

# Complex Analysis Qualifying Exam Notes

D. Zack Garza

Wednesday 5<sup>th</sup> August, 2020

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## Preface

### References

- Simon

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## 1 Definitions

**Definition 1.0.1** (Complex Differentiable).

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Equal to its Taylor series expansion:  $\{ \text{definition title="Analytic"} \}$  ???

Once complex differentiable in neighborhoods of every point:  $\{ \text{definition title="Holomorphic"} \}$  ???

**Definition 1.0.2** (Meromorphic).

???

## 2 Theorems

### 2.1 Basics

**Theorem 2.1** (*Baire Category Theorem*).

The intersection of open dense sets is open.

**Theorem 2.2** (*Mean Value Theorem*).

?

???

**Theorem 2.3** (*Green's Theorem*).

If  $\Omega \subseteq \mathbb{C}$  is bounded with  $\partial\Omega$  piecewise smooth and  $f, g \in C^1(\bar{\Omega})$ , then

$$\int_{\partial\Omega} f dx + g dy = \iint_{\Omega} \left( \frac{\partial g}{\partial x} - \frac{\partial f}{\partial y} \right) dA.$$

**Theorem 2.4** (*Summation by Parts*).

Define the forward difference operator  $\Delta f_k = f_{k+1} - f_k$ , then

$$\sum_{k=m}^n f_k \Delta g_k + \sum_{k=m}^{n-1} g_{k+1} \Delta f_k = f_n g_{n+1} - f_m g_m$$

Note: compare to  $\int_a^b f dg + \int_a^b g df = f(b)g(b) - f(a)g(a)$ .

### 2.2 Integrals and Residues

**Theorem 2.5** ( $\star$  *Cauchy Integral Formula*).

Suppose  $f$  is holomorphic on  $\Omega$ , then

$$f(z) = \frac{1}{2\pi i} \oint_{\partial\Omega} \frac{f(z)}{z-a} dz$$

and

$$\frac{\partial^n f}{\partial z^n}(z) = \frac{n!}{2\pi i} \oint_{\partial\Omega} \frac{f(\xi)}{(\xi-z)^{n+1}} d\xi.$$

The  $n$ th Taylor coefficient of an analytic function is at most  $\sup_{|z|=R} |f|/R^n$ : :::{.theorem title="Cauchy's Inequality"} For  $z_0 \in D_R(z_0) \subset \Omega$ , we have

$$|f^{(n)}(z_0)| \leq \frac{n!}{2\pi} \int_0^{2\pi} \frac{\|f\|_{C_R}}{R^{n+1}} R d\theta = \frac{n! \|f\|_{C_R}}{R^n}.$$

...

These don't quite match up.

*Proof.*

Given  $z_0 \in \Omega$ , pick the largest disc  $D_R(z_0) \subset \Omega$  and let  $C_R = \partial D_R$ . Using the integral formula, defining  $\|f\|_{C_R} = \max_{|z-z_0|=R} |f(z)|$

$$|f^{(n)}(z_0)| \leq \frac{n!}{2\pi} \int_0^{2\pi} \frac{\|f\|_{C_R}}{R^{n+1}} R d\theta = \frac{n! \|f\|_{C_R}}{R^n}.$$

■

## 2.3 Holomorphic and Entire Functions

Integrals of holomorphic functions vanish: :::{.theorem title="Cauchy's Theorem"} If  $f$  is holomorphic on  $\Omega$ , then

$$\int_{\partial\Omega} f(z) dz = 0.$$

...

All integrals vanishing along every triangle implies holomorphic: :::{.theorem title="Morera's Theorem"} If  $f$  is continuous on a domain  $\Omega$  and  $\int_T f = 0$  for every triangle  $T \subset \Omega$ , then  $f$  is holomorphic. ...

**Theorem 2.6 (Liouville).**

If  $f$  is entire and bounded,  $f$  is constant.

## 2.4 Rouché

The logarithmic derivative measures the difference of zeros and poles: :::{.theorem title="Argument Principle"} For  $f$  meromorphic in  $\gamma^\circ$ ,

$$\Delta_\gamma \arg f(z) = 2\pi(Z_f - P_f).$$

...

Argument principle.

**Theorem 2.7(★ Rouché).**

If  $f, g$  are analytic on a domain  $\Omega$  with finitely many zeros in  $\Omega$  and  $\gamma \subset \Omega$  is a closed curve surrounding each point exactly once, where  $|g| < |f|$  on  $\gamma$ , then  $f$  and  $f + g$  have the same number of zeros.

**Alternatively:** Suppose  $f = g + h$  with  $g \neq 0, \infty$  on  $\gamma$  with  $|g| > |h|$  on  $\gamma$ . Then

$$\Delta_\gamma \arg(f) = \Delta_\gamma \arg(h) \quad \text{and} \quad Z_f - P_f = Z_g - P_g.$$

**Example 2.1.** • Take  $P(z) = z^4 + 6z + 3$ .

- On  $|z| < 2$ :
  - Set  $f(z) = z^4$  and  $g(z) = 6z + 3$ , then  $|g(z)| \leq 6|z| + 3 = 15 < 16 = |f(z)|$ .
  - So  $P$  has 4 zeros here.
- On  $|z| < 1$ :
  - Set  $f(z) = 6z$  and  $g(z) = z^4 + 3$ .
  - Check  $|g(z)| \leq |z|^4 + 3 = 4 < 6 = |f(z)|$ .
  - So  $P$  has 1 zero here.

**Example 2.2.** • Claim: the equation  $\alpha z e^z = 1$  where  $|\alpha| > e$  has exactly one solution in  $\mathbb{D}$ .

- Set  $f(z) = \alpha z$  and  $g(z) = e^{-z}$ .
- Estimate at  $|z| = 1$  we have  $|g| = |e^{-z}| = e^{-\Re(z)} \leq e^1 < |\alpha| = |f(z)|$
- $f$  has one zero at  $z_0 = 0$ , thus so does  $f + g$ .

Holomorphic functions preserve open sets: :::{theorem title=“Open Mapping”} Any holomorphic non-constant map is an open map. :::

**Theorem 2.8(Maximum Modulus).**

If  $f$  is holomorphic and nonconstant on an open region  $\Omega$ , then  $|f|$  can not attain a maximum on  $\Omega$ .

If  $\Omega$  is bounded and  $f$  is continuous on  $\bar{\Omega}$ , then  $\max_{\bar{\Omega}} |f|$  occurs on  $\partial\Omega$ .

Conversely, if  $f$  attains a local maximum at  $z_0 \in \bar{\Omega}$ , then  $f$  is constant on  $\Omega$ .

The image of a disc punctured at an essential singularity is dense in  $\mathbb{C}$ : :::{theorem title=“★ Casorati-Weierstrass”} If  $f$  is holomorphic on  $\Omega \setminus \{z_0\}$  where  $z_0$  is an essential singularity, then for every  $V \subset \Omega \setminus \{z_0\}$ ,  $f(V)$  is dense in  $\mathbb{C}$ . :::

**Theorem 2.9(Cayley Transform).**

The fractional linear transformation given by  $F(z) = \frac{i - z}{i + z}$  maps  $\mathbb{D} \longrightarrow \mathbb{H}$  with inverse

$$G(w) = i \frac{1 - w}{1 + w}.$$

Two functions agreeing on a set with a limit point are equal on a domain: :::{theorem title=“Continuation Principle / Identity Theorem”} If  $f$  is holomorphic on a bounded connected domain  $\Omega$  and there exists a sequence  $\{z_i\}$  with a limit point in  $\Omega$  such that  $f(z_i) = 0$ , then  $f \equiv 0$  on  $\Omega$ . :::

**Corollary 2.10.**

The ring of holomorphic functions on a domain in  $\mathbb{C}$  has no zero divisors.

**Theorem 2.11 (Schwarz Reflection).**

If  $f$  is continuous and holomorphic on  $\mathbb{H}^+$  and real-valued on  $\mathbb{R}$ , then the extension defined by  $F(z) = \overline{f(\bar{z})}$  for  $z \in \mathbb{H}^-$  is a well-defined holomorphic function on  $\mathbb{C}$ .

**Remark 1.**

$\mathbb{H}^+, \mathbb{H}^-$  can be replaced with any region symmetric about a line segment  $L \subseteq \mathbb{R}$ .

**Theorem 2.12 (Schwarz Lemma).**

If  $f : \mathbb{D} \rightarrow \mathbb{D}$  is holomorphic with  $f(0) = 0$ , then

1.  $|f(z)| \leq |z|$  for all  $z \in \mathbb{D}$
2.  $|f'(0)| \leq 1$ .

Moreover, if  $|f(z_0)| = |z_0|$  for any  $z_0 \in \mathbb{D}$  or  $|f'(0)| = 1$ , then  $f$  is a rotation

**Theorem 2.13 (Little Picard).**

Todo

???

## 2.5 Conformal Maps

**Theorem 2.14 (Riemann Mapping).**

If  $\Omega$  is simply connected, nonempty, and not  $\mathbb{C}$ , then for every  $z_0 \in \Omega$  there exists a unique conformal map  $F : \Omega \rightarrow \mathbb{D}$  such that  $F(z_0) = 0$  and  $F'(z_0) > 0$ .

Thus any two such sets  $\Omega_1, \Omega_2$  are conformally equivalent.

**Theorem 2.15 (Classification of Conformal Maps).**

There are 8 major types of conformal maps:

- ?
- ?

???

## 3 Stuff

## 3.0.1 Fundamental Theorem of Algebra: Argument Principle

- Let  $P(z) = a_n z^n + \cdots + a_0$  and  $g(z) = P'(z)/P(z)$ , note  $P$  is holomorphic
- Since  $\lim_{|z| \rightarrow \infty} P(z) = \infty$ , there exist an  $R > 0$  such that  $P$  has no roots in  $\{|z| \geq R\}$ .
- Apply the argument principle:

$$N(0) = \frac{1}{2\pi i} \oint_{|\xi|=R} g(\xi) d\xi.$$

- 
- Check that  $\lim_{|z| \rightarrow \infty} zg(z) = n$ , so  $g$  has a simple pole at  $\infty$
  - Then  $g$  has a Laurent series  $\frac{n}{z} + \frac{c_2}{z^2} + \dots$
  - Integrate term-by-term to get  $N(0) = n$ .

### 3.0.2 Fundamental Theorem of Algebra: Rouché's Theorem

- Let  $P(z) = a_n z^n + \dots + a_0$
- Set  $f(z) = a_n z^n$  and  $g(z) = P(z) - f(z) = a_{n-1} z^{n-1} + \dots + a_0$ , so  $f + g = P$ .
- Choose  $R > \max\left(\frac{|a_{n-1}| + \dots + |a_0|}{|a_n|}, 1\right)$ , then

$$\begin{aligned}
|g(z)| &:= |a_{n-1} z^{n-1} + \dots + a_1 z + a_0| \\
&\leq |a_{n-1} z^{n-1}| + \dots + |a_1 z| + |a_0| \quad \text{by the triangle inequality} \\
&= |a_{n-1}| \cdot |z|^{n-1} + \dots + |a_1| \cdot |z| + |a_0| \\
&= |a_{n-1}| \cdot R^{n-1} + \dots + |a_1| R + |a_0| \\
&\leq |a_{n-1}| \cdot R^{n-1} + |a_{n-2}| \cdot R^{n-1} + \dots + |a_1| \cdot R^{n-1} + |a_0| \cdot R^{n-1} \quad \text{since } R > 1 \implies R^{a+b} \geq R^a \\
&= R^{n-1} (|a_{n-1}| + |a_{n-2}| + \dots + |a_1| + |a_0|) \\
&\leq R^{n-1} (|a_n| \cdot R) \quad \text{by choice of } R \\
&= R^n |a_n| \\
&= |a_n z^n| \\
&:= |f(z)|
\end{aligned}$$

- Then  $a_n z^n$  has  $n$  zeros in  $|z| < R$ , so  $f + g$  also has  $n$  zeros.

### 3.0.3 Fundamental Theorem of Algebra: Liouville's Theorem

- Suppose  $p$  is nonconstant and has no roots, then  $\frac{1}{p}$  is entire
- Write  $g(z) := \frac{p(z)}{z^n} = a_n \left( \frac{a_{n-1}}{z} + \dots + \frac{a_0}{z^n} \right)$
- Outside a disc:
  - Note  $\lim_{z \rightarrow \infty} = 0$  for the parenthesized terms, so there exists an  $R$  large enough such that  $|g(z)| \geq \frac{1}{2} |a_n|$
  - Then  $|p(z)| \geq \frac{R^n}{2} |a_n|$  implies  $\frac{1}{p}$  is bounded in  $|z| > R$
- Inside a disc:
  - $p$  is continuous with no roots so  $p$  is bounded below on  $|z| < R$ .
  - $p$  is continuous on a compact set and thus achieves a min  $A$
  - Set  $B = \min(A, \frac{R^n}{2} |a_n|)$ , then  $p \geq B$  on  $|z| < R$ .
- Thus  $p$  is bounded below everywhere and thus  $\frac{1}{p}$  is bounded above everywhere, thus bounded.
- Thus  $\frac{1}{p}$  is constant, forcing  $p$  to be constant.

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### 3.0.4 Fundamental Theorem of Algebra: Open Mapping Theorem

- $p$  induces a continuous map  $\mathbb{CP}^1 \rightarrow \mathbb{CP}^1$
- The continuous image of compact space is compact;
- Since the codomain is Hausdorff space, the image is closed.
- $p$  is holomorphic and non-constant, so by the Open Mapping Theorem, the image is open.
- Thus the image is clopen in  $\mathbb{CP}^1$ .
- The image is nonempty, since  $p(1) = \sum a_i \in \mathbb{C}$
- $\mathbb{CP}^1$  is connected
- But the only nonempty clopen subset of a connected space is the entire space.
- So  $p$  is surjective, and  $p^{-1}(0)$  is nonempty.
- So  $p$  has a root.

## 4 Conformal Maps

Conformal maps  $\mathbb{D} \rightarrow \mathbb{D}$  have the form

$$g(z) = \lambda \frac{1-a}{1-\bar{a}z}, \quad |a| < 1, \quad |\lambda| = 1.$$

### 4.1 Plane to Disc

$$\begin{aligned} \varphi : \mathbb{H} &\rightarrow \mathbb{D} \\ \varphi(z) &= \frac{z-i}{z+i} \quad f^{-1}(z) = i \left( \frac{1+w}{1-w} \right). \end{aligned}$$

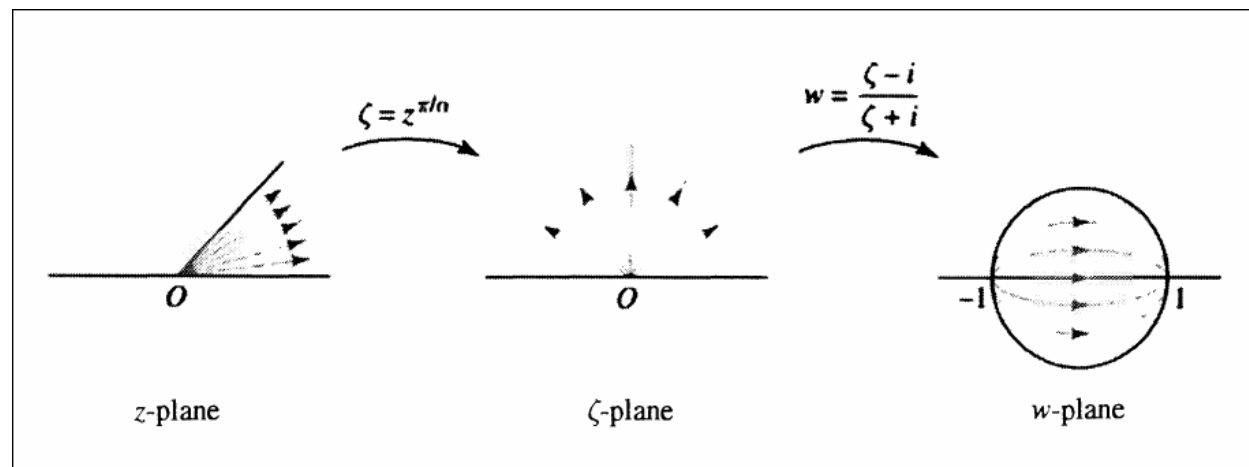
### 4.2 Sector to Disc

For  $S_\alpha := \{z \in \mathbb{C} \mid 0 < \arg(z) < \alpha\}$  an open sector for  $\alpha$  some angle, first map the sector to the half-plane:

$$\begin{aligned} g : S_\alpha &\rightarrow \mathbb{H} \\ g(z) &= z^{\frac{\pi}{\alpha}}. \end{aligned}$$

Then compose with a map  $\mathbb{H} \rightarrow \mathbb{D}$ :

$$\begin{aligned} f : S_\alpha &\rightarrow \mathbb{D} \\ f(z) &= (\varphi \circ g)(z) = \frac{z^{\frac{\pi}{\alpha}} - i}{z^{\frac{\pi}{\alpha}} + i}. \end{aligned}$$



### 4.3 Strip to Disc

- Map to horizontal strip by rotation  $z \mapsto \lambda z$ .
- Map horizontal strip to sector by  $z \mapsto e^z$
- Map sector to  $\mathbb{H}$  by  $z \mapsto z^{\frac{\pi}{\alpha}}$ .
- Map  $\mathbb{H} \rightarrow \mathbb{D}$ .

## 5 Appendix

$$\begin{aligned}
 dz &= dx + i dy \\
 d\bar{z} &= dx - i dy \\
 f_z &= f_x = i^{-1} f_y \\
 \int_0^{2\pi} e^{i\ell x} dx &= \begin{cases} 2\pi & (\ell = 0) \\ 0 & (\ell \neq 0) \end{cases} .
 \end{aligned}$$

### 5.1 Things to know well:

- Estimates for derivatives, mean value theorem

### 5.2 Theorems

#### 5.2.1 The Argument Principle

#### 5.2.2 Rouché

**Theorem (Statement 1)** Suppose  $f = g + h$  with  $g \neq 0, \infty$  on  $\gamma$  with  $|g| > |h|$  on  $\gamma$ . Then

$$\Delta_\gamma \arg(f) = \Delta_\gamma \arg(h) \quad \text{and} \quad Z_f - P_f = Z_g - P_g.$$

### 5.3 Misc Prereq

Standard forms of conic sections:



- Circle:  $x^2 + y^2 = r^2$
- Ellipse:  $\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1$
- Hyperbola:  $\left(\frac{x}{a}\right)^2 - \left(\frac{y}{b}\right)^2 = 1$ 
  - Rectangular Hyperbola:  $xy = \frac{c^2}{2}$ .
- Parabola:  $-4ax + y^2 = 0$ .

Mnemonic: Write  $f(x, y) = Ax^2 + Bxy + Cy^2 + \dots$ , then consider the discriminant  $\Delta = B^2 - 4AC$ :

- $\Delta < 0 \iff$  ellipse
  - $\Delta < 0$  and  $A = C, B = 0 \iff$  circle
- $\Delta = 0 \iff$  parabola
- $\Delta > 0 \iff$  hyperbola

**Completing the square:**

$$x^2 - bx = (x - s)^2 - s^2 \quad \text{where } s = \frac{b}{2}$$

$$x^2 + bx = (x + s)^2 - s^2 \quad \text{where } s = \frac{b}{2}.$$

**Useful Properties**

- $\Re(z) = \frac{1}{2}(z + \bar{z})$  and  $\Im(z) = \frac{1}{2i}(z - \bar{z})$ .
- $z\bar{z} = |z|^2$
- $\cos(\theta) = \frac{1}{2}(e^{i\theta} + e^{-i\theta})$
- $\sin(\theta) = \frac{1}{2i}(e^{i\theta} - e^{-i\theta})$ .

**Useful Series**

$$\sum_{k=1}^n k = \frac{n(n+1)}{2}$$

$$\sum_{k=1}^n k^2 = \frac{n(n+1)(2n+1)}{6}$$

$$\sum_{k=1}^n k^3 = \frac{n^2(n+1)^2}{4}$$

$$\log(z) = \sum_{j=0}^{\infty} (-1)^j \frac{(z-a)^j}{j}$$

**Cauchy-Riemann Equations**

$$u_x = v_y \quad \text{and} \quad u_y = -v_x$$

$$\frac{\partial u}{\partial r} = \frac{1}{r} \frac{\partial v}{\partial \theta} \quad \text{and} \quad \frac{\partial v}{\partial r} = -\frac{1}{r} \frac{\partial u}{\partial \theta}$$

## 5.4 Useful Techniques

**Showing a function is constant:**

- Write  $f = u + iv$  and use Cauchy-Riemann to show  $u_x, u_y = 0$ , etc.
- Show that  $f$  is entire and bounded.

**Showing a function is zero:** Show  $f$  is entire, bounded, and  $\lim_{z \rightarrow \infty} f(z) = 0$ .

**Deriving Polar Cauchy-Riemann:** See walkthrough here. Take derivative along two paths, along a ray with constant angle  $\theta_0$  and along a circular arc of constant radius  $r_0$ . Then equate real and imaginary parts. See problem set 1.

**Computing Arguments:**  $\text{Arg}(z/w) = \text{Arg}(z) - \text{Arg}(w)$ .

The sum of the interior angles of an  $n$ -gon is  $(n-2)\pi$ , where each angle is  $\frac{n-2}{n}\pi$ .

## 5.5 Residues

If  $p$  is a simple pole,  $\text{Res}(p, f) = \lim_{z \rightarrow p} (z-p)f(z)$ . Example: Let  $f(z) = \frac{1}{1+z^2}$ , then  $\text{Res}(i, f) = \frac{1}{2i}$ .

Green's Theorem: Todo

$$\frac{\partial}{\partial z} \sum_{j=0}^{\infty} a_j z^j = \sum_{j=0}^{\infty} a_{j+1} z^j.$$

Basics

- Show that  $\frac{1}{z} \sum_{k=1}^{\infty} \frac{z^k}{k}$  converges on  $S^1 \setminus \{1\}$  using summation by parts.
- Show that any power series is continuous on its domain of convergence.
- Show that a uniform limit of continuous functions is continuous.

??

- Show that if  $f$  is holomorphic on  $\mathbb{D}$  then  $f$  has a power series expansion that converges uniformly on every compact  $K \subset \mathbb{D}$ .
- Show that any holomorphic function  $f$  can be uniformly approximated by polynomials.
- Show that if  $f$  is holomorphic on a connected region  $\Omega$  and  $f' \equiv 0$  on  $\Omega$ , then  $f$  is constant on  $\Omega$ .
- Show that if  $|f| = 0$  on  $\partial\Omega$  then either  $f$  is constant or  $f$  has a zero in  $\Omega$ .

- Show that if  $\{f_n\}$  is a sequence of holomorphic functions converging uniformly to a function  $f$  on every compact subset of  $\Omega$ , then  $f$  is holomorphic on  $\Omega$  and  $\{f'_n\}$  converges uniformly to  $f'$  on every such compact subset.
- Show that if each  $f_n$  is holomorphic on  $\Omega$  and  $F := \sum f_n$  converges uniformly on every compact subset of  $\Omega$ , then  $F$  is holomorphic.
- Show that if  $f$  is once complex differentiable at each point of  $\Omega$ , then  $f$  is holomorphic.