D-modules Techniques for Feynman Integrals

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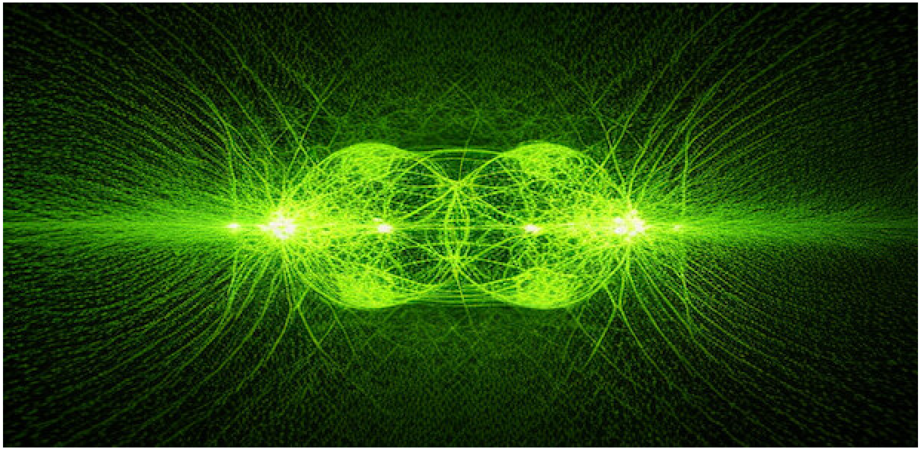
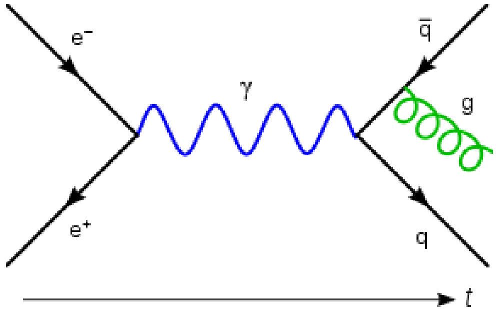


Overview

- Scattering amplitudes to PDEs
- D-modules: why are they useful?



This presentation is based on joint work with Johannes Henn, Anna-Laura Sattelberger, and Simone Zoia, available at https://arxiv.org/abs/2303.11105.

Scattering Amplitudes to PDEs

Observation 1: A scattering amplitude is a sum over Feynman integrals

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Idea: What if we exploited symmetry to find some differential equations that the integrals satisfy, and solve those?

Encoding Symmetry Using PDEs

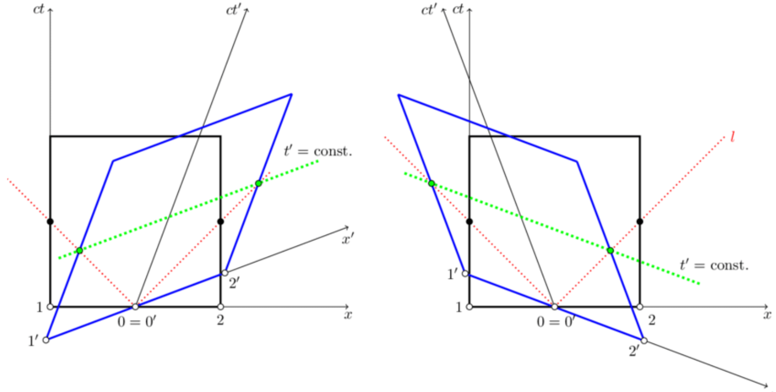
Example (Dilation in two variables)

Observe that by Taylor expansion,

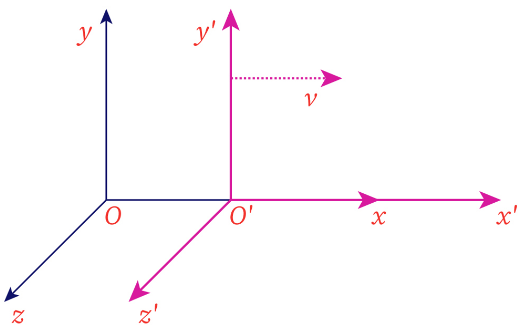
$$f((1+\epsilon)x, (1+\epsilon)y) = f(x,y) + \epsilon\left(x\frac{df}{dx} + y\frac{df}{dy}\right) + O(\epsilon^2).$$

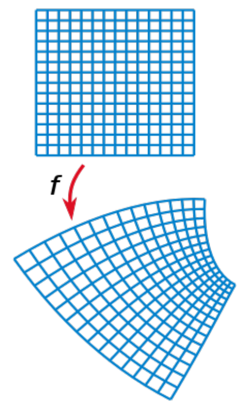
Thus $f(x,y)$ is invariant under infinitesimal dilation whenever $T(x) := x\frac{d}{dx} + y\frac{d}{dy}$ annihilates $f(x,y)$. Solutions are $\frac{x}{y}$, etc.

The scattering amplitude will be annihilated by these differential operators.



(a) (b)



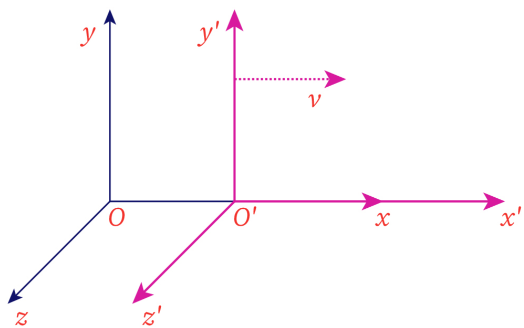


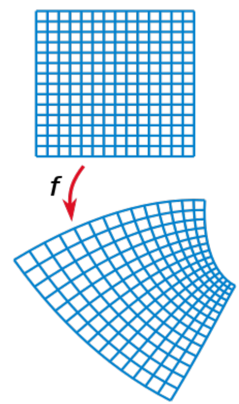
Functions of these particles which are physically meaningful should be invariant under *conformal* (or angle-preserving) transformations.

PDEs for Conformal Symmetry

After translating from position to momentum space, the full list of operators that capture conformal symmetry is

- Translation: $P_\mu = \partial_\mu$
- Lorentz transformations: $M_{\mu\nu} = p_\mu \partial_\nu - p_\nu \partial_\mu$
- Dilation: $D_\Delta = -i\left(p^\mu \partial_\mu + \Delta\right)$
- Special conformal boosts: $K^\mu_\Delta = i\left(p^2 \partial^\mu - 2p^\mu p^\nu \partial_\nu - 2\Delta p^\mu\right)$





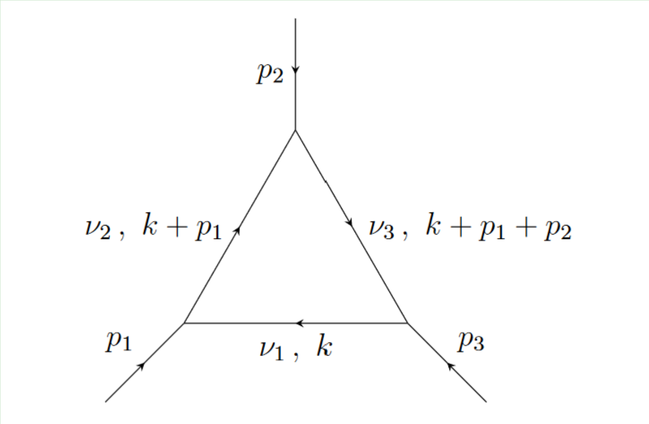
PDEs to D-modules

Example (Triangle Feynman integral)

Conformally invariant functions of three particles are annihilated by

$$\begin{aligned} P_1 &= 4(x_1\partial_1^2 - x_3\partial_3^2) + 4(\partial_1 - \partial_3), \\ P_2 &= 4(x_2\partial_2^2 - x_3\partial_3^2) + 4(\partial_2 - \partial_3), \\ P_3 &= x_1\partial_1 + x_2\partial_2 + x_3\partial_3 + 1. \end{aligned}$$

with the change of coordinates $x_1 = p_1^2$, $x_2 = p_2^2$, and $x_3 = p_1 \cdot p_2$.



Main result

Theorem (Henn-P.-Sattelberger-Zoia)

The series solutions to the triangle Feynman integral are

$$\begin{aligned}
\tilde{f}_1(y_2,y_3) &= 1 + y_2 + y_3 + y_2^2 + 4y_2y_3 + y_3^2 + y_2^3 + 9y_2^2y_3 + y_2^4 + \cdots, \\
\tilde{f}_2(y_2,y_3) &= \log(y_2) + \log(y_2)y_2 + (2+\log(y_2))y_3 + \log(y_2)y_2^2 + (4+4\log(y_2))y_2y_3 \\
&\quad + (3+\log(y_2))y_3^2 + (\log(y_2))y_2^3 + (6+9\log(y_2))y_2^2y_3 + \cdots, \\
\tilde{f}_3(y_2,y_3) &= \log(y_3) + (2+\log(y_3))y_2 + \log(y_3)y_3 + (3+\log(y_3))y_2^2 \\
&\quad + (4+4\log(y_3))y_2y_3 + \log(y_3)y_3^2 + \left(\frac{11}{3}+\log(y_3)\right)y_2^3 \\
&\quad + (15+9\log(y_3))y_2^2y_3 + \left(\frac{25}{6}+\log(y_3)\right)y_2^4 + \cdots, \\
\tilde{f}_4(y_2,y_3) &= \log(y_2)\log(y_3) + (-2+2\log(y_2)+\log(y_2)\log(y_3))y_2 \\
&\quad + (-2+2\log(y_3)+\log(y_2)\log(y_3))\,y_3 \\
&\quad + \left(-\frac{5}{2}+3\log(y_2)+\log(y_2)\log(y_3)\right)y_2^2 \\
&\quad + (-6+4\log(y_2)+4\log(y_3)+4\log(y_2)\log(y_3))\,y_2y_3 + \cdots.
\end{aligned}$$

where $y_2 = \frac{x_1}{x_2}$, $y_3 = \frac{x_1}{x_3}$.

D-modules

Q: How to we understand systems of linear PDEs algebraically?

Definition (D-module)

The *nth Weyl algebra*, denoted D_n or D, is the $\mathbb{C}$-algebra

$$D := \mathbb{C}[x_1, \ldots, x_n]\langle \partial_1, \ldots, \partial_n \rangle,$$

where all generators commute except ∂_i and x_i, which satisfy the "Leibniz rule"

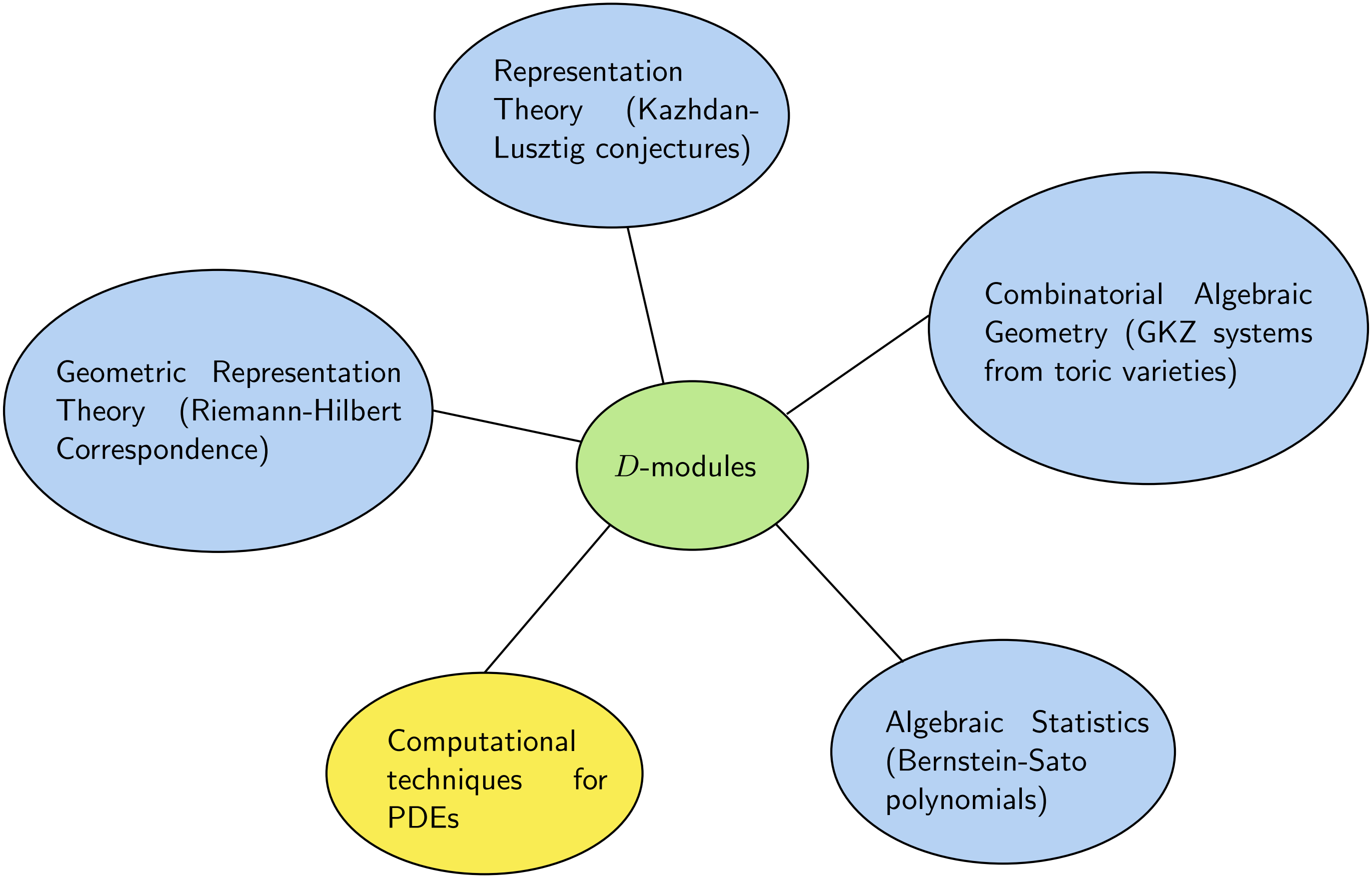
$$[\partial_i, x_i] = \partial_i x_i - x_i \partial_i = 1.$$

A D-module is a module over the Weyl algebra.

Example

Let I be any left D-ideal. Then D/I is D-module.

Why Are D-modules Cool?



Why Are D-modules Useful for PDEs?

Suppose your D-ideal is *holonomic*. Then one can compute:

- The number of linearly independent holomorphic solutions in a simply connected neighborhood of a generic point (the *holonomic rank*)

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- Where your solutions can have singularities (the *singular locus*)
- Solutions in the form of series expansions

An Example in Macaulay 2

```
i3 : R = QQ[x1, x2, x3]; D = makeWA R;

i5 : q_1 = 4*(x1*dx1^2-x3*dx3^2) + 4*(dx1 - dx3);

i6 : q_2 = 4*(x2*dx2^2-x3*dx3^2) + 4*(dx2 - dx3);

i7 : q_3 = x1*dx1 + x2*dx2 + x3*dx3 + 1;

i8 : I = ideal{q_1, q_2, q_3}
```

```
i9 : isHolonomic(I)

o9 = true

i10 : holonomicRank(I)

o10 = 4

i11 : singLocus(I)

                3            2   2           3         2      2
o11 = ideal(x1 x2*x3 - 2x1 x2 x3 + x1*x2 x3 - 2x1 x2*x3  -
      -----------------------------------------------------
            2   2           3
      2x1*x2 x3  + x1*x2*x3 )
```

Singular Locus

Here Sing(I) is the union of a cone and the hyperplanes $x_i = 0$.

Sing$(I) = \{x_1x_2x_3(x_1^2 + x_2^2 + x_3^2 - 2x_1x_2 - 2x_1x_3 - 2x_2x_3) = 0\}$.

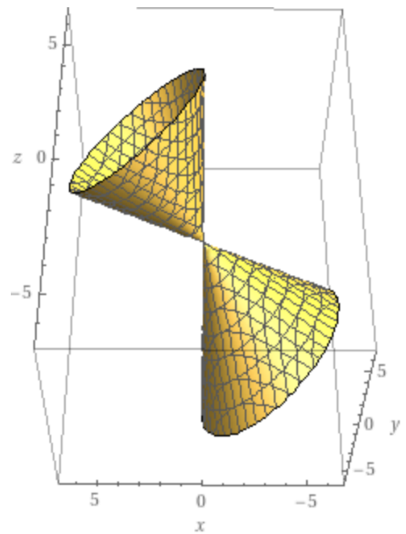


Figure 1: Hypersurface $x_1^2 + x_2^2 + x_3^2 - 2x_1x_2 - 2x_1x_3 - 2x_2x_3$

Solving differential equations?

Q: Given an ODE, how to obtain series solutions?

Example (Frobenius algorithm)

Let $P = \partial^2 + 1$ and guess the solution is of the form $f(x) = \sum_n a_n x^n$. Then we get

$$\begin{aligned} 0 &= P \cdot f(x) \\ &= \sum_n n(n-1) a_n x^{n-2} - \sum_n a_n x^n \\ &= \sum_n (n+2)(n+1) a_{n+2} x^n - \sum_n a_n x^n \\ &= \sum_n ((n+2)(n+1) a_{n+2} - a_n) x^n. \end{aligned}$$

So $a_{n+2} = \frac{1}{(n+1)(n+2)} a_n$, and plugging in initial values we recover the power series for $\sin(x), \cos(x)$.

The SST (Saito, Sturmfels, Takayama) algorithm

Inputs:

- A regular holonomic D-ideal I
- A direction w to expand in, which is in the interior of a Gröbner cone C_w of I

Output:

- A list of starting monomials
- For each starting monomial $x^A \log(x)^B$, with $A \in \mathbb{C}$ and $B \in \mathbb{Z}$, a *Nilsson series*

$$x^A \sum_{p,\ 0 \leq b_i \leq \mathrm{rk}(I) \in \mathbb{Z}} c_{pb} x^p \log(x)^b$$

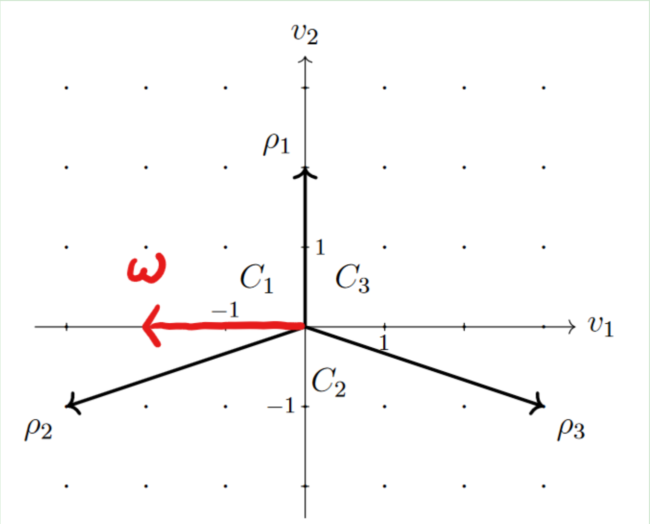
which converges for z such that $(-\log(|z_1|), ..., -\log(|z_n|))$ is in a translate of C_w^*.

Source: Gröbner Deformations of Hypergeometric Differential Equations (Mutsumi Saito, Bernd Sturmfels, Nobuki Takayama)

Example of SST

Example (Scattering function of three particles)

The Gröbner fan lives in $\mathbb{R}^3/\mathbb{R}(1,1,1)$ and looks like



The starting monomials are:

$$x_1^{-1},\ x_1^{-1}\log\left(\frac{x_1}{x_2}\right),\ x_1^{-1}\log\left(\frac{x_1}{x_3}\right),\ x_1^{-1}\log\left(\frac{x_1}{x_2}\right)\log\left(\frac{x_1}{x_3}\right).$$

Main result

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Solutions from physics:

$$f_1(x_1,x_2,x_3) = \frac{1}{\sqrt{\lambda}}\Big[\mathrm{Li}_2(\tau_2) + \mathrm{Li}_2(\tau_3) + \frac{\pi^2}{6} + \frac{1}{2}\log\left(\frac{\tau_3}{\tau_2}\right)\log\left(\frac{1-\tau_3}{1-\tau_2}\right) + \frac{1}{2}\log(-\tau_2)\log(-\tau_3)\Big],$$

$$f_2(x_1,x_2,x_3) = \frac{1}{\sqrt{\lambda}}\log\left(\frac{x_1-x_2-x_3-\sqrt{\lambda}}{x_1-x_2-x_3+\sqrt{\lambda}}\right),$$

$$f_3(x_1,x_2,x_3) = \frac{1}{\sqrt{\lambda}}\log\left(\frac{x_2-x_1-x_3-\sqrt{\lambda}}{x_2-x_1-x_3+\sqrt{\lambda}}\right),$$

$$f_4(x_1,x_2,x_3) = \frac{1}{\sqrt{\lambda}},$$

where

$$\tau_2 = -\frac{2x_2}{(x_1-x_2-x_3-\sqrt{\lambda})}, \quad \tau_3 = -\frac{2x_3}{(x_1-x_2-x_3-\sqrt{\lambda})}.$$

Outlook

- Can D-module techniques be used to find scattering amplitudes of systems with more particles? (Involves finding more differential equations)
- Can we use SST to catalogue series expansions of multivariate functions?

Thanks for listening!