COMPLEX ANALYSIS - Problems

Nicolae Cotfas, version 29 May 2020 (for future updates see   https://unibuc.ro/user/nicolae.cotfas/)

R **Fundamental definitions and results**

R0)
$$(x_1+y_1 i)(x_2+y_2 i)=(x_1 x_2 - y_1 y_2)+(x_1 y_2 + x_2 y_1)i$$
$$\overline{x+yi}=x-yi, \quad |x+yi|=\sqrt{x^2+y^2}, \quad d(z_1,z_2)=|z_1-z_2|$$

R1
$$\frac{1}{1-z}=1+z+z^2+z^3+\dots \quad \text{for } |z|<1$$

R2
$$e^z=1+\frac{z}{1!}+\frac{z^2}{2!}+\frac{z^3}{3!}+\dots \quad \text{for any } z$$

R3 In the neighbourhood of a pole z_0 of order k
$$f(z)=\frac{a_{-k}}{(z-z_0)^k}+\dots+\frac{a_{-1}}{(z-z_0)}+a_0+a_1(z-z_0)+\dots$$
and $\mathbf{Res}_{z_0}f=a_{-1}=\frac{1}{(k-1)!}\lim_{z\to z_0}\left((z-z_0)^k f(z)\right)^{(k-1)}$

R4 Complex integral of $f:D\longrightarrow\mathbb{C}$ along $\gamma:[a,b]\longrightarrow D$ is
$$\int_\gamma f(z)\,dz=\int_a^b f(\gamma(t))\gamma'(t)\,dt$$

R4 **Theorem of Residues.** For an open set $D\subseteq\mathbb{C}$:
$$\begin{array}{l} f:D\longrightarrow\mathbb{C} \text{ holomorphic function}\\ S \text{ set of isolated singular points}\\ \gamma \text{ path homotopic to zero in } D\cup S \end{array} \Rightarrow \begin{array}{l}\int_\gamma f(z)dz=\\ =2\pi i\sum_{z\in S} n(z,\gamma)\mathbf{Res}_z f\end{array}$$

R4 **Lemma 1.** For $\gamma_r:[\alpha,\beta]\longrightarrow\mathbb{C}$, $\gamma_r(t)=re^{it}$
$$\lim_{z\to\infty} z\, f(z)=0 \Rightarrow \lim_{r\to\infty}\int_{\gamma_r} f(z)\,dz=0$$

R5 **Lemma 2 (Jordan).** For $\gamma_r:[0,\pi]\longrightarrow\mathbb{C}$, $\gamma_r(t)=re^{it}$
$$\lim_{z\to\infty} f(z)=0 \Rightarrow \lim_{r\to\infty}\int_{\gamma_r} f(z)e^{iz}\,dz=0$$

A **Problems**

1 $(1-2i)^3=?, \quad \frac{1}{3+4i}=?, \quad e^{\frac{2\pi i}{3}}=?, \quad d(1+i,2-i)=?,$
$(z\sin z)'=?, \quad (e^{z^2})'=?, \quad \lim_{n\to\infty}\left(\frac{n}{n+1}+\frac{1}{n}i\right)=?.$

2 Expand in a power series of z the functions
$$f_1(z)=e^{z^2}, \qquad f_2(z)=z\,e^{\frac{1}{z}}, \qquad f_3(z)=\frac{1}{1-z^2}$$

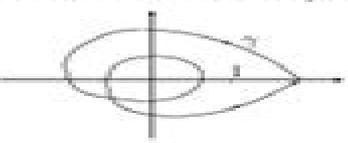*Solution.*
$f_1(z)=1+\frac{z^2}{1!}+\frac{z^4}{2!}+\frac{z^6}{3!}+\dots,$ for any z.
$f_2(z)=z\left(1+\frac{1}{1!}\frac{1}{z}+\frac{1}{2!}\frac{1}{z^2}+\frac{1}{3!}\frac{1}{z^3}+\dots\right)=\dots+\frac{1}{3!}\frac{1}{z^2}+\frac{1}{2!}\frac{1}{z}+1+z$ for $|z|>0$.
$f_3(z)=\frac{1}{z^2}(1+z+z^2+z^3+\dots)=\frac{1}{z^2}+\frac{1}{z}+1+z+\dots$ for $0<|z|<1$.

3 Compute the residues of $f(z)=\frac{1}{z^3(z^2+1)}$

Hint. 0 is a pole of order 3 and $\pm i$ are poles of order 2.

B **Problems**

1 Prove that $f:\mathbb{C}\longrightarrow\mathbb{C}, \quad f(z)=1+\bar{z}$ is not $\mathbb{C}$-differentiable.
Hint. Use the Cauchy-Riemann theorem.

2 For $\gamma:[0,\pi]\longrightarrow\mathbb{C}, \gamma(t)=e^{it}$, compute $\int_\gamma(\bar{z}+i)\,dz$.
Hint. Use the definition of the complex line integral.

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3 Compute the integral $\int_\gamma \frac{1}{z^2(1-z)}\,dz$ where γ is the path from the figure above.
Solution. By using the theorem of residues, we get
$$\int_\gamma \frac{1}{z^2(1-z)}\,dz = 2\pi i(2\,\mathbf{Res}_1 f + \mathbf{Res}_0 f)=2\pi i.$$

4 Compute the residue of $f(z)=z\,e^{\frac{1}{z}}$ at the singular point $z_0=0$.
Solution. $f(z)=\dots+\frac{1}{3!}\frac{1}{z^2}+\frac{1}{2!}\frac{1}{z}+1+z$ for any z $\Rightarrow$ $\mathbf{Res}_0 f=\frac{1}{2}$.
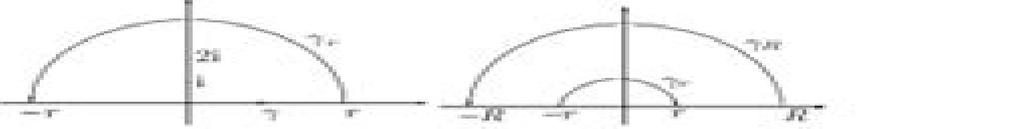
C **Problems**

1 Compute the residues of $f(z)=z^2 e^{\frac{1}{z-1}}$ at the singular point $z_0=1$.
Hint. $f(z)=((z-1)^2+2(z-1)+1)\left(1+\frac{1}{1!}\frac{1}{z-1}+\frac{1}{2!}\frac{1}{(z-1)^2}+\frac{1}{3!}\frac{1}{(z-1)^3}+\dots\right).$

2 Compute the integrals $I_1=\int_0^{2\pi}\frac{1}{2+\cos t}\,dt$ and $I_2=\int_0^{2\pi}\frac{1}{2+\sin t}\,dt$
Solution. By using the path $\gamma:[0,2\pi]\longrightarrow\mathbb{C}$, $\gamma(t)=e^{it}$, we get
$$I_1=\int_0^{2\pi}\frac{1}{2+\frac{e^{it}+e^{-it}}{2}}\,dt=\int_0^{2\pi}\frac{2}{4+e^{it}+e^{-it}}(e^{it})'\,dt$$
$$=-i\int_\gamma \frac{1}{z}\frac{2}{4+z+\frac{1}{z}}\,dz=-i\int_\gamma\frac{2}{z^2+4z+1}\,dz=2\pi\,\mathbf{Res}_{-2+\sqrt{3}}\frac{2}{z^2+4z+1}=\frac{2\pi}{\sqrt{3}}$$

3 Compute the integrals $\int_0^\infty\frac{x^2}{(x^2+1)(x^2+4)}\,dx; \quad \int_0^\infty\frac{x^2}{(x^2+1)(x^2+9)}\,dx$
Solution. The integral is convergent at infinity $\frac{x^2}{(x^2+1)(x^2+4)}\sim\frac{1}{x^2}$.
By using $\gamma_r:[0,\pi]\longrightarrow\mathbb{C}$, $\gamma_r(t)=re^{it}$ and $f(z)=\frac{z^2}{(z^2+1)(z^2+4)}$, we get
$$\int_{\gamma_r} f(z)\,dz+\int_{-r}^r f(x)\,dx=2\pi i\,(\mathbf{Res}_i f+\mathbf{Res}_{2i}f), \quad\text{whence}$$
$$\lim_{r\to\infty}\int_{\gamma_r} f(z)\,dz+\int_{-\infty}^\infty f(x)\,dx=2\pi i\,(\mathbf{Res}_i f+\mathbf{Res}_{2i}f).$$
Since $|z\,f(z)|=\frac{|z|^3}{|(z^2+1)(z^2+4)|}\le\frac{|z|^3}{(|z|^2-1)(|z|^2-4)}$,
we have $\lim_{z\to\infty} z\,f(z)=0$ and in view of lemma 1, $\lim_{r\to\infty}\int_{\gamma_r} f(z)\,dz=0$.
Consequently, $\int_0^\infty f(x)\,dx=\pi i\,(\mathbf{Res}_i f+\mathbf{Res}_{2i}f)=\frac{\pi}{6}$.

4 Prove that $\int_0^\infty\frac{\sin x}{x}=\frac{\pi}{2}$ (Poisson's integral).
Solution. Let $0<r<R$ and $\gamma_R,\gamma_r:[0,\pi]\longrightarrow\mathbb{C}$, $\gamma_R(t)=Re^{it}$, $\gamma_r(t)=r\,e^{i(\pi-t)}$.
From the residue theorem (right hand side of fig.) it follows the relation
$$\int_{\gamma_R}\frac{e^{iz}}{z}\,dz+\int_{-R}^{-r}\frac{e^{ix}}{x}\,dx+\int_{\gamma_r}\frac{e^{iz}}{z}\,dz+\int_r^R\frac{e^{ix}}{x}\,dx=0, \text{ that is}$$
$$\int_{\gamma_R}\frac{e^{iz}}{z}\,dz+\int_{\gamma_r}\frac{e^{iz}}{z}\,dz+\int_r^R\frac{e^{ix}-e^{-ix}}{x}\,dx=0,$$
$$\int_{\gamma_R}\frac{e^{iz}}{z}\,dz+\int_{\gamma_r}\frac{1}{z}\,dz+\int_r^R\frac{e^{ix}-1}{x}\,dz=2i\int_r^R\frac{\sin x}{x}\,dx=0.$$
If g is an antiderivative of $f(z)=\frac{e^{iz}-1}{z}$, by using $\int_{\gamma_r}\frac{1}{z}\,dz=-\pi i$, we get
$$\int_{\gamma_R}\frac{e^{iz}}{z}\,dz-\pi i+(g(r)-g(-r))+2i\int_r^R\frac{\sin x}{x}\,dx=0.$$
But, in view of Jordan's lemma $\lim_{R\to\infty}\int_{\gamma_R}\frac{e^{iz}}{z}=0$,
and for $R\to\infty$ and $r\to0$ we get $2i\int_0^\infty\frac{\sin x}{x}\,dx=\pi i$.

5 Find the holomorphic function $f:\mathbb{C}\longrightarrow\mathbb{C}$ with $\begin{array}{l}\mathfrak{Im}\,f(x+yi)=2xy-2x,\\ f(i)=0.\end{array}$

6 For $z_0\neq0$, expand $f:\mathbb{C}^*\longrightarrow\mathbb{C}$, $f(z)=\frac{1}{z}$ in a power series of $(z-z_0)$.
Solution. We have
$$f(z)=\frac{1}{z_0+z-z_0}=\frac{1}{z_0}\frac{1}{1+\frac{z-z_0}{z_0}}=\frac{1}{z_0}\left(1-\frac{1}{z_0}(z-z_0)+\frac{1}{z_0^2}(z-z_0)^2-\dots\right),$$
$$\text{for } |z-z_0|<|z_0|;$$
$$f(z)=\frac{1}{z_0+z-z_0}=\frac{1}{z-z_0}\frac{1}{1+\frac{z_0}{z-z_0}}=\frac{1}{z-z_0}\left(1-\frac{z_0}{z-z_0}+\frac{z_0^2}{(z-z_0)^2}-\dots\right),$$
$$\text{for } |z-z_0|>|z_0|.$$

7 Expand in a power series of $(z-i)$ the functions:
$$f_1(z)=\frac{1}{z}, \qquad f_2(z)=\frac{1}{z-2i}, \qquad f_3(z)=\frac{1}{z}+\frac{1}{z-2i}.$$

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