Complex Analysis Problems

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Contents

1 Integrals and Cauchy's Theorem

1.1 1

Suppose $f, g : [0,1] \longrightarrow \mathbb{R}$ where f is Riemann integrable and for $x, y \in [0,1]$,

$$|g(x) - g(y)| \leq |f(x) - f(y)|.$$

Prove that g is Riemann integrable.

1.2 2

State and prove Green's Theorem for rectangles.

Then use it to prove Cauchy's Theory for functions that are analytic in a rectangle.

1.3 3

Suppose $\{f_n\}_{n\in\mathbb{N}}$ is a sequence of analytic functions on $\mathbb{D}^\circ := \left\{z \in \mathbb{C} \;\middle|\; |z| < 1\right\}$.

Show that if $f_n \longrightarrow g$ for some $g : \mathbb{D}^\circ \longrightarrow \mathbb{C}$ uniformly on every compact $K \subset \mathbb{D}^\circ$, then g is analytic on $\mathbb{D}^\circ$.

1.4 4

Suppose $\{f_n\}_{n\in\mathbb{N}}$ is a sequence of entire functions where

- $f_n \longrightarrow g$ pointwise for some $g : \mathbb{C} \longrightarrow \mathbb{C}$.
- On every line segment in $\mathbb{C}$, $f_n \longrightarrow g$ uniformly.

Show that

- g is entire, and
- $f_n \longrightarrow g$ uniformly on every compact subset of $\mathbb{C}$.

1.5 5

Prove that there is no sequence of polynomials that uniformly converge to $f(z) = \dfrac{1}{z}$ on S^1.

1.6 6

Suppose that $f : \mathbb{R} \longrightarrow \mathbb{R}$ is a continuous function that vanishes outside of some finite interval. For each $z \in \mathbb{C}$, define

$$g(z) = \int_{-\infty}^{\infty} f(t) e^{-izt}\, dt.$$

Show that g is entire.

1.7 7

Suppose $f : \mathbb{C} \longrightarrow \mathbb{C}$ is entire and

$$|f(z)| \leq |z|^{\frac{1}{2}} \quad \text{when } |z| > 10.$$

Prove that f is constant.

1.8 8

Let γ be a smooth curve joining two distinct points $a, b \in \mathbb{C}$.

Prove that the function

$$f(z) \coloneqq \int_\gamma \frac{g(w)}{w - z}\, dw$$

is analytic in $\mathbb{C} \setminus \gamma$.

1.9 9

Suppose that $f : \mathbb{C} \longrightarrow \mathbb{C}$ is continuous everywhere and analytic on $\mathbb{C} \setminus \mathbb{R}$ and prove that f is entire.

1.10 10

Prove Liouville's theorem: suppose $f : \mathbb{C} \longrightarrow \mathbb{C}$ is entire and bounded. Use Cauchy's formula to prove that $f' \equiv 0$ and hence f is constant.

2 Liouville's Theorem, Power Series

2.1 1

Suppose f is analytic on a region Ω such that $\mathbb{D} \subseteq \Omega \subseteq \mathbb{C}$ and $f(z) = \displaystyle\sum_{n=0}^{\infty} a_n z^n$ is a power series with radius of convergence exactly 1.

a. Give an example of such an f that converges at every point of S^1.

b. Given an example of such an f which is analytic at 1 but $\displaystyle\sum_{n=0}^{\infty} a_n$ diverges.

c. Prove that f can not be analytic at *every* point of S^1.

2.2 2

Suppose f is entire and has Taylor series $\sum a_n z^n$ about 0.

a. Express a_n as a contour integral along the circle $|z| = R$.

b. Apply (a) to show that the above Taylor series converges uniformly on every bounded subset of $\mathbb{C}$.

c. Determine those functions f for which the above Taylor series converges uniformly on all of $\mathbb{C}$.

2.3 3

Suppose D is a domain and f, g are analytic on D.

Prove that if $fg = 0$ on D, then either $f \equiv 0$ or $g \equiv 0$ on D.

2.4 4

Suppose f is analytic on $\mathbb{D}^\circ$. Determine with proof which of the following are possible:

a. $f\left(\frac{1}{n}\right) = (-1)^n$ for each $n > 1$.

b. $f\left(\frac{1}{n}\right) = e^{-n}$ for each even integer $n > 1$ while $f\left(\frac{1}{n}\right) = 0$ for each odd integer $n > 1$.

c. $f\left(\frac{1}{n^2}\right) = \frac{1}{n}$ for each integer $n > 1$.

d. $f\left(\frac{1}{n}\right) = \frac{n-2}{n-1}$ for each integer $n > 1$.

2.5 5

Prove the Fundamental Theorem of Algebra (using complex analysis).

2.6 6

Find all entire functions that satisfy

$$|f(z)| \geq |z| \quad \forall z \in \mathbb{C}.$$

Prove this list is complete.

2.7 7

Suppose $\sum_{n=0}^{\infty} a_n z^n$ converges for some $z_0 \neq 0$.

a. Prove that the series converges absolutely for each z with $|z| < |z|_0$.

b. Suppose $0 < r < |z_0|$ and show that the series converges uniformly on $|z| \leq r$.

2.8 8

Suppose f is entire and suppose that for some integer $n \geq 1$,

$$\lim_{z \longrightarrow \infty} \frac{f(z)}{z^n} = 0.$$

Prove that f is a polynomial of degree at most $n - 1$.

2.9 9

Find all entire functions satisfying

$$|f(z)| \leq |z|^{\frac{1}{2}} \quad \text{for } |z| > 10.$$

2.10 10

Prove that the following series converges uniformly on the set $\left\{z \;\middle|\; \Im(z) < \ln 2\right\}$:

$$\sum_{n=1}^{\infty} \frac{\sin(nz)}{2^n}.$$

3 Spring 2020 Homework 1

3.1 1

Geometrically describe the following subsets of $\mathbb{C}$:

a. $|z-1| = 1$
b. $|z-1| = 2|z-2|$
c. $1/z = \bar{z}$
d. $\Re(z) = 3$
e. $\Im(z) = a$ with $a \in \mathbb{R}$.
f. $\Re(z) > a$ with $a \in \mathbb{R}$.
g. $|z-1| < 2|z-2|$

3.2 2

Prove the following inequality, and explain when equality holds:

$$|z+w| \geq ||z| - |w||.$$

3.3 3

Prove that the following polynomial has its roots outside of the unit circle:

$$p(z) = z^3 + 2z + 4.$$

> Hint: What is the maximum value of the modulus of the first two terms if $|z| \leq 1$?

3.4 4

a. Prove that if $c > 0$,

$$|w_1| = c|w_2| \implies \left|w_1 - c^2 w_2\right| = c|w_1 - w_2|.$$

b. Prove that if $c > 0$ and $c \neq 1$, with $z_1 \neq z_2$, then the following equation represents a circle:

$$\left|\frac{z - z_1}{z - z_2}\right| = c.$$

Find its center and radius.

> Hint: use part (a)

3.5 5

a. Let $z, w \in \mathbb{C}$ with $\bar{z}w \neq 1$. Prove that

$$\left|\frac{w-z}{1-\overline{w}z}\right| < 1 \quad \text{if } |z|<1,\ |w|<1$$

with equality when $|z| = 1$ or $|w| = 1$.

b. Prove that for a fixed $w \in \mathbb{D}$, the mapping $F : z \mapsto \dfrac{w-z}{1-\overline{w}z}$ satisfies

- F maps $\mathbb{D}$ to itself and is holomorphic.
- $F(0) = w$ and $F(w) = 0$.
- $|z| = 1$ implies $|F(z)| = 1$.

3.6 6

Use nth roots of unity to show that

$$2^{n-1}\sin\left(\frac{\pi}{n}\right)\sin\left(\frac{2\pi}{n}\right)\cdots\sin\left(\frac{(n-1)\pi}{n}\right) = n.$$

Hint:

$$\begin{aligned} 1-\cos(2\theta) &= 2\sin^2(\theta) \\ 2\sin(2\theta) &= 2\sin(\theta)\cos(\theta). \end{aligned}$$

3.7 7

Prove that $f(z) = |z|^2$ has a derivative at $z = 0$ and nowhere else.

3.8 8

Let $f(z)$ be analytic in a domain, and prove that f is constant if it satisfies any of the following conditions:

a. $|f(z)|$ is constant.
b. $\Re(f(z))$ is constant.
c. $\arg(f(z))$ is constant.
d. $\overline{f(z)}$ is analytic.

How do you generalize (a) and (b)?

3.9 9

Prove that if $z \mapsto f(z)$ is analytic, then $z \mapsto \overline{f(\bar{z})}$ is analytic.

3.10 10

a. Show that in polar coordinates, the Cauchy-Riemann equations take the form

$$\frac{\partial u}{\partial r} = \frac{1}{r}\frac{\partial v}{\partial \theta} \text{ and } \frac{\partial v}{\partial r} = -\frac{1}{r}\frac{\partial u}{\partial \theta}.$$

b. Use (a) to show that the logarithm function, defined as

$$\log z = \log r + i\theta \text{ where } z = re^{i\theta} \text{ with } -\pi < \theta < \pi.$$

is holomorphic on the region $r > 0, -\pi < \theta < \pi$.

Also show that this function is not continuous in $r > 0$.

3.11 11

Prove that the distinct complex numbers z_1, z_2, z_3 are the vertices of an equilateral triangle if and only if

$$z_1^2 + z_2^2 + z_3^2 = z_1 z_2 + z_2 z_3 + z_3 z_1.$$

4 Spring 2020 Homework 2

Note on notation: I sometimes use $f_x \coloneqq \frac{\partial f}{\partial x}$ to denote partial derivatives, and $\partial_z^n f$ as $f^{(n)}(z)$.

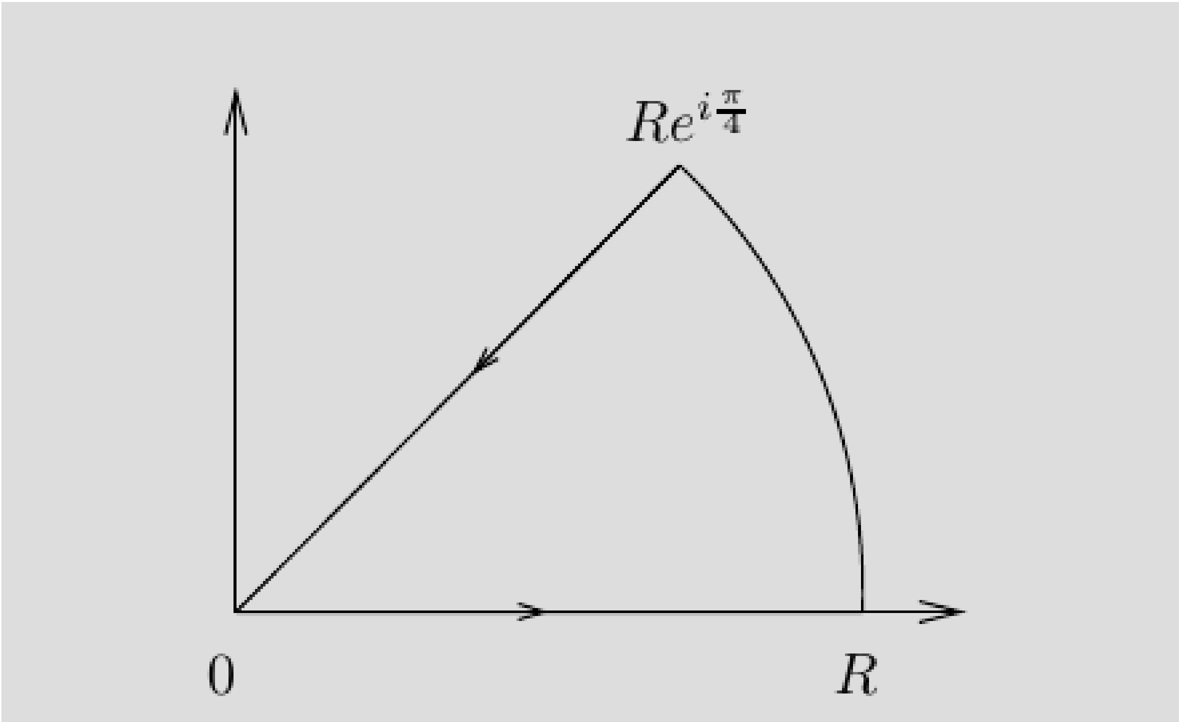
4.1 Stein And Shakarchi

4.1.1 2.6.1

Show that

$$\int_0^\infty \sin\left(x^2\right) dx = \int_0^\infty \cos\left(x^2\right) dx = \frac{\sqrt{2\pi}}{4}.$$

Hint: integrate e^{-x^2} over the following contour, using the fact that $\int_{-\infty}^\infty e^{-x^2} dx = \sqrt{\pi}$:



4.1.2 2.6.2

Show that

$$\int_0^\infty \frac{\sin x}{x} dx = \frac{\pi}{2}.$$

Hint: use the fact that this integral equals $\dfrac{1}{2i}\displaystyle\int_{-\infty}^{\infty} \frac{e^{ix}-1}{x} dx$, and integrate around an indented semicircle.

4.1.3 2.6.5

Suppose $f \in C^1_{\mathbb{C}}(\Omega)$ and $T \subset \Omega$ is a triangle with $T^\circ \subset \Omega$. Apply Green's theorem to show that $\displaystyle\int_T f(z)\ dz = 0$.

Assume that f' is continuous and prove Goursat's theorem.

Hint: Green's theorem states

$$\int_T F dx + G dy = \int_{T^\circ} \left(\frac{\partial G}{\partial x} - \frac{\partial F}{\partial y} \right) dx dy.$$

4.1.4 2.6.6

Suppose that f is holomorphic on a punctured open set $\Omega \setminus \{w_0\}$ and let $T \subset \Omega$ be a triangle containing w_0. Prove that if f is bounded near w_0, then $\displaystyle\int_T f(z)\ dz = 0$.

4.1.5 2.6.7

Suppose $f : \mathbb{D} \longrightarrow \mathbb{C}$ is holomorphic and let $d \coloneqq \sup\limits_{z,w \in \mathbb{D}} |f(z) - f(w)|$ be the diameter of the image of f. Show that $2|f'(0)| \leq d$, and that equality holds iff f is linear, so $f(z) = a_1 z + a_2$.

> Hint: $2f'(0) = \dfrac{1}{2\pi i} \displaystyle\int_{|\xi|=r} \frac{f(\xi) - f(-\xi)}{\xi^2}\ d\xi$ whenever $0 < r < 1$.

4.1.6 2.6.8

Suppose that f is holomorphic on the strip $S = \left\{ x + iy \ \middle|\ x \in \mathbb{R},\ -1 < y < 1 \right\}$ with $|f(z)| \leq A(1 + |z|)^\nu$ for ν some fixed real number. Show that for all $z \in S$, for each integer $n \geq 0$ there exists an $A_n \geq 0$ such that $\left| f^{(n)}(x) \right| \leq A_n (1 + |x|)^\nu$ for all $x \in \mathbb{R}$.

> Hint: Use the Cauchy inequalities.

4.1.7 2.6.9

Let $\Omega \subset \mathbb{C}$ be open and bounded and $\varphi : \Omega \longrightarrow \Omega$ holomorphic. Prove that if there exists a point $z_0 \in \Omega$ such that $\varphi(z_0) = z_0$ and $\varphi'(z_0) = 1$, then φ is linear.

> Hint: assume $z_0 = 0$ (explain why this can be done) and write $\varphi(z) = z + a_n z^n + O(z^{n+1})$ near 0. Let $\varphi_k = \varphi \circ \varphi \circ \cdots \circ \varphi$ and prove that $\varphi_k(z) = z + k a_n z^n + O(z^{n+1})$. Apply Cauchy's inequalities and let $k \longrightarrow \infty$ to conclude.

4.1.8 2.6.10

Can every continuous function on $\overline{\mathbb{D}}$ be uniformly approximated by polynomials in the variable z?

> Hint: compare to Weierstrass for the real interval.

4.1.9 2.6.13

Suppose f is analytic, defined on all of $\mathbb{C}$, and for each $z_0 \in \mathbb{C}$ there is at least one coefficient in the expansion $f(z) = \displaystyle\sum_{n=0}^{\infty} c_n (z - z_0)^n$ is zero. Prove that f is a polynomial.

> Hint: use the fact that $c_n n! = f^{(n)}(z_0)$ and use a countability argument.

4.1.10 2.6.14

Suppose that f is holomorphic in an open set containing $\mathbb{D}$ except for a pole $z_0 \in \partial\mathbb{D}$. Let $\sum_{n=0}^{\infty} a_n z^n$ be the power series expansion of f in $\mathbb{D}$, and show that $\lim \frac{a_n}{a_{n+1}} = z_0$.

4.1.11 2.6.15

Suppose f is continuous and nonvanishing on $\overline{\mathbb{D}}$, and holomorphic in $\mathbb{D}$. Prove that if $|z| = 1 \implies |f(z)| = 1$, then f is constant.

> Hint: Extend f to all of $\mathbb{C}$ by $f(z) = 1/\overline{f(1/\bar{z})}$ for any $|z| > 1$, and argue as in the Schwarz reflection principle.

4.2 Additional Problems

4.2.1 1

Let $a_n \neq 0$ and show that

$$\lim_{n \longrightarrow \infty} \frac{|a_{n+1}|}{|a_n|} = L \implies \lim_{n \longrightarrow \infty} |a_n|^{\frac{1}{n}} = L.$$

In particular, this shows that when applicable, the ratio test can be used to calculate the radius of convergence of a power series.

4.2.2 2

Let f be a power series centered at the origin. Prove that f has a power series expansion about any point in its disc of convergence.

4.2.3 3

Prove the following:

a. $\sum_n nz^n$ does not converge at any point of S^1

b. $\sum_n \frac{z^n}{n^2}$ converges at every point of S^1.

c. $\sum_n \frac{z^n}{n}$ converges at every point of S^1 except $z = 1$.

4.2.4 4

Without using Cauchy's integral formula, show that if $|a| < r < |b|$, then

$$\int_\gamma \frac{dz}{(z-\alpha)(z-\beta)} = \frac{2\pi i}{\alpha - \beta}$$

where γ denotes the circle centered at the origin of radius r with positive orientation.

4.2.5 5

Assume f is continuous in the region $\left\{x+iy \;\middle|\; x \geq x_0,\ 0 \leq y \leq b\right\}$, and the following limit exists independent of y:

$$\lim_{x \longrightarrow +\infty} f(x+iy) = A.$$

Show that if $\gamma_x := \left\{z = x + it \;\middle|\; 0 \leq t \leq b\right\}$, then

$$\lim_{x \longrightarrow +\infty} \int_{\gamma_x} f(z)\, dz = iAb.$$

4.2.6 6

Show by example that there exists a function $f(z)$ that is holomorphic on $\left\{z \in \mathbb{C} \;\middle|\; 0 < |z| < 1\right\}$ and for all $r < 1$,

$$\int_{|z|=r} f(z)\, dz = 0,$$

but f is not holomorphic at $z = 0$.

4.2.7 7

Let f be analytic on a region R and suppose $f'(z_0) \neq 0$ for some $z_0 \in R$. Show that if C is a circle of sufficiently small radius centered at z_0, then

$$\frac{2\pi i}{f'(z_0)} = \int_C \frac{dz}{f(z) - f(z_0)}.$$

Hint: use the inverse function theorem.

4.2.8 8

Assume two functions $u, b : \mathbb{R}^2 \longrightarrow \mathbb{R}$ have continuous partial derivatives at (x_0, y_0). Show that $f := u + iv$ has derivative $f'(z_0)$ at $z_0 == x_0 + iy_0$ if and only if

$$\lim_{r \to 0} \frac{1}{\pi r^2} \int_{|z - z_0| = r} f(z) dz = 0.$$

4.2.9 9 (Cauchy's Formula for Exterior Regions)

Let γ be a piecewise smooth simple closed curve with interior Ω_1 and exterior Ω_2. Assume f' exists in an open set containing γ and Ω_2 with $\lim_{z \longrightarrow \infty} f(z) = A$. Show that

$$\frac{1}{2\pi i} \int_\gamma \frac{f(\xi)}{\xi - z} d\xi = \begin{cases} A, & \text{if } z \in \Omega_1 \\ -f(z) + A, & \text{if } z \in \Omega_2 \end{cases}.$$

4.2.10 10

Let $f(z)$ be bounded and analytic in $\mathbb{C}$. Let $a \neq b$ be any fixed complex numbers. Show that the following limit exists:

$$\lim_{R \longrightarrow \infty} \int_{|z|=R} \frac{f(z)}{(z-a)(z-b)}\, dz.$$

Use this to show that $f(z)$ must be constant.

4.2.11 11

Suppose $f(z)$ is entire and

$$\lim_{z \longrightarrow \infty} \frac{f(z)}{z} = 0.$$

Show that $f(z)$ is a constant.

4.2.12 12

Let f be analytic in a domain D and γ be a closed curve in D. For any $z_0 \in D$ not on γ, show that

$$\int_\gamma \frac{f'(z)}{(z-z_0)} dz = \int_\gamma \frac{f(z)}{(z-z_0)^2} dz.$$

Give a generalization of this result.

4.2.13 13

Compute

$$\int_{|z|=1} \left(z + \frac{1}{z}\right)^{2n} \frac{dz}{z}$$

and use it to show that

$$\in_0^{2\pi} \cos^{2n}(\theta)\, d\theta = 2\pi \left(\frac{1 \cdot 3 \cdot 5 \cdots (2n-1)}{2 \cdot 4 \cdot 6 \cdots (2n)} \right).$$

5 Spring 2020 Homework 3

5.1 Stein and Shakarchi

5.1.1 3.8.1

Use the following formula to show that the complex zeros of $\sin(\pi z)$ are exactly the integers, and they are each of order 1:

$$\sin \pi z = \frac{e^{i\pi z} - e^{-i\pi z}}{2i}.$$

Calculate the residue of $\dfrac{1}{\sin(\pi z)}$ at $z = n \in \mathbb{Z}$.

5.1.2 3.8.2

Evaluate the integral

$$\int_{\mathbb{R}} \frac{dx}{1+x^4}.$$

What are the poles of $\dfrac{1}{1+z^4}$?

5.1.3 3.8.4

Show that

$$\int_{-\infty}^{\infty} \frac{x \sin x}{x^2+a^2} dx = \pi e^{-a}, \qquad \text{for all } a > 0.$$

5.1.4 3.8.5

Show that if $\xi \in \mathbb{R}$, then

$$\int_{-\infty}^{\infty} \frac{e^{-2\pi i x \xi}}{(1+x^2)^2} dx = \frac{\pi}{2}(1+2\pi|\xi|)e^{-2\pi|\xi|}.$$

5.1.5 3.8.6

Show that

$$\int_{-\infty}^{\infty} \frac{dx}{(1+x^2)^{n+1}} = \frac{1 \cdot 3 \cdot 5 \cdots (2n-1)}{2 \cdot 4 \cdot 6 \cdots (2n)} \cdot \pi.$$

5.1.6 3.8.7

Show that

$$\int_0^{2\pi} \frac{d\theta}{(a+\cos\theta)^2} = \frac{2\pi a}{(a^2-1)^{3/2}}, \qquad \text{whenever } a > 1.$$

5.1.7 3.8.8

Show that if $a, b \in \mathbb{R}$ with $a > |b|$, then

$$\int_0^{2\pi} \frac{d\theta}{a + b\cos\theta} = \frac{2\pi}{\sqrt{a^2-b^2}}.$$

5.1.8 3.8.9

Show that

$$\int_0^1 \log(\sin \pi x)dx = -\log 2.$$

Hint: use the following contour.

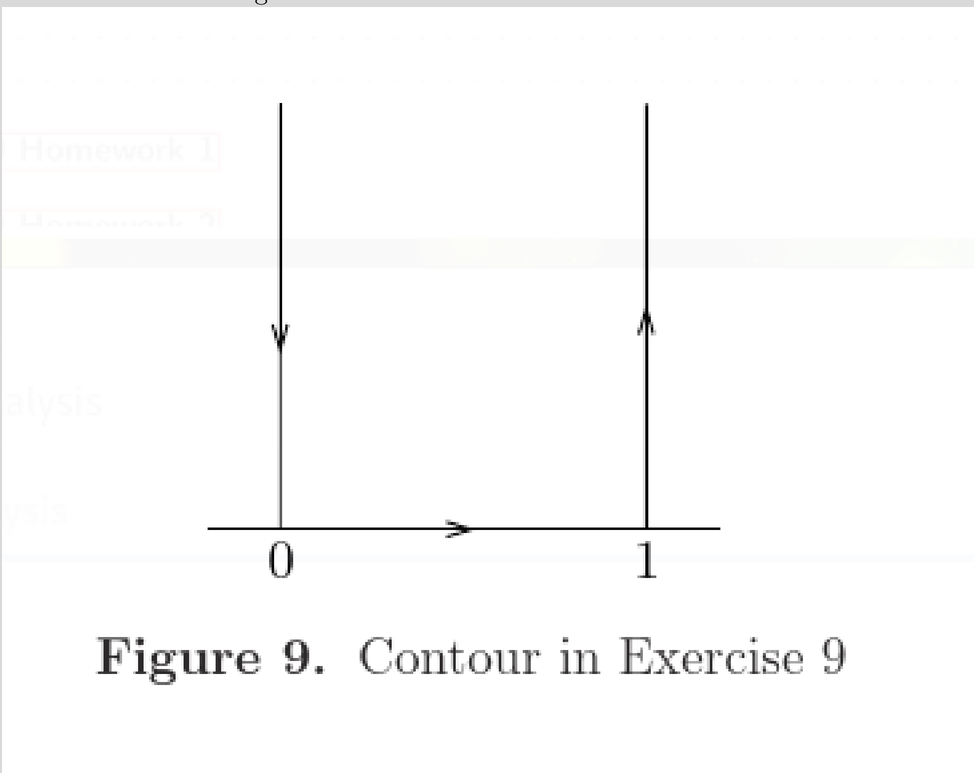


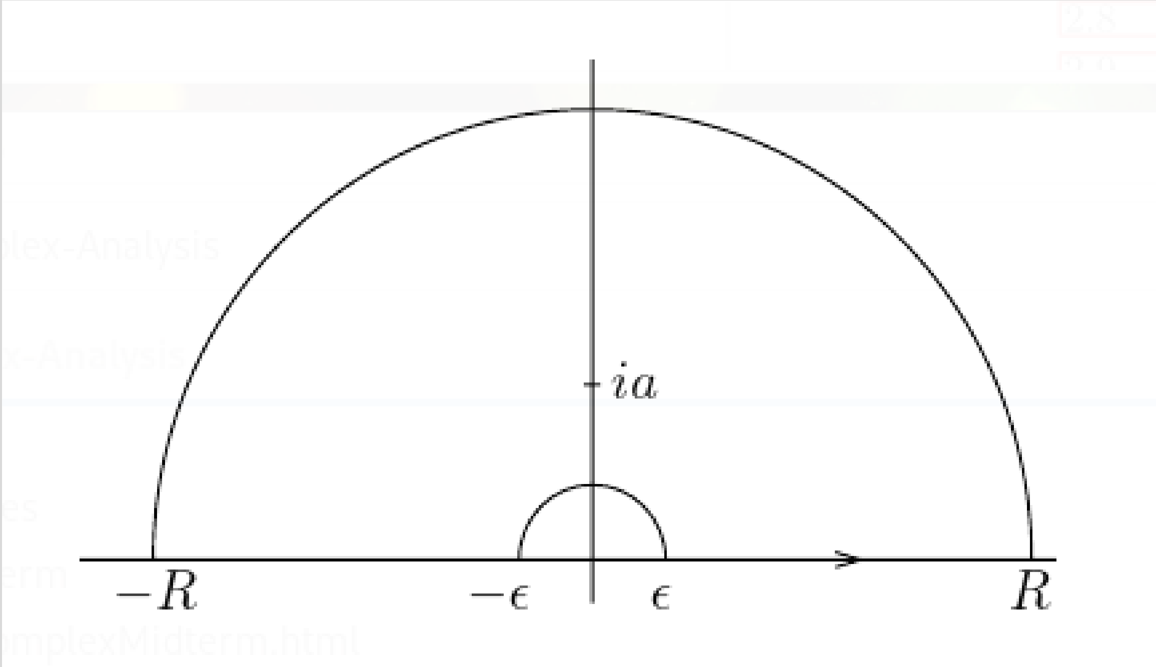
Figure 9. Contour in Exercise 9

5.1.9 3.8.10

Show that if $a > 0$, then

$$\int_0^\infty \frac{\log x}{x^2 + a^2} dx = \frac{\pi}{2a} \log a.$$

Hint: use the following contour.



5.1.10 3.8.14

Prove that all entire functions that are injective are of the form $f(z) = az + b$ with $a, b \in \mathbb{C}$ and $a \neq 0$.

Hint: Apply the Casorati-Weierstrass theorem to $f(1/z)$.

5.1.11 3.8.15

Use the Cauchy inequalities or the maximum modulus principle to solve the following problems:

a. Prove that if f is an entire function that satisfies

$$\sup_{|z|=R} |f(z)| \leq AR^k + B$$

for all $R > 0$, some integer $k \geq 0$, and some constants $A, B > 0$, then f is a polynomial of degree $\leq k$.

b. Show that if f is holomorphic in the unit disc, is bounded, and converges uniformly to zero in the sector $\theta < \arg(z) < \varphi$ as $|z| \longrightarrow 0$, then $f \equiv 0$.

c. Let $w_1, \cdots w_n$ be points on $S^1 \subset \mathbb{C}$. Prove that there exists a point $z \in S^1$ such that the product of the distances from z to the points w_j is at least 1.

Conclude that there exists a point $w \in S^1$ such that the product of the above distances is *exactly* 1.

d. Show that if the real part of an entire function is bounded, then f is constant.

5.1.12 3.8.17

Let f be non-constant and holomorphic in an open set containing the closed unit disc.

a. Show that if $|f(z)| = 1$ whenever $|z| = 1$, then the image of f contains the unit disc.

> Hint: Show that $f(z) = w_0$ has a root for every $w_0 \in \mathbb{D}$, for which it suffices to show that $f(z) = 0$ has a root. Conclude using the maximum modulus principle.

b. If $|f(z)| \geq 1$ whenever $|z| = 1$ and there exists a $z_0 \in \mathbb{D}$ such that $|f(z_0)| < 1$, then the image of f contains the unit disc.

5.1.13 3.8.19

Prove that maximum principle for harmonic functions, i.e.

a. If u is a non-constant real-valued harmonic function in a region Ω, then u can not attain a maximum or a minimum in Ω.

b. Suppose Ω is a region with compact closure $\overline{\Omega}$. If u is harmonic in Ω and continuous in $\overline{\Omega}$, then

$$\sup_{z \in \Omega} |u(z)| \leq \sup_{z \in \overline{\Omega} - \Omega} |u(z)|.$$

> Hint: to prove (a), assume u attains a local maximum at z_0. Let f be holomorphic near z_0 with $\Re(f) = u$, and show that f is not an open map. Then (a) implies (b).

5.2 Problems From Tie

5.2.1 1

Prove that if f has two Laurent series expansions,

$$f(z) = \sum c_n (z-a)^n \quad \text{and} \quad f(z) = \sum c_n' (z-a)^n$$

then $c_n = c_n'$.

5.2.2 2

Find Laurent series expansions of

$$\frac{1}{1-z^2} + \frac{1}{3-z}$$

How many such expansions are there? In what domains are each valid?

5.2.3 3

Let P, Q be polynomials with no common zeros. Assume a is a root of Q. Find the principal part of P/Q at $z = a$ in terms of P and Q if a is (1) a simple root, and (2) a double root.

5.2.4 4

Let f be non-constant, analytic in $|z| > 0$, where $f(z_n) = 0$ for infinitely many points z_n with $\lim_{n \longrightarrow \infty} z_n = 0$.
Show that $z = 0$ is an essential singularity for f.

Example: $f(z) = \sin(1/z)$.

5.2.5 5

Show that if f is entire and $\lim_{z \longrightarrow \infty} f(z) = \infty$, then f is a polynomial.

5.2.6 6

a. Show (without using 3.8.9 in the S&S) that

$$\int_0^{2\pi} \log \left|1 - e^{i\theta}\right| \, d\theta = 0$$

b. Show that this identity is equivalent to S&S 3.8.9:

$$\int_0^1 \log(\sin(\pi x)) \, dx = -\log 2.$$

5.2.7 7

Let $0 < a < 4$ and evaluate

$$\int_0^\infty \frac{x^{\alpha-1}}{1+x^3} \, dx$$

5.2.8 8

Prove the fundamental theorem of Algebra using
a. Rouche's Theorem.
b. The maximum modulus principle.

5.2.9 9

Let f be analytic in a region D and γ a rectifiable curve in D with interior in D.
Prove that if $f(z)$ is real for all $z \in \gamma$, then f is constant.

5.2.10 10

For $a > 0$, evaluate

$$\int_0^{\pi/2} \frac{d\theta}{a + \sin^2 \theta}$$

5.2.11 11

Find the number of roots of $p(z) = 4z^4 - 6z + 3$ in $|z| < 1$ and $1 < |z| < 2$ respectively.

5.2.12 12

Prove that $z^4 + 2z^3 - 2z + 10$ has exactly one root in each open quadrant.

5.2.13 13

Prove that for $a > 0$, $z \tan z - a$ has only real roots.

5.2.14 14

Let f be nonzero, analytic on a bounded region Ω and continuous on its closure $\overline{\Omega}$.
Show that if $|f(z)| \equiv M$ is constant for $z \in \partial\Omega$, then $f(z) \equiv Me^{i\theta}$ for some real constant θ.

6 Extra Questions from Jingzhi Tie

6.1 Fall 2009

6.1.1 ?

(1) Assume $f(z) = \sum_{n=0}^{\infty} c_n z^n$ converges in $|z| < R$. Show that for $r < R$,

$$\frac{1}{2\pi}\int_0^{2\pi} |f(re^{i\theta})|^2 d\theta = \sum_{n=0}^{\infty} |c_n|^2 r^{2n} .$$

(2) Deduce Liouville's theorem from (1).

6.1.2 ?

Let f be a continuous function in the region

$$D = \{z \mid |z| > R, 0 \le \arg z \le \theta\} \quad \text{where} \quad 1 \le \theta \le 2\pi.$$

If there exists k such that $\lim_{z \longrightarrow \infty} zf(z) = k$ for z in the region D. Show that

$$\lim_{R' \longrightarrow \infty} \int_L f(z)dz = i\theta k,$$

where L is the part of the circle $|z| = R'$ which lies in the region D.

6.1.3 ?

Suppose that f is an analytic function in the region D which contains the point a. Let

$$F(z) = z - a - qf(z), \quad \text{where } q \text{ is a complex parameter.}$$

(1) Let $K \subset D$ be a circle with the center at point a and also we assume that $f(z) \neq 0$ for $z \in K$. Prove that the function F has one and only one zero $z = w$ on the closed disc $\overline{K}$ whose boundary is the circle K if $|q| < \min_{z \in K} \frac{|z-a|}{|f(z)|}$.

(2) Let $G(z)$ be an analytic function on the disk $\overline{K}$. Apply the residue theorem to prove that $\frac{G(w)}{F'(w)} = \frac{1}{2\pi i}\int_K \frac{G(z)}{F(z)}dz$, where w is the zero from (1).

(3) If $z \in K$, prove that the function $\frac{1}{F(z)}$ can be represented as a convergent series with respect to q: $\frac{1}{F(z)} = \sum_{n=0}^{\infty} \frac{(qf(z))^n}{(z-a)^{n+1}}$.

6.1.4 ?

Evaluate

$$\int_0^{\infty} \frac{x \sin x}{x^2 + a^2}\, dx.$$

6.1.5 ?

Let $f = u + iv$ be differentiable (i.e. $f'(z)$ exists) with continuous partial derivatives at a point $z = re^{i\theta}$, $r \neq 0$. Show that

$$\frac{\partial u}{\partial r} = \frac{1}{r}\frac{\partial v}{\partial \theta}, \quad \frac{\partial v}{\partial r} = -\frac{1}{r}\frac{\partial u}{\partial \theta}.$$

6.1.6 ?

Show that $\displaystyle\int_0^\infty \frac{x^{a-1}}{1+x^n}dx = \frac{\pi}{n\sin\frac{a\pi}{n}}$ using complex analysis, $0 < a < n$. Here n is a positive integer.

6.1.7 ?

For $s > 0$, the **gamma function** is defined by $\Gamma(s) = \displaystyle\int_0^\infty e^{-t}t^{s-1}dt$.

1. Show that the gamma function is analytic in the half-plane $\Re(s) > 0$, and is still given there by the integral formula above.
2. Apply the formula in the previous question to show that

$$\Gamma(s)\Gamma(1-s) = \frac{\pi}{\sin \pi s}.$$

Hint: You may need $\Gamma(1-s) = t\displaystyle\int_0^\infty e^{-vt}(vt)^{-s}dv$ for $t > 0$.

6.1.8 ?

Apply Rouché's Theorem to prove the Fundamental Theorem of Algebra: If

$$P_n(z) = a_0 + a_1 z + \cdots + a_{n-1}z^{n-1} + a_n z^n \quad (a_n \neq 0)$$

is a polynomial of degree n, then it has n zeros in $\mathbb{C}$.

6.1.9 ?

Suppose f is entire and there exist $A, R > 0$ and natural number N such that

$$|f(z)| \geq A|z|^N \text{ for } |z| \geq R.$$

Show that (i) f is a polynomial and (ii) the degree of f is at least N.

6.1.10 ?

Let $f : \mathbb{C} \to \mathbb{C}$ be an injective analytic (also called *univalent*) function. Show that there exist complex numbers $a \neq 0$ and b such that $f(z) = az + b$.

6.1.11 ?

Let g be analytic for $|z| \leq 1$ and $|g(z)| < 1$ for $|z| = 1$.

1. Show that g has a unique fixed point in $|z| < 1$.
2. What happens if we replace $|g(z)| < 1$ with $|g(z)| \leq 1$ for $|z| = 1$? Give an example if (a) is not true or give an proof if (a) is still true.
3. What happens if we simply assume that f is analytic for $|z| < 1$ and $|f(z)| < 1$ for $|z| < 1$? Suppose that $f(z) \not\equiv z$. Can f have more than one fixed point in $|z| < 1$?

> Hint: The map $\psi_\alpha(z) = \dfrac{\alpha - z}{1 - \bar{\alpha} z}$ may be useful.

6.1.12 ?

Find a conformal map from $D = \{z : \ |z| < 1, \ |z - 1/2| > 1/2\}$ to the unit disk $\Delta = \{z : \ |z| < 1\}$.

6.1.13 ?

Let $f(z)$ be entire and assume values of $f(z)$ lie outside a *bounded* open set Ω. Show without using Picard's theorems that $f(z)$ is a constant.

6.1.14 ?

(1) Assume $f(z) = \displaystyle\sum_{n=0}^{\infty} c_n z^n$ converges in $|z| < R$. Show that for $r < R$,

$$\frac{1}{2\pi} \int_0^{2\pi} |f(re^{i\theta})|^2 d\theta = \sum_{n=0}^{\infty} |c_n|^2 r^{2n} \, .$$

(2) Deduce Liouville's theorem from (1).

6.1.15 ?

Let $f(z)$ be entire and assume that $f(z) \leq M|z|^2$ outside some disk for some constant M. Show that $f(z)$ is a polynomial in z of degree ≤ 2.

6.1.16 ?

Let $a_n(z)$ be an analytic sequence in a domain D such that $\displaystyle\sum_{n=0}^{\infty} |a_n(z)|$ converges uniformly on bounded and closed sub-regions of D. Show that $\displaystyle\sum_{n=0}^{\infty} |a_n'(z)|$ converges uniformly on bounded and closed sub-regions of D.

6.1.17 ?

Let $f(z)$ be analytic in an open set Ω except possibly at a point z_0 inside Ω. Show that if $f(z)$ is bounded in near z_0, then $\int_\Delta f(z)dz = 0$ for all triangles Δ in Ω.

6.1.18 ?

Assume f is continuous in the region: $0 < |z-a| \le R,\ 0 \le \arg(z-a) \le \beta_0$ $(0 < \beta_0 \le 2\pi)$ and the limit $\lim_{z\to a}(z-a)f(z) = A$ exists. Show that

$$\lim_{r\to 0}\int_{\gamma_r} f(z)dz = iA\beta_0\ ,$$

where $\gamma_r := \{z \mid z = a + re^{it},\ 0 \le t \le \beta_0\}$.

6.1.19 ?

Show that $f(z) = z^2$ is uniformly continuous in any open disk $|z| < R$, where $R > 0$ is fixed, but it is not uniformly continuous on $\mathbb{C}$.

6.1.20 ?

(1) Show that the function $u = u(x,y)$ given by

$$u(x,y) = \frac{e^{ny} - e^{-ny}}{2n^2}\sin nx \quad \text{for } n \in \mathbf{N}$$

is the solution on $D = \{(x,y)\ |x^2 + y^2 < 1\}$ of the Cauchy problem for the Laplace equation

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0, \quad u(x,0) = 0, \quad \frac{\partial u}{\partial y}(x,0) = \frac{\sin nx}{n}.$$

(2) Show that there exist points $(x,y) \in D$ such that $\limsup_{n\longrightarrow\infty}|u(x,y)| = \infty$.

6.2 Fall 2011

6.2.1 ?

(1) Assume $f(z) = \sum_{n=0}^{\infty} c_n z^n$ converges in $|z| < R$. Show that for $r < R$,

$$\frac{1}{2\pi}\int_0^{2\pi} |f(re^{i\theta})|^2 d\theta = \sum_{n=0}^{\infty} |c_n|^2 r^{2n}\ .$$

(2) Deduce Liouville's theorem from (1).

6.2.2 ?

Let f be a continuous function in the region

$$D = \{z \,||z| > R, 0 \le \arg Z \le \theta\} \quad \text{where} \quad 0 \le \theta \le 2\pi.$$

If there exists k such that $\lim\limits_{z\longrightarrow\infty} zf(z) = k$ for z in the region D. Show that

$$\lim_{R'\longrightarrow\infty} \int_L f(z)dz = i\theta k,$$

where L is the part of the circle $|z| = R'$ which lies in the region D.

6.2.3 ?

Suppose that f is an analytic function in the region D which contains the point a. Let

$$F(z) = z - a - qf(z), \quad \text{where} \quad q \text{ is a complex parameter.}$$

(1) Let $K \subset D$ be a circle with the center at point a and also we assume that $f(z) \neq 0$ for $z \in K$. Prove that the function F has one and only one zero $z = w$ on the closed disc $\overline{K}$ whose boundary is the circle K if $|q| < \min\limits_{z\in K} \dfrac{|z-a|}{|f(z)|}$.

(2) Let $G(z)$ be an analytic function on the disk $\overline{K}$. Apply the residue theorem to prove that $\dfrac{G(w)}{F'(w)} = \dfrac{1}{2\pi i}\displaystyle\int_K \frac{G(z)}{F(z)}dz$, where w is the zero from (1).

(3) If $z \in K$, prove that the function $\dfrac{1}{F(z)}$ can be represented as a convergent series with respect to q: $\dfrac{1}{F(z)} = \displaystyle\sum_{n=0}^{\infty} \frac{(qf(z))^n}{(z-a)^{n+1}}$.

6.2.4 ?

Evaluate $\displaystyle\int_0^\infty \frac{x \sin x}{x^2 + a^2}\, dx$.

6.2.5 ?

Let $f = u + iv$ be differentiable (i.e. $f'(z)$ exists) with continuous partial derivatives at a point $z = re^{i\theta}$, $r \neq 0$. Show that

$$\frac{\partial u}{\partial r} = \frac{1}{r}\frac{\partial v}{\partial \theta}, \quad \frac{\partial v}{\partial r} = -\frac{1}{r}\frac{\partial u}{\partial \theta}.$$

6.2.6 ?

Show that $\displaystyle\int_0^\infty \frac{x^{a-1}}{1+x^n}dx = \frac{\pi}{n \sin \frac{a\pi}{n}}$ using complex analysis, $0 < a < n$. Here n is a positive integer.

6.2.7 ?

For $s > 0$, the **gamma function** is defined by $\Gamma(s) = \int_0^\infty e^{-t} t^{s-1} dt$.

1. Show that the gamma function is analytic in the half-plane $\Re(s) > 0$, and is still given there by the integral formula above.
2. Apply the formula in the previous question to show that
$$\Gamma(s)\Gamma(1-s) = \frac{\pi}{\sin \pi s}.$$

Hint: You may need $\Gamma(1-s) = t \int_0^\infty e^{-vt}(vt)^{-s} dv$ for $t > 0$.

6.2.8 ?

Apply Rouché's Theorem to prove the Fundamental Theorem of Algebra: If

$$P_n(z) = a_0 + a_1 z + \cdots + a_{n-1} z^{n-1} + a_n z^n \quad (a_n \neq 0)$$

is a polynomial of degree n, then it has n zeros in $\mathbb{C}$.

6.2.9 ?

Suppose f is entire and there exist $A, R > 0$ and natural number N such that

$$|f(z)| \geq A|z|^N \text{ for } |z| \geq R.$$

Show that (i) f is a polynomial and (ii) the degree of f is at least N.

6.2.10 ?

Let $f : \mathbb{C} \to \mathbb{C}$ be an injective analytic (also called univalent) function. Show that there exist complex numbers $a \neq 0$ and b such that $f(z) = az + b$.

6.2.11 ?

Let g be analytic for $|z| \leq 1$ and $|g(z)| < 1$ for $|z| = 1$.

- Show that g has a unique fixed point in $|z| < 1$.
- What happens if we replace $|g(z)| < 1$ with $|g(z)| \leq 1$ for $|z| = 1$? Give an example if (a) is not true or give an proof if (a) is still true.
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Hint: The map $\psi_\alpha(z) = \dfrac{\alpha - z}{1 - \bar{\alpha} z}$ may be useful.

6.2.12 ?

Find a conformal map from $D = \{z : \ |z| < 1, \ |z - 1/2| > 1/2\}$ to the unit disk $\Delta = \{z : \ |z| < 1\}$.

6.2.13 ?

Let $f(z)$ be entire and assume values of $f(z)$ lie outside a *bounded* open set Ω. Show without using Picard's theorems that $f(z)$ is a constant.

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(1) Assume $f(z) = \sum_{n=0}^{\infty} c_n z^n$ converges in $|z| < R$. Show that for $r < R$,

$$\frac{1}{2\pi} \int_0^{2\pi} |f(re^{i\theta})|^2 d\theta = \sum_{n=0}^{\infty} |c_n|^2 r^{2n} \ .$$

(2) Deduce Liouville's theorem from (1).

6.2.16 ?

Let $f(z)$ be entire and assume that $f(z) \leq M|z|^2$ outside some disk for some constant M. Show that $f(z)$ is a polynomial in z of degree ≤ 2.

6.2.17 ?

Let $a_n(z)$ be an analytic sequence in a domain D such that $\sum_{n=0}^{\infty} |a_n(z)|$ converges uniformly on bounded and closed sub-regions of D. Show that $\sum_{n=0}^{\infty} |a_n'(z)|$ converges uniformly on bounded and closed sub-regions of D.

6.2.18 ?

Let $f(z)$ be analytic in an open set Ω except possibly at a point z_0 inside Ω. Show that if $f(z)$ is bounded in near z_0, then $\int_\Delta f(z)dz = 0$ for all triangles Δ in Ω.

6.2.19 ?

Assume f is continuous in the region: $0 < |z-a| \le R,\ 0 \le \arg(z-a) \le \beta_0$ $(0 < \beta_0 \le 2\pi)$ and the limit $\lim\limits_{z \to a}(z-a)f(z) = A$ exists. Show that

$$\lim_{r \to 0} \int_{\gamma_r} f(z)dz = iA\beta_0 \ ,$$

where $\gamma_r := \{z \mid z = a + re^{it},\ 0 \le t \le \beta_0\}$.

6.2.20 ?

Show that $f(z) = z^2$ is uniformly continuous in any open disk $|z| < R$, where $R > 0$ is fixed, but it is not uniformly continuous on $\mathbb{C}$.

(1) Show that the function $u = u(x,y)$ given by

$$u(x,y) = \frac{e^{ny} - e^{-ny}}{2n^2} \sin nx \quad \text{for } n \in \mathbf{N}$$

is the solution on $D = \{(x,y) \mid x^2 + y^2 < 1\}$ of the Cauchy problem for the Laplace equation

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0, \quad u(x,0) = 0, \quad \frac{\partial u}{\partial y}(x,0) = \frac{\sin nx}{n}.$$

(2) Show that there exist points $(x,y) \in D$ such that $\limsup\limits_{n \longrightarrow \infty} |u(x,y)| = \infty$.

6.3 Spring 2014

6.3.1 ?

The question provides some insight into Cauchy's theorem. Solve the problem without using the Cauchy theorem.

1. Evaluate the integral $\int_\gamma z^n dz$ for all integers n. Here γ is any circle centered at the origin with the positive (counterclockwise) orientation.
2. Same question as (a), but with γ any circle not containing the origin.
3. Show that if $|a| < r < |b|$, then $\int_\gamma \frac{dz}{(z-a)(z-b)} dz = \frac{2\pi i}{a-b}$. Here γ denotes the circle centered at the origin, of radius r, with the positive orientation.

6.3.2 ?

(1) Assume the infinite series $\sum\limits_{n=0}^{\infty} c_n z^n$ converges in $|z| < R$ and let $f(z)$ be the limit. Show that for $r < R$,

$$\frac{1}{2\pi} \int_0^{2\pi} |f(re^{i\theta})|^2 d\theta = \sum_{n=0}^{\infty} |c_n|^2 r^{2n} \ .$$

(2) Deduce Liouville's theorem from (1). Liouville's theorem: If $f(z)$ is entire and bounded, then f is constant.

6.3.3 ?

Let f be a continuous function in the region

$$D = \{z \,||z| > R, 0 \leq \arg Z \leq \theta\} \quad \text{where} \quad 0 \leq \theta \leq 2\pi.$$

If there exists k such that $\lim_{z \longrightarrow \infty} zf(z) = k$ for z in the region D. Show that

$$\lim_{R' \longrightarrow \infty} \int_L f(z)dz = i\theta k,$$

where L is the part of the circle $|z| = R'$ which lies in the region D.

6.3.4 ?

Evaluate $\displaystyle\int_0^\infty \frac{x \sin x}{x^2 + a^2}\, dx$.

6.3.5 ?

Let $f = u + iv$ be differentiable (i.e. $f'(z)$ exists) with continuous partial derivatives at a point $z = re^{i\theta}$, $r \neq 0$. Show that

$$\frac{\partial u}{\partial r} = \frac{1}{r}\frac{\partial v}{\partial \theta}, \quad \frac{\partial v}{\partial r} = -\frac{1}{r}\frac{\partial u}{\partial \theta}.$$

6.3.6 ?

Show that $\displaystyle\int_0^\infty \frac{x^{a-1}}{1+x^n} dx = \frac{\pi}{n \sin \frac{a\pi}{n}}$ using complex analysis, $0 < a < n$. Here n is a positive integer.

6.3.7 ?

For $s > 0$, the **gamma function** is defined by $\Gamma(s) = \displaystyle\int_0^\infty e^{-t} t^{s-1} dt$.

- Show that the gamma function is analytic in the half-plane $\Re(s) > 0$, and is still given there by the integral formula above.
- Apply the formula in the previous question to show that

$$\Gamma(s)\Gamma(1-s) = \frac{\pi}{\sin \pi s}.$$

Hint: You may need $\Gamma(1-s) = t \displaystyle\int_0^\infty e^{-vt}(vt)^{-s} dv$ for $t > 0$.

6.3.8 ?

Apply Rouché's Theorem to prove the Fundamental Theorem of Algebra: If

$$P_n(z) = a_0 + a_1 z + \cdots + a_{n-1} z^{n-1} + a_n z^n \quad (a_n \neq 0)$$

is a polynomial of degree n, then it has n zeros in $\mathbf{C}$.

6.3.9 ?

Suppose f is entire and there exist $A, R > 0$ and natural number N such that

$$|f(z)| \geq A|z|^N \text{ for } |z| \geq R.$$

Show that (i) f is a polynomial and (ii) the degree of f is at least N.

6.3.10 ?

Let $f : \mathbb{C} \to \mathbb{C}$ be an injective analytic (also called univalent) function. Show that there exist complex numbers $a \neq 0$ and b such that $f(z) = az + b$.

6.3.11 ?

Let g be analytic for $|z| \leq 1$ and $|g(z)| < 1$ for $|z| = 1$.

- Show that g has a unique fixed point in $|z| < 1$.
- What happens if we replace $|g(z)| < 1$ with $|g(z)| \leq 1$ for $|z| = 1$? Give an example if (a) is not true or give an proof if (a) is still true.
- What happens if we simply assume that f is analytic for $|z| < 1$ and $|f(z)| < 1$ for $|z| < 1$? Suppose that $f(z) \not\equiv z$. Can f have more than one fixed point in $|z| < 1$?

> Hint: The map $\psi_\alpha(z) = \dfrac{\alpha - z}{1 - \bar{\alpha} z}$ may be useful.

6.3.12 ?

Find a conformal map from $D = \{z : \ |z| < 1,\ |z - 1/2| > 1/2\}$ to the unit disk $\Delta = \{z : \ |z| < 1\}$.

6.4 Fall 2015

6.4.1 ?

Let $a_n \neq 0$ and assume that $\lim_{n\to\infty} \dfrac{|a_{n+1}|}{|a_n|} = L$. Show that $\lim_{n\to\infty} \sqrt[n]{|a_n|} = L$. In particular, this shows that when applicable, the ratio test can be used to calculate the radius of convergence of a power series.

6.4.2 ?

(a) Let z, w be complex numbers, such that $\bar{z}w \neq 1$. Prove that

$$\left|\frac{w - z}{1 - \overline{w}z}\right| < 1 \quad \text{if } |z| < 1 \text{ and } |w| < 1,$$

and also that

$$\left|\frac{w - z}{1 - \overline{w}z}\right| = 1 \quad \text{if } |z| = 1 \text{ or } |w| = 1.$$

(b) Prove that for fixed w in the unit disk $\mathbb{D}$, the mapping

$$F : z \mapsto \frac{w - z}{1 - \overline{w}z}$$

satisfies the following conditions:

(c) F maps $\mathbb{D}$ to itself and is holomorphic.

(ii) F interchanges 0 and w, namely, $F(0) = w$ and $F(w) = 0$.

(iii) $|F(z)| = 1$ if $|z| = 1$.

(iv) $F : \mathbb{D} \mapsto \mathbb{D}$ is bijective.

Hint: Calculate $F \circ F$.

6.4.3 ?

Use n-th roots of unity (i.e. solutions of $z^n - 1 = 0$) to show that

$$2^{n-1} \sin \frac{\pi}{n} \sin \frac{2\pi}{n} \cdots \sin \frac{(n-1)\pi}{n} = n \ .$$

Hint: $1 - \cos 2\theta = 2\sin^2\theta,\ \sin 2\theta = 2\sin\theta\cos\theta.$

(a) Show that in polar coordinates, the Cauchy-Riemann equations take the form

$$\frac{\partial u}{\partial r} = \frac{1}{r}\frac{\partial v}{\partial \theta} \quad \text{and} \quad \frac{\partial v}{\partial r} = -\frac{1}{r}\frac{\partial u}{\partial \theta}$$

(b) Use these equations to show that the logarithm function defined by

$$\log z = \log r + i\theta \ \text{ where } z = re^{i\theta} \text{ with } -\pi < \theta < \pi$$

is a holomorphic function in the region $r > 0,\ -\pi < \theta < \pi$. Also show that $\log z$ defined above is not continuous in $r > 0$.

6.4.4 ?

Assume f is continuous in the region: $x \geq x_0,\ 0 \leq y \leq b$ and the limit

$$\lim_{x \to +\infty} f(x + iy) = A$$

exists uniformly with respect to y (independent of y). Show that

$$\lim_{x \to +\infty} \int_{\gamma_x} f(z)dz = iAb\ ,$$

where $\gamma_x := \{z \mid z = x + it,\ 0 \leq t \leq b\}$.

6.4.5 ?

(Cauchy's formula for "exterior" region) Let γ be piecewise smooth simple closed curve with interior Ω_1 and exterior Ω_2. Assume $f'(z)$ exists in an open set containing γ and Ω_2 and $\lim_{z\to\infty} f(z) = A$. Show that

$$\frac{1}{2\pi i}\int_\gamma \frac{f(\xi)}{\xi - z}\,d\xi = \begin{cases} A, & \text{if } z \in \Omega_1, \\ -f(z) + A, & \text{if } z \in \Omega_2 \end{cases}$$

6.4.6 ?

Let $f(z)$ be bounded and analytic in $\mathbb{C}$. Let $a \neq b$ be any fixed complex numbers. Show that the following limit exists

$$\lim_{R\to\infty}\int_{|z|=R}\frac{f(z)}{(z-a)(z-b)}dz.$$

Use this to show that $f(z)$ must be a constant (Liouville's theorem).

6.4.7 ?

Prove by *justifying all steps* that for all $\xi \in \mathbb{C}$ we have $e^{-\pi\xi^2} = \int_{-\infty}^{\infty} e^{-\pi x^2} e^{2\pi i x\xi} dx$.

> Hint: You may use that fact in Example 1 on p. 42 of the textbook without proof, i.e., you may assume the above is true for real values of ξ.

6.4.8 ?

Suppose that f is holomorphic in an open set containing the closed unit disc, except for a pole at z_0 on the unit circle. Let denote the the power series in the open disc. Show that (1) $c_n \neq 0$ for all large enough n's, and (2) $\lim_{n\to\infty}\frac{c_n}{c_{n+1}} = z_0$.

6.4.9 ?

Let $f(z)$ be a non-constant analytic function in $|z| > 0$ such that $f(z_n) = 0$ for infinite many points z_n with $\lim_{n\to\infty} z_n = 0$. Show that $z = 0$ is an essential singularity for $f(z)$. (An example of such a function is $f(z) = \sin(1/z)$.)

6.4.10 ?

Let f be entire and suppose that $\lim_{z\to\infty} f(z) = \infty$. Show that f is a polynomial.

6.4.11 ?

Expand the following functions into Laurent series in the indicated regions:

(a) $f(z) = \dfrac{z^2-1}{(z+2)(z+3)}$, $2 < |z| < 3$, $3 < |z| < +\infty$.

(b) $f(z) = \sin \dfrac{z}{1-z}, \quad 0 < |z-1| < +\infty$

6.4.12 ?

Assume $f(z)$ is analytic in region D and Γ is a rectifiable curve in D with interior in D. Prove that if $f(z)$ is real for all $z \in \Gamma$, then $f(z)$ is a constant.

6.4.13 ?

Find the number of roots of $z^4 - 6z + 3 = 0$ in $|z| < 1$ and $1 < |z| < 2$ respectively.

6.4.14 ?

Prove that $z^4 + 2z^3 - 2z + 10 = 0$ has exactly one root in each open quadrant.

6.4.15 ?

(1) Let $f(z) \in H(\mathbb{D})$, $\mathrm{Re}(f(z)) > 0$, $f(0) = a > 0$. Show that

$$|\frac{f(z)-a}{f(z)+a}| \leq |z|, \quad |f'(0)| \leq 2a.$$

(2) Show that the above is still true if $\mathrm{Re}(f(z)) > 0$ is replaced with $\mathrm{Re}(f(z)) \geq 0$.

6.4.16 ?

Assume $f(z)$ is analytic in $\mathbb{D}$ and $f(0) = 0$ and is not a rotation (i.e. $f(z) \neq e^{i\theta} z$). Show that $\sum_{n=1}^{\infty} f^n(z)$ converges uniformly to an analytic function on compact subsets of $\mathbb{D}$, where $f^{n+1}(z) = f(f^n(z))$.

6.4.17 ?

Let $f(z) = \sum_{n=0}^{\infty} c_n z^n$ be analytic and one-to-one in $|z| < 1$. For $0 < r < 1$, let D_r be the disk $|z| < r$. Show that the area of $f(D_r)$ is finite and is given by

$$S = \pi \sum_{n=1}^{\infty} n|c_n|^2 r^{2n}.$$

(Note that in general the area of $f(D_1)$ is infinite.)

6.4.18 ?

Let $f(z) = \sum_{n=-\infty}^{\infty} c_n z^n$ be analytic and one-to-one in $r_0 < |z| < R_0$. For $r_0 < r < R < R_0$, let $D(r, R)$ be the annulus $r < |z| < R$. Show that the area of $f(D(r, R))$ is finite and is given by

$$S = \pi \sum_{n=-\infty}^{\infty} n|c_n|^2 (R^{2n} - r^{2n}).$$

6.5 Spring 2015

6.5.1 ?

Let $a_n(z)$ be an analytic sequence in a domain D such that $\sum_{n=0}^{\infty} |a_n(z)|$ converges uniformly on bounded and closed sub-regions of D. Show that $\sum_{n=0}^{\infty} |a_n'(z)|$ converges uniformly on bounded and closed sub-regions of D.

6.5.2 ?

Let f_n, f be analytic functions on the unit disk $\mathbb{D}$. Show that the following are equivalent.

(i) $f_n(z)$ converges to $f(z)$ uniformly on compact subsets in $\mathbb{D}$.

(ii) $\int_{|z|=r} |f_n(z) - f(z)|\,|dz|$ converges to 0 if $0 < r < 1$.

6.5.3 ?

Let f and g be non-zero analytic functions on a region Ω. Assume $|f(z)| = |g(z)|$ for all z in Ω. Show that $f(z) = e^{i\theta} g(z)$ in Ω for some $0 \le \theta < 2\pi$.

6.5.4 ?

Suppose f is analytic in an open set containing the unit disc $\mathbb{D}$ and $|f(z)| = 1$ when $|z|$=1. Show that either $f(z) = e^{i\theta}$ for some $\theta \in \mathbb{R}$ or there are finite number of $z_k \in \mathbb{D}$, $k \le n$ and $\theta \in \mathbb{R}$ such that $f(z) = e^{i\theta} \prod_{k=1}^{n} \frac{z - z_k}{1 - \bar{z}_k z}$.

Also cf. Stein et al, 1.4.7, 3.8.17

6.5.5 ?

(1) Let $p(z)$ be a polynomial, $R > 0$ any positive number, and $m \ge 1$ an integer. Let $M_R = \sup\{|z^m p(z) - 1| : |z| = R\}$. Show that $M_R > 1$.

(2) Let $m \ge 1$ be an integer and $K = \{z \in \mathbb{C} : r \le |z| \le R\}$ where $r < R$. Show (i) using (1) as well as, (ii) without using (1) that there exists a positive number $\varepsilon_0 > 0$ such that for each polynomial $p(z)$,

$$\sup\{|p(z) - z^{-m}| : z \in K\} \ge \varepsilon_0 .$$

6.5.6 ?

Let $f(z) = \frac{1}{z} + \frac{1}{z^2 - 1}$. Find all the Laurent series of f and describe the largest annuli in which these series are valid.

6.5.7 ?

Suppose f is entire and there exist $A, R > 0$ and natural number N such that $|f(z)| \leq A|z|^N$ for $|z| \geq R$. Show that (i) f is a polynomial and (ii) the degree of f is at most N.

6.5.8 ?

Suppose f is entire and there exist $A, R > 0$ and natural number N such that $|f(z)| \geq A|z|^N$ for $|z| \geq R$. Show that (i) f is a polynomial and (ii) the degree of f is at least N.

6.5.9 ?

(1) Explicitly write down an example of a non-zero analytic function in $|z| < 1$ which has infinitely zeros in $|z| < 1$.

(2) Why does not the phenomenon in (1) contradict the uniqueness theorem?

6.5.10 ?

(1) Assume u is harmonic on open set O and z_n is a sequence in O such that $u(z_n) = 0$ and $\lim z_n \in O$. Prove or disprove that u is identically zero. What if O is a region?

(2) Assume u is harmonic on open set O and $u(z) = 0$ on a disc in O. Prove or disprove that u is identically zero. What if O is a region?

(3) Formulate and prove a Schwarz reflection principle for harmonic functions

> cf. Theorem 5.6 on p.60 of Stein et al.

> Hint: Verify the mean value property for your new function obtained by Schwarz reflection principle.

6.5.11 ?

Let f be holomorphic in a neighborhood of $D_r(z_0)$. Show that for any $s < r$, there exists a constant $c > 0$ such that

$$||f||_{(\infty,s)} \leq c||f||_{(1,r)},$$

where $|f||_{(\infty,s)} = \sup_{z \in D_s(z_0)} |f(z)|$ and $||f||_{(1,r)} = \int_{D_r(z_0)} |f(z)| dxdy$.

> Note: Exercise 3.8.20 on p.107 in Stein et al is a straightforward consequence of this stronger result using the integral form of the Cauchy-Schwarz inequality in real analysis.

6.5.12 ?

(1) Let f be analytic in $\Omega : 0 < |z - a| < r$ except at a sequence of poles $a_n \in \Omega$ with $\lim_{n\to\infty} a_n = a$. Show that for any $w \in \mathbb{C}$, there exists a sequence $z_n \in \Omega$ such that $\lim_{n\to\infty} f(z_n) = w$.

(2) Explain the similarity and difference between the above assertion and the Weierstrass-Casorati theorem.

6.5.13 ?

Compute the following integrals.

(i) $\displaystyle\int_0^\infty \frac{1}{(1+x^n)^2}\,dx,\ n\geq 1$ (ii) $\displaystyle\int_0^\infty \frac{\cos x}{(x^2+a^2)^2}\,dx,\ a\in\mathbb{R}$ (iii) $\displaystyle\int_0^\pi \frac{1}{a+\sin\theta}\,d\theta,\ a>1$

(iv) $\displaystyle\int_0^{\frac{\pi}{2}} \frac{d\theta}{a+\sin^2\theta},\ a>0.$ (v) $\displaystyle\int_{|z|=2} \frac{1}{(z^5-1)(z-3)}\,dz$ (v) $\displaystyle\int_{-\infty}^\infty \frac{\sin\pi a}{\cosh\pi x+\cos\pi a}e^{-ix\xi}\,dx,\ 0<a<1,$ $\xi\in\mathbb{R}$ (vi) $\displaystyle\int_{|z|=1}\cot^2 z\,dz.$

6.5.14 ?

Compute the following integrals.

(i) $\displaystyle\int_0^\infty \frac{\sin x}{x}\,dx$ (ii) $\displaystyle\int_0^\infty (\frac{\sin x}{x})^2\,dx$ (iii) $\displaystyle\int_0^\infty \frac{x^{a-1}}{(1+x)^2}\,dx,\ 0<a<2$

(i) $\displaystyle\int_0^\infty \frac{\cos ax-\cos bx}{x^2}dx,\ a,b>0$ (ii) $\displaystyle\int_0^\infty \frac{x^{a-1}}{1+x^n}\,dx,\ 0<a<n$

(iii) $\displaystyle\int_0^\infty \frac{\log x}{1+x^n}\,dx,\ n\geq 2$ (iv) $\displaystyle\int_0^\infty \frac{\log x}{(1+x^2)^2}dx$ (v) $\displaystyle\int_0^\pi \log|1-a\sin\theta|d\theta,\ a\in\mathbb{C}$

6.5.15 ?

Let $0<r<1$. Show that polynomials $P_n(z)=1+2z+3z^2+\cdots+nz^{n-1}$ have no zeros in $|z|<r$ for all sufficiently large n's.

6.5.16 ?

Let f be an analytic function on a region Ω. Show that f is a constant if there is a simple closed curve γ in Ω such that its image $f(\gamma)$ is contained in the real axis.

6.5.17 ?

(1) Show that $\dfrac{\pi^2}{\sin^2\pi z}$ and $g(z)=\displaystyle\sum_{n=-\infty}^{\infty}\frac{1}{(z-n)^2}$ have the same principal part at each integer point.

(2) Show that $h(z)=\dfrac{\pi^2}{\sin^2\pi z}-g(z)$ is bounded on $\mathbb{C}$ and conclude that $\dfrac{\pi^2}{\sin^2\pi z}=\displaystyle\sum_{n=-\infty}^{\infty}\frac{1}{(z-n)^2}$.

6.5.18 ?

Let $f(z)$ be an analytic function on $\mathbb{C}\backslash\{z_0\}$, where z_0 is a fixed point. Assume that $f(z)$ is bijective from $\mathbb{C}\backslash\{z_0\}$ onto its image, and that $f(z)$ is bounded outside $D_r(z_0)$, where r is some fixed positive number. Show that there exist $a,b,c,d\in\mathbb{C}$ with $ad-bc\neq 0$, $c\neq 0$ such that $f(z)=\dfrac{az+b}{cz+d}$.

6.5.19 ?

Assume $f(z)$ is analytic in $\mathbb{D} : |z| < 1$ and $f(0) = 0$ and is not a rotation (i.e. $f(z) \neq e^{i\theta}z$). Show that $\sum_{n=1}^{\infty} f^n(z)$ converges uniformly to an analytic function on compact subsets of $\mathbb{D}$, where $f^{n+1}(z) = f(f^n(z))$.

6.5.20 ?

Let f be a non-constant analytic function on $\mathbb{D}$ with $f(\mathbb{D}) \subseteq \mathbb{D}$. Use $\psi_a(f(z))$ (where $a = f(0)$, $\psi_a(z) = \frac{a-z}{1-\bar{a}z}$) to prove that $\frac{|f(0)| - |z|}{1 + |f(0)||z|} \leq |f(z)| \leq \frac{|f(0)| + |z|}{1 - |f(0)||z|}$.

6.5.21 ?

Find a conformal map

1. from $\{z : |z - 1/2| > 1/2, \mathrm{Re}(z) > 0\}$ to $\mathbb{H}$
2. from $\{z : |z - 1/2| > 1/2, |z| < 1\}$ to $\mathbb{D}$
3. from the intersection of the disk $|z + i| < \sqrt{2}$ with $\mathbb{H}$ to $\mathbb{D}$.
4. from $\mathbb{D} \backslash [a, 1)$ to $\mathbb{D} \backslash [0, 1)$ $(0 < a < 1)$. [Short solution possible using Blaschke factor]
5. from $\{z : |z| < 1, \mathrm{Re}(z) > 0\} \backslash (0, 1/2]$ to $\mathbb{H}$.

6.5.22 ?

Let C and C' be two circles and let $z_1 \in C$, $z_2 \notin C$, $z_1' \in C'$, $z_2' \notin C'$. Show that there is a unique fractional linear transformation f with $f(C) = C'$ and $f(z_1) = z_1'$, $f(z_2) = z_2'$.

6.5.23 ?

Assume $f_n \in H(\Omega)$ is a sequence of holomorphic functions on the region Ω that are uniformly bounded on compact subsets and $f \in H(\Omega)$ is such that the set $\{z \in \Omega : \lim_{n\to\infty} f_n(z) = f(z)\}$ has a limit point in Ω. Show that f_n converges to f uniformly on compact subsets of Ω.

6.5.24 ?

Let $\psi_\alpha(z) = \frac{\alpha - z}{1 - \bar{\alpha}z}$ with $|\alpha| < 1$ and $\mathbb{D} = \{z : \ |z| < 1\}$. Prove that

- $\frac{1}{\pi} \iint_{\mathbb{D}} |\psi_\alpha'|^2 dxdy = 1.$
- $\frac{1}{\pi} \iint_{\mathbb{D}} |\psi_\alpha'| dxdy = \frac{1 - |\alpha|^2}{|\alpha|^2} \log \frac{1}{1 - |\alpha|^2}.$

6.5.25 ?

Prove that $f(z) = -\dfrac{1}{2}\left(z + \dfrac{1}{z}\right)$ is a conformal map from half disc $\{z = x + iy : \ |z| < 1, \ y > 0\}$ to upper half plane $\mathbb{H} = \{z = x + iy : \ y > 0\}$.

6.5.26 ?

Let Ω be a simply connected open set and let γ be a simple closed contour in Ω and enclosing a bounded region U anticlockwise. Let $f : \ \Omega \longrightarrow \mathbb{C}$ be a holomorphic function and $|f(z)| \leq M$ for all $z \in \gamma$. Prove that $|f(z)| \leq M$ for all $z \in U$.

6.5.27 ?

Compute the following integrals. (i) $\displaystyle\int_0^\infty \frac{x^{a-1}}{1+x^n}\,dx$, $0 < a < n$ (ii) $\displaystyle\int_0^\infty \frac{\log x}{(1+x^2)^2}\,dx$

6.5.28 ?

Let $0 < r < 1$. Show that polynomials $P_n(z) = 1 + 2z + 3z^2 + \cdots + nz^{n-1}$ have no zeros in $|z| < r$ for all sufficiently large n's.

6.5.29 ?

Let f be holomorphic in a neighborhood of $D_r(z_0)$. Show that for any $s < r$, there exists a constant $c > 0$ such that

$$\|f\|_{(\infty,s)} \leq c\|f\|_{(1,r)},$$

where $\|f\|_{(\infty,s)} = \sup_{z\in D_s(z_0)}|f(z)|$ and $\|f\|_{(1,r)} = \displaystyle\int_{D_r(z_0)} |f(z)|dxdy$.

6.5.30 ?

Let $\psi_\alpha(z) = \dfrac{\alpha - z}{1 - \bar{\alpha}z}$ with $|\alpha| < 1$ and $\mathbb{D} = \{z : \ |z| < 1\}$. Prove that

- $\displaystyle\frac{1}{\pi}\iint_{\mathbb{D}} |\psi'_\alpha|^2 dxdy = 1.$
- $\displaystyle\frac{1}{\pi}\iint_{\mathbb{D}} |\psi'_\alpha| dxdy = \frac{1-|\alpha|^2}{|\alpha|^2}\log\frac{1}{1-|\alpha|^2}.$

Prove that $f(z) = -\dfrac{1}{2}\left(z + \dfrac{1}{z}\right)$ is a conformal map from half disc $\{z = x + iy : \ |z| < 1, \ y > 0\}$ to upper half plane $\mathbb{H} = \{z = x + iy : \ y > 0\}$.

6.5.31 ?

Let Ω be a simply connected open set and let γ be a simple closed contour in Ω and enclosing a bounded region U anticlockwise. Let $f : \ \Omega \longrightarrow \mathbb{C}$ be a holomorphic function and $|f(z)| \leq M$ for all $z \in \gamma$. Prove that $|f(z)| \leq M$ for all $z \in U$.

6.5.32 ?

Compute the following integrals. (i) $\int_0^\infty \frac{x^{a-1}}{1+x^n}\,dx$, $0 < a < n$ (ii) $\int_0^\infty \frac{\log x}{(1+x^2)^2}\,dx$

6.5.33 ?

Let $0 < r < 1$. Show that polynomials $P_n(z) = 1 + 2z + 3z^2 + \cdots + nz^{n-1}$ have no zeros in $|z| < r$ for all sufficiently large n's.

6.5.34 ?

Let f be holomorphic in a neighborhood of $D_r(z_0)$. Show that for any $s < r$, there exists a constant $c > 0$ such that

$$\|f\|_{(\infty,s)} \le c\|f\|_{(1,r)},$$

where $\|f\|_{(\infty,s)} = \sup_{z\in D_s(z_0)}|f(z)|$ and $\|f\|_{(1,r)} = \int_{D_r(z_0)} |f(z)|dxdy$.

6.6 Fall 2016

6.6.1 ?

Let $u(x,y)$ be harmonic and have continuous partial derivatives of order three in an open disc of radius $R > 0$.

(a) Let two points $(a,b),(x,y)$ in this disk be given. Show that the following integral is independent of the path in this disk joining these points:

$$v(x,y) = \int_{a,b}^{x,y} (-\frac{\partial u}{\partial y}dx + \frac{\partial u}{\partial x}dy).$$

(b)

(i) Prove that $u(x,y) + iv(x,y)$ is an analytic function in this disc.

(ii) Prove that $v(x,y)$ is harmonic in this disc.

6.6.2 ?

(a) $f(z) = u(x,y) + iv(x,y)$ be analytic in a domain $D \subset \mathbb{C}$. Let $z_0 = (x_0, y_0)$ be a point in D which is in the intersection of the curves $u(x,y) = c_1$ and $v(x,y) = c_2$, where c_1 and c_2 are constants. Suppose that $f'(z_0) \neq 0$. Prove that the lines tangent to these curves at z_0 are perpendicular.

(b) Let $f(z) = z^2$ be defined in $\mathbb{C}$.

(c) Describe the level curves of $\mathrm{Re}(f)$ and of $\mathrm{Im}(f)$.

(ii) What are the angles of intersections between the level curves $\mathrm{Re}(f) = 0$ and $\mathrm{Im}(f)$? Is your answer in agreement with part a) of this question?

6.6.3 ?

(a) $f : D \to \mathbb{C}$ be a continuous function, where $D \subset \mathbb{C}$ is a domain.Let $\alpha : [a, b] \to D$ be a smooth curve. Give a precise definition of the *complex line integral*

$$\int_\alpha f.$$

(b) Assume that there exists a constant M such that $|f(\tau)| \le M$ for all $\tau \in \text{Image}(\alpha)$. Prove that

$$|\int_\alpha f| \le M \times \text{length}(\alpha).$$

(c) Let C_R be the circle $|z| = R$, described in the counterclockwise direction, where $R > 1$. Provide an upper bound for $|\int_{C_R} \frac{\log(z)}{z^2}|$, which depends only on R and other constants.

6.6.4 ?

(a) Let Let $f : \mathbb{C} \to \mathbb{C}$ be an entire function. Assume the existence of a non-negative integer m, and of positive constants L and R, such that for all z with $|z| > R$ the inequality

$$|f(z)| \le L|z|^m$$

holds. Prove that f is a polynomial of degree $\le m$.

(b) Let $f : \mathbb{C} \to \mathbb{C}$ be an entire function. Suppose that there exists a real number M such that for all $z \in \mathbb{C}$

$$\text{Re}(f) \le M.$$

Prove that f must be a constant.

6.6.5 ?

Prove that all the roots of the complex polynomial

$$z^7 - 5z^3 + 12 = 0$$

lie between the circles $|z| = 1$ and $|z| = 2$.

6.6.6 ?

(a) Let F be an analytic function inside and on a simple closed curve C, except for a pole of order $m \ge 1$ at $z = a$ inside C. Prove that

$$\frac{1}{2\pi i} \oint_C F(\tau) d\tau = \lim_{\tau \to a} \frac{d^{m-1}}{d\tau^{m-1}} ((\tau - a)^m F(\tau))).$$

(b) Evaluate

$$\oint_C \frac{e^\tau}{(\tau^2 + \pi^2)^2} d\tau$$

where C is the circle $|z| = 4$.

6.6.7 ?

Find the conformal map that takes the upper half-plane comformally onto the half-strip $\{w = x + iy : \ -\pi/2 < x < \pi/2 \ y > 0\}$.

6.6.8 ?

Compute the integral $\displaystyle\int_{-\infty}^{\infty} \frac{e^{-2\pi i x\xi}}{\cosh \pi x} dx$ where $\cosh z = \dfrac{e^z + e^{-z}}{2}$.