

# Complex Analysis

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*Complex Analysis - Comprehensive Note*

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## **Part I**

# **Functions of a Complex Variable**

# Chapter 1

## Sets in the Complex Plane

We already have scratched the basics of working with the **imaginary unit**  $j = \sqrt{-1}$  in other coursework, and it will not be covered again for the 845th time! If you need a refresher, [try this out!](#) In this chapter we will be talking about types of sets in the complex plane, some formal definitions and what they geometrically are, we do this so that we can eventually work our way up to understanding functions of a complex variable.

### 1.1 Terminology

Lets start by introducing some essential terminology about sets in the complex plane.

Suppose we have some  $z_0 = x_0 + jy_0$ . Since the expression  $|z - z_0|$  represents the distance between points  $z$  and  $z_0$  on the complex plane, we can denote **a circle**, in other words set of circular points lying on some radial distance  $\rho$  from a center point  $z_0$  as Equation 1.1

$$|z - z_0| = \rho \tag{1.1}$$

This means that  $|z| = 1$  is the unit circle centered at the origin, and that  $|z - 1 - 2j| = 5$  is a circle of radius 5, centered at the

point  $1 + 2j$ . What happens if we modify the equality in Equation 1.1 to the inequality seen in Equation 1.2?

$$|z - z_0| < \rho \quad (1.2)$$

The inequality in Equation 1.2 is called the **neighborhood of  $z_0$**  or an **open disk**. It defines the set of points that lie within, but not on the circle defined by Equation 1.1.

## 1.2 Interior, Exterior & Boundary Points

Using this definition of the neighborhood in Equation 1.2 we can formally define an **interior point**. A point  $z_0$  is said to be an interior point of some set  $S$  of the complex plane if there exists some (possibly infinitely small!) neighborhood of  $z_0$  that lies entirely within  $S$ .

Through the same logic, a point  $z_0$  is said to be an **exterior point** of some set  $S$  if there exists some (possibly infinitely small!) neighborhood of  $z_0$  that lies entirely outside of  $S$ .

We can also say that a point  $z_0$  is said to be a **boundary point** of the set  $S$  if *every* neighborhood of  $z_0$  contains at least one point within  $S$ , and one point outside of  $S$ .

## 1.3 Open & Closed Sets

Now that we have formally defined the three types of points, we can talk about **open-sets** and **closed-sets**.

If every point within a set  $S$  is an interior-point, the set  $S$  is said to be an **open-set**. If this condition is not met, this means that the set possesses boundary points, and it is called a **closed-set**.

This is basically a strange way of saying that open-sets have no boundaries. The set defined in Equation 1.2 is an example of an open-set because for every point within the set we can get infinitely closer and closer to the boundary without ever touching the boundary. On the other hand a closed-set does have a boundary and if we take a point on the boundary, some of this point's neighborhood will lie outside the set  $S$ , rendering it a non-open (closed) set.

Open sets manifest when there is no semblance of an 'equals' in the inequality, and closed sets manifest when there are semblances of the 'equals'. For example, the symbols  $\geq, \leq$  define a closed set, while the symbols  $<, >$  define an open set. Here are some examples of open-sets

- $\text{Im}(z) > 0$  - The upper-half of the complex plane
- $1 < \text{Re}(z) < 2$  - An infinitely tall strip
- $|z| > 1$  - The exterior of a unit circle
- $1 < |z| < 2$  - The open annulus (donut) centered at the origin with inner radius 1 and outer radius 2.

Through these examples we can see that the inequality in Equation 1.3 represents the general **open-annulus** centered at  $z_0$ , with inner and outer radii of  $\rho_1$  and  $\rho_2$  respectively. There is a lot of other stuff that we can cover related to sets, but it is not required to understand the preceeding chapters.

$$\rho_1 < |z - z_0| < \rho_2 \tag{1.3}$$

## Chapter 2

# Functions of a Complex Variable

Now that we have defined what sets are in the complex plane, we will have noticeably easier time thinking about what **functions of a complex variable** are. Recall that a function is essentially a sort of **correspondance** between two sets: the input, and the output. Each element in the input set is mapped to only one element in the output set. While the same element in the output set can be reached through multiple elements in the input set. Every  $x$  produces only one  $y$ , but every  $y$  may have more than one  $x$  that produces it.

### 2.1 *Complex Functions*

Suppose we have some real valued function  $y = f(x)$ . If the domain of this function is extended to include the complex numbers  $z$ , we call it a **function of a complex variable** - or a **complex function** for short. We also write it in a slightly differently as Equation 2.1 to imply that it is a complex function.

The image (output)  $w$ , of a complex number (input)  $z$ , will be some complex number  $u + jv$  Where  $u$  and  $v$  are the real and imaginary parts of  $w$ , and are entirely-real valued functions. In other words, we can define some complex function in terms



of purely  $u$  and  $v$ . This fact is also shown in Equation 2.1

$$w = f(z) = u(x, y) + jv(x, y) \quad (2.1)$$

Although we cannot draw a 4-dimensional graph to represent a complex-function. We can think of it as a **mapping between planes**. more specifically, from the input-plane ( $z$ -plane) to the output-plane ( $w$ -plane) This is shown in Figure 2.1

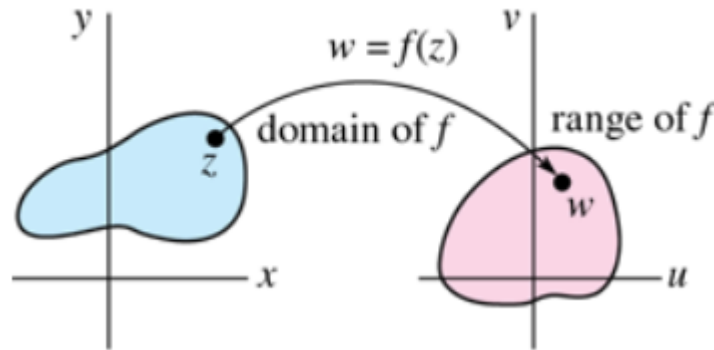


Figure 2.1: The mapping from  $z$ -plane to  $w$ -plane

## 2.2 Limits & Continuity

The **limit-definition of a complex function** looks the same as the epsilon-delta limit-definition for real valued functions. All it means is that the points  $f(z)$  can be made arbitrarily close to the point  $L$  if we choose a point  $z$  close to, but never equal to the point  $z_0$ .

$$\lim_{z \rightarrow z_0} f(z) = L \quad (2.2)$$

The fundamental difference between the limits of real-valued functions and complex functions lies in the geometric meaning of the limit. For real-valued functions, we can approach from either the left or the right, but for complex functions we should approach the same thing no matter what path we follow. In other words: when we say that the limit in Equation 2.2 exists, we mean that  $f(z)$  approaches  $L$  as the point  $z$  approaches  $z_0$  from *any* direction. The properties of limits are the exact-same as real valued limits.

A complex function is said to be **continuous** at a point  $z_0$  if the equality in Equation 2.3 holds true, which makes sense.

$$\lim_{z \rightarrow z_0} f(z) = f(z_0) \quad (2.3)$$

## 2.3 Complex Derivatives

Now that we have discussed the basics of limits and continuity for complex functions, the next question to ask is “what is a complex derivative?”. As we will see, this is very different from asking that its real and imaginary parts have partial derivatives with respect to  $x$  and  $y$ .

We can say that a complex function  $f(z)$  is **complex differentiable** at  $z_0$  if the limit in equation 2.4 or 2.5 exists. These are the regular definitions of a derivative, thus the **real-valued rules of differentiation are the same** as the complex differentiation.

If a complex function is differentiable at point  $z_0$  and at every point in some neighborhood of  $z_0$  we call that function an **analytic function**.

$$f'(z_0) = \lim_{h \rightarrow 0} \frac{f(z_0 + h) - f(z_0)}{h} \quad (2.4)$$

$$f'(c) = \lim_{z \rightarrow c} \frac{f(z) - f(z_0)}{z - z_0} \quad (2.5)$$

Another useful thing to know about analyticity of functions is that **if we can express a complex-function as a rational function** (numerator and denominator are polynomials) we can say that **the function is analytic** wherever the denominator is not equal to zero. This is shown below. The only requirement here is that  $N$  and  $D$  are polynomials.

*Recall:* This is the case because the limits of complex-polynomials exist everywhere, so they are differentiable and analytic everywhere, thus the rational function is only non-analytic wherever the fraction is undefined (denominator is 0).

$$\text{if } f(z) = \frac{N(z)}{D(z)}, \text{ then } f \text{ is analytic wherever } D(z) \neq 0$$

## 2.4 Cauchy-Riemann Equations

We now turn to the question of systematically deciding when some complex function is differentiable. If the complex derivative exists at some point  $z$  then we should be able to compute it via any path we choose. Let's choose to approach them via purely horizontal and vertical paths. We can use Equation 2.4 to carry this out.

*Note:* In each of the two limits in the equation below corresponds to approaching the limit horizontally (along a purely real  $t$ ) or vertically (along a purely imaginary  $t$ ), all for some  $t \in \mathbb{R}$ .

$$f'(z) = \lim_{t \rightarrow 0} \frac{f(z+t) - f(z)}{t} = \lim_{t \rightarrow 0} \frac{f(z+jt) - f(z)}{jt}$$

We can rewrite this in terms of  $u$  and  $v$ . First let's approach the derivative along a horizontal line. We can see that this simplifies into the definitions of the partial derivatives of  $u$  and  $v$  in Equation 2.6

$$\begin{aligned} f'(z) &= \lim_{t \rightarrow 0} \frac{u(x+t, y) + jv(x+t, y) - u(x, y) - jv(x, y)}{t} \\ f'(z) &= \lim_{t \rightarrow 0} \frac{u(x+t, y) - u(x, y)}{t} + j \lim_{t \rightarrow 0} \frac{v(x+t, y) - v(x, y)}{t} \\ f'(z) &= \frac{\partial u}{\partial x} + j \frac{\partial v}{\partial x} \end{aligned} \tag{2.6}$$

Now if we approach the derivative along a vertical line, we can see similar partial derivatives appear in Equation 2.7, but this time with respect to  $y$  instead of  $x$

$$f'(z) = \lim_{t \rightarrow 0} \frac{u(x, y+t) + jv(x, y+t) - u(x, y) - jv(x, y)}{jt}$$

$$f'(z) = -j \lim_{t \rightarrow 0} \frac{u(x, y+t) - u(x, y)}{t} + \lim_{t \rightarrow 0} \frac{v(x, y+t) - v(x, y)}{t}$$

$$f'(z) = \frac{\partial v}{\partial y} - j \frac{\partial u}{\partial y} \quad (2.7)$$

We can now equation Equations 2.6 and 2.7 by equating real and imaginary components. In doing so we obtain the **Cauchy-Riemann Equations**. Which tell us the complex values ( $z$  values) where a function is differentiable.

We can use these equations to test analyticity of a function on some domain  $D$  by checking if they are differentiable everywhere on this domain  $D$  (are the cauchy-riemann equations satisfied everywhere in  $D$ ?).

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y}$$

$$\frac{\partial v}{\partial x} = -\frac{\partial u}{\partial y}$$

## 2.5 Using the Cauchy-Riemann Equations

Lets use the equations we just derived to show that the function  $f(z) = |z|^2$  is differentiable only at  $z = 0$ , and analytic nowhere.

$$f(z) = |z|^2 = (x^2 + y^2) + j(0)$$

This gives  $u = x^2 + y^2$  and  $v = 0$ . Thus the Cauchy-Riemann Equations reduce to the equations below, which are only simultaneously satisfied when  $x = y = 0$ . This function is only differentiable at a single point,  $z = 0$  thus it is analytic nowhere (*Recall*: analyticity is a neighborhood property)

$$2x = 0$$

$$0 = -2y$$

## 2.6 Relation to Laplace's Equation

Suppose we have some analytic function (aka function that is differentiable everywhere)  $f(z) = u + jv$  we call its constituent functions  $u$  and  $v$  **harmonic functions** because they can be related to **Laplace's Equation** (Steady State Heat) through the **Cauchy-Riemann Equations**.

Let's write the Cauchy-Riemann Equations, and partially differentiate one of these equations w.r.t  $x$ , the other to  $y$ .

$$\begin{aligned}\frac{\partial^2 u}{\partial x^2} &= \frac{\partial v}{\partial x \partial y} \\ -\frac{\partial v}{\partial x \partial y} &= \frac{\partial^2 u}{\partial y^2}\end{aligned}$$

We can combine these to get the following relation to Laplace's equation. We can follow a similar process (switching the equation differentiation variables) to prove the second line.

$$\begin{aligned}\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} &= 0 \\ \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} &= 0\end{aligned}$$

## Chapter 3

# Complex Function Families

There are a couple families of functions that behave differently when their domain is extended to include the complex plane. In this chapter we will learn about them.

### *3.1 The Exponential Function*

Recall that real-valued exponential function has the following properties

$$\frac{d}{dx} [e^x] = e^x$$

$$e^{x+y} = e^x e^y$$

If we define the **complex-valued exponential** in terms of the complex variable  $z = x + jy$ .

$$w = e^z = e^{x+jy}$$

Then by properties of the real-valued exponential we can write the following. Giving the formal definition of the complex-argument exponential function in Equation 3.1

*Note:* the complex-valued exponential reduces to the real-valued one when  $y = 0$

$$\begin{aligned} e^z &= e^x e^{jy} \\ e^z &= e^x (\cos y + j \sin y) = e^x \cos y + j e^x \sin y \end{aligned} \quad (3.1)$$

Through Equation 2.6 or 2.7 you can prove that **the complex exponential satisfies both properties** shown at the start of this section. The complex exponential is also said to be periodic with a complex period  $2\pi j$ .

## 3.2 Logarithmic Function

The **logarithm of a complex number**  $z = x + jy$  is defined as the **inverse of the complex-exponential** function. That is  $w = \ln z$  if  $z = e^w$ . Just like the real-valued logarithm, the complex-logarithm is not defined at  $z = 0$ .

to find the the real and imaginary parts of the logarithm, we write  $w = u + jv$ .

$$\begin{aligned} z &= e^w \\ x + jy &= e^u \cos v + j e^u \sin v \end{aligned}$$

This implies that  $x = e^u \cos v$ , and that  $y = e^u \sin v$ . We can solve these for  $u$  and  $v$  (the real and complex parts of the  $\ln$ ) by squaring both of these results and adding them together. This gives a solution for  $u$ .

*Note:* here the  $u$  value is the natural logarithm of the modulus (a real-number)

$$\begin{aligned} e^{2u} (1) &= x^2 + y^2 = |z|^2 \\ u &= \ln |z| \end{aligned}$$

To solve for  $v$ , we have to divide both equations, to obtain the following. The below equation means that  $v$  is  $\theta$ , the argument of  $z$

$$v = \arctan \frac{y}{x}$$

This gives a final definition of the complex-logarithm, which depends on the mod and (non-unique) argument of  $z$

$$\ln z = \ln |z| + j \arg(z)$$



## **Part II**

# **Integration in the Complex Plane**

## Chapter 4

# Complex Contour Integration

Integration in the complex plane is defined in a somewhat similar manner to that of a line integral in the plane. In other words, we will be dealing with an integral of a complex function  $f(z)$  that is defined along a curve  $C$  in the complex plane.

These curves are parametrized in  $t \in \mathbb{R}$  with equations  $x = x(t)$  and  $y = y(t)$ . By using  $x$  and  $y$  as the real and imaginary parts, we can parametrize a curve  $C$  in the complex plane by means of a real-variable.

### 4.1 Defining the Complex Integral

Since the complex plane is a 2-dimensional plane, every complex integral is at least a complex contour integral, leading to the nomenclature of calling them **complex integrals**. We can start to define the complex integral similarly to how we would a real integral. This leads to the general definition of a complex integral in Equation 4.1

$$\int_C f(z) dz = \lim_{\Delta z \rightarrow 0} \sum f(z) \Delta z$$
$$\int_C f(z) dz = \lim_{\Delta x, \Delta y \rightarrow 0} \sum (u + jv) (\Delta x + j\Delta y)$$

$$\begin{aligned}\int_C f(z) dz &= \lim_{\Delta x, \Delta y \rightarrow 0} \sum (u\Delta x - v\Delta y) + j(v\Delta x + u\Delta y) \\ \int_C f(z) dz &= \int_C u dx - v dy + j \int_C v dx + u dy\end{aligned}\tag{4.1}$$

## 4.2 Evaluation of a Complex Integral

Evaluate the integral below, given that the curve  $C$  can be parametrized as  $x = 3t$ ,  $y = t^2$ , for  $t \in [-1, 4]$ .

$$\int_C \bar{z} dz$$

To begin lets write  $z(t) = x(t) + jy(t)$ . Lets also find  $z'(t)$ . This means that the integrand (complex conjugate) has its middle sign flipped. Note that we are also finding  $dz$  and not  $d\bar{z}$ .

$$z(t) = 3t + jt^2$$

$$\frac{dz}{dt} = 3 + j2t$$

$$\bar{z}(t) = 3t - jt^2$$

We can now entirely parametrize the integral. We get the following computable line integral upon doing so. At this point the question is basically done, we evaluate the integral and simplify the result into its real and complex parts.

$$\int_{-1}^4 (3t - jt^2)(3 + j2t) dt = 196 + 65j$$

## 4.3 Fundamental Theorem of Complex Contour Integrals

Just like in multivariate calculus, we can show (and come up with) a formulation that proves the independence of path for a complex line integral.

Suppose  $f$  is continuous (analytic) in  $D$ . If there exists a function,  $F$  such that it is antiderivative of  $f$  in  $D$ . Then for any contour  $C$  in  $D$  with an initial point  $z_0$  and terminating point  $z_1$  we can write:

$$\int_C f(z) dz = F(z_1) - F(z_0)$$

## Chapter 5

# Cauchy-Goursat Theorem

In this chapter we will learn the **cauchy-goursat** theorem, which is just a complex sounding term for something very simple!

### 5.1 *The Cauchy-Goursat Theorem*

The theorem in question tells us that if we are taking the closed contour integral of some complex function  $f(z)$  on some closed contour  $C$ , the result will be zero if  $f$  is analytic in the region enclosed by  $C$ .

$$\text{if } f \text{ is analytic within } C \dots \oint_C f(z) dz = 0$$

*Note:* When evaluating complex-integrals, another theorem for analyticity that is very useful was briefly covered in Section 2.3. The theorem tells us that if a complex-function can be expressed as a ratio between polynomials in  $z$ . Then the function is differentiable and analytic everywhere except where the denominator is equal to 0.

## 5.2 Deforming Contours

Suppose the function we are trying to take the contour integral of is analytic everywhere, except for a point within the closed contour. The simple process of **deformation of contours** helps us avoid having to actually take the line integral here. Consider the orange region in Figure 5.1 which represents the regions of analyticity. What would we do if we were trying to find the contour integral of  $C_1$ ?

Consider the fact that we can connect the two contours in (a) by going through points A and B, and that by doing this, we only encircle a region where the function is fully analytic, thus the entire thing would equal to 0. We would then arrive at the following formulation. Given that the line integrals from A to B and B to A cancel out, we are left with Equation 5.1.

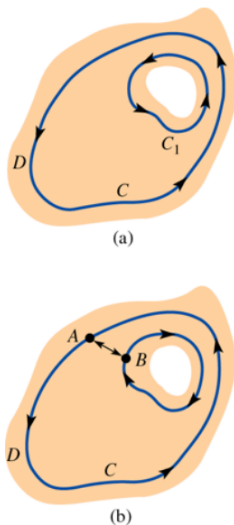


Figure 5.1: Deforming a contour for a Doubly-Connected Domain

$$\oint_C + \int_{AB} - \oint_{C_1} + \int_{BA} = 0$$

$$\oint_C f(z) dz = \oint_{C_1} f(z) dz \quad (5.1)$$

We can do this for any number of smaller closed contours  $C_n$  within a larger (encompassing) contour  $C$ . We can repeat the process above for **multiply connected domains** and come to Equation 5.2. Figure 5.2 shows the process for a triply-connected-domain where  $n = 2$

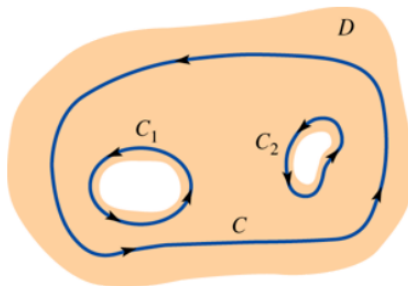


Figure 5.2: Deforming a contour for a Triply-Connected Domain

$$\oint_C f(z) dz = \sum_n \oint_{C_n} f(z) dz \quad (5.2)$$

### 5.3 Applying Deformation of Contours

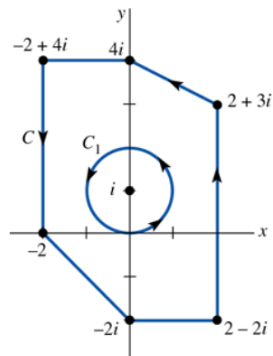


Figure 5.3: Evaluate  $\oint_C (z - j)^{-1} dz$  where  $C$  is the outer contour

Using deformation of contours (our function  $z^2$  is a polynomial and is analytic everywhere) we can conclude that the complicated contour integral around  $C$  is equal to the simpler contour integral around the circle  $|z - j| = 1$ , which we can parametrize as  $x = \cos t$ ,  $y = 1 + \sin t$ , for  $t \in [0, 2\pi]$ . Now we can write our definition of  $z$

$$z = x + jy = \cos t + j(1 + \sin t)$$

$$z = \cos t + j \sin t + j = j + e^{jt}$$

$$z - j = e^{jt}$$

$$\frac{dz}{dt} = je^{jt}$$



Now we can do our integral, which gives us the following result

$$\oint_C \frac{dz}{z-j} = \int_0^{2\pi} \frac{je^{jt}}{e^{jt}} dt = 2\pi j$$

## Chapter 6

# Cauchy-Integrals

### 6.1 A Useful Theorem

The integral we come across at the end of section 5.3 can be generalized using deformation of contours. Suppose we had to evaluate the following integral instead...

$$\oint_C \frac{1}{(z - z_0)^n} dz$$

Lets pick a simpler contour  $C_1$  with radius 1 such that the point  $z_0$  is an interior point to this integral, for simplicity lets simply center the contour  $C_1$  at  $z_0$  such that it is guaranteed to be an interior point. Via deformation of contours, we can say that the below integral is equal to our original one.

$$\oint_{C_1} \frac{1}{(z - z_0)^n} dz$$

Now lets parametrize our complex with  $x = \operatorname{Re}\{z_0\} + \cos t$ ,  $y = \operatorname{Im}\{z_0\} + \sin t$ , for  $t \in [0, 2\pi]$ .

$$z = x + jy = (\operatorname{Re}\{z_0\} + j\operatorname{Im}\{z_0\}) + (\cos t + j \sin t)$$

$$\begin{aligned}
z &= z_0 + e^{jt} \\
z - z_0 &= e^{jt} \\
(z - z_0)^n &= e^{njt} \\
\frac{dz}{dt} &= je^{jt}
\end{aligned}$$

Our integral now becomes

$$\begin{aligned}
&j \int_0^{2\pi} \frac{e^{jt}}{e^{njt}} dt \\
&j \int_0^{2\pi} \exp((1-n)jt) dt = \left. \frac{\exp((1-n)jt)}{1-n} \right|_0^{2\pi}
\end{aligned}$$

Which evaluates to the following. The numerator is a complex exponential with an argument that is always a multiple of  $2\pi j$ , which means it is a phasor of magnitude 1, and angle always on the x-axis (always just a 1). This is the case for all values except for  $n = 1$ , where the output is undefined.

We also must somehow evaluate the expression as  $n = 1$  (which should equal  $2\pi j$ ), which I have no clue how to do properly here. Regardless, **this is as close as possible to showing that the theorem below holds true.**

$$\frac{\exp((1-n)2\pi j) - 1}{1-n} = \begin{cases} 0, & n \in \mathbb{Z} \neq 1 \\ 2\pi j, & n \in \mathbb{Z} = 1 \end{cases}$$

We did all this work to show that the following is true, considering the earlier expression is **the result of our very first integral**, we can say that:

$$\oint_C \frac{1}{(z - z_0)^n} dz = \begin{cases} 0, & n \in \mathbb{Z} \neq 1 \\ 2\pi j, & n = 1 \end{cases} \quad (6.1)$$

## 6.2 Cauchy's Integral Formula

Suppose we have some analytic  $f$  over some simply-connected domain  $D$ . Let  $C$  be a simple-closed-contour lying entirely within  $D$ . Then if  $z_0$  is any point within  $C$ , we can say the following.

$$f(z_0) = \frac{1}{2\pi j} \oint_C \frac{f(z)}{z - z_0} dz \quad (6.2)$$

This can be easily shown by adding and subtracting  $f(z_0)$  in the numerator.

$$\begin{aligned} \oint_C \frac{f(z)}{z - z_0} dz &= \oint_C \frac{f(z) + f(z_0) - f(z_0)}{z - z_0} dz \\ \oint_C \frac{f(z)}{z - z_0} dz &= \oint_C \frac{f(z_0)}{z - z_0} dz + \oint_C \frac{f(z) - f(z_0)}{z - z_0} dz \\ \oint_C \frac{f(z)}{z - z_0} dz &= f(z_0) \oint_C \frac{1}{z - z_0} dz + \oint_C \frac{f(z) - f(z_0)}{z - z_0} dz \end{aligned}$$

We have shown in equation 6.1 that the first term is equal to  $2\pi j$ , and through some fancy pure math stuff the second term cancels out. Leaving the following as an equivalent expression to equation 6.2

$$\oint_C \frac{f(z)}{z - z_0} dz = 2\pi j f(z_0)$$

This formula is useful, because we can avoid doing the integral completely if we recognize an  $f(z)$  from an integral in the form of equation 6.2, and evaluate the integral by finding the value of  $f(z_0)$ , and maybe multiplying it by  $2\pi j$