Complex and Hypercomplex Iterative Methods

Samuel J Monson

Seattle Univerisity

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Introduction

Definition (Function Iteration)

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$$f^{k+1} := f \circ f^k$$

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$$f^0(x) = x$$
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Example

Given $f(x) = x + 1$,

$$f^0(x) = x$$
$$f^1(x) = x + 1$$
$$f^2(x) = (x + 1) + 1$$

Definition (Function Iteration)

$f^0 := \boldsymbol{I}$
$f^{k+1} := f \circ f^k$

Example

Given $f(x) = x + 1$,

$$
\begin{aligned}
f^0(x) &= x \\
f^1(x) &= x + 1 \\
f^2(x) &= (x + 1) + 1 \\
f^3(x) &= ((x + 1) + 1) + 1
\end{aligned}
$$

Definition (Dynamical System)

A system that enacts rules on a set of variables to produce a state.

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Definition (Complex Dynamics)

The study of dynamical systems defined by complex functions.

Definition (Complex Numbers)

$\boldsymbol{i}^2 = -1$

$\{a + b\boldsymbol{i} \; : \; a, b \in \mathbb{R}\} \in \mathbb{C}$

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Addition

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- Let $a, b, x, y \in \mathbb{R}$,

$$(a + b\boldsymbol{i}) + (x + y\boldsymbol{i})$$

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Addition

- Let $a, b, x, y \in \mathbb{R}$,

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Multiplication

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Addition

- Let $a, b, x, y \in \mathbb{R}$,

$$(a + b\boldsymbol{i}) + (x + y\boldsymbol{i}) = (a + x) + (b + y)\boldsymbol{i}$$

Multiplication

- Let $a, b, x, y \in \mathbb{R}$,

$$(a + b\boldsymbol{i}) \times (x + y\boldsymbol{i})$$

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- Let $a, b, x, y \in \mathbb{R}$,

$$(a + b\boldsymbol{i}) + (x + y\boldsymbol{i}) = (a + x) + (b + y)\boldsymbol{i}$$

Multiplication

- Let $a, b, x, y \in \mathbb{R}$,

$$(a + b\boldsymbol{i}) \times (x + y\boldsymbol{i}) = ax + ay\boldsymbol{i} + bx\boldsymbol{i} + by\boldsymbol{i}^2$$

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Addition

- Let $a, b, x, y \in \mathbb{R}$,

$$(a + b\boldsymbol{i}) + (x + y\boldsymbol{i}) = (a + x) + (b + y)\boldsymbol{i}$$

Multiplication

- Let $a, b, x, y \in \mathbb{R}$,

$$\begin{aligned}(a + b\boldsymbol{i}) \times (x + y\boldsymbol{i}) &= ax + ay\boldsymbol{i} + bx\boldsymbol{i} + by\boldsymbol{i}^2 \\ &= (ax - by) + (ay + bx)\boldsymbol{i}\end{aligned}$$

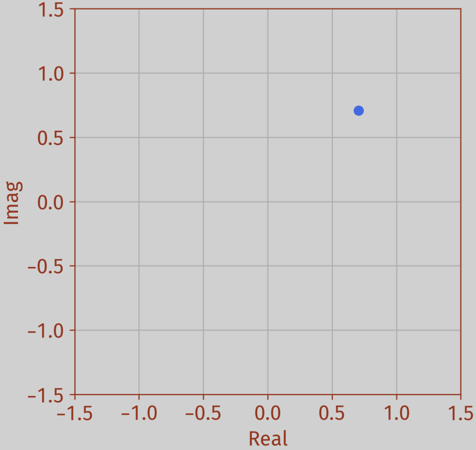
Complex Iterative Methods

Rules

$f(z) = z^2$

$z_0 = \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\boldsymbol{i}$

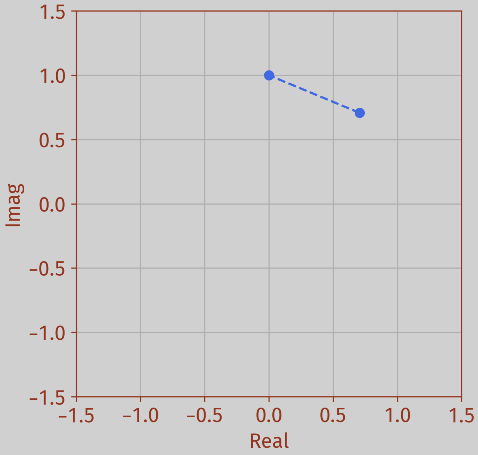
- $f^0(z) = \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\boldsymbol{i}$



Rules

$f(z) = z^2$
$z_0 = \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\boldsymbol{i}$

- $f^0(z) = \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\boldsymbol{i}$
- $f^1(z) = \left(\frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\boldsymbol{i}\right)^2 =$
  $\left(\frac{1}{\sqrt{2}}\right)^2 - \left(\frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\right)^2 + \left(\frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\right)^2 \boldsymbol{i} = \boldsymbol{i}$

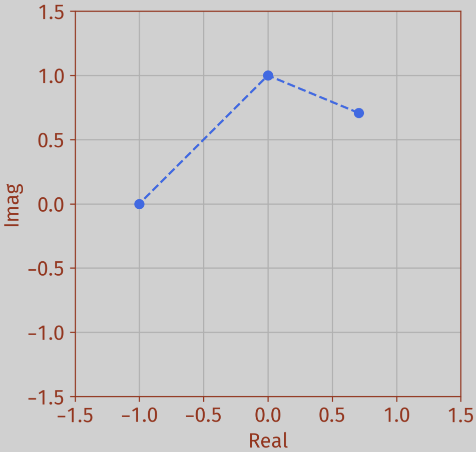


Rules

$f(z) = z^2$

$z_0 = \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\boldsymbol{i}$

- $f^0(z) = \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\boldsymbol{i}$
- $f^1(z) = \boldsymbol{i}$
- $f^2(z) = -1$



Rules

$f(z) = z^2$
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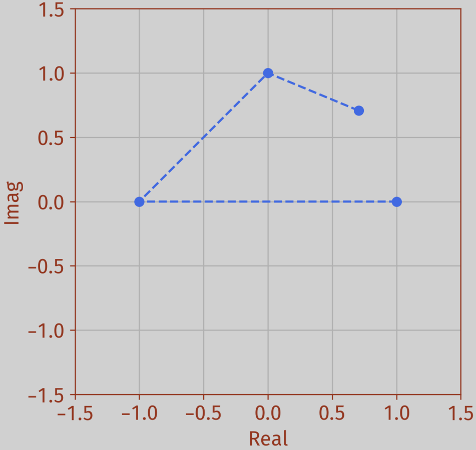
- $f^1(z) = \boldsymbol{i}$
- $f^2(z) = -1$
- $f^3(z) = 1$



Rules

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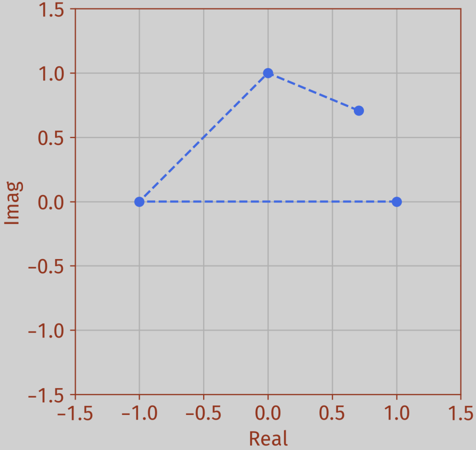
- $f^0(z) = \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\boldsymbol{i}$
- $f^1(z) = \boldsymbol{i}$
- $f^2(z) = -1$
- $f^3(z) = 1$
- $f^4(z) = f^5(z) = f^6(z) = 1$

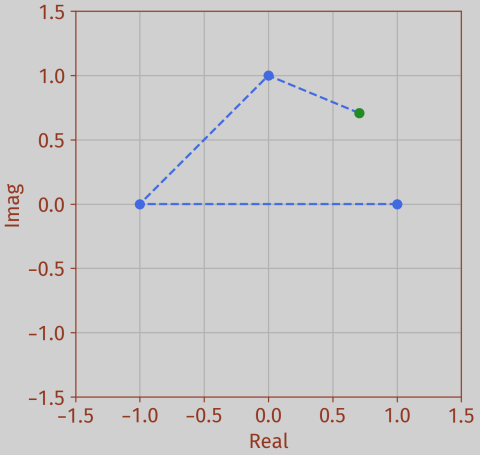


Rules

$$f(z) = z^2 - \frac{1}{10} - \frac{1}{10}\boldsymbol{i}$$

$$z_0 = \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\boldsymbol{i}$$

- $f^0(z) = \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\boldsymbol{i}$

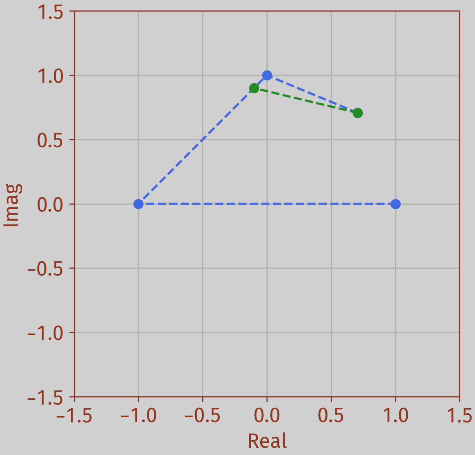


Rules

$f(z) = z^2 - \frac{1}{10} - \frac{1}{10}\boldsymbol{i}$

$z_0 = \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\boldsymbol{i}$

- $f^0(z) = \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\boldsymbol{i}$
- $f^1(z) = -\frac{1}{10} + \left(1 - \frac{1}{10}\right)\boldsymbol{i} = -0.1 + 0.9\boldsymbol{i}$



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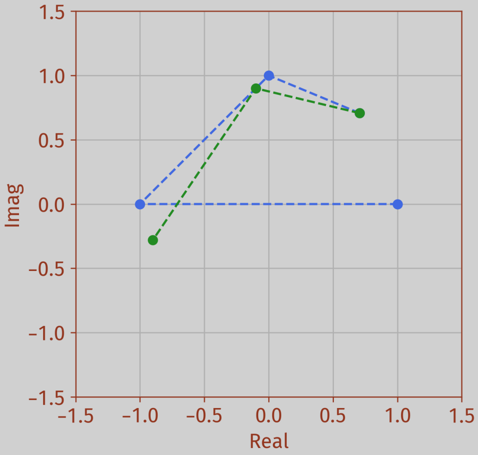
- $f^1(z) = -0.1 + 0.9\boldsymbol{i}$
- $f^2(z) = -0.9 - 0.28\boldsymbol{i}$



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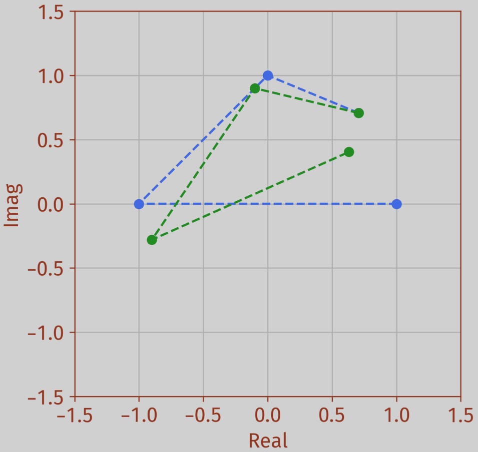
- $f^3(z) = 0.6316 + 0.404\boldsymbol{i}$



Complex Iteration

Rules

$$f(z) = z^2 - \frac{1}{10} - \frac{1}{10}\boldsymbol{i}$$
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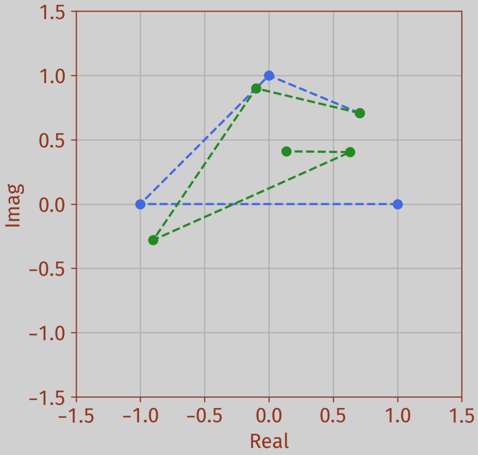
- $f^3(z) = 0.6316 + 0.404\boldsymbol{i}$
- $f^4(z) \approx 0.13570256 + 0.4103328\boldsymbol{i}$



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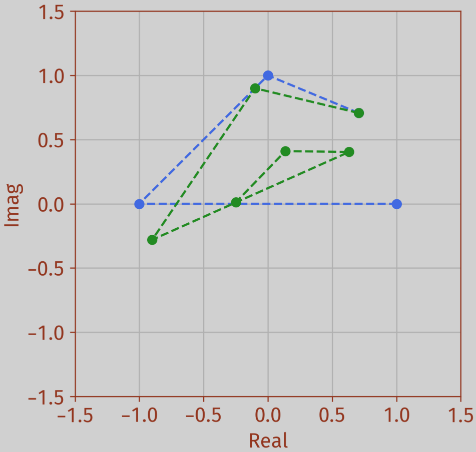
- $f^5(z) \approx -0.24995782 + 0.01136642\boldsymbol{i}$



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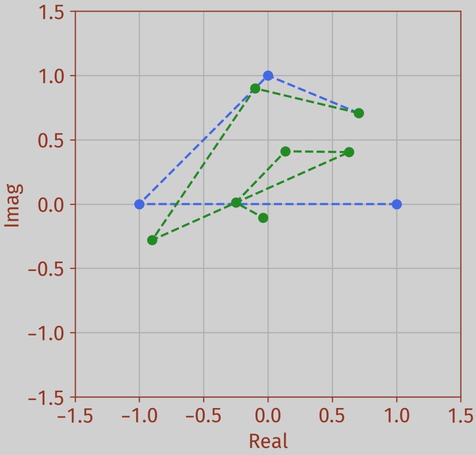
- $f^6(z) \approx -0.03765028 - 0.10568225\boldsymbol{i}$



Group Activity

$f(z) = z^2 + c$

Easier	Harder
$c = -0.2 + 0\boldsymbol{i}$	$c = -0.2 + 0.4\boldsymbol{i}$
$z_0 = 0.5 + 0\boldsymbol{i}$	$z_0 = 0.5 - 0.5\boldsymbol{i}$

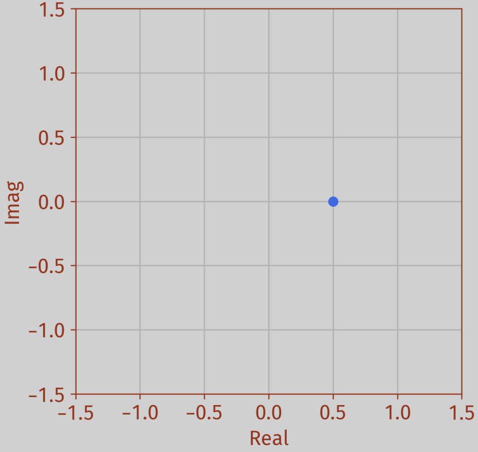
Rules

$f(z) = z^2 + c$

$c = -0.2 + 0\boldsymbol{i}$

$z_0 = 0.5 + 0\boldsymbol{i}$

- $f^0(z) = 0.5$

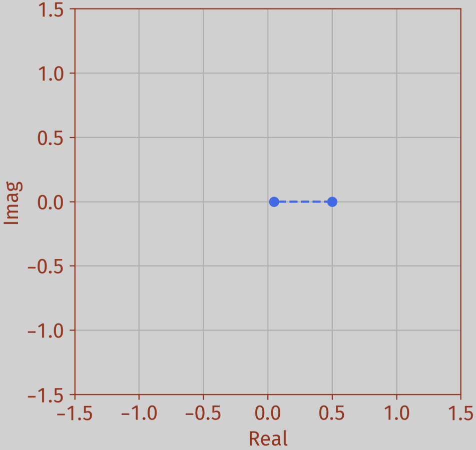


Group Activity (Easier)

Rules

$f(z) = z^2 + c$
$c = -0.2 + 0\boldsymbol{i}$
$z_0 = 0.5 + 0\boldsymbol{i}$

- $f^0(z) = 0.5$
- $f^1(z) = 0.05$



Group Activity (Easier)

Rules

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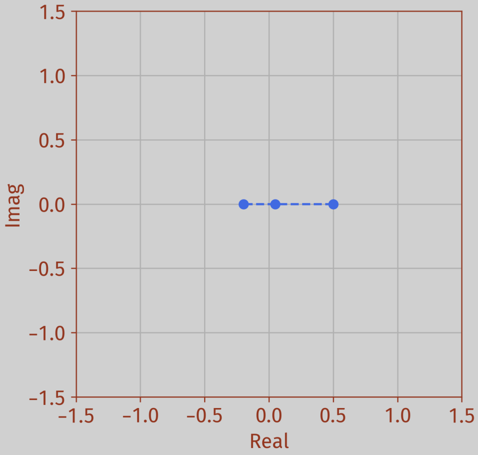
$z_0 = 0.5 + 0\boldsymbol{i}$

- $f^0(z) = 0.5$
- $f^1(z) = 0.05$
- $f^2(z) = -0.1975$



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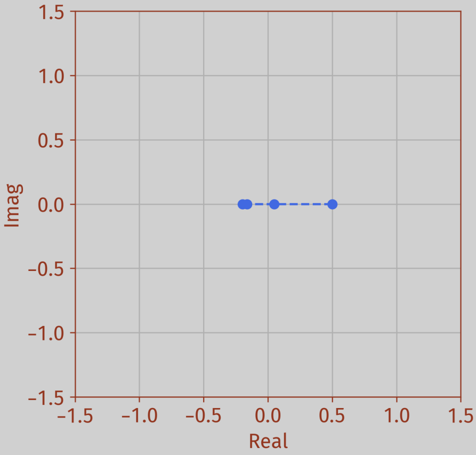
- $f^1(z) = 0.05$
- $f^2(z) = -0.1975$
- $f^3(z) = -0.16099375$



Rules

$f(z) = z^2 + c$
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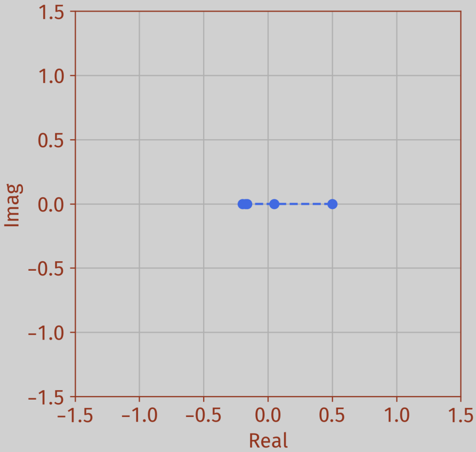
- $f^0(z) = 0.5$
- $f^1(z) = 0.05$
- $f^2(z) = -0.1975$
- $f^3(z) = -0.16099375$
- $f^4(z) \approx -0.1740810125$

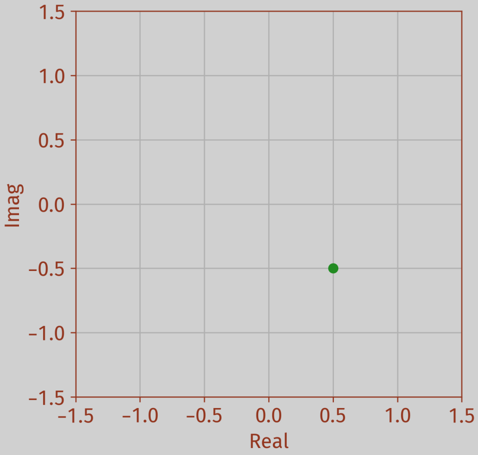


Group Activity (Harder)

Rules

$f(z) = z^2 + c$
$c = -0.2 + 0.4\boldsymbol{i}$
$z_0 = 0.5 - 0.5\boldsymbol{i}$

- $f^0(z) = 0.5 - 0.5\boldsymbol{i}$

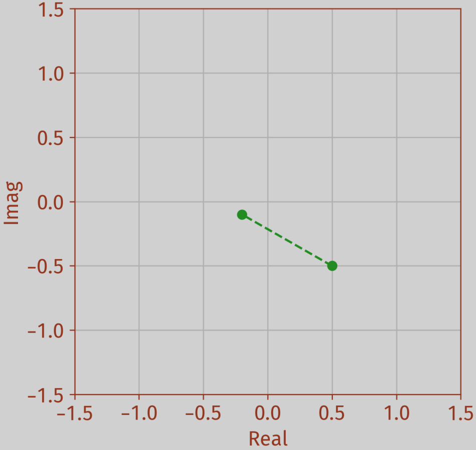


Group Activity (Harder)

Rules

$f(z) = z^2 + c$
$c = -0.2 + 0.4\boldsymbol{i}$
$z_0 = 0.5 - 0.5\boldsymbol{i}$

- $f^0(z) = 0.5 - 0.5\boldsymbol{i}$
- $f^1(z) = -0.2 - 0.1\boldsymbol{i}$



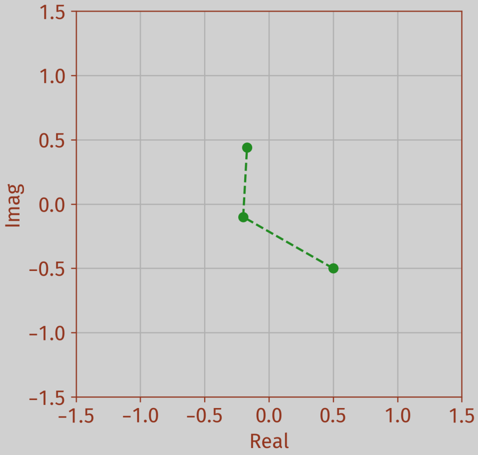
Rules

$f(z) = z^2 + c$

$c = -0.2 + 0.4\boldsymbol{i}$

$z_0 = 0.5 - 0.5\boldsymbol{i}$

- $f^0(z) = 0.5 - 0.5\boldsymbol{i}$
- $f^1(z) = -0.2 - 0.1\boldsymbol{i}$
- $f^2(z) = -0.17 + 0.44\boldsymbol{i}$



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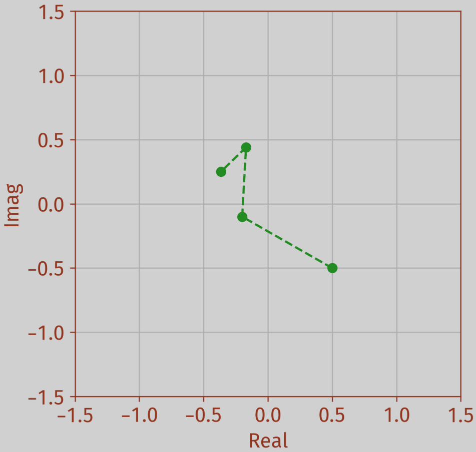
- $f^3(z) = -0.3647 + 0.2504\boldsymbol{i}$

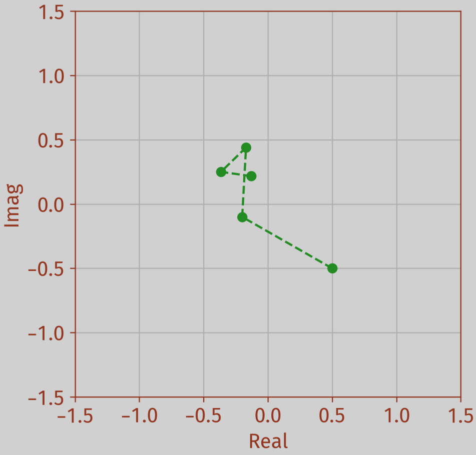


Group Activity (Harder)

Rules

$f(z) = z^2 + c$
$c = -0.2 + 0.4i$
$z_0 = 0.5 - 0.5i$

- $f^0(z) = 0.5 - 0.5i$
- $f^1(z) = -0.2 - 0.1i$
- $f^2(z) = -0.17 + 0.44i$
- $f^3(z) = -0.3647 + 0.2504i$
- $f^4(z) = -0.12969407 + 0.21735824i$



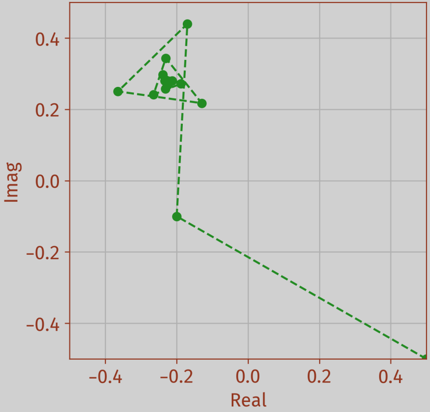
Iteration (Python)

```python
N = 128
B = 16
c = complex(-0.2, 0.4)
def iterate(z):
    for n in range(N):
        z = z*z + c
        if abs(z) > B: break
    return n
```

Implementation

Iteration (Python)

```python
N = 128
B = 16
c = complex(-0.2, 0.4)
def iterate(z):
    for n in range(N):
        z = z*z + c
        if abs(z) > B: break
    return n
```



Complex Juila Set Example

Defined by iterative function in complex space

- $f_c(z) = z^2 + c$
- $\{z_0 \in \mathbb{C} : |f_c^k(z_0)| \in \mathbb{C} \text{ as } k \to \infty\} \in K_c$

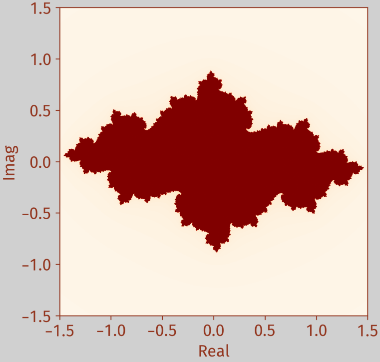


Figure: $f(z) = z^2 - 0.675 - 0.112i$

Hypercomplex Numbers

Definition (Quaternion)

$\boldsymbol{i}^2 = \boldsymbol{j}^2 = \boldsymbol{k}^2 = \boldsymbol{ijk} = -1$

$\{d + a\boldsymbol{i} + b\boldsymbol{j} + c\boldsymbol{k} : a, b, c, d \in \mathbb{R}\} \in \mathbb{H}$

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- $\boldsymbol{i}^2 = \boldsymbol{ijk}$

$$\boldsymbol{i}^{-1}\boldsymbol{i}^2 = \boldsymbol{i}^{-1}\boldsymbol{ijk}$$
$$\boldsymbol{i} = \boldsymbol{jk}$$

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$\boldsymbol{i}^2 = \boldsymbol{j}^2 = \boldsymbol{k}^2 = \boldsymbol{ijk} = -1$

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- $\boldsymbol{i}^2 = \boldsymbol{ijk}$

$$\boldsymbol{i}^{-1}\boldsymbol{i}^2 = \boldsymbol{i}^{-1}\boldsymbol{ijk}$$
$$\boldsymbol{i} = \boldsymbol{jk}$$

- $\boldsymbol{k}^2 = \boldsymbol{ijk}$

$$\boldsymbol{k}^2\boldsymbol{k}^{-1} = \boldsymbol{ijkk}^{-1}$$
$$\boldsymbol{k} = \boldsymbol{ij}$$

- $\boldsymbol{j} = \boldsymbol{ki}$

Definition (Quaternion)

$\boldsymbol{i}^2 = \boldsymbol{j}^2 = \boldsymbol{k}^2 = \boldsymbol{ijk} = -1$

$\{d + a\boldsymbol{i} + b\boldsymbol{j} + c\boldsymbol{k} : a, b, c, d \in \mathbb{R}\} \in \mathbb{H}$

- $\boldsymbol{i}^2 = \boldsymbol{ijk}$

$$\boldsymbol{i}^{-1}\boldsymbol{i}^2 = \boldsymbol{i}^{-1}\boldsymbol{ijk}$$
$$\boldsymbol{i} = \boldsymbol{jk}$$

- $\boldsymbol{k}^2 = \boldsymbol{ijk}$

$$\boldsymbol{k}^2\boldsymbol{k}^{-1} = \boldsymbol{ijkk}^{-1}$$
$$\boldsymbol{k} = \boldsymbol{ij}$$

- $\boldsymbol{j} = \boldsymbol{ki}$

- $\boldsymbol{i} = \boldsymbol{jk}$

$$\boldsymbol{ji} = \boldsymbol{jjk}$$
$$\boldsymbol{ji} = \boldsymbol{j}^2\boldsymbol{k}$$
$$\boldsymbol{ji} = -\boldsymbol{k}$$
$$-\boldsymbol{k} = \boldsymbol{ji}$$

Definition (Quaternion)

$\boldsymbol{i}^2 = \boldsymbol{j}^2 = \boldsymbol{k}^2 = \boldsymbol{ijk} = -1$

$\{d + a\boldsymbol{i} + b\boldsymbol{j} + c\boldsymbol{k} : a, b, c, d \in \mathbb{R}\} \in \mathbb{H}$

- $\boldsymbol{i}^2 = \boldsymbol{ijk}$

$$\boldsymbol{i}^{-1}\boldsymbol{i}^2 = \boldsymbol{i}^{-1}\boldsymbol{ijk}$$
$$\boldsymbol{i} = \boldsymbol{jk}$$

- $\boldsymbol{k}^2 = \boldsymbol{ijk}$

$$\boldsymbol{k}^2\boldsymbol{k}^{-1} = \boldsymbol{ijkk}^{-1}$$
$$\boldsymbol{k} = \boldsymbol{ij}$$

- $\boldsymbol{j} = \boldsymbol{ki}$

- $\boldsymbol{i} = \boldsymbol{jk}$

$$\boldsymbol{ji} = \boldsymbol{jjk}$$
$$\boldsymbol{ji} = \boldsymbol{j}^2\boldsymbol{k}$$
$$\boldsymbol{ji} = -\boldsymbol{k}$$
$$-\boldsymbol{k} = \boldsymbol{ji}$$

- $-\boldsymbol{i} = \boldsymbol{kj}$
- $-\boldsymbol{j} = \boldsymbol{ik}$

Let,

$\mathbf{i}^2 = \mathbf{j}^2 = \mathbf{k}^2 = \mathbf{ijk} = -1$

$p = d + a\mathbf{i} + b\mathbf{j} + c\mathbf{k}$

$q = w + x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$

$$\begin{aligned} p \times q = {} & dw + dx\mathbf{i} + dy\mathbf{j} + dz\mathbf{k} \\ & + aw\mathbf{i} + ax\mathbf{i}^2 + ay\mathbf{ij} + az\mathbf{ik} \\ & + bw\mathbf{j} + bx\mathbf{ji} + by\mathbf{j}^2 + bz\mathbf{jk} \\ & + cw\mathbf{k} + cx\mathbf{ki} + cy\mathbf{kj} + cz\mathbf{k}^2 \end{aligned}$$

Let,

$\mathbf{i}^2 = \mathbf{j}^2 = \mathbf{k}^2 = \mathbf{ijk} = -1$
$p = d + a\mathbf{i} + b\mathbf{j} + c\mathbf{k}$
$q = w + x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$

$$\begin{aligned}
p \times q &= dw + dx\mathbf{i} + dy\mathbf{j} + dz\mathbf{k} \\
&+ aw\mathbf{i} + ax\mathbf{i}^2 + ay\mathbf{ij} + az\mathbf{ik} \\
&+ bw\mathbf{j} + bx\mathbf{ji} + by\mathbf{j}^2 + bz\mathbf{jk} \\
&+ cw\mathbf{k} + cx\mathbf{ki} + cy\mathbf{kj} + cz\mathbf{k}^2 \\
&= dw - ax - by - cz \\
&+ dx\mathbf{i} + aw\mathbf{i} + bz\mathbf{i} - cy\mathbf{i} \\
&+ dy\mathbf{j} - az\mathbf{j} + bw\mathbf{j} + cx\mathbf{j} \\
&+ dz\mathbf{k} + ay\mathbf{k} - bx\mathbf{k} + cw\mathbf{k}
\end{aligned}$$

Let,

$\boldsymbol{i}^2 = \boldsymbol{j}^2 = \boldsymbol{k}^2 = \boldsymbol{ijk} = -1$
$p = d + a\boldsymbol{i} + b\boldsymbol{j} + c\boldsymbol{k}$
$q = w + x\boldsymbol{i} + y\boldsymbol{j} + z\boldsymbol{k}$

$$\begin{aligned} p \times q = {} & dw - ax - by - cz \\ & + dx\boldsymbol{i} + aw\boldsymbol{i} + bz\boldsymbol{i} - cy\boldsymbol{i} \\ & + dy\boldsymbol{j} - az\boldsymbol{j} + bw\boldsymbol{j} + cx\boldsymbol{j} \\ & + dz\boldsymbol{k} + ay\boldsymbol{k} - bx\boldsymbol{k} + cw\boldsymbol{k} \end{aligned}$$

Let,

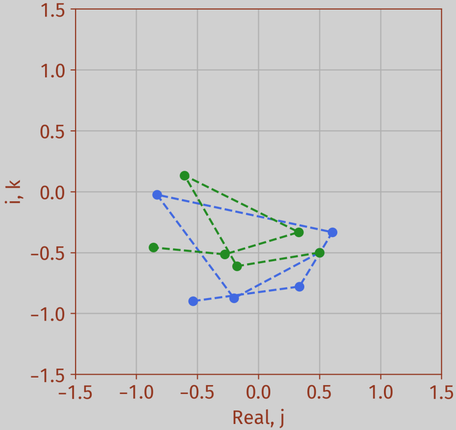
$\boldsymbol{i}^2 = \boldsymbol{j}^2 = \boldsymbol{k}^2 = \boldsymbol{ijk} = -1$
$p = d + a\boldsymbol{i} + b\boldsymbol{j} + c\boldsymbol{k}$
$q = w + x\boldsymbol{i} + y\boldsymbol{j} + z\boldsymbol{k}$

$$\begin{aligned} p \times q = dw - \left\langle \begin{matrix} a \\ b \\ c \end{matrix} \right\rangle \cdot \left\langle \begin{matrix} x \\ y \\ z \end{matrix} \right\rangle \\ + \left\langle \begin{matrix} dx + aw + bz - cy \\ dy - az + bw + cx \\ dz + ay - bx + cw \end{matrix} \right\rangle \cdot \left\langle \begin{matrix} \boldsymbol{i} \\ \boldsymbol{j} \\ \boldsymbol{k} \end{matrix} \right\rangle \end{aligned}$$

Let,

$\boldsymbol{i}^2 = \boldsymbol{j}^2 = \boldsymbol{k}^2 = \boldsymbol{ijk} = -1$
$p = d + a\boldsymbol{i} + b\boldsymbol{j} + c\boldsymbol{k}$
$q = w + x\boldsymbol{i} + y\boldsymbol{j} + z\boldsymbol{k}$

$$
\begin{aligned}
p \times q &= dw - \left\langle \begin{matrix} a \\ b \\ c \end{matrix} \right\rangle \cdot \left\langle \begin{matrix} x \\ y \\ z \end{matrix} \right\rangle \\
&\quad + \left\langle \begin{matrix} dx + aw + bz - cy \\ dy - az + bw + cx \\ dz + ay - bx + cw \end{matrix} \right\rangle \cdot \left\langle \begin{matrix} \boldsymbol{i} \\ \boldsymbol{j} \\ \boldsymbol{k} \end{matrix} \right\rangle \\
&= dw - \left\langle \begin{matrix} a \\ b \\ c \end{matrix} \right\rangle \cdot \left\langle \begin{matrix} x \\ y \\ z \end{matrix} \right\rangle + \left(d \left\langle \begin{matrix} x \\ y \\ z \end{matrix} \right\rangle + w \left\langle \begin{matrix} a \\ b \\ c \end{matrix} \right\rangle + \left\langle \begin{matrix} a \\ b \\ c \end{matrix} \right\rangle \times \left\langle \begin{matrix} x \\ y \\ z \end{matrix} \right\rangle \right) \cdot \left\langle \begin{matrix} \boldsymbol{i} \\ \boldsymbol{j} \\ \boldsymbol{k} \end{matrix} \right\rangle
\end{aligned}
$$


1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
i, k
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
Real, j

Hypercomplex Iterative Methods

Implementation

Quaternion Multiplication

```
def qMult(p, q):
    r = Quat(
        p.r*q.r - p.i*q.i - p.j*q.j - p.k*q.k,
        p.r*q.i + p.i*q.r + p.j*q.k - p.k*q.j,
        p.r*q.j - p.i*q.k + p.j*q.r + p.j*q.i,
        p.r*q.k + p.i*q.j - p.j*q.i + p.k*q.r
    )
    return r
```

Quaternion Square

```
def qSquare(q):
    r = Quat(
        q.r*q.r - q.i*q.i - q.j*q.j - q.k*q.k,
        2*q.r*q.i,
        2*q.r*q.j,
        2*q.r*q.k
    )
    return r
```

Quaternion Add

```
def qAdd(p, q):
    r = Quat(
        p.r + q.r,
        p.i + q.i,
        p.j + q.j,
        p.k + q.k
    )
    return r
```

Iteration

```
N = 12
B = 16
c = Quat(-0.2, 0.4, -0.4, -0.4)
def iterate(z):
    for n in range(N):
        z = z*z + c
        if abs(z) > B: break
    return n
```

Ploting

Hypercomplex Juila Set Example

- Defined by iterative function in 4D Quaternion space

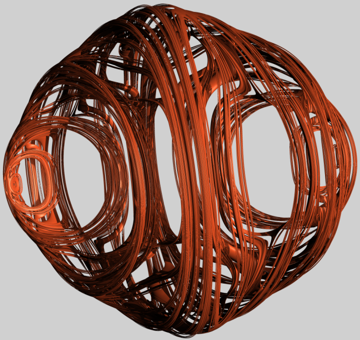


Figure: $f(z) = z^2 + 0.3 - 0.375\boldsymbol{i} - 0.675\boldsymbol{j} - 0.112\boldsymbol{k}$

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Questions?

https://github.com/scrufulufugus/senior-synthesis