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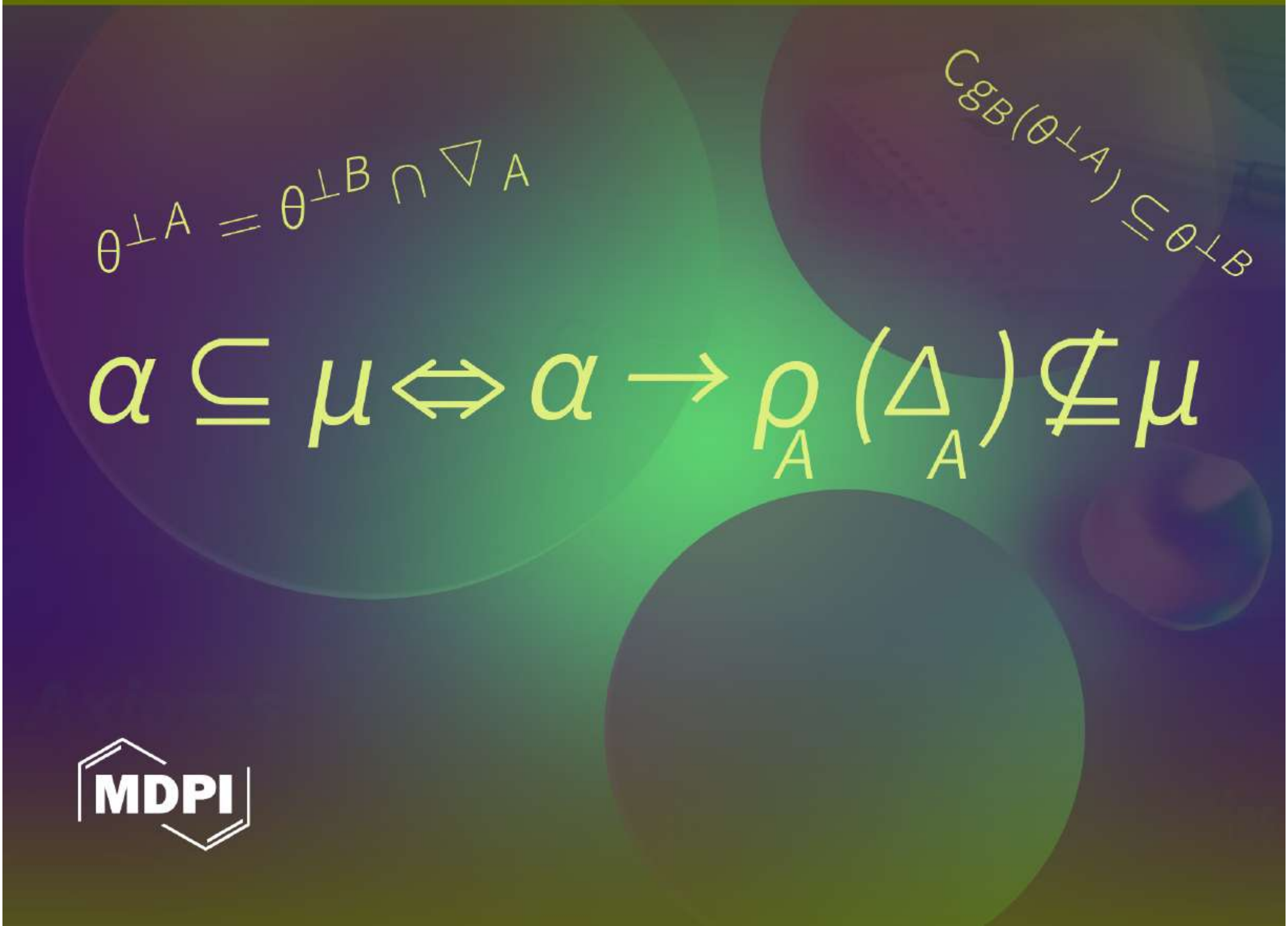
# Congruence Extensions in Congruence–Modular Varieties

Volume 13 · Issue 12 December 2024

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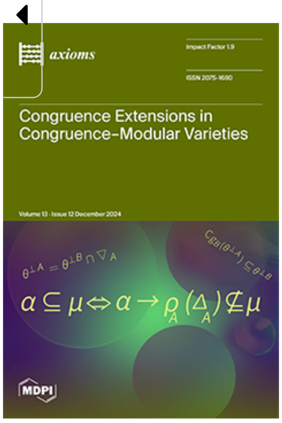


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**Evaluation of Certain Definite Integrals Involving Generalized Hypergeometric Functions (/2075-1680/13/12/887)**

by **Prathima Jayarama**, **Dongkyu Lim**, **Arjun K. Rathie** and **Adem Kilicman**

*Axioms* **2024**, *13*(12), 887; **https://doi.org/10.3390/axioms13120887 (https://doi.org/10.3390/axioms13120887)** - 23 Dec 2024

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**Abstract** In 2012, Chu investigated the generalization of classical Watson–Whipple–Dixon summation theorems in the form of analytical formulas. By employing four generalized Watson summation formulas, the objective of this paper is to evaluate a new class of several Eulerian-type integrals (single and double) and **[...] Read more.**

(This article belongs to the Special Issue **Advances in Generalized Hypergeometric Functions, Integral Transforms and Number Theory ( /journal/axioms/special_issues/87MIOC9S78 )**)

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**Exploring Stochastic Heat Equations: A Numerical Analysis with Fast Discrete Fourier Transform Techniques (/2075-1680/13/12/886)**

by **Ahmed G. Khattab**, **Mourad S. Semary**, **Doaa A. Hammad** and **Aisha F. Fareed**

*Axioms* **2024**, *13*(12), 886; **https://doi.org/10.3390/axioms13120886 (https://doi.org/10.3390/axioms13120886)** - 21 Dec 2024

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**Abstract** This paper presents an innovative numerical technique for specific classes of stochastic heat equations. Our approach uniquely combines a sixth-order compact finite difference algorithm with fast discrete Fourier transforms. While traditional discrete sine transforms are effective for approximating second-order derivatives, they are inadequate **[...] Read more.**

(This article belongs to the Special Issue **Research on Stochastic Analysis and Applied Statistics ( /journal/axioms/special_issues/4Y3HXY252M )**)

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**Parametric Integrals for Binomial Series with Harmonic Polynomials (/2075-1680/13/12/885)**

by **Chunli Li** and **Wenchang Chu**

*Axioms* **2024**, *13*(12), 885; https://doi.org/10.3390/axioms13120885 (https://doi.org/10.3390/axioms13120885) - 21 Dec 2024



**Abstract** Binomial series involving harmonic polynomials are expressed in terms of parametric integrals. By evaluating these parametric integrals, we establish several remarkable closed formulae for the infinite series containing both central binomial coefficients and harmonic numbers. Most of the values for binomial series found [...] Read more.

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**The Maximal Regularity of Nonlinear Second-Order Hyperbolic Boundary Differential Equations (/2075-1680/13/12/884)**

by **Xingyu Liu**

*Axioms* **2024**, *13*(12), 884; https://doi.org/10.3390/axioms13120884 (https://doi.org/10.3390/axioms13120884) - 20 Dec 2024



**Abstract** In this paper, we show the maximal regularity of nonlinear second-order hyperbolic boundary differential equations. We aim to show if the given second-order partial differential operator satisfies the specific ellipticity condition; additionally, if solutions of the function, which are related to the first-order [...] Read more.

(This article belongs to the Special Issue **Advances in Differential Equations and Its Applications ( /journal/axioms/special_issues/9T0N2E2DXU )**)

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**Parametric Inference in Biological Systems in a Random Environment (/2075-1680/13/12/883)**

by **Manuel Molina-Fernández** and **Manuel Mota-Medina**

*Axioms* **2024**, *13*(12), 883; https://doi.org/10.3390/axioms13120883 (https://doi.org/10.3390/axioms13120883) - 20 Dec 2024

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**Abstract** This research focuses on biological systems with sexual reproduction in which female and male individuals coexist together, forming female–male couples with the purpose of procreation. The couples can originate new females and males according to a certain probability law. Consequently, in this type **[...] Read more.**
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**Analysis of Optimal Prediction Under Stochastically Restricted Linear Model and Its Subsample Models (/2075-1680/13/12/882)**

by **Nesrin Güler**

*Axioms* **2024**, *13*(12), 882; **https://doi.org/10.3390/axioms13120882 (https://doi.org/10.3390/axioms13120882)** - 19 Dec 2024


**Abstract** This paper provides a study on optimal prediction problems in a linear model and its subsample models with linear stochastic restrictions, using matrix theory for precise analytical solutions. It focuses on deriving analytical expressions using block matrix inertia and rank methods to determine **[...] Read more.**
(This article belongs to the Special Issue **Stochastic and Statistical Analysis in Natural Sciences ( /journal/axioms/special_issues/KH3TUTT8QM )**)

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**Mathematical Modeling of Fractals via Proximal F-Iterated Function Systems (/2075-1680/13/12/881)**

by **Muhammad Zahid**, **Fahim Ud Din**, **Mudasir Younis**, **Haroon Ahmad** and **Mahpeyker Öztürk**

*Axioms* **2024**, *13*(12), 881; **https://doi.org/10.3390/axioms13120881 (https://doi.org/10.3390/axioms13120881)** - 19 Dec 2024


**Abstract** We propose a novel approach to fractals by leveraging the approximation of fixed points, emphasizing the deep connections between fractal theory and fixed-point theory. We include a condition of isomorphism, which not only generates traditional fractals but also introduces the concept of generating **[...] Read more.**
(This article belongs to the Special Issue **New Theory and Applications of Nonlinear Analysis, ...tional Calculus and Optimization, 2nd Edition ( /journal/axioms/**

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**Efficient Newton-Type Solvers Based on for Finding the Solution of Nonlinear Algebraic Problems (/2075-1680/13/12/880)**

by **Haifa Bin Jebreen**, **Hongzhou Wang** and **Yurilev Chalco-Cano**

*Axioms* **2024**, *13*(12), 880; https://doi.org/10.3390/axioms13120880 (https://doi.org/10.3390/axioms13120880) - 19 Dec 2024



**Abstract** The purpose of this study is to improve the computational efficiency of solvers for nonlinear algebraic problems with simple roots. To this end, a multi-step solver based on Newton's method is utilized. Divided difference operators are applied at two substeps in various forms **[...] Read more.**

(This article belongs to the Special Issue **Differential Equations and Inverse Problems, 2nd Edition ( /journal/axioms/special_issues/BR02IEU31J )**)

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**The Norm Function for Commutative $\mathbb{Z}_2$-Graded Rings (/2075-1680/13/12/879)**

by **Azzh Saad Alshehry** and **Rashid Abu-Dawwas**

*Axioms* **2024**, *13*(12), 879; https://doi.org/10.3390/axioms13120879 (https://doi.org/10.3390/axioms13120879) - 18 Dec 2024



**Abstract** Consider a commutative $\mathbb{Z}_2$-graded ring ($R = R_0 \bigoplus R_1$). Consequently, each element ($x \in R$) can be uniquely expressed as $x = x_0 + x_1$, where $x_0 \in R_0$ **[...] Read more.**

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**New Results of Differential Subordination for a Specific Subclass of *p*-Valent Meromorphic Functions Involving a New Operator (/2075-1680/13/12/878)**

by **Nihad Hameed Shehab**, **Abdul Rahman S. Juma**, **Luminița-Ioana Cotîrlă** and **Daniel Breaz**

*Axioms* **2024**, *13*(12), 878; https://doi.org/10.3390/axioms13120878 (https://doi.org/10.3390/axioms13120878) - 18 Dec 2024



**Abstract** The present article aims to significantly improve geometric function theory by making an important contribution to *p*-valent meromorphic and analytic functions. It focuses on subordination, which describes the relationships of analytic functions. In order to achieve this, we utilize a technique that **[...] Read more.**

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**Commutative Chain Rings with Index of Nilpotency 5 and Residue Field $\mathbb{F}_{p^m}$ (/2075-1680/13/12/877)**

by **Alhanouf Ali Alhomaidhi**, **Sami Alabiad** and **Nawal A. Alsarori**

*Axioms* **2024**, *13*(12), 877; https://doi.org/10.3390/axioms13120877 (https://doi.org/10.3390/axioms13120877) - 17 Dec 2024



**Abstract** This paper gives a thorough characterization of chain rings with index of nilpotency 5 and residue field $\mathbb{F}_{p^m}$, where *p* represents a prime number, contributing valuable insights to the field of algebraic structures. It carefully identifies and categorizes the family **[...] Read more.**

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**A Fractional Gompertz Model with Generalized Conformable Operators to Forecast the Dynamics of Mexico's Hotel Demand and Tourist Area Life Cycle (/2075-1680/13/12/876)**

by **Fidel Meléndez-Vázquez**, **Josué N. Gutiérrez-Corona**, **Luis A. Quezada-Téllez**, **Guillermo Fernández-Anaya** and **Jorge E. Macías-Díaz**

*Axioms* **2024**, *13*(12), 876; https://doi.org/10.3390/axioms13120876 (https://doi.org/10.3390/

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**Abstract** This study explores the application of generalized conformable derivatives in modeling hotel demand dynamics in Mexico, using the Gompertz-type model. The research focuses on customizing conformable functions to fit the unique characteristics of the Mexican hotel industry, considering the Tourist Area Life Cycle **[...] Read more.**
(This article belongs to the Special Issue **Fractional Calculus—Theory and Applications, 3rd Edition ( /journal/axioms/special_issues/H7NEH8139S )**)

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Open Access Article 12 pages, 2211 KiB **(/2075-1680/13/12/875/pdf?version=1734427334)**

**Computing the Set of RBF-FD Weights Within the Integrals of a Kernel-Based Function and Its Applications (/2075-1680/13/12/875)**

by **Tao Liu**, **Bolin Ding** and **Stanford Shateyi**

*Axioms* **2024**, *13*(12), 875; **https://doi.org/10.3390/axioms13120875 (https://doi.org/10.3390/axioms13120875)** - 17 Dec 2024

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**Abstract** This paper offers an approach to computing Radial Basis Function–Finite Difference (RBF-FD) weights by integrating a kernel-based function. We derive new weight sets that effectively approximate both the first and second differentiations of a function, demonstrating their utility in interpolation and the resolution **[...] Read more.**
(This article belongs to the Special Issue **Differential Equations and Inverse Problems, 2nd Edition ( /journal/axioms/special_issues/BR02IEU31J )**)

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Open Access Article 19 pages, 5115 KiB **(/2075-1680/13/12/874/pdf?version=1734251897)**

**Geometric Nature of the Turánian of Modified Bessel Function of the First Kind (/2075-1680/13/12/874)**

by **Samanway Sarkar**, **Dimiter Prodanov**, **Anish Kumar** and **Sourav Das**

*Axioms* **2024**, *13*(12), 874; **https://doi.org/10.3390/axioms13120874 (https://doi.org/10.3390/axioms13120874)** - 15 Dec 2024

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**Abstract** This work explores the geometric properties of the Turanian of the modified Bessel function of the first kind (TMBF). Using the properties of the digamma function, we establish conditions under which the normalized TMBF satisfies starlikeness, convexity, *k*-starlikeness, *k*-uniform convexity, pre-starlikeness, **[...] Read more.**
(This article belongs to the Special Issue **Special Functions and Related Topics ( /journal/axioms/special_issues/8T89E31WG8 )**)

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Open Access Article 22 pages, 1715 KiB (/2075-1680/13/12/873/pdf?version=1734341577)

**Laplacian Spectrum and Vertex Connectivity of the Unit Graph of the Ring $\mathbb{Z}_{p^r q^s}$ (/2075-1680/13/12/873)**

by **Amal Alsaluli**, **Wafaa Fakieh** and **Hanaa Alashwali**

*Axioms* **2024**, *13*(12), 873; https://doi.org/10.3390/axioms13120873 (https://doi.org/10.3390/axioms13120873) - 15 Dec 2024



**Abstract** In this paper, we examine the interplay between the structural and spectral properties of the unit graph $G(\mathbb{Z}_n)$ for $n = p_1^{r_1} p_2^{r_2} \ldots p_k^{r_k}$, where **[...] Read more.**

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Open Access Article 14 pages, 2003 KiB (/2075-1680/13/12/872/pdf?version=1734241922)

**Numerical Solution of the Sine–Gordon Equation by Novel Physics-Informed Neural Networks and Two Different Finite Difference Methods (/2075-1680/13/12/872)**

by **Svetislav Savović**, **Miloš Ivanović**, **Branko Drljača** and **Ana Simović**

*Axioms* **2024**, *13*(12), 872; https://doi.org/10.3390/axioms13120872 (https://doi.org/10.3390/axioms13120872) - 15 Dec 2024



**Abstract** This study employs a novel physics-informed neural network (PINN) approach, the standard explicit finite difference method (EFDM) and unconditionally positivity preserving FDM to tackle the one-dimensional Sine–Gordon equation (SGE). Two test problems with known analytical solutions are investigated to demonstrate the effectiveness of **[...] Read more.**

(This article belongs to the Special Issue **Axioms and Methods for Handling Differential Equations and Inverse Problems ( /journal/axioms/special_issues/E8DD052O4A )**)

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Open Access Article 23 pages, 339 KiB (/2075-1680/13/12/871/pdf?version=1734569275)

**Stepanov-like Pseudo *S*-Asymptotically ($\omega$, $c$)-Periodic Solutions of a Class of Stochastic Integro-Differential Equations (/2075-1680/13/12/871)**

by **Marko Kostić**, **Halis Can Koyuncuoğlu** and **Daniel Velinov**

*Axioms* **2024**, *13*(12), 871; https://doi.org/10.3390/axioms13120871 (https://doi.org/10.3390/axioms13120871) - 14 Dec 2024



**Abstract** The study of long-term behavior in stochastic systems is critical for understanding the dynamics of complex processes influenced by randomness. This paper addresses the existence and uniqueness of Stepanov-like pseudo *S*-asymptotically $(\omega, c)$-periodic solutions for a class of **[...] Read more.**

(This article belongs to the Special Issue **Recent Advances in Function Spaces and Their Applications ( /journal/axioms/special_issues/K4M57698PG )**)

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**Quasi-Lower *C*$^2$ Functions and Their Application to Nonconvex Variational Problems (/2075-1680/13/12/870)**

by **Messaoud Bounkhel**

*Axioms* **2024**, *13*(12), 870; https://doi.org/10.3390/axioms13120870 (https://doi.org/10.3390/axioms13120870) - 13 Dec 2024



**Abstract** This study presents a novel category of nonconvex functions in Banach spaces, referred to as quasi-lower $C^2$ functions on nonempty closed sets. We establish the existence of solutions for nonconvex variational problems involving quasi-lower $C^2$ functions defined in Banach spaces. To **[...] Read more.**

(This article belongs to the Special Issue **New Developments in Analysis of Variational Inequalities and Related Fields ( /journal/axioms/special_issues/4G4283YL59 )**)

Open Access Article 21 pages, 331 KiB (/2075-1680/13/12/869/pdf?version=1734080675)

**Global Existence and Decay Estimates for a Viscoelastic Petrovsky–Kirchhoff-Type Equation with a Delay Term (/2075-1680/13/12/869)**

by **Noureddine Sebih**, **Abdelhamid Mohammed Djaouti**, **Chafi Boudekhil** and **Ashraf Al-Quran**

*Axioms* **2024**, *13*(12), 869; https://doi.org/10.3390/axioms13120869 (https://doi.org/10.3390/axioms13120869) - 13 Dec 2024



**Abstract** In this paper, we consider a viscoelastic Kirchhoff equation with a delay term in the internal

feedback. By using the Faedo–Galerkin approximation method, we prove the well posedness of the global solutions. Introducing suitable energy, we prove the general uniform decay results. **Full article (/2075-1680/13/12/869)**

(This article belongs to the Special Issue **Advances in Partial Differential Equations: Qualitative Analysis and Numerical Methods ( /journal/axioms/special_issues/BK32X3777F )**)



Open Access Article 15 pages, 299 KiB **(/2075-1680/13/12/868/pdf?version=1734342491)**

**RHS and Quantum Mechanics: Some Extra Examples (/2075-1680/13/12/868)**

by **Maria Blazquez**, **Manuel Gadella** and **Gerardo Jimenez-Trejo**

*Axioms* **2024**, *13*(12), 868; **https://doi.org/10.3390/axioms13120868 (https://doi.org/10.3390/axioms13120868)** - 12 Dec 2024



**Abstract** Rigged Hilbert spaces (RHSs) are the right mathematical context that include many tools used in quantum physics, or even in some chaotic classical systems. It is particularly interesting that in RHS, discrete and continuous bases, as well as an abstract basis and the **[...] Read more.**

(This article belongs to the Special Issue **Recent Advances in Representation Theory with Applications ( /journal/axioms/special_issues/OE1Y92JMK3 )**)

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**Fixed-Point Results for Krasnoselskii, Meir–Keeler, and Boyd–Wong-Type Mappings with Applications to Dynamic Market Equilibrium (/2075-1680/13/12/867)**

by **Lifang Guo**, **Rabia Bibi**, **Abeer Alshejari**, **Ekrem Savas**, **Tayyab Kamran** and **Umar Ishtiaq**

*Axioms* **2024**, *13*(12), 867; https://doi.org/10.3390/axioms13120867 (registering DOI) - 12 Dec 2024



**Abstract** This paper introduces the idea of a cone *m*-hemi metric space, which extends the idea of an *m*-hemi metric space. By presenting non-trivial examples, we demonstrate the superiority of cone *m*-hemi metric spaces over *m*-hemi metric spaces. Further, we **[...] Read more.**

(This article belongs to the Special Issue **Advances in Fixed Point Theory with Applications ( / journal/axioms/special_issues/31W0CF7S70 )**)

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Open Access Article 18 pages, 621 KiB **(/2075-1680/13/12/866/pdf?version=1733925565)**

**On Non-Linear Differential Systems with Mixed Boundary Conditions (/2075-1680/13/12/866)**

by **Miklós Rontó**

*Axioms* **2024**, *13*(12), 866; **https://doi.org/10.3390/axioms13120866 (https://doi.org/10.3390/axioms13120866)** - 11 Dec 2024



**Abstract** For the constructive analysis of locally Lipschitzian system of non-linear differential equations with mixed periodic and two-point non-linear boundary conditions, a numerical-analytic approach is developed, which allows one to study the solvability and construct approximations to the

solution. The values of the unknown **[...] Read more.**
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Open Access Article 16 pages, 262 KiB **(/2075-1680/13/12/865/pdf?version=1733908920)**

**Neutrosophic Strongly Preopen Sets and Neutrosophic Strong Precontinuity (/2075-1680/13/12/865)**

by **Ahu Açikgöz** and **Ferhat Esenbel**

*Axioms* **2024**, *13*(12), 865; **https://doi.org/10.3390/axioms13120865 (https://doi.org/10.3390/axioms13120865)** - 11 Dec 2024



**Abstract** : In this study, we introduce a novel class of generalized neutrosophic open sets, referred to as neutrosophic strongly preopen sets. Building on this foundation, we propose a new type of continuity and several new types of mappings. These concepts aim to inspire **[...] Read more.**

Open Access Article 12 pages, 1132 KiB **(/2075-1680/13/12/864/pdf?version=1733908627)**

**Random Traveling Wave Equations for the Heisenberg Ferromagnetic Spin Chain Model and Their Optical Stochastic Solutions in a Ferromagnetic Materials (/2075-1680/13/12/864)**

by **Wael W. Mohammed**, **Fakhr Gassem** and **Rabeb Sidaoui**

*Axioms* **2024**, *13*(12), 864; **https://doi.org/10.3390/axioms13120864 (https://doi.org/10.3390/axioms13120864)** - 10 Dec 2024



**Abstract** In this paper, we investigate the stochastic Heisenberg ferromagnetic equation (SHFE) derived by a multiplicative Wiener process. We use a suitable transformation to change the SHF equation into another Heisenberg ferromagnetic equation with random variable coefficients (HFE-RVCs). We employ the mapping approach to **[...] Read more.**
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Open Access Article 12 pages, 222 KiB (/2075-1680/13/12/863/pdf?version=1733993920)

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**[Regularity of n-P-V-Rings and n-P-V'-Rings (/2075-1680/13/12/863)]**

by **Liuwen Li**, **Wenlin Zou** and **Ying Li**

*Axioms* **2024**, *13*(12), 863; https://doi.org/10.3390/axioms13120863 (https://doi.org/10.3390/axioms13120863) - 10 Dec 2024



**Abstract** The regularity of the n-P-V-rings and n-P-V'-rings is systematically investigated in this paper. Employing the notions of quasi-ideals, weakly left (or right) ideals, and generalized weak ideals, we focus on investigating the strong $\pi$-regularity and weak $\pi$-regularity of the n-P-V-rings and [...] Read more.

Open Access Article 24 pages, 1804 KiB (/2075-1680/13/12/862/pdf?version=1733827945)

**[The Golden Ratio Family of Extremal Kerr-Newman Black Holes and Its Implications for the Cosmological Constant (/2075-1680/13/12/862)]**

by **Giorgio Sonnino** and **Pasquale Nardone**

*Axioms* **2024**, *13*(12), 862; https://doi.org/10.3390/axioms13120862 (https://doi.org/10.3390/axioms13120862) - 10 Dec 2024



**Abstract** This work explores the geometry of extremal Kerr-Newman black holes by analyzing their mass/energy relationships and the conditions ensuring black hole existence. Using differential geometry in $E^3$, we examine the topology of the event horizon surface and identify two distinct families [...] Read more.

(This article belongs to the Special Issue **Advances in Differential Geometry and Mathematical Physics ( /journal/axioms/special_issues/0Y0GIZ99I1 )**)

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Open Access Article 17 pages, 1633 KiB (/2075-1680/13/12/861/pdf?version=1733755556)

**Stochastic Models for Ontogenetic Growth (/2075-1680/13/12/861)**

by **Chau Hoang**, **Tuan Anh Phan** and **Jianjun Paul Tian**

*Axioms* **2024**, *13*(12), 861; https://doi.org/10.3390/axioms13120861 (https://doi.org/10.3390/axioms13120861) - 9 Dec 2024



**Abstract** Based on allometric theory and scaling laws, numerous mathematical models have been proposed to study ontogenetic growth patterns of animals. Although deterministic models have provided valuable insight into growth dynamics, animal growth often deviates from strict deterministic patterns due to stochastic factors such [...] Read more.

(This article belongs to the Special Issue **Advances in Mathematical Modeling and Related Topics (/journal/axioms/special_issues/I017IZD531)**)

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Open Access Article 11 pages, 271 KiB (/2075-1680/13/12/860/pdf?version=1733797151)

**On Qi's Normalized Remainder of Maclaurin Power Series Expansion of Logarithm of Secant Function (/2075-1680/13/12/860)**

by **Hong-Chao Zhang**, **Bai-Ni Guo** and **Wei-Shih Du**

*Axioms* **2024**, *13*(12), 860; https://doi.org/10.3390/axioms13120860 (https://doi.org/10.3390/axioms13120860) - 8 Dec 2024

**Abstract** In the study, the authors introduce Qi's normalized remainder of the Maclaurin power series expansion of the function $\ln \sec x = -\ln \cos x$; in view of a monotonicity rule for the ratio of two Maclaurin power series and by [...] Read more.
(This article belongs to the Special Issue **New Theory and Applications of Nonlinear Analysis, Fractional Calculus and Optimization, 2nd Edition ( /journal/axioms/special_issues/29183R155A )**)

Open Access Article 15 pages, 294 KiB (/2075-1680/13/12/859/pdf?version=1733727180)

**Investigating Multidimensional Degenerate Hybrid Special Polynomials and Their Connection to Appell Sequences: Properties and Applications (/2075-1680/13/12/859)**

by **Awatif Muflih Alqahtani**, **Saleem Yousuf**, **Shahid Ahmad Wani** and **Roberto S. Costas-Santos**
*Axioms* **2024**, *13*(12), 859; https://doi.org/10.3390/axioms13120859 (https://doi.org/10.3390/axioms13120859) - 7 Dec 2024


**Abstract** This paper explores the operational principles and monomiality principles that significantly shape the development of various special polynomial families. We argue that applying the monomiality principle yields novel results while remaining consistent with established findings. The primary focus of this study is the [...] Read more.
(This article belongs to the Special Issue **Advances in Hypergeometric Series, Orthogonal Polynomials and Their Natural Extensions ( /journal/axioms/special_issues/49C7444H66 )**)

Open Access Article 31 pages, 2537 KiB (/2075-1680/13/12/858/pdf?version=1733811497)

**A Novel Framework for Belief and Plausibility Measures in Intuitionistic Fuzzy Sets: Belief and Plausibility Distance, Similarity, and TOPSIS for Multicriteria Decision Making (/2075-1680/13/12/858)**

by **Shahid Hussain**, **Zahid Hussain**, **Rashid Hussain**, **Ahmad Bakhet**, **Hussain Arafat**, **Mohammed Zakarya**, **Amirah Ayidh I Al-Thaqfan** and **Maha Ali**
*Axioms* **2024**, *13*(12), 858; https://doi.org/10.3390/axioms13120858 (https://doi.org/10.3390/axioms13120858) - 7 Dec 2024


**Abstract** Dempster–Shafer Theory (DST) relies significantly on belief and plausibility measures to handle ambiguity and uncertainty; however, DST has been extended to fuzzy sets (FSs) and intuitionistic fuzzy sets (IFSs) with only a few extensions focusing on belief and plausibility intuitionistic fuzzy distance (BP-distance) [...] Read more.
(This article belongs to the Special Issue **Stochastic Modeling and Optimization Techniques ( /journal/axioms/special_issues/6X5S8752Y7 )**)

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Open Access Article 16 pages, 1257 KiB (/2075-1680/13/12/857/pdf?version=1733889115)

**A Novel Sine Step Size for Warm-Restart Stochastic Gradient Descent (/2075-1680/13/12/857)**

by **Mahsa Soheil Shamaee** and **Sajad Fathi Hafshejani**

*Axioms* **2024**, *13*(12), 857; https://doi.org/10.3390/axioms13120857 (https://doi.org/10.3390/axioms13120857) - 6 Dec 2024



**Abstract** This paper proposes a novel sine step size for warm-restart stochastic gradient descent (SGD). For the SGD based on the new proposed step size, we establish convergence rates for smooth non-convex functions with and without the Polyak–Łojasiewicz (PL) condition. To assess the effectiveness [...] Read more.

(This article belongs to the Special Issue **Advances in Stochastic Processes and Stochastic Differential Equations ( /journal/axioms/special_issues/9147RB08QG )**)

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Open Access Article 13 pages, 272 KiB (/2075-1680/13/12/856/pdf?version=1733393136)

**Stable Solutions of a Class of Degenerate Elliptic Equations (/2075-1680/13/12/856)**

by **Yin Lang** and **Hairong Liu**

*Axioms* **2024**, *13*(12), 856; https://doi.org/10.3390/axioms13120856 (https://doi.org/10.3390/axioms13120856) - 5 Dec 2024



**Abstract** This paper deals with the second-order semi-linear degenerate elliptic equation [...] Read more.

Open Access Article 16 pages, 501 KiB (/2075-1680/13/12/855/pdf?version=1733316315)

**...bility of Differential Equations with Random Impulses and Caputo-Type Fractional ...vatives (/2075-1680/13/12/855)**

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by **Snezhana Hristova**, **Billur Kaymakçalan** and **Radoslava Terzieva**
*Axioms* **2024**, *13*(12), 855; **https://doi.org/10.3390/axioms13120855 (https://doi.org/10.3390/axioms13120855)** - 4 Dec 2024
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**Abstract** In this paper, we study nonlinear differential equations with Caputo fractional derivatives with respect to other functions and impulses. The main characteristic of the impulses is that the time between two consecutive impulsive moments is defined by random variables. These random variables are **[...] Read more.**

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Open Access Article 13 pages, 400 KiB **(/2075-1680/13/12/854/pdf?version=1733312925)**

**Impulsive Linearly Implicit Euler Method for the SIR Epidemic Model with Pulse Vaccination Strategy (/2075-1680/13/12/854)**

by **Gui-Lai Zhang**, **Zhi-Yong Zhu**, **Lei-Ke Chen** and **Song-Shu Liu**
*Axioms* **2024**, *13*(12), 854; **https://doi.org/10.3390/axioms13120854 (https://doi.org/10.3390/axioms13120854)** - 4 Dec 2024
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**Abstract** In this paper, a new numerical scheme, which we call the impulsive linearly implicit Euler method, for the SIR epidemic model with pulse vaccination strategy is constructed based on the linearly implicit Euler method. The sufficient conditions for global attractivity of an infection-free **[...] Read more.**
(This article belongs to the Special Issue **Differential Equations and Inverse Problems, 2nd Edition ( /journal/axioms/special_issues/BR02IEU31J )**)

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Open Access Article 19 pages, 308 KiB **(/2075-1680/13/12/853/pdf?version=1733221429)**

**Method for Investigation of Convergence of Formal Series Involved in Asymptotics of Solutions of Second-Order Differential Equations in the Neighborhood of Irregular Singular Points (/2075-1680/13/12/853)**

by **Maria Korovina** and **Ilya Smirnov**
*Axioms* **2024**, *13*(12), 853; **https://doi.org/10.3390/axioms13120853 (https://doi.org/10.3390/**

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axioms13120853) - 3 Dec 2024
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**Abstract** The aim of the article is to create a method for studying the asymptotics of solutions to second-order differential equations with irregular singularities. The method allows us to prove the convergence of formal series included in the asymptotics of solutions for a wide **[...] Read more.**

Open Access Article 18 pages, 11181 KiB (/2075-1680/13/12/852/pdf?version=1733221207)

**Topological Properties of the Intersection Curves Between a Torus and Families of Parabolic or Elliptical Cylinders (/2075-1680/13/12/852)**

by **Ana Breda**, **Alexandre Trocado** and **José Dos Santos**

*Axioms* **2024**, *13*(12), 852; https://doi.org/10.3390/axioms13120852 (https://doi.org/10.3390/axioms13120852) - 3 Dec 2024
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**Abstract** This paper reports the research work carried out with the goal of geometrically and algebraically describing, as well as topologically classifying, the curves resulting from the intersection of a torus with families of parabolic and elliptical cylinders within a purely Euclidean framework. The **[...] Read more.**

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Open Access Article 10 pages, 237 KiB (/2075-1680/13/12/851/pdf?version=1733215466)

**A Note on Injective g-Frames in Quaternionic Hilbert Spaces (/2075-1680/13/12/851)**

by **Jianxia Zhang**, **Fugen Gao** and **Guoqing Hong**

*Axioms* **2024**, *13*(12), 851; https://doi.org/10.3390/axioms13120851 (https://doi.org/10.3390/axioms13120851) - 3 Dec 2024



**Abstract** Motivated by recent advancements in the quantum detection problem employing both discrete and continuous frames, this paper delves into a quantum detection problem utilizing g-frames within the context of quaternionic Hilbert spaces. We offer several equivalent representations of injective g-frames in separable quaternionic **[...] Read more.**

(This article belongs to the Section **Geometry and Topology (/journal/axioms/sections/geometry_and_topology)**)

Open Access Article 16 pages, 4018 KiB (/2075-1680/13/12/850/pdf?version=1735194755)

**Fractals as Julia Sets for a New Complex Function via a Viscosity Approximation Type Iterative Methods (/2075-1680/13/12/850)**

by **Ahmad Almutlg** and **Iqbal Ahmad**

*Axioms* **2024**, *13*(12), 850; https://doi.org/10.3390/axioms13120850 (https://doi.org/10.3390/axioms13120850) - 3 Dec 2024



**Abstract** In this article, we examine and investigate various variants of Julia set patterns for complex exponential functions $W(z) = \alpha e^{z^n} + \frac{\beta}{z^m} + \log c^t$, and **[...] Read more.**

(This article belongs to the Special Issue **Fractal Analysis and Mathematical Integration ( /journal/axioms/special_issues/2HRWJ7O7E4 )**)

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Open Access Article 23 pages, 469 KiB (/2075-1680/13/12/849/pdf?version=1733208243)

**Variational Bayesian Estimation of Quantile Nonlinear Dynamic Latent Variable Models with Possible Nonignorable Missingness (/2075-1680/13/12/849)**

by **Mulati Tuerde** and **Ahmadjan Muhammadhaji**

*Axioms* **2024**, *13*(12), 849; https://doi.org/10.3390/axioms13120849 (https://doi.org/10.3390/axioms13120849) - 3 Dec 2024



**Abstract** Our study presents an innovative variational Bayesian parameter estimation method for the Quantile Nonlinear Dynamic Latent Variable Model (QNDLVM), particularly when dealing with missing data and nonparametric priors. This method addresses the computational inefficiencies associated with the traditional Markov chain Monte Carlo (MCMC) [...] Read more.

(This article belongs to the Special Issue **Recent Advances in Statistical Modeling and Simulations with Applications, 2nd Edition ( /journal/axioms/special_issues/79B78G6W8I )**)

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Open Access Article 16 pages, 2141 KiB (/2075-1680/13/12/848/pdf?version=1733299177)

**An Optimization Model for Production Scheduling in Parallel Machine Systems (/2075-1680/13/12/848)**

by **Leting Zu**, **Wenzhu Liao** and **Xiaoxia Yang**

*Axioms* **2024**, *13*(12), 848; **https://doi.org/10.3390/axioms13120848 (https://doi.org/10.3390/axioms13120848)** - 2 Dec 2024



**Abstract** The efficiency and quality of the manufacturing industry are greatly influenced by production scheduling, which makes it a crucial aspect. A well-designed production scheduling scheme can significantly enhance manufacturing efficiency and reduce enterprise costs. This paper presents a tailored optimization model designed to **[...] Read more.**
(This article belongs to the Special Issue **Advances in Mathematical Modeling, Analysis and Optimization ( /journal/axioms/special_issues/LJ24X4SNVA )**)

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Open Access Article 28 pages, 375 KiB **(/2075-1680/13/12/847/pdf?version=1733141777)**

**Functional Differential Equations with an Advanced Neutral Term: New Monotonic Properties of Recursive Nature to Optimize Oscillation Criteria (/2075-1680/13/12/847)**

by **Amany Nabih**, **Wedad Albalawi**, **Mohammad S. Jazmati**, **Ali Elrashidi**, **Hegagi M. Ali** and **Osama Moaaz**
*Axioms* **2024**, *13*(12), 847; **https://doi.org/10.3390/axioms13120847 (https://doi.org/10.3390/axioms13120847)** - 2 Dec 2024


**Abstract** The goal of this study is to derive new conditions that improve the testing of the oscillatory and asymptotic features of fourth-order differential equations with an advanced neutral term. By using Riccati techniques and comparison with lower-order equations, we establish new criteria that **[...] Read more.**
(This article belongs to the Special Issue **Difference, Functional, and Related Equations ( /journal/axioms/special_issues/JE46991137 )**)

Open Access Article 24 pages, 356 KiB **(/2075-1680/13/12/846/pdf?version=1733135942)**

**Set-Theoretical Solutions for the Yang–Baxter Equation in GE-Algebras: Applications to Quantum Spin Systems (/2075-1680/13/12/846)**

by **Ibrahim Senturk**, **Tahsin Oner**, **Abdullah Engin Çalık**, **Hüseyin Şirin**, **Metin Bilge** and **Ramegarajan Rajesh**

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*Axioms* **2024**, *13*(12), 846; **https://doi.org/10.3390/axioms13120846 (https://doi.org/10.3390/axioms13120846)** - 2 Dec 2024


**Abstract** This manuscript presents set-theoretical solutions to the Yang–Baxter equation within the framework of GE-algebras by constructing mappings that satisfy the braid condition and exploring the algebraic properties of GE-algebras. Detailed proofs and the use of left and right translation operators are provided to **[...] Read more.**
(This article belongs to the Special Issue **Yang-Baxter Equations, Nonassociative Structures and Applications—In Memoriam, Stefan Papadima ( /journal/axioms/special_issues/Yang_Baxter_equations_2022 )**)

Open Access Article 28 pages, 2723 KiB **(/2075-1680/13/12/845/pdf?version=1733133653)**

## A Comprehensive Model and Numerical Study of Shear Flow in Compressible Viscous Micropolar Real Gases (/2075-1680/13/12/845)

by **Nelida Črnjarić** and **Ivan Dražić**
*Axioms* **2024**, *13*(12), 845; **https://doi.org/10.3390/axioms13120845 (https://doi.org/10.3390/axioms13120845)** - 2 Dec 2024


**Abstract** Understanding shear flow behavior in compressible, viscous, micropolar real gases is essential for both theoretical advancements and practical engineering applications. This study develops a comprehensive model that integrates micropolar fluid theory with compressible flow dynamics to accurately describe the behavior of real gases **[...] Read more.**
(This article belongs to the Special Issue **Recent Progress in Computational Fluid Dynamics ( /journal/axioms/special_issues/32U01Y02J8 )**)

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Open Access Article 19 pages, 317 KiB (/2075-1680/13/12/844/pdf?version=1733915971)

**Sharp Second-Order Hankel Determinants Bounds for Alpha-Convex Functions Connected with Modified Sigmoid Functions (/2075-1680/13/12/844)**

by **Muhammad Abbas**, **Reem K. Alhefthi**, **Daniele Ritelli** and **Muhammad Arif**

*Axioms* **2024**, *13*(12), 844; https://doi.org/10.3390/axioms13120844 (https://doi.org/10.3390/axioms13120844) - 1 Dec 2024



**Abstract** The study of the Hankel determinant generated by the Maclaurin series of holomorphic functions belonging to particular classes of normalized univalent functions is one of the most significant problems in geometric function theory. Our goal in this study is first to define a **[...] Read more.**

(This article belongs to the Special Issue **Recent Advances in Complex Analysis and Related Topics ( /journal/axioms/special_issues/LO9M85MI3P )**)

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**Computational Study on Flow Characteristics of Shocked Light Backward-Triangular Bubbles in Polyatomic Gas (/2075-1680/13/12/843)**

by **Salman Saud Alsaeed** and **Satyvir Singh**

*Axioms* **2024**, *13*(12), 843; https://doi.org/10.3390/axioms13120843 (https://doi.org/10.3390/axioms13120843) - 1 Dec 2024



**Abstract** This study computationally examined the Richtmyer–Meshkov instability (RMI) evolution in a helium backward-triangular bubble immersed in monatomic argon, diatomic nitrogen, and polyatomic methane under planar shock wave interactions. Using high-fidelity numerical simulations based on the compressible Navier–Fourier equations based on the Boltzmann–Curtiss kinetic **[...]**

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Open Access Article 12 pages, 264 KiB (/2075-1680/13/12/842/pdf?version=1733214510)

**classes of *q*-Uniformly Starlike Functions Obtained via the *q*-Carlson–Shaffer Operator (/2075-1680/13/12/842)**

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by **Qiuxia Hu**, **Rizwan Salim Badar** and **Muhammad Ghaffar Khan**
*Axioms* **2024**, *13*(12), 842; **https://doi.org/10.3390/axioms13120842 (https://doi.org/10.3390/axioms13120842)** - 29 Nov 2024
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**Abstract** This article investigates the applications of the $q$-Carlson–Shaffer operator on subclasses of q-uniformly starlike functions, introducing the class $ST_q(m, c, d, \beta)$. The study establishes a necessary condition for membership in this class **[...] Read more.**
(This article belongs to the Special Issue **New Developments in Geometric Function Theory, 3rd Edition ( /journal/axioms/special_issues/0IUWDZAC19 )**)

Open Access Article 27 pages, 333 KiB **(/2075-1680/13/12/841/pdf?version=1735123302)**

**Fixed-Point Results for Multi-Valued Mappings in Topological Vector Space-Valued Cone Metric Spaces with Applications (/2075-1680/13/12/841)**

by **Hala Alzumi** and **Jamshaid Ahmad**
*Axioms* **2024**, *13*(12), 841; **https://doi.org/10.3390/axioms13120841 (https://doi.org/10.3390/axioms13120841)** - 29 Nov 2024
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**Abstract** The objective of this research article is to introduce Kikkawa and Suzuki-type contractions in the setting of topological vector space-valued cone metric space with a solid cone and establish some new fixed point results for multi-valued mappings. The problem of finding fixed points **[...] Read more.**
(This article belongs to the Special Issue **Advances in Fixed Point Theory with Applications ( / journal/axioms/special_issues/31W0CF7S70 )**)

Open Access Article 33 pages, 3247 KiB **(/2075-1680/13/12/840/pdf?version=1732865722)**

**Optimization of General Power-Sum Connectivity Index in Uni-Cyclic Graphs, Bi-Cyclic Graphs and Trees by Means of Operations (/2075-1680/13/12/840)**

by **Muhammad Yasin Khan**, **Gohar Ali** and **Ioan-Lucian Popa**
*Axioms* **2024**, *13*(12), 840; **https://doi.org/10.3390/axioms13120840 (https://doi.org/10.3390/axioms13120840)** - 28 Nov 2024
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**Abstract** The field of indices has been explored and advanced by various researchers for different purposes. One purpose is the optimization of indices in various problems. In this work, the general power-sum connectivity index is considered. The general power-sum connectivity index was investigated for **[...] Read more.**
(This article belongs to the Special Issue **Graph Theory and Combinatorics: Theory and Applications ( /journal/axioms/special_issues/D2Z84S8189 )**)

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21 pages, 377 KiB (/2075-1680/13/12/839/pdf?version=1733211201)

Open Access Feature Paper Article

**On Schur Forms for Matrices with Simple Eigenvalues (/2075-1680/13/12/839)**

by **Mihail Mihaylov Konstantinov** and **Petko Hristov Petkov**

*Axioms* **2024**, *13*(12), 839; https://doi.org/10.3390/axioms13120839 (https://doi.org/10.3390/axioms13120839) - 28 Nov 2024

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**Abstract** In this paper, we consider various aspects of the Schur problem for a square complex matrix *A*, namely the similarity unitary transformation of *A* into upper triangular form containing the eigenvalues of *A* on its diagonal. Since the profound work of I. [...] Read more.

Open Access Article 19 pages, 2188 KiB (/2075-1680/13/12/838/pdf?version=1732790446)

**Simultaneous Method for Solving Certain Systems of Matrix Equations with Two Unknowns (/2075-1680/13/12/838)**

by **Predrag S. Stanimirović**, **Miroslav Ćirić**, **Spyridon D. Mourtas**, **Gradimir V. Milovanović** and **Milena J. Petrović**

*Axioms* **2024**, *13*(12), 838; https://doi.org/10.3390/axioms13120838 (https://doi.org/10.3390/axioms13120838) - 28 Nov 2024

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**Abstract** Quantitative bisimulations between weighted finite automata are defined as solutions of certain systems of matrix-vector inequalities and equations. In the context of fuzzy automata and max-plus automata, testing the existence of bisimulations and their computing are performed through a sequence of matrices that [...] Read more.

(This article belongs to the Special Issue **Numerical Analysis and Optimization ( /journal/axioms/special_issues/0454E7HGRH )**)

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Open Access Article 16 pages, 307 KiB (/2075-1680/13/12/837/pdf?version=1732784838)

**Horadam–Lucas Cubes (/2075-1680/13/12/837)**

by **Elif Tan**, **Luka Podrug** and **Vesna Iršič Chenoweth**

*Axioms* **2024**, *13*(12), 837; https://doi.org/10.3390/axioms13120837 (https://doi.org/10.3390/axioms13120837) - 28 Nov 2024

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**Abstract** In this paper, we introduce a novel class of graphs referred to as the Horadam–Lucas cubes. This class extends the concept of Lucas cubes and retains numerous desirable properties associated with them. Horadam–Lucas cubes can also be viewed as a companion graph family [...] Read more.

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(This article belongs to the Special Issue **Recent Developments in Graph Theory ( /journal/axioms/special_issues/560T7U3LML )**)

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Open Access Article 23 pages, 1345 KiB **(/2075-1680/13/12/836/pdf?version=1732782478)**

**Fuzzy Decision Tree Based on Fuzzy Rough Sets and Z-Number Rules (/2075-1680/13/12/836)**

by **Boya Zhu**, **Jingqian Wang** and **Xiaohong Zhang**

*Axioms* **2024**, *13*(12), 836; **https://doi.org/10.3390/axioms13120836 (https://doi.org/10.3390/axioms13120836)** - 28 Nov 2024



**Abstract** The decision tree algorithm is widely used in various classification problems due to its ease of implementation and strong interpretability. However, information in the real world often has uncertainty and partial reliability, which poses challenges for classification tasks. To address this issue, this **[...] Read more.**

(This article belongs to the Special Issue **Advances in Fuzzy Theory and Decision-Making Theory ( /journal/axioms/special_issues/435O3KVYP4 )**)

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**Characterizing Affine Vector Fields on Pseudo-Riemannian Manifolds (/2075-1680/13/12/835)**

by **Norah Alshehri** and **Mohammed Guediri**

*Axioms* **2024**, *13*(12), 835; https://doi.org/10.3390/axioms13120835 (https://doi.org/10.3390/axioms13120835) - 28 Nov 2024



**Abstract** We study the characteristics of affine vector fields on pseudo-Riemannian manifolds and provide tensorial formulas that characterize these vector fields. Using our approach, we present a straightforward proof that any affine vector field on a compact Riemannian manifold is a Killing vector field. **[...] Read more.**

(This article belongs to the Special Issue **Advances in Differential Geometry and Mathematical Physics ( /journal/axioms/special_issues/0Y0GIZ99I1 )**)

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**Existence and Uniqueness of Second-Order Impulsive Delay Differential Systems (/2075-1680/13/12/834)**

by **Yingxia Zhou** and **Mengmeng Li**

*Axioms* **2024**, *13*(12), 834; https://doi.org/10.3390/axioms13120834 (https://doi.org/10.3390/axioms13120834) - 27 Nov 2024



**Abstract** In this paper, we study the existence and uniqueness of second-order impulsive delay differential systems. Firstly, we define cosine-type and sine-type delay matrix functions, which are used to derive the solutions of the impulsive delay differential systems. Secondly, based on the Schauder and **[...] Read more.**

(This article belongs to the Special Issue **Differential Equations and Its Application ( /journal/axioms/special_issues/YS106GYZ9L )**)

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**A B-Polynomial Approach to Approximate Solutions of PDEs with Multiple Initial Conditions (/2075-1680/13/12/833)**

by **Muhammad I. Bhatti** and **Md. Habibur Rahman**

*Axioms* **2024**, *13*(12), 833; https://doi.org/10.3390/axioms13120833 (https://doi.org/10.3390/axioms13120833) - 27 Nov 2024



**Abstract** In this article, we present a novel B-Polynomial Approach for approximating solutions to partial differential equations (PDEs), addressing the multiple initial conditions. Our method stands out by utilizing two-dimensional Bernstein polynomials (B-polynomials) in conjunction with their operational matrices to effectively manage the complexity **[...] Read more.**

(This article belongs to the Special Issue **Differential Equations and Related Topics, 2nd Edition ( /journal/axioms/special_issues/O72CZI54TK )**)

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Open Access Article 30 pages, 3059 KiB (/2075-1680/13/12/832/pdf?version=1733238917)

**Fuzzy Computation Tree Temporal Logic with Quality Constraints and Its Model Checking (/2075-1680/13/12/832)**

by **Xianfeng Yu**, **Yongming Li**, **Shengling Geng** and **Huirong Li**

*Axioms* **2024**, *13*(12), 832; https://doi.org/10.3390/axioms13120832 (https://doi.org/10.3390/axioms13120832) - 27 Nov 2024



**Abstract** The encapsulation of particular quality functions and predicates within temporal logic formulas markedly enhances the representation of detailed temporal characteristics within a system. During our preliminary investigations, we innovatively combined quality constraint functions and predicates with Possibility Linear Temporal Logic (PoLTL), yielding the [...] Read more.

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Open Access Article 17 pages, 397 KiB (/2075-1680/13/12/831/pdf?version=1732702582)

**Smoothed Weighted Quantile Regression for Censored Data in Survival Analysis (/2075-1680/13/12/831)**

by **Kaida Cai**, **Hanwen Liu**, **Wenzhi Fu** and **Xin Zhao**

*Axioms* **2024**, *13*(12), 831; https://doi.org/10.3390/axioms13120831 (https://doi.org/10.3390/axioms13120831) - 27 Nov 2024



**Abstract** In this study, we propose a smoothed weighted quantile regression (SWQR), which combines convolution smoothing with a weighted framework to address the limitations. By smoothing the non-differentiable quantile regression loss function, SWQR can improve computational efficiency and allow for more stable model estimation **[...] Read more.**

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Open Access Article 21 pages, 300 KiB (/2075-1680/13/12/830/pdf?version=1732702970)

**A Few Kinds of Loop Algebras and Some Applications (/2075-1680/13/12/830)**

by **Yanmei Sun**, **Weiwei Zhang**, **Nina Xue** and **Yufeng Zhang**

*Axioms* **2024**, *13*(12), 830; https://doi.org/10.3390/axioms13120830 (https://doi.org/10.3390/axioms13120830) - 27 Nov 2024



**Abstract** In this paper, we search for some approaches for generating (1+1)-dimensional, (2+1)-dimensional and (3+1)-dimensional integrable equations by making use of various Lie algebras and the corresponding loop algebras under the frame of the Tu scheme. The well-known modified KdV

equation, the heat conduction **[...] Read more.**

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**Some Innovative Results for Interpolative Reich–Rus–Ćirić-Type Contractions in Rectangular *m*-Metric Spaces (/2075-1680/13/12/829)**

by **Muhammad Zahid**, **Ali Raza** and **Safeer Hussain Khan**

*Axioms* **2024**, *13*(12), 829; **https://doi.org/10.3390/axioms13120829 (https://doi.org/10.3390/axioms13120829)** - 27 Nov 2024

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**Abstract** In this paper, we study the existence of fixed points for interpolative Reich–Rus–Ćirić-type contractions in the setting of rectangular *m*-metric spaces. The use of the rectangular inequality, in place of the conventional triangle inequality, introduces a higher level of complexity in the **[...] Read more.**

Open Access Article 11 pages, 293 KiB (/2075-1680/13/12/828/pdf?version=1732686846)

**A Kuramoto Model for the Bound State Aharonov–Bohm Effect (/2075-1680/13/12/828)**

by **Alviu Rey Nasir**, **José Luís Da Silva**, **Jingle Magallanes**, **Herry Pribawanto Suryawan** and **Roshin Marielle Nasir-Britos**

*Axioms* **2024**, *13*(12), 828; **https://doi.org/10.3390/axioms13120828 (https://doi.org/10.3390/axioms13120828)** - 27 Nov 2024

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**Abstract** The Aharonov–Bohm effect can be described as a phase difference in interfering charged particles that travel through two distinct pathways oppositely surrounding a perpendicularly-positioned solenoid. The magnetic field emanates from the solenoid but does not intersect the pathways. On the other hand, the **[...] Read more.**

(This article belongs to the Special Issue **Recent Advances in Quantum Mechanics and Mathematical Physics ( /journal/axioms/special_issues/Q1R4352Q0U )**)

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**...ulé Structure of Angularly Connected Even Ring Systems (/2075-1680/13/12/827)**

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by **Simon Brezovnik**
*Axioms* **2024**, *13*(12), 827; **https://doi.org/10.3390/axioms13120827 (https://doi.org/10.3390/axioms13120827)** - 26 Nov 2024
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**Abstract** An even ring system *G* is a simple 2-connected plane graph with all interior vertices of degree 3, all exterior vertices of either degree 2 or 3, and all finite faces of an even length. *G* is angularly connected if all of the **[...] Read more.**
(This article belongs to the Special Issue **Recent Developments in Graph Theory ( /journal/axioms/special_issues/560T7U3LML )**)

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**Relations of Harmonic Starlike Function Subclasses with Mittag–Leffler Function (/2075-1680/13/12/826)**

by **Naci Taşar**, **Fethiye Müge Sakar**, **Seher Melike Aydoğan** and **Georgia Irina Oros**
*Axioms* **2024**, *13*(12), 826; **https://doi.org/10.3390/axioms13120826 (https://doi.org/10.3390/axioms13120826)** - 26 Nov 2024
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**Abstract** In this study, the connection between certain subfamilies of harmonic univalent functions is established by utilizing a convolution operator involving the Mittag–Leffler function. The investigation reveals inclusion relations concerning harmonic $\gamma$-uniformly starlike mappings in the open unit disc, harmonic starlike functions and **[...] Read more.**
(This article belongs to the Special Issue **New Developments in Geometric Function Theory, 3rd Edition ( /journal/axioms/special_issues/0IUWDZAC19 )**)

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**Extension of Chu–Vandermonde Identity and Quadratic Transformation Conditions (/2075-1680/13/12/825)**

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by **Mohamed Jalel Atia** and **Maged Alkilayh**
*Axioms* **2024**, *13*(12), 825; **https://doi.org/10.3390/axioms13120825 (https://doi.org/10.3390/axioms13120825)** - 25 Nov 2024


**Abstract** In 1812, Gauss stated the following identity: **[...] Read more.**
(This article belongs to the Special Issue **Orthogonal Polynomials, Special Functions and Applications: 2nd Edition ( /journal/axioms/special_issues/S094Z2585M )**)

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**Congruence Extensions in Congruence–Modular Varieties (/2075-1680/13/12/824)**

by **George Georgescu**, **Leonard Kwuida** and **Claudia Mureşan**
*Axioms* **2024**, *13*(12), 824; **https://doi.org/10.3390/axioms13120824 (https://doi.org/10.3390/axioms13120824)** - 25 Nov 2024


**Abstract** We investigate from an algebraic and topological point of view the minimal prime spectrum of a universal algebra, considering the prime congruences with respect to the term condition commutator. Then we use the topological structure of the minimal prime spectrum to study extensions **[...] Read more.**
(This article belongs to the Special Issue **Advances in Classical and Applied Mathematics ( /journal/axioms/special_issues/YYXW321YX2 )**)

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**A Unified Approach to Aitchison's, Dually Affine, and Transport Geometries of the Probability Simplex (/2075-1680/13/12/823)**

by **Giovanni Pistone** and **Muhammad Shoaib**
*Axioms* **2024**, *13*(12), 823; **https://doi.org/10.3390/axioms13120823 (https://doi.org/10.3390/axioms13120823)** - 25 Nov 2024


**Abstract** A critical processing step for AI algorithms is mapping the raw data to a landscape where the similarity of two data points is conveniently defined. Frequently, when the data points are compositions of probability functions, the similarity is reduced to affine geometric concepts; **[...] Read more.**
(This article belongs to the Special Issue **Advances in Geometry and Its Applications ( /journal/axioms/special_issues/N5M54Z8T3A )**)

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Open Access Article 27 pages, 699 KiB (/2075-1680/13/12/822/pdf?version=1732605489)

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**Estimating the Lifetime Parameters of the Odd-Generalized-Exponential–Inverse-Weibull Distribution Using Progressive First-Failure Censoring: A Methodology with an Application (/2075-1680/13/12/822)**

by **Mahmoud M. Ramadan**, **Rashad M. EL-Sagheer** and **Amel Abd-El-Monem**

*Axioms* **2024**, *13*(12), 822; https://doi.org/10.3390/axioms13120822 (https://doi.org/10.3390/axioms13120822) - 25 Nov 2024



**Abstract** This paper investigates statistical methods for estimating unknown lifetime parameters using a progressive first-failure censoring dataset. The failure mode's lifetime distribution is modeled by the odd-generalized-exponential–inverse-Weibull distribution. Maximum-likelihood estimators for the model parameters, including the survival, hazard, and inverse hazard rate functions, are **[...] Read more.**

(This article belongs to the Special Issue **Reliability and Risk of Complex Systems: Modelling, Analysis and Optimization ( /journal/axioms/special_issues/E2V195JSIR )**)

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**Some Evaluations About Coefficients Boundaries for Specific Classes of Bi-Univalent Functions (/2075-1680/13/12/821)**

by **Suliman M. Sowileh**, **Gangadharan Murugusundaramoorthy**, **Borhen Halouani**, **Ibrahim S. Elshazly**, **Mohamed A. Mamon** and **Alaa H. El-Qadeem**

*Axioms* **2024**, *13*(12), 821; https://doi.org/10.3390/axioms13120821 (https://doi.org/10.3390/axioms13120821) - 25 Nov 2024



**Abstract** New subclasses of bi-univalent functions with bounded boundary rotation are presented in this study. We acquired estimates for the initial coefficients $a_2$, $a_3$ and $a_4$. Furthermore, we have verified the specific situations satisfying the famous hypothesis of Brannan **[...] Read more.**

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**A Theoretical Review of Area Production Rates as Test Statistics for Detecting Nonequilibrium Dynamics in Ornstein–Uhlenbeck Processes (/2075-1680/13/12/820)**

by **Alexander Strang**

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*Axioms* **2024**, *13*(12), 820; **https://doi.org/10.3390/axioms13120820 (https://doi.org/10.3390/axioms13120820)** - 24 Nov 2024
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**Abstract** A stochastic process is at thermodynamic equilibrium if it obeys time-reversal symmetry; forward and reverse time are statistically indistinguishable at a steady state. Nonequilibrium processes break time-reversal symmetry by maintaining circulating probability currents. In physical processes, these currents require a continual use and **[...] Read more.**
(This article belongs to the Special Issue **Research on Stochastic Analysis and Applied Statistics ( /journal/axioms/special_issues/4Y3HXY252M )**)

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**Second Hankel Determinant Bound Application to Certain Family of Bi-Univalent Functions (/2075-1680/13/12/819)**

by **Mohamed A. Mamon**, **Borhen Halouani**, **Ibrahim S. Elshazly**, **Gangadharan Murugusundaramoorthy** and **Alaa H. El-Qadeem**
*Axioms* **2024**, *13*(12), 819; **https://doi.org/10.3390/axioms13120819 (https://doi.org/10.3390/axioms13120819)** - 24 Nov 2024
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**Abstract** A novel family of bi-univalent holomorphic functions is introduced by the use of the Lindelöf principle. The upper bound of the second Hankel determinant, $H_{2,2}(\chi)$, is evaluated. Furthermore, specific results are obtained as special cases of **[...] Read more.**
(This article belongs to the Special Issue **Advances in Geometric Function Theory and Related Topics ( /journal/axioms/special_issues/D8PU5YP4F2 )**)

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**Fixed-Point Results with Applications in Generalized Neutrosophic Rectangular *b*-Metric Spaces (/2075-1680/13/12/818)**

by **Nawab Hussain**, **Nawal Alharbi** and **Ghada Basendwah**
*Axioms* **2024**, *13*(12), 818; **https://doi.org/10.3390/axioms13120818 (https://doi.org/10.3390/axioms13120818)** - 24 Nov 2024
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**Abstract** In this paper, we introduce several new concepts: generalized neutrosophic rectangular *b*-metric-like spaces (GNRBMLSs), generalized intuitionistic rectangular *b*-metric-like spaces (GIRBMLSs), and generalized fuzzy rectangular *b*-metric-like spaces (GFRBMLSs). These innovative

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spaces can expand various topological spaces, including neutrosophic rectangular extended *b* **[...] Read more.**
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**From Uncertainty Relations to Quantum Acceleration Limits (/2075-1680/13/12/817)**

by **Carlo Cafaro**, **Christian Corda**, **Newshaw Bahreyni** and **Abeer Alanazi**
*Axioms* **2024**, *13*(12), 817; **https://doi.org/10.3390/axioms13120817 (https://doi.org/10.3390/axioms13120817)** - 22 Nov 2024
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**Abstract** The concept of quantum acceleration limit has been recently introduced for any unitary time evolution of quantum systems under arbitrary nonstationary Hamiltonians. While Alsing and Cafaro used the Robertson uncertainty relation in their derivation, employed the Robertson–Schrödinger uncertainty relation to find the upper **[...] Read more.**
(This article belongs to the Special Issue **Mathematical Aspects of Quantum Field Theory and Quantization ( /journal/axioms/special_issues/J75J1JS211 )**)

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**The Extension of Noncommutative Modified KP Hierarchy and Its Quasideterminant Solutions (/2075-1680/13/12/816)**

by **Hongxia Wu**, **Chunxia Li** and **Haifeng Wang**
*Axioms* **2024**, *13*(12), 816; **https://doi.org/10.3390/axioms13120816 (https://doi.org/10.3390/axioms13120816)** - 22 Nov 2024
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**Abstract** The extended noncommutative modified KP (exncmKP) hierarchy is firstly constructed, which gives rise to two types of the ncmKP equation with self-consistent sources (ncmKPESCSs). Then, the noncommutative (NC) Miura transformation between the extended noncommutative KP (exncKP) hierarchy and the exncmKP hierarchy is presented, **[...] Read more.**
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**Approximating Fixed Points via Hybrid Enriched Contractions in Convex Metric Space with an Application (/2075-1680/13/12/815)**

by **Bhumika Rani**, **Jatinderdeep Kaur** and **Satvinder Singh Bhatia**
*Axioms* **2024**, *13*(12), 815; **https://doi.org/10.3390/axioms13120815 (https://doi.org/10.3390/axioms13120815)** - 22 Nov 2024
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**Abstract** In the present study, we define hybrid enriched contractions of the Hardy–Rogers type and of the Ćirić–Reich–Rus type in the framework of convex metric space. We demonstrate the presence and the approximation of fixed points for contraction mappings by using Krasnoselskij iteration. The [...] Read more.



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**Shock Model of *K*/*N*: G Repairable Retrial System Based on Discrete PH Repair Time (/2075-1680/13/12/814)**

by **Xiaoyun Yu**, **Linmin Hu** and **Zebin Hu**

*Axioms* **2024**, *13*(12), 814; https://doi.org/10.3390/axioms13120814 (https://doi.org/10.3390/axioms13120814) - 21 Nov 2024



**Abstract** A discrete time modeling method is employed in this paper to analyze and evaluate the reliability of a discrete time *K*/*N*: G repairable retrial system with Bernoulli shocks and two-stage repair. Lifetime and shocks are two factors that lead to **[...] Read more.**

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Open Access Article 15 pages, 261 KiB (/2075-1680/13/12/813/pdf?version=1733279511)

**Factorization of Hausdorff Operators (/2075-1680/13/12/813)**

by **Hadi Roopaei**

*Axioms* **2024**, *13*(12), 813; https://doi.org/10.3390/axioms13120813 (https://doi.org/10.3390/axioms13120813) - 21 Nov 2024

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**Abstract** Throughout this study, we will gain a deeper understanding of Hausdorff operators that are commonly used in operator theory. The Hausdorff matrices Gamma, Cesàro, and Hölder are factorized here to derive novel inequalities. Specifically, a factorization based on the Gamma operator has also **[...] Read more.**

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**Interval Linguistic-Valued Intuitionistic Fuzzy Concept Lattice and Its Application to Linguistic Association Rule Extraction (/2075-1680/13/12/812)**

by **Kuo Pang**, **Chao Fu**, **Li Zou**, **Gaoxuan Wang** and **Mingyu Lu**

*Axioms* **2024**, *13*(12), 812; **https://doi.org/10.3390/axioms13120812 (https://doi.org/10.3390/axioms13120812)** - 21 Nov 2024

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**Abstract** In a world rich with linguistic-valued data, traditional methods often lead to significant information loss when converting such data into other formats. This paper presents a novel approach for constructing an interval linguistic-valued intuitionistic fuzzy concept lattice, which adeptly manages qualitative linguistic information **[...] Read more.**

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**Power Truncated Positive Normal Distribution: A Quantile Regression Approach Applied to Health Databases (/2075-1680/13/12/811)**

by **Karol I. Santoro**, **Héctor J. Gómez**, **Isaac E. Cortés**, **Tiago M. Magalhães** and **Diego I. Gallardo**

*Axioms* **2024**, *13*(12), 811; **https://doi.org/10.3390/axioms13120811 (https://doi.org/10.3390/axioms13120811)** - 21 Nov 2024

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**Abstract** In this paper we present a new extension of the truncated positive normal (TPN) model, called power truncated positive normal. This extension incorporates a shape parameter that provides more flexibility to the model. In addition, this new extension was reparameterized based on the **[...] Read more.**

(This article belongs to the Special Issue **Advances in the Theory and Applications of Statistical Distributions ( /journal/axioms/special_issues/M456B3RK3Y )**)

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Open Access Article 10 pages, 254 KiB (/2075-1680/13/12/810/pdf?version=1732179461)

**Extremal *k*-Connected Graphs with Maximum Closeness (/2075-1680/13/12/810)**

by **Fazal Hayat** and **Daniele Ettore Otera**

*Axioms* **2024**, *13*(12), 810; https://doi.org/10.3390/axioms13120810 (https://doi.org/10.3390/axioms13120810) - 21 Nov 2024



**Abstract** Closeness is a measure that quantifies how quickly information can spread from a given node to all other nodes in the network, reflecting the efficiency of communication within the network by indicating how close a node is to all other nodes. For a [...] Read more.

(This article belongs to the Special Issue **Recent Developments in Graph Theory ( /journal/axioms/special_issues/560T7U3LML )**)

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Alviu Rey Nasir, José Luís Da Silva, Jingle Magallanes, Herry Pribawanto Suryawan and Roshin Marielle Nasir-Britos

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# A Kuramoto Model for the Bound State Aharonov–Bohm Effect

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**Abstract:** The Aharonov–Bohm effect can be described as a phase difference in interfering charged particles that travel through two distinct pathways oppositely surrounding a perpendicularly-positioned solenoid. The magnetic field emanates from the solenoid but does not intersect the pathways. On the other hand, the Kuramoto model can be used to identify the synchronization conditions that lead to a particular phase difference by treating the phases as coupled oscillators. Starting with the overall wave function expression for the electron in an Aharonov–Bohm potential, we derive a version of the Kuramoto model describing the phase dynamics of the bound state of the quantum mechanical system. We show that the resulting synchronization condition of the model coincides with the allowable values of the flux parameter for our case to achieve an Aharonov–Bohm effect.

**Keywords:** Aharonov–Bohm effect; Kuramoto model; bound states quantum systems

**MSC:** 34C15; 35Q40; 81Q70; 81U05

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## 1. Introduction and Motivation

The Aharonov–Bohm (AB) effect [1], which is an interference phenomenon, continues to exhibit quantum mechanical features that have not yet been fully understood, e.g., the anomalous AB interference in a quantum Hall Fabry–Pérot interferometer as observed in Ref. [2], the time-dependent AB effect and the absence of its apparent experimental evidence (as also mentioned in a recent study Ref. [3]), the topological nature of the AB effect (see, e.g., a recent study that challenges its conventional concept in Ref. [4]). On the other hand, the Kuramoto model (KM) [5] has been applied to many branches of science (see review papers, e.g., Refs. [6–8]) but scarcely to quantum mechanics. For quantum applications of the KM, see the examples given in Refs. [9–12]. Describing the AB effect from the KM's perspective is, therefore, of interest and not considered elsewhere.

Synchronizations in quantum systems have recently been studied based on either having a classical analog (see, e.g., Refs. [13,14]) or none at all, e.g., Ref. [15]. Furthermore, synchronizations of interfering particles, such as between photons (see, e.g., Ref. [16]) and between electrons (see, e.g., Ref. [17]) have also been considered. Since the synchronization condition is a main characteristic of the KM, it is, therefore, of particular interest to use the model to study the synchronization conditions of the bound state AB effect and their relationship with the interference occurring within the quantum system. Alongside the synchronization conditions, we are also interested in determining the extent of the magnetic field region near the interference line of the AB effect.

In this letter, beginning with the general case of the AB effect [1], we consider its simplest case, the bound state, by constraining the path taken by the electron to that of a circle with constant radius, e.g., Refs. [18–20]. Then, with its known interference phase difference and wave functions (see, e.g., Ref. [1]), we propose a version of the KM and study the phase dynamics of the system.

## 2. A Kuramoto Model for the System

Begin with a KM model of the form [5]

$$\dot{\sigma}_i := \frac{\mathrm{d}\sigma_i}{\mathrm{d}t} = \omega_i + \frac{K}{N}\sum_{j=1}^{N}\sin(\sigma_j - \sigma_i), \tag{1}$$

where $\sigma_i = \sigma_i(t)$ is the phase of the phase oscillator $i$ (with $i = 1, 2, \ldots, N$) as a function of time $t \geq 0$, $\omega_i$ its angular frequency, $K$ a uniform coupling strength coefficient and $N$ the total number of phase oscillators.

Consider now a two-electron system, with each electron initially in the angular position $\theta_0 := \theta(0) = 0$ moving along a circular path of constant radius $R$, one in the upper semicircle and the other in the lower semicircle; see Figure 1. The two paths, namely, Path 1 and Path 2, form a circular ring except at the endpoint $\theta(t) = \pi$.

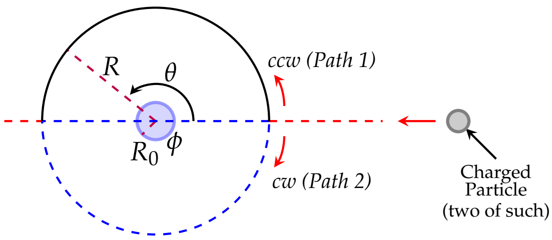


**Figure 1.** A top-view illustration of the paths taken by a spinning electron around the solenoid from which the magnetic flux "inducing" Aharonov–Bohm effect came.

In the center of the ring, there is an AB effect source, a magnetically impenetrable solenoid of radius $R_0$ oriented perpendicular to the semicircular paths and generating a magnetic field of flux $\phi$. The resulting magnetic field lines emerge from the top, flow down the sides of the solenoid beyond the trajectories, and return through the bottom. Since this magnetic field does not intersect the paths of the electrons, the paths (of radius $R \gg R_0$) of the electrons are in a region where the magnetic field is excluded. Consequently, there is a phase shift between the electron trajectories at their mutual endpoint, specifically at $\theta(t) = \pi$.

In the general case where the "detecting" particles (i.e., the charged particles moving along the semicircular paths that will sense the AB effect) have charge $le$, $l \in \mathbb{Z} \setminus \{0\}$, the phase difference between Path 1 and Path 2 when they interfere at $\theta(t) = \pi$, is [1,18]

$$\sigma_1 - \sigma_2 = \frac{S_1 - S_2}{\hbar} = 2\pi\alpha, \qquad \alpha := \frac{le\phi}{2\pi\hbar c}; \tag{2}$$

where $S_i$ represents the action of the classical Path $i$, $\hbar$ the reduced Planck's constant, and $c$ the speed of light in vacuum. In Equation (2), it is observed that the interference depends on the phase difference by a factor of $2\pi$. This specifically entails that, when the parameter $\alpha$ (called the flux parameter) is shifted by an integer value, the interference phenomenon remains completely "unaffected". Thus, $\alpha$ only takes specific discrete values of $\phi = (\phi_0/n)$, $n \in \mathbb{Z} \setminus \{0\}$, where $\phi_0 := 2\pi\hbar c/e$ (known as the quantum of flux or London's unit) and $ne$ is the charge used by the "source" of the magnetic flux in the solenoid, e.g., Refs. [1,18]. In particular, with $\alpha = l/n$, the AB effect is detectable only for $\{l/n\}$, where $\{\cdot\}$ represents the fractional part of the number. In our case, where $l = -1$, the AB effect is detectable whenever $|n| \neq 1$. We can find a detailed theoretical description in Refs. [1,18] and some supporting experiments in the works [21,22].

Hence, with $N = 2$, i.e., for Paths 1 and 2 in Figure 1, Equation (1) gives

$$\dot{\sigma}_1 = \omega_1 + \frac{K}{2}\sin(\sigma_2 - \sigma_1), \tag{3}$$

and

$$\dot{\sigma}_2 = \omega_2 - \frac{K}{2}\sin(\sigma_2 - \sigma_1). \tag{4}$$

This study aims to determine $\omega_1$, $\omega_2$, and $K$. To do so, we make the following assumptions:

1. The probability for an electron to take either of the two paths is the same;
2. The two electrons simultaneously start at $\theta_1(t_0) = \theta_2(t_0) = 0$, one then proceeds towards the end of the semicircular track through Path 1 and the other through Path 2;
3. The electrons travel the same amount of angular displacement $\theta := \theta(t)$ (differing only in the sign of $\theta$), at the time interval $t - t_0 = t$, thus enabling them to interfere as $|\theta(t)| \to \pi$.

Now, in quantum mechanics, the wave function $\psi(t)$ for the (bound state) Aharonov–Bohm effect can be expressed in terms of $S_1$ and $S_2$ as [1]

$$\psi(t) = \psi_1^0(t)\mathrm{e}^{-(\mathrm{i}/\hbar)S_1} + \psi_2^0(t)\mathrm{e}^{-(\mathrm{i}/\hbar)S_2}, \tag{5}$$

where $\psi_i^0$ denotes the wave function for the free particle moving along path $i$. Furthermore, since this system also undergoes a scattering process [1], then $\psi$ can further be expressed in terms of the incident wave function $\psi_{\mathrm{inc}}$ and the scattered wave function $\psi_{\mathrm{scatt}}$ as [1]

$$\psi(t) = \psi_{\mathrm{inc}}(t) + \psi_{\mathrm{scatt}}(t), \tag{6}$$

where, for $|\theta| < \pi \Leftrightarrow |\theta(t)| < \pi, \forall t \geq 0$,

$$\psi_{\mathrm{inc}}(t) := \mathrm{e}^{-\mathrm{i}(\alpha\theta(t) + Rk\cos(\theta(t)))}, \tag{7}$$

and

$$\psi_{\mathrm{scatt}}(t) := \frac{\sin(\pi\alpha)}{\sqrt{2\pi\mathrm{i}Rk}\cos(\theta(t)/2)}\mathrm{e}^{-\mathrm{i}\left(\frac{\theta(t)}{2} - Rk\right)}, \tag{8}$$

with $k \in \mathbb{R}^+$ being the magnitude of the wave vector of the incident electron.

Let

$$\psi_{\mathrm{inc}}(t) = A(t)\mathrm{e}^{-\mathrm{i}\int_0^t \omega_{\mathrm{inc}}(s)\,\mathrm{d}s}, \tag{9}$$

and

$$\psi_{\mathrm{scatt}}(t) = B(t)\mathrm{e}^{-\mathrm{i}\int_0^t \omega_{\mathrm{scatt}}(s)\,\mathrm{d}s}, \quad A(t), B(t) \in \mathbb{R}, \tag{10}$$

where $\omega_{\mathrm{inc}} := \omega_{\mathrm{inc}}(t)$ and $\omega_{\mathrm{scatt}} := \omega_{\mathrm{scatt}}(t)$ are a form of phase frequency (i.e., having the dimensions of phase divided by time) for the incident and the scattered waves, respectively. Then, upon inspecting Equations (2)–(10), we propose that $\omega_1$ and $\omega_2$ can be obtained as having the same expression but different in the sign of $\theta$ due to Path 1 (ccw) and Path 2 (cw), namely, $\omega_1 = \omega_{\mathrm{inc}}$ for $0 \leq \theta < \pi$ (let $\omega_{\mathrm{inc}}^+ := \omega_1$), and $\omega_2 = \omega_{\mathrm{inc}}$ for $-\pi < \theta \leq 0$ (let $\omega_{\mathrm{inc}}^- := \omega_2$). Therefore,

$$\int_0^t \omega_{\mathrm{inc}}(s)\,\mathrm{d}s = \alpha\theta(t) + Rk\cos(\theta(t)),$$

which follows

$$\omega_{\text{inc}}(t) = \frac{\mathrm{d}}{\mathrm{d}t}\big(\alpha\theta(t) + Rk\cos(\theta(t))\big) = \big(\alpha - Rk\sin(\theta(t))\big)\dot{\theta}(t). \tag{11}$$

We now want to establish the connection between $K/2$ and $\omega_{\text{scatt}}$. We first observe that, unlike $\omega_i$, the second term on the rhs of Equation (1) (containing $K$) is typically the fluctuating part (i.e., phase-oscillating) of the model. Similarly, the second term on the rhs of Equation (6) (containing $\omega_{\text{scatt}}$ cf. Equation (10)) is a varying term, which depends, for example, on the type of intercept boundary causing the scattering (in contrast to $\omega_{\text{inc}}$). Also, we are aiming to obtain the synchronization conditions (which is related to $K/2$) of the interference (which is related to $\omega_{\text{scatt}}$). Together with the fact that the phase difference experienced by the incident electrons can be observed at the interference, we consequently link $K/2$ and $\omega_{\text{scatt}}$. In other words, looking at the rhs of Equation (6), we link $\omega_i$ to the argument of $\psi_{\text{inc}}(t)$ and $K/2$ to that of $\psi_{\text{scatt}}(t)$. This entails saying that

$$\frac{K}{2} = \frac{1}{2}K(\theta(t),\dot{\theta}(t)) = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\theta(t)}{2} - Rk + \frac{\pi}{4}\right) = \frac{\dot{\theta}(t)}{2}. \tag{12}$$

In particular, from Equations (8) and (10), it follows that

$$\frac{\theta(t)}{2} - Rk + \frac{\pi}{4} = \pm\int_0^t \omega_{\text{scatt}}(s)\,\mathrm{d}s + 2k\pi,\ k \in \mathbb{Z}, \tag{13}$$

or

$$\frac{\theta(t)}{2} - Rk + \frac{\pi}{4} = \pi - \int_0^t \omega_{\text{scatt}}(s)\,\mathrm{d}s + 2k\pi,\ k \in \mathbb{Z}, \tag{14}$$

from whence we deduce that

$$\frac{\dot{\theta}(t)}{2} = \pm\omega_{\text{scatt}}(t) \iff \omega_{\text{scatt}} = \pm\frac{1}{2}K(\theta(t),\dot{\theta}(t)) = \pm\frac{K}{2}. \tag{15}$$

Notice that we have excluded the terms arising from the prefactor on the right-hand side of Equation (8), which would contribute to an imaginary phase $z$ when represented as $e^{-\mathrm{i}z}$. In other words, we have not included the real term $B(t)$ in modeling $K$.

With Equations (1), (11) and (12), Equations (3) and (4) now read, respectively, (for $0 \le \theta < \pi$),

$$\dot{\sigma}_1 = \left[\alpha - Rk\sin(\theta) + \frac{1}{2}\sin(\sigma_2 - \sigma_1)\right]\dot{\theta}, \tag{16}$$

and (for $-\pi < \theta \le 0$)

$$\dot{\sigma}_2 = \left[\alpha - Rk\sin(\theta) - \frac{1}{2}\sin(\sigma_2 - \sigma_1)\right]\dot{\theta}. \tag{17}$$

Note, that in the case of Path 2 in Figure 1, $\dot{\theta} < 0$ is the angular velocity in the clockwise (cw) direction. At this point, using Equations (16) and (17), we obtain for $0 \le \theta < \pi$

$$\sigma_2 - \sigma_1 = -2\theta\alpha, \tag{18}$$

and for $-\pi < \theta \le 0$

$$\sigma_2 - \sigma_1 = 2\theta\alpha, \tag{19}$$

which confirms the results of Ref. [1] (see Equation (2)) as $|\theta| \to \pi$. Therefore, (for $0 \le \theta < \pi$),

$$\lim_{\theta\to\pi}\dot{\sigma}_1 = \left[\alpha - \frac{1}{2}\sin(2\pi\alpha)\right]\dot{\theta}, \tag{20}$$

and (for $-\pi < \theta \leq 0$)

$$\lim_{\theta \to -\pi} \dot{\sigma}_2 = \left[\alpha + \frac{1}{2}\sin(2\pi\alpha)\right]\dot{\theta}, \tag{21}$$

on Table 1 we list the corresponding values of $\dot{\sigma}_1/\dot{\theta}$ (for $\dot{\theta} \neq 0$) for different values of $\alpha$. We plot these numbers on a diagram in Figure 2.

**Table 1.** AB Effect with the electron as the detecting particle as $\theta \to \pi$ for $\dot{\theta} \neq 0$ with different flux parameter values, $\alpha$.

| $\alpha$ | $n$ | Similar Element | $\dot{\sigma}_1/\dot{\theta}$ | AB Effect? |
|---|---|---|---|---|
| $-1$ | 1 | H | $-1.0$ | No |
| $-\frac{1}{2}$ | 2 | He | $-0.5$ | Yes |
| $-\frac{1}{3}$ | 3 | Li | 0.1 | Yes |
| $-\frac{1}{4}$ | 4 | Be | 0.250 | Yes |
| $-\frac{1}{5}$ | 5 | B | 0.276 | Yes |
| $-\frac{1}{6}$ | 6 | C | 0.266 | Yes |
| $-\frac{1}{7}$ | 7 | N | 0.248 | Yes |
| $-\frac{1}{8}$ | 8 | O | 0.229 | Yes |
| $-\frac{1}{9}$ | 9 | F | 0.21 | Yes |
| $-\frac{1}{10}$ | 10 | Ne | 0.194 | Yes |
| $-\frac{1}{11}$ | 11 | Na | 0.179 | Yes |
| $-\frac{1}{12}$ | 12 | Mg | 0.167 | Yes |
| $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ |
| $-\frac{1}{118}$ | 118 | Og | 0.018 | Yes |

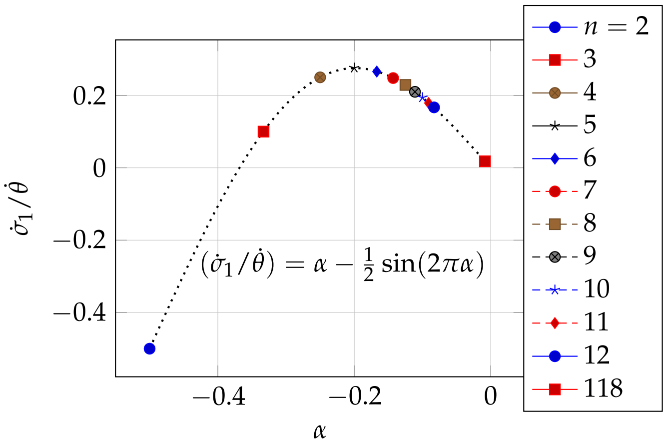


**Figure 2.** The plot of $\dot{\sigma}_1/\dot{\theta}$ versus $\alpha$ as $\theta \to \pi$ for $\dot{\theta} \neq 0$ (see values in Table 1).

Note here that at the interference point (in polar coordinates $(r, \theta) = (R, \pi)$), the phase of each of the electrons is independent of the radius of the circular path. However, it is essential to remember that the circle's radius must meet the constraint to ensure the paths remain within the magnetically excluded region. Therefore, we must further analyze our KM to determine the "critical" radius $R_{\text{crit}}$. This radius is likely related to the radius through which the magnetic field lines pass, i.e., no longer magnetically excluded.

Now, looking at Equations (2) and (16)–(19), we find (for $0 \leq \theta < \pi$)

$$\dot{\sigma}_1 = \left[\alpha - Rk\sin(\theta) + \frac{1}{2}\sin(-2\theta\alpha)\right]\dot{\theta}, \tag{22}$$

and (for $-\pi < \theta \leq 0$)

$$\dot{\sigma}_2 = \left[\alpha - Rk\sin(\theta) + \frac{1}{2}\sin(-2\theta\alpha)\right]\dot{\theta}, \tag{23}$$

with which we plot the values of $\dot{\sigma}_1/\dot{\theta}$ versus $\theta$ for $\dot{\theta} \neq 0$ on a diagram in Figure 3 for $\alpha = -1/2$, and in Figure 4 for $\alpha = -1/3$.

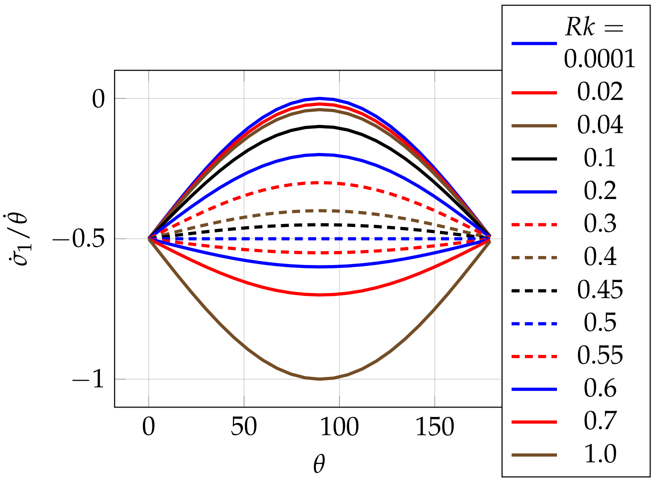


**Figure 3.** The plot of $\dot{\sigma}_1/\dot{\theta}$ versus $\theta$ for $\dot{\theta} \neq 0$ (see Equation (22)) for different values of $Rk$ when $\alpha = -1/2$.

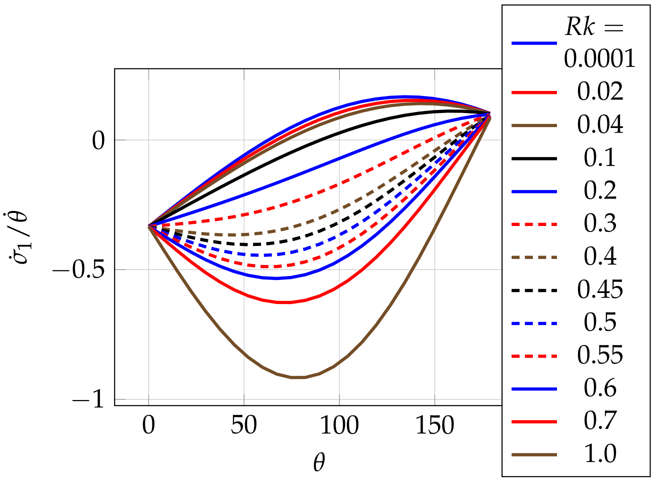


**Figure 4.** The plot of $\dot{\sigma}_1/\dot{\theta}$ versus $\theta$ for $\dot{\theta} \neq 0$ (see Equation (22)) for different values of $Rk$ when $\alpha = -1/3$.

We need to determine the range of values for R in which the AB effect can be detected. This depends on the magnetic field and how much $R$ is within the excluded region. A more precise question would be the following: with a given flux parameter $\alpha$, how can we determine the maximum or critical $R$ to ensure that it remains in the exclusive region?

Looking at the graph in Figure 3, one can see that the function $\dot{\sigma}_1/\dot{\theta}$ is concave (i.e., the extreme is a maximum) until a certain value $Rk = R_{\text{crit}}k$, when it becomes a horizontal line. After this, i.e., when $R > R_{\text{crit}}$, increasing $Rk$ would make the function convex, that is, the extreme is a minimum. On the other hand, a similar feature can be observed in the graph in Figure 4 but slanting upward (from the left) in a pattern instead of just symmetric along the horizontal.

We propose that for $\alpha = -1/2$, together with a given value of $k$, $R_{\text{crit}}$ entails a unique radius $R$, at which the bound state AB effect cannot be detected, that is, the magnetic field lines pass through this radius, and thus are not magnetically excluded. Beyond $R_{\text{crit}}$, the bound state AB effect resumes as there are no magnetic field lines in the region once again.

Although for $\alpha \neq -1/2$, for example, $\alpha = -1/3$, the function $\dot{\sigma}_1/\dot{\theta}$ is not as symmetrical as that for $\alpha = -1/2$; however, the critical radius, $R_{\text{crit}}$, can still indicate the "flipping" behavior, which is only attributable to the presence of the magnetic field lines.

We now carefully examine such values of $R$ that are "candidates" for $R_{\text{crit}}$ in the diagram in Figure 5. We, therefore, determine that in our model, $R_{\text{crit}} = 0.5/k$ for $\alpha = -1/2$. Pretty much in the same manner, we can find for $\alpha = -1/3$ that $R_{\text{crit}} \approx 0.22/k$ using the diagram in Figure 6.

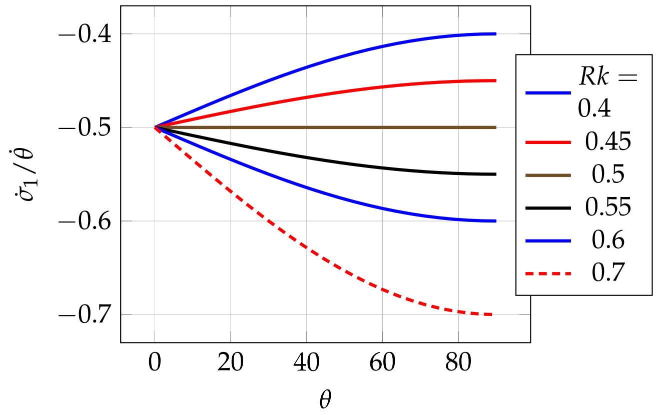


**Figure 5.** Finding $R_{\text{crit}}$ in the plot of $\dot{\sigma}_1/\dot{\theta}$ versus $\theta$ for $\dot{\theta} \neq 0$ for different values of $Rk$ when $\alpha = -1/2$.

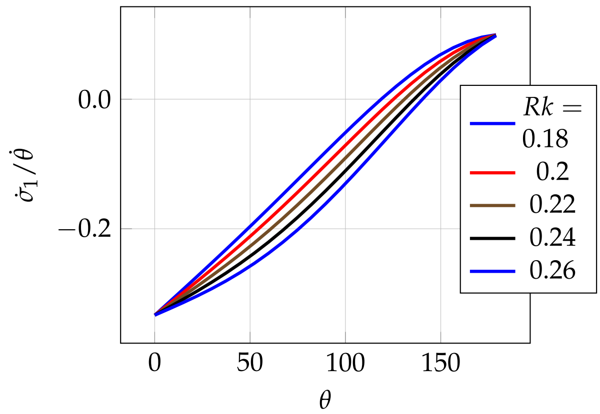


**Figure 6.** Finding $R_{\text{crit}}$ in the plot of $\dot{\sigma}_1/\dot{\theta}$ versus $\theta$ for $\dot{\theta} \neq 0$ for different values of $Rk$ when $\alpha = -1/3$.

### *2.1. The Critical Coupling Strength*

In order to find the synchronization condition using the KM, at first we have to introduce the order parameter $\rho \in [0,1]$, which measures the degree of synchronization, e.g., Refs. [5,23]:

$$\rho e^{i\zeta - \sigma_i} = \frac{1}{N}\sum_{j=1}^{N} e^{i\sigma_j - \sigma_i}, \qquad i = 1,2,\ldots,N, \tag{24}$$

where $\zeta \in \mathbb{R}$ is the average phase of the oscillators. Equating the imaginary part of both sides of Equation (24), we have

$$\rho \sin(\zeta - \sigma_i) = \frac{1}{N}\sum_{j=1}^{N} \sin(\sigma_j - \sigma_i). \tag{25}$$

With Equation (25), we may rewrite Equation (1) as

$$\dot{\sigma}_i = \omega_i + K\rho \sin(\zeta - \sigma_i). \tag{26}$$

Now, Equation (24) represents a mean field with which the phase oscillators "interact". If the function $K(t)$ is small, then Equation (26) implies $\dot{\sigma}_i \approx \omega_i$, which means that the oscillator does not interact much with the mean field. On the other hand, if $K$ is large, then $\sigma_i$ is entrained by the mean field. This entrainment in the long run produces order (i.e., synchronization) starting from a certain form of disorder (i.e., incoherence) on the phase oscillators. The threshold between these two states (synchronization/incoherence) occurs at a critical coupling strength coefficient, denoted by $K_{\text{crit}}$.

Looking at Equation (26) and the fact that $\rho \leq 1$, one can distinguish two regimes in terms of $K$ for $i \neq j$:

- Case 1. $K < |\omega_i - \omega_j|/2$, then no solution of Equation (26) of the form $\dot{\sigma}_i(t) - \dot{\sigma}_j(t) = 0$ exists.
- Case 2. $K \geq |\omega_i - \omega_j|/2$, then the solution exists, and the oscillators can synchronize. This case also provides a lower bound for $K_{\text{crit}}$.

In our case, $K_{\text{crit}}$, which is the threshold for the jump from the state of incoherence to that of bound state AB effect synchronization, has the form

$$K \geq K_{\text{crit}} := \frac{|\omega_2 - \omega_1|}{2} = |\alpha\dot{\theta}|. \tag{27}$$

This further implies that

$$\frac{|\dot{\theta}|}{2} \geq |\alpha\dot{\theta}|, \tag{28}$$

and so the threshold from incoherency to synchronization based on this KM of the bound state AB effect occurs when

$$|\alpha| \leq \frac{1}{2}. \tag{29}$$

This means, for example, if we use an electron as the moving charged particle (the detector), and the source of the magnetic flux is a particle with charge $ne$, then synchronization can occur for $|n| \geq 2$, as specified in Equation (29). The condition in Equation (29) confirms that our version of the KM agrees with the physics of the bound state AB effect in that we have obtained the synchronization condition that coincides with the allowable values of $\alpha$ for the AB effect to occur in the case when the detecting particle is the electron.

### *2.2. A More General Case*

We now write a more general form of the KM, i.e., when $|\theta_1|$ is not necessarily equal to $|\theta_2|$ ($0 \leq \theta_1 < \pi$ and $-\pi < \theta_2 \leq 0$):

$$\dot{\sigma}_1 = \left[\alpha - Rk\sin(\theta_1) + \frac{1}{2}\sin(\sigma_2 - \sigma_1)\right]\dot{\theta}_1, \tag{30}$$

and

$$\dot{\sigma}_2 = \left[\alpha - Rk\sin(\theta_2) - \frac{1}{2}\sin(\sigma_2 - \sigma_1)\right]\dot{\theta}_2, \tag{31}$$

yielding more general conditions for synchronization in terms of the critical coupling strength coefficient $K_{\text{crit, gen}}$:

$$\frac{1}{2}\dot{\theta}_1 =: K_1 \geq K_{\text{crit, gen}} := \frac{1}{2}\left|\alpha\left(\dot{\theta}_2 - \dot{\theta}_1\right) - Rk\dot{\theta}_2\sin(\theta_2) + Rk\dot{\theta}_1\sin(\theta_1)\right|, \tag{32}$$

and

$$-\frac{1}{2}\dot{\theta}_2 =: K_2 \geq K_{\text{crit, gen}}. \tag{33}$$

In the most general case of $N$ electrons, our version of the KM has the form

$$\dot{\sigma}_i = \left[\alpha - Rk\sin(\theta_i) + \frac{1}{N}\sum_{j=1}^{N}\sin(\sigma_j - \sigma_i)\right]\dot{\theta}_i. \tag{34}$$

## 3. Discussion and Outlook

We have derived a version of the KM (see Equations (22) and (23)), which is capable of describing the phase of the bound state AB effect, starting from the expression of the overall wave function for the scattering problem of the quantum system, e.g., Section 4 of Ref. [1].

In this model, to observe the AB effect with an electron as the detecting charged particle, for a non-zero angular velocity $\dot{\theta}$ and for $\alpha = -1/2$, the radius $R$ of the circular path through which the electron can orbit around the solenoid, which has a constant magnetic flux $\phi$, should be such that $R < R_{\text{crit}} = 0.5/k$.

Notice that, when $\alpha = -1/2$ at $R = R_{\text{crit}}$, $\dot{\sigma}_i/\dot{\theta}$ becomes constant w.r.t. $\theta$. We interpret this as the radius through which the magnetic field lines pass, making it magnetically included. When $R > R_{\text{crit}}$ and $\alpha = -1/2$, the function $\dot{\sigma}_i/\dot{\theta}$ "flips" w.r.t. that when $R < R_{\text{crit}}$, indicating its behavior beyond the magnetic field region. In this model, the magnetic field region is concentrated at $R_{\text{crit}}$, which means that the field lines in that area are uniformly vertical, perpendicular to the trajectories of the electrons. This suggests that for $\alpha = -1/2$, our KM yields the characteristics we desire in the quantum system. For instance, it ensures that the solenoid is sufficiently long and its radius is small enough to create uniform magnetic field lines that pass along its sides at $R_{\text{crit}}$. The "flipping" behavior only confirms that indeed $R_{\text{crit}}$ is the "interface" between the two regions (i.e., less than and beyond the magnetic field) when $\alpha = -1/2$. In other words, utilizing our KM, we can now understand the magnetically excluded and "included" regions for $\alpha = -1/2$.

In the case of $\alpha = -1/3$, the graph of the function $\dot{\sigma}_i/\dot{\theta}$ is not as symmetric as that of $\alpha = -1/2$, due to the fact that $\sin(-2\theta\alpha) \neq \sin(\theta)$; however, the radius $R_{\text{crit}} \approx 0.22/k$ still indicates the magnetic field region, see Figures 4 and 6.

One can approximately express the incident wave vector of the electron as $k = 2\pi/\lambda_0$, where $\lambda_0$ is the de Broglie wavelength of the incident electron given by (see, e.g., Ref. [24]) $\lambda_0 = 2\pi\hbar/(m_0 R|\dot{\theta}_0|)$, $\dot{\theta}_0 \in \mathbb{R}\setminus\{0\}$, with $m_0$ being the mass of the electron and $\dot{\theta}_0$ its initial angular velocity. Then, for $\alpha = -1/2$, we can have an expression for $R_{\text{crit}}$ in terms of $\dot{\theta}_0$:

$$R_{\text{crit}} = C\sqrt{0.5}\left(|\dot{\theta}_0|\right)^{-1/2}, \tag{35}$$

where $C = \sqrt{\hbar/m_0}$.

For any "allowable" values of $\alpha$ (see, e.g., Table 1), we notice that as $Rk \to 0$, the function $\dot{\sigma}_i/\dot{\theta}$ versus $\theta$ converges into one single plot; see and compare when $Rk = 0.0001$ and $Rk = 0.02$ in both Figures 3 and 4. Beyond the magnetic field lines (i.e., $R > R_{\text{crit}}$), it can be seen that for $\alpha = -1/2$ the function $\dot{\sigma}_i/\dot{\theta}$ at $R = 1/k$ is symmetric w.r.t. $R \to 0$; any $R$ larger than this would render behavior that is no longer symmetrical to that as $R \to 0$. Further analysis of these graphs, or as an extension of the current study, would provide valuable insights into the behavior of the detecting electron well beyond this region, specifically $R \gg R_{\text{crit}}$.

In addition, the condition for the system to undergo a synchronization is $|\alpha| \leq 1/2$, implying that the magnetic flux has the form $\phi = \phi_0/n$ with $|n| \geq 2$. Since the synchronization coincides with the condition (see Equation (29)) when $\alpha$ yields a detectable AB effect we, therefore, say that in our KM, a synchronization means the detection of the AB effect, while incoherence does not involve the AB effect. We have also generalized our model into $N$ electrons (or, in general, $N$ charged particles); see Equation (34).

This study also shows that the KM can be derived from a quantum mechanical system with central symmetry (similar to that of the bound state Aharonov–Bohm effect with constant radius and magnetic flux), by expressing its wave function in terms of the incident wave function and the scattered wave function; see Appendix A for the outline of a slightly different alternative derivation of the KM.

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## Appendix A. Alternative Derivation of the Kuramoto Model

Let $t \in [0, T]$, $T > 0$, be the time of interference, $\vartheta_i := \sigma_i/2$, and $f = f(\vartheta_j(t) - \vartheta_i(t)) \in \mathbb{R}$ be a function that contains the information related to the AB effect, described by the phase difference $\vartheta_j(t) - \vartheta_i(t)$. Furthermore, looking at Equation (10), let $B(t) = B_0(t) f(\vartheta_j(T) - \vartheta_i(T))$ in order to identify $f$. Then, we propose that, from the general expression of the wave function of a quantum mechanical system, which is symmetrical in the polar coordinates, of the form in Equation (6), one can formulate a version of the KM of the form

$$\dot{\vartheta}_i(t) = \omega_{\text{inc},i} + \frac{2}{N}\omega_{\text{scatt},i} \sum_{j=1}^{N} f(\vartheta_j(t) - \vartheta_i(t)), \tag{A1}$$

to describe the phase dynamics of the system. In our case $N = 2$, we can identify through Equations (2) and (8) that

$$f(\vartheta_1(T) - \vartheta_2(T)) = \sin(\pi\alpha).$$

Therefore, with Equation (A1), we could also have a version of the KM for the bound state AB effect as given in Equation (34).

Also, in our case it is important to note that $\omega_{\text{inc},i} = (1 - ky_i/\alpha)V_{\text{AB},i}$, where $y_i = R\sin(\theta_i)$ and $V_{\text{AB},i} = \alpha\dot{\theta}_i$. Here, $V_{\text{AB},i}$ represents the potential energy of the system; see, e.g., Ref. [19].

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