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)
$$(x_1+y_1\mathbf{i})(x_2+y_2\mathbf{i})=(x_1x_2-y_1y_2)+(x_1y_2+x_2y_1)\mathbf{i}$$
$$\overline{x+y\mathbf{i}}=x-y\mathbf{i},\quad |x+y\mathbf{i}|=\sqrt{x^2+y^2},\quad d(z_1,z_2)=|z_1-z_2|$$

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

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

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 $\mathbf{Res}_{z_0}f=a_{-1}=\frac{1}{(k-1)!}\lim_{z\to z_0}((z-z_0)^k f(z))^{(k-1)}$

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 $D\subseteq\mathbb{C}$:
$$f:D\longrightarrow\mathbb{C} \text{ holomorphic function}$$
S set of isolated singular points $\Rightarrow$ $\int_\gamma f(z)dz = 2\pi i\sum_{z\in S} n(z,\gamma)\mathbf{Res}_z f$
γ path homotopic to zero in $D\cup S$

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

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

A **Problems**

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

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 $f(z)=\frac{1}{z(z^2+1)^2}$
Hint. 0 is a pole of order 3 and $\pm i$ are poles of order 2.

B **Problems**

1 Prove that $f:\mathbb{C}\longrightarrow\mathbb{C}$, $f(z)=1+\bar z$ 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.

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 $\Rightarrow$ $\mathbf{Res}_0 f=\frac{1}{2}$.
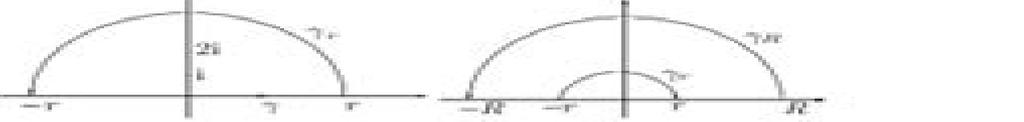
C **Problems**

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
$I_1=\int_0^{2\pi}\frac{1}{2+\frac{e^{it}+e^{-it}}{2}}\,dt=\int_0^{2\pi}\frac{2}{e^{it}+4+e^{-it}}\frac{1}{(e^{it})'}(e^{it})'\,dt$
$=-i\int_\gamma\frac{1}{z}\frac{2}{z+4+\frac{1}{z}}\,dz=-i\int_\gamma\frac{2}{z^2+4z+1}\,dz=2\pi\mathbf{Res}_{-2+\sqrt3}\frac{2}{z^2+4z+1}=\frac{2\pi}{\sqrt3}$

3 Compute the integrals $\int_0^\infty\frac{x^2}{(x^2+1)(x^2+4)}\,dx$; $\int_0^\infty\frac{x^2}{(x^2+4)(x^2+9)}\,dx$
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
$\int_{\gamma_r}f(z)\,dz+\int_{-r}^r f(x)\,dx=2\pi i\,(\mathbf{Res}_i f+\mathbf{Res}_{2i}f)$, 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 $\gamma_R,\gamma_r:[0,\pi]\longrightarrow\mathbb{C}$, $\gamma_R(t)=Re^{it}$, $\gamma_r(t)=re^{i(\pi-t)}$.
From the residue theorem (right hand side of fig.) it follows the relation
$\int_{\gamma_R}\frac{e^{iz}}{z}\,dz+\int_{-R}^{-r}\frac{e^{ix}}{x}\,dx+\int_{\gamma_r}\frac{e^{iz}}{z}\,dz+\int_r^R\frac{e^{ix}}{x}\,dx=0$, that is
$\int_{\gamma_R}\frac{e^{iz}}{z}\,dz+\int_{\gamma_r}\frac{e^{iz}}{z}\,dz+\int_r^R\frac{e^{ix}-e^{-ix}}{x}\,dx=0$,
$\int_{\gamma_R}\frac{e^{iz}}{z}\,dz+\int_{\gamma_r}\frac{1}{z}\,dz+\int_{\gamma_r}\frac{e^{iz}-1}{z}\,dz+2i\int_r^R\frac{\sin x}{x}\,dx=0$.
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 $r\to 0$ 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 $\frac{\partial\mathrm{Im}\,f(x+y\mathbf{i})}{\partial x}=2xy-2x$, $f(i)=0$.

6 For $z_0\ne 0$, expand $f:\mathbb{C}^*\to\mathbb{C}$, $f(z)=\frac{1}{z}$ in a power series of $(z-z_0)$.
Solution. We have
$f(z)=\frac{1}{z_0+z-z_0}=\frac{1}{z_0}\frac{1}{1+\frac{z-z_0}{z_0}}=\frac{1}{z_0}\left(1-\frac{1}{z_0}(z-z_0)+\frac{1}{z_0^2}(z-z_0)^2-\dots\right)$, for $|z-z_0|<|z_0|$;
$f(z)=\frac{1}{z_0+z-z_0}=\frac{1}{z-z_0}\frac{1}{1+\frac{z_0}{z-z_0}}=\frac{1}{z-z_0}\left(1-\frac{z_0}{(z-z_0)}+\frac{z_0^2}{(z-z_0)^2}-\dots\right)$, for $|z-z_0|>|z_0|$.

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

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