

Complex Analysis Problems

D. Zack Garza

Wednesday 17th June, 2020

Contents

1	Integrals and Cauchy's Theorem	5
1.1	1	5
1.2	2	5
1.3	3	5
1.4	4	6
1.5	5	6
1.6	6	6
1.7	7	6
1.8	8	6
1.9	9	6
1.10	10	7
2	Liouville's Theorem, Power Series	7
2.1	1	7
2.2	2	7
2.3	3	7
2.4	4	7
2.5	5	8
2.6	6	8
2.7	7	8
2.8	8	8
2.9	9	8
2.10	10	8
3	Spring 2020 Homework 1	8
4	Spring 2020 Homework 2	8
4.1	Stein And Shakarchi	9
4.1.1	2.6.1	9
4.1.2	2.6.2	9
4.1.3	2.6.5	9
4.1.4	2.6.6	10
4.1.5	2.6.7	10
4.1.6	2.6.8	10
4.1.7	2.6.9	10

4.1.8	2.6.10	10
4.1.9	2.6.13	11
4.1.10	2.6.14	11
4.1.11	2.6.15	11
4.2	Additional Problems	11
4.2.1	1	11
4.2.2	2	11
4.2.3	3	11
4.2.4	4	12
4.2.5	5	12
4.2.6	6	12
4.2.7	7	12
4.2.8	8	12
4.2.9	9 (Cauchy's Formula for Exterior Regions)	13
4.2.10	10	13
4.2.11	11	13
4.2.12	12	13
4.2.13	13	13
5	Spring 2020 Homework 3	14
5.1	Stein and Shakarchi	14
5.1.1	3.8.1	14
5.1.2	3.8.2	14
5.1.3	3.8.4	14
5.1.4	3.8.5	14
5.1.5	3.8.6	14
5.1.6	3.8.7	14
5.1.7	3.8.8	15
5.1.8	3.8.9	15
5.1.9	3.8.10	15
5.1.10	3.8.14	16
5.1.11	3.8.15	16
5.1.12	3.8.17	16
5.1.13	3.8.19	16
5.2	Problems From Tie	16
5.2.1	1	16
5.2.2	2	17
5.2.3	3	17
5.2.4	4	17
5.2.5	5	17
5.2.6	6	17
5.2.7	7	18
5.2.8	8	18
5.2.9	9	18
5.2.10	10	18
5.2.11	11	18
5.2.12	12	18
5.2.13	13	18

5.2.14	14	19
6	Extra Questions from Jingzhi Tie	19
6.1	Fall 2009	19
6.1.1	?	19
6.1.2	?	19
6.1.3	?	19
6.1.4	?	20
6.1.5	?	20
6.1.6	?	20
6.1.7	?	20
6.1.8	?	20
6.1.9	?	20
6.1.10	?	21
6.1.11	?	21
6.1.12	?	21
6.1.13	?	21
6.1.14	?	21
6.1.15	?	22
6.1.16	?	22
6.1.17	?	22
6.1.18	?	22
6.1.19	?	22
6.1.20	?	22
6.2	Fall 2011	23
6.2.1	?	23
6.2.2	?	23
6.2.3	?	23
6.2.4	?	23
6.2.5	?	24
6.2.6	?	24
6.2.7	?	24
6.2.8	?	24
6.2.9	?	24
6.2.10	?	24
6.2.11	?	25
6.2.12	?	25
6.2.13	?	25
6.2.14	?	25
6.2.15	?	25
6.2.16	?	25
6.2.17	?	26
6.2.18	?	26
6.2.19	?	26
6.2.20	?	26
6.3	Spring 2014	26
6.3.1	?	26
6.3.2	?	27

6.3.3	?	27
6.3.4	?	27
6.3.5	?	27
6.3.6	?	28
6.3.7	?	28
6.3.8	?	28
6.3.9	?	28
6.3.10	?	28
6.3.11	?	28
6.3.12	?	29
6.4	Fall 2015	29
6.4.1	?	29
6.4.2	?	29
6.4.3	?	30
6.4.4	?	30
6.4.5	?	30
6.4.6	?	31
6.4.7	?	31
6.4.8	?	31
6.4.9	?	31
6.4.10	?	31
6.4.11	?	32
6.4.12	?	32
6.4.13	?	32
6.4.14	?	32
6.4.15	?	32
6.4.16	?	32
6.4.17	?	33
6.4.18	?	33
6.5	Spring 2015	33
6.5.1	?	33
6.5.2	?	33
6.5.3	?	33
6.5.4	?	33
6.5.5	?	34
6.5.6	?	34
6.5.7	?	34
6.5.8	?	34
6.5.9	?	34
6.5.10	?	35
6.5.11	?	35
6.5.12	?	35
6.5.13	?	35
6.5.14	?	36
6.5.15	?	36
6.5.16	?	36
6.5.17	?	36
6.5.18	?	37

6.5.19	?	37
6.5.20	?	37
6.5.21	?	37
6.5.22	?	38
6.5.23	?	38
6.5.24	?	38
6.5.25	?	38
6.5.26	?	38
6.5.27	?	39
6.5.28	?	39
6.5.29	?	39
6.5.30	?	39
6.5.31	?	39
6.5.32	?	40
6.5.33	?	40
6.5.34	?	40
6.6	Fall 2016	40
6.6.1	?	40
6.6.2	?	40
6.6.3	?	41
6.6.4	?	41
6.6.5	?	41
6.6.6	?	41
6.6.7	?	42
6.6.8	?	42

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}° .

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 γ 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 Ω 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}° . 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**

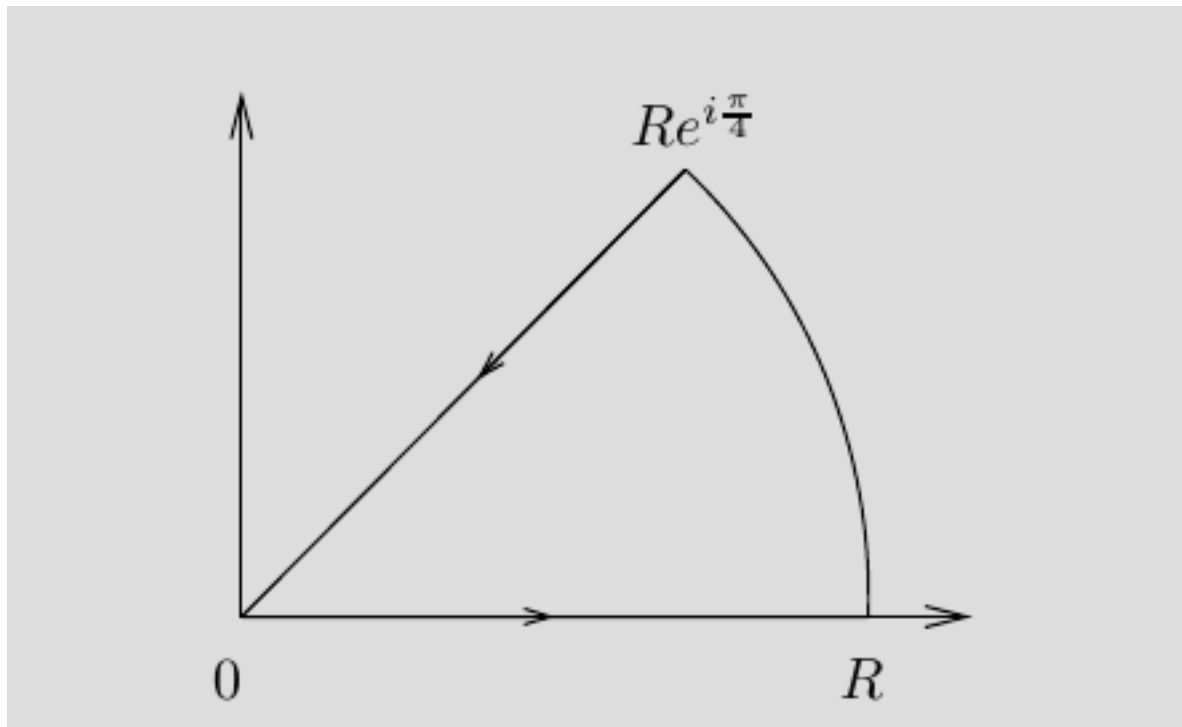
Note on notation: I sometimes use $f_x := \frac{\partial f}{\partial x}$ to denote partial derivatives, and $\partial_z^n f$ as $f^{(n)}(z)$.

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

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

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

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 $f(z) = a_1 z + a_2$.

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 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 $|f^{(n)}(x)| \leq A_n(1 + |x|)^\nu$ 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 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 $k \rightarrow \infty$ 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 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 $\{x + iy \mid x \geq x_0, 0 \leq y \leq b\}$, 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 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 $\lim_{z \rightarrow \infty} f(z) = A$. 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 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

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

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.

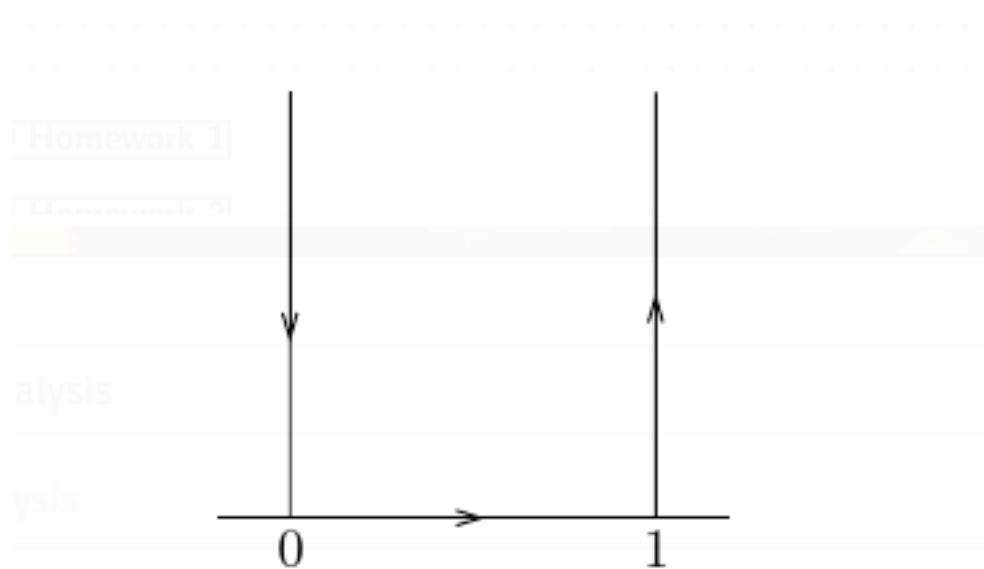


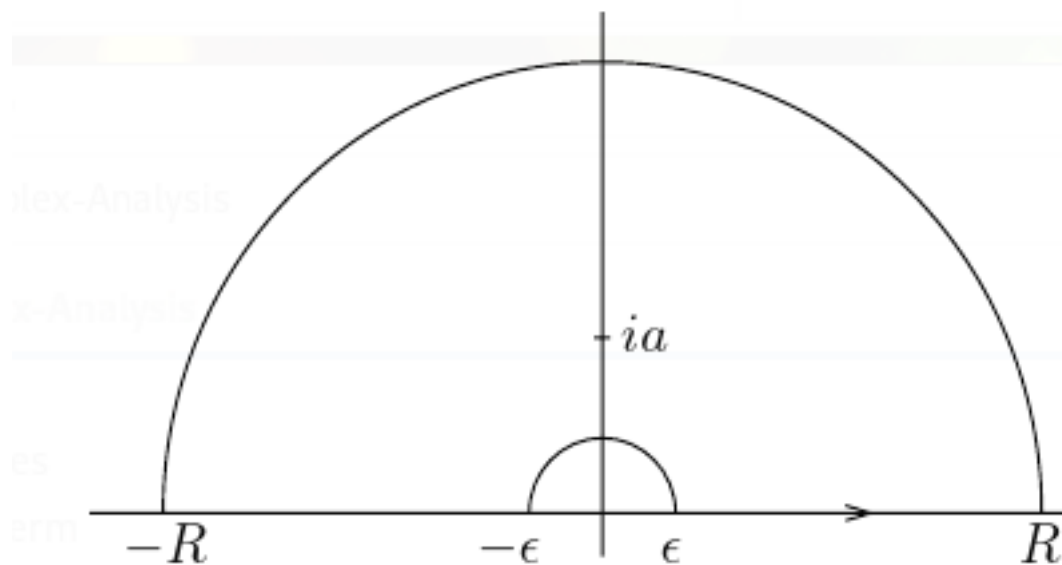
Figure 9. Contour in Exercise 9

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**5.1.12 3.8.17****5.1.13 3.8.19****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

- Rouche's Theorem.
- 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 $D = \{z \text{ such that } |z| > R, 0 \leq \arg z \leq \theta\}$ where $1 \leq \theta \leq 2\pi$. 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 .

6.1.3 ?

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
$$\frac{G(w)}{F'(w)} = \frac{1}{2\pi i} \int_K \frac{G(z)}{F(z)} dz,$$
 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 $\int_0^{\infty} \frac{x^{a-1}}{1+x^n} dx = \frac{\pi}{n \sin \frac{a\pi}{n}}$ 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 Ω . 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 ≤ 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 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:

$0 < |z - a| \leq R$, $0 \leq \arg(z - a) \leq \beta_0$ ($0 < \beta_0 \leq 2\pi$) 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 $u(x, y) = \frac{e^{ny} - e^{-ny}}{2n^2} \sin nx$ 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 $\limsup_{n \rightarrow \infty} |u(x, y)| = \infty$.

6.2 Fall 2011**6.2.1 ?**

(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).

6.2.2 ?

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 .

6.2.3 ?

Suppose that f is an analytic function in the region D which contains the point a . Let
 $F(z) = z - a - qf(z)$, 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 $\min_{z \in K} \frac{|z-a|}{|f(z)|} > 1$.

(2) Let $G(z)$ be an analytic function on the disk \bar{K} . Apply the residue theorem to prove that
$$\frac{1}{2\pi i} \int_K G(z) F'(z) dz = G(w)$$
 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 :
$$\frac{1}{F(z)} = \sum_{n=0}^{\infty} \frac{(qf(z))^n}{(z-a)^{n+1}}.$$

6.2.4 ?

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

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 $\int_0^\infty \frac{x^{a-1}}{1+x^n} dx = \frac{\pi}{n \sin \frac{a\pi}{n}}$ 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 $\operatorname{Re}(s) > 0$, 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 $t > 0$.

6.2.8 ?

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 $|f(z)| \geq A |z|^N$ 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.
- 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.

6.2.12 ?

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.

6.2.14 ?

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.

6.2.15 ?

(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 ≤ 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:
 $0 < |z-a| \leq R$, $0 \leq \arg(z-a) \leq \beta_0$
 $(0 < \beta_0 \leq 2\pi)$ 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
 $u(x,y) = \frac{e^{-ny} - e^{-ny}}{2n^2} \sin nx$ 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
 $\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0$,
 $u(x,0) = 0$, $\frac{\partial u}{\partial y}(x,0) = \frac{\sin nx}{n}$.
- (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 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 $\int_{\gamma} \frac{dz}{(z-a)(z-b)} = \frac{2\pi i}{a-b}$. Here γ denotes the circle centered at the origin, of radius r , with the positive orientation.

6.3.2 ?

(1) Assume the infinite series $\sum_{n=0}^{\infty} c_n z^n$ 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 $D = \{z \mid |z| > R, 0 \leq \arg z \leq \theta\}$ 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 .

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

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) $F: \mathbb{D} \rightarrow \mathbb{D}$ 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 $\log z = \log r + i\theta$ 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 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 $\lim_{z \rightarrow \infty} f(z) = A$. Show that

$$\frac{1}{2\pi i} \int_{\gamma} \frac{f(\xi)}{\xi - z} d\xi = \begin{cases} A, & \text{if } z \in \Omega_1, \\ 0, & \text{if } z \in \Omega_2. \end{cases}$$

$-f(z) + A$, & \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 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
$$f(z) = \sum_{n=1}^{\infty} a_n z^n$$
 $f(z) = \sum_{n=1}^{\infty} c_n z^n$ 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)

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

(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 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 $f(z) \in H(\mathbb{D})$, $\operatorname{Re}(f(z)) > 0$, $f(0) = a > 0$. Show that $\left| \frac{f(z)-a}{f(z)+a} \right| \leq |z|$, $|f'(0)| \leq 2a$.

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

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 Ω and z_n is a sequence in Ω such that $u(z_n) = 0$ and $\lim z_n \in \Omega$. Prove or disprove that u is identically zero. What if Ω is a region?

(2) Assume u is harmonic on open set Ω and $u(z) = 0$ on a disc in Ω . Prove or disprove that u is identically zero. What if Ω 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)
 $\int_0^\pi \frac{1}{a + \sin \theta} d\theta$,
 $a > 1$

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

6.5.14 ?

Compute the following integrals.

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

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

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

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 $\frac{\pi^2}{\sin^2 \pi z}$ 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 Ω 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 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

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

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 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 $f: \Omega \rightarrow \mathbb{C}$ 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

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

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

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 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 $f : \Omega \rightarrow \mathbb{C}$ 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 $\cosh z = \frac{e^z + e^{-z}}{2}$.