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Early Days in Complex Dynamics

A History of Complex Dynamics in One Variable During 1906–1942

Daniel S. Alexander
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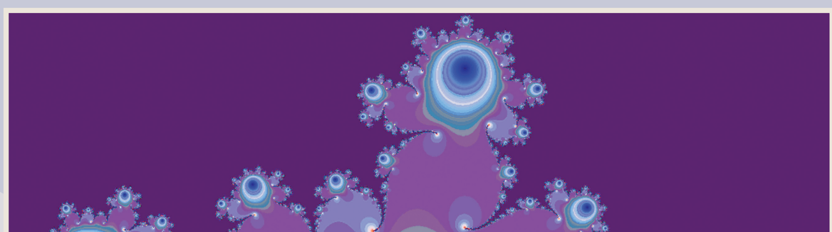

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Preface

Our goal is to tell the story of the development of complex dynamics in the first half of the 20th century. We introduce the reader to the mathematics we cover through its origins in the 19th century. We then provide additional context for our work through discussions of differential equations, in particular, the relation of Henri Poincaré to the study of complex dynamics and the problem of small divisors.

The works of Pierre Fatou and Gaston Julia, and the controversial events surrounding their work, take up the middle third of our story. But the study of complex dynamics in the first half of the 20th century did not stop with Fatou and Juila's exploration of rational functions, and so we cover subsequent developments in the last third of our narrative, including the beginnings of transcendental and algebraic dynamics, as well as a detailed examination of the center problem, which culminated in 1942 with Carl Ludwig Siegel's successful solution of a small divisors problem that links complex dynamics to KAM theory.

The conclusion of our own narrative, however, does not signal the end of our book: we include numerous appendices, the bulk of which are written by mathematicians currently involved in the development of complex dynamics. Our hope is that they underscore the connections between current research and its history.

Our book ends with the usual back matter—a glossary, a detailed index and an exhaustive bibliography—but we also include four appendices of our own devising: Two contain extended biographical sketches of Fatou and Julia, and the next consists of capsule biographies of many of the other mathematicians whose work you encounter along the way. Our last appendix discusses the computer graphics we use to illustrate the works we discuss. Appendices where the author's name is not given were written by us.

Some brief comments regarding our methodology: Unless explicitly noted, translations are our own. For the sake of notational coherence, we have made very inconsequential changes in notation in some of our direct quotations. For example, most functions will be referred to as f whether or not that was the name used by the author. However, when we refer to an equation number in our quotations, you may assume the author did likewise, although obviously using a different number.

Most of the technical terms we use are introduced in the first chapter and can be located through the index where their first reference will be to their definition. Definitions of terms introduced later are indexed similarly. Bibliographical citations are keyed by the publication date and a name is added only if the citation is unclear.

We hope you enjoy our work. In the words of the great Stan Lee, we produced the kind of story we ourselves would enjoy reading.*

*The actual quote is, "For just once, I would do the type of story I myself would enjoy reading. . ." (Lee [**1974**, p. 17]).

Acknowledgments

First we would like to thank our families whose support during this project has meant more to us than they will ever know. In particular, Dan wishes to thank Rebecca, Caroline and Elise, and he dedicates this book to them. Felice wishes to dedicate the present work to his uncle Felice, to his parents Tina and Pietro, to his wife Miriam, to Vittorio D'Andria, and to Donato Trigiante whose invaluable and steadfast advice unveiled the innermost beauty of mathematics. Sandro wishes to dedicate this book to his family, and to the memory of the beloved Alfonso Farina, who took a little student and taught him to love mathematics.

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Glossary

Note: Italicized terms in the glossary indicate another glossary entry.

$\overline{\mathbb{C}}$**:** The extended complex plane or the Riemann sphere.
$\mathbb{D}$**:** The open unit disc: $\{z : |z| < 1\}$.
$\mathbb{H}$**:** The upper half-plane: $\{z : \Re(z) < 1\}$.
$\mathcal{I}$**:** The iterative family of f, that is, the set $\mathcal{I} = \{f^n : n = 0, 1, \dots\}$.

Abel functional equation: The functional equation $A \circ f = A + c$, where f is known, and c is a complex constant. In the canonical Abel functional equation, $c = 1$.
antecedent: An image of a point z under the iteration of f, that is, $f^n(z)$, where $n \in \mathbb{N}$.
attracting cycle (or orbit): An *attracting fixed point* or *attracting periodic orbit.* We will refer generically to an *attracting periodic orbit* or an *attracting fixed point* as an *attracting orbit*, *attracting cycle* or attractor.
attracting fixed point: Given a function f, a *fixed point* λ satisfying $|f'(\lambda)| < 1$. If $f'(\lambda) = 0$ then the fixed point λ is a *superattracting fixed point.*
attracting periodic orbit of order p**:** A *periodic orbit of order* p such that

$$\left|\frac{d}{dz} f^p(\lambda_k)\right| = \left|\prod_{k=0}^{p-1} f'(\lambda_k)\right| < 1.$$

Also called an *attracting cycle.*

backward orbit: The set $O^-(z) = \{f^{-n}(z) : n = 0, 1, 2, \dots\}$, where f^{-1} is the *total inverse* of f. One can also consider the orbit of a point under a branch of the inverse.
Baker domain: A region D in $\overline{\mathbb{C}}$, *forward invariant* under f, with an essential singularity $a \in \partial D$, with the property that while no orbits $O^+(z)$ originating in D have an accumulation point in D, there is a $p \in \mathbb{N}$ such that for all $z \in D$, $f^{pk}(z) \to a$ as $k \to \infty$.
basin of infinity: If the point at infinity is an *attracting fixed point*, then its *domain of convergence* is referred to as the basin of infinity.
Böttcher functional equation: The functional equation $B \circ f = (B)^k$ where f is known, and k is the order of the first nonzero term in the Taylor series of f expanded about a point c.

Cantor set: A totally disconnected, perfect set.
center: Given a function f, a point λ satisfying $f(\lambda) = \lambda$ where iteration is conformally equivalent to a rotation of $\mathbb{D}$. Alternatively, λ is a center if it is satisfies the canonical *Schröder functional equation* $S \circ f = f'(\lambda) \cdot S$, on a neighborhood surrounding λ.
completely invariant domain: A connected component D of the *Fatou set* such that $f(D) \subseteq D$ and $f^{-1}(D) \subseteq D$ for all branches of the inverse of f.
consequent: A *preimage of a point* z under the iteration of f, that is, a point w such that $z = f^n(w)$, where $n \in \mathbb{N}$.
critical point: A point z such that $f'(z) = 0$.
critical value: The point $w = f(z)$, where z is a *critical point* of f.

degree of a rational function: If $f = p/q$ is a *rational function*, the maximum of $\{\deg f, \deg q\}$, written $\deg f$.
derived set: The set S' of limit points of a given set S.

domain: An open, connected set in $\overline{\mathbb{C}}$. Sometimes this will be part of the name of a particular set and is not intended to imply that the set is open or connected; for example, the domain of nonnormality is closed, and the domain of normality can be an infinite union of open, connected sets.

domain of convergence: The set of all z such that $f^k(z)$ converges to a fixed point λ, often denoted $A(\lambda)$. It is possible that this set has infinitely many connected components in which case the component containing λ is called the *immediate domain of convergence*.

domain of nonnormality: The set of points z from $\overline{\mathbb{C}}$ on which the *iterative family* $\mathcal{I}$ is not a *normal family* on neighborhoods of z. Also called the *Julia set* of f.

domain of normality: The set of points z from $\overline{\mathbb{C}}$ on which the *iterative family* $\mathcal{I}$ is a *normal family* on some neighborhood of z. Also called the *Fatou set* of f.

entire function: An analytic function which is single valued at all finite points of the plane.

exceptional value: Let $\mathcal{F}$ be a family of analytic (or *meromorphic*) functions on a *domain* D. If $w \notin \bigcup_{f\in\mathcal{F}} f(D)$, then then w is an exceptional value for $\mathcal{F}$ on D.

Fatou set: For a given function f the *domain of normality* for the *iterative family* $\mathcal{I}$. Since this term did not come into common usage until the 1980s, our use of it is somewhat anachronistic.

filled-in Julia set: The union of the *Julia set* J and the set of all $z \in \mathbb{C}$ for which the *forward orbit* of z, under f, is bounded. This is usually applied when J is a closed curve in which case the filled-in Julia set equals the union of J and its interior.

fixed point: A point λ satisfying $f(\lambda) = \lambda$ for a given function f.

forward invariant: A connected component D of the *Fatou set* such that $f(D) \subseteq D$. It is also referred to as an *invariant domain.* If a forward invariant domain is also invariant for the *total inverse* of f, that is, if $f^{-1}(D) \subseteq D$ for all branches of the inverse, it is said to be *completely invariant.*

forward orbit: The set $O^+(z) = \{f^n(z) : n = 0, 1, 2, \ldots\}$.

fundamental circle: A circle C in $\overline{\mathbb{C}}$ such that $f(C) = C$ and $f(\mathrm{Int}(C)) = \mathrm{Int}(C)$.

Herman ring: A doubly connected component D of the *Fatou set* of f which is conformally isomorphic to an annulus A on which iteration by f (or some iterate of f) is conformally equivalent to a rotation of A. It is an example of a *rotation domain.*

immediate domain of convergence: The component D of the *domain of convergence* of an *attracting fixed point* λ that contains λ. If the domain of convergence only consists of one component, then the domain of convergence coincides with the immediate domain of convergence.

invariant domain: A connected component D of the *Fatou set* such that $f(D) \subseteq D$. An invariant domain is sometimes called *forward invariant.* If an invariant domain is also invariant under all branches of the *total inverse* of f, that is, if $f^{-1}(D) \subseteq D$ for all branches of the inverse, it is *completely invariant.*

irrationally neutral or indifferent fixed point: Given a function f, a *fixed point* λ where $|f'(\lambda)| = 1$ but is not a root of unity.

iterative family: The set $\mathcal{I} = \{f^n : n = 0, 1, \ldots\}$.

Julia set: For a given function f, the *domain of nonnormality* for the iterative family $\mathcal{I}$. For *rational functions* of degree two or more, this is is equivalent to the closure of the set of *repelling periodic points.* Since this term was not used until at least the 1920s and did not come into common usage until the 1980s, our use of it is somewhat anachronistic.

Kœnigs' linearization theorem: Let f be analytic on a neighborhood of λ. If λ is a *fixed point* of f satisfying $0 < |\lambda| < 1$, then there is a conformal mapping S from a neighborhood of λ onto a neighborhood of the origin satisfying the canonical *Schröder functional equation*, $S \circ f = f'(\lambda)S$.

Lattès function: A *rational function* l whose *Julia set* equals the entire Riemann sphere.

limit function: A function L on a component D of the *Fatou set* of f, such that a subsequence of the *iterative family* $\mathcal{I}$ converges uniformly to L on compact subsets of D.

meromorphic function: A function which has a pole at one or more points z in a *domain* D is said to be meromorphic on D.

Montel's normality criterion: Let $\mathcal{F}$ be a family of *meromorphic* functions on a *domain* D. If $\mathcal{F}$ has at least three *exceptional values* on D, then it is a *normal family* on D. If the family is analytic, only two exceptional values are sufficient.

multiplicity of a fixed point λ: The multiplicity of a *fixed point* λ viewed as a root of $f(z) = z$. Since $f(z) = z$ reduces to

$$0 = (\lambda - z) + a_1(z - \lambda) + a_{n+1}(z - \lambda)^{n+1} + \cdots,$$

near λ, its multiplicity is greater than one only when the *multiplier* $f'(\lambda) = a_1$ is one, in which case the multiplicity equals $n + 1$.

multiplier of a fixed point: The quantity $f'(\lambda)$ where λ is a fixed point of f.

neighborhood of infinity: The set $\{z : |z| > R\}$, usually for large R.

neutral (or indifferent) fixed point: Given a function f, a *fixed point* λ with $|f'(\lambda)| = 1$. A neutral fixed point is *rationally neutral or indifferent* if $f'(\lambda)$ is a root of unity; if it is not, λ is an *irrationally neutral or indifferent* fixed point.

normal family: A family of functions $\mathcal{F}$ is normal on a *domain* D if every sequence of functions from $\mathcal{F}$ contains a subsequence f_n which converges uniformly on compact subsets of D, or converges uniformly to ∞ on D.

periodic orbit of order p: The set $O^+(z_0) = \{z_0, z_1 = f(z), \ldots, z_{p-1} = f^{p-1}(z)\}$, where p is a *periodic point of order* p.

periodic point of order p: A point z satisfying $f^p(z_0) = z_0$, for $p \in \mathbb{N}$, with $f^k(z_0) \neq z_0$ for $0 < k < p - 1$.

Picard's Big Theorem: In any neighborhood of an isolated essential singularity, an analytic function takes on every value of $\mathbb{C}$ except at most one. Each nonomitted value is taken on an infinite number of times in this neighborhood. The omitted value is called an *exceptional value*. For the case of an essential singularity of a *meromorphic function*, two values are excluded.

Picard's Little Theorem: An *entire function* from $\mathbb{C}$ to $\mathbb{C}$ that omits two or more values is constant.

Poincaré functional equation: The functional equation $f \circ \theta = \theta \circ (s \cdot I)$, where f is known, and s is a complex constant. Usually, $s = f'(\lambda)$ where λ is a *fixed point* of f with $|s| \geq 1$.

post-critical set: The union of the sets $O^+(w)$, as w ranges over the set of *critical values* of f.

preimage of a point z: A point w such that $z = f^n(w)$, where $n \in \mathbb{N}$.

properly discontinuous group: Our usage is intended to suggest how the term was used when those mathematicians we wrote about used it. The action of a group G is discontinuous on a set D if G contains no infinitesimal transformations; that is, there is no element $g \neq I$ of G such that $g(z)$ is infinitesimally close to z for all $z \in D$. If there are points in D where an infinitesimal transformation exists, a discontinuous group is improperly discontinuous at that point, a term that is generally out of use nowadays; otherwise, its action is properly discontinuous. See Forsyth [**1918**, pp. 717–719].

rational function: A complex function $f = p/q$, where p and q are polynomials.

rationally neutral or indifferent fixed point: Given a function f, a *fixed point* λ where $|f'(\lambda)|$ is a root of unity.

repelling cycle (or orbit): A *repelling fixed point* or *repelling periodic orbit.*

repelling fixed point: A *fixed point* λ of a function f with $|f'(\lambda)| > 1$.

repelling periodic orbit of order p: A *periodic orbit of order* p such that

$$\left|\frac{d}{dz} f^p(\lambda_k)\right| = \left|\prod_{k=0}^{p-1} f'(\lambda_k)\right| > 1.$$

Also called a *repelling cycle*.

rotation domain: The collective name for a *Siegel disc* or a *Herman ring*.

Schröder functional equation: The functional equation $S \circ f = c \cdot S$, where f is known and c is a complex constant. In the canonical Schröder functional equation, $c = f'(\lambda)$ where λ is a *fixed point* of f.

***d'un seul tenant*:** Used by Fatou and Julia to describe path connectedness. Julia gave the following definition: a set is *d'un seul tenant* if, given $\epsilon > 0$, "one can find in the set a succession of points beginning and ending with the two points, such that the distance of each to the one following it is less than ϵ" [**1918a**, p. 58].

Siegel disc: A singly connected region D of the *Fatou set* of f which is conformally isomorphic to $\mathbb{D}$ on which f (or some iterate of f) is conformally equivalent to a rotation of $\mathbb{D}$. It is an example of a *rotation domain*. The *fixed point* is called a *center*.

singular domain: A component of the *Fatou set* of f such that the *iterative family* $\mathcal{I}$ has nonconstant *limit functions*.

superattracting fixed point: Given a function f, a point λ satisfying $f(\lambda) = \lambda$ and $|f'(\lambda)| = 0$.

total inverse: The multifunction defined by $f^{-1}(z) = \{w : f(z) = w\}$.

total orbit: The union of the *forward orbit* $O^+(z)$ and the *backward orbit* $O^-(z)$.

wandering domain: A component of the *Fatou set* D such that the infinite sequence $\{f^n(D)\}$ is pairwise disjoint.

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We list archival material first, followed by a list publications by author, publisher, or journal. In the case of joint authorhship we have ordered the names alphabetically. Our citation key is the year of publication, followed by a lower-case letter (e.g., Fatou [**1906b**]) when there are multiple publications for the author in a given year. An upper-case "W" following a year indicates the work is available only on the World Wide Web. A paper that is accepted for publication but has yet to appear is denoted by "appear" and a paper in preparation but not submitted is denoted by "prep".

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Index

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The theory of complex dynamics, whose roots lie in 19th-century studies of the iteration of complex function conducted by Kœnigs, Schöder, and others, flourished remarkably during the first half of the 20th century, when many of the central ideas and techniques of the subject developed. This book by Alexander, Iavernaro, and Rosa paints a robust picture of the field of complex dynamics between 1906 and 1942 through detailed discussions of the work of Fatou, Julia, Siegel, and several others.

A recurrent theme of the authors' treatment is the center problem in complex dynamics. They present its complete history during this period and, in so doing, bring out analogies between complex dynamics and the study of differential equations, in particular, the problem of stability in Hamiltonian systems. Among these analogies are the use of iteration and problems involving small divisors which the authors examine in the work of Poincaré and others, linking them to complex dynamics, principally via the work of Samuel Lattès, in the early 1900s, and Jürgen Moser, in the 1960s.

Many details will be new to the reader, such as a history of Lattès functions (functions whose Julia set equals the Riemann sphere), complex dynamics in the United States around the time of World War I, a survey of complex dynamics around the world in the 1920s and 1930s, a discussion of the dynamical programs of Fatou and Julia during the 1920s, and biographical material on several key figures. The book contains graphical renderings of many of the mathematical objects the authors discuss, including some of the intriguing fractals Fatou and Julia studied, and concludes with several appendices by current researchers in complex dynamics which collectively attest to the impact of the work of Fatou, Julia, and others upon the present-day study.

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