Complex-Order and Fractional Derivatives: A First Exploration II

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1 Introduction

2 The Field of orders

Before we get through, we need to make some claims since in this section, we will be working with multiple mathematical sets.
this is the normal definition of D^α

$$D^\alpha x^n = \frac{\Gamma(n+1)}{\Gamma(n-\alpha+1)} x^{n-\alpha}$$

but we need a generalized version
since $x^{n-\alpha}$ may not always be defined directly for groups like $\mathbb{H}$ we can define it like this $\exp((n-\alpha)\ln(x))$ for any definition of the $\exp()$ function, which allows us to use the definition needed for any case weather it's $\lim_{n\to\infty}(1+\frac{x}{n})^n$ or the infinite summation definition $\exp(x) = \sum_{n=0}^{\infty} \frac{x^n}{n!}$ or any definition
second we can define $\Gamma(x)$ using Euler's product or Weierstrass product for any set of numbers that doesn't have any nice form of integral like $\mathbb{H}$ although the Weierstrass definition is preferred since it has e^x in it which is easier to deal with in most cases.
so we can write the defenition of $D^\alpha x^n$ in the most abstract way like this

$$D^\alpha x^n = \frac{\frac{e^{-\gamma(n+1)}}{n+1}\prod_{k=1}^{\infty}(1+\frac{n+1}{k})^{-1}e^{\frac{n+1}{k}}}{\frac{e^{-\gamma(n+1-\alpha)}}{n+1-\alpha}\prod_{j=1}^{\infty}(1+\frac{n+1-\alpha}{j})^{-1}e^{\frac{n+1-\alpha}{j}}} e^{(n-\alpha)\ln(x)}$$

we can take both the $\frac{e^{-\gamma(n+1)}}{n+1}$ over

$$\frac{e^{-\gamma(n+1-\alpha)}}{n+1-\alpha}$$

out to give us this expression

$$\frac{n+1-\alpha}{e^{-\gamma(n+1-\alpha)}} \times \frac{e^{-\gamma(n+1)}}{n+1} = \frac{n+1-\alpha}{e^{\gamma\alpha}(n+1)} = \frac{n+1}{e^{\gamma\alpha}(n+1)} + \frac{-\alpha}{e^{\gamma\alpha}(n+1)} = e^{-\gamma\alpha}(1-\frac{\alpha}{n+1})$$

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for the infinite product; since we have two infinite products with the same index we can combine them

$$\frac{\prod_{k=1}^{\infty}(1+\frac{n+1}{k})^{-1}e^{\frac{n+1}{k}}}{\prod_{j=1}^{\infty}(1+\frac{n+1-\alpha}{j})^{-1}e^{\frac{n+1-\alpha}{j}}} = \prod_{k=1}^{\infty}\frac{(1+\frac{n+1}{k})^{-1}e^{\frac{n+1}{k}}}{(1+\frac{n+1-\alpha}{k})^{-1}e^{\frac{n+1-\alpha}{k}}} = \prod_{k=1}^{\infty}e^{\frac{n+1}{k}-\frac{n+1-\alpha}{k}}\frac{1+\frac{n+1-\alpha}{k}}{1+\frac{n+1}{k}}$$

with the exponent being $e^{\frac{\alpha}{k}}$ at the end we get this expression

$$D^{\alpha}x^n = e^{(n-\alpha)\ln(x)-\gamma\alpha}(1-\frac{\alpha}{n+1})\prod_{k=1}^{\infty}e^{\frac{\alpha}{k}}\frac{1+\frac{n+1-\alpha}{k}}{1+\frac{n+1}{k}}$$

This definition proves to us that this framework can work with any set of numbers where multiplication and addition are defined. Currently, this is only here for analyzing and understanding the D^z operator, but moving forward, we will still use the symbol definition of $\frac{\Gamma(n+1)}{\Gamma(n+1-\alpha)}x^{n-\alpha}$, when analyzing isn't needed

2.1   Generalized Index Law and D^z identities

The index law has been proven to work on the operator before, but the proof held for $\alpha \in \mathbb{R}$; therefore, a generalized one is needed for other sets like $\mathbb{C}, \mathbb{H}, ...$

Theorem 2.1 (The Index Law Theorem) *Let $(G,+)$ be a semi group , for any element $\alpha, \beta \in G$*
$$D^{\beta}D^{\alpha} = D^{\beta+\alpha}$$

Proof:

$$D^{\alpha}x^n = \frac{\Gamma(n+1)}{\Gamma(n+1-\alpha)}x^{n-\alpha} \qquad D^{\beta}D^{\alpha}x^n = \frac{\Gamma(n+1)}{\Gamma(n+1-\alpha)}\frac{\Gamma(n+1-\alpha)}{\Gamma(n+1-\alpha-\beta)}x^{n-\alpha-\beta}$$

$$= \frac{\Gamma(n+1)}{\Gamma(n+1-\alpha-\beta)}x^{n-\alpha-\beta}$$

and let this be 1
$$D^{\alpha+\beta}x^n = \frac{\Gamma(n+1)}{\Gamma(n+1-\alpha-\beta)}x^{n-\alpha-\beta}$$

and let this be 2
since 1 and 2 are equal; hence

$$D^{\beta}D^{\alpha} = D^{\alpha+\beta}$$

this works for when $\alpha, \beta \in \mathbb{R}, \mathbb{C}$ and extend to $\mathbb{H}$ with choice of logarithmic branks and multiplication order.
We define D^{α} initially on monomials and extend linearly; thus, operator equality is determined by its action on x^n We can also turn this observation into an axiom We axiomatize that any family $D^g, g \in G$ where $(G,+)$ satisfying $D^{g_1}D^{g_2} = D^{g_1+g_2}$, $D^0 = I$ where I is the identity operator in most cases $f(x)$ with

linearity ; is a generalized derivative semi group

and it's proven for $\mathbb{R}, \mathbb{C}, \mathbb{H}$ with the Γ formula that such families satisfy these conditions naturally

From here, we can assume some laws are true based on these axioms

- **Commutativity:** $D^\alpha D^\beta = D^\beta D^\alpha$
  since $\alpha, \beta \in G$ where $(G, +)$ and commutativity of addition in G exist (G is also known as an abelian group), then

$$D^{\alpha+\beta} = D^{\beta+\alpha}$$

  Hence, this is true

- **Associativity:** $(D^\alpha D^\beta) D^\gamma = D^\alpha (D^\beta D^\gamma)$
  since $\alpha, \beta, \gamma \in G$ where $(G, +)$ then

$$D^{\alpha+(\beta+\gamma)} = D^{(\alpha+\beta)+\gamma}$$

  Hence, this is true

- **Multiplication law for integer:** $^n D^\alpha = D^{\alpha n}$
  since $\alpha \in G$ where $(G, +)$ and $n \in \mathbb{Z}$, we can treat n as a scaler or as a number depending on G then

$$\underbrace{D^\alpha D^\alpha \dots D^\alpha}_{n \text{ times}} = D^{\alpha+\alpha+\dots+\alpha} = D^{\alpha n} =\,^n D^\alpha$$

  Hence, this is true

- **Inverse order:** $D^{-\alpha} D^\alpha = D^0 = I$ exists in the semi group of orders
  since $\alpha \in G$ where $(G, +)$ is a group(which makes it has Inverse elements) form a group of derivative orders where D^0 must exist where

$$D^\alpha D^0 = D^\alpha I = D^\alpha$$

  Then an inverse must exist in the same group that assures the result of D^0

$$D^\alpha D^{-\alpha} = D^{\alpha-\alpha} = D^0 = I$$

  Hence, this is True

This subsection serves more as an extension of algebraic groups/sets to what was already defined with algebraic manipulation in the first paper, which allows us to extend this operator on the abstract level to any group/set that fulfills the conditions without a proof each time

2.2   The generalized multiplication law

2.3 D^z analytic continuation

We know that $D^\alpha x^n = \frac{\Gamma(n+1)}{\Gamma(n+1-\alpha)} x^{n-\alpha}$ is the main formula for the α-th derivative where $\alpha \in G$ where G is at least defined as a semi group $(G, +)$ known as the general derivatives order semi-group, which includes $\mathbb{R}, \mathbb{C}$ that we are going to work with in this subsection.

and we have derived a formula for D^z that doesn't include any integrals; built on basic arithmetic and constants

$$D^\alpha x^n = e^{(n-\alpha)\ln(x) - \gamma\alpha}(1 - \frac{\alpha}{n+1}) \prod_{k=1}^{\infty} e^{\frac{\alpha}{k}} \frac{1 + \frac{n+1-\alpha}{k}}{1 + \frac{n+1}{k}}$$

where γ is the Euler-Mascheroni constant

We also know that overdifferentiating the formula $D^z x^n$ results in a gamma pole at the denominator, leading to the 0 result whenever it's a gamma of a non-positive integer; for example

$$D^{n+1} x^n = \frac{\Gamma(n+1)}{\Gamma(n+1-n-1)} x^{n-n-1} = \frac{\Gamma(n+1)}{\Gamma(0)} x^{-1} = 0$$

But the same doesn't apply to the product formula

$$D^{n+1} x^n = e^{(n-n-1)\ln(x) - \gamma(n+1)}(1 - \frac{n+1}{n+1}) \prod_{k=1}^{\infty} e^{\frac{n+1}{k}} \frac{1 + \frac{n+1-n-1}{k}}{1 + \frac{n+1}{k}}$$

$$= e^{-1\ln(x) - \gamma(n+1)}(1 - 1) \prod_{k=1}^{\infty} e^{\frac{n+1}{k}} \frac{1 + \frac{0}{k}}{1 + \frac{n+1}{k}} = x^{-1} e^{-\gamma(n+1)}(0) = 0$$

What happens here is that instead of a gamma pole it's a simple multiplication by zero, and the result is correct as $D^n x^n = \frac{\Gamma(n+1)}{\Gamma(1)}$ the next integer derivative is simply $D^1 C$ which is 0

Not only that, but this happens to any n from any semi-group.

we can also skip this by making $\alpha = n + 2$, and this is supposed to return 0 by all means since 0 is a constant and there is supposed to be a gamma pole coming on the way; but here there isn't any gamma function, and we aren't starting from zero

$$D^{n+2} x^n = e^{(n-n-2)\ln(x) - \gamma(n+2)}(1 - \frac{n+2}{n+1}) \prod_{k=1}^{\infty} e^{\frac{n+2}{k}} \frac{1 + \frac{n+1-n-2}{k}}{1 + \frac{n+1}{k}}$$

$$= e^{(-2)\ln(x) - \gamma(n+2)}(1 - \frac{n+1+1}{n+1}) \prod_{k=1}^{\infty} e^{\frac{n+2}{k}} \frac{1 + \frac{-1}{k}}{1 + \frac{n+1}{k}} = x^{-2} e^{-\gamma(n+2)}(-\frac{1}{n+1}) \prod_{k=1}^{\infty} e^{\frac{n+2}{k}} \frac{1 - k^{-1}}{1 + \frac{n+1}{k}}$$

This new function looks weird and unexpected, since in the original definition, this was a gamma pole, but in this function, what happened is n changed from

the power on the x to be the power on e, meaning whichever function x^n we choose, it won't make a change on x but rather on e.

This is sort of similar to a transformtive function, changing the differentiation main independence, like $\sin^{-1}(x)$, is depends mainly on the inside of it when differentiation, but its first derivative $\frac{1}{\sqrt{1-x^2}}$ depends mainly on the power of x

We can test this for x^2 as an example

$$D^4 x^2 = e^{(2-4)\ln(x)-4\gamma}(1 - \frac{4}{3}) \prod_{k=1}^{\infty} e^{\frac{4}{k}} \frac{1 + \frac{-1}{k}}{1 + \frac{3}{k}} = x^{-2}e^{-4\gamma}(-\frac{1}{3}) \prod_{k=1}^{\infty} e^{\frac{4}{k}} \frac{1 - k^{-1}}{1 + \frac{3}{k}}$$

which is the same value if we used the $\alpha = n + 2$ formula.

Continuing this example, the product value turns out to be 0, this is because in the first term $\frac{1-1}{1-3} = 0$, and this is actually a problem that happens in every series where $\alpha = n + 2$, as there will always be $1 - 1$ term in the product

For this function, we can try and regularize it by taking out the factor that is the cause of this, that is the first one.

we let $r = \prod_{k=1}^{1} 1 + \frac{3-\alpha}{k} = \prod_{k=1}^{1} 1 + \frac{-1}{k} = 1 - 1 = 0$, then taking the limit as $\alpha \to 4$we get this regularized expression

$$D^4 x^2 = \lim_{\alpha \to 4} \frac{D^\alpha x^2}{r} = x^{-2}e^{-4\gamma}(-\frac{1}{3}) \lim_{\alpha \to 4} \prod_{k=1}^{\infty} e^{\frac{4}{k}} \frac{1 - \frac{3-\alpha}{k}}{1 + \frac{3}{k}}$$

This allows us to work our way out. The product converges very slowly to 4.423, to the final result being

$$D^4 x^2 = \frac{-0.147}{x^2}$$

doing the same for D^5 we get $\frac{0.024}{x^2}$

We can say that removing the zero factor was helpful

2.4 x^{-n} , Taylor series and more

we can't say D^z is the derivative operator any more, instead we can say that it's a sort of transform operator that works on any function $f(x)$ and returns the same result as the derivative operator only when the derivative operator is defined, and for now; the only condition for this is no Γ poles as it's first and main formula being $D^z x^n = \frac{\Gamma(n+1)}{\Gamma(n+1-\alpha)}$ has $\Gamma()$ in it.

The derivative of a constant We can find the D^z of any constant C using the product formula and considering $C = Cx^0$

$$D^\alpha C = e^{(0-\alpha)\ln(x)-\gamma\alpha}(1 - \frac{\alpha}{1}) \prod_{k=1}^{\infty} e^{\frac{\alpha}{k}} \frac{1 + \frac{1-\alpha}{k}}{1 + \frac{1}{k}}$$

This formula works when $\alpha = 1$ (which is the $\alpha = n + 1$ relation from the previous sub-section) as the $(1 - \frac{\alpha}{1})$ becomes zero, and it works for any integer value order as the product $\prod_{k=1}^{\infty} e^{\frac{\alpha}{k}} \frac{1+\frac{1-\alpha}{k}}{1+\frac{1}{k}}$ will have a -1 resulting a zero term

and the whole value becoming zero , we will consider this one a derivative since firstly it matchs classical calculus results and second even when there is a Gamma pole in the denominator this function is still depending on itself, but when we differentiate it more it depends on skipping that zero and continuing with the rules, it still works but it's not differentiation

we can try and plug in x^{-n} in this formula, with changing α to $-\alpha$ to see what it gets us

$$D^{-\alpha}x^{-n} = e^{(-n+\alpha)\ln(x)+\gamma\alpha}(1 - \frac{-\alpha}{-n+1})\prod_{k=1}^{\infty} e^{\frac{-\alpha}{k}} \frac{1 + \frac{-n+1-\alpha}{k}}{1 + \frac{-n+1}{k}}$$

we test it for simple integer values

$$D^{-2}x^{-2} = e^{0\ln(x)+2\gamma}(-1)\prod_{k=1}^{\infty} e^{\frac{2}{k}} \frac{1 + \frac{-3}{k}}{1 + \frac{-1}{k}} = -e^{2\gamma}$$

A

2.5 Taylor series memory

2.6 The Big family of D^z

3 More to the Imagination

3.1 The imaginary derivative order polar form and D(i)

from what we know about D^z we can say that
D^1 and D^{-1} represents a half turn on the $D(i)$ plane
D^i and D^{-i} represents a quarter turn on the $D(i)$ plane
So if we want to get the generalized form of this, we need to use the polar form instead of the Cartesian form, so

$$D^i f(x) = D^{e^{\frac{i\pi}{2}}} f(x) \qquad D^{-1} f(x) = D^{e^{i\pi}} f(x)$$

and generally speaking, for the unit circle around D^0(the function itself)

$$D^z f(x) = D^{e^{i\theta}} f(x)$$

And to make this formula for the whole complex plane, we write it like this

$$D^z f(x) = D^{re^{i\theta}} f(x)$$

where r is the length from D^0 to the wanted function

3.2 so how does the complex derivative changes the nature of the function?

as we can see complex derivative have a significant change on the function; while Real derivatives only change the power and the coefficient, the complex derivative changes the whole nature of the function from linear function to oscillator function in most cases, with the only thing holding meaning between everything is the D^z operator and it's nature of continuity and semi-group order. we can use $D^{re^{i\theta}}f(x)$ from the previous section to understand how it works; we will let $r = 1$ so we aren't moving anywhere outside of the first derivative and first integral space.
the formula for x^n is:

$$D^{e^{i\theta}}x^n = \frac{\Gamma(n+1)}{\Gamma(n+1-e^{i\theta})}x^{n-e^{i\theta}} = \frac{\Gamma(n+1)}{\Gamma(n+1-\cos(\theta)-i\sin(\theta))}x^{n-\cos(\theta)-i\sin(\theta)}$$

when $\theta = 0$ $e^{i\theta} = 1$ giving us the first derivative D^1, so we can move it by $\frac{\pi}{180} \approx 0.017$ (which is 1°) we get

$$D^{e^{\frac{i\pi}{180}}} = \frac{\Gamma(n+1)}{\Gamma(n+1-\cos(\frac{\pi}{180})-i\sin(\frac{\pi}{180}))}x^{n-\cos(\frac{\pi}{180})-i\sin(\frac{\pi}{180})} \approx \frac{\Gamma(n+1)}{\Gamma(n-0.017i)}x^{n-1-0.017i}$$

(Note: this value is approximated to the fourth digit, as the whole number is $0.99984769516 - 0.01745240644i$)
we can see that the result value is like D^1 but with a little moment on the i-axis to the.
also we can see that it moves clockwise; to get the picture imagine $D^\alpha x^n$ as a vector in the $x - i$ plane with length one, and α as another vector with length one; the more value we add to the α the lesser value the $D^\alpha x^n$ we get, they are moving against each other but get the same value when they reach real axis.
Expanding the sum we get this expression

$$D^{e^{i\frac{\pi}{180}}}x^n = \frac{\Gamma(n+1)}{\Gamma(n-0.017i)}x^{n-1}(\cos(0.017\ln(x)) + i\sin(0.017\ln(x)))$$

This expression oscillates so slowly that it behaves like a line,

6 Yes, the whole space is a matrix system

As we have explored in the first paper, the possibility of matrix order derivative with this simple formula

$$D^A = \frac{\Gamma(n+1)}{\Gamma(n-A+1)}x^{n-A} = \frac{\Gamma(n+1)}{\Gamma(n-A+1)}x^n e^{-A\ln(x)} = \frac{\Gamma(n+1)}{\Gamma(n-A+1)}x^n \sum_{k=0}^{\infty}\frac{(-1)^k \ln(x)^k}{k!}A^k$$

But let's refine it a little to make it fully clear by changing all the scalers to matrices

$$D^A = \frac{\Gamma((n+1)I)}{\Gamma((n+1)I-A)}x^{nI-A} = \frac{\Gamma((n+1)I)}{\Gamma((n+1)I-A)}x^{nI}e^{-A\ln(x)}$$

$$= \frac{\Gamma((n+1)I)}{\Gamma((n+1)I-A)}x^{nI}\sum_{k=0}^{\infty}\frac{(-1)^k \ln(x)^k}{k!}A^k$$

For now, to define $\Gamma(A)$ we are going to use eigenvalues, although Cuchy Integrals are better, but for the sake of intuition and understanding, we are going to discuss them in later sections

This means that the formula only works for **square matrices** for now

We can see a simple example with the matrix $A = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$; the rotation matrix

for a function $f(x) = x^2$ we are going to take the A-th derivative like this

$$D^A f(x) = \frac{\Gamma(3)}{\Gamma(\begin{pmatrix} 3 & 0 \\ 0 & 3 \end{pmatrix} - \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix})}x^2 \sum_{n=0}^{\infty}\frac{(-1)^n \ln(x)^n}{n!}\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}^n$$

The matrix A returns back at the $4n$-th powers, and the Gamma expression is $\Gamma(\begin{pmatrix} 3 & 1 \\ -1 & 3 \end{pmatrix})$, but to continue, we need to find the eigenvalues of this matrix

$$\det\left(\begin{pmatrix} 3 & 1 \\ -1 & 3 \end{pmatrix} - \begin{pmatrix} \lambda & 0 \\ 0 & \lambda \end{pmatrix}\right) = \det\left(\begin{pmatrix} 3-\lambda & 1 \\ -1 & 3-\lambda \end{pmatrix}\right) \qquad (3-\lambda)(3-\lambda)+1 = 0$$

$$(3 - \lambda)^2 + 1 = 0 \implies 3 - \lambda = \pm i \qquad \lambda = 3 - i, 3 + i$$

This equation doesn't have any real roots but only complex roots that are $-3 - i$ and $-3 + i$

We are going to find the eigenvectors for all roots

$$((3I - A) - \lambda_1 I)v_1 = 0, \begin{pmatrix} 3 - (3 - i) & 1 \\ -1 & 3 - (3 - i) \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} i & 1 \\ -1 & i \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

then $ix + y = 0$ so $y = -ix$, let $x = 1$, $y = -i$, the first vector $= v_1 = \begin{pmatrix} 1 \\ -i \end{pmatrix}$

doing the same for the other root, we get the second vector $v_2 = \begin{pmatrix} 1 \\ i \end{pmatrix}$

We are going to let the Model matrix $P = [v_1 | v_2] = \begin{pmatrix} 1 & 1 \\ -i & i \end{pmatrix}$ and the diagonal

matrix $\begin{pmatrix} (3 - i) & 0 \\ 0 & (3 + i) \end{pmatrix}$ so we can calculate $f(3I - A) = Pf(\Lambda)P^{-1}$

we can calculate P^{-1} using the inverse of 2×2 matrix formula

$$A^{-1} = \frac{1}{\det(A)} = \begin{pmatrix} d & -b \\ -c & a \end{pmatrix} \implies P^{-1} = \frac{1}{\det(P)} \begin{pmatrix} i & -1 \\ i & 1 \end{pmatrix}$$

and the determinant of P is $(1)(i) - (1)(-i) = i + i = 2i$, therefore we have the expression $P^{-1} = \frac{1}{2i}...$, for simplification we multiply the scaler by $\frac{-i}{-i}$

$$P^{-1} = \frac{-i}{2} \begin{pmatrix} i & -1 \\ i & 1 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} (-i)i & (-i)(-1) \\ (-i)i & (-i)1 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & i \\ 1 & -i \end{pmatrix}$$

Since the original gamma function is in the denominator, we can calculate $\Gamma(3I - A)^{-1}$ to get a direct result. We can so $\Gamma(3I - A) = P\Gamma(\Lambda)^{-1}P^{-1} =$

$$\begin{pmatrix} 1 & 1 \\ -i & i \end{pmatrix} \begin{pmatrix} \frac{1}{\Gamma(3-i)} & 0 \\ 0 & \frac{1}{\Gamma(3+i)} \end{pmatrix} \frac{1}{2} \begin{pmatrix} 1 & i \\ 1 & -i \end{pmatrix} = \frac{1}{2} \left[\begin{pmatrix} 1 & 1 \\ -i & i \end{pmatrix} \begin{pmatrix} 0.354 + 0.492i & 0 \\ 0 & 0.354 - 0.492i \end{pmatrix} \right] \begin{pmatrix} 1 & i \\ 1 & -i \end{pmatrix}$$

$$= \frac{1}{2} \begin{pmatrix} 0.354 + 0.492i & 0.354 - 0.492i \\ -i(0.354 + 0.492i) & i(0.354 - 0.492i) \end{pmatrix} \begin{pmatrix} 1 & i \\ 1 & -i \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 0.354 + 0.492i & 0.354 - 0.492i \\ 0.492 - 0.354i & 0.492 + 0.354i \end{pmatrix} \begin{pmatrix} 1 & i \\ 1 & -i \end{pmatrix}$$

$$= \frac{1}{2} \begin{pmatrix} 0.354 + 0.492i + 0.354 - 0.492i & i(0.354 + 0.492i - 0.354 + 0.492i) \\ -i(0.354 + 0.492i - 0.354 - 0.492i) & 0.354 + 0.492i + 0.354 - 0.492i \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 0.708 & -0.984 \\ 0.984 & 0.708 \end{pmatrix}$$

which at the end results $\begin{pmatrix} 0.354 & -0.492 \\ 0.492 & 0.354 \end{pmatrix}$, substituting it back to the original derivative formula we get

$$D^A f(x) = 2 \begin{pmatrix} 0.354 & -0.492 \\ 0.492 & 0.354 \end{pmatrix} x^2 \sum_{n=0}^{\infty} \frac{(-1)^n \ln(x)^n}{n!} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}^n$$

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Note that the infinite sum acts like the imaginary unit (because it's the matrix representation for it), in which we can replace this sum with $\begin{pmatrix} \cos(\ln(x)) & \sin(\ln(x)) \\ -\sin(\ln(x)) & \cos(\ln(x)) \end{pmatrix}$

We will test this for some values

$$D^A f(x)\big|_e = \begin{pmatrix} 8.941 & 0.473 \\ -0.473 & 8.941 \end{pmatrix} \qquad D^A f(x)\big|_1 = \begin{pmatrix} 0.708 & -0.984 \\ 0.984 & 0.708 \end{pmatrix}$$

$$D^A f(x)\big|_3 = \begin{pmatrix} 10.785 & 1.647 \\ -1.647 & 10.785 \end{pmatrix}$$

We can see that first of all, and as expected, the matrix order changes the type of the function from a scalar to 2×2 matrix in this example

We can also see that in this example that the main diagonal of the matrix is equal in sign and value to a quicker increasing value rather than the other diagonal

We can also see that for some value of x , the second diagonal reaches zero and changes sign of its elements

This is supposed to be similar to $D^i x^2$ since the matrix we used is isomorphic to the imaginary unit; we know that they have some sort of relationship, nonetheless

6.1 exploring more about Matrix derivatives

6.2 Term-wise matrix order

7 To the third dimension

7.1 Modeler differentiation

7.2 Set order derivatives

7.3 group order derivatives

7.4 Vector order derivatives

8 Structural series analysis

Up till this point in this research series, we have always been using series to identify derivatives, which isn't bad by itself, but the problem arises; these are good for calculation, but we can't get any information about the function from the series, we can't get identities or similarities or any information at all.

This makes the identity of the function hidden for D^z

And in this section, we will analyze some series and try to make them informative by any means

8.1 The similarities between functions

Functions can be expressed using summation series, which makes them look easy to identify and see the secrets between them.

For example, we have a function $e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + ... = \sum_{n=0}^{\infty} \frac{x^n}{n!}$, this function is responsible for cyclic derivatives and have some key properties like it's natural logarithm is 1 which makes it very good for hyper operations that changes addition and multiplication to powers

On the other side, we have a function that has no connection to e^x, that is $\frac{1}{1-x}$ with its series being $1 + x + x^2 + x^3 + ... = \sum_{n=0}^{\infty} x^n$

These two functions are very similar, although they aren't connected, we can use the D^z operator on both of them to understand more about them

$$D^\alpha e^x = \sum_{n=0}^{\infty} \frac{x^{n-\alpha}}{\Gamma(n-\alpha+1)} \qquad D^\alpha \frac{1}{1-x} = \sum_{k=0}^{\infty} \frac{\Gamma(k+1)}{\Gamma(k-\alpha+1)} x^{k-\alpha}$$

We can see that both functions are very similar, except that e^x doesn't have a gamma term in the denominator

We can try to find a function in the middle of them constructively

The reason e^x doesn't have a $\Gamma(n+1)$ is that it cancels out with the denominator, so if them were both different slightly, we could see more structure, in which we are asking for this coefficient $\frac{\Gamma(n+1)}{\Gamma(m+1)\Gamma(n-\alpha+1)}$ or something similar of it, and we can find this in ^nC_m, which can be found in the series of $(1+x)^m = \sum_{n=0}^{\infty} {}^mC_n x^n$

$$D^\alpha (1+x)^m = \frac{\Gamma(m+1)}{\Gamma(m-\alpha+1)}(1+x)^{m-\alpha} = \frac{\Gamma(m+1)}{\Gamma(m-\alpha+1)} \sum_{n=0}^{\infty} {}^nC_{m-\alpha} x^n =$$

$$\sum_{n=0}^{\infty} \frac{\Gamma(m-\alpha+1)}{\Gamma(n+1)\Gamma(m-\alpha-n+1)} \frac{\Gamma(m+1)}{\Gamma(m-\alpha+1)} x^n = \sum_{n=0}^{\infty} \frac{\Gamma(m+1)}{\Gamma(n+1)\Gamma(m-\alpha-n+1)} x^n$$

This function acts like e^x only when $m = n$ as they will cancel it and leave for use $\frac{x^n}{\Gamma(\alpha+1)}$ and when m approaches ∞ the fraction diverges leaving only x^n acting like $\frac{1}{1-x}$

8.2 the difference between $\ln(x)$ and e^x is the series

8.3 The classifications of functions in GDI

8.4 construction from functions

8.5 convergence and divergence

Since D^z is a function transformer, we need to analyze its convergence and divergence

For x^n the it always converges and maps from $\mathbb{R} \to \mathbb{R}$ unless:

$n - \alpha \leq 0 \qquad n - \alpha \in \mathbb{Z}$ as in this case we would get $\frac{n!}{\infty} x^{n-\alpha} = 0$ so the whole function turns to zero (Note that $\alpha = n + 1$ is a special zero as it the only

equation that turns the $(1 - \frac{\alpha}{n+1})$ to 0)

Or it maps from $\mathbb{R} \to \mathbb{C}$ when $n - \alpha$ is irrational or can be expressed as a ratio $\frac{a}{b}$ where b is even, as when $x < 0$ we get the even/irrational roots of a negative number

and when $\alpha \in \mathbb{C}$ we get a function that maps $\mathbb{C} \to \mathbb{C}$

For functions that expand to series expansion we can apply this exact rule

for example, in the Maclaurin series of $f(x)$

$$f(x) = \sum_{n=0}^{\infty} a_n x^n \qquad\qquad D^{\alpha} \sum_{n=0}^{\infty} a_n \frac{\Gamma(n+1)}{\Gamma(n-\alpha+1)} x^{n-\alpha}$$

which lets us apply the same information from above for each term, we can apply the same for the Laurent series and Taylor series expansion

For the Laurent series, we have a problem that most of the terms will vanish due to the Gamma pole, so instead we are going to differentiate the first series as x^{-n} and the second as x^n

$$f(x) = \sum_{n=-\infty}^{-1} a_n(x-c)^n + \sum_{n=0}^{\infty} a_n(x-c)^n \implies f(x) = \sum_{n=1}^{\infty} a_{-n}(x-c)^{-n-\alpha} + \sum_{n=0}^{\infty} a_n(x-c)^n$$

$$D^{\alpha} f(x) = \sum_{n=1}^{\infty} a_{-n} \frac{(-1)^{\alpha}\Gamma(n)}{\Gamma(n+\alpha)}(x-c)^{-(n+\alpha)} + \sum_{n=0}^{\infty} a_n \frac{\Gamma(n+1)}{\Gamma(n-\alpha+1)}(x-c)^{n-\alpha}$$

This doesn't only inherit the x^n convergence, but it also adds another term of convergence that makes it even more restrictive, because when $\alpha \notin \mathbb{Z}$ the function maps from $\mathbb{R} \to \mathbb{C}$

And for the Taylor series, we have

$$f(a) = \sum_{n=0}^{\infty} \frac{f^n(a)}{n!} x^n \qquad\qquad D^{\alpha} f(x) = \sum_{n=0}^{\infty} \frac{f^{(n+\alpha)}(a)}{\Gamma(n-\alpha+1)} x^{n-\alpha}$$

But what does that mean for the function's convergence radius?

Well, from the Cauchy–Hadamard theorem, we know a power series' convergence is determined by this equation, where R is the radius

$$\frac{1}{R} = \limsup_{n \to \infty} |a_n|^{\frac{1}{n}}$$

for large values of n we get $\frac{\Gamma(n+1)}{\Gamma(n-\alpha+1)} \sim n^{\alpha}$, which means that this is polynomial growth, not an exponential one, therefore

$$\limsup_{n \to \infty} |a_n \frac{\Gamma(n+1)}{\Gamma(n+1-\alpha)}|^{\frac{1}{n}} = \limsup_{n \to \infty} |a_n|^{\frac{1}{n}}$$

which means that for the Maclaurin and tylor expansion of a function, the radius of convergence doesn't change, only the type of singularities at the center

While for the Laurent series, we have two sums which make the inner and outer convergence radius, they also follow the same rule, leaving them both unchanged, but for the $(-1)^{\alpha}$ terms, it means this won't be single valued in $\mathbb{C}$

9 variable order derivatives

since D^α operator extends to linear input, which is α, we can go further and extend it to different inputs as functions

9.1 function order derivatives

The simple function derivative is a function of another variable rather than the differentiated function variable,. The fundamental function is the linear function of alpha $D^\alpha x^n = \frac{\Gamma(n+1)}{\Gamma(n+1-\alpha)} x^{n-\alpha}$, of course, this function is what defines what type of differentiation we are doing, in other words in which direction we are going, as the main linear function α is for derivatives, when multiplied by negatives gives us $-\alpha$ which is for integrals. There exists αi, which represents imaginary differentiation. Then, we have $\alpha + \beta i$ for complex differentiation, which is a simple multivariable linear function.

So we know functional orders exist and change like the function depending on its type, and we can write their general formula like this

$$D^{g(\alpha)} x^n = \frac{\Gamma(n+1)}{\Gamma(n - g(\alpha) + 1)} x^{n - g(\alpha)}$$

We can try a simple example on this formula

$$g(\alpha) = \alpha^2, f(x) = x^2 \qquad D^{g(\alpha)} f(x) = \frac{\Gamma(2+1)}{\Gamma(2 - \alpha^2 + 1)} x^{2 - \alpha^2} = \frac{2}{\Gamma(3 - \alpha^2)} x^{2 - \alpha^2}$$

if we want to see when this function hits gamma pole we can put it in test

$$3 - \alpha^2 \leq 0 \qquad a^2 \geq 3 \qquad \sqrt{3} \geq a \geq -\sqrt{3} \quad \{3 - a^2 \in \mathbb{Z}\}$$

so this function has gamma poles when $\alpha \in \{\pm\sqrt{3}, \pm 2, \pm\sqrt{5}, \pm\sqrt{6}....\}$, other than that, there will be no gamma pole, so the expression is defined like this

$$D^{g(x)} f(x) = \frac{2}{\Gamma(\alpha^2 - 3)} x^{2 - \alpha^2} \quad \{\alpha \in [-\sqrt{3}, \sqrt{3}]\}$$

We can see that in general, the function isn't defined only when

$$n + 1 - g(\alpha) \leq 0 \qquad n + 1 \leq g(\alpha) \quad \{n + 1 - g(\alpha) \in \mathbb{Z}\}$$

another example that we can test on

$$g(\alpha) = \sin(\alpha), f(\alpha) = x^2 \quad D^{g(\alpha)} f(\alpha) = \frac{2}{\Gamma(3 - \sin(\alpha))} x^{2 - \sin(\alpha)}$$

This function is actually defined for all $\alpha \in \mathbb{R}$ as the range of this function is between $[-1, 1]$, the expression $D^{g(\alpha)} f(\alpha)$ ranges between the first derivative and the second derivative

9.2   self variable order derivatives

We can define a simple self variable order derivative as

$$D^x x^n = \frac{\Gamma(n+1)}{\Gamma(n+1-x)} x^{n-x}$$

However, we need to refine this expression further.
first we write x^{n-x} as $x^n e^{-x \ln(x)}$ for simpler calculations.
now we can use the series expansion for $e^{-x \ln(x)} = \sum_{k=0}^{\infty} \frac{(-1)^k x^k (\ln(x))^k}{k!}$ then we substitute it back

$$D^x x^n = \frac{\Gamma(n+1)}{\Gamma(n+1-x)} x^n \sum_{k=0}^{\infty} \frac{(-1)^k x^k (\ln(x))^k}{k!}$$

Analyzing this function, we can see that the function reaches it's peaks when $n > x$, as then the Gamma function would be for positives, and the power would be positive, to find where it hits zer,o we can solve for the equation

$$\frac{\Gamma(n+1)}{\Gamma(n+1-x)} x^{n-x} = 0$$

But looking at the function closely, there can only be one reason for it to happen. for any power of x it can never reach zero as there is no number that has a changing power will be zero, and when the numerator is zero of gamma poles, the function itself is non non-differentiable in the first place, leaving only the denominator, it can only reach zero when the gamma function hits zero, so we solve for the equation

$$n+1-x \le 0 \qquad n+1 \le x \quad (n+1-x \in \mathbb{Z})$$

only when x is bigger than or equal to $n+1$ and the result is an integer we get a gamma pole which leads to an infinity in the denominator leading to a zero , these are the zeros of the derivative

9.3   Nested differentiation

10   Integrals May I present

10.1   Where is the constant of integration?

As we saw from this whole paper, we can use D^z to differentiate and integrate Real, imaginary, or matrix, yet something seems to be missing.
The constant of integration, something so fundamental in calculus, yet seems to be missing
But here in fractional calculus, things are different; here we have a lot of "Differentiating" forward or backward, 2D or 3D, and a lot of directions that make it hard even to put it somewhere But at first, we need to understand why, not

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in standard terms, but in this research term

The constant of Integration is something that arises when integrating, that is, because under differentiation, we lose constants and variables according to the order

That is because of the definition of D^z, which transforms functions from one state to another.

take, for example, $f(x) = x^5 + 14$, from a prescriptive of stranded calculus, when we differentiate, constants are gone because they don't have any rate of change, the answer is simply

$$D^1 f(x) = 5x^4$$

But as we discussed, the rate of change isn't a core in the derivative but a side effect. To see the full picture, we need to use the whole Gamma formula with the knowledge that $C = Cx^0$

$$D^1 f(x) = \frac{\Gamma(6)}{\Gamma(5)} x^{5-1} + 14 \frac{\Gamma(1)}{\Gamma(0)} x^{0-1} = 5x^4 + \frac{14}{\Gamma(0)} x^{-1}$$

We can see that the denominator has a Gamma pole in it, which leads the whole term to be 0, taking the constant with it

In other words, differentiation, as we discussed, loses memory; the more it differentiates, the more it's gone

Integration is the exact opposite; it retains memory, and we can see that too from the standard calculus approach

$$D^{-1}(x^2) = \frac{x^3}{3} + C$$

We see that here the constant of integration is dependent on logic, the simple logic is that if we differentiate, we lose constants, then integration, the opposite of it must return them

Let's see what happens from the fractional derivatives point of view. First, we assume that there exists a pole $C\frac{\Gamma(1)}{\Gamma(0)} x^{-1}$ that went to zero, which is in the range of possibility

$$D^{-1}(x^2) = \frac{\Gamma(3)}{\Gamma(4)} x^{2-(-1)} + C\frac{\Gamma(1)}{\Gamma(0)} \frac{\Gamma(0)}{\Gamma(1)} x^{-1-(-1)}$$

We can see that both fractions cancel out, leaving only Cx^0, which is C

$$D^{-1}(x^2) = \frac{x^3}{3} + C$$

We can see that this works mathematically here, no matter how many constants may be there, all of them will simply add up under the term x^0

That is, of course, with one problem, there are infinite Gamma poles; whenever the denominator hits a non-positive integer, it hits a pole, we can't really make

sure if the gamma pole was at the second derivative, or the tenth, the memory of the functions is wide, and for that we need to define two categories of derivatives

Pure derivatives: these are derivatives that don't hold any memory.
Memory derivatives: these are functions that hold memory and can be separated into three:

1. **Memory stated functions:** functions that have a stated amount of change in order of D^z

2. **Always existed functions:** functions that have an infinite series of memory

3. **Application derivatives:** where the constant exists if and only if it satisfies the required equation or does not make any change to it (Although doubtful since any change in the function will lead to a change in the derivative)

11 So what is D^z in the first place

11.1 So how are rectangles and the rate of change in the same object

The classic idea behind derivatives is that they are a rate of change, as we zoom to an infinitesimal value to keep track of how the function changes, we do it again, and we get the rate of change of the rate of change of that function
Then we have integrals, which calculate the area under the curve, and later we got the rectangle's definition of integrals by the hands of Georg Riemann, followed by the Lebesgue integral from Henri Lebesgue
Although up till this point the differentiation operation was "Discrete", it was proven that they are opposites of each other, but the operation itself was working only when we differentiate a natural number of times or an integer. If we consider the integrals, the -1 of the derivatives at this time, although it wasn't strictly necessary
Then there comes fractional calculus, and we need to define what a half derivative is from a function's perspective, is it a rate of change? Is it some sort of summation? quite both
to understand what I mean, we need to take a look at this $\sin(x)$ first antiderivative

$$\sin(x) = x - \frac{x^3}{3!} + \frac{x^5}{5!} - .... = \sum_{n=0}^{\infty} \frac{x^{2n+1}}{(2n+1)!}$$

$$\int \sin(x) = -\cos(x) + C \implies \int x - \int \frac{x^3}{3!} + \int \frac{x^5}{5!} - .... = \int \sum_{n=0}^{\infty} \frac{x^{2n+1}}{(2n+1)!} = \sum_{n=0}^{\infty} \frac{x^{2n+2}}{(2n+2)!}$$

We can then take 2 as a common factor and let $k = n+1$ to get an exact $\cos(x)$ infinite sum

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The main idea here is that when applying this integral, we have two different ways: one is via limits and infinite sums under the curve, the other is by applying it one by one in each term of its expansion.

But the approach we are using here for fractional derivatives prefers to use the infinite sum method most of the time, which is why saying it's only the rate of change or is an area under the curve won't make much sense; instead, we can say that

The derivative/integral operation is done in different parts of the function simultaneously; it doesn't work on the function as a whole, but rather small parts of it one by one, not any parts but the essence functions this is made of, and we can see this definition returning the same result as the other definitions

from the path of Integral to derivative when we integrate the function 2 times we add 3D rectangle prisms, then if we move smoothly to the first integral we are working on one part of this 3D shape; we make it the scope, so we do one change with different effects but all relates to the same 3D object, local change with global effect, zooming more to the function itself, from the 2D shape we choose one line from all the lines that make it, only then we get the function itself, the first derivative we makes us choose one point from this lane, and the second one we choose building block of a point, which we cant go further than that, which sorts of explains the over differentiation problem with x^n, even we have shape of x^3 this doesnt break as there is still room for expansion

from the path of the derivative to the integral we are calculating by adding up area, likewise in a smooth way, adding points, then lines, then rectangles

Then, for the fractional derivatives, we actually have two perspectives that are both not wrong

The First explanation goes like this:

We can go by adding small rectangles under the function, changing to add 3D rectangular prisms, and in the way we are still adding rectangles, but not in a whole dimension, as rectangular prisms as the 3D definition of rectangle and the 2D one is simple a rectangle, and lines are the 1D definition, we are adding rectangles but in α-D dimensions, this is either because the dimensions themselves change as in 2D we are would need one input for the function but when the dimension change we force another input, or we are getting the function itself with inputs and add or delete them from inside the function without any forces

(of course, this is only a geometric definition, as we can add as many inputs as outputs without changing dimension, but the rules here hold there), Both explanations of this have different interpretations, as when the dimension changes, we don't necessarily need to force new input variables; we can simply make it a double integral, and now we are calculating 3D cubes made out of 2D rectangles, the same thing can happen here, we can calculate the area under function $f(x)$ when we are in a 1.5D dimension using equal sides shapes that are from this dimension nature

But if we said that the function itself transcends to that dimension, we can add as many inputs as we want for whatever reason, it's that which changes how

the function reacts to see how it adapts to this dimension

The other Explanation : is that this simply is a memory effect of the change in the function

To put it simply, we can imagine it as a time freeze scene, a moving car, an image from when it didn't move, an image when the engine starts, and an image when it moves. It works something like

Fractional derivatives aren't the image from when the engine is working; it is a wider image, where it has some parts from the moving image and some parts from the stopping image, and the image when the engine works

Either way, we can agree that the derivative operator transforms a function, not necessarily by stretching or rotating, but by making a local change that affects the global function nature, which is applied in most cases in simple, clean arithmetic and infinite products

11.2   The other orders of differentiation

With the product definition of $D^z x^n$, we get introduced to other types of orders that aren't necessarily $\alpha \in \mathbb{R}$, like:

Complex orders: here we have two separate components the real part α and the imaginary part βi and both of them work differently

α is the one responsible for the normal differentiation part while βi is responsible for the rotation and oscillation of the function

to understand more, we are going to make an imaginary $x - y - i$ plot, like $x - y - z$ but with the imaginary variables

When $\beta = 0$, we have the normal function of ours with its normal differentiation process; however,w hen we have $\beta \neq 0$ we have different values of input,all controlling the same graph, we can imagine them as the image of every input being a rotation on the i-axis, when compressed we get this weird image of $D^\alpha x^n$, that is for one order, when β gets greater the oscillations compress more and more to small oscillation patterns and make more noise on the function

much or less, it's quite hard to imagine a change in βi geometrically, it's not simply built up or focused on like real parts, it's more like noise getting added to the function, more noise the more we get far from the Real number line

Matrix order: this one is a matrix-level operation, and instead of focusing only on how the function $f(x)$ changes when α changes, this one focuses on multiple dimensions and directions, this one transforms in space on multiple dimensions

we can imagine this by imagining the function $f(x)$ with it's expansion or the polynomials that form it; this matrix order A can perform local change in multiple directions with a global change

$D^A f(x)$ will allow the function to return $n \times n$ outputs, which means that instead of four functions we can compress them in n directions and n permaters, so it's not simple $f : \mathbb{R} \to \mathbb{R}$ but rather a complicated $n \times n$ function

11.3 How does order multiplication work geometrically

12 Compression to original fractional derivative work

The author started this work without having prior knowledge of this field, and since the moment I knew it existed, I decided to continue my framework anyway And now, I make this compression between known literature and my framework This comparison focuses on conceptual differences rather than exhaustive coverage."

12.1 Riemann–Liouville integral

One, if not the first, definition of fractional calculus.
The Riemann–Liouville definition shaped how fractional derivatives are now; it works using iterated integration

$$I^\alpha f(x) = \frac{1}{\Gamma(\alpha)} \int_a^x f(t)(x-t)^{\alpha-1} dt \qquad \{\alpha \in \mathbb{C}, Re(\alpha) > 0, f : \mathbb{R} \to \mathbb{R}\}$$

This definition works for any analytic function that is locally integrable, and a here represents a freedom but fixed point.
I^1 here represents the first Anti-derivative of the function $f(x)$
We can get the fractional derivative $D^\alpha f(x)$ from this formula

$$D_x^\alpha f(x) = \begin{cases} \frac{d^{\lceil \alpha \rceil}}{dx^{\lceil \alpha \rceil}} I^{\lceil \alpha \rceil - \alpha} f(x) & \alpha > 0 \\ f(x) & \alpha = 0 \\ I^{-\alpha} f(x) & \alpha < 0 \end{cases}$$

the motivation for this definition that started to field was some questions between Leibniz and L'Hôpital in the 17th, but then Joseph Liouville started working on the idea in 1830s using Cuchy's formula for n-integrals
the fundamental proprieties for this definition hold

$$\frac{d}{dx} I^{\alpha+1} f(x) = I^\alpha f(x) \qquad I^\alpha(I^\beta f(x)) = I^{\alpha+\beta} f(x)$$

this definition had the propriety of "change between constants"; which means that $I^\alpha C$ where C is a constant doesn't always return 0 we can use this to calculate four functions that are going to be used for compression later

$$I^\alpha x^n = \frac{1}{\Gamma(\alpha)} \int_a^x t^n (x-t)^{\alpha-1} dt = \frac{\Gamma(n+1)}{\Gamma(n+1+\alpha)} x^{n+\alpha}$$

$$I^\alpha e^{ax} = \frac{1}{\Gamma(\alpha)} \int_a^x e^{at}(x-t)^{\alpha-1} dt = \frac{e^{ax}}{a^\alpha}$$

$$I^\alpha a^x = \frac{1}{\Gamma(\alpha)} \int_a^x a^t (x-t)^{\alpha-1} dt = \frac{a^x}{\ln(a)^\alpha}$$

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$$I^\alpha \sin(x) = \frac{1}{\Gamma(\alpha)} \int_a^x \sin(t)(x-t)^{\alpha-1} dt = \sin(x - \frac{\alpha\pi}{2})$$

Evaluating these functions step by step will take so much space and use integrals that are outside the scope of this paper, like the Beta integral; so we are going to use the known results directly

12.2 Caputo definitions and initial conditions

Motivated by Riemann-Liouville's integral, we get the Caputo definition of fractional derivatives, which is

$$^C D_x^\alpha f(x) = \frac{1}{\Gamma(\lceil\alpha\rceil - \alpha)} \int_0^x \frac{f^{\lceil\alpha\rceil}(t)}{(x-t)^{\alpha+1-\lceil\alpha\rceil}} dt$$

This definition has the initial condition of fulfilling $D^\alpha x^n = 0$ where $\alpha > n$ and fulfilling the Index law $D^\alpha D^\beta = D^{\alpha+\beta}$ when $\beta \in \mathbb{Z}$, while not always fulfilling commutativity only when $\lceil\alpha\rceil = \lceil\beta\rceil$

This definition can also be obtained from the Reinmann-Livoulis integral with this relationship

$$_a^C D_x^\alpha [f(x)] = {}_a^{RL} D_x^\alpha [f(x)] - \sum_{k=0}^{\lfloor\alpha\rfloor} \left[\frac{x^{k-\alpha}}{\Gamma(k-\alpha+1)} \cdot f^{(k)}(0) \right]$$

where a changes the domain of the integral from $(0, \infty) \to (a, \infty)$

12.3 The comparison

The definition this research uses is motivited by the idea of a space where the function and its derivative exist, which leads to the need for a fractional derivative, starting from the formula $D^m x^n = {}^n P_m x^{n-m}$ where $n, m \in \mathbb{Z}$ then extending using Γ function for non-integral values and applying to the functions via their series expansion

The following comparison highlights conceptual and operational differences between classical fractional derivatives and the framework developed in this work. The comparison focuses on domain requirements, algebraic properties, initial conditions, and analytic behavior

Property	Riemann–Liouville	Caputo	This work
Function class	L^1_{loc}	C^n	Analytic / series-expandable
Definition type	Integral (nonlocal)	Integral of derivatives	Algebraic continuation
$D^\alpha C$	$\neq 0$	$= 0$	Depends on series representation
Initial conditions	Fractional	Classical	Implicit via coefficients
Commutivity property	Yes (restricted)	Partial	Yes (formal series)
Field of order	$\mathbb{R}, \mathbb{C}$	$\mathbb{R}, \mathbb{C}$ but Limited	Any abelian group $(G, +)$
Locality	Nonlocal	Nonlocal	Local in coefficient space

Table 1: Comparison between classical fractional derivatives and the proposed framework

Unlike Riemann–Liouville and Caputo derivatives, which are defined through nonlocal integral operators, the definition adopted in this work is constructed through algebraic continuation of integer-order differentiation. This leads to a framework naturally suited for analytic functions and series representations, at the cost of requiring stronger regularity assumptions. While this approach does not directly encode classical initial conditions, it provides a transparent extension to complex, matrix, and higher-order derivative operators.

13 Combinations

13.1 the fractional derivative of x!

13.2 the fractional derivative of permutations and combinations

14 Differential equations

14.1 Bessel functions

14.2 Hermite polynomials

14.3 Legendre polynomials

14.4 Hyper geometric functions

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