

# Complex Analysis Problems

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## 1 Integrals and Cauchy's Theorem

### 1.1 1

Suppose  $f, g : [0, 1] \rightarrow \mathbb{R}$  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 Theorem 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  $\mathbb{D}^\circ := \{z \in \mathbb{C} \mid |z| < 1\}$ .

Show that if  $f_n \rightarrow g$  for some  $g : \mathbb{D}^\circ \rightarrow \mathbb{C}$  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

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

Show that

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

**1.5 5**

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

**1.6 6**

Suppose that  $f : \mathbb{R} \rightarrow \mathbb{R}$  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  $f : \mathbb{C} \rightarrow \mathbb{C}$  is entire and

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

Prove that  $f$  is constant.

**1.8 8**

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

Prove that the function

$$f(z) := \int_{\gamma} \frac{g(w)}{w - z} dw$$

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

**1.9 9**

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

- Give an example of such an  $f$  that converges at every point of  $S^1$ .
- Given an example of such an  $f$  which is analytic at 1 but  $\sum_{n=0}^{\infty} a_n$  diverges.
- 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.

- Express  $a_n$  as a contour integral along the circle  $|z| = R$ .
- Apply (a) to show that the above Taylor series converges uniformly on every bounded subset of  $\mathbb{C}$ .
- 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:

- $f\left(\frac{1}{n}\right) = (-1)^n$  for each  $n > 1$ .
- $f\left(\frac{1}{n}\right) = e^{-n}$  for each even integer  $n > 1$  while  $f\left(\frac{1}{n}\right) = 0$  for each odd integer  $n > 1$ .
- $f\left(\frac{1}{n^2}\right) = \frac{1}{n}$  for each integer  $n > 1$ .
- $f\left(\frac{1}{n}\right) = \frac{n-2}{n-1}$  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  $z_0 \neq 0$ .

- Prove that the series converges absolutely for each  $z$  with  $|z| < |z_0|$ .
- 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  $n \geq 1$ ,

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

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  $\{z \mid \Im(z) < \ln 2\}$ :

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

**3 Spring 2020 Homework 1****4 Spring 2020 Homework 2**

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

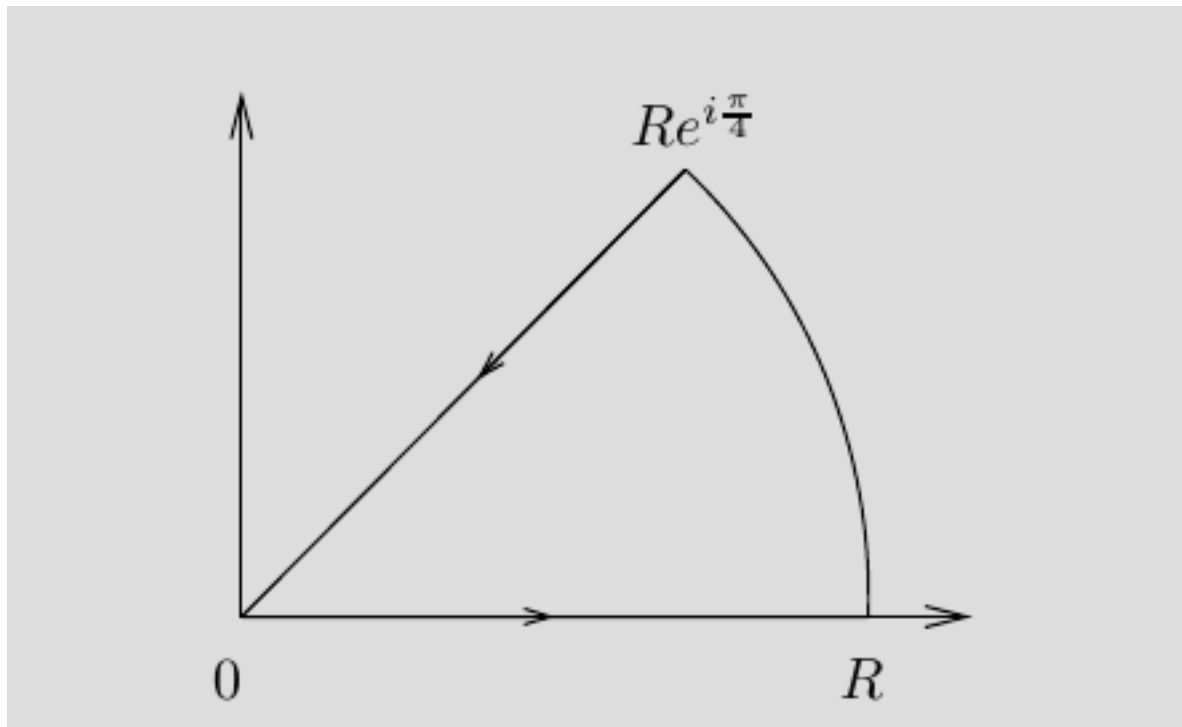


**4.1 Stein And Shakarchi****4.1.1 2.6.1**

Show that

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

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  $\frac{1}{2i} \int_{-\infty}^\infty \frac{e^{ix} - 1}{x} dx$ , 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  $\int_T f(z) dz = 0$ .

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

Hint: Green's theorem states

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

#### 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  $\int_T f(z) dz = 0$ .

#### 4.1.5 2.6.7

Suppose  $f : \mathbb{D} \rightarrow \mathbb{C}$  is holomorphic and let  $d := \sup_{z, w \in \mathbb{D}} |f(z) - f(w)|$  be the diameter of the image of  $f$ . Show that  $2|f'(0)| \leq d$ , and that equality holds iff  $f$  is linear, so  $f(z) = a_1z + a_2$ .

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

#### 4.1.6 2.6.8

Suppose that  $f$  is holomorphic on the strip  $S = \{x + iy \mid x \in \mathbb{R}, -1 < y < 1\}$  with  $|f(z)| \leq A(1 + |z|)^\nu$  for  $\nu$  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  $|f^{(n)}(x)| \leq A_n(1 + |x|)^\nu$  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  $\varphi : \Omega \rightarrow \Omega$  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  $\varphi$  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  $\varphi_k = \varphi \circ \varphi \circ \dots \circ \varphi$  and prove that  $\varphi_k(z) = z + k a_n z^n + O(z^{n+1})$ . Apply Cauchy's inequalities and let  $k \rightarrow \infty$  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  $f(z) = \sum_{n=0}^{\infty} c_n(z - z_0)^n$  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  $\lim_{n \rightarrow \infty} \frac{a_n}{a_{n+1}} = z_0$ .

**4.1.11 2.6.15**

Suppose  $f$  is continuous and nonvanishing on  $\bar{\mathbb{D}}$ , 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

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

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:

- $\sum_n n z^n$  does not converge at any point of  $S^1$
- $\sum_n \frac{z^n}{n^2}$  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  $\gamma$  denotes the circle centered at the origin of radius  $r$  with positive orientation.

**4.2.5 5**

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

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

Show that if  $\gamma_x := \{z = x + it \mid 0 \leq t \leq b\}$ , then

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

**4.2.6 6**

Show by example that there exists a function  $f(z)$  that is holomorphic on  $\{z \in \mathbb{C} \mid 0 < |z| < 1\}$  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  $u, v : \mathbb{R}^2 \rightarrow \mathbb{R}$  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

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

**4.2.9 9 (Cauchy's Formula for Exterior Regions)**

Let  $\gamma$  be a piecewise smooth simple closed curve with interior  $\Omega_1$  and exterior  $\Omega_2$ . Assume  $f'$  exists in an open set containing  $\gamma$  and  $\Omega_2$  with  $\lim_{z \rightarrow \infty} f(z) = A$ . 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:

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

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

**4.2.11 11**

Suppose  $f(z)$  is entire and

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

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

**4.2.12 12**

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

$$\int_0^{2\pi} \cos^{2n}(\theta) d\theta = 2\pi \left( \frac{1 \cdot 3 \cdot 5 \cdots (2n-1)}{2 \cdot 4 \cdot 6 \cdots (2n)} \right).$$

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## 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  $\frac{1}{\sin(\pi z)}$  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  $\frac{1}{1+z^4}$  ?

#### 5.1.3 3.8.4

Show that

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

#### 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

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

**5.1.7 3.8.8**

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

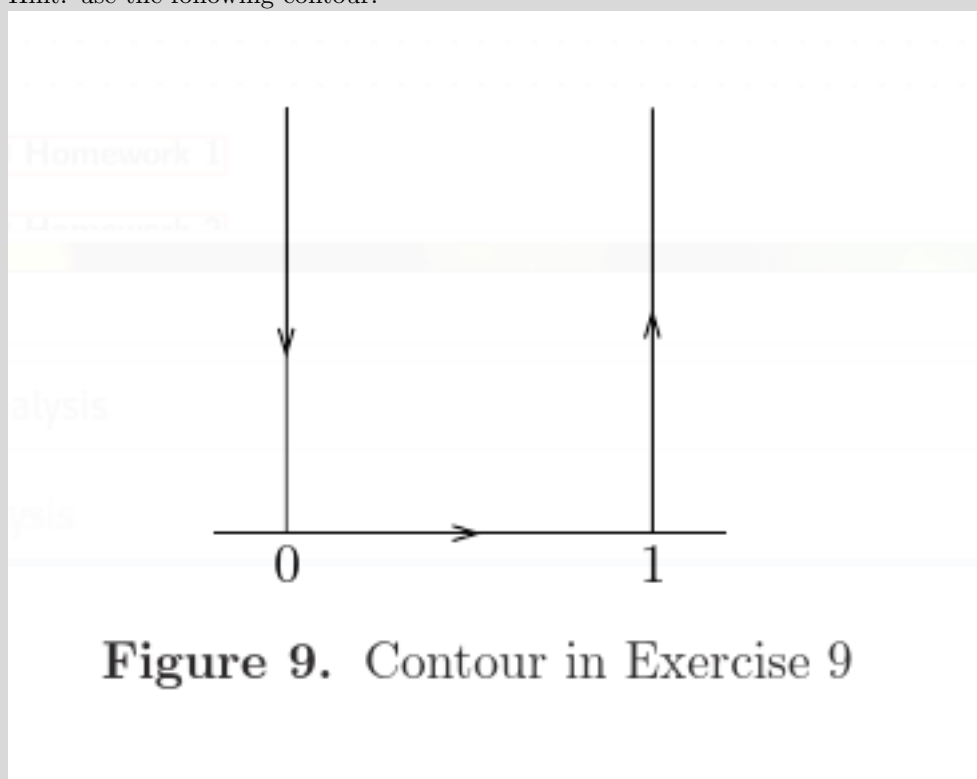
$$\int_0^{2\pi} \frac{d\theta}{a + b \cos \theta} = \frac{2\pi}{\sqrt{a^2 - b^2}}.$$

**5.1.8 3.8.9**

Show that

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

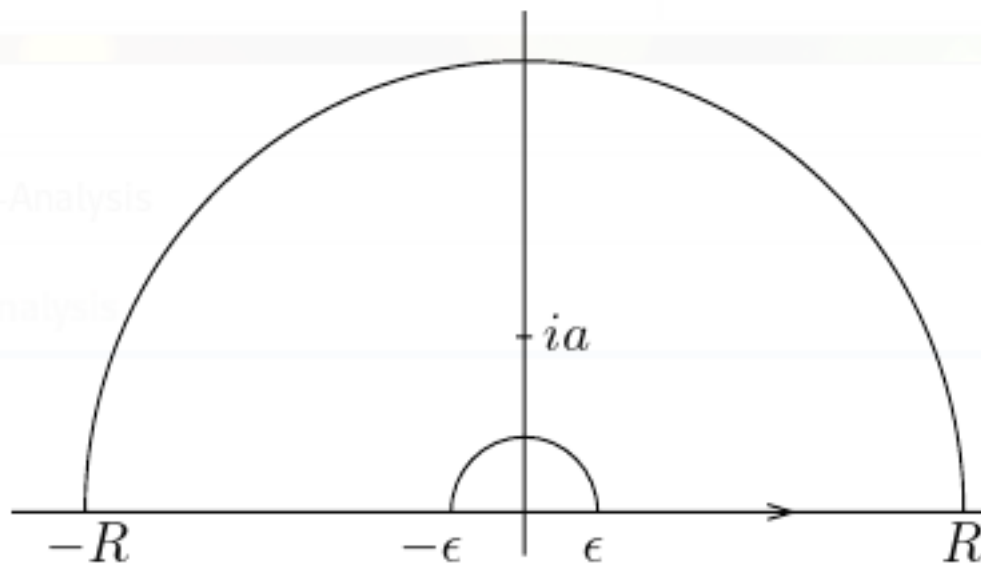
Hint: use the following contour.

**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  $|z| \rightarrow 0$ , then  $f \equiv 0$ .
- c. Let  $w_1, \dots, w_n$  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  $\Omega$ , then  $u$  can not attain a maximum or a minimum in  $\Omega$ .
- b. Suppose  $\Omega$  is a region with compact closure  $\bar{\Omega}$ . If  $u$  is harmonic in  $\Omega$  and continuous in  $\bar{\Omega}$ , then

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

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  $\lim_{n \rightarrow \infty} z_n = 0$ .

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  $\lim_{z \rightarrow \infty} f(z) = \infty$ , then  $f$  is a polynomial.

**5.2.6 6**

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

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

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. Rouché's Theorem.
- b. The maximum modulus principle.

**5.2.9 9**

Let  $f$  be analytic in a region  $D$  and  $\gamma$  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  $\Omega$  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  $\theta$ .

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## 6 Extra Questions from Jingzhi Tie

### 6.1 Fall 2009

#### 6.1.1 ?

(1) Assume  $\displaystyle f(z) = \sum_{n=0}^{\infty} c_n z^n$  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  
 $D = \{z \text{ such that } |z| > R, 0 \leq \arg z \leq \theta\}$  where  $0 < \theta < 2\pi$ . If there exists  $k$  such that  
$$\lim_{z \rightarrow \infty} z f(z) = k$$
 for  $z$  in the region  $D$ .  
Show that  $\lim_{R' \rightarrow \infty} \int_{L'} f(z) dz = i\theta k$ , 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  
$$F(z) = z - a - qf(z),$$
 where  $q$  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  $\bar{K}$  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  $\bar{K}$ . Apply the residue theorem to prove that  
$$\frac{1}{2\pi i} \int_K \frac{G(z)}{F(z)} dz,$$
 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  $\int_0^{\infty} \frac{x^{a-1}}{1+x^n} dx = \frac{\pi}{n \sin \frac{a\pi}{n}}$  using complex analysis,  $0 < a < n$ . Here  $n$  is a positive integer.

**6.1.7 ?**

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

1. Show that the gamma function is analytic in the half-plane  $\operatorname{Re}(s) > 0$ , 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  $\Gamma(1-s) = \int_0^{\infty} e^{-vt} (vt)^{-s} dv$  for  $t > 0$ .

**6.1.8 ?**

Apply Rouché's Theorem to prove the Fundamental Theorem of Algebra: If  $P_n(z) = a_0 + a_1 z + \cdots + a_{n-1} z^{n-1} + a_n z^n$  ( $a_n \neq 0$ ) 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  $|f(z)| \geq A |z|^N$  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  $f: \mathbb{C} \rightarrow \mathbb{C}$  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 a 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  $\psi_{\alpha}(z) = \frac{\alpha - z}{1 - \bar{\alpha}z}$  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  $\Omega$ . Show without using Picard's theorems that  $f(z)$  is a constant.

**6.1.14 ?**

(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).

**6.1.15 ?**

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  $\leq 2$ .

**6.1.16 ?**

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  $D$ .

**6.1.17 ?**

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

**6.1.18 ?**

Assume  $f$  is continuous in the region:

$0 < |z - a| \leq R$ ,  $0 \leq \arg(z - a) \leq \beta_0$  ( $0 < \beta_0 \leq 2\pi$ ) and the limit  $\lim_{z \rightarrow a} (z - a)f(z) = A$  exists. Show that

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

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

**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

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

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

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

(2) Show that there exist points  $(x, y) \in D$  such that

$$\limsup_{n \rightarrow \infty} |u(x, y)| = \infty.$$

**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  $r < R$ ,

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

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

### 6.2.2 ?

Let  $f$  be a continuous function in the region  $D = \{z \mid |z| > R, 0 \leq \arg z \leq \theta\}$  where  $0 \leq \theta \leq 2\pi$ . If there exists  $k$  such that  $\lim_{z \rightarrow \infty} zf(z) = k$  for  $z$  in the region  $D$ . Show that  $\lim_{R' \rightarrow \infty} \int_{L'} f(z) dz = i\theta k$ , where  $L'$  is the part of the circle  $|z| = R'$  which lies in the region  $D$ .

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(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  $\bar{K}$  whose boundary is the circle  $K$  if  $\min_{z \in K} \frac{|z-a|}{|f(z)|} > 1$ .

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### 6.2.4 ?

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

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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

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### 6.2.6 ?

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

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

### 6.2.8 ?

Apply Rouché's Theorem to prove the Fundamental Theorem of Algebra: If  $P_n(z) = a_0 + a_1 z + \cdots + a_{n-1} z^{n-1} + a_n z^n$  ( $a_n \neq 0$ ) 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  $|f(z)| \geq A |z|^N$  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  $f: \mathbb{C} \rightarrow \mathbb{C}$  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

$$\psi_{\alpha}(z) = \frac{\alpha - z}{1 - \bar{\alpha}z}$$

> may be useful.

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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  $\Omega$ . Show without using Picard's theorems that  $f(z)$  is a constant.

### 6.2.14 ?

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

### 6.2.15 ?

(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  $\leq 2$ .

**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  $\Omega$  except possibly at a point  $z_0$  inside  $\Omega$ . Show that if  $f(z)$  is bounded in near  $z_0$ , then  $\int_{\Delta} f(z) dz = 0$  for all triangles  $\Delta$  in  $\Omega$ .

**6.2.19 ?**

Assume  $f$  is continuous in the region:  
 $0 < |z-a| \leq R$ ,  $0 \leq \arg(z-a) \leq \beta_0$   
 $(0 < \beta_0 \leq 2\pi)$  and the limit  
 $\lim_{z \rightarrow a} (z-a) f(z) = A$  exists. Show that  
 $\lim_{r \rightarrow 0} \int_{\gamma_r} f(z) dz = i A \beta_0$ ,  
 where  
 $\gamma_r = \{ z \mid z = a + r e^{it}, 0 \leq t \leq \beta_0 \}$ .

**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  
 $u(x, y) = \frac{e^{ny} - e^{-ny}}{2n^2} \sin nx$  is the solution on  $D = \{(x, y) \mid x^2 + y^2 < 1\}$  of the Cauchy problem for the Laplace equation  
 $\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0$ ,  
 $u(x, 0) = 0$ ,  $\frac{\partial u}{\partial y}(x, 0) = \frac{\sin nx}{n}$ .
- (2) Show that there exist points  $(x, y) \in D$  such that  
 $\limsup_{n \rightarrow \infty} |u(x, y)| = \infty$ .

**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  $\gamma$  is any circle centered at the origin with the positive (counterclockwise) orientation.

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

### 6.3.2 ?

(1) Assume the infinite series
 
$$\sum_{n=0}^{\infty} c_n z^n$$
 converges in  $|z| < R$  and let  $f(z)$  be the limit. Show that for  $r < R$ ,
 
$$\frac{1}{2\pi i} \int_0^{2\pi} |f(re^{i\theta})|^2 d\theta = \sum_{n=0}^{\infty} |c_n|^2 r^{2n};$$

(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
 
$$D = \{z \mid |z| > R, 0 \leq \arg z \leq \theta\} \quad \text{where} \quad 0 \leq \theta \leq 2\pi.$$
 If there exists  $k$  such that
 
$$\lim_{z \rightarrow \infty} zf(z) = k$$
 for  $z$  in the region  $D$ . Show that
 
$$\lim_{R' \rightarrow \infty} \int_L f(z) dz = i\theta k,$$
 where  $L$  is the part of the circle  $|z| = R'$  which lies in the region  $D$ .

### 6.3.4 ?

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

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

**6.3.7 ?**

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

- Show that the gamma function is analytic in the half-plane  $\operatorname{Re}(s) > 0$ , 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  $\Gamma(1-s) = \int_0^\infty e^{-vt} (vt)^{-s} dv$  for  $t > 0$ .

**6.3.8 ?**

Apply Rouché's Theorem to prove the Fundamental Theorem of Algebra: If  $P_n(z) = a_0 + a_1 z + \cdots + a_{n-1} z^{n-1} + a_n z^n \neq 0$  is a polynomial of degree  $n$ , then it has  $n$  zeros in  $\mathbb{C}$ .

**6.3.9 ?**

Suppose  $f$  is entire and there exist  $A, R > 0$  and natural number  $N$  such that  $|f(z)| \geq A |z|^N$  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  $f: \mathbb{C} \rightarrow \mathbb{C}$  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 a 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

$$\psi_{\alpha}(z) = \frac{\alpha - z}{1 - \bar{\alpha}z}$$

> 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 
$$\lim_{n \rightarrow \infty} \frac{|a_{n+1}|}{|a_n|} = L.$$
 Show that 
$$\lim_{n \rightarrow \infty} \sqrt[n]{|a_n|} = L.$$
 In particular, this shows that when  $\rho_n^{\frac{1}{n}} = L$ , 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

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

and also that

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

(b) Prove that for fixed  $w$  in the unit disk  $\mathbb{D}$ , the mapping  $F: z \mapsto \frac{w - z}{1 - \bar{w}z}$  satisfies the following conditions:

(i)  $F$  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

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

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

defined by  $\log z = \log r + i\theta$ ;  
 $\text{where } z = r e^{i\theta}$ ;  $-\pi < \theta < \pi$   
 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  
 $\lim_{x \rightarrow +\infty} f(x + iy) = A$  exists  
 uniformly with respect to  $y$  (independent of  $y$ ). Show that  
 $\lim_{x \rightarrow +\infty} \int_{\gamma_x} f(z) dz = iA$ ;  
 where  $\gamma_x := \{z \mid z = x + it, 0 \leq t \leq b\}$ .

### 6.4.5 ?

(Cauchy's formula for "exterior" region) Let  $\gamma$  be piecewise smooth simple closed curve with interior  $\Omega_1$  and exterior  $\Omega_2$ . Assume  $f'(z)$  exists in an open set containing  $\gamma$  and  $\Omega_2$  and  $\lim_{z \rightarrow \infty} f(z) = A$ . Show that

$$\frac{1}{2\pi i} \int_{\gamma} \frac{f(\xi)}{\xi - z} d\xi =$$

$\begin{cases} A, & \text{if } z \in \Omega_1, \\ \end{cases}$

$-f(z) + A$ , & \text{if} \ \$z \in \Omega\_2\$ \\ \end{cases} \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 
$$\lim_{R \rightarrow \infty} \int_{|z|=R} \frac{f(z)}{(z-a)(z-b)} dz.$$
 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  $\xi$ .

#### 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 
$$f(z) = \sum_{n=1}^{\infty} a_n z^n$$
  $f(z) = \sum_{n=1}^{\infty} c_n z^n$  denote the power series in the open disc. Show that (1)  $c_n \neq 0$  for all large enough  $n$ 's, and (2) 
$$\lim_{n \rightarrow \infty} \frac{c_n}{c_{n+1}} = z_0.$$

#### 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  $\lim_{n \rightarrow \infty} z_n = 0$ . 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  $\lim_{z \rightarrow \infty} f(z) = \infty$ . Show that  $f$  is a polynomial.



**6.4.11 ?**

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

(a)

$$f(z) = \frac{z^2 - 1}{(z+2)(z+3)}, \quad 2 < |z| < 3,$$

(b)

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

**6.4.12 ?**

Assume  $f(z)$  is analytic in region  $D$  and  $\Gamma$  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  $f(z) \in H(\mathbb{D})$ ,  $\operatorname{Re}(f(z)) > 0$ ,  $f(0) = a > 0$ . Show that  $|\frac{f(z)-a}{f(z)+a}| \leq |z|$ ,  $|f'(0)| \leq 2a$ .

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

**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  $\Omega$ . Assume  $|f(z)| = |g(z)|$  for all  $z$  in  $\Omega$ . Show that  $f(z) = e^{i\theta} g(z)$  in  $\Omega$  for some  $0 \leq \theta < 2\pi$ .

**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  $z_k \in \mathbb{D}$ ,  $k \leq n$  and  $\theta \in \mathbb{R}$  such that

$$f(z) = e^{i\theta} \prod_{k=1}^n \frac{z - z_k}{1 - \bar{z}_k z}, \quad .$$

> 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  $m \geq 1$  an integer. Let

$$M_R = \sup \{ |z^m| p(z) - 1 : |z| = R \}.$$
 Show that  $M_R > 1$ .

(2) Let  $m \geq 1$  be an integer and

$$K = \{z \in \mathbb{C} : r \leq |z| \leq R\}$$
 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  $p(z)$ ,
$$\sup \{ |p(z) - z^{-m}| : z \in K \} \geq \varepsilon_0, \quad .$$

### 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  $\Omega$  and  $z_n$  is a sequence in  $\Omega$  such that  $u(z_n) = 0$  and  $\lim_{n \rightarrow \infty} z_n \in \Omega$ . Prove or disprove that  $u$  is identically zero. What if  $\Omega$  is a region?

(2) Assume  $u$  is harmonic on open set  $\Omega$  and  $u(z) = 0$  on a disc in  $\Omega$ . Prove or disprove that  $u$  is identically zero. What if  $\Omega$  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 
$$\|f\|_{(1, r)} = \int_{D_r(z_0)} |f(z)| dx dy.$$

> 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  $\lim_{n \rightarrow \infty} a_n = a$ . Show that for any  $w \in \mathbb{C}$ , there exists a sequence  $z_n \in \Omega$  such that  $\lim_{n \rightarrow \infty} f(z_n) = w$ .

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

**6.5.13 ?**

Compute the following integrals.

(i) 
$$\int_0^\infty \frac{1}{(1+x^n)^2} dx,$$

$n \geq 1$  (ii)

$$\int_0^\infty \frac{\cos x}{(x^2 + a^2)^2} dx,$$

$a \in \mathbb{R}$  (iii)  
$$\int_0^\pi \frac{1}{a + \sin \theta} d\theta, \quad a > 1$$

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

#### 6.5.14 ?

Compute the following integrals.

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

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

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

#### 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  $\Omega$ . Show that  $f$  is a constant if there is a simple closed curve  $\gamma$  in  $\Omega$  such that its image  $f(\gamma)$  is contained in the real axis.

#### 6.5.17 ?

(1) Show that 
$$\frac{\pi^2}{\sin^2 \pi z}$$
 and

$$g(z) = \sum_{n=-\infty}^{\infty} \frac{1}{(z-n)^2}$$
 have the same principal part at each integer point.

(2) Show that

$$h(z) = \frac{\pi^2}{\sin^2 \pi z} - g(z)$$
 is bounded

on  $\mathbb{C}$  and conclude that

$$\frac{\pi^2}{\sin^2 \pi z} = \sum_{n=-\infty}^{\infty} \frac{1}{(z-n)^2} + \dots$$

### 6.5.18 ?

Let  $f(z)$  be an analytic function on

$\mathbb{C} \setminus \{z_0\}$ , where  $z_0$  is a fixed point.

Assume that  $f(z)$  is bijective from

$\mathbb{C} \setminus \{z_0\}$  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

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

### 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  $\{z: |z - 1/2| > 1/2, \operatorname{Re}(z) > 0\}$  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  $\mathbb{D} \setminus [a, 1)$  to  $\mathbb{D} \setminus [0, 1)$  ( $0 < a < 1$ ). [Short solution possible using Blaschke factor]
5. from  $\{z: |z| < 1, \operatorname{Re}(z) > 0\} \setminus (0, 1/2]$  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  $\Omega$  that are uniformly bounded on compact subsets and  $f \in H(\Omega)$  is such that the set  $\{z \in \Omega: \lim_{n \rightarrow \infty} f_n(z) = f(z)\}$  has a limit point in  $\Omega$ . Show that  $f_n$  converges to  $f$  uniformly on compact subsets of  $\Omega$ .

**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

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

**6.5.25 ?**

Prove that 
$$f(z) = -\frac{1}{2} \left( z + \frac{1}{z} \right)$$
 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  $\Omega$  be a simply connected open set and let  $\gamma$  be a simple closed contour in  $\Omega$  and enclosing a bounded region  $U$  anticlockwise. Let  $f: \Omega \rightarrow \mathbb{C}$  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)

$\int_0^\infty \frac{x^{a-1}}{1+x^n} dx$ ,

$0 < a < n$  (ii)

$\int_0^\infty \frac{\log x}{(1+x^2)^2} dx$

### 6.5.28 ?

Let  $0 < r < 1$ . Show that polynomials

$P_n(z) = 1 + 2z + 3z^2 + \dots + n z^{n-1}$  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  $|f|_{(1, r)} = \int_{D_r(z_0)} |f(z)| dx dy$ .

### 6.5.30 ?

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

$$\frac{1}{\pi} \iint_{\mathbb{D}} |\psi'_\alpha|^2 dx dy = 1.$$

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

Prove that  $f(z) = -\frac{1}{2} \left( z + \frac{1}{z} \right)$  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  $\Omega$  be a simply connected open set and let  $\gamma$  be a simple closed contour in  $\Omega$  and enclosing a bounded region  $U$  anticlockwise. Let  $f : \Omega \rightarrow \mathbb{C}$  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)

$$\int_0^{\infty} \frac{x^{a-1}}{1+x^n} dx, \quad 0 < a < n$$

(ii)  $\int_0^{\infty} \frac{\log x}{(1+x^2)^2} dx$

**6.5.33 ?**

Let  $0 < r < 1$ . Show that polynomials

$P_n(z) = 1 + 2z + 3z^2 + \cdots + n z^{n-1}$  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

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

$$\|f\|_{(\infty, s)} = \sup_{z \in D_s(z_0)} |f(z)|$$

$$\text{and } \|f\|_{(1, r)} = \int_{D_r(z_0)} |f(z)| dx dy.$$

**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:

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

(b)  $\hfill$

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

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

**6.6.2 ?**

(a)  $f(z) = u(x, y) + i v(x, y)$  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  $\mathbb{C}$ .
- (i) Describe the level curves of  $\operatorname{Re}\{f\}$  and of  $\operatorname{Im}\{f\}$ .
- (ii) What are the angles of intersections between the level curves  $\operatorname{Re}\{f\}=0$  and  $\operatorname{Im}\{f\}$ ? Is your answer in agreement with part a) of this question?

### 6.6.3 ?

- (a)  $f: D \rightarrow \mathbb{C}$  be a continuous function, where  $D \subset \mathbb{C}$  is a domain. Let  $\alpha: [a, b] \rightarrow D$  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  $|f(\tau)| \leq M$  for all  $\tau \in \operatorname{Image}(\alpha)$ . Prove that  $\left| \int_{\alpha} f \right| \leq M \times \operatorname{length}(\alpha).$
- (c) Let  $C_R$  be the circle  $|z|=R$ , described in the counterclockwise direction, where  $R>1$ . Provide an upper bound for  $\left| \int_{C_R} \frac{\log(z)}{z^2} dz \right|$ , which depends [only] on  $R$  and other constants.

### 6.6.4 ?

- (a) Let  $f: \mathbb{C} \rightarrow \mathbb{C}$  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  $|f(z)| \leq L |z|^m$  holds. Prove that  $f$  is a polynomial of degree  $\leq m$ .
- (b) Let  $f: \mathbb{C} \rightarrow \mathbb{C}$  be an entire function. Suppose that there exists a real number  $M$  such that for all  $z \in \mathbb{C}$   $\operatorname{Re}(f) \leq M$ . 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  $m \geq 1$  at  $z=a$  inside  $C$ .

Prove that

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

(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 conformally onto the half-strip  $\{w = x+iy : -\pi/2 < x < \pi/2, y > 0\}$ .

### 6.6.8 ?

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