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# Complex Analysis I:

## Problem Set IV

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### Abstract

This work contains the solutions to the problem set IV of Complex Analysis I 2015 at Courant Institute of Mathematical Sciences.

#### Question 1. Brown p.147-2.

**Solution. (b)** We first have that  $\cos(z/2)$  is continuous everywhere on the complex plane. Therefore, any contour from 0 to  $\pi + 2i$  will have the same value of  $F(\pi + 2i) - F(0)$ , where  $F$  denotes the antiderivative of  $\cos(z/2)$ . We can compute the exact value as follows:

$$\begin{aligned}\int_0^{\pi+2i} \cos\left(\frac{z}{2}\right) dz &= \left[2\sin\left(\frac{z}{2}\right)\right]_0^{\pi+2i} \\ &= 2\sin\left(\frac{\pi}{2} + i\right) \\ &= 2\cos(i) \\ &= e + \frac{1}{e},\end{aligned}$$

as desired.  $\square$

#### Question 2. Brown p.147-5.

**Solution.** Let  $C$  be a contour from  $-1$  to  $1$  that lies above the x-axis. We wish to compute the following integral:

$$\int_C z^i dz,$$

where  $z^i$  denotes the principal branch  $\exp(i\operatorname{Log}(z))$  for  $|z| > 0, -\pi < \operatorname{Arg}(z) < \pi$ . Notice that under the principal branch,  $z = -1$  is not defined. The following branch, however, agrees with the integrand along  $C$  and has anti-derivative along  $C$ :

$$z^i = \exp(i\log(z)) \text{ for } (|z| > 0, -\frac{\pi}{2} < \arg(z) < \frac{3\pi}{2}).$$

We then can compute the integral as follows:

$$\begin{aligned}
\int_C z^i dz &= \left[ \frac{z^{i+1}}{i+1} \right]_{-1}^1 \\
&= \frac{1}{i+1} (e^{(i+1)\log 1} - e^{(i+1)\log(-1)}) \\
&= \frac{1}{i+1} (e^{(i+1)(\ln 1)} - e^{(i+1)\ln(1+i\pi)}) \\
&= \frac{1}{i+1} (1 + e^{i\pi}) \\
&= \frac{1 + e^{-\pi}}{2} (1 - i),
\end{aligned}$$

as desired.  $\square$

**Question 3. Brown p.159-2.**

**Solution. (b)** Let  $C_1$  denote the positively oriented boundary of the square whose sides lie along the line  $x = \pm 1, y = \pm 1$  and let  $C_2$  be the positively oriented circle  $|z| = 4$ . Observe that  $C_1$  is interior to  $C_2$  and the given function  $\frac{z+2}{\sin(\frac{z}{2})}$  is analytic in the closed region consisting of the  $C_1$  and  $C_2$  contours and all points between them. Hence, by the corollary, we have

$$\int_{C_1} f(z) dz = \int_{C_2} f(z) dz,$$

for  $f(z) = \frac{z+2}{\sin(\frac{z}{2})}$ .  $\square$

**Question 4. Brown 159-4.**

**Solution. (a)** Observe that along the lower horizontal leg, we have  $z = x$  ( $-a \leq x \leq a$ ). Hence, the integral along the lower horizontal leg from  $-a$  to  $a$  can be written as

$$2 \int_0^a e^{-x^2} dx.$$

For the upper horizontal leg, we have  $z = x + ib$  ( $-a \leq x \leq a$ ). Hence, the integral along the upper horizontal from  $a$  to  $-a$  can be written as

$$\int_a^{-a} e^{-(x+ib)^2} dx,$$

wich can be simplified as follows:

$$\begin{aligned}
\int_a^{-a} e^{-(x+ib)^2} dx &= -e^{b^2} \int_{-a}^a e^{-x^2 - 2ibx} dx \\
&= -2e^{b^2} \int_0^a e^{-x^2} \cos(2bx) dx.
\end{aligned}$$

Hence, we have

$$2 \int_0^a e^{-x^2} dx - 2e^{b^2} \int_0^a e^{-x^2} \cos(2bx) dx,$$

for the sum of contour integrals along each horizontal leg.

Now, observe that along the vertical legs, we have  $z = \pm a + iy$  ( $0 \leq y \leq b$ ). Hence, the integral along the vertical legs can be written as

$$I = \int_0^b e^{-(a+iy)^2} i dy + \int_b^0 e^{-(-a+iy)^2} i dy,$$

which can be simplified as follows:

$$\begin{aligned} I &= \int_0^b e^{-a^2-2ia y+y^2} i dy - \int_0^b e^{-a^2+2ia y+y^2} i dy \\ &= i e^{-a^2} \int_0^b e^{y^2} e^{-i2a y} - i e^{-a^2} \int_0^b e^{y^2} e^{i2a y} dy. \end{aligned}$$

Hence, by the Cauchy-Goursat Theorem, we have

$$\begin{aligned} 2 \int_0^a e^{-x^2} dx - 2e^{b^2} \int_0^a e^{-x^2} \cos(2bx) dx \\ + i e^{-a^2} \int_0^b e^{y^2} e^{-i2a y} - i e^{-a^2} \int_0^b e^{y^2} e^{i2a y} dy = 0, \end{aligned}$$

which by re-arranging and simplifying becomes

$$\int_0^a e^{-x^2} \cos(2bx) dx = e^{-b^2} \int_0^a e^{-x^2} dx + e^{-a^2-b^2} \int_0^b e^{y^2} \sin(2ay) dy,$$

as desired.

(b) As  $a \rightarrow \infty$ , we have that

$$e^{-a^2-b^2} \int_0^b e^{y^2} dy \rightarrow 0.$$

Observe that

$$\left| e^{-a^2-b^2} \int_0^b e^{y^2} \sin(2ay) dy \right| \leq e^{-a^2-b^2} \int_0^b e^{y^2} dy.$$

Hence, by the squeeze theorem, we have as  $a \rightarrow \infty$

$$e^{-a^2-b^2} \int_0^b e^{y^2} \sin(2ay) dy \rightarrow 0.$$

Therefore, with the given result in the problem, we obtain

$$\int_0^\infty e^{-x^2} \cos(2bx) dx = \frac{\sqrt{\pi}}{2} e^{-b^2},$$

as desired.  $\square$

#### Question 5. Brown p.170-1.

**Solution.** Let  $C$  denote the positively oriented boundary of the square whose sides lie along the lines  $x = \pm 2$  and  $y = \pm 2$ . We evaluate the following integrals.

(b) We are given the following integral:

$$\int_C \frac{\cos(z)}{z(z^2+8)} dz,$$

which can be written as

$$\int_C \frac{\frac{\cos(z)}{(z^2+8)}}{z} dz.$$

As  $\frac{\cos(z)}{(z^2+8)}$  is analytic everywhere inside and on the given contour, which is simple and closed, taken in the positive sense, by the Cauchy Integral formula, we obtain

$$\frac{\cos(0)}{8} = \frac{1}{2\pi i} \int_C \frac{\frac{\cos(z)}{(z^2+8)}}{z} dz,$$

which simplifies to

$$\int_C \frac{\frac{\cos(z)}{(z^2+8)}}{z} dz = \frac{\pi i}{4}.$$

(d) We are given the following integral:

$$\int_C \frac{\cosh(z)}{z^4} dz.$$

As  $\frac{\cosh(z)}{z^4}$  is analytic everywhere inside and on the given contour, which is simple and closed, taken in the positive sense, by the extended Cauchy Integral formula, we obtain

$$\cosh^{(3)}(z_0) = \frac{3!}{2\pi i} \int_C \frac{\cosh(z)}{(z - z_0)^4} dz,$$

for  $z_0$  inside and on the given contour. Observe that  $\cosh^{(3)} = \sinh$ . Hence, taking  $z_0 = 0$  yields

$$0 = \frac{3!}{2\pi i} \int_C \frac{\cosh(z)}{z^4} dz,$$

which simplifies to

$$\int_C \frac{\cosh(z)}{z^4} dz = 0.$$

(e) We are given the following integral:

$$\int_C \frac{\tan(\frac{z}{2})}{(z - x_0)^2} dz,$$

for  $-2 < x_0 < 2$ . Notice that  $x_0$  is inside the given contour. As  $\frac{\tan(\frac{z}{2})}{(z - x_0)^2}$  is analytic everywhere inside and on the given contour, which is simple and closed, taken in the positive sense, by the extended Cauchy Integral formula, we obtain

$$\frac{1}{2} \sec^2\left(\frac{x_0}{2}\right) = \frac{1!}{2\pi i} \int_C \frac{\tan(\frac{z}{2})}{(z - x_0)^2} dz,$$

which simplifies to

$$\int_C \frac{\tan(\frac{z}{2})}{(z - x_0)^2} dz = i\pi \sec^2\left(\frac{x_0}{2}\right),$$

for  $-2 < x_0 < 2$ .  $\square$

### Question 6. Brown 170.3.

**Solution.** Let  $C$  be the circle  $|z| = 3$ , described in the positive sense. As  $2s^2 - s - 2$  is analytic everywhere inside and on the given contour, which is simple and closed, taken in the positive sense, by the extended Cauchy Integral formula, we obtain

$$2z^2 - z - 2 = \frac{1}{2\pi i} \int_C \frac{2s^2 - s - 2}{s - z} ds,$$

for  $|z| < 3$ . As  $g(z) = \int_C \frac{2s^2 - s - 2}{s - z} ds$ , we have

$$g(z) = 2\pi i(2z^2 - z - 2),$$

for  $|z| < 3$ . Hence, it follows that  $g(2) = 8\pi i$ . For  $|z| > 3$ , we have that  $\frac{2s^2 - s - 2}{s - z}$  is analytic at all points interior to and on  $C$ . Hence, by the Cauchy-Goursat theorem, we obtain

$$\int_C \frac{2s^2 - s - 2}{s - z} dz = 0,$$

for  $|z| > 3$ . Therefore,  $g(z) = 0$  when  $|z| > 3$ , which completes the solution for the problem.  $\square$

**Question 7. Brown 170-4.**

**Solution.** Let  $C$  be any simple closed contour, described in the positive sense in the  $z$  plane. As  $s^3 + 2s$  is entire, by the extended Cauchy Integral formula, we obtain

$$6z = \frac{2!}{2\pi i} \int_C \frac{s^3 + 2s}{(s - z)^3} ds,$$

for  $z$  at the interior of  $C$ . As  $g(z) = \int_C \frac{s^3 + 2s}{(s - z)^3} ds$ , we have

$$g(z) = 6\pi iz,$$

for  $z$  inside  $C$ . Now, if  $z$  is outside of  $C$ , then  $\frac{s^3 + 2s}{s - z}$  is analytic at points interior to and on  $C$ . Hence, by the Cauchy-Goursat Theorem, we have that

$$\int_C \frac{s^3 + 2s}{(s - z)^3} ds = 0,$$

for  $z$  outside of  $C$ . Hence  $g(z) = 0$  when  $z$  is outside.  $\square$

**Question 8. Brown 170-7.**

**Solution.** Let  $C$  be the unit circle. As  $e^{az}$  is entire, by the Cauchy Integral formula, we obtain

$$e^{az_0} = \frac{1}{2\pi i} \int_C \frac{e^{az}}{z - z_0} dz,$$

for  $z_0$  inside  $C$ . By taking  $z_0 = 0$ , we get

$$1 = \frac{1}{2\pi i} \int_C \frac{e^{az}}{z} dz,$$

which simplifies to

$$\int_C \frac{e^{az}}{z} dz = 2\pi i.$$

As  $C$  is the unit circle, we have a polar parametrization as  $z = e^{i\theta}$ . Hence, by substitution, we have

$$\begin{aligned} \int_C \frac{e^{az}}{z} dz &= \int_{-\pi}^{\pi} \frac{\exp(ae^{i\theta})}{e^{i\theta}} i e^{i\theta} d\theta \\ &= i \int_{-\pi}^{\pi} \exp(ae^{i\theta}) d\theta \\ &= i \int_{-\pi}^{\pi} e^{a \cos(\theta)} e^{i a \sin(\theta)} d\theta \\ &= i \int_{-\pi}^{\pi} e^{a \cos(\theta)} (\cos(a \sin(\theta)) + i \sin(a \sin(\theta))) d\theta \\ &= - \int_{-\pi}^{\pi} \sin(a \sin(\theta)) d\theta + i \int_{-\pi}^{\pi} e^{a \cos(\theta)} \cos(a \sin(\theta)) d\theta \end{aligned}$$

As the above integral equals  $2\pi i$ , we have

$$\int_{-\pi}^{\pi} e^{a \cos(\theta)} \cos(a \sin(\theta)) d\theta = 2\pi,$$

which, as the integrand is even, simplifies to

$$\int_0^{\pi} e^{a \cos(\theta)} \cos(a \sin(\theta)) d\theta = \pi,$$

as desired.  $\square$

**Question 9. Brown 170-8.**

**Solution.** The Legendre polynomials are defined by

$$P_n(z) = \frac{1}{2^{n+1}\pi i} \int_C \frac{(s^2 - 1)^n}{(s - z)^{n+1}} ds,$$

for any simple closed contour surrounding  $z$ . For  $z = -1$ , and by having  $C$  to be any arbitrary simple closed contour that surrounds  $z = -1$ , it follows that

$$P_n(-1) = \frac{1}{2^{n+1}\pi i} \int_C \frac{(s^2 - 1)^n}{(s + 1)^{n+1}} ds,$$

which, by using the suggestion, simplifies to

$$P_n(z) = \frac{1}{2^{n+1}\pi i} \int_C \frac{(s - 1)^n}{s + 1} ds.$$

Since  $(s - 1)^n$  is entire,  $(s - 1)^n$  is analytic inside and on  $C$ . Hence, by the Cauchy Integral formula, we have

$$(-2)^n 2\pi i = \int_C \frac{(s - 1)^n}{s + 1} ds.$$

Substituting the above equality into the simplified formula of Legendre polynomials yields

$$\begin{aligned} P_n(z) &= \frac{(-2)^n 2\pi i}{2^{n+1}\pi i} \\ &= (-1)^n, \end{aligned}$$

as desired.  $\square$

**Question 10. Brown 177-1.**

**Solution.** Assume that  $f(z)$  is entire, and that the harmonic function  $u(x, y) = \operatorname{Re}[f(z)]$  has an upper bound  $u_0$ . Observe that  $g(z) = e^{f(z)}$  is entire, and

$$|e^{f(z)}| = |e^{u(x,y)+iv(x,y)}| = |e^{u(x,y)}| \leq e^{u_0},$$

as  $u_0$  is an upper bound for  $u(x, y)$ . Therefore, by the Liouville's theorem, we have that  $g$  is constant. Then,  $g'(z) = 0$  for all  $z$ . By the complex chain rule, we obtain

$$g'(z) = f'(z)e^{f(z)}.$$

Since  $e^{f(z)} \neq 0$ , we have  $f'(z) = 0$ , and  $f(z)$  is constant. Hence, the real part  $u(x, y)$  is constant as well.  $\square$