



Lecture 2

Complex Functions (複素関数)

What you will learn in Lecture 2

2.1 Complex Functions (複素関数)

2.2 Complex Function as Mappings (写像、変換)

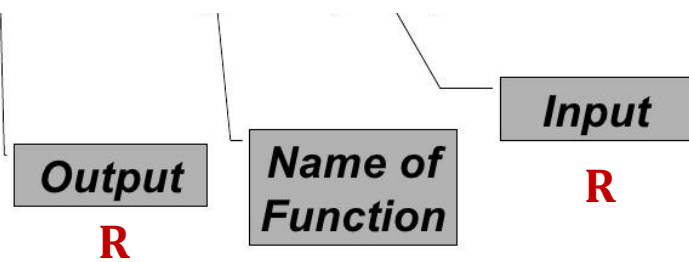
2.3 Limits (極限) and Continuity (連続性)

2.1 Complex Functions

(複素関数)

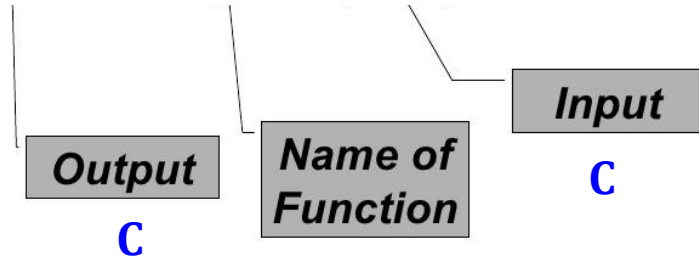
2.1 Complex Functions (複素関数)

$$y = f(x)$$



real-valued functions (実数値関数)
of a real variable (実変数)

$$w = f(z)$$



complex-valued function of a
complex variable (複素変数)

Definition (定義) 2.1 Complex Function (複素関数)

A **complex function (複素関数)** is a function f whose **domain (定義域)** and **range (値域)** are subsets of the set \mathbf{C} of complex numbers.

We denote the domain and range of a function f by $\text{Dom}(f)$ and $\text{Range}(f)$, respectively.

2.1 Complex Functions (複素関数)

EXAMPLE (例題) 2.1.1 Complex Function (複素関数)

(a) Evaluate $f(z) = z^2 - (2 + i)z$ when (1) $z = i$ and (2) $z = 1 + i$

(b) Evaluate $g(z) = z + 2\operatorname{Re}(z)$ when (1) $z = i$ and (2) $z = 2 - 3i$

Solution (解答):

$$(a) \quad (1) \quad f(i) = i^2 - (2 + i)(i) = -1 - 2i + 1 = -2i.$$

$$\begin{aligned} (2) \quad f(1 + i) &= (1 + i)^2 - (2 + i)(1 + i) \\ &= (1 + 2i - 1) - (2 + 2i + i - 1) = -1 - i. \end{aligned}$$

$$(b) \quad (1) \quad g(i) = i + 2\operatorname{Re}(i) = i + 2 \cdot (0) = i$$

$$(2) \quad g(2 - 3i) = 2 - 3i + 2\operatorname{Re}(2 - 3i) = 2 - 3i + 2 \cdot (2) = 6 - 3i$$

Notice: When the domain (定義域) of a complex function (複素関数) is not explicitly stated, we assume the domain (定義域) to be the set of all complex numbers z for which $f(z)$ is defined.

2.1 Complex Functions (複素関数)

Real and Imaginary Parts of a Complex Function

If $w = f(z)$ is a complex function (複素関数), then the image (値域) of a complex number $z = x + iy$ under f is a complex number $w = u + iv$.

For example, suppose we have the complex function $w = f(z) = z^2$, then

$$\begin{aligned} w = z^2 &= (x + iy)^2 = (x^2 - y^2) + 2xyi \\ &= u + iv \end{aligned} \tag{2.1.1}$$

It shows that, if $w = u + iv = f(z) = f(x + iy)$ is a complex function, then both u and v are real functions of the two real variables x and y , i.e.

$$w = f(z) = u(x, y) + iv(x, y) \tag{2.1.2}$$

The functions (i.e. 実2変数関数) $u(x, y)$ and $v(x, y)$ in (2.1.2) are called the real and imaginary parts of f , respectively.

2.1 Complex Functions (複素関数)

EXAMPLE (例題) 2.1.2

If $z = x + iy$, find the real and imaginary parts (実部と虚部) of the functions (a) $f(z) = z^2 - (2 + i)z$ (b) $g(z) = z + 2\operatorname{Re}(z)$

Solution (解答):

$$\begin{aligned} \text{(a) } f(z) &= z^2 - (2 + i)z = (x + iy)^2 - (2 + i)(x + iy) \\ &= x^2 + 2xyi - y^2 - (2x + 2yi + ix - y) \\ &= x^2 - 2x + y - y^2 + (2xy - x - 2y)i \end{aligned}$$

$$\text{Therefore } u(x, y) = x^2 - 2x + y - y^2 \quad v(x, y) = 2xy - x - 2y$$

$$\text{(b) } g(z) = z + 2\operatorname{Re}(z) = x + iy + 2\operatorname{Re}(x + iy) = x + iy + 2x = 3x + iy$$

$$\text{Therefore } u(x, y) = 3x \quad v(x, y) = y$$

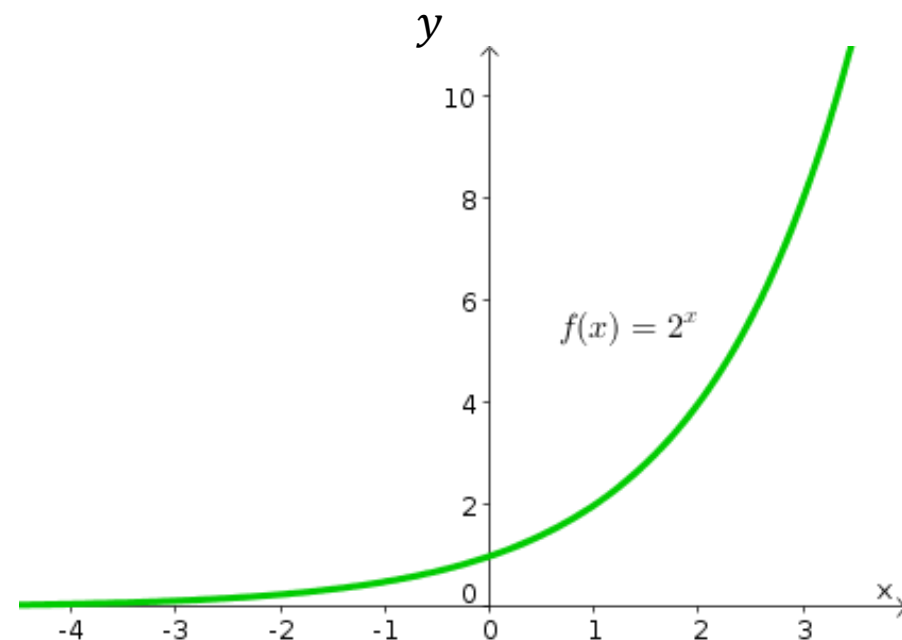
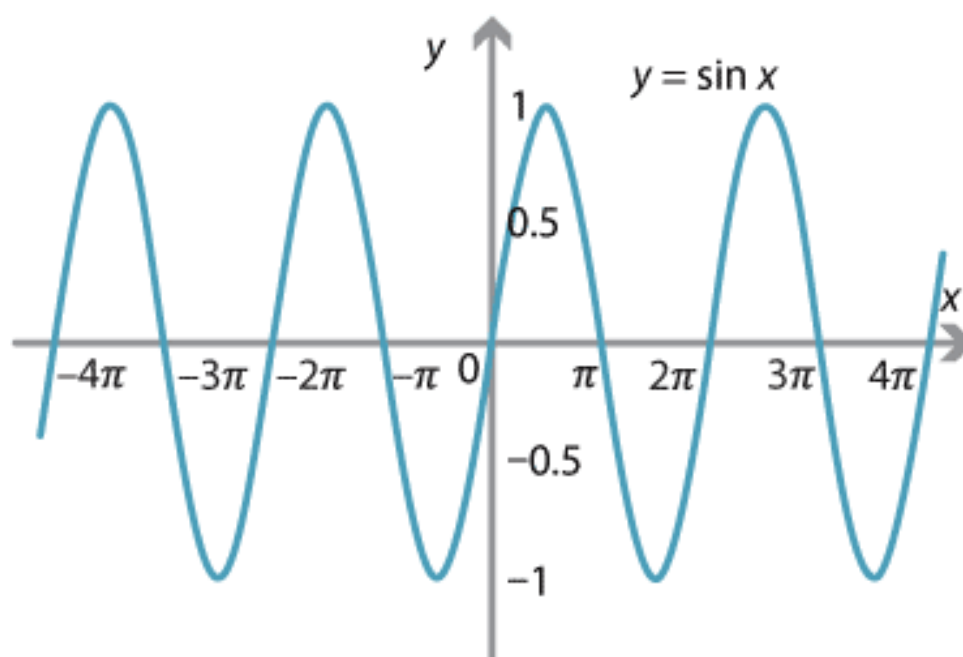
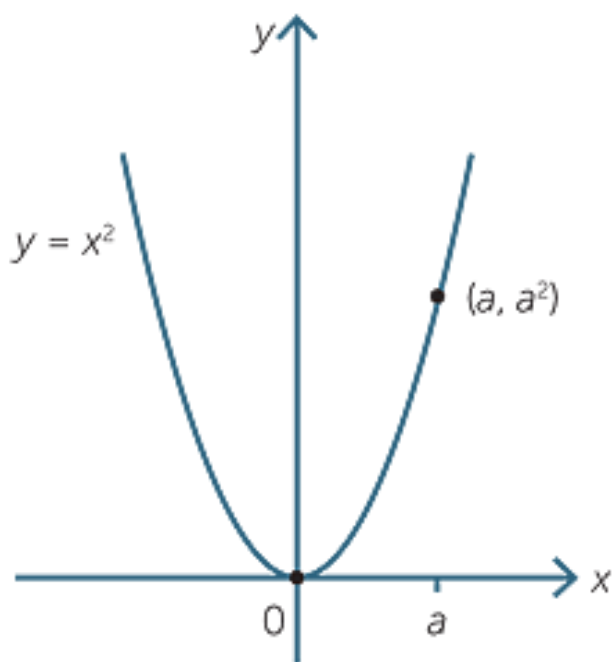
2.2 Complex Function as Mappings

(写像、変換)

2.2 Complex Function as Mappings (写像、変換)

We can plot the **graph (グラフ)** of **real-valued function** !

Recall that in *Calculus I*, if $y = f(x)$ is a real-valued function (実数値関数) of a real variable x , then **the graph (グラフ) of f** is defined to be **the set of all points $(x, f(x))$ (i.e. (x, y))** in the **two-dimensional Cartesian plane (i.e. 2次元空間)** (デカルト座標系、直交座標系).



2.2 Complex Function as Mappings (写像、変換)

Can we plot **graph** of **complex function**?

However, if $w = f(z)$ is a complex function, then both z and w lie in a complex plane (複素平面).

It follows that **the set** (集合) of all points $(z, f(z))$ (i.e. (z, w)) lies in **four-dimensional space** (4次元空間) (two dimensions from the input z and two dimensions from the output w).

Therefore,

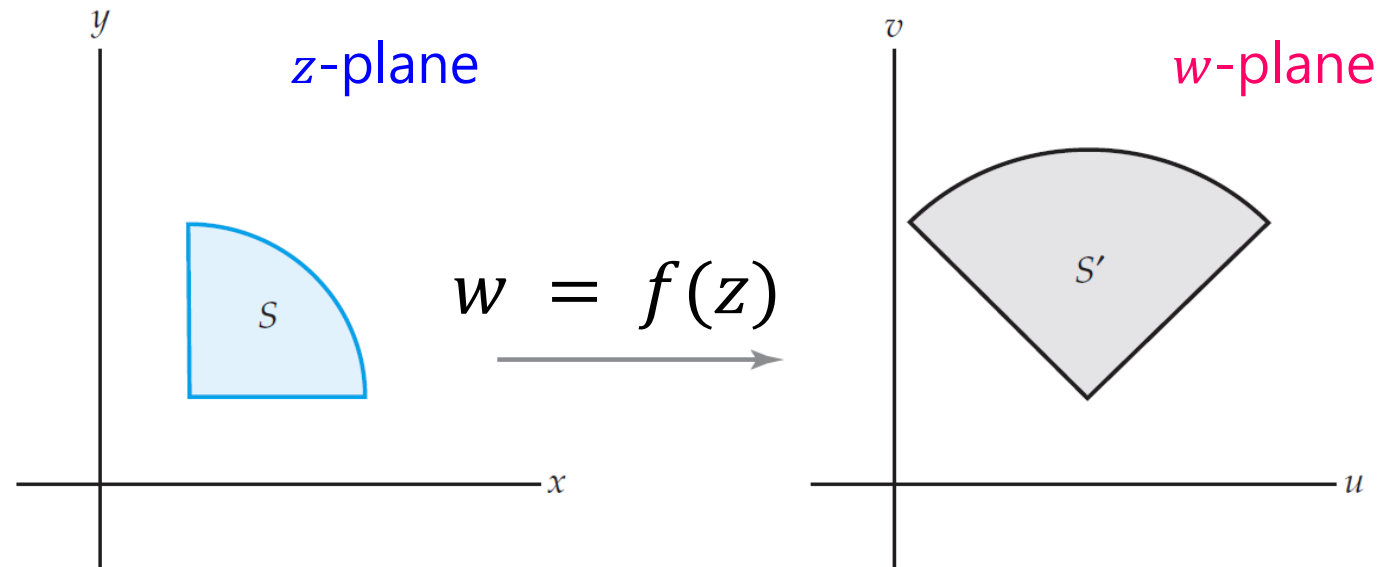
We cannot draw the graph of a complex function.

Instead (代わりに), we use the idea of mapping (写像、変換).

2.2 Complex Function as Mappings (写像、变换)

Complex Function as Mappings (写像、变换)

- Define two complex planes.
- The point z in the z -plane is associated with the unique point $w = f(z)$ in the w -plane.
- Every complex function $w = f(z)$ describes a correspondence (i.e. mapping) between points in two complex planes.



2.2 Complex Function as Mappings (写像、变换)

Complex Function as Mappings (写像、变换)

If $w = f(z)$ is a complex mapping and if S is a set of points in the z -plane, then we call the image (值域) of S under f as the set S' .

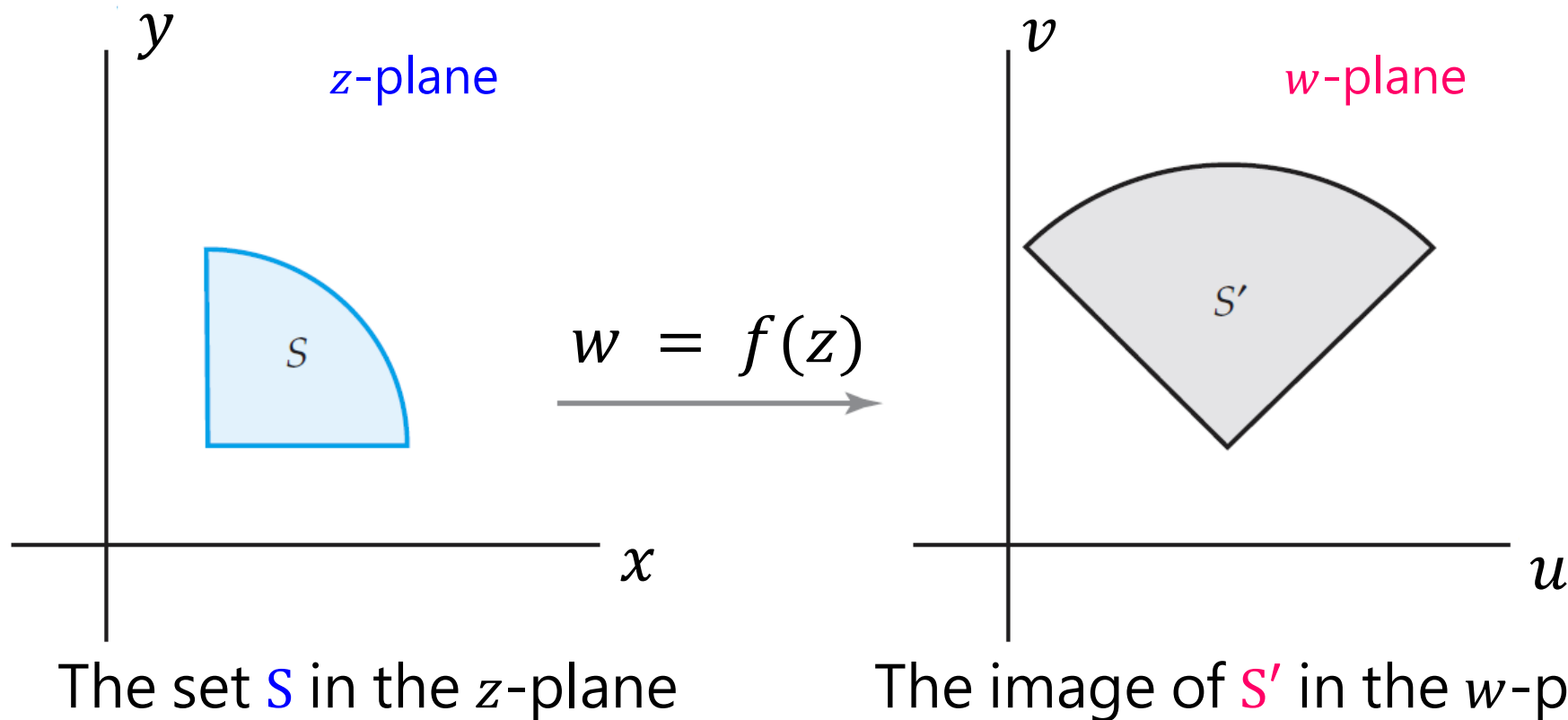


Figure 2.1 The image (值域) of a set S under a mapping $w = f(z)$

2.2 Complex Function as Mappings (写像、変換)

EXAMPLE (例題) 2.2.1 Image of a Half-Plane under $w = iz$

Find the image of the half-plane $\operatorname{Re}(z) \geq 2$ under the complex mapping $w = f(z) = iz$ and represent the mapping graphically.

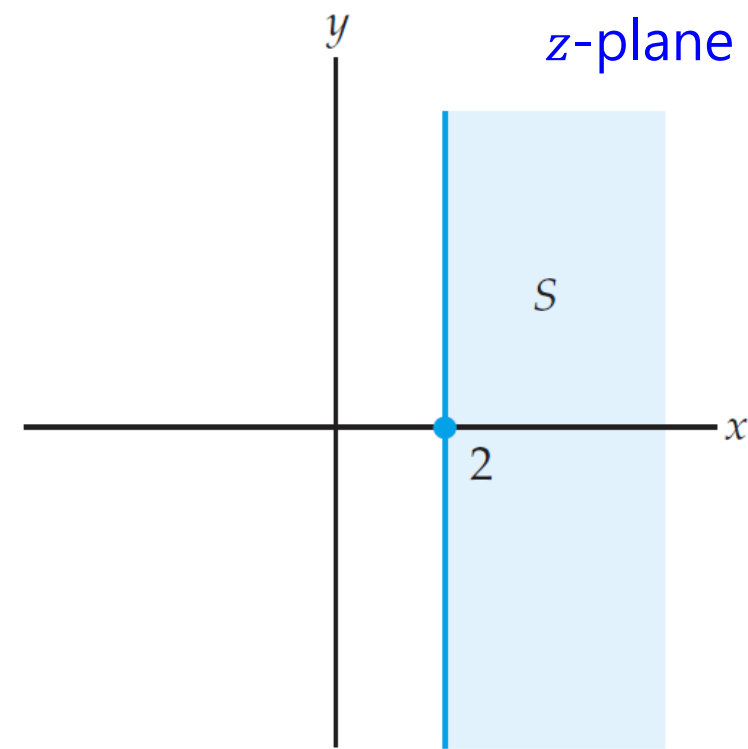
Solution (解答):

The vertical (垂直の) boundary line (境界線)

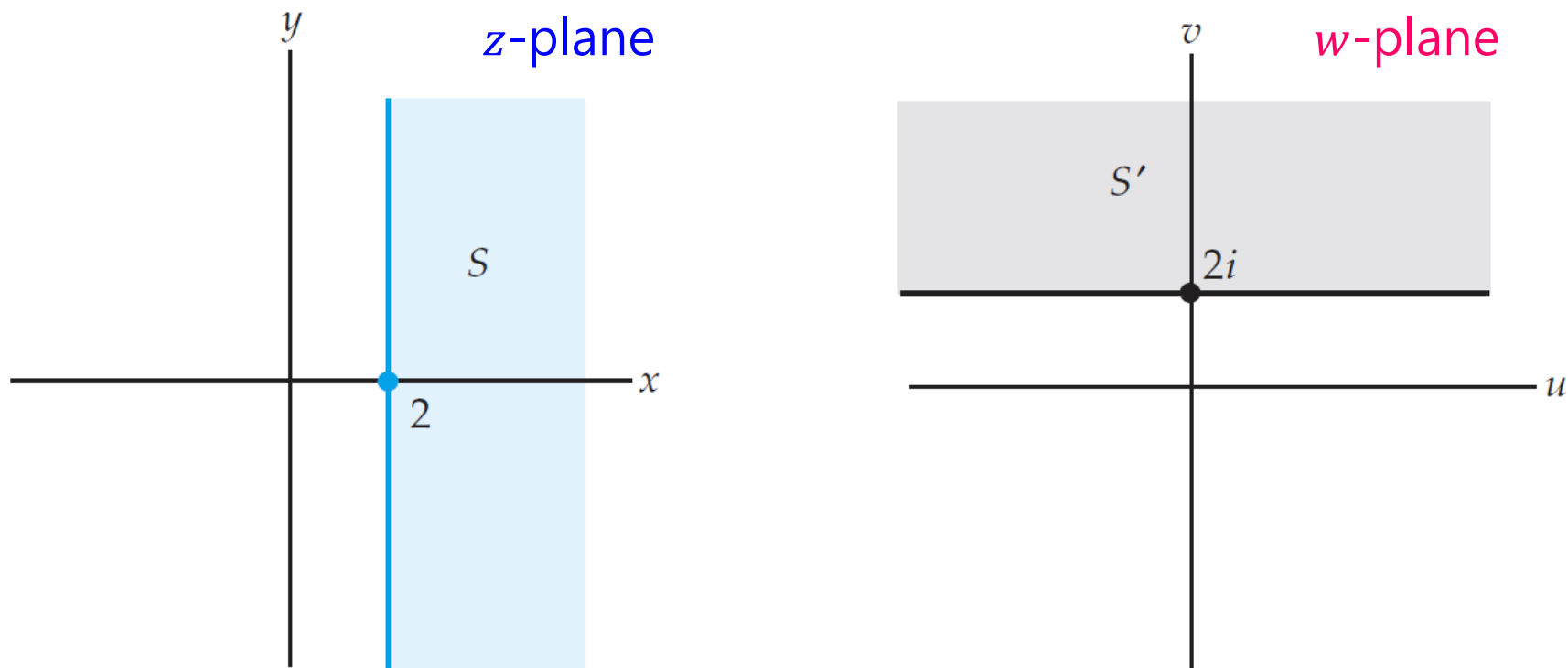
$$\operatorname{Re}(z) = x = 2 \text{ of } S$$

For any point z on this line we have $z = 2 + iy$ where $-\infty < y < \infty$.

$$w = f(z) = f(2 + iy) = i(2 + iy) = -y + 2i$$



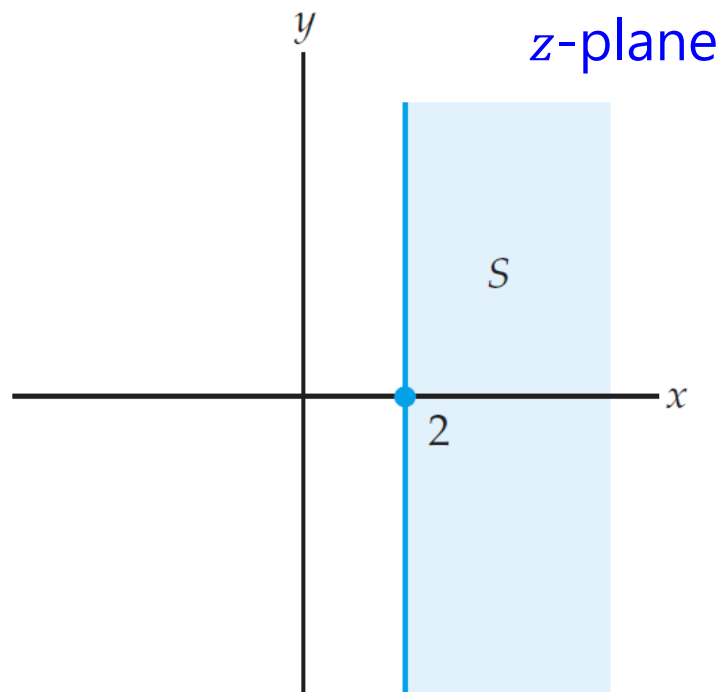
2.2 Complex Function as Mappings (写像、変換)



Because the set of points $w = -y + 2i$, $-\infty < y < \infty$, is the line $v = 2$ in the w -plane,

We conclude that the vertical line (垂直線) $x = 2$ in the z -plane is mapped onto the horizontal line (水平線) $v = 2$ in the w -plane by the mapping $w = f(z) = iz$.

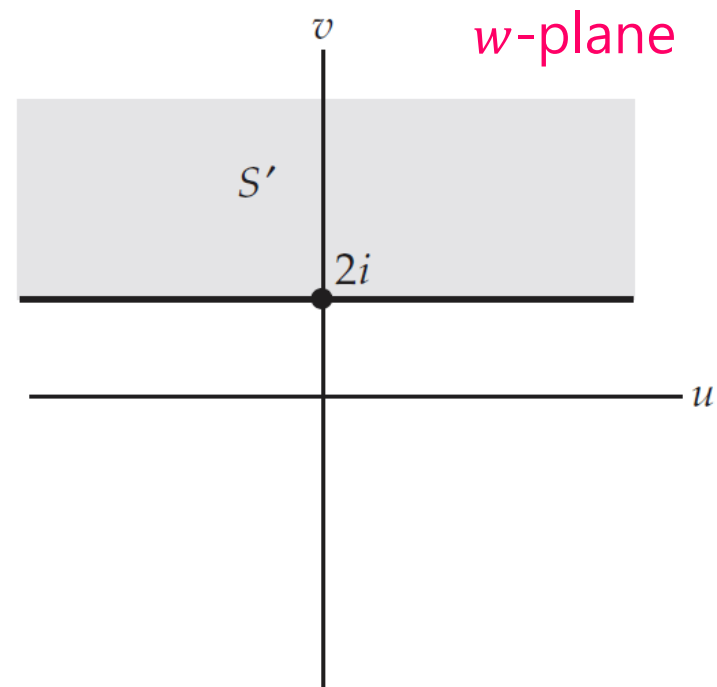
2.2 Complex Function as Mappings (写像、变换)



The set **S** satisfies inequalities (不等式):

$$x \geq 2 \text{ and } -\infty < y < \infty$$

➡ $\text{Re}(z) \geq 2$



The set **S'** satisfies inequalities (不等式):

$$v \geq 2 \text{ and } -\infty < u < \infty.$$

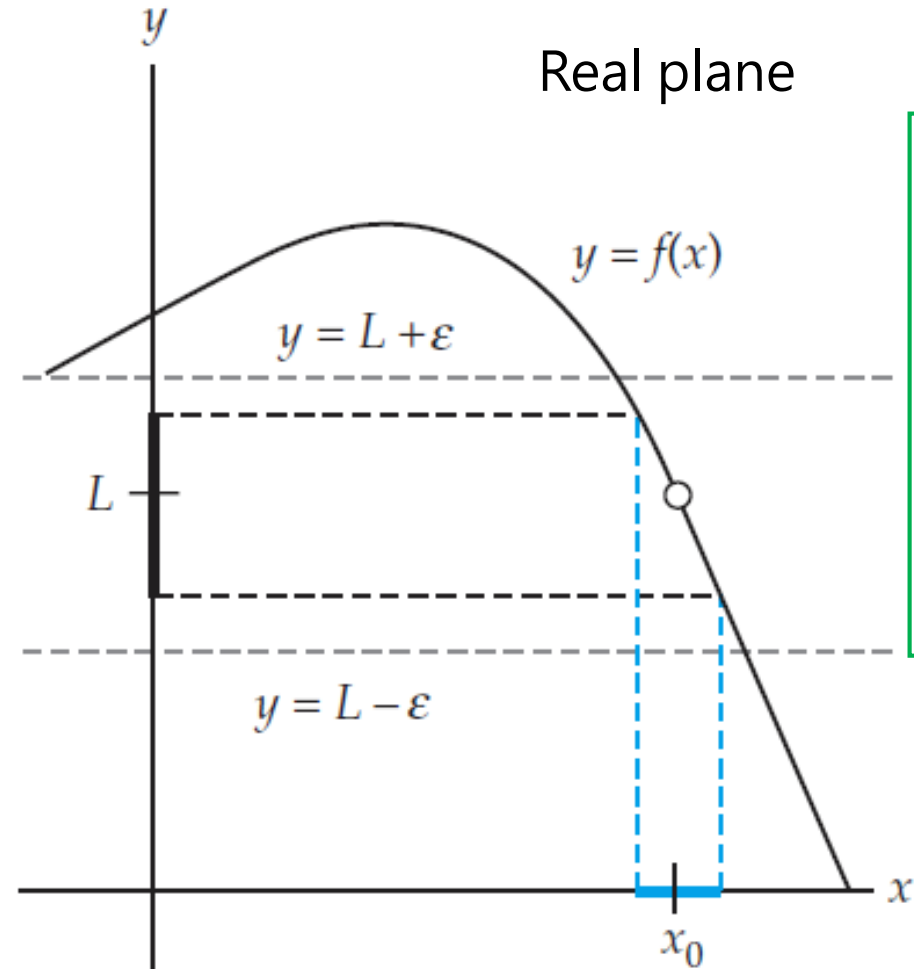
➡ $\text{Im}(w) \geq 2$

In summary, the half-plane $\text{Re}(z) \geq 2$ shown in blue color of left figure is mapped onto the half-plane $\text{Im}(w) \geq 2$ shown in gray color (灰色) in right figure by the complex mapping $w = f(z) = iz$.

2.3 Limits (極限) and Continuity (連続性)

2.3 Limits (極限) and Continuity (連続性)

Limit of Real Function



The limit of f as x tends x_0 exists and is equal to L if for every $\varepsilon > 0$ there exists a $\delta > 0$ such that $|f(x) - L| < \varepsilon$ whenever $0 < |x - x_0| < \delta$.

$$\lim_{x \rightarrow x_0} f(x) = L$$

Figure 2.50 Geometric (幾何学の) meaning of a real limit.

2.3 Limits (極限) and Continuity (連続性)

Limit of Complex Function (複素関数の極限)

Definition (定義) 2.8

Limit of a Complex Function (複素関数の極限)

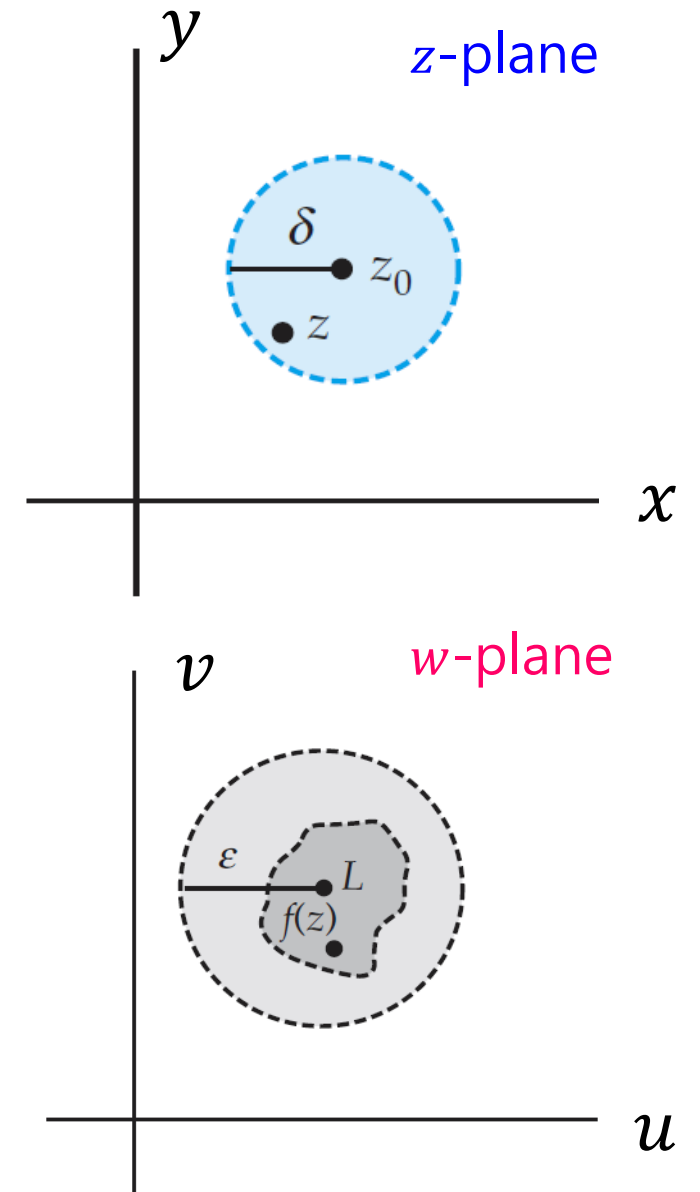
Suppose that a **complex function** f is defined in a deleted neighborhood of z_0 and suppose that L is a **complex number**. **The limit of f** as z tends to z_0 exists and is equal to L , written as $\lim_{z \rightarrow z_0} f(z) = L$, if for

every $\varepsilon > 0$ there exists a $\delta > 0$ such that

$$|f(z) - L| < \varepsilon \text{ whenever } 0 < |z - z_0| < \delta.$$

in w -plane

in z -plane



2.3 Limits (極限) and Continuity (連続性)

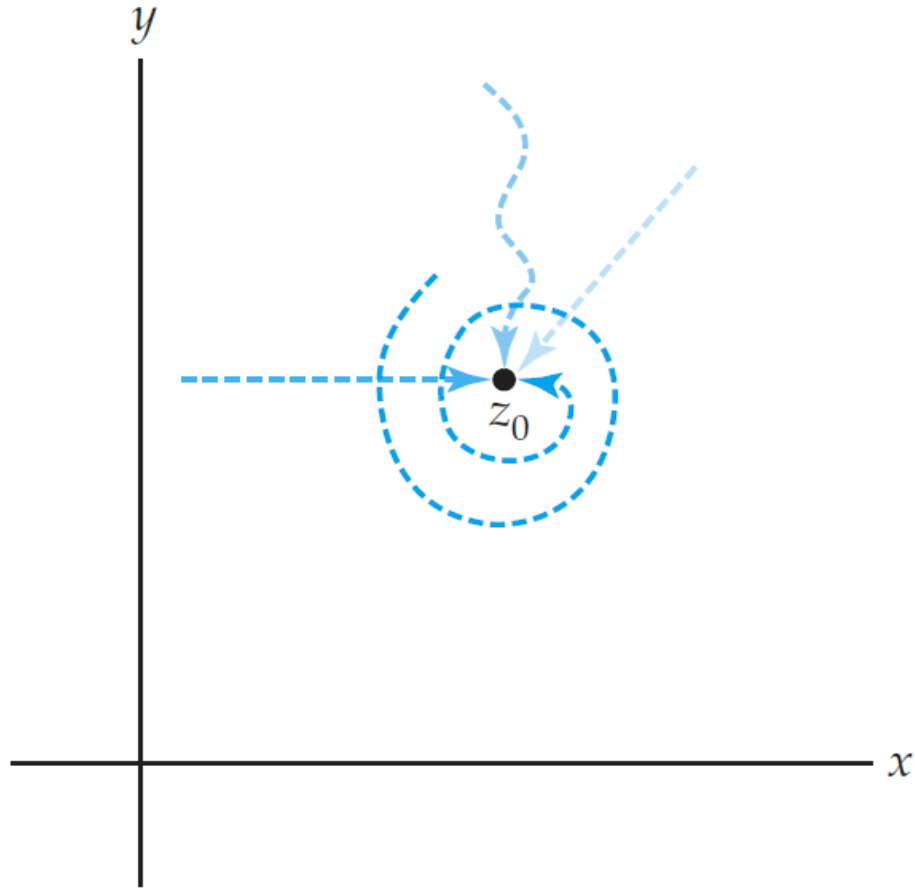


Figure 2.53 Different ways to approach z_0 in a limit.

Criterion (基準) for the Nonexistence (存在しない) of a Limit

If f approaches two complex numbers $L_1 \neq L_2$ for two different curves or paths through z_0 ,

then $\lim_{z \rightarrow z_0} f(z) = L$ does not exist.

2.3 Limits (極限) and Continuity (連續性)

EXAMPLE (例題) 2.6.1

Show that $\lim_{z \rightarrow 0} \frac{z}{\bar{z}}$ does not exist.

Solution (解答):

First, we let z approach 0 along the real axis, i.e. we consider complex numbers of the form $z = x + 0i$ where the real number x is approaching 0

$$\lim_{z \rightarrow 0} \frac{z}{\bar{z}} = \lim_{x \rightarrow 0} \frac{x + 0i}{x - 0i} = \lim_{x \rightarrow 0} 1 = 1$$

Second, we let z approach 0 along the imaginary axis, then $z = 0 + iy$ where the real number y is approaching 0

$$\lim_{z \rightarrow 0} \frac{z}{\bar{z}} = \lim_{y \rightarrow 0} \frac{0 + iy}{0 - iy} = \lim_{y \rightarrow 0} (-1) = -1$$

The two limits are not same, then conclude that $\lim_{z \rightarrow 0} \frac{z}{\bar{z}}$ does not exist.

2.3 Limits (極限) and Continuity (連続性)

Theorem 2.1 Real and Imaginary Parts (実部と虚部) of a Limit

Suppose that $f(z) = u(x, y) + iv(x, y)$ and $z_0 = x_0 + iy_0$, and

$L = u_0 + iv_0$. Then $\lim_{z \rightarrow z_0} f(z) = L$ if and only if

$$\lim_{(x,y) \rightarrow (x_0,y_0)} u(x, y) = u_0 \text{ and } \lim_{(x,y) \rightarrow (x_0,y_0)} v(x, y) = v_0$$

2.3 Limits (極限) and Continuity (連續性)

EXAMPLE (例題) 2.6.3

Use Theorem 2.1 to compute $\lim_{z \rightarrow 1+i} (z^2 + i)$, where $z = x + iy$.

Solution (解答):

Since $f(z) = z^2 + i = x^2 - y^2 + (2xy + 1)i$,

Apply Theorem 2.1 with $u(x, y) = x^2 - y^2$, $v(x, y) = 2xy + 1$, and $z_0 = 1 + i \Rightarrow x_0 = 1, y_0 = 1$

$$u_0 = \lim_{(x,y) \rightarrow (x_0,y_0)} u(x, y) = \lim_{(x,y) \rightarrow (1,1)} (x^2 - y^2) = \lim_{(x,y) \rightarrow (1,1)} (1^2 - 1^2) = 0$$

$$v_0 = \lim_{(x,y) \rightarrow (x_0,y_0)} v(x, y) = \lim_{(x,y) \rightarrow (1,1)} (2xy + 1) = \lim_{(x,y) \rightarrow (1,1)} (2 \cdot 1 \cdot 1 + 1) = 3$$

so $L = u_0 + iv_0 = 0 + i(3) = 3i$. Therefore, $\lim_{z \rightarrow 1+i} (z^2 + i) = 3i$

2.3 Limits (極限) and Continuity (連續性)

Theorem 2.2 Properties (性質) of Complex Limits

Suppose that f and g are complex functions. Then $\lim_{z \rightarrow z_0} f(z) = L$ and $\lim_{z \rightarrow z_0} g(z) = M$, then

(i) $\lim_{z \rightarrow z_0} cf(z) = cL$, where c is a complex constant,

(ii) $\lim_{z \rightarrow z_0} (f(z) \pm g(z)) = L \pm M$,

(iii) $\lim_{z \rightarrow z_0} f(z) \cdot g(z) = L \cdot M$, and

(iv) $\lim_{z \rightarrow z_0} \frac{f(z)}{g(z)} = \frac{L}{M}$, provided $M \neq 0$.

2.3 Limits (極限) and Continuity (連續性)

We establish two basic complex limits:

- The **complex constant** (定数) function $f(z) = c$, where c is a complex constant (定数)

$$\lim_{z \rightarrow z_0} c = c \quad (2.6.15)$$

- The **complex identity** (恒等) function $f(z) = z$

$$\lim_{z \rightarrow z_0} z = z_0 \quad (2.6.16)$$

2.3 Limits (極限) and Continuity (連續性)

EXAMPLE (例題) 2.6.4

Use Theorem 2.2 and the basic limits (2.6.15) and (2.6.16) to compute the limits $\lim_{z \rightarrow i} \frac{(3+i)z^4 - z^2 + 2z}{z+1}$.

Solution (解答):

By Theorem 2.2(iii) and (2.6.16),

$$\lim_{z \rightarrow i} z^2 = \lim_{z \rightarrow i} z \cdot z = \left(\lim_{z \rightarrow i} z \right) \cdot \left(\lim_{z \rightarrow i} z \right) = i \cdot i = -1$$

$$\text{Similarly, } \lim_{z \rightarrow i} z^4 = \left(\lim_{z \rightarrow i} z \right) \cdot \left(\lim_{z \rightarrow i} z \right) \cdot \left(\lim_{z \rightarrow i} z \right) \cdot \left(\lim_{z \rightarrow i} z \right) = i^4 = i^2 \cdot i^2 = 1$$

2.3 Limits (極限) and Continuity (連續性)

Solution (解答) (cont.):

Using these limits, Theorems 2.2(i), 2.2(ii), and (2.6.16), we obtain:

$$\begin{aligned}\lim_{z \rightarrow i} ((3 + i)z^4 - z^2 + 2z) &= (3 + i) \lim_{z \rightarrow i} z^4 - \lim_{z \rightarrow i} z^2 + 2 \lim_{z \rightarrow i} z \\ &= (3 + i) \cdot (1) - (-1) + 2 \cdot (i) \\ &= 4 + 3i\end{aligned}$$

$$\lim_{z \rightarrow i} z + 1 = 1 + i$$

Therefore, by Theorem 2.2(iv), we have:

$$\lim_{z \rightarrow i} \frac{(3 + i)z^4 - z^2 + 2z}{z + 1} = \frac{\lim_{z \rightarrow i} ((3 + i)z^4 - z^2 + 2z)}{\lim_{z \rightarrow i} z + 1} = \frac{4 + 3i}{1 + i} = \frac{7}{2} - \frac{1}{2}i$$

2.3 Limits (極限) and Continuity (連続性)

Continuity (連続性) of Complex Functions

Definition 2.9 Continuity (連続性) of a Complex Function

A complex function f is continuous at a point z_0 if

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

2.3 Limits (極限) and Continuity (連続性)

Continuity (連続性) of Complex Functions

Criteria (基準) for Continuity (連続) at a Point

A complex function f is continuous at a point z_0 if each of the following three conditions (条件) hold (満たす):

- (i) $\lim_{z \rightarrow z_0} f(z)$ exists,
- (ii) f is defined at z_0 , and
- (iii) $\lim_{z \rightarrow z_0} f(z) = f(z_0)$

2.3 Limits (極限) and Continuity (連續性)

Continuity (連續性) of Complex Functions

EXAMPLE (例題) 2.6.5 Checking Continuity at a Point

Consider the function $f(z) = z^2 - iz + 2$ to determine if f is continuous at the point $z_0 = 1 - i$.

Solution (解答):

From Theorem 2.2 and the limits in (2.6.15) and (2.6.16) we obtain:

$$\lim_{z \rightarrow z_0} f(z) = \lim_{z \rightarrow z_0} (z^2 - iz + 2) = (1 - i)^2 - i(1 - i) + 2 = 1 - 3i.$$

Furthermore, for $z_0 = 1 - i$ we have:

$$f(z_0) = f(1 - i) = (1 - i)^2 - i(1 - i) + 2 = 1 - 3i.$$

Since $\lim_{z \rightarrow z_0} f(z) = f(z_0)$, we conclude that f is continuous at the point $z_0 = 1 - i$.

2.3 Limits (極限) and Continuity (連続性)

Continuity (連続性) of Complex Functions

Theorem 2.3 Real and Imaginary Parts of a Continuous Function

Suppose that $f(z) = u(x, y) + iv(x, y)$ and $z_0 = x_0 + iy_0$.

Then the complex function (複素関数) f is continuous at the point z_0 if and only if both real functions (実数値関数) u and v are continuous at the point (x_0, y_0) .

2.3 Limits (極限) and Continuity (連続性)

Continuity (連続性) of Complex Functions

EXAMPLE (例題) 2.6.7 Checking Continuity Using Theorem 2.3

Show that the function $f(z) = \bar{z}$ is continuous on \mathbb{C} .

Solution (解答):

According to Theorem 2.3, $f(z) = \bar{z} = x + iy = x - iy$ is continuous at $z_0 = x_0 + iy_0$ if both $u(x, y) = x$ and $v(x, y) = -y$ are continuous at (x_0, y_0) .

$$\lim_{(x,y) \rightarrow (x_0,y_0)} u(x, y) = x_0 \text{ and } \lim_{(x,y) \rightarrow (x_0,y_0)} v(x, y) = -y_0$$

Because u and v are two-variable polynomial functions, we have (2.6.13) that

$$\lim_{(x,y) \rightarrow (x_0,y_0)} p(x, y) = p(x_0, y_0) \quad (2.6.13)$$

This implies that u and v are continuous at (x_0, y_0) , and, therefore, that f is continuous at $z_0 = x_0 + iy_0$ by Theorem 2.3.

Since $z_0 = x_0 + iy_0$ was an arbitrary (任意の) point, we conclude that the function $f(z) = \bar{z}$ is continuous on \mathbb{C} .

2.3 Limits (極限) and Continuity (連續性)

Continuity (連續性) of Complex Functions

Theorem 2.4 Properties (性質) of Continuous Functions

If f and g are continuous at the point z_0 , then the following functions are continuous at the point z_0 :

- (i) cf , where c is a complex constant,
- (ii) $f \pm g$,
- (iii) $f \cdot g$,
- (iv) $\frac{f}{g}$, provided $g(z_0) \neq 0$.

2.3 Limits (極限) and Continuity (連続性)

Continuity (連続性) of Complex Functions

Theorem 2.5 Continuity of Polynomial Functions (多項式関数)

Polynomial functions (多項式関数) are continuous on the entire complex plane \mathbb{C} .

Review for Lecture 2

- Complex Functions
- Complex Functions as Mapping
- Limit of Complex Function
- Continuity of Complex Function

Exercise

Please Check <https://github.com/uoaworks/ComplexAnalysisAY2018>

Reading Materials: Section 2.1, 2.2, 2.6, Textbook

References

- [1] A first course in Complex Analysis with application, Dennis G. Zill and Patrick D. Shanahan, Jones and Bartlett Publishers, Inc. 2003
- [2] Wikipedia