosh(0) = \sin x = 1000$. This is impossible
- If $x = (2n+1)\dfrac{\pi}{2}$, then equation 1 gives $\sin\left((2n+1)\dfrac{\pi}{2}\right)\cosh y = 1000$, so $\cosh y = 1000 \cdot (-1)^n$



But $\cosh y > 0$, so use $n = 2N$ (always even). So $\cosh y = 1000$, and $y = \pm\cosh^{-1}(1000) \approx \pm 7.6$ (There are two solutions, i.e. note the $\pm$ sign, as the figure above shows).

The final answer is that $z = x + iy = (4N+1)\frac{\pi}{2} \pm i\cosh^{-1}(1000)$

3.3 Logarithmic Functions

How to define $\log z$? Let $z = e^w$ and solve for w. Note that:

- exponential function is periodic, so log will be a "multi-valued function"
- in $\mathbb{C}$, we use "log" instead of "ln"

Definition 3.12. Now,

$$\begin{aligned} z = e^w \Rightarrow \; & re^{i\theta+2\pi k} = e^{u+iv} \\ \Rightarrow \; & r = e^u, \;\; \theta + 2\pi k = v \\ \Rightarrow \; & u = \ln r, \;\; v = \theta + 2\pi k \end{aligned}$$

So, we define

$$\boxed{\log z = \ln|z| + i\arg z}$$

Example 3.13.

- $\log(1+i) = \ln|1+i| + i\arg(1+i) = \ln\sqrt{2} + i\left(\frac{\pi}{4} + 2\pi k\right)$
- $\log(i) = \ln|i| + i\arg(i) = 0 + i\left(\frac{\pi}{2} + 2\pi k\right)$

Proposition 3.14. We have the following identity:

$$\begin{aligned} \log(z_1 z_2) &= \ln|z_1 z_2| + i\arg(z_1 z_2) \\ &=^* \ln|z_1| + \ln|z_2| + i(\arg z_1 + \arg z_2) \\ &= \log(z_1) + \log(z_2) \end{aligned}$$

Similarly

$$\log\left(\frac{z_1}{z_2}\right) =^* \log(z_1) - \log(z_2)$$

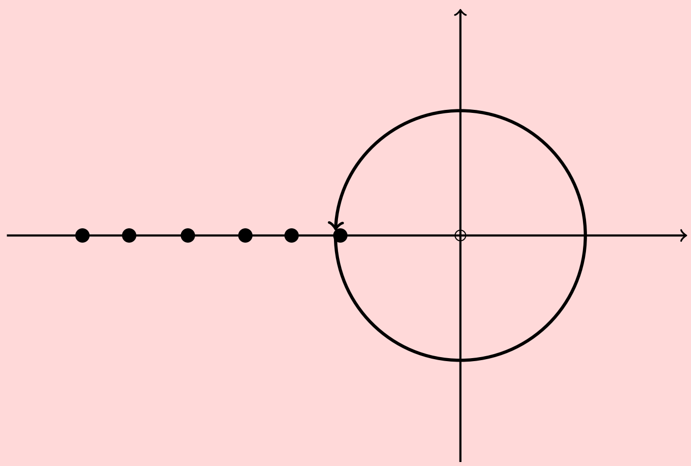
By $=^*$, we actually mean that <u>the set of values</u> of $\log(z_1 z_2)$ is equal to <u>the set of values</u> of $\log(z_1) + \log(z_2)$, due to the multi-valuedness of log.

Definition 3.15. The **principle value of the Logarithm** is

$$\operatorname{Log}(z) = \ln|z| + i \underbrace{\operatorname{Arg}(z)}_{\in(-\pi,\pi] \text{ usually}}$$

Example 3.16.

- $\operatorname{Log}(1+i) = \ln|1+i| + i\operatorname{Arg}(1+i) = \ln\sqrt{2} + i\dfrac{\pi}{4}$
- $\operatorname{Log}(i) = \ln|i| + i\operatorname{Arg}(i) = 0 + i\pi$
- $\operatorname{Log} e^z = z$ if and only if $Im(z) \in (-\pi, \pi]$
- $\operatorname{Log} z$ has discontinuity on negative real axis



- $\operatorname{Log} z$ is analytic everywhere else, with

$$\frac{d}{dz}\operatorname{Log} z = \frac{1}{z}$$

Proof 3.17. Let

$$\begin{aligned} w = \operatorname{Log} z &= \ln|z| + i\operatorname{Arg}(z) \\ &= \frac{1}{2}\ln(x^2+y^2) + i\left(\arctan(\frac{y}{x}) \pm \pi\right) \\ &= u(x,y) + iv(x,y) \end{aligned}$$

Now,

$$\begin{aligned}\frac{dw}{dz} &= \frac{\partial u}{\partial x} - i\frac{\partial u}{\partial y} \\ &= \frac{x}{x^2+y^2} - i\frac{y}{x^2+y^2} \\ &= \frac{x-iy}{x^2+y^2}\cdot\frac{x+iy}{x+iy} \\ &= \frac{1}{z}\end{aligned}$$

□

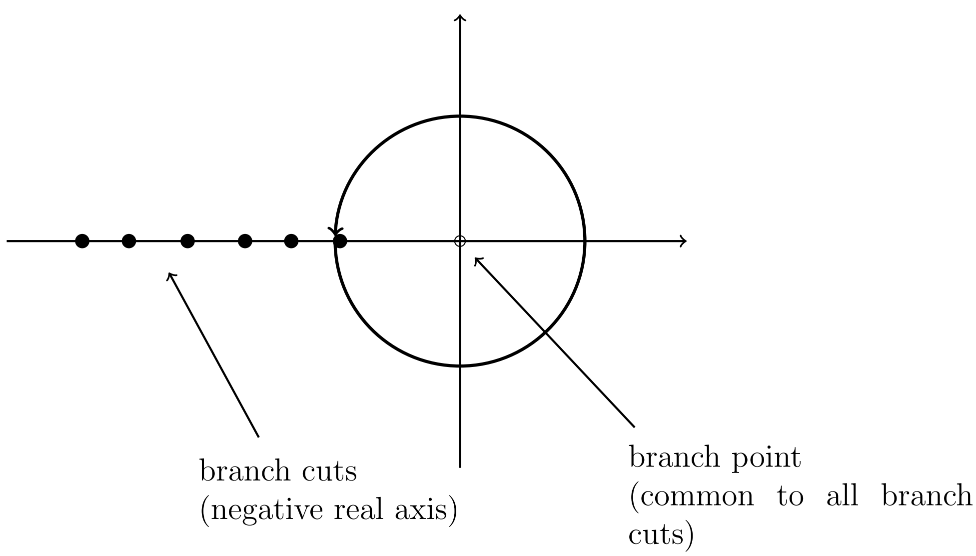
Definition 3.18. **Branch Cuts**: Let $f(z)$ be a multivalued function. $F(z)$ is said to be a **branch** of $f(z)$ on a domain D if $F(z)$ is continuous on D and for each $z \in D$, $F(z)$ is one and only one of the values of $f(z)$.

Example 3.19. $\operatorname{Log} z$ is a branch of $\log z$

We could define different branches of $\log z$ by

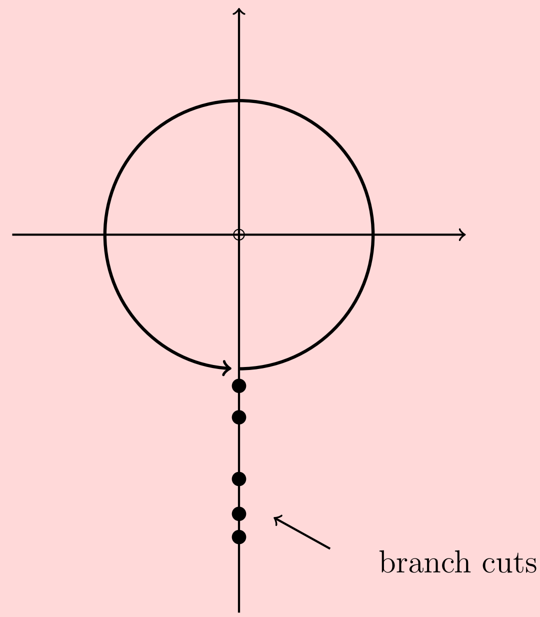
$$\operatorname{Log}_\tau z = \ln|z| + i\operatorname{Arg}_\tau(z)$$

where $\operatorname{Arg}_\tau(z) \in (\tau, \tau+2\pi]$. Note that $\operatorname{Log} z = \operatorname{Log}_{-\pi}$



Example 3.20.

$$\operatorname{Log}_{-\frac{\pi}{2}} \ln|z| + i\operatorname{Arg}_{-\frac{\pi}{2}}(z)$$



Example 3.21. Find a branch of $f(z) = \log(z+4)$ that is analytic at $z = -5$ and equals $7\pi i$ there.

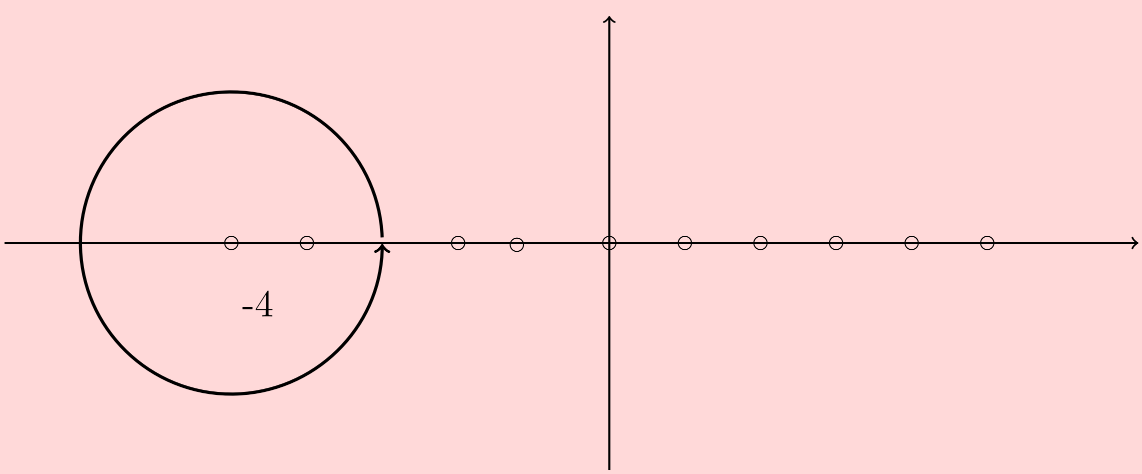
<u>**Solution**</u>: We want $\mathrm{Log}_\tau(-5+4) = \mathrm{Log}_\tau(-1) = 7\pi i$ for some τ.

So, $\ln|-1| + i\,\mathrm{Arg}_\tau(-1) = 7\pi i$ for some k, i.e.

$$0 + i\underbrace{(\pi + 2k\pi)}_{\in(\tau,\tau+2\pi]} = 7\pi i \quad \text{for some } k$$

Hence, $k = 3$. We can choose $\tau = 6\pi$ so that $7\pi \in (6\pi, 8\pi]$.

The final answer would be $F(z) = \mathrm{Log}_{6\pi}(z+4)$



Example 3.22. Where is $f(z) = \text{Log}(z^2 + 1)$ analytic?

Solution: We need $z^2 + 1 \neq 0$ and not equal to negative real number.

So, $z^2 + 1 = (x + yi)^2 + 1 = (x^2 - y^2 + 1) + i(2xy)$.

$$z^2 + 1 = 0 \text{ when } \begin{cases} x = 0 \text{ and } y = \pm 1 \\ \text{or} \\ y = 0 \text{ and } x^2 + 1 = 0 \text{ This is impossible for } x \in \mathbb{R} \end{cases}$$

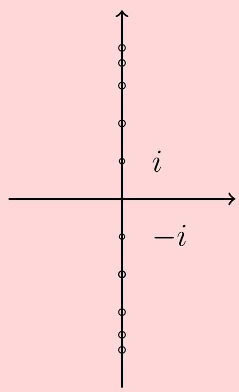
Hence, $z = \pm i$ here.

$$z^2 + 1 < 0 \text{ (real) when } \begin{cases} x = 0 \text{ and } 1 - y^2 < 0 \quad \Rightarrow y^2 > 1 \Rightarrow y > 1 \text{ or } y < -1 \\ \text{or} \\ y = 0 \text{ and } 1 + x^2 < 0 \quad \text{Impossible} \end{cases}$$

Hence, $z = iy$ where $|y| > 1$.

For all other points,

$$f'(z) = \frac{2z}{z^2 + 1}$$



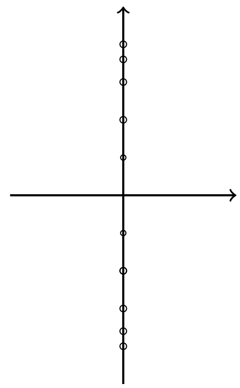
Here is another way to solve the above problem.

$$\text{Log}(z^2 + 1) = \text{Log}((z + i)(z - i)) = \text{Log}_{\tau_1}(z + i) + \text{Log}_{\tau_2}(z - i)$$

for some τ_1, τ_2

Some possibilities are:

- $\tau_1 = \dfrac{-\pi}{2}$, $\tau_2 = \dfrac{-3\pi}{2}$
- $\tau_1 = \dfrac{3\pi}{2}$, $\tau_2 = \dfrac{-7\pi}{2}$
- $\cdots$

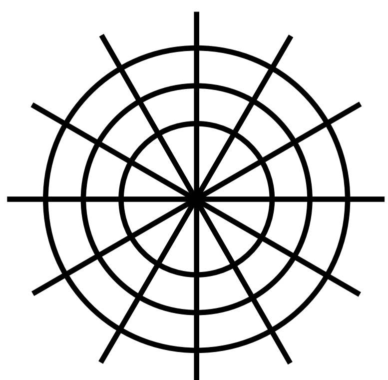


Finally, note that

$$\operatorname{Log} z = \ln|z| + i \operatorname{Arg} z$$

$\operatorname{Log} z$ is analytic, so $\ln|z|$ and $\operatorname{Arg} z$ are harmonic.

Level curves of $\ln|z| = k$ and $\operatorname{Arg} z = k$ are circles and rays. This would be particularly useful when we deal with temperature problems later.



useful for temp problems later

3.4 Complex Powers and Inverse Trigonometric Functions

Definition 3.23. Complex Powers: We define

$$z^\alpha = e^{\alpha \log z} \quad \text{for } \alpha \in \mathbb{C}, z \neq 0$$

Example 3.24. 1.

$$\begin{aligned}
4^{1/2} &= e^{\frac{1}{2}\log 4} \\
&= e^{\frac{1}{2}(\ln|4|+i\arg(4))} \\
&= e^{\frac{1}{2}\ln 4+i\frac{1}{2}(0+2\pi k)} \\
&= e^{\frac{1}{2}2\ln 2+i\pi k} \\
&= e^{\ln 2}e^{i\pi k} \\
&= 2\cdot(\pm 1) \\
&= \pm 2
\end{aligned}$$

2.

$$\begin{aligned}
(1+i)^3 &= e^{3\log(1+i)} \\
&= e^{3\left(\ln\sqrt{2}+i\arg(1+i)\right)} \\
&= e^{\frac{3}{2}\ln 2}e^{i3\left(\frac{\pi}{4}+2k\pi\right)} \\
&= (e^{\ln 2})^{\frac{3}{2}}\cdot\left(\cos\frac{3\pi}{4}+i\sin\frac{3\pi}{4}\right) \\
&= 2^{\frac{3}{2}}\cdot\left(\frac{-1}{\sqrt{2}}+i\frac{1}{\sqrt{2}}\right) \\
&= -2+2i
\end{aligned}$$

3.

$$\begin{aligned}
i^i &= e^{i\ln|i|+i\arg i} \\
&= e^{i\left(0+i(\frac{\pi}{2}+2k\pi)\right)} \\
&= e^{-\left(\frac{\pi}{2}+2\pi k\right)} \\
&= \cdots, e^{\frac{-5\pi}{2}}, e^{\frac{-\pi}{2}}, e^{\frac{3\pi}{2}}, \cdots
\end{aligned}$$

If we want a single value, take the principal branch to be $e^{\alpha \operatorname{Log} z}$, which is analytic everywhere $\operatorname{Log} z$ is, and

$$\frac{d}{dz}z^\alpha = \frac{d}{dz}e^{\alpha\operatorname{Log} z} = e^{\alpha\operatorname{Log} z}\cdot\frac{\alpha}{z} = z^\alpha\cdot\frac{\alpha}{z} = \alpha z^\alpha$$

as expected.

Definition 3.25. **Inverse Trigonometric Functions**: First, we see that $w = \sin^{-1} z$ means $z = \sin w$, etc. Also, we've accepted multivalued functions.

In $\mathbb{R}$, the inverse hyperbolic function can be expressed in terms of logs:

$$\begin{aligned}
y = \sinh x &= \frac{1}{2}(e^x - e^{-x}) \\
e^x - 2y - e^{-x} &= 0 \\
(e^x)^2 - 2y(e^x) - 1 &= 0 \quad \text{note that this is a quadratic equation for } e^x \\
e^x = \frac{2y \pm \sqrt{4y^2+4}}{2} &= y \pm \sqrt{y^2+1} \text{ we take the plus sign since } e^x > 0
\end{aligned}$$

So, $x = \ln(y + \sqrt{y^2+1}) = \sinh^{-1} y$.

In $\mathbb{C}$, we define $\sinh^{-1} z = \log(z + \sqrt{z^2+1})$.

Similarly, $\sin^{-1} z = -i\log(iz + (1-z^2)^{\frac{1}{2}})$. Note that for this fefinition, it involves two sets of branches, one with log, and the other one with $(1-z^2)^{\frac{1}{2}}$

Chapter 4 Complex Integration

4.1 Contours

How to integrate in $\mathbb{C}$?

Complex values functions of a real variable are easy to integrate:

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

Example 4.1. 1.

$$\int_0^1 (t+i)^2 dt \int_0^1 \Big((t^2-1) + i(2t)\Big)dt = \frac{-2}{3} + 2i$$

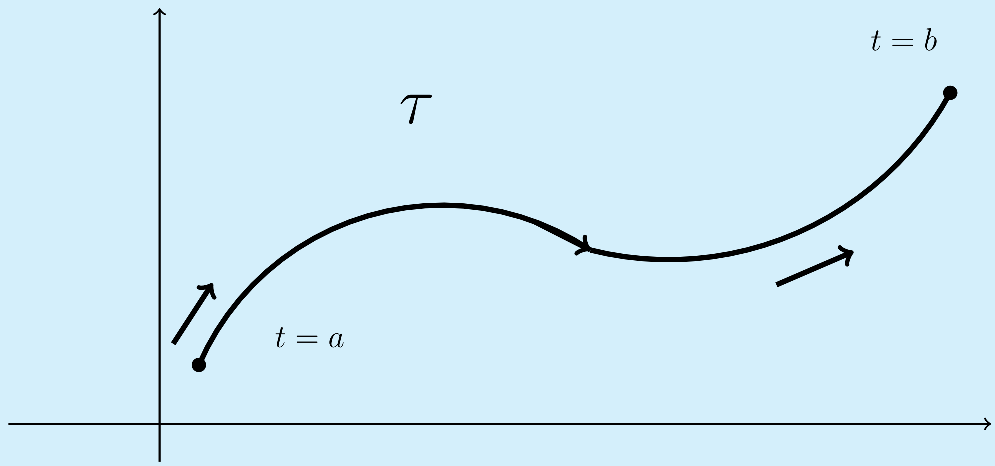
2. We can use a special trick (instead of using integration by parts twice).

$$\begin{aligned}
\int_0^\pi e^{2\pi}\cos x dx &= \int_0^\pi e^2 x(Re(e^i x))dx \\
&= Re\Bigg(\int_0^\pi e^{(2+i)\pi}\Bigg) \\
&= Re\Bigg(\frac{e^{(2+i)}}{2+i}\Bigg|_0^\pi\Bigg) \\
&= Re\Bigg(\frac{e^{2x}(\cos x + i\sin x)}{2+i}\cdot\frac{2-i}{2-i}\Bigg|_0^\pi\Bigg) \\
&= \left[\frac{2}{5}e^{2x}\cos x + \frac{1}{5}e^{2x}\sin x\right]\Bigg|_0^\pi \\
&= -\frac{2}{5}e^{-2\pi} + \frac{2}{5}
\end{aligned}$$

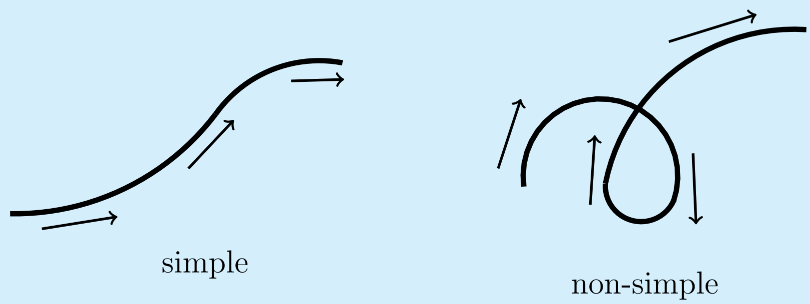
What about integrating a function of a complex variable?

We will replace the intervals with paths.

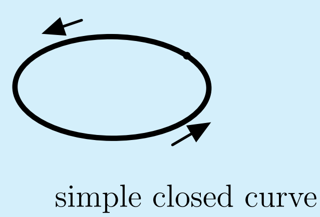
Definition 4.2. Let $z(t) = x(t) + iy(t)$ on $t \in [a,b]$ be continuous. The range is a **curve** $\mathcal{C}$, and is called a **smooth curve** if $z'(t)$ is continuous and non-zero on $[a,b]$



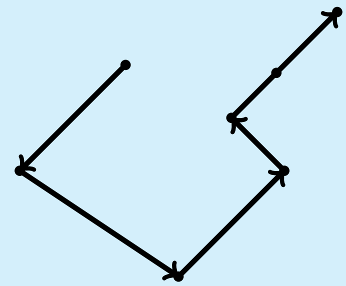
A curve is called **simple** if $z(t_1) \neq z(t_2)$ whenever $t_1 \neq t_2$ for $a < t_i < b$ (basically no self intersection)



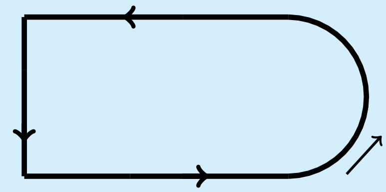
If $z(a) = z(b)$, then the curve is called a **closed** curve.



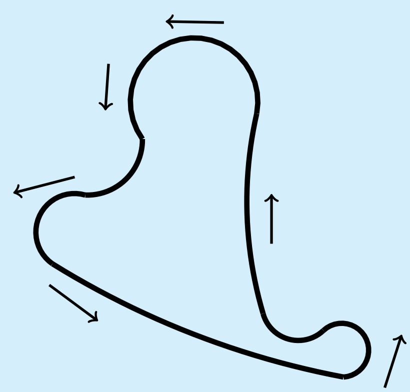
Definition 4.3. **Contour**: a curve that is composed of finitely many smooth curves, joined end-to-end



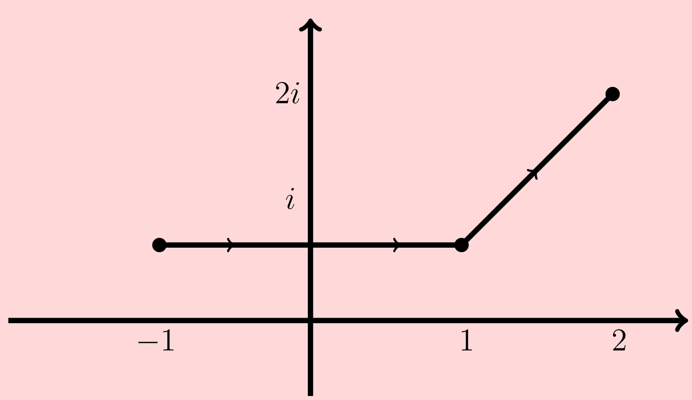
Definition 4.4. **Jordan Curve**: a simple closed contour.



Definition 4.5. **Positively Oriented**: means its interior lies to the **left** as we follow the curve



Example 4.6. Parameterize this:



Solution: Line segment from z_0 to z_1 can be parameterized as: $z(t) = z_0 + (z_1 - z_0)t, t \in [0, 1]$.

For the first curve,

$$\begin{aligned} z_1(t) &= (-1 + i) + (1 + i - (-1 + i))t \\ &= -1 + i + 2t, \quad t \in [0, 1] \end{aligned}$$

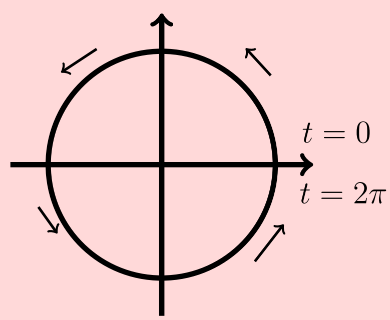
For the second curve,

$$\begin{aligned} z_2(t) &= (1 + i) + (2 + 2i - (1 + i))t \\ &= 1 + i + (1 + i)t, \quad t \in [0, 1] \end{aligned}$$

Put everything together we get

$$z(t) = \begin{cases} -1 + i + 2t & t \in [0, 1) \\ 1 + i + (1 + i)(t - 1) & t \in [1, 2] \end{cases}$$

Example 4.7. Let $\mathcal{C}$ be a unit circle centered at 0.



Solution: $\mathcal{C} : z(t) = e^{it} \quad t \in [0, 2\pi]$

Example 4.8. Circle, radius r_0, centered at z_0?

Solution: $\mathcal{C} : z(t) = z_0 + r_0 e^{it} \quad t \in [0, 2\pi]$

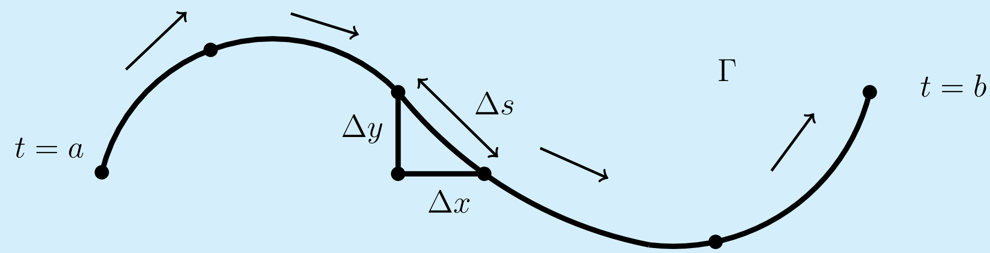
Example 4.9. Parameterize $y = f(x), x \in [a, b]$

Solution: just let $x(t) = t$,

$$z(t) = x(t) + iy(t) = t + if(t), \quad t \in [a, b]$$

For example, $y = x^2$ will be parameterized as $z(t) = t + it^2$

Definition 4.10. **Arclength**: We define the arclength as follows:



Partition the curve

$$\begin{aligned} \Delta s &\approx \sqrt{\Delta x^2 + \Delta y^2} \\ &= \sqrt{\left(\frac{\Delta x}{\Delta t}\right)^2 + \left(\frac{\Delta y}{\Delta t}\right)^2}\Delta t \end{aligned}$$

Sum all pieces and let $\Delta t \to 0$ (Performing a Riemann Sum there):

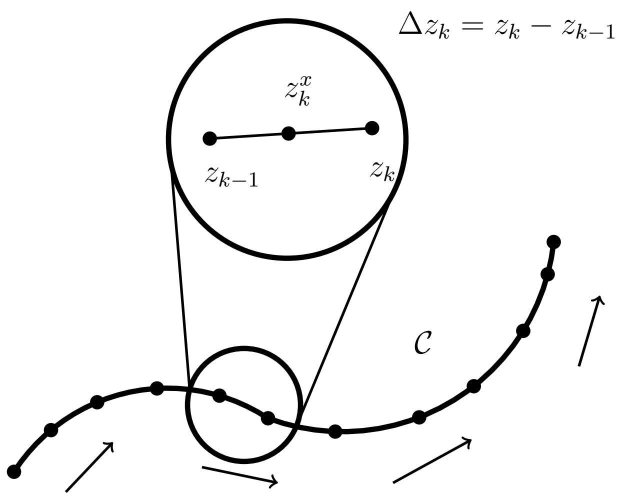
$$\begin{aligned} L = \int_R ds &= \int_a^b \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt \\ &= \int_a^b \left|\frac{dz}{dt}\right| dt \quad \text{we use modulus here} \end{aligned}$$

The physical interpretation could be: total_distance $= \int_a^b (\text{speed})\, dt$

Now we are ready to integrate $f(z)$ along a curve.

4.2 Contour Integrals

Partition curve $\mathcal{C}$ as shown.



Sum, and let $\max|\Delta z_k| \to 0$:

$$\int_{\mathcal{C}} f(z)dz = \lim_{\max|\Delta z_k|\to 0} \sum_k f(z_k^*)\Delta z_k$$

See the text for more detail.

If $\mathcal{C}$ is a single point, define $\int_{\mathcal{C}} f(z)dz = 0$.

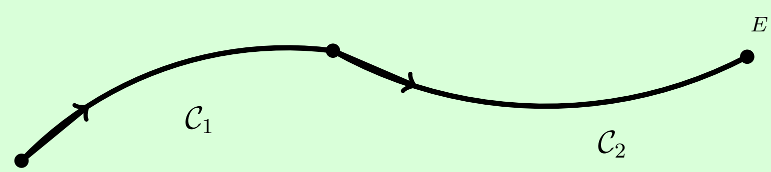
How to calculate?

Definition 4.11. Assume $\mathcal{C}$ has a parameterization. Call it $z(t), t \in [a,b]$. Then:

$$\begin{aligned}\int_{\mathcal{C}} f(z)dz &= \lim_{\max|\Delta z_k|\to 0} \sum_k f(z_k^*)\frac{\overbrace{z(t_k)}^{z_k} - \overbrace{z(t_{k-1})}^{z_{k-1}}}{\Delta t_k}\Delta t_k \\ &= \int_a^b f(z)z'(t)dt\end{aligned}$$

Proposition 4.12. Properties:

- $\int_{\mathcal{C}} \Big(f(z) + g(z)\Big)dz = \int_{\mathcal{C}} f(z)dz + \int_{\mathcal{C}} g(z)dz$
- $\int_{\mathcal{C}} kf(z)dz = k\int_{\mathcal{C}} f(z)dz$
- $\int_{-\mathcal{C}} f(z)dz = -\int_{\mathcal{C}} f(z)dz$. Here $-\mathcal{C}$ means $\mathcal{C}$ traversed in the opposite direction
- $\int_{\mathcal{C}_1+\mathcal{C}_2} f(z)dz = \int_{\mathcal{C}_1} f(z)dz + \int_{\mathcal{C}_2} f(z)dz$. Here it means that we traverse $\mathcal{C}_1$ then traverse $\mathcal{C}_2$.



Is there a triangle inequality? i.e.

$$\left|\int_{\mathcal{C}} f(z)dz\right| \leq_? \int_{\mathcal{C}} |f(z)|\, dz$$

No! LHS is real, but RHS is complex. "$\leq$" does NOT make any sense here.

Proposition 4.13. **<u>The "ML" Inequality</u>**: If $f(z)$ is continuous on a contour $\mathcal{C}$, then

$$\left|\int_{\mathcal{C}} f(z)dz\right| \leq ML$$

where M is an upper bound for $|f(z)|$ on $\mathcal{C}$ and L is the length of $\mathcal{C}$.

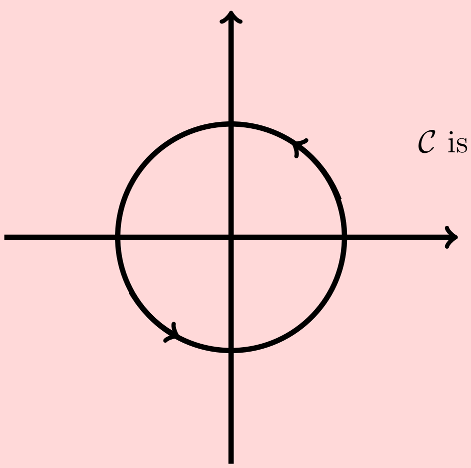
Proof 4.14. Let $z(t)$, $t \in [a,b]$ be a parameterization of $\mathcal{C}$. Then

$$\begin{aligned}
\left|\int_{\mathcal{C}} f(z)dz\right| &= \left|\int_a^b f(z(t))z'(t)dt\right| \\
&\le \int_a^b \left|f(z(t))z'(t)\right|dt \quad \text{by triangle inequality for integrals w.s.t. real variables} \\
&= M\int_a^b \left|z'(t)\right|dt \\
&= ML
\end{aligned}$$

Second last step: since $|f(z)| \le M$ on $\mathcal{C}$.

Last step: from last lecture. See Definition 4.10. □

Example 4.15. Find an upper bound on $\left|\int_{\mathcal{C}} e^{\frac{1}{z}}\right|$



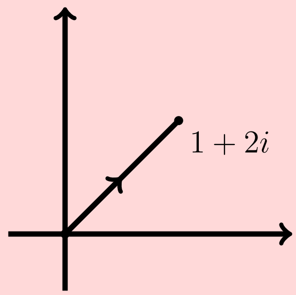
$\mathcal{C}$ is unit circle, traversed <u>once</u> in positive direction

<u>**Solution**</u>: $M = ?$

$$\begin{aligned}
\left|e^{\frac{1}{z}}\right| &= \left|e^{\frac{1}{x+iy}}\right| \\
&= \left|e^{\frac{x-iy}{x^2+y^2}}\right| \\
&= \left|e^{\frac{x}{x^2+y^2}} \cdot e^{-i\frac{y}{x^2+y^2}}\right| \\
&\le e^{\frac{x}{1}} \quad \text{since } x^2+y^2=1 \\
&\le e^1 \quad \text{since } x \le 1
\end{aligned}$$

Clearly, $L = 2\pi$, so $\left|e^{\frac{1}{z}}\right| \leq e^1 \cdot 2\pi = 2\pi e$ by ML inequality.

Example 4.16. Evaluate $\int_{\mathcal{C}} \cos z dz$ where $\mathcal{C}$ is the line segment from 0 to 1+2i.



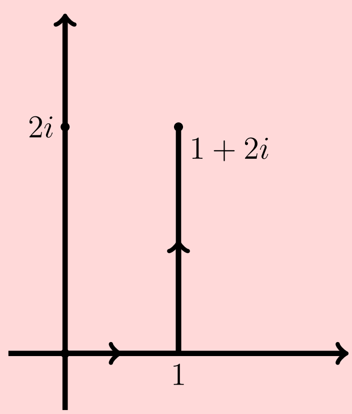
<u>Solution</u>: Parameterize $\mathcal{C}$ by

$$z(t) = 0 + (1 + 2i - 0)t, \quad t \in [0, 1]$$

Then

$$\int_{\mathcal{C}} \cos z dx = \int_0^1 \underbrace{\cos\Big((1+2i)t\Big)}_{f(z(t))} \cdot \underbrace{(1+2i)}_{z'(t)} dt = \sin\Big((1+2i)t\Big)\Big|_0^1 = \sin(1+2i) - 0 = \sin(1+2i)$$

Example 4.17. Evaluate $\int_{\mathcal{C}} \cos z dz$ where $\mathcal{C}$ is:

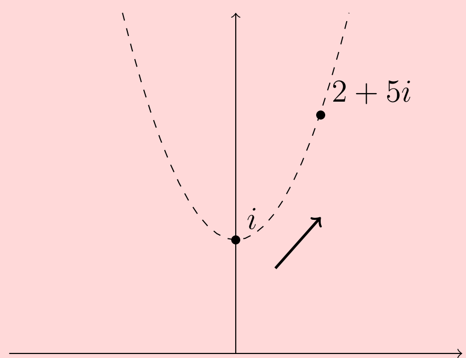


Solution: $\mathcal{C} = \mathcal{C}_1 \cup \mathcal{C}_2$ where $\begin{cases} C_1: & z(t) = t, \quad t \in [0,1) \\ C_2: & z(t) = 1 + (t-1)i, \quad t \in [1,3] \end{cases}$. So

$$\begin{aligned}
\int_{\mathcal{C}} \cos z dx &= \int_{\mathcal{C}_1} \cos z dx + \int_{\mathcal{C}_2} \cos z dx \\
&= \int_0^1 \cos t dt + \int_1^3 \cos(1 + (t-1)i) i dt \\
&= \sin t|_0^1 + \sin(1 + (t-1)i)|_1^3 \\
&= \sin(1) + (\sin(1+2i) - \sin(1)) \\
&= \sin(1+2i)
\end{aligned}$$

As before

Example 4.18. Evaluate $\int_{\mathcal{C}} e^z dz$ where $\mathcal{C}$ is part of $y = x^2 + 1$ from $z = i$ to $z = 2 + 5i$.



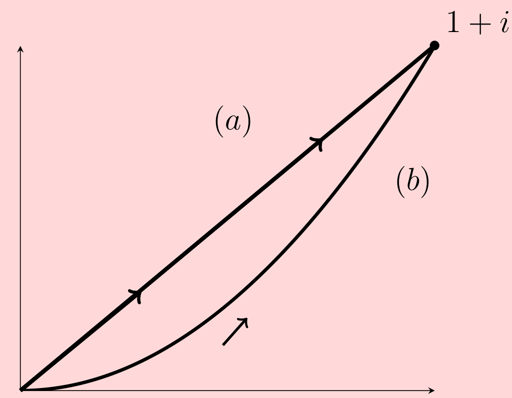
Solution: Let $z(t) = \underbrace{t}_{x} + \underbrace{(t^2+1)}_{y} i, \quad t \in [0,2]$. Then,

$$\begin{aligned}
\int_{\mathcal{C}} e^z dz &= \int_0^2 e^{z(t)} z'(t) dt \\
&= \int_0^2 e^{t^2 + (t^2+1)i}(1 + 2ti) dt \\
&= e^{t^2 + (t^2+1)i}\Big|_0^2 \\
&= e^{2+5i} - e^i \\
&= e^z\Big|_i^{2+5i}
\end{aligned}$$

Does it always work that way? See the following example

Example 4.19. Evaluate $\int_{\mathcal{C}} \overline{z} dz$ where

1. $\mathcal{C}$ is line segment from 0 to $1+i$
2. $\mathcal{C}$ is the smallest arc of circle $x^2 + (y-1)^2 = 1$ from 0 to $1+i$



__Solution__:

1. parameterization: $z(t) = t(1+i), \;\; t \in [0,1]$

$$\begin{aligned}\int_{\mathcal{C}} \overline{z} dz &= \int_0^1 t(1-i)\cdot(1+i)dt \\ &= \int_0^1 2tdt \\ &= 1\end{aligned}$$

2. parameterization: $z(t) = e^{it} + i, \;\; t \in [\frac{-\pi}{2}, 0]$. It's the unit circle, shifted up by 1 unit.

$$\begin{aligned}\int_{\mathcal{C}} \overline{z} dz &= \int_{-\pi/2}^0 (e^{-it} - i)(ie^{it})dt \\ &= \cdots \\ &= 1 + i(\frac{\pi}{2} - 1)dt \\ &\neq 1\end{aligned}$$

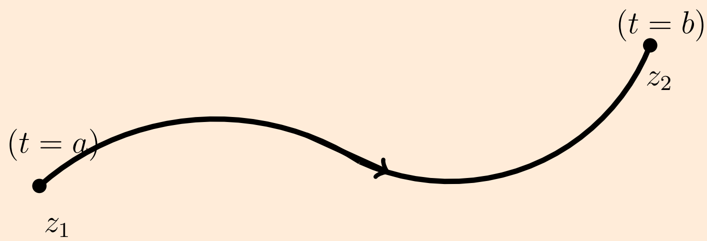
So, the general answer is no. Different paths might yield different results.

4.3 Independence of Path

Theorem 4.20. **Complex Extension of Fundamental Theorem of Calculus**:

If $f(z)$ is continuous in a domain D and has antiderivative $F(z)$ throughout D, then, for any contour $\mathcal{C}$ lying in D with initial point z_1 and terminal point z_2, we have

$$\int_{\mathcal{C}} f(z)dz = F(z_2) - F(z_1)$$

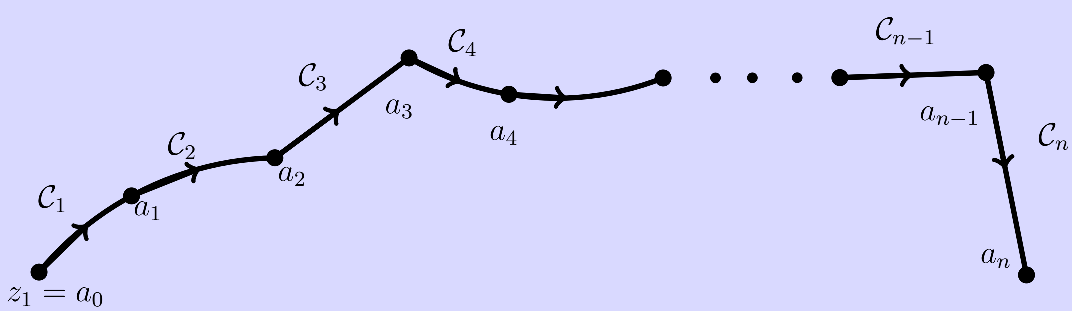


Proof 4.21. First, suppose $\mathcal{C}$ is smooth, i.e. $z'(t) \neq 0$, continuous.

Parameterize by $z(t), t \in [a, b]$. Then,

$$\begin{aligned} \int_{\mathcal{C}} f(z)dz &= \int_a^b f(z(t))z'(t)dt \\ &= \int_{\mathcal{C}} \frac{d}{dt}\Big(F\big(z(t)\big)\Big)dt \quad \text{by chain rule} \\ &= F(z(t))\Big|_{t=a}^{b} \\ &= F(z(b)) - F(z(a)) \\ &= F(z_2) - F(z_1) \end{aligned}$$

Next, if $\mathcal{C}$ is not smooth, it has a finite number of smooth pieces, since it's a contour.

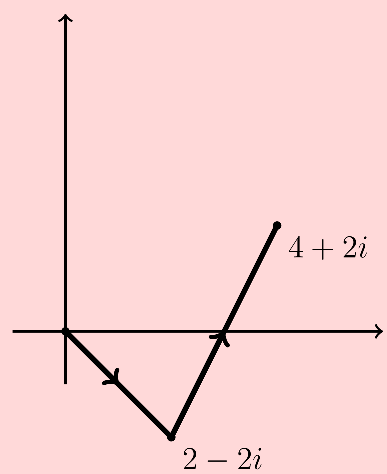


Apply the result above to each piece:

$$\begin{aligned}
\int_{\mathcal{C}} f(z)dz &= \int_{\mathcal{C}_1} f(z)dz + \cdots + \int_{\mathcal{C}_n} f(z)dz \\
&= \Big(F(a_1) - F(a_0)\Big) + \Big(F(a_2) - F(a_1)\Big) + \cdots + \Big(F(a_n) - F(a_{n-1})\Big) \\
&= F(a_n) - F(a_0) \\
&= F(z_2) - F(z_1)
\end{aligned}$$

□

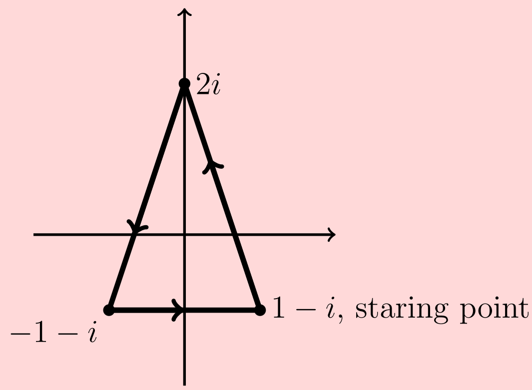
Example 4.22. Evaluate $\int_{\mathcal{C}}(1+z^2)dz$ where $\mathcal{C}$ is:



Solution:

$$\begin{aligned}
\int_{\mathcal{C}}(1+z^2)dz &= \left(z + \frac{z^3}{4}\right)\Bigg|_{z=0}^{z=4+2i} \\
&= \cdots \\
&= \frac{28}{3} + \frac{94}{3}i
\end{aligned}$$

Example 4.23. Evaluate $\int_{\mathcal{C}} e^z dz$ where $\mathcal{C}$ is:



Solution:

$$\begin{aligned}\int_{\mathcal{C}}(1+z^2)dz &= e^z\Big|_{z=1-i}^{z=1-i} \\ &= e^{1-i}-e^{1-i} \\ &= 0\end{aligned}$$

Theorem 4.24. Let f be a continuous function in a domain D. Then, the following statements are equivalent:

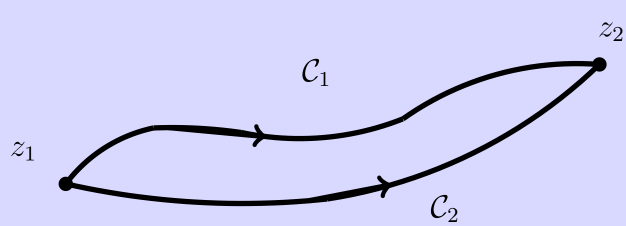
1. f has an antiderivative in D.
2. If $\mathcal{C}$ is any closed contour in D, then $\int_{\mathcal{C}} f(z)dz = 0$.
3. The contour integrals of f are independent of path in D.

Proof 4.25. $1 \Rightarrow 2$: It follows immediately from Theorem 4.20 with $\mathcal{C}$ being a closed contour.

$2 \Rightarrow 3$: Let $\mathcal{C}_1$ and $\mathcal{C}_2$ be any two contours in D with same end points. Let $\mathcal{C}$ be the closed contour $\mathcal{C}_1 + (-\mathcal{C}_2)$.

Then, $\int_{\mathcal{C}} f(z)dz = 0$. So $\int_{\mathcal{C}_1} f(z)dz + \int_{-\mathcal{C}_2} f(z)dz = 0$. So $\int_{\mathcal{C}_1} f(z)dz - \int_{\mathcal{C}_2} f(z)dz = 0$, implying that

$$\int_{\mathcal{C}_1} f(z)dz = \int_{\mathcal{C}_2} f(z)dz$$



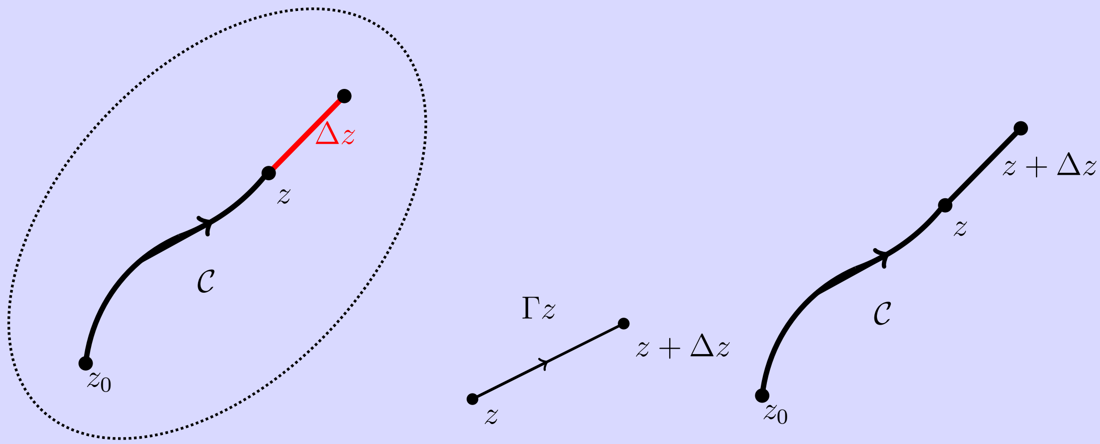
3 $\Rightarrow$ 1: Construct the antiderivative. Choose a point $z_0 \in D$, and let $\mathcal{C}$ be the contour as shown. Recall the D is a connected set.

Define $F(z) = \int_{\mathcal{C}} f(w)dw$. By 3, $F(z)$ is single valued; We will show that $F'(z) = f(z)$.

For any point z, choose Δz small enough such that the line segment Γ parameterized by

$$z(t) = z + t\Delta z, \quad t \in [0, 1]$$

is in D (This is possible since D is open)



Then

$$\begin{aligned}
F(z+\Delta z) - F(z) &= \left(\int_{\mathcal{C}} f(w)dw + \int_{\Gamma} f(w)dw\right) - \int_{\mathcal{C}} f(w)dw \\
&= \int_{\Gamma} f(w)dw \\
&= \int_0^1 f(z(t))z'(t)dt \\
&= \int_0^1 f(z+t\Delta z)(\Delta z)dt \\
\Rightarrow \quad \frac{F(z+\Delta z) - F(z)}{\Delta z} &= \int_0^1 f(z+t\Delta z)dt
\end{aligned}$$

Let $\Delta z \to 0$.

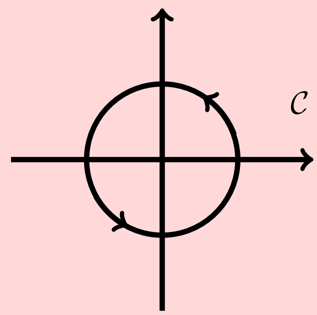
$$F'(z) = \int_0^1 f(z)dt = f(z)\int_0^1 dt = f(z)$$

$\square$

We showed that $\overline{z}$ can be integreated, but the result depends on path. So $\overline{z}$ is integrable, but not anti-differentiable. Also, functions with antiderivatives are easy; for those without, we must parameterize.

4.4 Cauchy's Integral Theorem

Example 4.26. Most Important Example in this Course: Evaluate $\int_{\mathcal{C}} \frac{1}{z} dz$ where $\mathcal{C}$ is the unit circle.

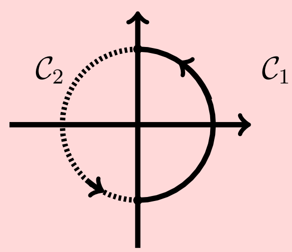


__**Solution**__: $\frac{1}{z}$ does not have antiderivative over all of $\mathcal{C}$. Any branch of $\log z$ will have a problem, i.e. $\mathcal{C}$ will cross a branch cut.

Method 1: Parameterize $\mathcal{C}$ by $e^{it}, t \in [0, 2\pi]$. By definition,

$$\int_{\mathcal{C}} \frac{1}{z} dz = \int_0^{2\pi} \frac{1}{e^{it}} \cdot ie^{it} dt = 2\pi i$$

Method 2: Split $\mathcal{C}$ in two, and use Theorem 4.20 on each.



$$\begin{aligned}
\int_{\mathcal{C}_1} \frac{1}{z} dz &= \operatorname{Log} z\Big|_{-i}^{i} \quad \text{branch cut at } \theta = -\pi \\
&= \operatorname{Log} i - \operatorname{Log}(-i) \\
&= i\frac{\pi}{2} - i\left(\frac{-\pi}{2}\right) \\
&= \pi i \\
\int_{\mathcal{C}_2} \frac{1}{z} dz &= \operatorname{Log}_0 z\Big|_{i}^{-i} \\
&= \operatorname{Log}_0(-i) - \operatorname{Log}_0(i) \\
&= \frac{3\pi}{2} i - \frac{\pi}{2} i \\
&= \pi i
\end{aligned}$$

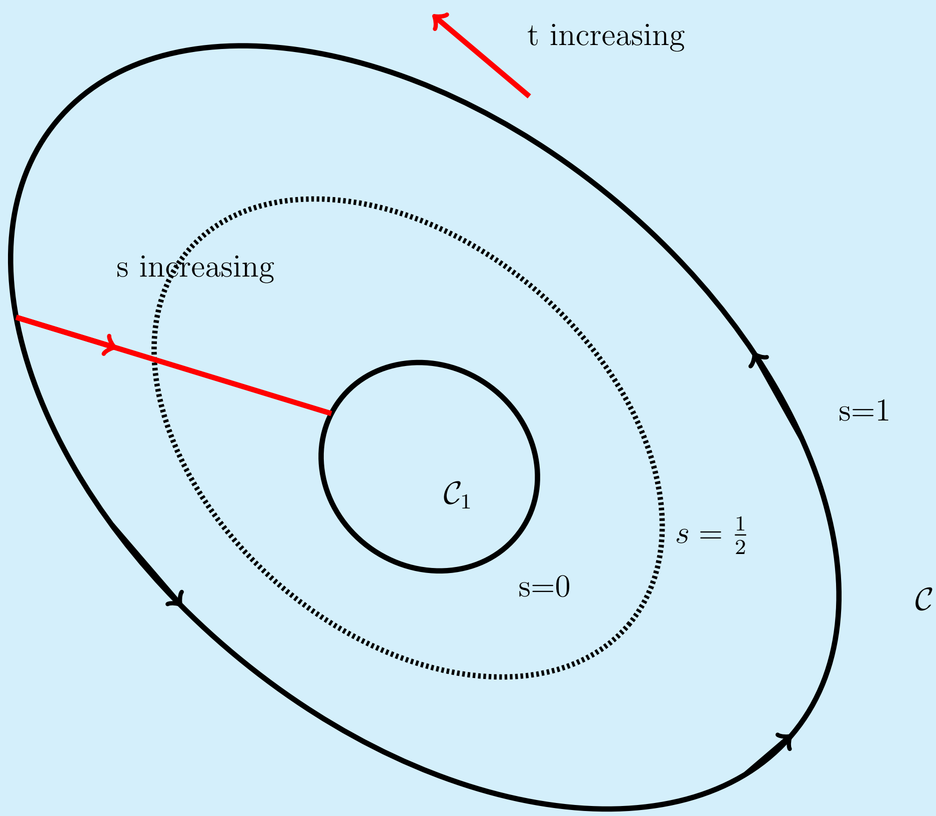
Therefore,

$$\int_{\mathcal{C}} \frac{1}{z} dz = \int_{\mathcal{C}_1} \frac{1}{z} dz + \int_{\mathcal{C}_2} \frac{1}{z} dz = \pi i + \pi i = 2\pi i$$

Go around the contour twice, what's the result? It would be $4\pi i$. Also, going counter-clockwise would yield the result $-2\pi i$

Definition 4.27. A closed contour $\mathcal{C}$ is said to be **continuously deformable** to a contour $\mathcal{C}_1$ in a domain D if there exists a function $z(s,t)$, continuous for $s \in [0,1], t \in [0,1]$, such that

1. $z(s,t)$ is a closed contour in D for each $s \in [0,1]$
2. $z(0,t)$ is a parameterization of $\mathcal{C}$
3. $z(1,t)$ is a parameterization of $\mathcal{C}_1$



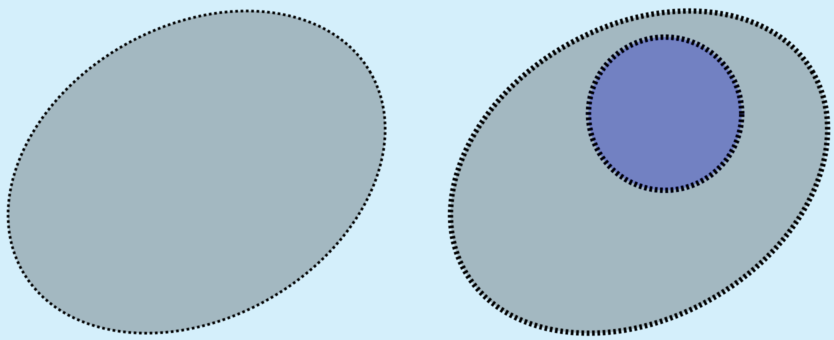
Theorem 4.28. **Deformation Invariance Theorem**: Let f be analytic in a domain D,

containing closed contours $\mathcal{C}_1$ and $\mathcal{C}_2$. If $\mathcal{C}_1$ can be continuously deformed into $\mathcal{C}_2$, then

$$\int_{\mathcal{C}_1} f(z)dz = \int_{\mathcal{C}_2} f(z)dz$$

Proof 4.29. It's too hard - 12 pages long in one text. $\square$

Definition 4.30. A **simply connected domain** is a domain in which every "loop" (closed contour) in D can be continuously deformed to a point (while remaining in D).



simply connected Not simply connected

Theorem 4.31. **Cauchy's Integral Theorem (Cauchy-Goursat Theorem)**:

If f is analytic in a simply connected domain D, and $\mathcal{C}$ is a closed contour in D, then

$$\int_{\mathcal{C}} f(z)dz = 0$$

Proof 4.32. Follows from Theorem 4.28 by shrinking $\mathcal{C}$ continuously to a point. $\square$

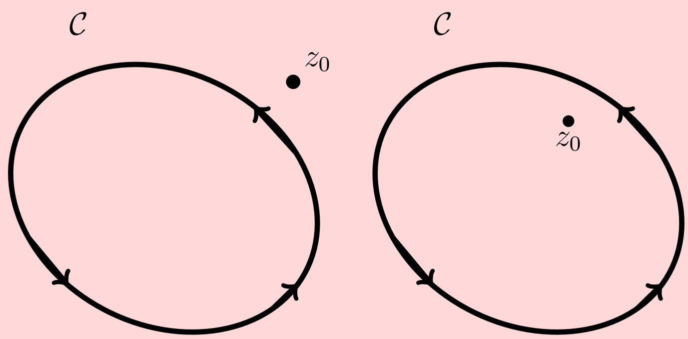
Corollary 4.33. Since $\int_{\mathcal{C}} f(z)dz = 0 \Leftrightarrow f$ has an antiderivative in D, we have that if f is analytic, then f also has an antiderivative, which is analytic. So every analytic function is infinitely antidifferentiable.

Example 4.34. Back to Example 4.26. We know that $\int_{\mathcal{C}} \frac{1}{z}dz = 2\pi i$ for <u>any</u> closed contour enclosing the origin.

Also, $\int_{\mathcal{C}} \frac{1}{z} dz = 0$ for any closed contours <u>not</u> enclosing the origin.

Could shift results:

$$\int_{\mathcal{C}} \frac{1}{z - z_0} dz = \begin{cases} 0 & \text{if } z_0 \text{ is exterior to } \mathcal{C} \\ 2\pi i & \text{if } z_0 \text{ is interior to } \mathcal{C} \end{cases}$$



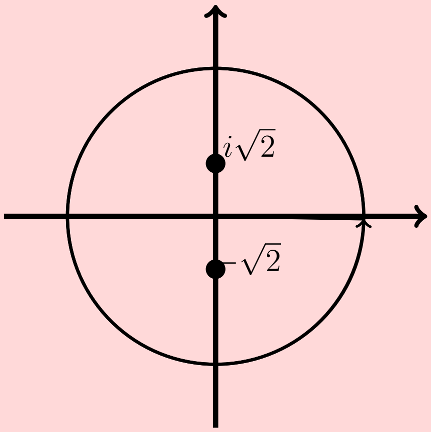
Example 4.35. Evaluate $\int_{\mathcal{C}} \frac{2z}{z^2+2} dz$ where $\mathcal{C}$ is the positively oriented circle of radius 2 centered at origin.

<u>Solution</u>: We can do partial fractions:

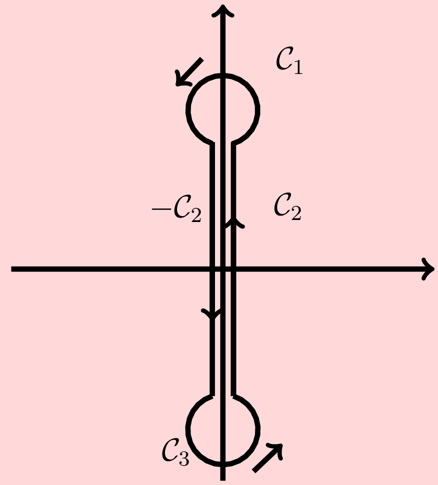
$$\frac{2z}{z^2+2} = \frac{1}{z + i\sqrt{2}} + \frac{1}{z - i\sqrt{2}}$$

So we have singularities at $z = \pm i\sqrt{2}$. We can use the **Deformation Invariance Theorem** to deform $\mathcal{C}$ like below. So

$$\begin{aligned} \int_{\mathcal{C}} &= \int_{\mathcal{C}_2} + \int_{\mathcal{C}_1} + \int_{-\mathcal{C}_2} + \int_{\mathcal{C}_3} \\ &= \int_{\mathcal{C}_1} + \int_{\mathcal{C}_3} \end{aligned}$$



$\longrightarrow$



And

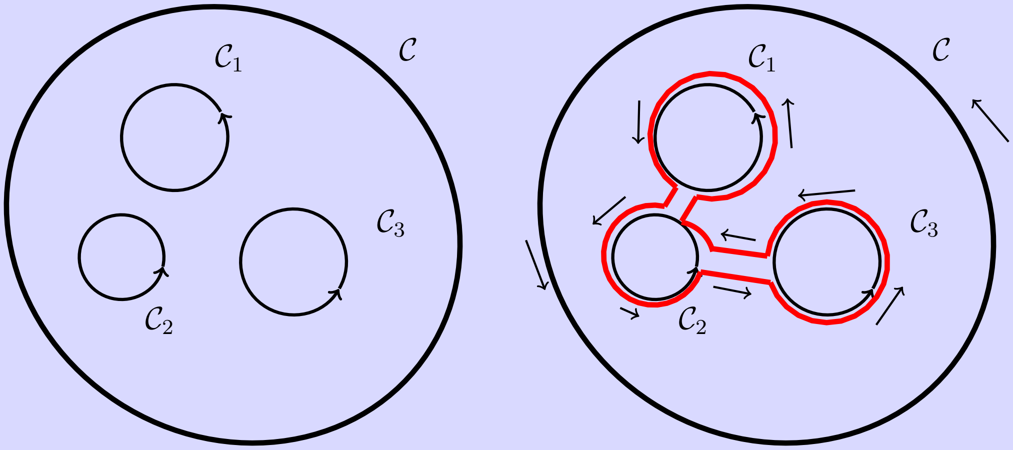
$$\begin{aligned}
\int_{\mathcal{C}} \frac{2z}{z^2+2} dz &= \int_{\mathcal{C}} \left(\frac{1}{z+i\sqrt{2}} + \frac{1}{z-i\sqrt{2}} \right) dz \\
&= \int_{\mathcal{C}_1} \left(\frac{1}{z+i\sqrt{2}} + \frac{1}{z-i\sqrt{2}} \right) dz + \int_{\mathcal{C}_3} \left(\frac{1}{z+i\sqrt{2}} + \frac{1}{z-i\sqrt{2}} \right) dz \\
&= \int_{\mathcal{C}_1} \frac{1}{z+i\sqrt{2}} dz + \int_{\mathcal{C}_1} \frac{1}{z-i\sqrt{2}} dz + \int_{\mathcal{C}_3} \frac{1}{z+i\sqrt{2}} dz + \int_{\mathcal{C}_3} \frac{1}{z-i\sqrt{2}} dz \\
&= 0 + 2\pi i + 2\pi i + 0 \\
&= 4\pi i
\end{aligned}$$

Theorem 4.36. **Extended Cauchy-Goursat Theorem**:

$$\int_{\mathcal{C}} f(z) dz = \sum_{i=1}^{n} \int_{\mathcal{C}_i} f(z) dz$$

Proof 4.37. Ideas (for the case of $n = 3$): Deform $\mathcal{C}$ to Γ as shown:

$$\int_{\mathcal{C}} = \int_{\tilde{\mathcal{C}}} = \int_{\mathcal{C}_1} + \int_{\mathcal{C}_2} + \int_{\mathcal{C}_3}$$



□

What about $\int_{\mathcal{C}} \frac{1}{(z-z_0)^2} dz$ or other powers of $z - z_0$?

Consider $\int_{\mathcal{C}} (z-z_0)^n dz$ where $n \neq -1$.

- If z_0 is external to $\mathcal{C}$, the integral is zero, by **Cauchy's Integral Theorem**.
- If z_0 is internal to $\mathcal{C}$, deform $\mathcal{C}$ to the unit circle $|z - z_0| = 1$, parameterized by $z = z_0 + e^{it}$, $t \in [0, 2\pi]$. We may use the radius ϵ if the circle is not small enough. The result would be the same.

  Then

$$\begin{aligned}\int_{\mathcal{C}} (z-z_0)^n dz &= \int_{\mathcal{C}} \left(e^{it}\right)^n ie^{it} dt \\ &= \frac{i}{n+1} e^{i(n+1)t} \Big|_0^{2\pi} \\ &= 0\end{aligned}$$

Thus for an interioir point z_0 in $\mathcal{C}$

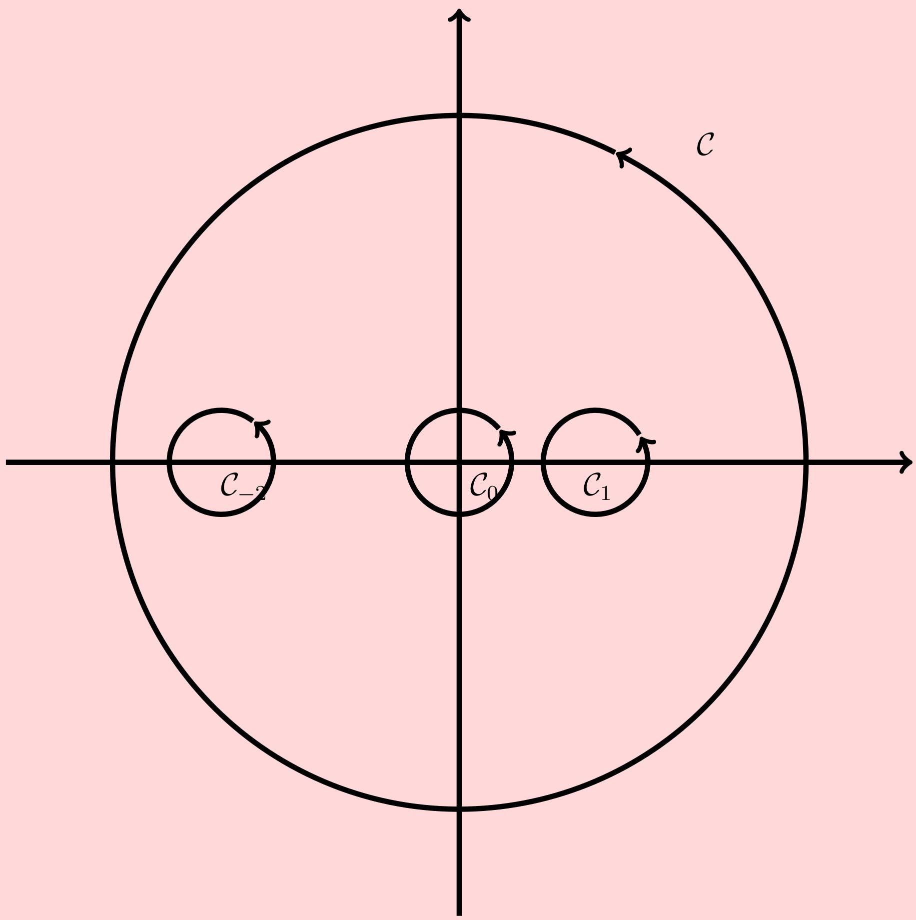
$$\boxed{\int_{\mathcal{C}} (z-z_0)^n dz = \begin{cases} 0 & \text{if } n \neq -1 \\ 2\pi i & \text{if } n = -1 \end{cases}}$$

Example 4.38. Let $\mathcal{C}$ be the positively oriented circle of radius 3 centered at the origin. Evaluate $\int_{\mathcal{C}} \frac{3z^3+2}{z^4+z^3-2z^2} dz$

Solution: Note that $z^4 + z^3 - 2z^2 = z^2(z^2 + z - 2) = z^2(z-1)(z+2)$. These give us the location of the singularities.

Note the partial fractions:

$$\frac{3z^3+2}{z^4+z^3-2z^2} = \frac{-1/2}{z} + \frac{-1}{z} + \frac{5/3}{z-1} + \frac{11/6}{z+2}$$



By the **Extended Cauchy-Goursat Theorem**,

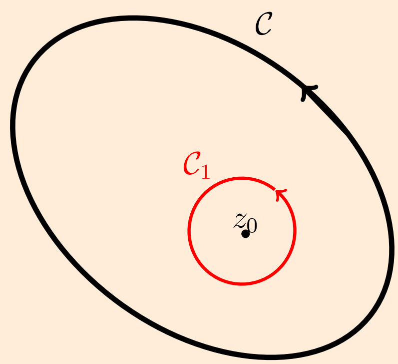
$$\begin{aligned}\int_{\mathcal{C}} f(z)dz &= \int_{\mathcal{C}_{-2}} f(z)dz + \int_{\mathcal{C}_0} f(z)dz + \int_{\mathcal{C}_1} f(z)dz \\ &= \frac{11}{6}\cdot(2\pi i) + \frac{-1}{2}\cdot(2\pi i) + \frac{5}{3}\cdot(2\pi i) \\ &= 6\pi i\end{aligned}$$

4.5 Cauchy's Integral Formula

Theorem 4.39. **Cauchy's Integral Formula (CIF)**: Let $\mathcal{C}$ be a simple, closed, positively-oriented contour. If f is analytic in some simply connected domain D containing

$\mathcal{C}$, and z_0 is any point inside $\mathcal{C}$. Then,

$$\int_{\mathcal{C}} \frac{f(z)}{z-z_0} dz = 2\pi i f(z_0)$$



Proof 4.40. deform $\mathcal{C}$ to $\mathcal{C}_r$, a positively oriented circle of radius r centered at z_0: $|z-z_0| = r$. We will let $r \to 0$.

Then,

$$\begin{aligned}
\int_{\mathcal{C}} \frac{f(z)}{z-z_0} dz &= \int_{\mathcal{C}_r} \frac{f(z)}{z-z_0} dz \\
&= \int_{\mathcal{C}_r} \frac{f(z)-f(z_0)}{z-z_0} dz + \int_{\mathcal{C}_r} \frac{f(z_0)}{z-z_0} dz \quad \text{by linearity} \\
&= 0 + 2\pi i f(z_0) \\
&= 2\pi i f(z_0)
\end{aligned}$$

To show $\int_{\mathcal{C}_r} \frac{f(z)-f(z_0)}{z-z_0} dz = 0$, we consider the following:

On $\mathcal{C}_r$, we have $|f(z) - f(z_0)| \leq M$ for some M. Then

$$\left| \frac{f(z)-f(z_0)}{z-z_0} \right| \leq \frac{M}{r} \quad \text{since } |z-z_0| = r \text{ on } C_r$$

By ML inequality,

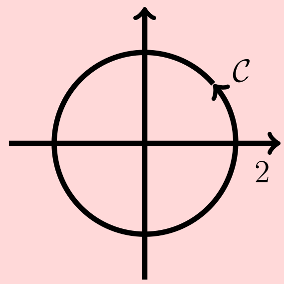
$$\left| \int_{\mathcal{C}_r} \frac{f(z)-f(z_0)}{z-z_0} dz \right| \leq \frac{M}{r} \cdot \text{length}(\mathcal{C}_r) = \frac{M}{r} 2\pi r = 2\pi M$$

Let $r \to 0$, then $M \to 0$ by continuity of f, and so

$$\int_{\mathcal{C}_r} \frac{f(z)-f(z_0)}{z-z_0} dz = 0$$

□

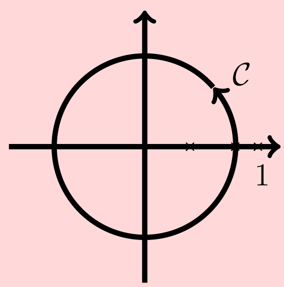
Example 4.41. Evaluate $\int_{\mathcal{C}} \frac{e^z}{z-1} dz$.



<u>**Solution**</u>: Let $f(z) = e^z$. Since $f(z)$ is entire, and $z_0 = 1$ is inside $\mathcal{C}$, we have, by **CIF**,

$$\int_{\mathcal{C}} \frac{e^z}{z-1} dz = 2\pi i f(1) = 2\pi i e^1 = 2\pi e i$$

Example 4.42. Evaluate $\int_{\mathcal{C}} \frac{e^{i\pi z}}{2z^2 - 5z + 2} dz$.

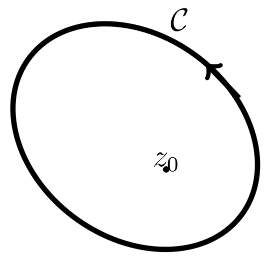


<u>**Solution**</u>:

$$\begin{aligned}
\int_{\mathcal{C}} \frac{e^{i\pi z}}{2z^2 - 5z + 2} dz &= \int_{\mathcal{C}} \frac{e^{i\pi z}}{2(z - \frac{1}{2})(z-2)} dz \\
&= \int_{\mathcal{C}} \frac{\frac{e^{i\pi z}}{2(z-2)}}{z - \frac{1}{2}} dz \quad \text{regard the numerator as } f(z) \\
&= 2\pi i f(\frac{1}{2}) \quad \text{by CIF} \\
&= 2\pi i \frac{e^{i\pi/2}}{2(\frac{-3}{2})} \\
&= \frac{2\pi}{3}
\end{aligned}$$

From CIF, we know

$$f(z_0) = \frac{1}{2\pi i}\int_{\mathcal{C}} \frac{f(z)}{z-z_0}dz$$



So the value of f at any point <u>inside</u> $\mathcal{C}$ is determined by the values of f <u>on</u> $\mathcal{C}$

Proposition 4.43. **<u>Mean Value Property</u>**: If $\mathcal{C}$ is a circle of radius R centered at z_0:

$$\begin{aligned}
f(z_0) &= \frac{1}{2\pi i}\int_0^{2\pi} \frac{f\left(\overbrace{z_0 + Re^{it}}^{z(t)}\right)}{z_0 + Re^{it} - z_0}\overbrace{\left(iRe^{it}\right)}^{z'(t)} \quad \text{by parameterizing circle} \\
&= \frac{\int_0^{2\pi} f\left(z_0 + Re^{it}\right)}{2\pi - 0} \\
&= \text{ averge value of } f \text{ on the circle, recall that } \frac{\int_a^b f(x)dx}{b-a} = \overline{f}
\end{aligned}$$

Theorem 4.44. **<u>Derivatives of f</u>**:

$$f(z_0) = \frac{1}{2\pi i}\int_{\mathcal{C}} \frac{f(z)}{z-z_0}dz = \frac{1}{2\pi i}\int_{\mathcal{C}} \frac{f(w)}{w-z}dw$$

Differentiate:

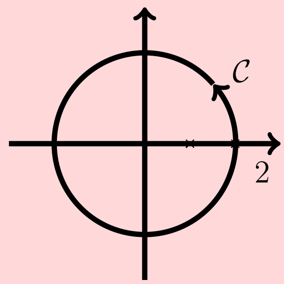
$$\begin{aligned}
f'(z) &= \frac{1}{2\pi i}\int_{\mathcal{C}} f(w)\frac{d}{dz}\left(\frac{1}{w-z}\right)dw \quad \text{by Leibniz's rule} \\
&= \frac{1}{2\pi i}\int_{\mathcal{C}} \frac{f(w)}{(w-z)^2}dw
\end{aligned}$$

which is also differentiable.

Repeating and switch back to z_0 we get **<u>Cauchy's Integral Formula for Derivatives (CIFD)</u>**:

$$\boxed{f^{(n)}(z_0) = \frac{n!}{2\pi i}\int_{\mathcal{C}} \frac{f(z)}{(z-z_0)^{n+1}}dz \qquad \text{where } z_0 \text{ is inside } \mathcal{C}}$$

Example 4.45. Evaluate $\int_{\mathcal{C}} \frac{z^3+2z+1}{(z-1)^3} dz$.



<u>**Solution**</u>: Use **CIFD** with $n=2$.

$$f''(z_0) = \frac{2!}{2\pi i} \int_{\mathcal{C}} \frac{f(z)}{(z-z_0)^3} dz$$

Let $f(z) = z^3 + 2z + 1$ and $z_0 = 1$. Then we have

$$\begin{aligned} (6z+0+0)\Big|_{z=1} &= \frac{1}{\pi i} \int_{\mathcal{C}} \frac{f(z)}{(z-z_0)^3} dz \\ 6\pi i &= \int_{\mathcal{C}} \frac{z^3+2z+1}{(z-1)^3} dz \end{aligned}$$

4.6 Implication of CIFD

Corollary 4.46. An analytic function is infinitely differentiable. Furthermore, with $f(z) = u(x,y) + iv(x,y)$, u and $v \in C^\infty$ (i.e. have continuous partials of all order)

Proof 4.47. $f = u + iv$, then

$$f' = \begin{cases} u_x + iv_x & \Rightarrow f'' = \begin{cases} u_{xx} + iv_{xx} & \cdots \\ v_{xy} - iu_{xy} & \cdots \end{cases} \\ v_y - iu_y & \Rightarrow f'' = \begin{cases} v_{yx} - iu_{yx} & \cdots \\ -u_{yy} - iv_{yy} & \cdots \end{cases} \end{cases}$$

Existence of f'' implies u_x, u_y, v_x, v_y are all continous. Also, observe that $u_{xx} = -u_{yy}$, $v_{xx} = -v_{yy}$, $v_{xy} = v_{yx}$, $u_{xy} = u_{yx}$ $\square$

Theorem 4.48. Morera's Theorem: (the converse of **Cauchy's Integral Theorem**)

Let f be a continuous function in a simply connected domain D. If $\int_{\mathcal{C}} f(z)dz = 0$ for every closed contour $\mathcal{C}$ in D, then f is analytic in D.

Proof 4.49. We've shown that $\int_{\mathcal{C}} f(z)dz = 0$ for all $\mathcal{C}$ implies that f has antiderivative in D, call it $F(z)$.

Now D is open, and F is differentiable in D ($F' = f$), so therefore F is analytic, therefore $F' = f$ is analytic. $\square$

Lemma 4.50. "Cauchy's Estimate": Let f be analytic on and inside a circle $\mathcal{C}$ of radius R centered at z_0.

If $|f(z)| \leq M$ for all z on $\mathcal{C}$, then $\left|f^{(n)}(z_0)\right| \leq \dfrac{n!M}{R^n}$.

Proof 4.51. From **CIFD**,

$$\left|f^{(n)}(z_0)\right| = \left|\frac{n!}{2\pi i}\int_{\mathcal{C}} \frac{f(z)}{(z-z_0)^{n+1}}dz\right| \leq \left|\frac{n!}{2\pi i}\right| \overbrace{\left(\frac{M}{R^{n+1}}\right)}^{\text{“}M\text{''}} \cdot \overbrace{(2\pi R)}^{\text{“}\ell\text{''}}$$

since $|z - z_0| = R$ and the $M\ell$-inequality. $\square$

Theorem 4.52. Liouville's Theorem: If f is entire, and bounded for all $z \in \mathbb{C}$, then f is constant.

Proof 4.53. Have $|f(z)| \leq M$ for all $z \in \mathbb{C}$. Consider $z_0 \in \mathbb{C}$, and let $\mathcal{C}$ be circle of radius R centered at z_0. Cauchy's estimate yields $|f'(z_0)| \leq \dfrac{M}{R}$. True for all R, no matter how large. So $|f'(z_0)| = 0 \Rightarrow f'(z_0) = 0$.

z_0 is arbitrary, so f must be constant. $\square$

Corollary 4.54. Every non-constant, entire function is unbounded.

We can use this to prove the **Fundamental Theorem of Algebra**.

Theorem 4.55. **Fundamental Theorem of Algebra**: Every nonconstant polynomial with complex coefficients has at least one zero.

Proof 4.56. If $P(z)$ has no zeros, then $\dfrac{1}{P(z)}$ is entire. Since it is continuous, we must have $|P(z)| \geq \epsilon$ for some $\epsilon > 0$.

So, $\dfrac{1}{|P(z_0)|} \leq \dfrac{1}{\epsilon}$, implying that $\dfrac{1}{P(z_0)}$ is constant, by **Liouville's Theorem**.

So, $P(z_0)$ is constant. Hence, a non-constant polynomial must have a zero. $\square$

Proposition 4.57. **Maximum Modulus Principle**: If $f(z)$ is analytic on a bounded domain D, and continuous on $\overline{D}$, the closure of D. Then, $|f(z)|$ attains a maximum value on $\overline{D}$ and it occurs on the boundary.