A2: Metric Spaces and Complex Analysis

Sheet 8, sections 11.4-12 from the notes — MT20

1. Evaluate, using a keyhole contour cut along the positive real axis, or otherwise,

$$\int_0^\infty \frac{x^{1/2}\log x}{(1+x)^2}\mathrm{d}x.$$

2. Let $n \geqslant 2$. By using the contour comprising $[0,R]$, the circular arc from R to $Re^{2\pi i/n}$, and $\left[0, Re^{2\pi i/n}\right]$, show that

$$\int_0^\infty \frac{\mathrm{d}x}{1+x^n} = \frac{\pi}{n}\csc\left(\frac{\pi}{n}\right).$$

3. Suppose that $f\colon U \to \mathbb{C}$ is a holomorphic function on an open set $U \subseteq \mathbb{C}$, and suppose $f'(a) \neq 0$ for some $a \in U$. Show that there is an $r > 0$ such that f is injective on $B(a,r)$ and that its inverse g is given on the image of such a disk by

$$g(w) = \frac{1}{2\pi i}\int_\gamma \frac{zf'(z)}{f(z)-w}dz.$$

where $\gamma(t) = a + re^{it}$, $t \in [0, 2\pi]$.

[*Hint: You may find it helpful to use the winding number version of Cauchy Integral Formula.*]

4. In each of the following cases find a conformal mapping from the given region G onto the open unit disc $\mathbb{D} = B(0,1)$.

   i) $G = \{z \in \mathbb{C} : \operatorname{Im} z > 0\}$,

   ii) $G = \{z \in \mathbb{C} : z \neq 0 \text{ and } -\pi/4 < \arg z < \pi/4\}$,

   iii) $G = \{z \in \mathbb{C} : |z-i| < \sqrt{2} \text{ and } |z+i| > \sqrt{2}\}$.

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5. Let

$$A = \{z \in \mathbb{C} : |z-2| < 2 \text{ and } |z-1| > 1\}; \qquad B = \{z \in \mathbb{C} : 0 < \operatorname{Re} z < \pi\}.$$

Find the image of A under the map $z \mapsto 1/z$ and the image of B under the map $z \mapsto \exp(iz)$.

Let $H = \{z \in \mathbb{C} : \operatorname{Im} z > 0\}$. Given $a, b \in H$ find a conformal bijection $H \to H$ of the form $z \mapsto \lambda z + \mu$ which maps a to b.

Deduce that for any two points $a, b \in A$ there is a conformal bijection $f : A \to A$ such that $f(a) = b$.

6. Let $\mathbb{R}_\infty = \mathbb{R} \cup \{\infty\} \subset \mathbb{C}_\infty$.

   i. Show that group Γ of Mobius transformations T for which $T(\mathbb{R}_\infty) = \mathbb{R}_\infty$ are exactly those of the form $T(z) = (az+b)/(cz+d)$ where a, b, c, d can be chosen to be real.

   ii. Calculate the group Γ_1 of Mobius tranformations which preserve $\mathbb{H} = \{z \in \mathbb{C} : \Im(z) > 0\}$

   [*Hint: Why must* Γ_1 *be a subgroup of* Γ*?*]

7. Write down a bounded solution $u(x, y)$ to the Dirichlet problem for the following region and boundary conditions:

$$U = \{x + iy : 0 \leqslant y \leqslant 1\}, \qquad u(x, 0) = 0, \qquad u(x, 1) = 1.$$

Hence, using appropriate conformal maps, solve the Dirichlet problem for the following regions and boundary conditions.

i) $U = \{z : r_1 \leqslant |z| \leqslant r_2\}$, $\quad u(z) = 0$ when $|z| = r_1$, $\quad u(z) = 1$ when $|z| = r_2$.

ii) $U = \{z : \operatorname{Im} z \geqslant 0\}$, $\quad u(x, 0) = 0$ when $x > 0$, $\quad u(x, 0) = 1$ when $x < 0$.

iii) $U = \{z : |z| \leqslant 1\}$, $\quad u(z) = 0$ when $|z| = 1$ and $\operatorname{Im} z < 0$, $\quad u(z) = 1$ when $|z| = 1$ and $\operatorname{Im} z > 0$.

iv) $U = \{z : \operatorname{Im} z \geqslant 0\}$, $\quad u(x, 0) = 0$ when $|x| > 1$, $\quad u(x, 0) = 1$ when $|x| < 1$.

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8. (*Optional.*) Let $f : \mathbb{D} \to \mathbb{D}$ be a holomorphic function, where $\mathbb{D} = B(0,1)$.

   i) Show that if $f(0) = 0$ then $|f(z)| \leq |z|$ for all $z \in \mathbb{D}$. (*hint*: show that $|f(z)/z| \leq 1/r$ if $|z| \leq r$, for any $r < 1$).

   Show that if, moreover, $|f(z_0)| = |z_0|$ for some $z_0 \in \mathbb{D}, z_0 \neq 0$, then f is a rotation.

   ii) Show that if $a \in \mathbb{D}$ the function

   $$g_a(z) = \frac{a - z}{1 - \bar{a}z}$$

   maps $\mathbb{D}$ to $\mathbb{D}$.

   iii) Show that if $f : \mathbb{D} \to \mathbb{D}$ is holomorphic and bijective then there is some $\theta \in \mathbb{R}$ and $a \in \mathbb{D}$ such that $f(z) = e^{i\theta} g_a(z)$.

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