

1. The complex plane and Riemann sphere

- $\mathbb{C}^* = \mathbb{C} - \{0\}$
- $z_1 z_2 = 0 \iff z_1 = 0 \text{ or } z_2 = 0$.
- $|z| = \sqrt{z \bar{z}}$.
- $\operatorname{Re}(z) = (z + \bar{z}) / 2$, $\operatorname{Im}(z) = (z - \bar{z}) / 2i$.
- $z^{-1} = \bar{z} / |z|^2$.
- **Principal value of $\arg(z)$** : in interval $(-\pi, \pi]$, written $\operatorname{Arg}(z)$.
- $\arg(z_1 z_2) \equiv \arg(z_1) + \arg(z_2) \pmod{2\pi}$.
- $\arg(1/z) = -\arg(z) \pmod{2\pi}$.
- $\arg(\bar{z}) = -\arg(z) \pmod{2\pi}$.
- Multiplication by $z_1 = r_1 e^{i\theta_1}$ represents rotation by θ_1 followed by dilation by factor r_1 .
- Addition represents translation.
- Conjugation represents reflection in the real axis.
- Taking the real (imaginary) part represents projection onto the real (imaginary) axis.
- $|z_1 z_2| = |z_1| |z_2|$.
- $(\cos(\theta) + i \sin(\theta))^n = \cos(n\theta) + i \sin(n\theta)$.
- **Triangle inequality**: $|z_1 + z_2| \leq |z_1| + |z_2|$.
- $|z| \geq 0$ and $|z| = 0 \iff z = 0$.
- $\max\{|\operatorname{Re}(z)|, |\operatorname{Im}(z)|\} \leq |z| \leq |\operatorname{Re}(z)| + |\operatorname{Im}(z)|$.
- **Complex exponential function**:

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

- $\forall z \in \mathbb{C}, e^z \neq 0$.
- $e^{z_1 + z_2} = e^{z_1} e^{z_2}$.
- $e^z = 1 \iff z = 2\pi i k$ for some $k \in \mathbb{Z}$.
- $e^{-z} = 1 / e^z$.
- $|e^z| = e^{\operatorname{Re}(z)}$.
- $\forall k \in \mathbb{Z}, \exp(z) = \exp(z + 2k\pi i)$.
- $$\sin(z) := \frac{1}{2i}(e^{iz} - e^{-iz}), \quad \cos(z) := \frac{1}{2}(e^{iz} + e^{-iz})$$
- $$\sinh(z) := \frac{1}{2}(e^z - e^{-z}), \quad \cosh(z) := \frac{1}{2}(e^z + e^{-z})$$
- For every $w \in \mathbb{C}^*$,

$$e^z = w = |w| e^{i\varphi}$$

has solutions

$$z = \log(|w|) + i(\varphi + 2k\pi), \quad k \in \mathbb{Z}$$

- Let $\theta_2 - \theta_1 = 2\pi$, let \arg be the argument function in $(\theta_1, \theta_2]$. Then

$$\log(z) := \log(|z|) + i \arg(z)$$

is a **branch of logarithm**. Jump discontinuity on **branch cut**, the ray $R_{\theta_1} = R_{\theta_2}$.

- **Principal branch of log**: where $\arg(z) = \operatorname{Arg}(z) \in (-\pi, \pi]$.

- $e^{\log(z)} = z$.
- Generally, $\log(zw) \neq \log(z) + \log(w)$.
- Generally, $\log(e^z) \neq z$.
- Given a branch of \log , **power function** is

$$z^w := \exp(w \log(z))$$

- $\hat{\mathbb{C}} = \mathbb{C} \cup \{\infty\}$.
- Unit sphere: $S^2 = \{(x, y, s) \in \mathbb{R}^3 : x^2 + y^2 + s^2 = 1\}$, north pole: $N = (0, 0, 1) \in S^2$.
Stereographic projection: map that takes $v \in S^2 - \{N\}$ to $x + iy \in \mathbb{C}$, where (x, y) is where the line from N through v intersects the (x, y) -plane.
- **Stereographic projection formula**:

$$P(x, y, s) = \frac{x}{1-s} + \frac{iy}{1-s}$$

North pole is mapped to ∞ .

- Inverse of stereographic projection found by intersection of line (from $z \in \mathbb{C}$ to N) and S^2 .
- **Riemann sphere**: unit sphere S^2 with stereographic projections from north and south pole.

2. Metric spaces

- **Metric space**: set X and **metric** function $d : X \times X \rightarrow \mathbb{R}_{\geq 0}$, for every $x, y, z \in X$
 - **positivity**: $d(x, y) \geq 0$ and $d(x, y) = 0 \iff x = y$
 - **symmetry**: $d(x, y) = d(y, x)$
 - **triangle inequality**: $d(x, y) \leq d(x, z) + d(z, y)$
- **norm** on vector space V :
 - $\|v\| \geq 0$ and $\|v\| = 0 \iff v = 0$
 - $\|\lambda v\| = |\lambda| \cdot \|v\|$
 - $\|v + w\| \leq \|v\| + \|w\|$
- $d(v, w) = \|v - w\|$ always defines a metric
- $d(v, w) = \sqrt{\langle v - w, v - w \rangle}$
- **l_p norm**:

$$\|x\|_p = \sqrt[p]{\sum_{i=1}^n |x_i|^p}$$

- **Taxicab norm**: l_1 norm
- **l_∞ norm (sup-norm)**: $\|x\|_\infty := \max_{i=1, \dots, n} |x_i|$
- **Riemannian (chordal) metric on $\hat{\mathbb{C}}$** : $d(z, w) = \|f(z) - f(w)\|_2$ where $f : \hat{\mathbb{C}} \rightarrow S^2$ is the inverse stereographic projection.
- **Discrete metric**:

$$d(x, y) := \begin{cases} 0 & \text{if } x = y \\ 1 & \text{if } x \neq y \end{cases}$$

- **Open ball of radius r centred at x** : $B_r(x) := \{y \in X : d(x, y) < r\}$

- **Closed ball of radius r centred at x :** $\overline{B}_r(x) := \{y \in X : d(x, y) \leq r\}$
- $U \subseteq X$ **open** if $\forall x \in U, \exists \varepsilon > 0, B_\varepsilon(x) \subset U$
- $U \subseteq X$ **closed** if $X - U$ open
- **clopen:** open and closed, e.g. empty set and X
- Open balls are open
- Closed balls are closed
- Arbitrary unions of open sets are open
- Finite intersections of open sets are open
- Finite unions of closed sets are closed
- Arbitrary intersections of closed sets are closed
- **Interior of A :** $A^0 := \{x \in A : \text{for some open } U \subseteq A, x \in U\}$. It is the largest open set in A .
- **Closure of A :** complement of interior of complement:
 $\overline{A} := \{x \in X : U \cup A \neq \emptyset \text{ for every open set } U \text{ with } x \in U\} = X - (X - A)^0$. It is the smallest closed set containing A .
- **Boundary of A :** closure without interior: $\partial A := \overline{A} - A^0$
- **Exterior of A :** complement of closure: $A^e := X - \overline{A} = (X - A)^0$
- A is open $\iff \partial A \cap A = \emptyset \iff A = A^0$
- A is closed $\iff \partial A \subseteq A \iff A = \overline{A}$
- For simple sets in \mathbb{R}^n or \mathbb{C}^n , closure (or interior) is obtained by replacing $<$ by \leq (or vice versa).
- Sequence $\{x_n\}$ **converges to** $x \in X$ if $\lim_{n \rightarrow \infty} d(x_n, x) = 0$ or equivalently,

$$\forall \varepsilon > 0, \exists N \in \mathbb{N}, \forall n > N, d(x_n, x) < \varepsilon$$

- Limits in the complex plane follow COLT rules
- $\{z_n\}$ converges iff $\{\operatorname{Re}(z_n)\}$ and $\{\operatorname{Im}(z_n)\}$ converge.
- $\lim_{n \rightarrow \infty} x_n = x \iff \forall \text{ open } U \text{ with } x \in U, \exists N \in \mathbb{N}, \forall n > N, x_n \in U$
- $f : (X_1, d_1) \rightarrow (X_2, d_2)$ is **continuous at** $x_0 \in X_1$ if

$$\forall \varepsilon > 0, \exists \delta > 0, \forall x \in X_1, d_1(x, x_0) < \delta \implies d_2(f(x), f(x_0)) < \varepsilon$$

- f is **continuous on** X_1 if continuous at every $x_0 \in X_1$
- Products, sums and quotients of real/complex continuous functions are continuous
- Compositions of continuous functions are continuous
- **Preimage:** $f^{-1}(U) := \{x \in X_1 : f(x) \in U\}$
- **Properties of preimage:**
 - $f^{-1}(A \cup B) = f^{-1}(A) \cup f^{-1}(B)$
 - $f^{-1}(A \cap B) = f^{-1}(A) \cap f^{-1}(B)$
 - $f^{-1}(A - B) = f^{-1}(A) - f^{-1}(B)$
- $f : X_1 \rightarrow X_2$ continuous $\iff f^{-1}(U)$ open in $X_1 \forall$ open $U \subseteq X_2$
 $\iff f^{-1}(F)$ closed in $X_1 \forall$ closed $F \subseteq X_2$
- $f : X_1 \rightarrow X_2$ continuous at $x \in X_1 \iff f^{-1}(U)$ open in $X_1 \forall$ open $U \subseteq X_2$ containing $f(x)$
- Non-empty $K \subseteq X$ **compact** if for every sequence $\{x_k\}$ in K , there exists a convergent subsequence $\{x_{n_k}\}$ with limit in K .

- If $\{x_k\}$ is a convergent sequence in X then every subsequence $\{x_{n_k}\}$ converges to the same limit.
- $F \subseteq X$ is closed iff every sequence in F converging in X also converges in F .
- Compact sets are closed
- Every closed subset of a compact set is compact
- $A \subseteq X$ **bounded** if for some $R > 0, x \in X, A \subseteq B_R(x)$
- Compact sets are bounded
- **Heine-Borel for \mathbb{C}** : $K \subseteq \mathbb{C}$ is compact iff K is closed and bounded.
- $f : X \rightarrow Y$ is continuous at $x \in X$ iff

$$\lim_{n \rightarrow \infty} f(x_n) = f(x)$$

for every convergent sequence $\{x_n\}$ in X with $x_n \rightarrow x$.

- If $K \subseteq X$ is compact and $f : X \rightarrow Y$ is continuous, then $f(K)$ is compact in Y .

3. Complex differentiation

- $f : U \rightarrow \mathbb{C}$ for open U is **complex differentiable at $z_0 \in U$** if

$$\lim_{z \rightarrow z_0} \frac{f(z) - f(z_0)}{z - z_0}$$

exists. Limit is the **derivative of f at z_0** :

$$f'(z_0) = \lim_{h \rightarrow 0} \frac{f(z_0 + h) - f(z_0)}{h}$$

. $h \in \mathbb{C}$ so limit must exist from every direction.

- Complex differentiability at z_0 implies continuity at z_0 .
- Sums, products and quotients of complex differentiable functions are complex differentiable.
- Compositions of complex differentiable functions are complex differentiable.
- The product, quotient and chain rules hold for complex differentiable functions.
- Most non-constant purely real/imaginary functions are not complex differentiable.
- If $f = u + iv$ is complex differentiable at z_0 then u_x, u_y, v_x, v_y exist at z_0 and satisfy **Cauchy-Riemann equations**:

$$u_x(z_0) = v_y(z_0), \quad u_y(z_0) = -v_x(z_0)$$

. Also,

$$f'(z_0) = u_x(z_0) + iv_x(z_0)$$

- Let $f : U \rightarrow \mathbb{C}, U$ open, $f = u + iv$. If u_x, u_y, v_x, v_y exist and are continuous at z_0 and satisfy the Cauchy-Riemann equations at z_0 , then f is complex differentiable at z_0 .
- Let $U \subseteq \mathbb{C}$ open, $f : U \rightarrow \mathbb{C}$. f is **holomorphic on U** if f is complex differentiable at every $z_0 \in U$.
- f is **holomorphic at $z_0 \in U$** if f is complex differentiable on some $B_\varepsilon(z_0)$.
- Affine linear maps $z \rightarrow az + b, a \neq 0$ are holomorphic.

- **Path (curve) from a to b :** continuous function $\gamma : [0, 1] \rightarrow \mathbb{C}$ with $\gamma(0) = a$ and $\gamma(1) = b$. Path **closed** if $a = b$.
- **Smooth** path: continuously differentiable.
- $U \subseteq \mathbb{C}$ **path-connected** if for every $a, b \in U$, there exists a path γ from a to b with $\gamma(t) \in U$ for every $t \in [0, 1]$.
- **Domain (region):** open and path-connected.
- **Chain rule:** Let $U \subseteq \mathbb{C}$ open, $f : U \rightarrow \mathbb{C}$ holomorphic, $\gamma : [0, 1] \rightarrow U$ smooth path. Then

$$(f \circ \gamma)'(t_0) = f'(\gamma(t_0))\gamma'(t_0)$$

- Let D domain, $f : D \rightarrow \mathbb{C}$ holomorphic on D . If $\forall z \in D, f'(z) = 0$, or f is purely real/imaginary, or f has constant real/imaginary part, or f has constant modulus, then f is constant on D .
- Let D domain, $f : D \rightarrow \mathbb{C}$ **conformal at z_0** if f preserves angle and orientation of any two tangent vectors at z_0 . Equivalently, f preserves angle and orientation of any two smooth paths through z_0 . f **conformal** if conformal at every $z_0 \in D$.
- If f holomorphic, $f'(z_0) \neq 0$ then f conformal at z_0 .
- f transforms the tangent vector $\gamma'(t_0)$ by multiplying it by $f'(\gamma(t_0))$.
- If f is conformal at z_0 , then f is complex differentiable at z_0 and $f'(z_0) \neq 0$.
- f is conformal on domain D iff f is holomorphic on D and $\forall z \in D, f'(z) \neq 0$.
- Conformal maps map orthogonal grids in the (x, y) -plane to orthogonal grids. (Grids can be made of arbitrary smooth curves, not necessarily straight lines).
- For D and D' domains, $f : D \rightarrow D'$ is **biholomorphic** if f holomorphic, bijection and $f^{-1} : D' \rightarrow D$ holomorphic. f is a **biholomorphism**. D and D' are **biholomorphic** if such an f exists and write $f : D \sim_{\rightarrow} D'$
- Affine linear maps $z \rightarrow az + b, a \neq 0$, are biholomorphic from \mathbb{C} to \mathbb{C} .
- For D domain, set of all biholomorphic maps from D to D forms a group under composition, called **automorphism group of D** , $\text{Aut}(D)$.

4. Möbius transformations

- $\text{GL}_2(\mathbb{C}) := \{A \in M_2(\mathbb{C}) : \det(A) \neq 0\}$.
- Let $T = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \in \text{GL}_2(\mathbb{C})$, then **Möbius transformation** is $M_T(z) = \infty$ if $cz + d = 0$, else

$$M_T(z) = \frac{az + b}{cz + d}$$

Also

$$M_T(\infty) = \begin{cases} \frac{a}{c} & \text{if } c \neq 0 \\ \infty & \text{if } c = 0 \end{cases}$$

So $M_T : \hat{\mathbb{C}} \rightarrow \hat{\mathbb{C}}$.

- Let $k^2 = \det(T)$ then

$$M_{\frac{1}{k}T}(z) = \frac{\frac{az}{k} + \frac{b}{k}}{\frac{cz}{k} + \frac{d}{k}} = \frac{az + b}{cz + d} = M_T(z)$$

so any T can be scaled to $T' = \frac{1}{k}T$ so that $\det(T') = \det(\frac{1}{k}T) = \frac{1}{k^2} \det(T) = 1$.

- **Cayley map:** $M_T(z) = \frac{z-i}{z+i}$ where $T = \begin{bmatrix} 1 & -i \\ 1 & i \end{bmatrix}$.
- Cayley map maps $\mathbb{H} \rightarrow \mathbb{D}$.
- Set of Mobius transformations forms group under composition:
 - $M_{T_1} \circ M_{T_2} = M_{T_1 T_2}$.
 - $(M_T)^{-1} = M_{T^{-1}}$.
 - $M_T = \text{Id} \iff T = t \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, t \in \mathbb{C}^*$.
- Let $T = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \in \text{GL}_2(\mathbb{C})$. If $c = 0$, M_T is biholomorphic from $\hat{\mathbb{C}}$ to $\hat{\mathbb{C}}$. If $c \neq 0$, M_T is biholomorphic from $\mathbb{C} - \{-\frac{d}{c}\}$ to $\mathbb{C} - \{\frac{a}{c}\}$.
- M_T conformal at every $z \in \mathbb{C}$ where $M_T(z) \neq \infty$.
- M_T is bijection from $\hat{\mathbb{C}}$ to $\hat{\mathbb{C}}$.
- z is **fixed point** of M_T if $M_T(z) = z$.
- If M_T is not identity map, then it has at most 2 fixed points in $\hat{\mathbb{C}}$. So if M_T has 3 fixed points in $\hat{\mathbb{C}}$, it is identity map.
- **Cross ratio** of distinct $z_0, z_1, z_2, z_3 \in \mathbb{C}$:

$$(z_0, z_1; z_2, z_3) := \frac{(z_0 - z_2)(z_1 - z_3)}{(z_0 - z_3)(z_1 - z_2)}$$

If some $z_i = \infty$ then same definition but remove all differences involving z_i , so

$$(\infty, z_1; z_2, z_3) := \frac{(z_1 - z_3)}{(z_1 - z_2)}$$

- **Three points theorem:** Let $\{z_1, z_2, z_3\}, \{w_1, w_2, w_3\}$ be sets of distinct ordered points in $\hat{\mathbb{C}}$. Then exists unique Mobius transformation f such that $f(z_i) = w_i, i = 1, 2, 3$, given by $F^{-1} \circ G$, where

$$F(z) = (z, w_1; w_2, w_3), \quad G(z) = (z, z_1; z_2, z_3)$$

- **Mobius transformations preserve cross ratio:** For Mobius transformation f ,

$$(f(z_0), f(z_1); f(z_2), f(z_3)) = (z_0, z_1; z_2, z_3)$$

- **Strategy to find Mobius transformation from how it acts on three points:** since cross-ratio preserved, rearrange the equation

$$(f(z), w_1; w_2, w_3) = (z, z_1; z_2, z_3)$$

- **Strategy to find image of domain D under M_T :**
 - Find image of boundary: $M_T(\partial D)$.
 - Find image of point $z_0 \in D$ in interior: $M_T(z_0)$.
 - Image D' is domain bounded by $M_T(\partial D)$ and containing $M_T(z_0)$.
- **Circline:** circle or line.
- Mobius transformations map circlines in $\hat{\mathbb{C}}$ to circlines in $\hat{\mathbb{C}}$.
- **Equations of circles and lines in \mathbb{C} :**

$$\gamma z \bar{z} - \alpha \bar{z} - \bar{\alpha} z + \beta = 0$$

is equation of circle if $\gamma = 1$ and $|\alpha|^2 - \beta > 0$, and equation of line if $\gamma = 0$ and $\alpha \neq 0$. Also, any circle or line can be described by this equation.

- Circle uniquely determined by three points, line determined by two points, so to determine how Mobius transformation maps circle, check where three points on circle are mapped.
- Circles through N in S^2 correspond to lines in $\hat{\mathbb{C}}$. Circles not through N correspond to circles in $\hat{\mathbb{C}}$ (via stereographic projection).
- For domain D , $\text{Mob}(D)$ is set of Mobius transformations that map D to D .
- **H2H:**

$$f \in \text{Mob}(\mathbb{H}) \iff f = M_T, \quad T \in \text{SL}_2(\mathbb{R}) := \{A \in M_2(\mathbb{R}) : \det(A) = 1\}$$

- **D2D:**

$$f \in \text{Mob}(\mathbb{D}) \iff f = M_T, \quad T \in \text{SU}(1, 1) := \left\{ A = \begin{bmatrix} \alpha & \beta \\ \bar{\beta} & \bar{\alpha} \end{bmatrix} : \alpha, \beta \in \mathbb{C}, \det(A) = 1 \right\}$$

- **D2D*:**

- Every $f \in \text{Mob}(\mathbb{D})$ is of form

$$f(z) = e^{i\theta} \frac{z - z_0}{\bar{z}_0 z - 1}$$

where $z_0 \in \mathbb{D}$ is unique point such that $f(z_0) = 0$.

- Every $f \in \text{Mob}(\mathbb{D})$ where $f(0) = 0$ is a rotation about 0.
- **Strategy to find biholomorphic map between two domains:** build up biholomorphic map from simpler known ones, e.g. Mobius transformations, Cayley map, translations.

5. Notions of convergence in complex analysis and power series

- For X and Y metric spaces, $\{f_n\}_{n \in \mathbb{N}} : X \rightarrow Y$ **converges pointwise on X to f** if

$$\forall x \in X, \forall \varepsilon > 0, \exists N \in \mathbb{N}, \forall n > N, \quad d_Y(f_n(x), f(x)) < \varepsilon$$

$f(x) = \lim_{n \rightarrow \infty} f_n(x)$ is **limit function**.

- $\{f_n\}_{n \in \mathbb{N}}$ **converges uniformly on X to f** if

$$\forall \varepsilon > 0, \exists N \in \mathbb{N}, \forall n > N, \forall x \in X, \quad d_Y(f_n(x), f(x)) < \varepsilon$$

- Uniform convergence implies pointwise convergence.
- **Uniform limits of continuous functions are continuous:** let $\{f_n\}_{n \in \mathbb{N}}$ be all continuous on X and converge uniformly to f on X . Then f is continuous on X .
- **Test for uniform convergence:** let $\{f_n\} : X \rightarrow \mathbb{C}$ converge pointwise to f .
 - If $\forall x \in X, |f_n(x) - f(x)| \leq s_n$, $\{s_n\}$ is sequence with $\lim_{n \rightarrow \infty} s_n = 0$, then $\{f_n\}$ converges uniformly to f on X .

- If for some sequence $\{x_n\} \subset X$, $|f_n(x_n) - f(x_n)| \geq c$ for some $c > 0$, then f_n does not converge uniformly to f on X .
- **Weierstrass M-test:** Let $\{f_n\} : X \rightarrow \mathbb{C}$ satisfy

$$\forall x \in X, |f_n(x)| \leq M_n, \quad \sum_{n=1}^{\infty} M_n < \infty$$

Then $\sum_{n=1}^{\infty} f_n$ converges uniformly to some f on X .

- Let $\{f_n\} : [a, b] \rightarrow \mathbb{R}$ be continuous and converge uniformly to f on $[a, b]$. Then

$$\forall c \in [a, b], \quad \lim_{n \rightarrow \infty} \int_a^c f_n(x) dx = \int_a^c f(x) dx$$

- $\{f_n\}$ **converges locally uniformly on X to f** if $\forall x \in X$, exists open $U \subset X$ containing x such that $\{f_n\}$ converges uniformly to f on U .
- Let $\{f_n\}$ be continuous on X and converge locally uniformly to f on X . Then f is continuous on X .
- **Local M-test:** let $\{f_n\} : X \rightarrow \mathbb{C}$ be continuous, such that $\forall y \in X$, exists open $U \subset X$ containing y and $M_n > 0$ with

$$\forall x \in U, |f_n(x)| \leq M_n, \quad \sum_{n=1}^{\infty} M_n < \infty$$

Then $\sum_{n=1}^{\infty} f_n$ converges locally uniformly to continuous function on X .

- **Complex power series:**

$$\sum_{n=0}^{\infty} a_n(z - c)^n, \quad a_n, c \in \mathbb{C}$$

- Either:
 - Series converges only for $z = c$ ($R = 0$).
 - Series converges absolutely for $|z - c| < R \iff z \in B_R(c)$. R is **radius of convergence**, $B_R(c)$ is **disc of convergence** and diverges for $|z - c| > R$.
 - Series converges absolutely for all z ($R = \infty$).
- Power series with radius of convergence R converges absolutely on $B_r(c)$ for every $0 < r < R$. So series is locally uniformly convergent (but not uniformly convergent) on disc of convergence.
- **Term-by-term differentiation and integration preserve radius of convergence:** let $\sum_{n=0}^{\infty} a_n(z - c)^n$ have radius of convergence R . Then formal derivative and antiderivative

$$\sum_{n=1}^{\infty} n a_n(z - c)^{n-1}, \quad \sum_{n=0}^{\infty} \frac{a_n}{n+1}(z - c)^{n+1}$$

have radius of convergence R .

- **Power series can be differentiated term-by-term in disc of convergence:** let $\sum_{n=0}^{\infty} a_n(z - c)^n$ have radius of convergence R and converge to $f : B_R(c) \rightarrow \mathbb{C}$. Then f is holomorphic on $B_R(c)$ and

$$f'(z) = \sum_{n=1}^{\infty} n a_n (z - c)^{n-1}$$

- Power series with $R > 0$ can be differentiated infinitely many times and

$$f^{(k)}(z) = \sum_{n=k}^{\infty} k! \binom{n}{k} a_n (z - c)^{n-k}$$

So $f^{(k)}(c) = k! a_k$.

- **Power series can be integrated term-by-term in disc of convergence:** power series with $R > 0$ has holomorphic antiderivative $F : B_R(c) \rightarrow \mathbb{C}$ given by

$$F(z) = \sum_{n=0}^{\infty} \frac{a_n}{n+1} (z - c)^{n+1}$$

6. Complex integration over contours

- Let $f : [a, b] \rightarrow \mathbb{C}$, $f = u + iv$, then

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

- Let $f_1, f_2 : [a, b] \rightarrow \mathbb{C}$, $c \in \mathbb{C}$, then

$$\int_a^b (f_1(t) + f_2(t)) dt = \int_a^b f_1(t) dt + \int_a^b f_2(t) dt, \quad \int_a^b c f_1(t) dt = c \int_a^b f_1(t) dt$$

- Curve $\gamma : [a, b] \rightarrow \mathbb{C}$ is C^1 if **continuously differentiable** (derivative exists and is continuous).
- **Integral of continuous $f : U \rightarrow \mathbb{C}$ along curve $\gamma : [a, b] \rightarrow U$, $\gamma \in C^1$:**

$$\int_{\gamma} f(z) dz := \int_a^b f(\gamma(t)) \gamma'(t) dt$$

- Let $f_1, f_2 : [a, b] \rightarrow \mathbb{C}$, $c \in \mathbb{C}$, then

$$\int_{\gamma} (f_1(z) + f_2(z)) dz = \int_{\gamma} f_1(z) dz + \int_{\gamma} f_2(z) dz, \quad \int_{\gamma} c f_1(z) dz = c \int_{\gamma} f_1(z) dz$$

- $(-\gamma) : [-b, -a] \rightarrow \mathbb{C}$, $(-\gamma)(t) := \gamma(-t)$, then

$$\int_{-\gamma} f(z) dz = - \int_{\gamma} f(z) dz$$

- Let $\varphi : [a', b'] \rightarrow [a, b]$ be continuously differentiable, $\varphi(a') = a$, $\varphi(b') = b$, $\delta : [a', b'] \rightarrow \mathbb{C}$, $\delta = \gamma \circ \varphi$. Then

$$\int_{\gamma} f(z) dz = \int_{\delta} f(z) dz$$

- Let $\gamma : [a, b] \rightarrow \mathbb{C}$, $a = a_0 < a_1 < \dots < a_n = b$, $\gamma_i : [a_{i-1}, a_i] \rightarrow \mathbb{C}$ be C^1 , $\gamma_i(t) := \gamma(t)$ for $t \in [a_{i-1}, a_i]$. Then γ is **piecewise C^1 curve**, or **contour**.

$$\int_{\gamma} f(z) dz = \sum_{i=1}^n \int_{\gamma_i} f(z) dz$$

is a **contour integral**.

- **Contour union:** let $\gamma : [a, b] \rightarrow \mathbb{C}$, $\delta : [c, d] \rightarrow \mathbb{C}$, then

$$(\gamma \cup \delta) : [a, b + d - c] \rightarrow \mathbb{C}, \quad (\gamma \cup \delta)(t) := \begin{cases} \gamma(t) & \text{if } t \in [a, b] \\ \delta(t + c - b) & \text{if } t \in [b, b + d - c] \end{cases}$$

Then

$$\int_{\gamma \cup \delta} f(z) dz = \int_{\gamma} f(z) dz + \int_{\delta} f(z) dz$$

- **Complex Fundamental Theorem of Calculus (FTC)** Let $U \subseteq \mathbb{C}$ open, $F : U \rightarrow \mathbb{C}$ holomorphic with derivative f , $\gamma : [a, b] \rightarrow U$ contour. Then

$$\int_{\gamma} f(z) dz = F(\gamma(b)) - F(\gamma(a))$$

So if γ closed, then $\int_{\gamma} f(z) dz = 0$. Also, if γ_1 and γ_2 have same endpoints, then

$$\int_{\gamma_1} f(z) dz = \int_{\gamma_2} f(z) dz$$

- If $F' = f$, F is **antiderivative** or **primitive** of f .
- **Length** of contour γ :

$$L(\gamma) := \int_a^b |\gamma'(t)| dt$$

- **Estimation lemma:** Let $f : U \rightarrow \mathbb{C}$ continuous, $\gamma : [a, b] \rightarrow U$ contour. Then

$$\left| \int_{\gamma} f(z) dz \right| \leq L(\gamma) \cdot \sup_{\gamma} |f|$$

where $\sup_{\gamma} |f| := \sup\{|f(z)| : z \in \gamma\}$

- **Converse to FTC:** Let D domain, $f : D \rightarrow \mathbb{C}$ continuous, $\int_{\gamma} f(z) dz = 0$ for every closed contour $\gamma \in D$. Then exists holomorphic antiderivative $F : D \rightarrow \mathbb{C}$ (unique up to addition of constant) such that

$$F'(z) = f(z)$$

- Domain D **starlike** if for some $a_0 \in D$, for every $a_0 \neq b \in D$, straight line from a_0 to b contained in D .
- **Cauchy's theorem for starlike domains:** let D starlike domain, $f : D \rightarrow \mathbb{C}$ holomorphic, $\gamma \in D$ closed contour. Then

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

Same holds if f holomorphic on $D - S$, S finite set of points, and f continuous on D .

- Let U open, $f : U \rightarrow \mathbb{C}$ holomorphic, $\Delta \in U$ be triangle. Then

$$\int_{\partial\Delta} f(z) dz = 0$$

Same holds if f holomorphic on $U - S$, S finite set of points, and f continuous on U .

- By default, always use **anti-clockwise** parameterisation of contour.
- Let D starlike domain, $f : D \rightarrow \mathbb{C}$ continuous, $\int_{\partial\Delta} f(z) dz = 0$ for every triangle $\Delta \in D$. Then exists holomorphic $F : D \rightarrow \mathbb{C}$ such that $F' = f$.
- **Cauchy's integral formula (CIF)**: let $B = B_r(a)$, $f : B \rightarrow \mathbb{C}$ holomorphic. Then for every $w \in B$, ρ such that $|w - a| < \rho < r$,

$$f(w) = \frac{1}{2\pi i} \int_{|z-a|=\rho} \frac{f(z)}{z-w} dz$$

7. Features of holomorphic functions

- **Cauchy-Taylor theorem**: let $U \subseteq \mathbb{C}$ open, $f : U \rightarrow \mathbb{C}$ holomorphic, $r > 0$, $B_r(a) \subset U$. Then f is given by power series (**Taylor series of f around a**) that converges on $B_r(a)$:

$$f(z) = \sum_{n=0}^{\infty} c_n (z-a)^n, \quad z \in B_r(a)$$

where

$$c_n = \frac{1}{2\pi i} \int_{|z-a|=\rho} \frac{f(z)}{(z-a)^{n+1}} dz$$

for any $0 < \rho < r$.

- Function with Taylor series expansion on $B_r(a)$, $r > 0$, is **analytic at a** .
- Function **analytic** if analytic at every point in domain.
- Holomorphic \iff analytic.
- **Cauchy's integral formula (CIF) for derivatives**: let $B = B_r(a)$, $f : B \rightarrow \mathbb{C}$ holomorphic. For every $0 < \rho < r$,

$$\int_{|z-a|=\rho} \frac{f(z)}{(z-a)^{n+1}} dz = \frac{2\pi i}{n!} f^{(n)}(a)$$

- So f has Taylor series expansion on $B_r(a)$:

$$f(z) = \sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!} (z-a)^n$$

- Equivalent of Cauchy-Taylor doesn't hold for real analysis, e.g.

$$f(x) = \begin{cases} e^{-\frac{1}{x}} & \text{if } x > 0 \\ 0 & \text{if } x \leq 0 \end{cases}$$

has derivatives of all orders and $f^{(n)}(0) = 0$. But Taylor series around $x = 0$ would be

$$f(x) = \sum_{n=0}^{\infty} c_n x^n, \quad x \in (0 - \varepsilon, 0 + \varepsilon)$$

for some $\varepsilon > 0$. But then $c_n = \frac{f^{(n)}}{n!} = 0$ but f isn't identically zero in any neighbourhood of the origin. So f doesn't have a Taylor series.

- **Holomorphic functions have infinitely many derivatives:** let $U \subseteq \mathbb{C}$ open, $f : U \rightarrow \mathbb{C}$ holomorphic. Then f has derivatives of all orders on U which are all holomorphic.
- **Morera's theorem:** let D domain, $f : D \rightarrow \mathbb{C}$ continuous. If for every closed contour γ in D ,

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

then f holomorphic.

- $f : \mathbb{C} \rightarrow \mathbb{C}$ **entire** if holomorphic on \mathbb{C} .
- $f : \mathbb{C} \rightarrow \mathbb{C}$ **bounded** if for some $M > 0$, $|f(z)| \leq M$ for every $z \in \mathbb{C}$.
- **Liouville's theorem:** every bounded entire function is constant.
- **Fundamental theorem of algebra:** every non-constant polynomial with complex coefficients has complex root.
- **Local maximum modulus principle:** let $f : B_r(a) \rightarrow \mathbb{C}$ holomorphic. If

$$\forall z \in B_r(a), |f(z)| \leq |f(a)|$$

then f constant on $B_r(a)$.

- **Maximum modulus principle:** let D domain, $f : D \rightarrow \mathbb{C}$ holomorphic. If for some $a \in D$,

$$\forall z \in D, |f(z)| \leq |f(a)|$$

then f constant on D .

- If $U \subset \mathbb{C}$ path-connected and open, then not possible to write $U = U_1 \cup U_2$, where U_1, U_2 disjoint, open, non-empty. So domains are connected.
- $f : B_r(a) \rightarrow \mathbb{C}$ has **zero of order m at a** if for some $m > 0$, exists holomorphic $h : B_r(a) \rightarrow \mathbb{C}$ such that $f(z) = (z - a)^m h(z)$, $h(a) \neq 0$.
- f has zero of order m at a iff

$$f(a) = f^{(1)}(a) = \dots = f^{(m-1)}(a) = 0$$

and $f^{(m)}(a) \neq 0$.

- **Principle of isolated zeros:** let $f : B_r(a) \rightarrow \mathbb{C}$ holomorphic, $f \neq 0$. Then for some $0 < \rho \leq r$,

$$\forall z \in B_{\rho}(a) - \{a\}, \quad f(z) \neq 0$$

Holds for $f(a) = 0$, i.e. zeros of holomorphic functions are isolated.

- **Uniqueness of analytic continuation theorem:** let $D' \subset D$ non-empty domains, $f : D' \rightarrow \mathbb{C}$ holomorphic. Then exists at most one holomorphic $g : D \rightarrow \mathbb{C}$ such that

$$\forall z \in D', \quad f(z) = g(z)$$

If g exists, it is **analytic continuation of f to D** .

- Let D domain, $f, g : D \rightarrow \mathbb{C}$ holomorphic, $B_r(a) \subset D$. If $f(z) = g(z)$ on $B_r(a)$ then $f(z) = g(z)$ on D .
- Let $S \subset \mathbb{C}$, $w \in S$.
 - w **isolated point of S** if for some $\varepsilon > 0$, $B_\varepsilon(w) \cap S = \{w\}$.
 - w **non-isolated point of S** if $\forall \varepsilon > 0$, exists $w \neq z \in S$ such that $z \in B_\varepsilon(w)$.
- Let $f, g : D \rightarrow \mathbb{C}$ holomorphic on domain D . If $S := \{z \in D : f(z) = g(z)\}$ contains non-isolated point, then $f(z) = g(z)$ on D .
- Let $D \subseteq \mathbb{C}$ domain, $u : D \rightarrow \mathbb{R}$ **harmonic** if has continuous second order partial derivatives and satisfies **Laplace's equation**:

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

- Let $f = u + iv : D \rightarrow \mathbb{C}$ holomorphic on domain D . Then u and v harmonic.
- **Existence of harmonic conjugates theorem**: let D starlike domain, $u : D \rightarrow \mathbb{R}$ harmonic. Then exists harmonic $v : D \rightarrow \mathbb{R}$ such that $f = u + iv$ holomorphic on D . v is **harmonic conjugate of u** , unique up to addition of real constant. **Note**: condition of D being starlike is removed when Cauchy's theorem is proved in generality.
- Let $f : D \rightarrow \mathbb{C}$ holomorphic on domain D . Then f has holomorphic antiderivative on D .
- **Dirichlet problem**: let $D \subseteq \mathbb{C}$ domain with closure \bar{D} , boundary ∂D , $g : \partial D \rightarrow \mathbb{R}$ continuous. Find continuous $\mu : \bar{D} \rightarrow \mathbb{R}$ such that μ harmonic on D and $\mu = g$ on ∂D .
- Let $f = u + iv : D \rightarrow \mathbb{C}$ holomorphic on domain D , μ harmonic on $f(D)$. Then $\tilde{\mu} := \mu \circ f$ harmonic on D .

8. General form of Cauchy's theorem and C.I.F.

- Let curve $\gamma : [a, b] \rightarrow \mathbb{C}$, $\gamma(t) = w + r(t)e^{i\theta(t)}$, $w \in \mathbb{C}$, $r, \theta : [a, b] \rightarrow \mathbb{R}$, piecewise C^1 , $r(t) > 0$. **Winding number (index)** of γ around w is

$$I(\gamma; w) := \frac{\theta(b) - \theta(a)}{2\pi}$$

- Let contour $\gamma : [a, b] \rightarrow \mathbb{C}$, $w \in \mathbb{C}$, $w \notin \gamma$. Then exists $r, \theta : [a, b] \rightarrow \mathbb{R}$ piecewise C^1 , $r(t) > 0$ such that

$$\gamma(t) = w + r(t)e^{i\theta(t)}$$

. Here, $r(t) = |\gamma(t) - w|$.

- Let $\gamma : [a, b] \rightarrow \mathbb{C}$ closed contour, $w \notin \gamma$. Then

$$I(\gamma; w) = \frac{1}{2\pi i} \int_{\gamma} \frac{1}{z - w} dz$$

- Let D starlike domain, γ closed contour in D . If $w \notin D$, then $I(\gamma; w) = 0$.
- Let $U \subseteq \mathbb{C}$ open.
 - Closed contour γ in U **homologous to zero in U** if $I(\gamma; w) = 0$ for every $w \notin U$.
 - U is **simply connected** if every closed contour in U homologous to zero in U .
- **Cycle**: finite collection of closed contours in U , denoted as formal sum

$$\Gamma := \gamma_1 + \dots + \gamma_n$$

w **does not lie in Γ** if $w \notin \gamma_i$ for all i . Define

$$I(\Gamma; w) := \sum_{i=1}^n I(\gamma_i; w)$$

and

$$\int_{\Gamma} f(z) dz := \sum_{i=1}^n \int_{\gamma_i} f(z) dz$$

Γ **homologous to zero in U** if $I(\Gamma; w) = 0$ for every $w \notin U$.

- Closed curve $\gamma : [a, b] \rightarrow \mathbb{C}$ **simple** if for any $t_1 < t_2$, $\gamma(t_1) = \gamma(t_2) \implies t_1 = a$ and $t_2 = b$ (no self-crossing or backtracking).
- **Jordan curve theorem:** Let γ closed curve. Then $\mathbb{C} - \gamma$ is disjoint union of two domains, exactly one of which is bounded. Bounded domain is **interior** of γ , D_{γ}^{int} . Unbounded domain is **exterior**, D_{γ}^{ext} . w lies inside γ if $w \in D_{\gamma}^{\text{int}}$ and outside γ if $w \in D_{\gamma}^{\text{ext}}$.
- Let γ simple closed contour. Then possible to put orientation on γ such that $\forall w \in \mathbb{C} - \gamma$,

$$I(\gamma; w) = \begin{cases} 1 & \text{if } w \in D_{\gamma}^{\text{int}} \\ 0 & \text{if } w \in D_{\gamma}^{\text{ext}} \end{cases}$$

Then γ is **positively oriented** (interior always on left of curve - anticlockwise).

- Let D domain, $f : D \rightarrow \mathbb{C}$ holomorphic, Γ cycle in D , homologous to zero in D .
 - **General form of Cauchy's theorem:**

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

- **General form of CIF:**

$$\forall w \in D - \Gamma, \quad \int_{\Gamma} \frac{f(z)}{z - w} dz = 2\pi i I(\Gamma; w) f(w)$$

- For simple closed curve γ , f holomorphic on $D_{\gamma}^{\text{int}} \cup \gamma$ if exists domain D such that $D_{\gamma}^{\text{int}} \cup \gamma \subset D$ and f holomorphic on D .
- Let γ simple closed curve and f holomorphic on $D_{\gamma}^{\text{int}} \cup \gamma$.
 - **Cauchy's theorem for simple closed curves:**

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

- **CIF for simple closed contours:**

$$\forall w \in D_{\gamma}^{\text{int}}, \quad \int_{\gamma} \frac{f(z)}{z - w} dz = 2\pi i f(w)$$

9. Holomorphic functions on punctured domains

- **Laurent series:**

$$\sum_{n=-\infty}^{\infty} c_n (z-a)^n$$

Principal part: $\sum_{n=-\infty}^{-1} c_n (z-a)^n$. **Analytic part:** $\sum_{n=0}^{\infty} c_n (z-a)^n$.

- Laurent series converges at z iff principal and analytic parts converge at z .
- **Annulus centre a , internal/external radii r and R :**

$$A_{r,R}(a) := \{z \in \mathbb{C} : r < |z-a| < R\}$$

- If Laurent series isn't power series ($c_n \neq 0$ for some $n < 0$) then either:
 - It never converges or
 - Exists $0 \leq r < R \leq \infty$ such that it converges on $A_{r,R}(a)$ and diverges for $|z-a| < r$ or $|z-a| > R$. $A_{r,R}(a)$ is **annulus of convergence**.
- If Laurent series has annulus of convergence $A_{r,R}(a)$ then it converges uniformly on any A_{ρ_1, ρ_2} with $r < \rho_1 < \rho_2 < R$. So it converges locally uniformly on $A_{r,R}(a)$ so represents holomorphic function on $A_{r,R}(a)$.
- If Laurent series has annulus of convergence containing $A_{r,R}(a)$, then c_n are unique and given by, for any $\rho \in (r, R)$

$$c_n = \frac{1}{2\pi i} \int_{|z-a|=\rho} \frac{f(z)}{(z-a)^{n+1}} dz$$

So Laurent series in $A_{r,R}(a)$ unique.

- **Holomorphic functions on annuli have Laurent series:** let $f : A_{r,R}(a) \rightarrow \mathbb{C}$ holomorphic, then exist unique $c_n \in \mathbb{C}$ such that

$$\forall z \in A_{r,R}(a), \quad f(z) = \sum_{n=-\infty}^{\infty} c_n (z-a)^n$$

and annulus of convergence of Laurent series contains $A_{r,R}(a)$. Series is **Laurent series of f on A** .

- **Punctured ball:** $B_R^*(a) := B_R(a) - \{a\} = A_{0,R}(a)$.
- If f holomorphic on $B_R^*(a)$, f has **isolated singularity** at a .
- Types of isolated singularity:
 - f has **removable singularity** at $z = a$ if $c_n = 0$ for all $n \leq -1$ (principal part is zero).
 - f has **pole of order k** at $z = a$ if $c_{-k} \neq 0$ and $c_n = 0$ for all $n < -k$.
 - f has **essential singularity** at $z = a$ if exist infinitely many $n < 0$ such that $c_n \neq 0$.
- $f : B_R^*(a) \rightarrow \mathbb{C}$ has removable singularity at $z = a$ iff f extends to holomorphic function on $B_R(a)$.
- Let $f : B_R^*(a) \rightarrow \mathbb{C}$ holomorphic, $R > 0$. Then f has removable singularity at $z = a$ iff

$$\lim_{z \rightarrow a} (z-a)f(z) = 0$$

- **Riemann extension theorem:** Let $f : B_R^*(a) \rightarrow \mathbb{C}$ holomorphic and bounded, then f has removable singularity at $z = a$.
- Let $f : B_R^*(a) \rightarrow \mathbb{C}$ holomorphic. The following are equivalent:

- f has pole of order k at $z = a$.
- $f(z) = (z - a)^{-k}g(z)$, $g : B_R(a) \rightarrow \mathbb{C}$ holomorphic, $g(a) \neq 0$.
- Exists $0 < r \leq R$ and $h : B_r(a) \rightarrow \mathbb{C}$ holomorphic with zero of order k at $z = a$ such that $f(z) = 1/h(z)$ for $z \in B_r^*(a)$.
- Let $f : B_R^*(a) \rightarrow \mathbb{C}$ holomorphic. Then f has pole at $z = a$ iff

$$\lim_{z \rightarrow a} |f(z)| = \infty$$

- **Casorati-Weierstrass theorem:** let $f : B_R^*(a) \rightarrow \mathbb{C}$ holomorphic with essential singularity at $z = a$. Then

$$\forall w \in \mathbb{C}, \forall 0 < r < R, \forall \varepsilon > 0, \exists z \in B_r^*(a), \quad f(z) \in B_\varepsilon(w)$$

- **Big Picard theorem:** let $f : B_R^*(a) \rightarrow \mathbb{C}$ holomorphic with essential singularity at $z = a$. Then for some $b \in \mathbb{C}$,

$$\forall 0 < r < R, \quad \mathbb{C} - \{b\} \subseteq f(B_r^*(a))$$

10. Cauchy's residue theorem

- f **meromorphic** on domain D if f holomorphic on $D - S$, $S \subset D$ has no non-isolated points and f has pole at every $s \in S$.
- f meromorphic on $D_\gamma^{\text{in}} \cup \gamma$ if exists domain D containing $D_\gamma^{\text{in}} \cup \gamma$ and f meromorphic on D .
- Let f meromorphic on domain D with pole at a , with Laurent series

$$f(z) = \sum_{n=-k}^{\infty} c_n(z-a)^n$$

Residue of f at a is

$$\text{Res}_{z=a}(f) := c_{-1}$$

- **Cauchy's residue theorem:** Let f meromorphic on $D_\gamma^{\text{in}} \cup \gamma$, γ positively oriented simple closed contour, f has no poles on γ and finite number of poles inside γ , $\{a_1, \dots, a_m\}$. Then

$$\int_{\gamma} f(z) dz = 2\pi i \sum_{j=1}^m \text{Res}_{z=a_j}(f)$$

- **Simple pole:** pole of order 1.
- **Rules for calculating residues:**
 - **Linear combinations:** $\text{Res}_{z=a}(Af + Bg) = A\text{Res}_{z=a}(f) + B\text{Res}_{z=a}(g)$.
 - **Cover up rule for poles of order 1:** if $z = a$ is pole of order 1,

$$\text{Res}_{z=a}(f) = \lim_{z \rightarrow a} (z-a)f(z)$$

- **Simple zero on denominator:** if $f(z) = g(z)/h(z)$, g, h holomorphic at a , $g(a) \neq 0$, $z = a$ is zero of order 1 of h , then

$$\text{Res}_{z=a}(f) = \frac{g(a)}{h'(a)}$$

- **Poles of higher orders:** if $f(z) = g(z)/(z-a)^k$, $k > 0$, g holomorphic at a , then

$$\text{Res}_{z=a}(f) = \frac{g^{(k-1)}(a)}{(k-1)!}$$

- To calculate

$$\int_0^{2\pi} F(\sin(\theta), \cos(\theta)) d\theta$$

where F is rational function, use change of variable $z = e^{i\theta}$, and use

$$\int_0^{2\pi} F(\sin(\theta), \cos(\theta)) d\theta = \int_{|z|=1} F\left(\frac{z - z^{-1}}{2i}, \frac{z + z^{-1}}{2}\right) \frac{dz}{iz}$$

- To calculate

$$\lim_{R \rightarrow \infty} \int_{-R}^R \frac{p(x)}{q(x)} dx$$

where $\deg(q) \geq \deg(p) + 2$ and q has no real roots, integrate $f(z) = p(z) / q(z)$ over $\gamma_R = L_R \cup C_R$ where R greater than maximum modulus of roots of q . Use e.g. Estimation Lemma or Jordan's lemma to show $\lim_{R \rightarrow \infty} \int_{C_R} f(z) dz = 0$.

- $$\int_{-\infty}^{\infty} f(x) dx = \lim_{r \rightarrow \infty} \int_0^r f(x) dx + \lim_{s \rightarrow \infty} \int_{-s}^0 f(x) dx$$

- **Cauchy principal value** of $\int_{-\infty}^{\infty} f(x) dx$:

$$P.V. \int_{-\infty}^{\infty} f(x) dx = \lim_{r \rightarrow \infty} \int_{-r}^r f(x) dx$$

- If f even, $P.V. \int_{-\infty}^{\infty} f(x) dx = \int_{-\infty}^{\infty} f(x) dx$
- **Jordan's lemma**: let f holomorphic on $D = \{z \in \mathbb{C} : |z| > r\}$ for some $r > 0$, $zf(z)$ bounded on D . Then for every $\alpha > 0$,

$$\lim_{R \rightarrow \infty} \int_{C_R} f(z) e^{i\alpha z} dz = 0$$

where $C_R = Re^{i\theta}$, $\theta \in [0, \pi]$.

- To calculate

$$P.V. \int_{-\infty}^{\infty} f(x) \sin(\alpha x) dx \quad \text{or} \quad P.V. \int_{-\infty}^{\infty} f(x) \cos(\alpha x) dx$$

where f meromorphic in \mathbb{C} with no real poles and f satisfies Jordan's lemma, calculate integral

$$\int_{\gamma_R} f(z) e^{i\alpha z} dz$$

with CRT, where $\gamma_R = L_R \cup C_R$. Then use

$$\int_{L_R} f(z)e^{i\alpha z} dz = \int_{-R}^R f(x)\cos(\alpha x) dx + i \int_{-R}^R f(x)\sin(\alpha x) dx$$

and equate real/imaginary parts. Use Jordan's lemma to show

$$\lim_{R \rightarrow \infty} \int_{C_R} f(z)e^{i\alpha z} dz = 0.$$

- **Indentation lemma:** Let g meromorphic on \mathbb{C} with simple pole at 0, $C_\varepsilon(\theta) = \varepsilon e^{i\theta}, \theta \in [0, \pi]$. Then

$$\lim_{\varepsilon \rightarrow 0} \int_{C_\varepsilon} g(z) dz = \pi i \text{Res}_{z=0}(g)$$

- To calculate

$$\int_{-\infty}^{\infty} f(x) dx$$

where f has simple pole at $z = 0$, let $\gamma_{\rho,R} = L_2 \cup (-C_\rho) \cup L_1 \cup C_R$ where L_2 is line from $-R$ to $-\rho$, L_1 is line from ρ to R . Take $\rho \rightarrow 0$ and $R \rightarrow \infty$, use indentation lemma and Jordan's lemma. **Note:** may have to choose appropriate branch cut so that f holomorphic on D .

- Let f meromorphic with zero or pole order $k > 0$ at a . Then f' / f has simple pole at a and

$$\text{Res}_{z=a}(f' / f) = \begin{cases} k & \text{if } f \text{ has zero at } z = a \\ -k & \text{if } f \text{ has pole at } z = a \end{cases}$$

- **Argument principle:** let γ positively oriented simple closed contour, f meromorphic on $D_\gamma^{\text{int}} \cup \gamma$, f has no zeros or poles on γ , Z_f be number of zeros of f in D_γ^{int} (counted with multiplicity), P_f be number of poles of f in D_γ^{int} (counted with multiplicity). Then

$$\frac{1}{2\pi i} \int_\gamma \frac{f'(z)}{f(z)} dz = Z_f - P_f = I(\Gamma_f; 0), \quad \Gamma_f = f \circ \gamma$$

(Counted with multiplicity means zero/pole of order k counts k times).

- **Rouche's theorem:** let γ simple closed contour, f, g holomorphic on $D_\gamma^{\text{int}} \cup \gamma$, with

$$\forall z \in \gamma, |f(z) - g(z)| < |g(z)|$$

Then f and g have same number of zeros (counted with multiplicity) inside γ .

- **Open mapping theorem:** let f holomorphic, non-constant on domain D . Then if $U \subset D$ open, $f(U)$ is open.