Graphical functions applied to ϕ^3 in $D = 6$

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joint work with Oliver Schnetz

Motivation

Quantum Field theory

- Objects of interest: Correlation functions

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- $G(x_1, x_2, x_3) \in V \Rightarrow$ substructure at each point (e.g. spin).
- Arbitary number of points can be correlated $G(x_1, x_2, x_3, \ldots)$.

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$$G(x_1, x_2, x_3) = G_0(x_1, x_2, x_3) + \hbar G_1(x_1, x_2, x_3) + \hbar^2 G_2(x_1, x_2, x_3) + \ldots$$

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- Each $G_n(x_1, x_2, x_3)$ can be written as a sum over graphs:

$$G_n(x_1, x_2, x_3) = \sum_{\substack{\Gamma \\ \chi(\Gamma)=1-n}} \varphi(\Gamma)$$

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- The graphs are called Feynman graphs. The integrals are called Feynman integrals, the function φ is called Feynman rule.

Algebraic integrals: Periods

- The Feynman integrals are except for the dependence on the physical input algebraic integrals:

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- For small graphs this number is mostly a linear combination of multiple zeta values.
- There exists various number theoretic conjectures on the period: Coaction conjecture, Cosmic galois group, Motives etc.

Two viewpoints

Momentum space ⟷ (Fourier) ⟷ Position space

Correlation functions are parametrized by the momentum of particles

Correlation functions are parametrized by the position of particles

Why position space?

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Advantages

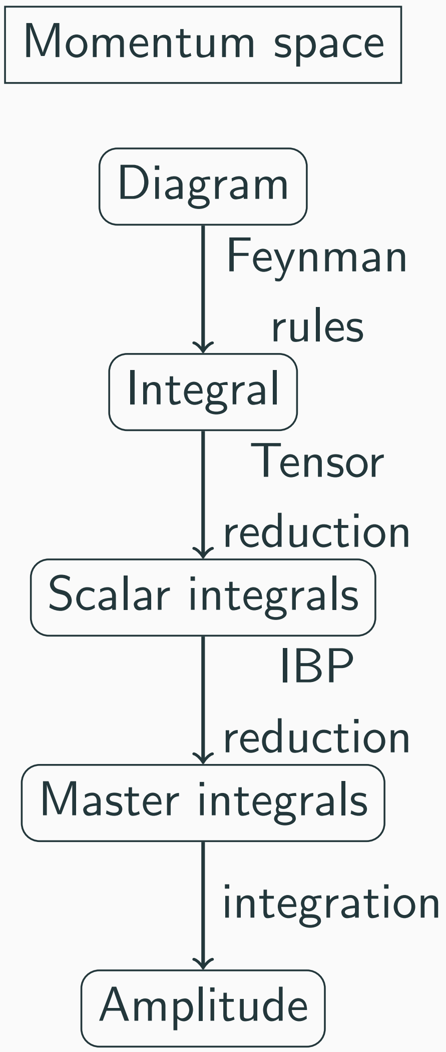
- Simpler Feynman rules
- No IBP reduction necessary
- Conceptually interesting viewpoint

Caveats

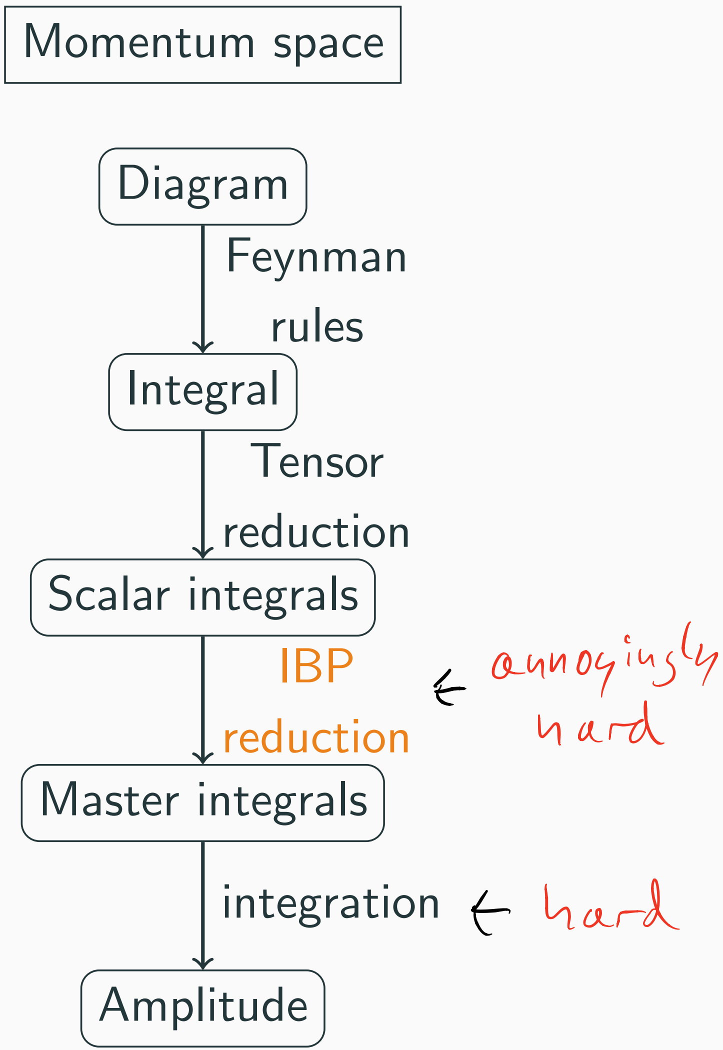
- New technology needed
- Only position space quantities accessible

Proof of concept:
7-loop β-function in ϕ^4 calculated in 2016 by Oliver Schnetz using graphical functions.

Loop integral workflow



Loop integral workflow



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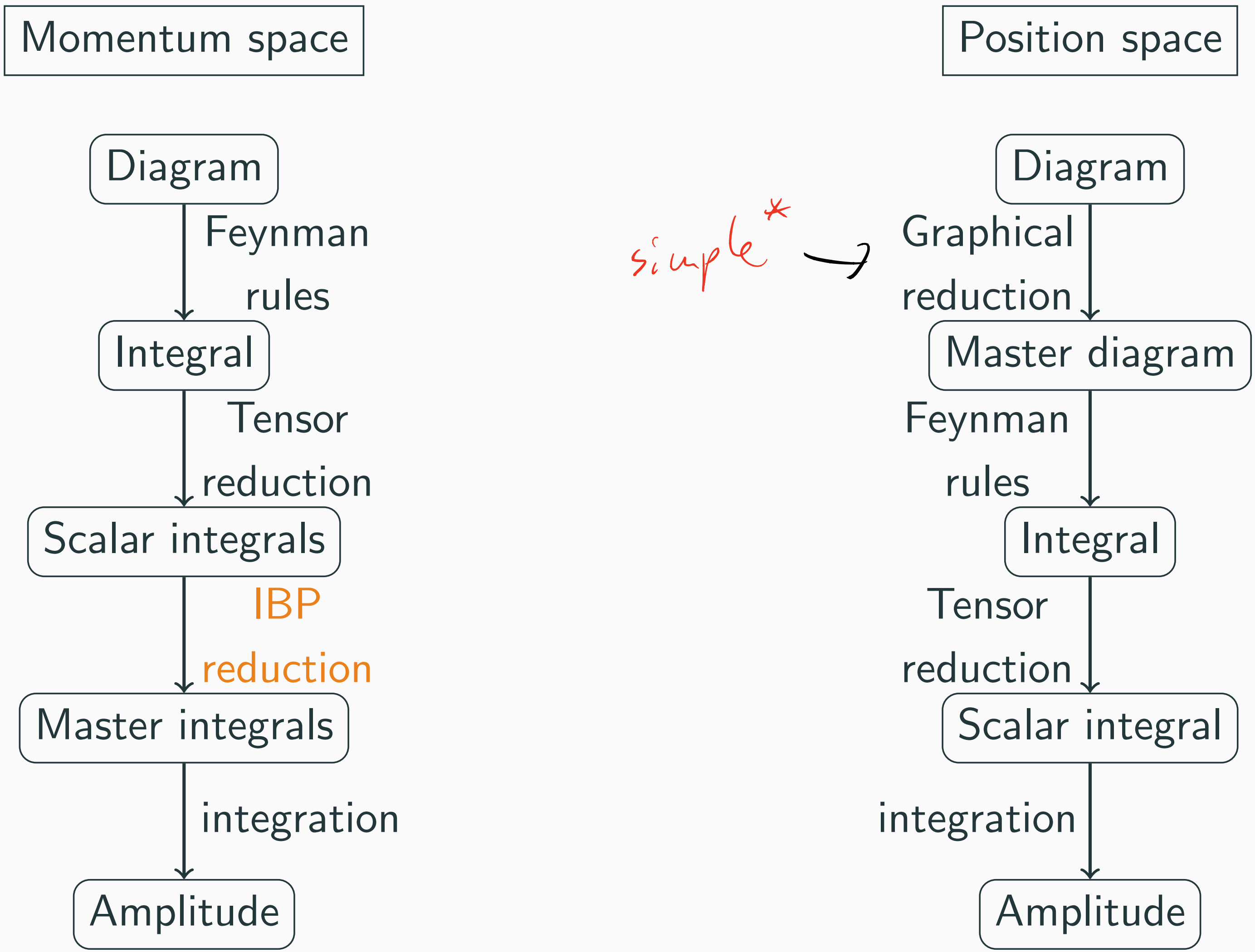

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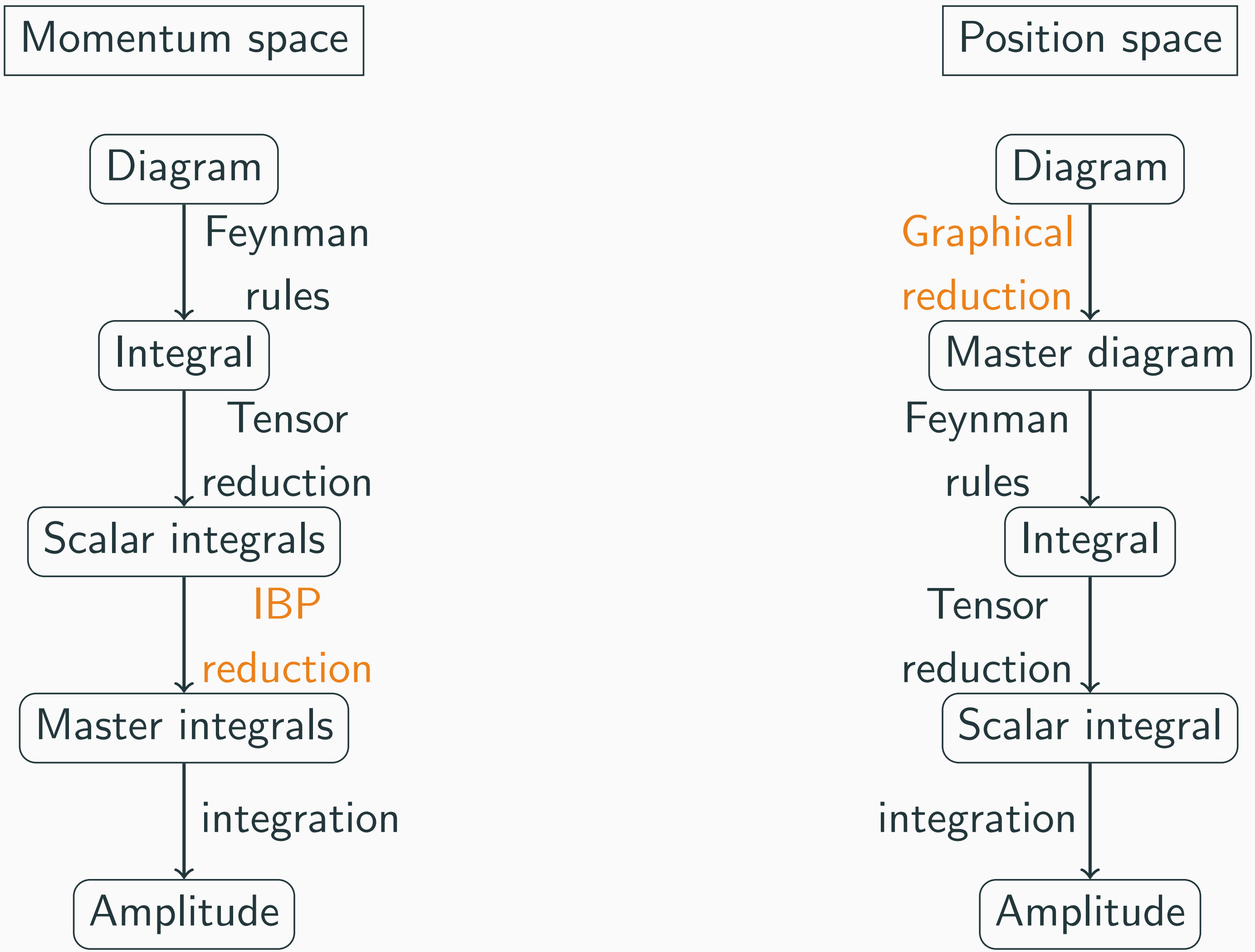


Feynman integral in momentum space

$$\widetilde{G}(p_1, \ldots, p_n) = \left(\prod_{e \in E} \int d^D k_e \widetilde{\Delta}(k_e) \right) \underbrace{\left(\prod_{v \in V_{\text{int}}} \delta^{(D)} \left(\sum_{e \ni v} k_e \right) \right)}$$

Lower dimensional integral

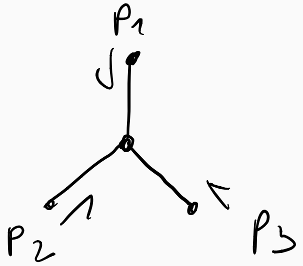
Feynman integral in position space

$$G(x_1, \ldots, x_n) = \left(\prod_{v \in V_{\text{int}}} \int d^D x_v \right) \underbrace{\left(\prod_{\{a,b\} \in E} \Delta(x_a - x_b) \right)}$$

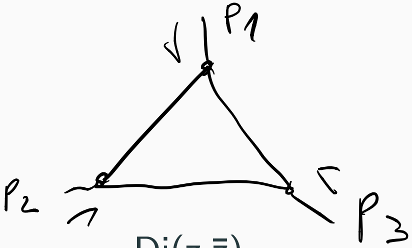
Better factorization properties

Examples

Momentum space



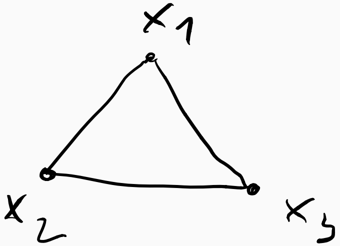
$\widetilde{\Delta}(p_{12})\widetilde{\Delta}(p_{23})\widetilde{\Delta}(p_{31})$



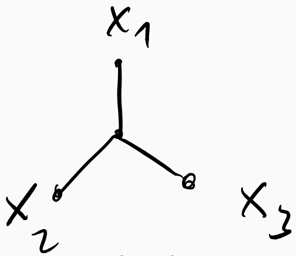
$$\frac{\mathrm{Di}(z,\bar{z})}{\sqrt{-\lambda(p_{12}^2,p_{23}^2,p_{31}^2)}}$$

$$\tilde{\Delta}(p) = \frac{1}{\|p\|^2}$$

Position space



$\Delta(x_{12})\Delta(x_{23})\Delta(x_{31})$



$$\frac{\mathrm{Di}(z,\bar{z})}{\sqrt{-\lambda(x_{12}^2,x_{23}^2,x_{31}^2)}}$$

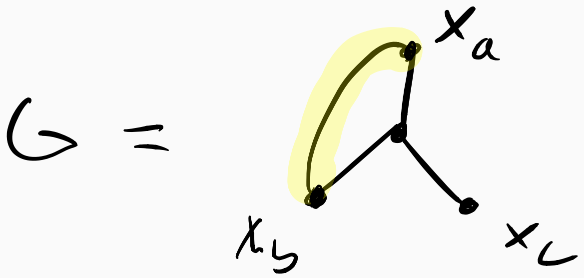
$$\Delta(x) = \frac{1}{\|x\|^2}$$

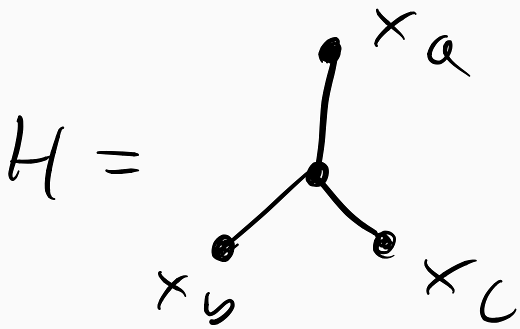
Graphical reductions

Graphical reduction rules

1. rule: propogators between external vertices

$$G(x_a, x_b, x_c) = \int d^D y \Delta(x_a - y)\Delta(x_b - y)\Delta(x_c - y)\Delta(x_a - x_b)$$
$$= \Delta(x_a - x_b) H(x_a, x_b, x_c)$$

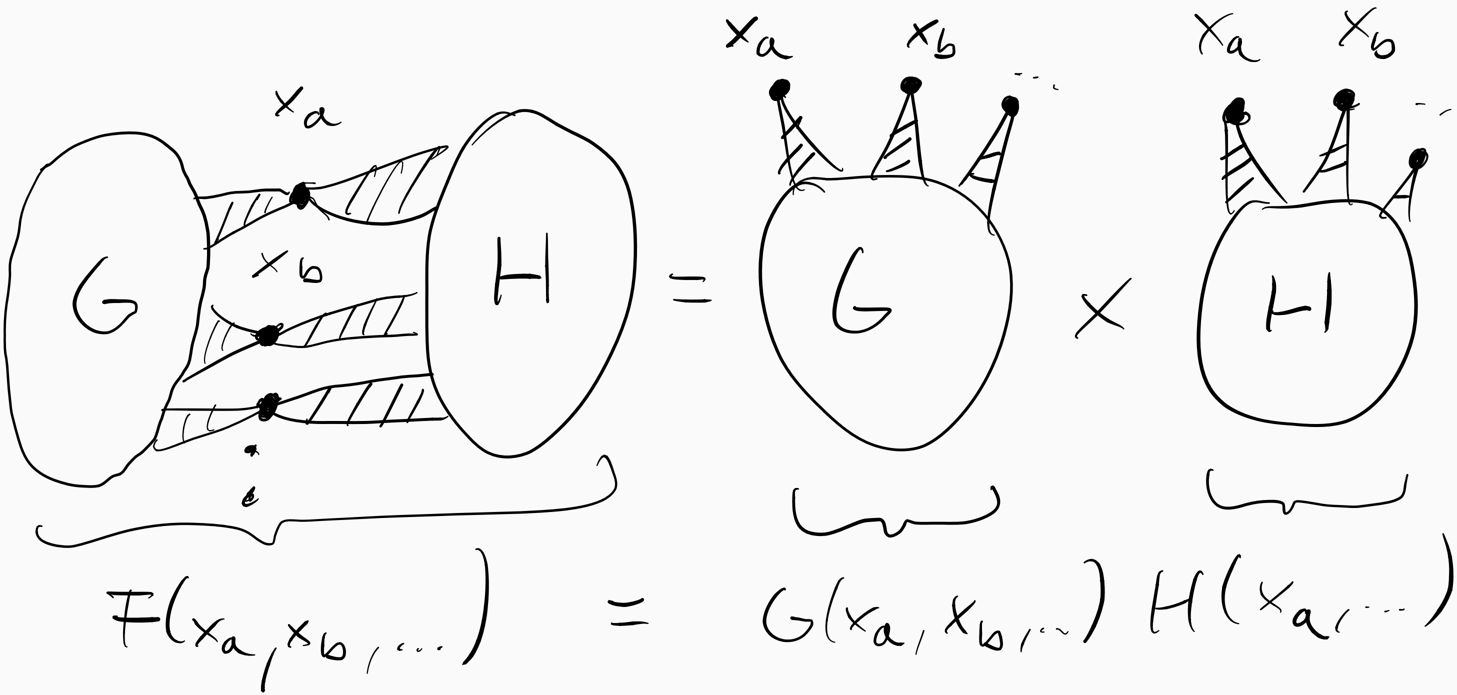




⇒ edges between external vertices factorize.

Graphical reduction rules

2. rule: split graph



⇒ factorizes if split along external vertices.

Graphical reduction rules

Intermezzo: amputating a propagator

Recall the definition of the propagator, Δ, as *Green's function for the free field equation*

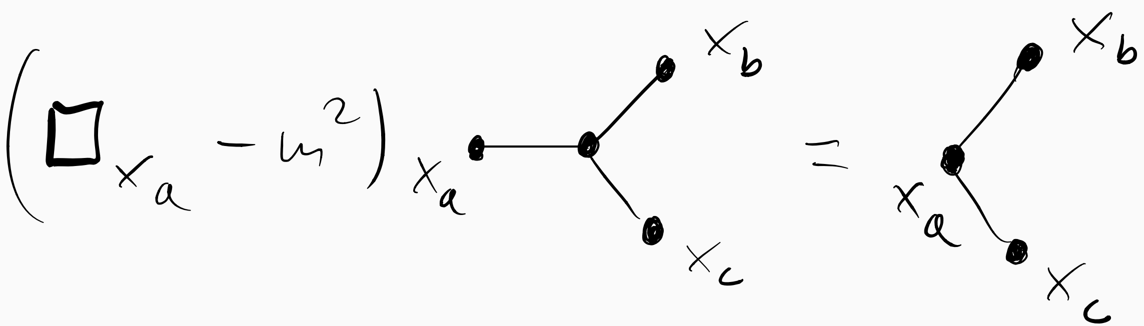
$$(\Box_x - m^2)\Delta(x-y) = \delta^{(D)}(x-y)$$

We can use this equation to *amputate* free external edges.

Graphical reduction rules

3. rule: amputating an external edge

$$(\Box_{x_a} - m^2)G(x_a, x_b, x_c) = \int d^D y(\Box_{x_a} - m^2)\Delta(x_a - y)\Delta(x_b - y)\Delta(x_c - y)$$
$$= \int d^D y \delta(x_a - y)\Delta(x_b - y)\Delta(x_c - y)$$
$$= \Delta(x_b - x_a)\Delta(x_c - x_a) = H(x_a, x_b, x_c)$$



$\Rightarrow$ solve differential equation to add external edge.

Differential equations

For rule 3, a differential equation needs to be solved:

$(\Box_{x_a} - m^2) G$  $(x_a, \ldots) = G$  $(x_a, \ldots)$

Can be solved systematically if (Schnetz 2013)

- particles are massless, $m = 0$,
- only 3-point functions are considered
- in $D = 4 - \epsilon$ Euklidean space.

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Related approach: (Drummond, Henn, Smirnov 2007) (Magic identities)

3-point configuration space is 2-dimensional, due to Poincare and scaling invariance:

$$G(x_a, x_b, x_c) = G(x'_a, x'_b, x'_c)$$

for

$$x'^{\,\mu}_k = \Lambda^\mu_\nu x^\nu_k$$
$$x'^{\,\mu}_k = v^\mu + x^\mu_k$$

with $\Lambda \in \mathrm{SO}(D)$ and $v \in \mathrm{R}^D$ and

$$G(\lambda x_a, \lambda x_b, \lambda x_c) = \lambda^\omega G(x_a, x_b, x_c).$$

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$$G(\lambda x_a, \lambda x_b, \lambda x_c) = \lambda^{\omega} G(x_a, x_b, x_c).$$

$\Rightarrow$ G only depends on the shape of the triangle spanned by x_a, x_b, x_c.

Exploit this symmetry by using complex paramater z such that

$$z\,\bar{z} = \frac{x_{ac}^2}{x_{ab}^2} \quad \text{and} \quad (1 - z)(1 - \bar{z}) = \frac{x_{bc}^2}{x_{ab}^2}$$

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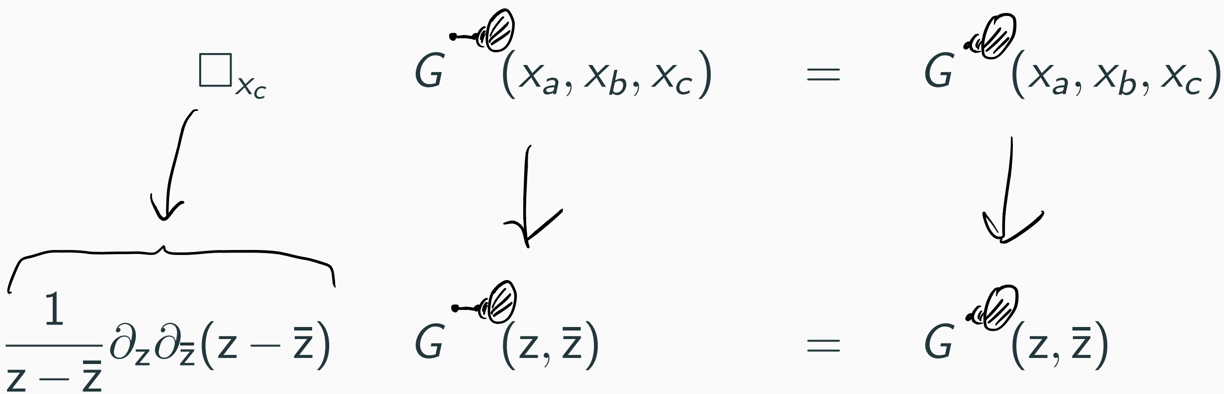

The ∂_z and $\partial_{\bar{z}}$ operators can be inverted in the function space of generalized single-valued hyperlogarithms (Chavez, Duhr 2012, Schnetz 2014, Schnetz 2017).

Graphical functions

- Rules 1,2,3 are part of a larger framework: graphical functions (Schnetz 2013).
- Graphical functions can also be applied in a broader context, e.g. to conformal amplitudes (Basso, Dixon 2017).
- Calculation within this framework are extremely efficient, due to the rapid reductions and small numbers of irreducible *master diagrams*.
- Additional identities specific to the theory (e.g. conformal transformations for scalar theories).

Graphical functions for gauge theory

Beyond scalar

Only change: adding an edge

For instance, for abelian gauge theory:

$$\Box_x \to \not{\partial} \text{ and } \eta^{\mu\nu}\Box_x$$

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The differential equation for appending an edge,

$\Box_{x_a} G$  $(x_a, \ldots) = G$  $(x_a, \ldots)$

becomes a system of differential equations

$\not{\partial}_{x_a} G$  $(x_a, \ldots) = G$  $(x_a, \ldots)$

Paramatrizing non-scalar graphical functions

$\not{\partial}_{x_c}$ G  $(x_a, x_b, x_c) \quad = \quad G$  (x_a, x_b, x_c)

Paramatrizing non-scalar graphical functions

$$\not\partial_{x_c} \qquad G(x_a, x_b, x_c) = G(x_a, x_b, x_c)$$

$$\left(\not\lambda\,\partial_z + \not\bar{\lambda}\,\partial_{\bar{z}} - \frac{P^{\mu\nu}}{z-\bar{z}}\left(\partial^\nu_\lambda - \partial^\nu_{\bar{\lambda}}\right)\right) \qquad G(z, \bar{z}, \lambda, \bar{\lambda}) = G(z, \bar{z}, \lambda, \bar{\lambda})$$

Using light-cone-like parametrization $z, \bar{z}, \lambda^\mu, \bar{\lambda}^\mu$ such that

$$z\,\bar{z} = \frac{x_{ac}^2}{x_{ab}^2} \quad \text{and} \quad (1-z)(1-\bar{z}) = \frac{x_{bc}^2}{x_{ab}^2}$$

$$x^\mu_{ab} = \lambda^\mu + \bar{\lambda}^\mu \qquad x^\mu_{ac} = z\,\lambda^\mu + \bar{z}\,\bar{\lambda}^\mu \qquad x^\mu_{bc} = (1-z)\,\lambda^\mu + (1-\bar{z})\,\bar{\lambda}^\mu$$

$$\lambda^\mu\,\lambda_\mu = \bar{\lambda}^\mu\,\bar{\lambda}_\mu = 0$$

Actual inversion becomes more complicated: $D \neq 4$ dimensional Laplacian has to be inverted.

Diagonalization of the equation system gives,

$$\begin{pmatrix} \Delta_D & 0 & 0 \\ 0 & \Delta_{D+2} & 0 \\ 0 & 0 & \Delta_{D+4} \end{pmatrix} \widetilde{G}$$  $$(x_a, x_b, x_c) \quad = \quad \widetilde{G}$$  $$(x_a, x_b, x_c),$$

where $\Delta_D = \frac{2}{\mathsf{z}-\bar{\mathsf{z}}}\partial_{\mathsf{z}}\partial_{\bar{\mathsf{z}}}(\mathsf{z}-\bar{\mathsf{z}}) - \frac{D-4}{\mathsf{z}-\bar{\mathsf{z}}}(\partial_{\mathsf{z}} - \partial_{\bar{\mathsf{z}}})$.

Diagonalization of the equation system gives,

$$\begin{pmatrix} \Delta_D & 0 & 0 \\ 0 & \Delta_{D+2} & 0 \\ 0 & 0 & \Delta_{D+4} \end{pmatrix} \widetilde{G}^{(1)}(x_a, x_b, x_c) = \widetilde{G}^{(2)}(x_a, x_b, x_c),$$

where $\Delta_D = \frac{2}{\mathsf{z}-\bar{\mathsf{z}}}\partial_{\mathsf{z}}\partial_{\bar{\mathsf{z}}}(\mathsf{z}-\bar{\mathsf{z}}) - \frac{D-4}{\mathsf{z}-\bar{\mathsf{z}}}(\partial_{\mathsf{z}} - \partial_{\bar{\mathsf{z}}})$.

$\Rightarrow$ we would like to invert Δ_D for general even D.

Extension to $D \neq 4$

- For general dimension D we need to solve,

$$\left(\frac{2}{z-\bar{z}}\partial_z\partial_{\bar{z}}(z-\bar{z}) - \frac{D-4}{z-\bar{z}}(\partial_z - \partial_{\bar{z}})\right) \quad G \quad (z,\bar{z}) \quad = \quad G \quad (z,\bar{z}).$$

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$$\left(\frac{2}{z-\bar{z}} \partial_z \partial_{\bar{z}} (z - \bar{z}) - \frac{D-4}{z-\bar{z}} (\partial_z - \partial_{\bar{z}}) \right) \; G(z, \bar{z}) \; = \; G(z, \bar{z}).$$

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$\Rightarrow$ Opens the door to calculations in gauge theories.

$\Rightarrow$ Immediately possible tools: ϕ^3-theory. With applications to percolation theory and other variants (e.g. biadjoint ϕ^3).

An inverse to the differential operator

$$\frac{1}{2}\Delta_{2+2n} = \frac{1}{z-\bar{z}}\partial_z\partial_{\bar{z}}(z-\bar{z}) - \frac{n-1}{z-\bar{z}}(\partial_z - \partial_{\bar{z}})$$

is given by the integration operator:

$$I_n = \sum_{k,l=0}^{n} c_{n,k,l}(z-\bar{z})^{-k}\int_{SV} d\,z(z-\bar{z})^{k+l}\int_{SV} d\,\bar{z}(z-\bar{z})^{-l}$$

where $c_{n,k,l}$ are some easily determined coefficients.

Results

$$\beta_{\phi^3}(g) = \left(\frac{5}{2016}\pi^6 - \frac{46519}{829440}\pi^4 + \frac{102052031}{6718464} + \frac{99}{16}\zeta(3)^2 + \right.$$
$$\left. + \frac{366647}{6912}\zeta(3) + \frac{151795}{3456}\zeta(5) - \frac{5495}{64}\zeta(7)\right) g^{11} +$$
$$+ \left(\frac{1}{192}\pi^4 - \frac{3404365}{746496} - \frac{4891}{864}\zeta(3) + \frac{5}{3}\zeta(5)\right) g^9 +$$
$$+ \left(\frac{33085}{20736} + \frac{5}{8}\zeta(3)\right) g^7 - \frac{125}{144}g^5 + \frac{3}{4}g^3$$

4- and 3-loop results due to (John Gracey 2015; de Alcantara Bonfim, Kirkham, McKane, 1980).

⇒ More accurate predictions for the critical exponents in percolation theory and for the Lee-Yang edge singularity.

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- Work in progress: extension to gauge theory.
- Intermediate step finished: extension to arbitrary even D.
- Application of ϕ^3-theory: Critical exponents in percolation theory.
- Question: Extension to odd D possible?

Example of a master diagram, which is irreducible w.r.t. rules 1–3: