LoopFest XXIV · Brookhaven National Laboratory

May 29, 2026

SubTropica

Sebastian Mizera (Columbia University)

PAPER

2604.20954

COLLABORATORS

Mathieu Giroux & Giulio Salvatori

WEBSITE

subtropi.ca

GITHUB

github.com/SubTropica

Closing talk retrospective

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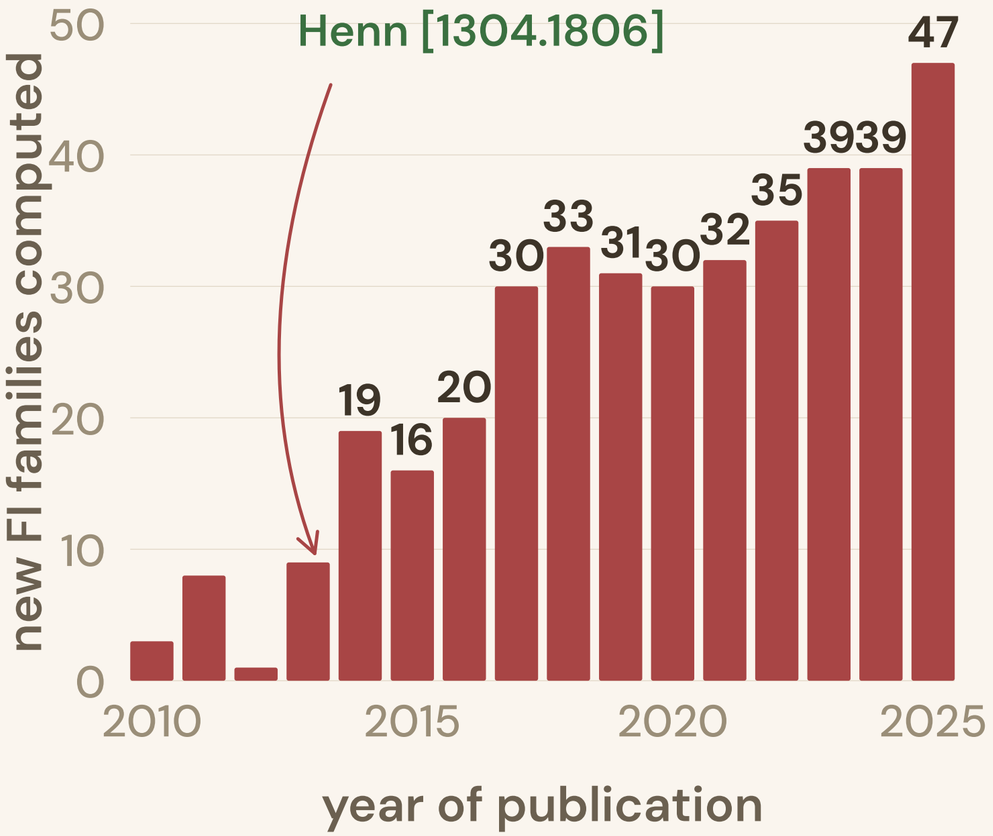

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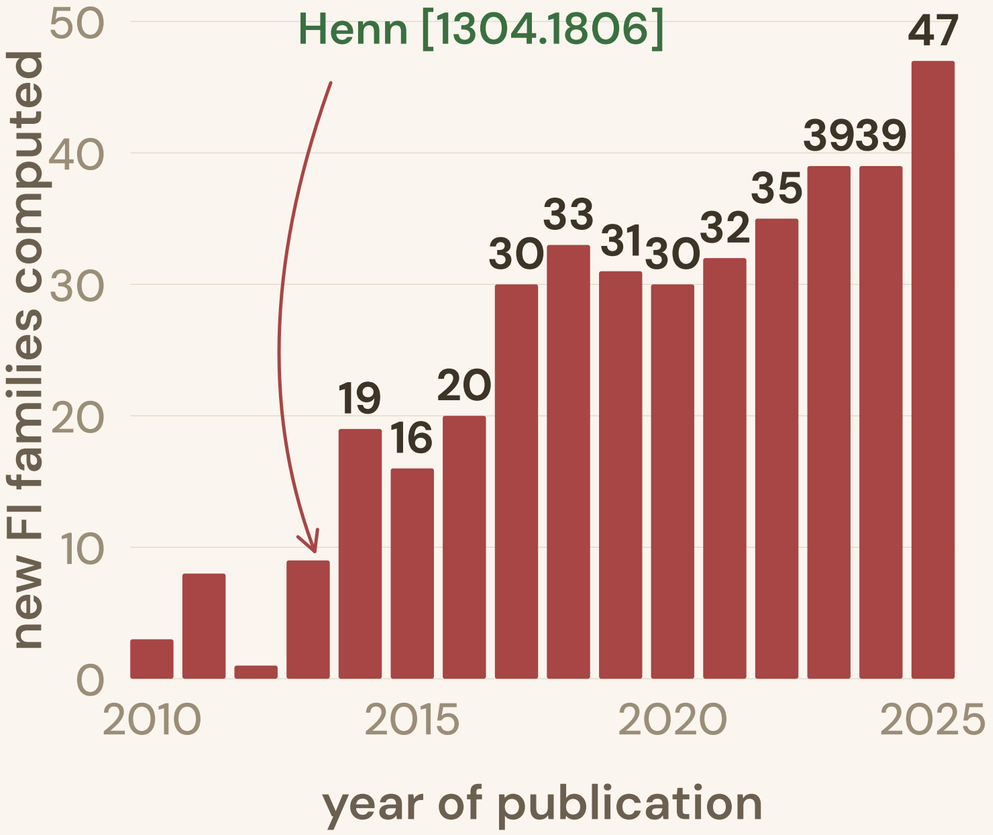

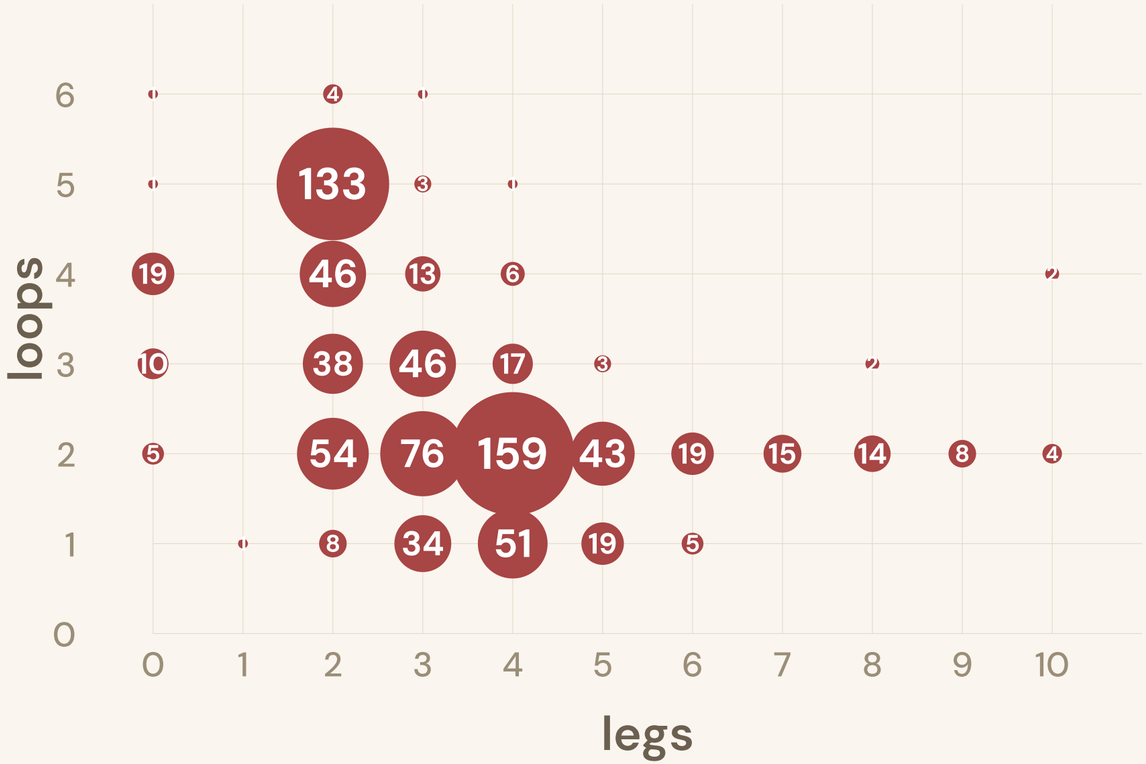

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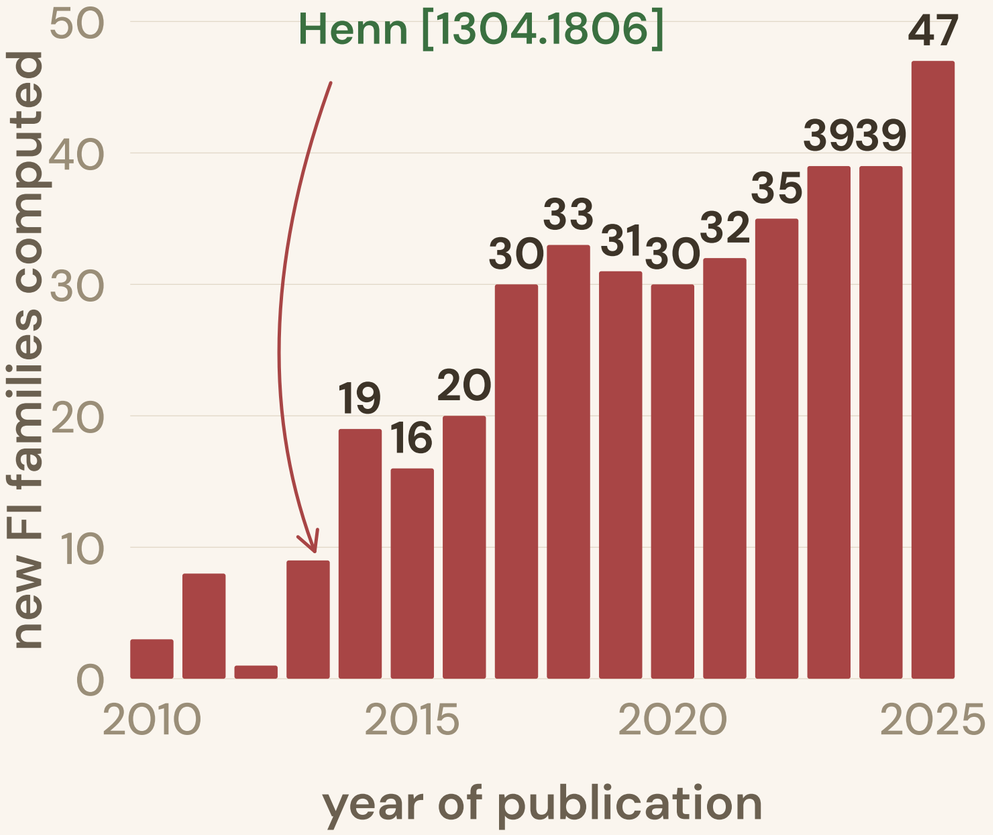
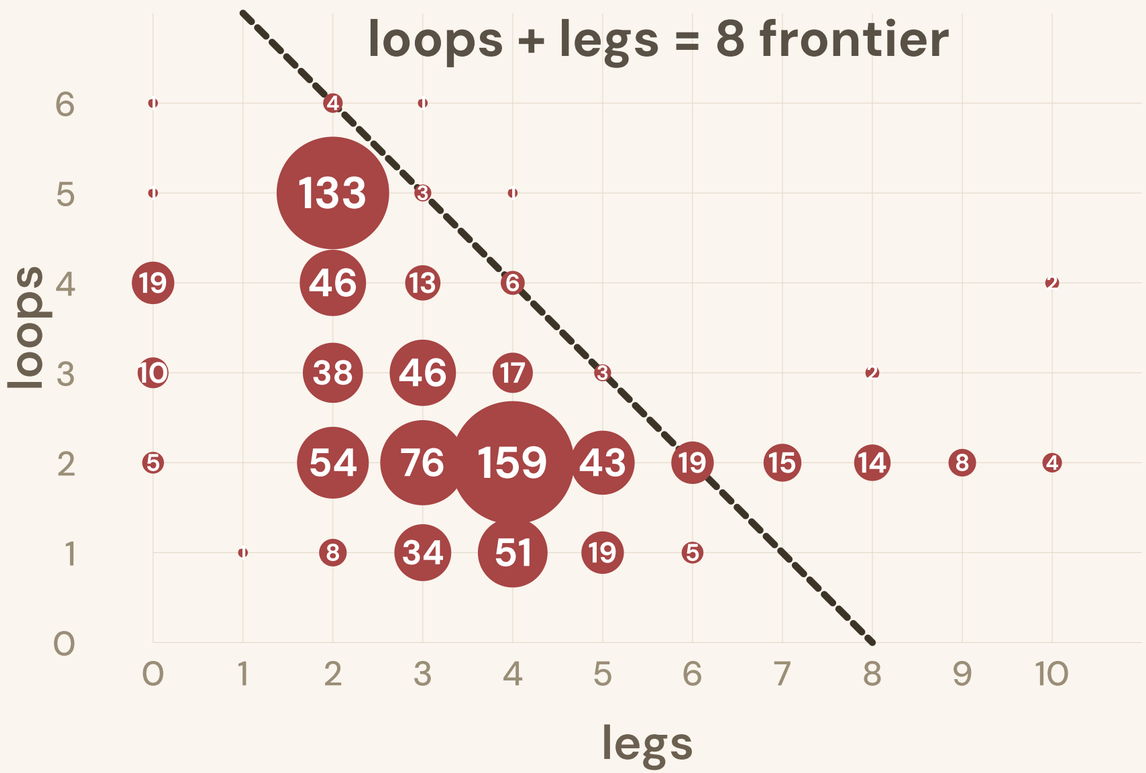
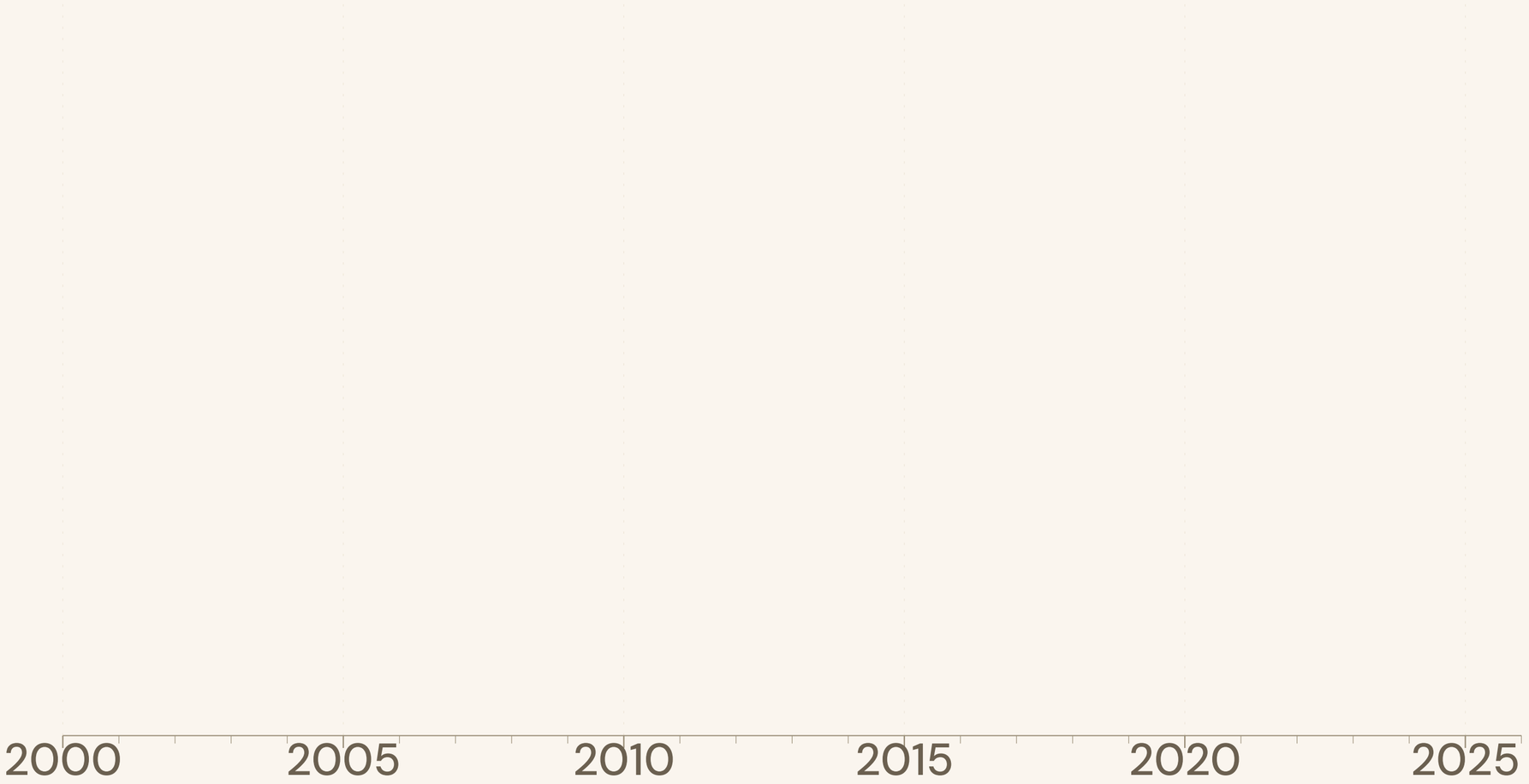




The toolbox today



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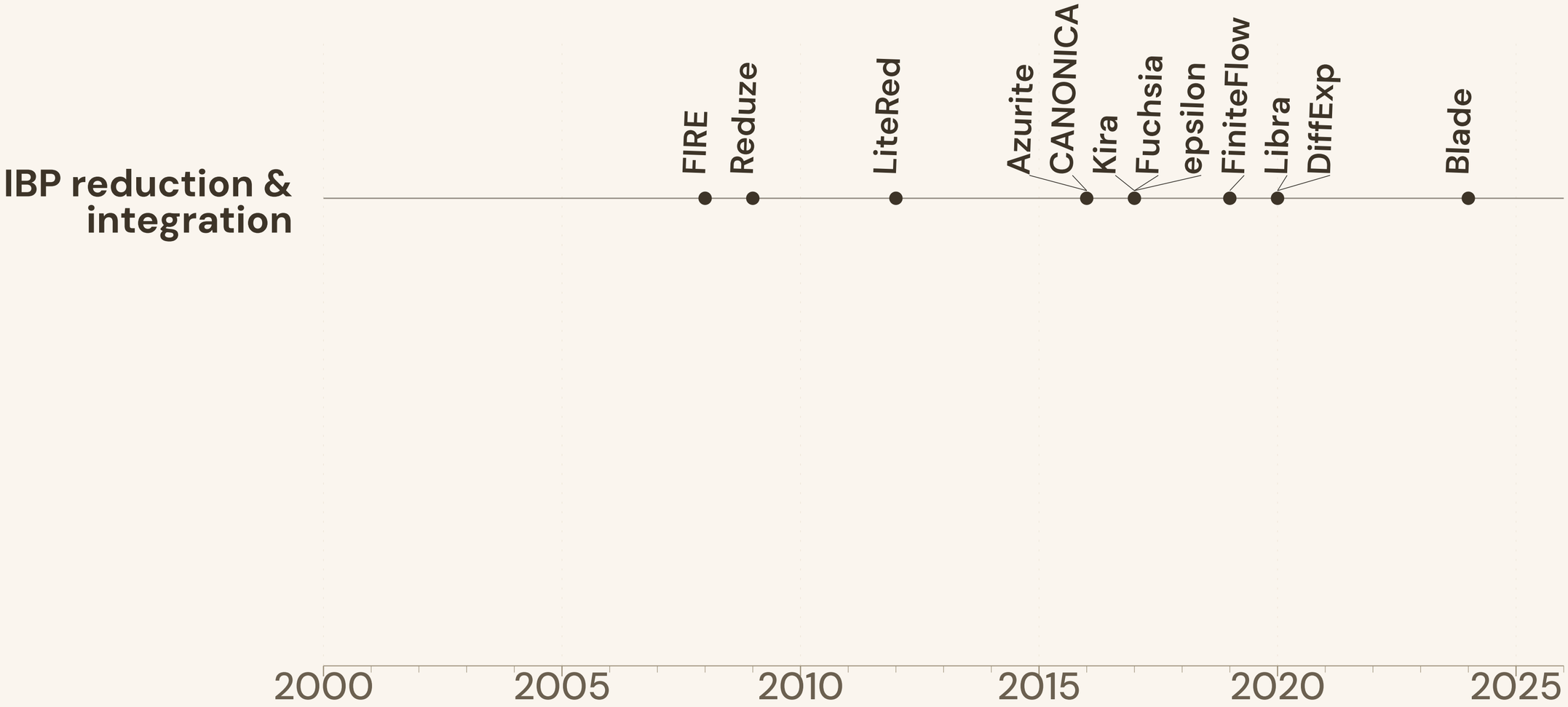

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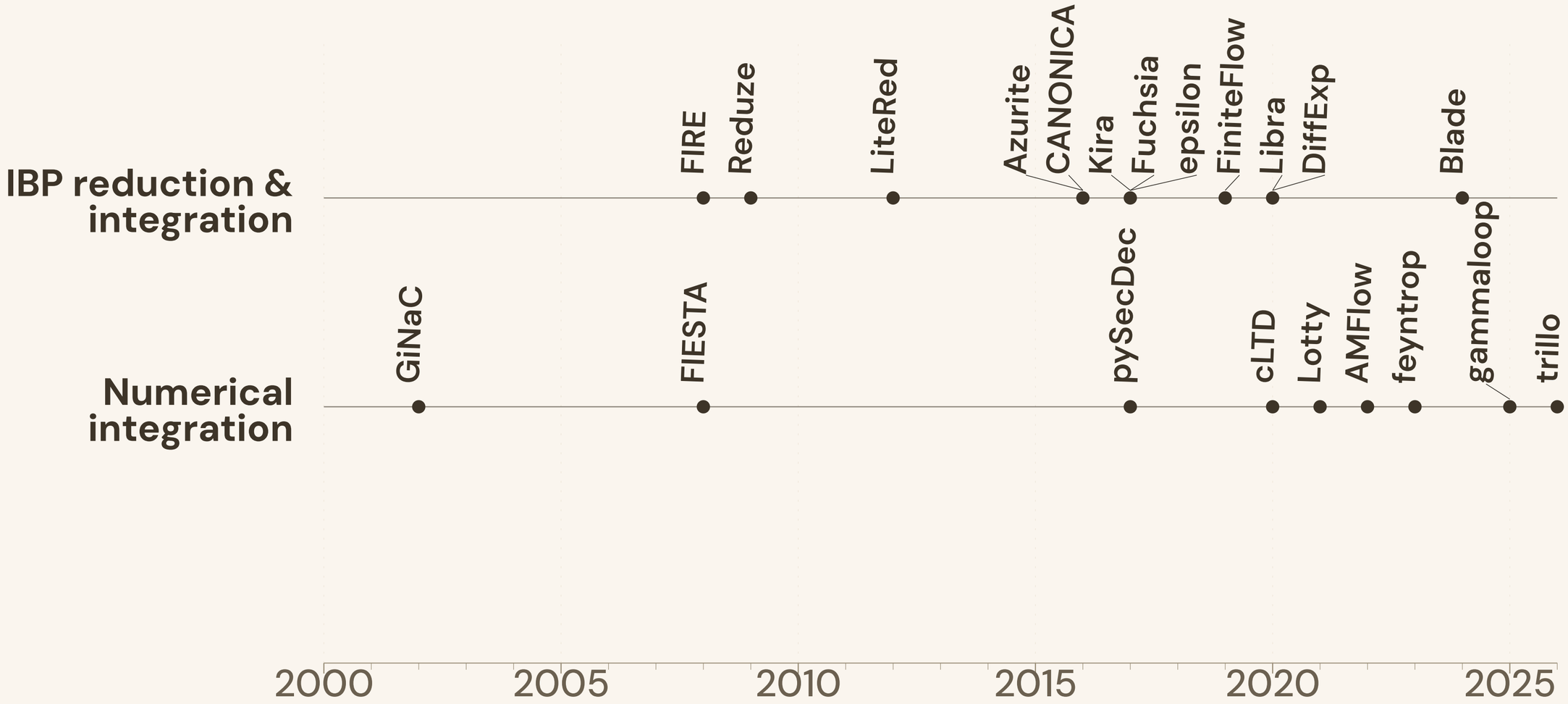

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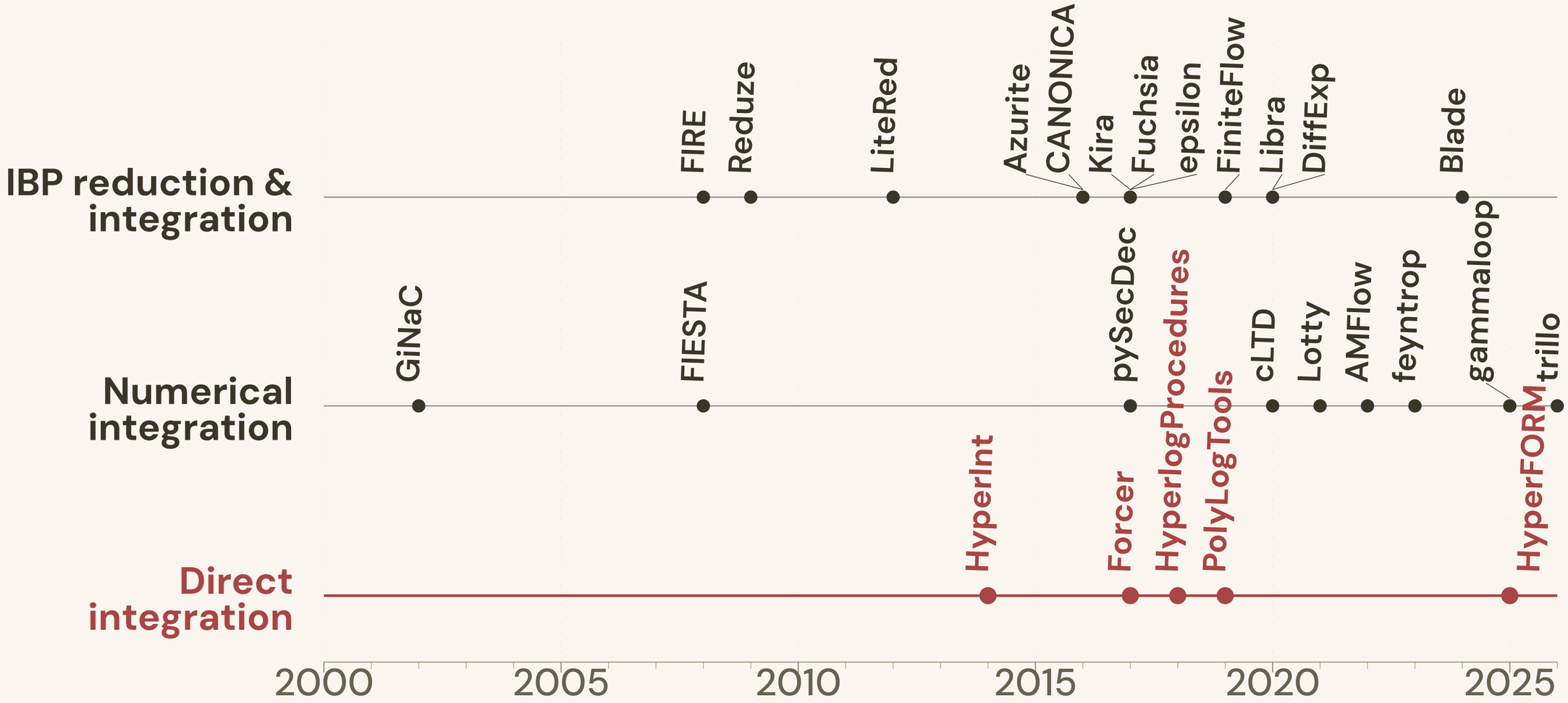

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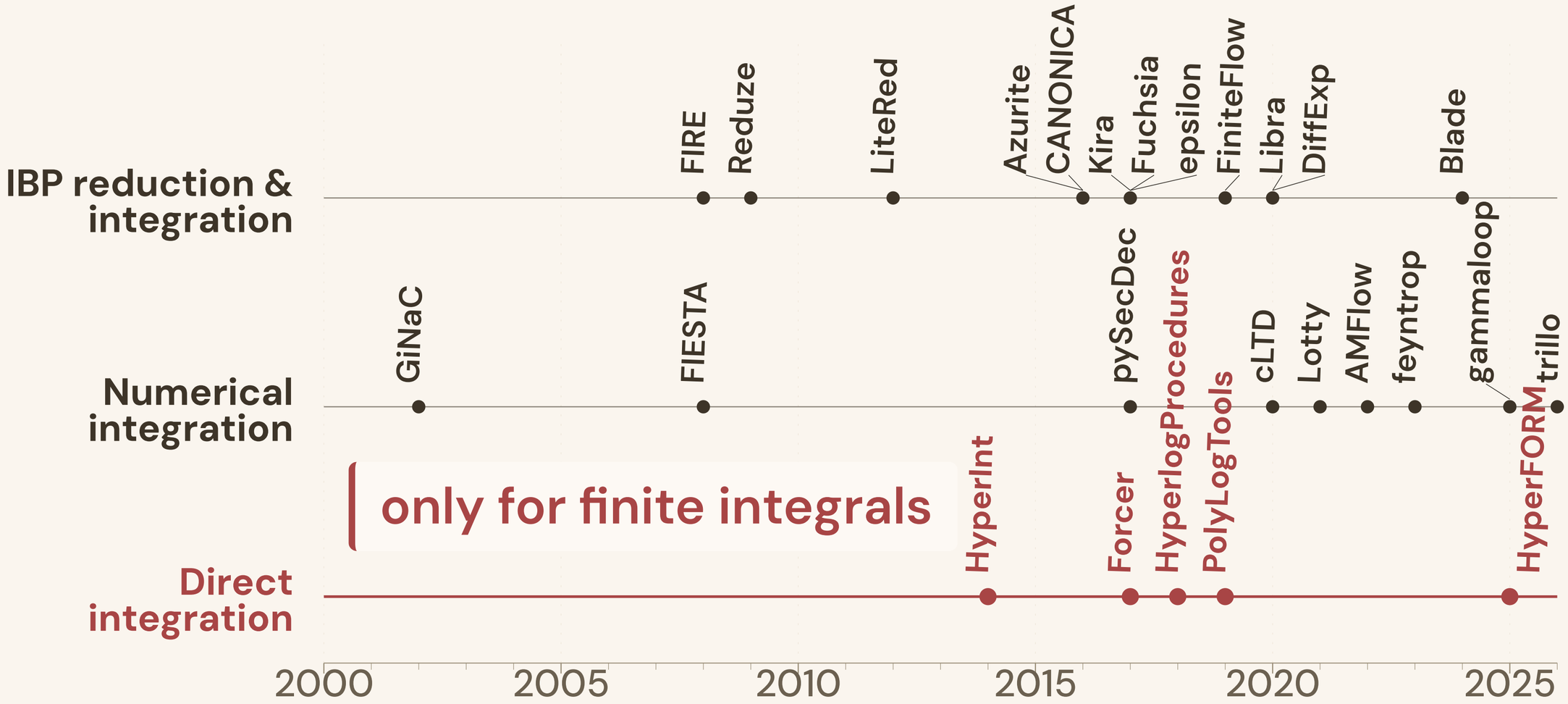

Outline

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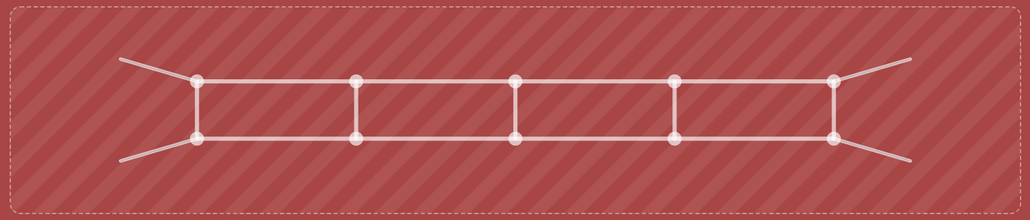

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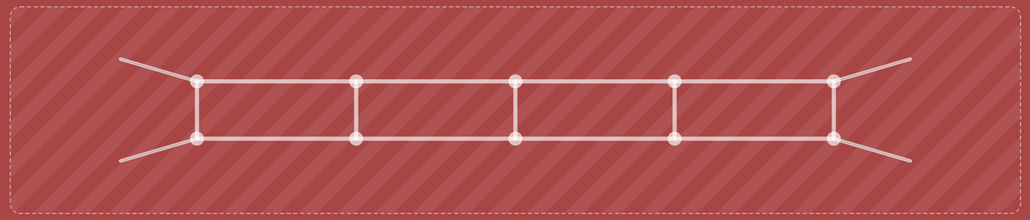

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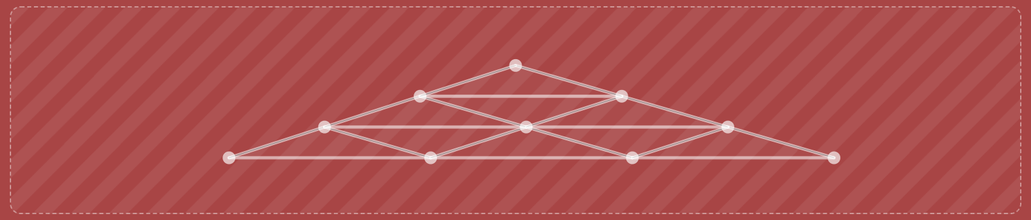

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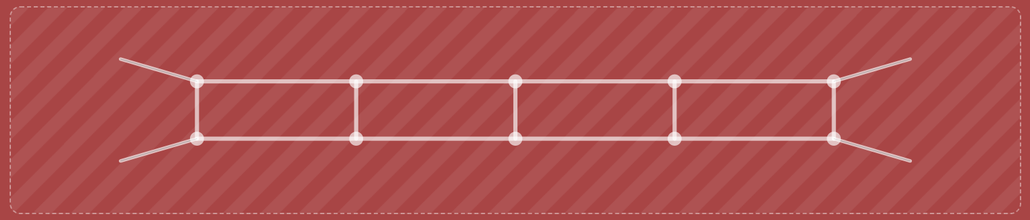

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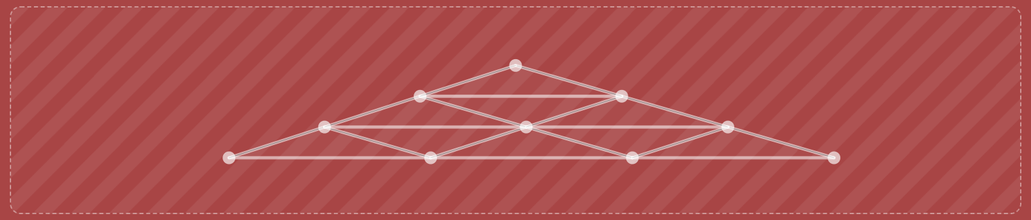

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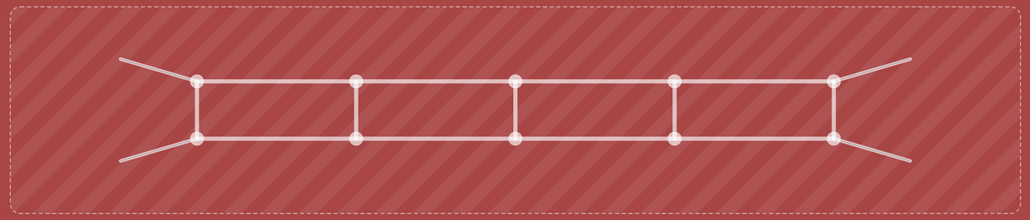

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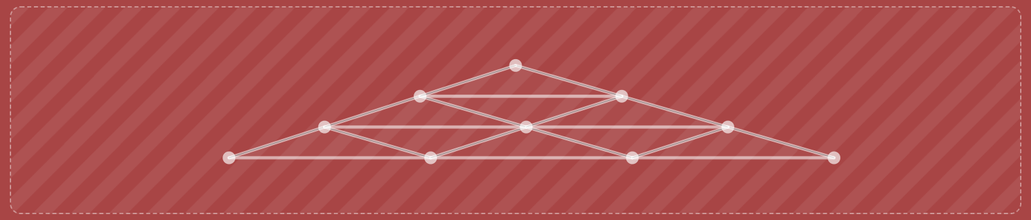

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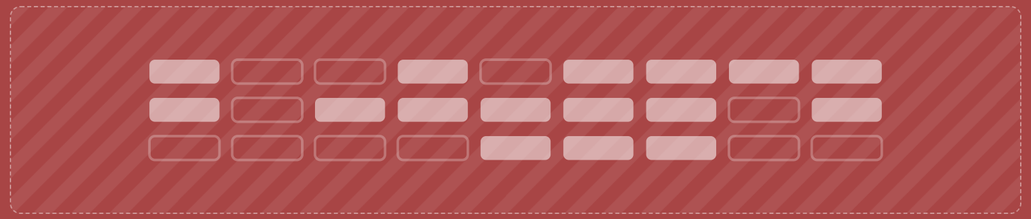

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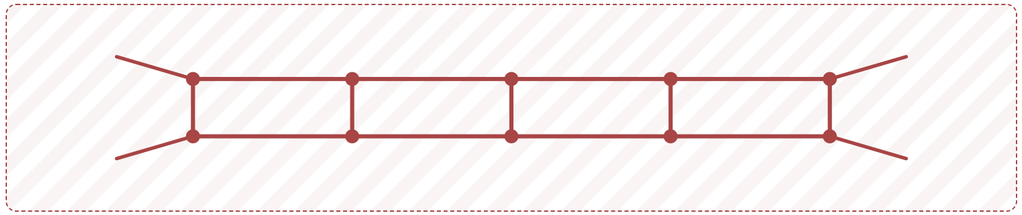

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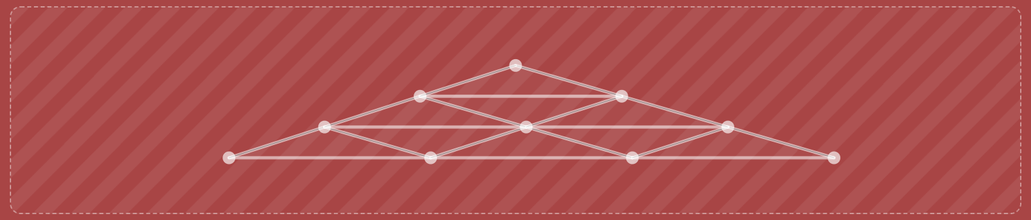

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Why is it difficult to evaluate divergent integrals?

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Toy model integral

$$I = \int_0^\infty \int_0^\infty \mathrm{d}x\,\mathrm{d}y\; x^{1+\varepsilon}\, y^{\varepsilon} \left(x^2 + y + xy\right)^{-2-\varepsilon}$$

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Toy model integral

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Integration and expansion don't commute for divergent integrals

The integrand is singular at the origin $(x, y) \to (0, 0)$

Blow up the origin

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Rescale $x \to \lambda x,\ \ y \to \lambda^2 y$ (set $y = 1$)

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\end{aligned}
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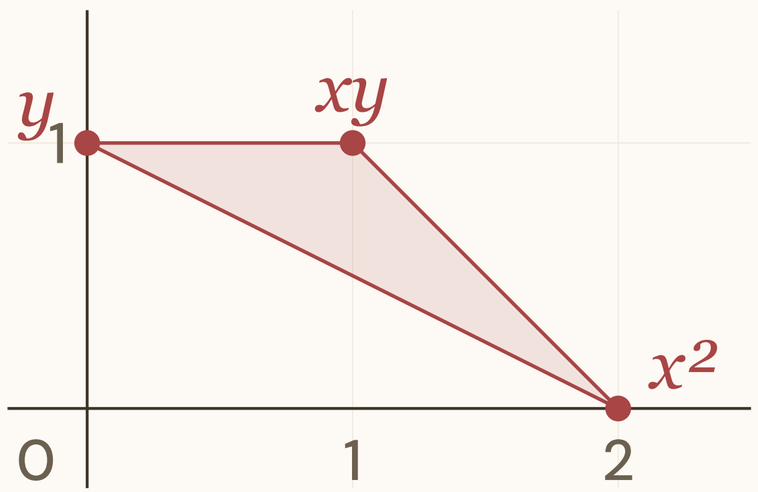
How did we know which rescaling to use?

Tropical geometry

Newton polytope of $x^2 + y + xy$



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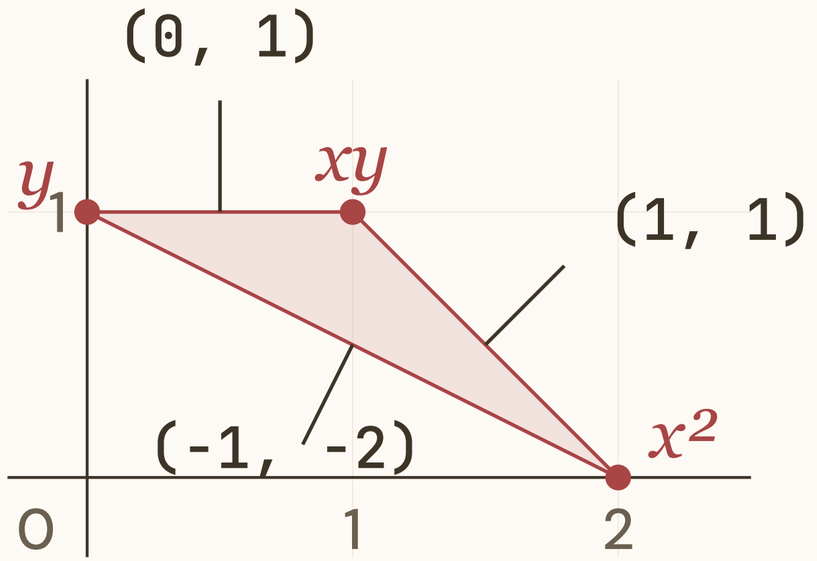

- Normal vector → rescaling, e.g. $(-1, -2)$ gives $(x, y) \to (\lambda x, \lambda^2 y)$

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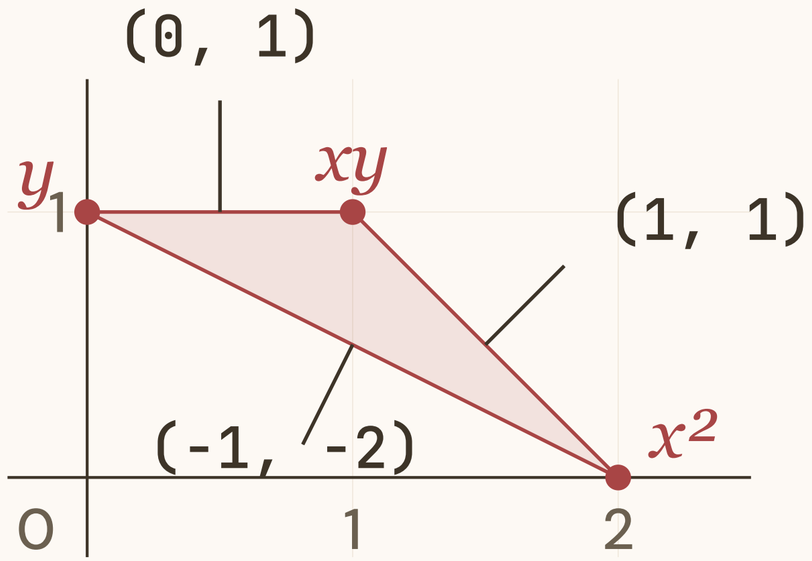

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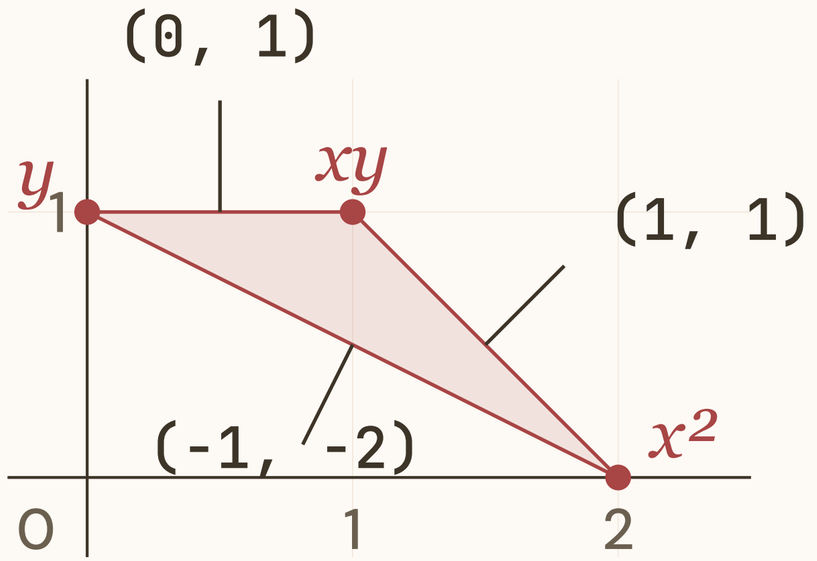

- Normal vector → rescaling, e.g. $(-1, -2)$ gives $(x, y) \to (\lambda x, \lambda^2 y)$
- Efficient implementation in `Polymake`
- Used in sector decomposition and Monte-Carlo sampling, e.g., `asy2.m`, `pySecDec`, and `feyntrop`

Bottom line

We need an efficient way to obtain the decomposition:

$$I \stackrel{?}{=} \sum_{p=P}^{\infty} \varepsilon^p \, I_p$$

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locally finite
*& **analytically tractable***

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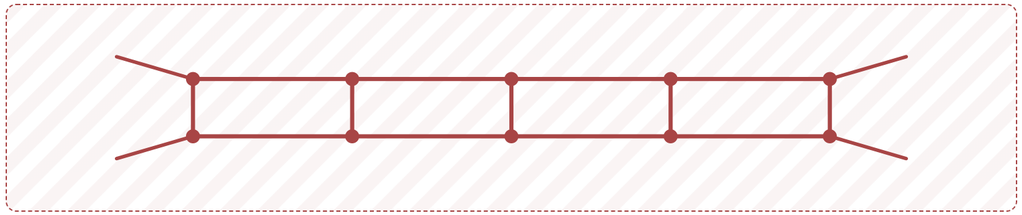

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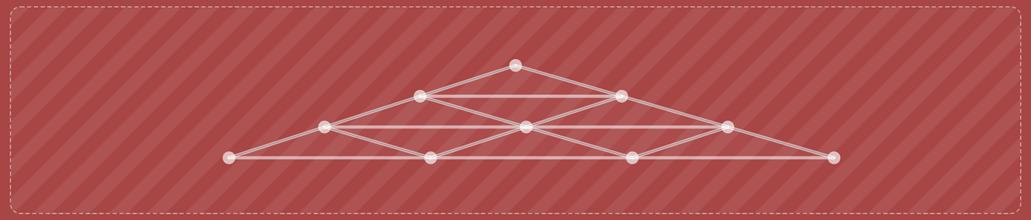

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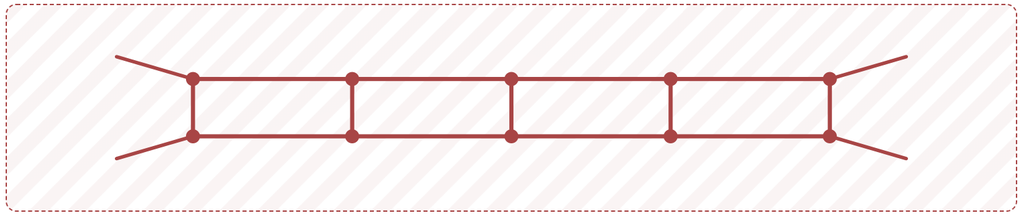

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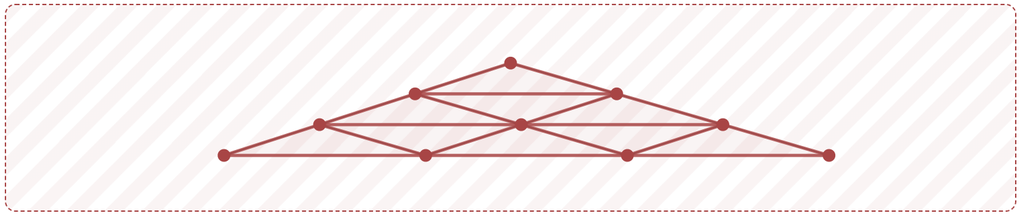

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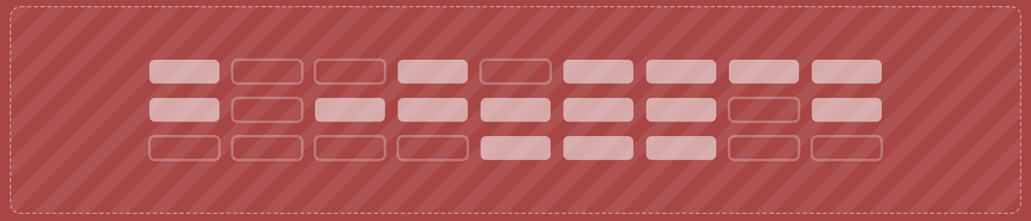

Tropical Subtraction scheme

Giulio Salvatori [2406.14606]

Tropical Subtraction scheme

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Schematic idea

$$I = \left(I - I_{\text{counter}}\right) + I_{\text{counter}}$$

Requirements:

- All divergences explicit in I_{counter}
- $I - I_{\text{counter}}$ locally finite and tractable analytically
- Algorithmic way of obtaining I_{counter}

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Net result

$$I = \sum_{p=P}^{\infty} \varepsilon^p \sum_i I_{p,i}$$

RELATED RESULTS Hillman [2311.03439] · Arkani-Hamed, Hillman, SM [2202.12296]

“Giulio, no one's gonna use it if it takes more than Shift+Enter”

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SubTropica

`v1.1` Initial release

`v1.2` LoopFest release

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Giulio Salvatori

Claude Code Opus

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Input

Shift+Enter

1

Schwinger parametrization

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1 Schwinger parametrization → **2** Tropical subtractions

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MPL

1 Schwinger parametrization → **2** Tropical subtractions → **3** Determine integration order

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1 Schwinger parametrization → **2** Tropical subtractions → **3** Determine integration order → **4** Integrate

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Input — *Shift+Enter*

MPL

Output

1	2	3	4	5
Schwinger parametrization	Tropical subtractions	Determine integration order	Integrate	Verify numerically

Input

Input

Literally just draw the diagram (demo soon)

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STIntegrate[]
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List of edges and external legs

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STIntegrate[{{{1,2},0}, {{2,3},0}, {{3,4},0}, {{4,1},0},
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Loop momentum form

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STIntegrate[{l[1]^2, (l[1]+p[1])^2, (l[1]+p[1]+p[2])^2, (l[1]-p[4])^2}]
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Your favorite Euler integral

```
STIntegrate[x^1+eps y^eps (x^2+y+xy)^-2-eps, {x, 0, ∞}, {y, 0, ∞}]
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Determining the integration order

Depending on the order, integration can take anywhere between 1 ms and 13.8 billion years

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- **Linear reducibility for MPL**
- **Fubini reduction algorithm**

  Brown [0804.1660]
  Panzer [1403.3385]
  Correia, Giroux, SM [2503.16601]

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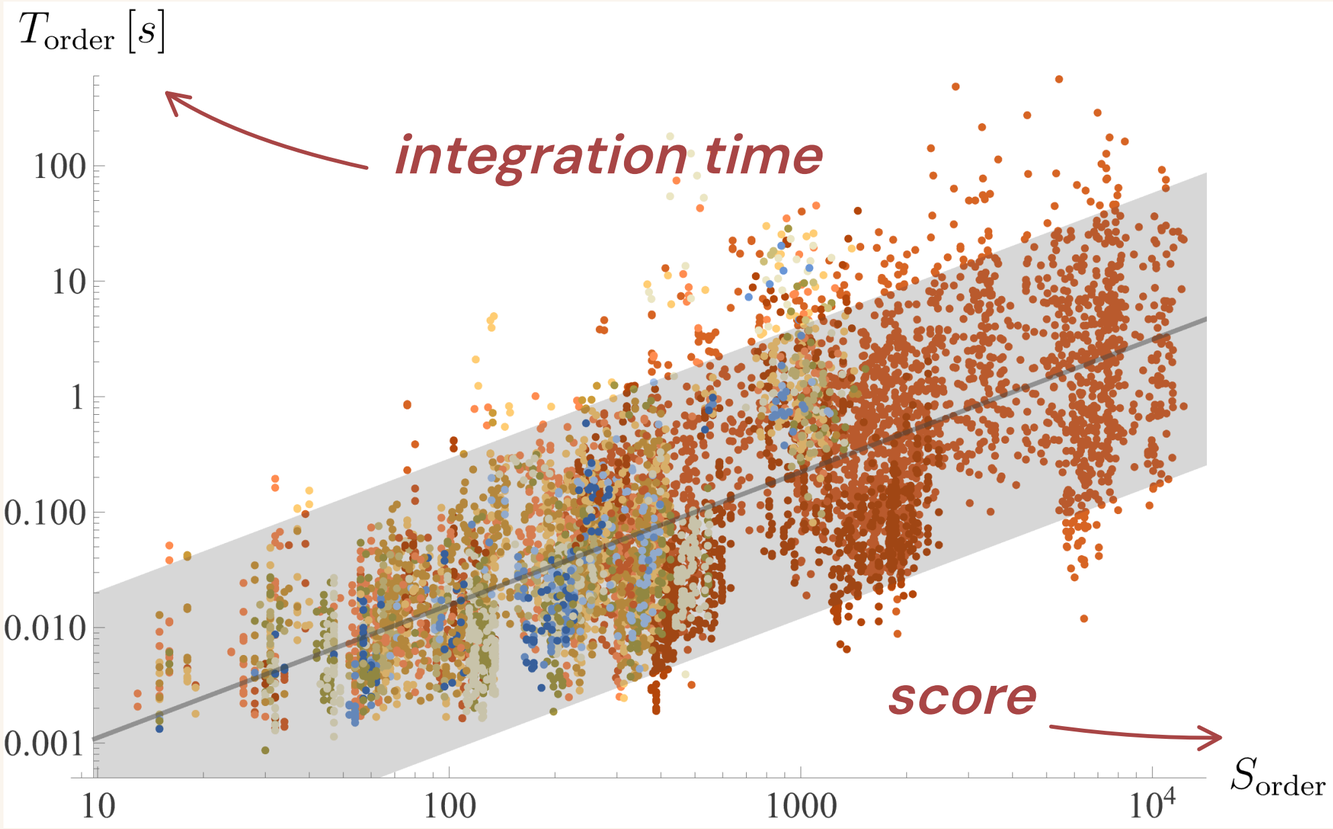
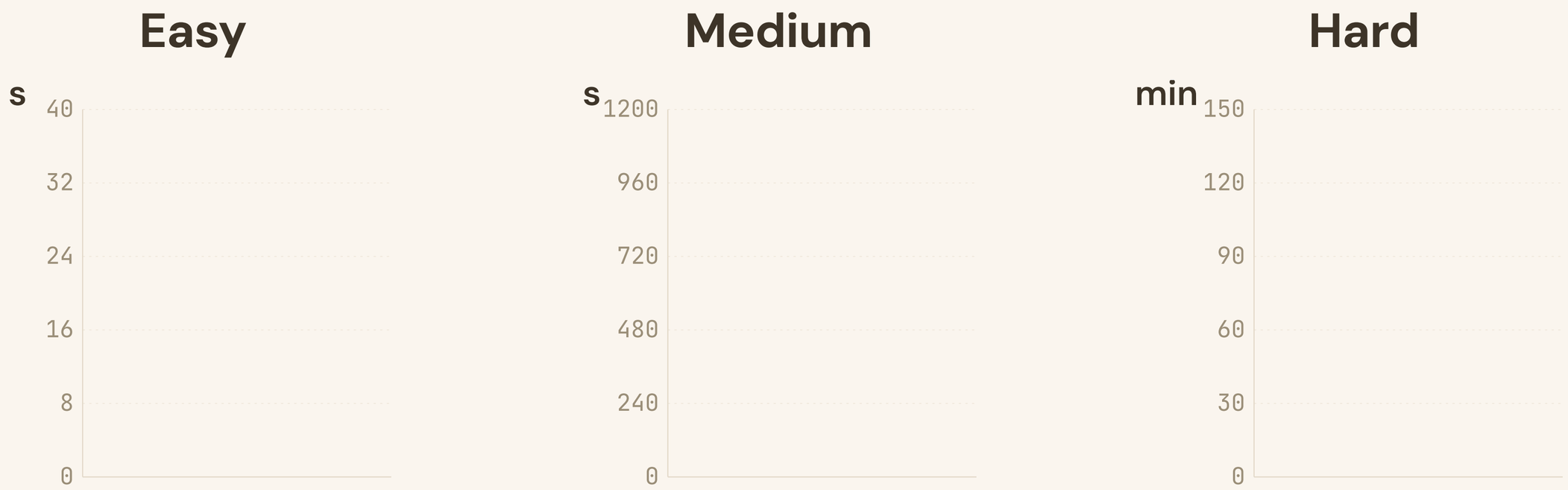


Benchmark: Integration backends

Wall time, MacBook Pro M4 with 48 GB RAM
(all 5-variable integrals with a fixed integration order)



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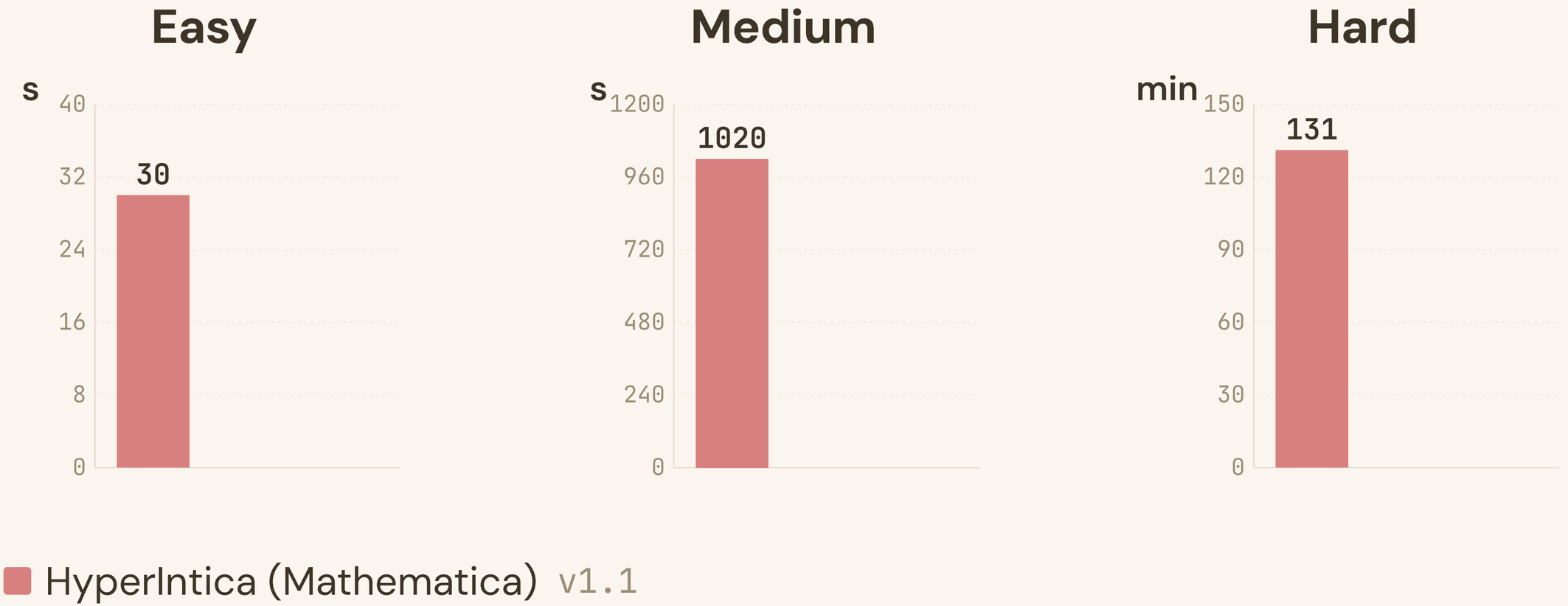

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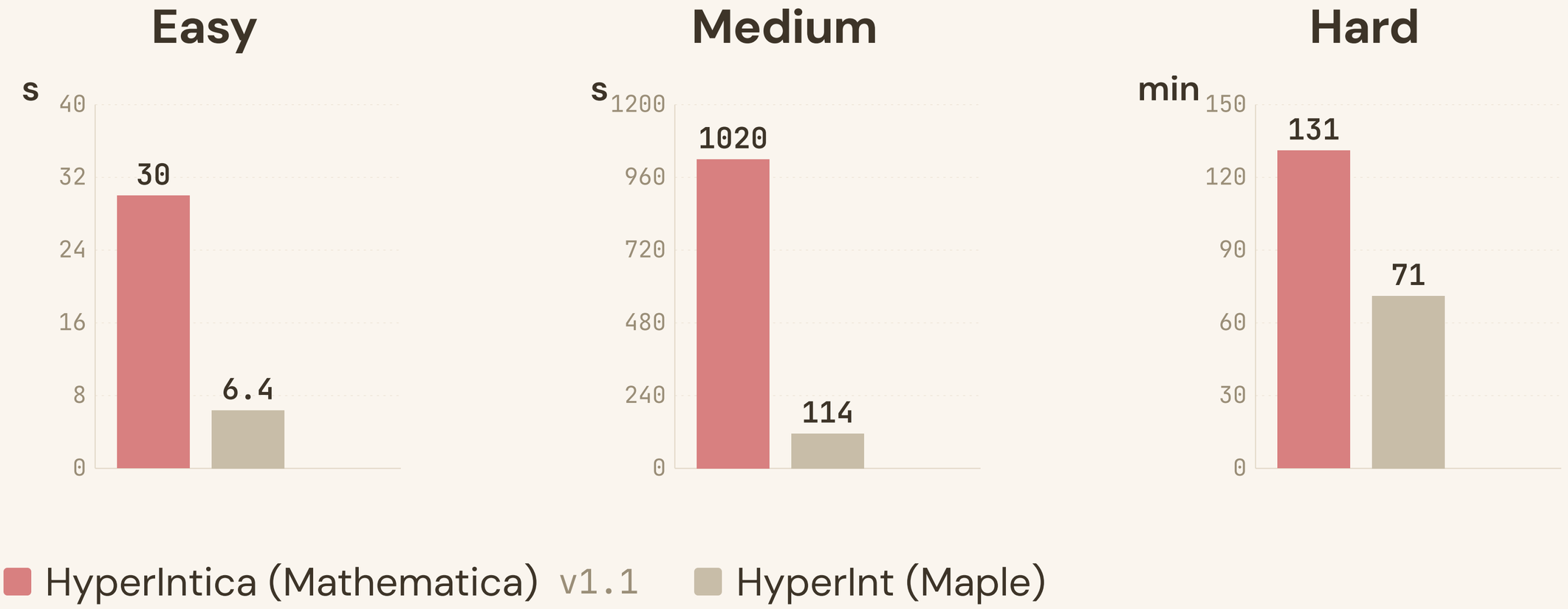

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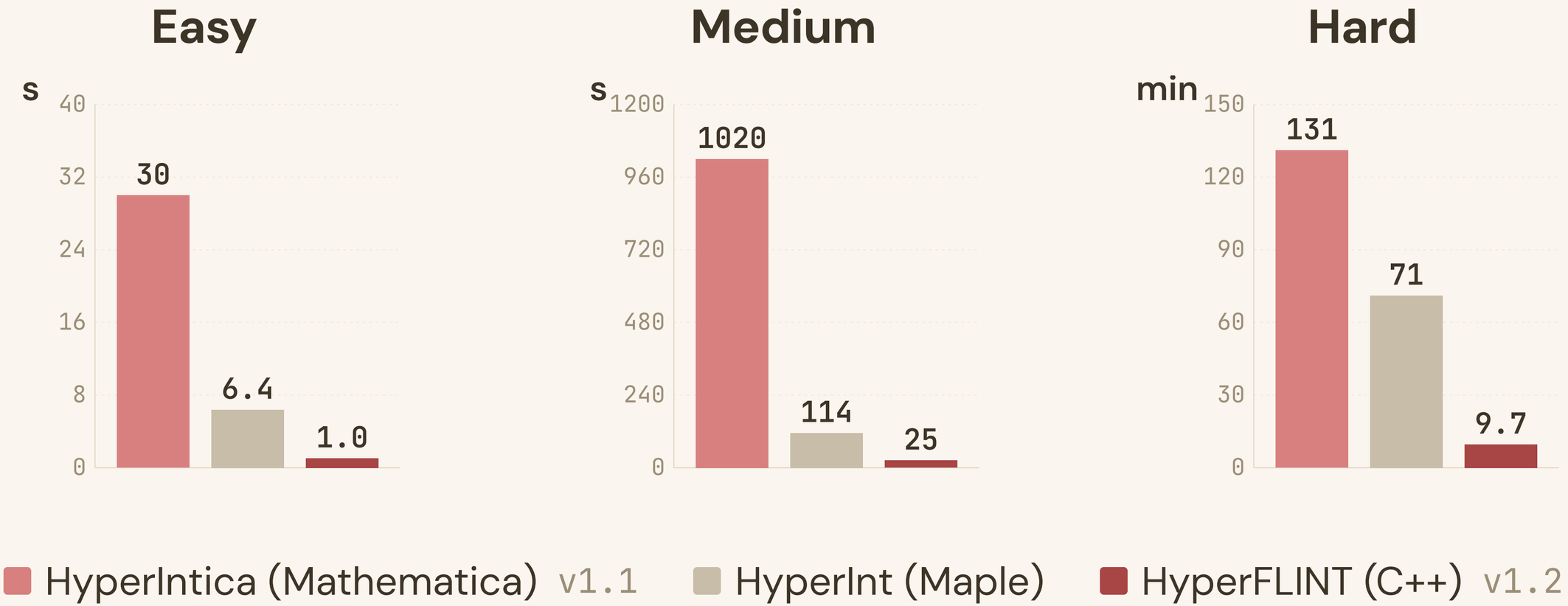
Wall time, MacBook Pro M4 with 48 GB RAM
(all 5-variable integrals with a fixed integration order)



Outline

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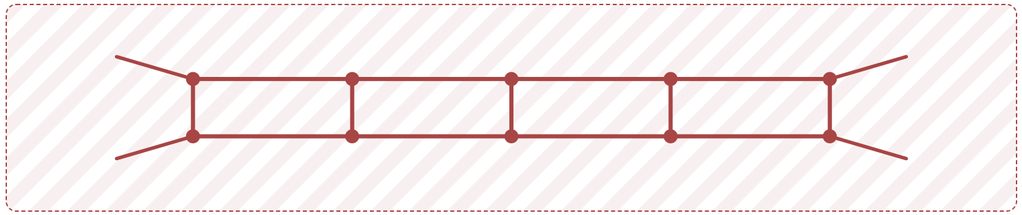
What's the problem?



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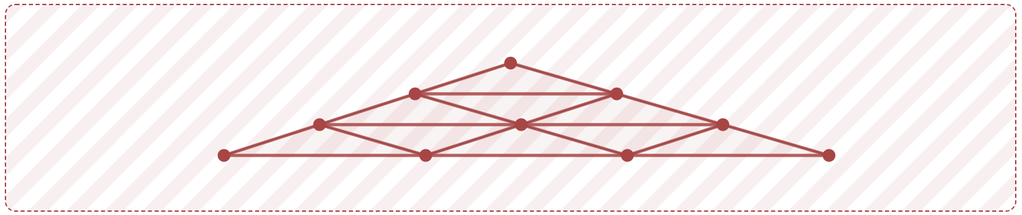
What's the solution?

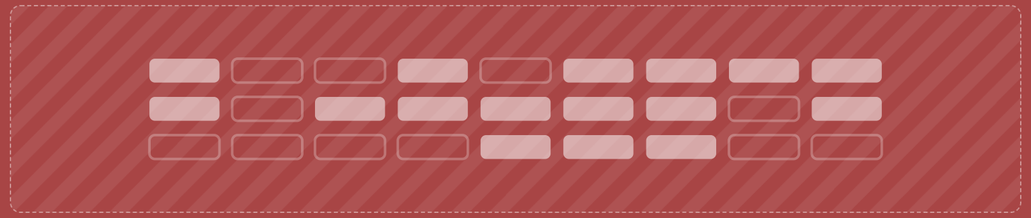


III.

Examples

IV.

Community library



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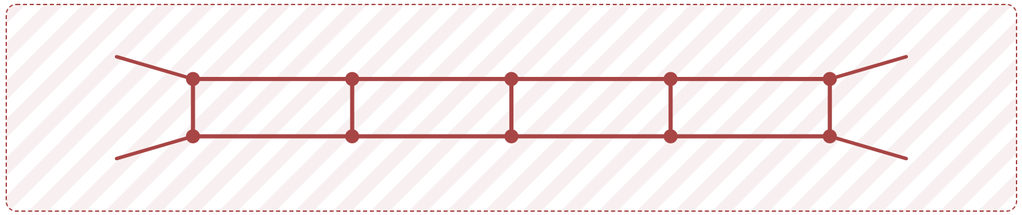

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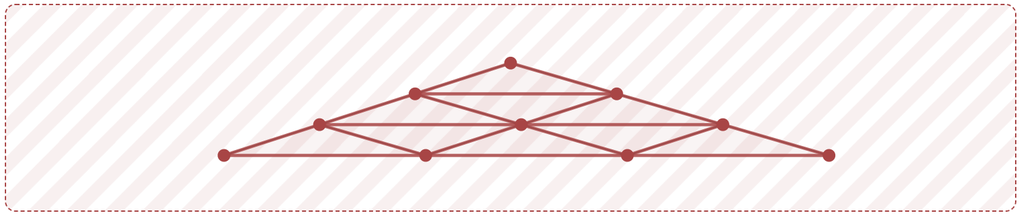

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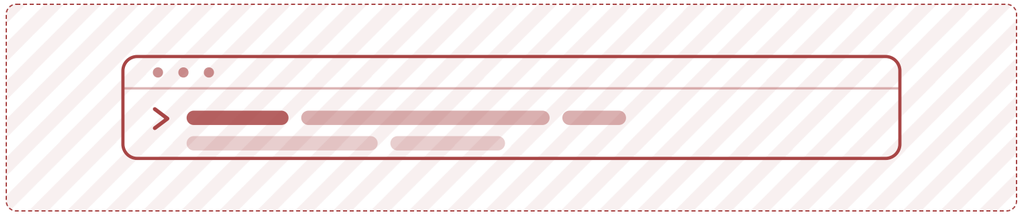
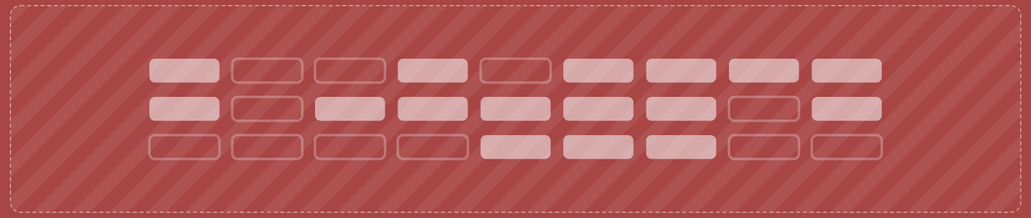
Examples



IV.

Community library



Try it yourself!

```
PacletInstall["https://subtropi.ca/SubTropica.paclet"]
```

REQUIRED

- Mathematica
- polymake

FINITE-FIELD ARITHMETIC

- FiniteFlow
- SPQR

NUMERICAL CHECKS

- pySecDec
- FIESTA
- AMFlow
- feyntrop
- ginsh

IBP REDUCTION

- LiteRed
- FIRE

ALTERNATIVE INTEGRATOR

- Maple + HyperInt

USER INTERFACE

- Python

Scope of applications

Feynman integrals | Eikonal | Energy correlators | BK kernel

$$\int \frac{\mathrm{e}^{4\varepsilon\gamma_E}\prod_{i=1}^{4}\frac{\mathrm{d}^{\mathrm{D}}\ell_i}{i\pi^{\mathrm{D}/2}}}{\left[(\ell_2+\ell_3+p_2+p_3)^2-m^2\right](\ell_1-\ell_3)^2\,\ell_1^2\,(\ell_1+\ell_2+p_3)^2\,\ell_2^2\,(\ell_2+\ell_3-\ell_4)^2\,\ell_3^2\,(\ell_4-p_4)^2\,\ell_4^2}$$

4 loops • 4 legs • 1 mass

Scope of applications

Feynman integrals | Eikonal | Energy correlators | BK kernel

```
(* Graph: edges {vertices}, weight *)
diag = {{{{4,5},0},{{1,4},0},{{1,2},1},
        {{2,3},0},{{3,5},0},{{5,6},0},
        {{2,5},0},{{4,6},0},{{1,6},0}},
        {{1,0},{2,0},{3,0},{4,0}}};

STIntegrate[diag, "Dimension"      → 4 - 2 eps,
                  "Gauge"          → {x3 → 1},
                  "SimplifyOutput" → Identity]
```

Scope of applications

Feynman integrals | Eikonal | Energy correlators | BK kernel

```
>> Time to set up integrands and directories:   4.7 s
>> Time to find linearly reducible orderings:  ≈ 1.2 h
>> Time to integrate:                          ≈ 36.6 h
```

Scope of applications

Feynman integrals | **Eikonal** | Energy correlators | BK kernel

$$\int \frac{\mathrm{d}^{\mathrm{D}}k_1}{i\pi^{\mathrm{D}/2}} \frac{\mathrm{d}^{\mathrm{D}}k_2}{i\pi^{\mathrm{D}/2}} \frac{(4\mathrm{e}^{\gamma_{\mathrm{E}}})^{2\varepsilon}[v_2\cdot k_1]^{-r_7}\,[\tilde{\beta}\cdot k_2]^{-r_8}\,[v_1\cdot k_2]^{-r_9}}{[k_1^2]^{r_1}\,[k_2^2]^{r_2}\,[(k_1+k_2)^2]^{r_3}\,[v_1\cdot k_1-1]^{r_4}\,[v_2\cdot k_2-1]^{r_5}\,[-\tilde{\beta}\cdot(k_1+k_2)]^{r_6}}$$

Gardi, Zhu [2509.18017]

Scope of applications

Feynman integrals | **Eikonal** | Energy correlators | BK kernel

```
(* Propagators and numerators *)
basisProp = {k[1]·k[1], k[2]·k[2],
             (k[1]+k[2])·(k[1]+k[2]),
             v[1]·k[1]-1, v[2]·k[2]-1,
             -β̃·(k[1]+k[2]),
             v[2]·k[1], β̃·k[2], v[1]·k[2]};

(* Powers for each element *)
basisExp = {1,1,1,1,1,1,-1,0,0};

(* Kinematic replacements *)
basisKin = {v[1]·v[1] | v[2]·v[2] → 1,
            v[1]·β̃ → -y,
            v[2]·β̃ → -1, β̃·β̃ → 0,
            v[1]·v[2] → -1/2 (1/a12 + a12)};
```

```
STIntegrate[basisProp,
  "Exponents"            → basisExp,
  "Substitutions"        → basisKin,
  "LoopMomenta"          → {k[1],k[2]},
  "Normalization"        → -(4 Exp[EulerGamma])^(2 eps),
  "Gauge"                → {x5 → 1},
  "MethodPolysAndPairs" → "Standard"
  ]
```

Scope of applications

Feynman integrals | **Eikonal** | Energy correlators | BK kernel

$$-\frac{1}{4\,\varepsilon^4\,y}-\frac{\pi^2(3+7y)+4(1+y)\log^2 a_{12}+4y\log^2 y}{8\,\varepsilon^2\,y\,(1+y)}+\dots$$

Scope of applications

Feynman integrals | Eikonal | **Energy correlators** | BK kernel

$$\mathrm{EEC}^{\mathrm{real}}_{J_1,J_2} = \frac{E^{-4-4\varepsilon}}{16(2\pi)^{5-4\varepsilon}} \int_0^1 \mathrm{d}x \, \frac{x^{J_1+1-2\varepsilon}(1-x)^{J_2+1-2\varepsilon}}{(1-zx)^{J_2+2-2\varepsilon}} \, \mathcal{M}_{2\to 3}$$

$$\mathcal{M}_{2\to 3} = \frac{8\,E^4\,\Delta(z,y_1,y_2)}{z(1-z)\,y_1\,y_2\,(1-y_1)(1-y_2)} \, \frac{(1-zx)^4}{x^2(1-x)^2\,P(x)\,Q(x)}$$

Chicherin, Korchemsky, Sokatchev, Zhiboedov [2512.23791]

Scope of applications

Feynman integrals | Eikonal | **Energy correlators** | BK kernel

```
(* Prefactor: *)
pref = ee^(-4-4 eps)/(16(2 Pi)^(5-4 eps)) 8 ee^4 Δ/(z(1-z) y1 y2 (1-y1)(1-y2));

(* Integrand on [0,∞) after x → x/(1+x): *)
integrand = d[x] x^(J1+1-2 eps)(1-x)^(J2+1-2 eps)/(1-z x)^(J2+2-2 eps) (1-z x)^4/(x^2(1-x)^2 Ppol[x] Qpol[x])
                /. x → x/(1+x) // Applyd[#, {x}] //. d[x_] :> 1 &;
(* Applyd computes the Jacobian on d[x] = dx. *)
```

```
(* Variables and coefficients: *)
xvars  = {x};
coeffs = {ee, Δ, z, y1, y2};

(* Jacobian between d[Log[x]] and d[x] *)
jac = (Times @@ xvars)
(* Tropical analysis *)
STPreAnalysis[jac integrand /.{J1→1+eps, J2→2+eps}
                /. FactorCompletely2[a_,b_,c_] :> a,
              xvars, coeffs]

(* Expand around J1 = 1, J2 = 2 *)
seriesJ1J2 = Series[integrand /. {J1 → 1 - δJ1, J2 → 2 - δJ2},
                    {eps, 0, 0}, {δJ1, 0, 1}, {δJ2, 0, 1}]
```

Scope of applications

Feynman integrals | Eikonal | **Energy correlators** | BK kernel

$$\mathrm{EEC}^{\mathrm{real}}_{J_1,J_2}\Big|_{\substack{J_1\to 1\\ J_2\to 2}} = \frac{E^{-4-4\varepsilon}}{16(2\pi)^{5-4\varepsilon}}\,\frac{8\,E^4\,\Delta(z,y_1,y_2)}{z(1-z)\,y_1\,y_2\,(1-y_1)(1-y_2)}\Big[\frac{1}{2}+\frac{3}{4}(1-J_1)$$
$$+\frac{(2-J_2)(1-z)\big(z+(1-z)\log(1-z)\big)}{2z^2}+\frac{(1-J_1)(2-J_2)}{4z^2}\Big[\big(1-4z+3z^2\big)\log(1-z)$$
$$+z\big(3-3z-2z\,\zeta_2\big)+(4z-2)\,\mathrm{Li}_2(z)\Big]+\mathcal{O}\big(\delta J_i\,\delta J_j\big)\Big]$$

Scope of applications

Feynman integrals | Eikonal | Energy correlators | **BK kernel**

$$I = \frac{\mathrm{e}^{-2\varepsilon\gamma_E}}{\pi^{\mathrm{D}}} \int \frac{\mathrm{d}^{\mathrm{D}}\ell_1\, \mathrm{d}^{\mathrm{D}}\ell_2}{\ell_1^2(\ell_1-\ell_2)^2}\, \log\left(\frac{\ell_1^2}{\ell_2^2}\right)\, \mathrm{e}^{i(\ell_1\cdot X_1+\ell_2\cdot X_2)}$$

Brunello, Caron-Huot, Crisanti, Giroux, Smith [2508.03794]

Scope of applications

Feynman integrals | Eikonal | Energy correlators | **BK kernel**

```
(* Jacobian between d[Log[x]] and d[x] *)
jac = (Times @@ xvars)

(* Tropical analysis *)
analysis = STPreAnalysis[jac integrand /. q → q eps, xvars, coeffs]

(* Ray {1,1}: x1 → x1/λ, x2 → x2/λ *)
STFactor[jac integrand /. {x1 → x1/λ, x2 → x2/λ}]
  (* → λ^q: regulated by q only *)

(* Ray {0,1}: x1 fixed, x2 → x2/λ *)
STFactor[jac integrand /. {x1 → x1, x2 → x2/λ}]
  (* → λ^-ε: regulated by ε *)
```

```
(* Ray {1,0}: x1 → x1/λ, x2 fixed *)
STFactor[jac integrand /. {x1 → x1/λ, x2 → x2}]
  (* → λ^(-ε+q): regulated by ε *)

{{pref1, int1}, {pref2, int2}} =
    STTropicalContinuation[
      {{pref, jac integrand}}, xvars, {{1,1}}]

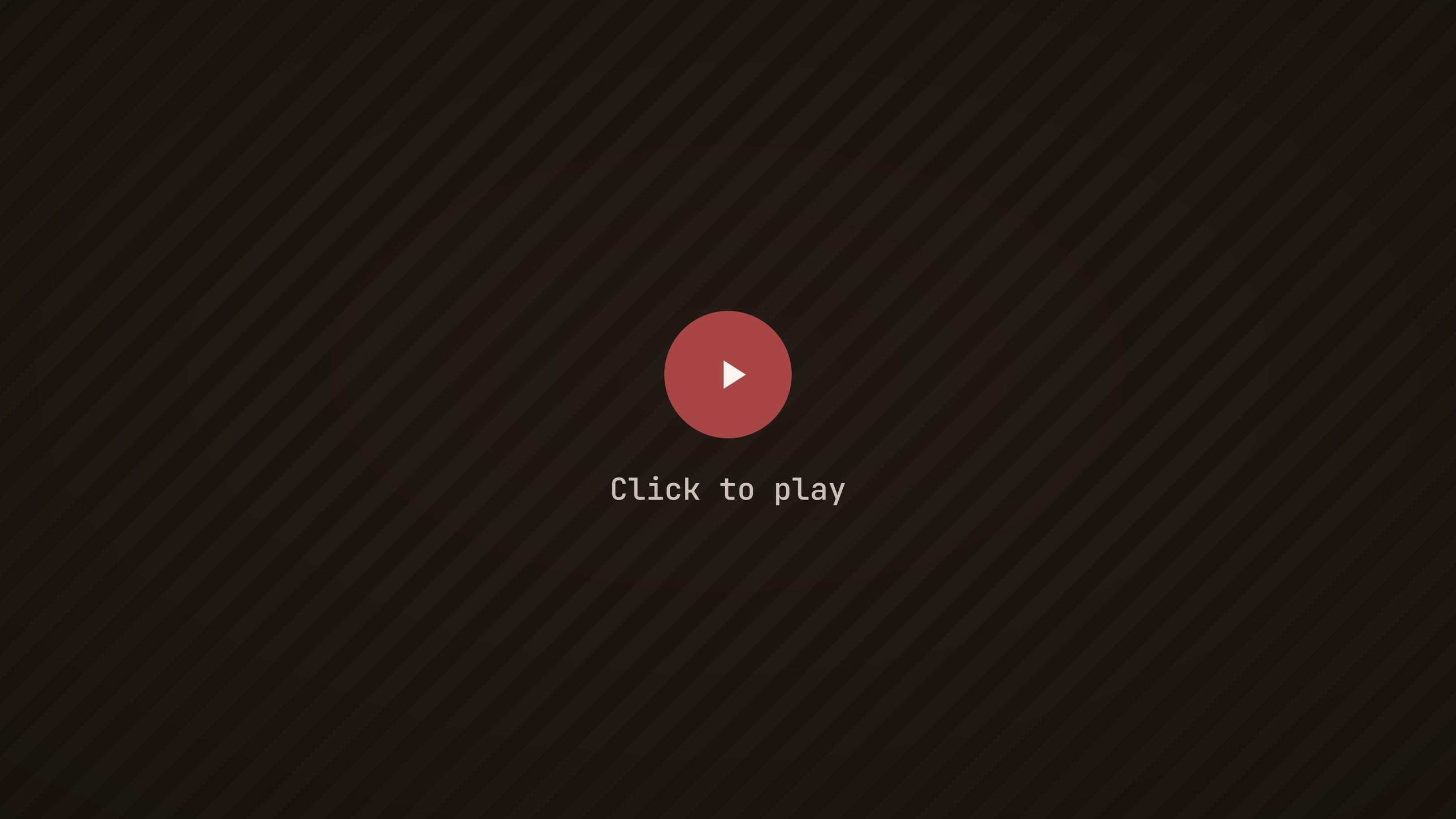
(* Extract O(q) coefficient of each term *)
int1 = SeriesCoefficient[pref1 int1, {q, 0, 1}];
int2 = SeriesCoefficient[pref2 int2, {q, 0, 1}];

(* Tropical subtraction in eps *)
serI1 = STExpandIntegral[int1, xvars, coeffs]
serI2 = STExpandIntegral[int2, xvars, coeffs]
```

Scope of applications

Feynman integrals | Eikonal | Energy correlators | **BK kernel**

$$I = \frac{1}{2\varepsilon^3} + \frac{\zeta_2}{2\varepsilon} + 4\,\mathrm{Re}[\mathrm{Li}_3(1-z)] + 4\,\mathrm{Re}[\log(1-z)]\,\mathrm{Re}[\mathrm{Li}_2(z)]$$
$$+ 4\,\mathrm{Re}[\log(1-z)](\mathrm{Re}[\log(1-z)\log z] - \zeta_2) + \frac{\zeta_3}{3} + \mathcal{O}(\varepsilon)$$


Click to play

Outline

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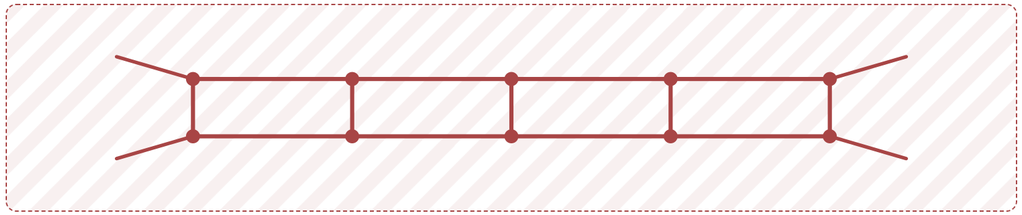

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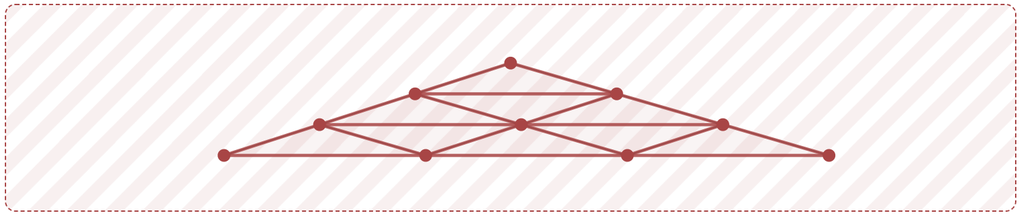

III.

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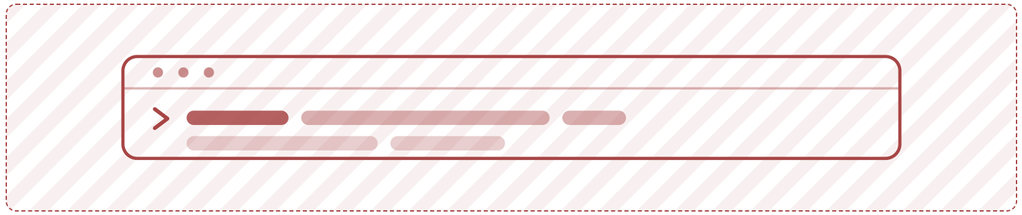
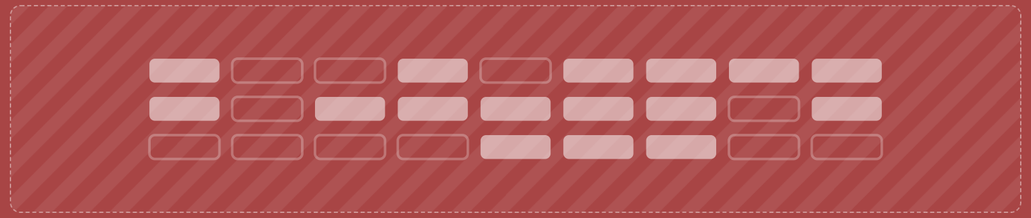


IV.

Community library



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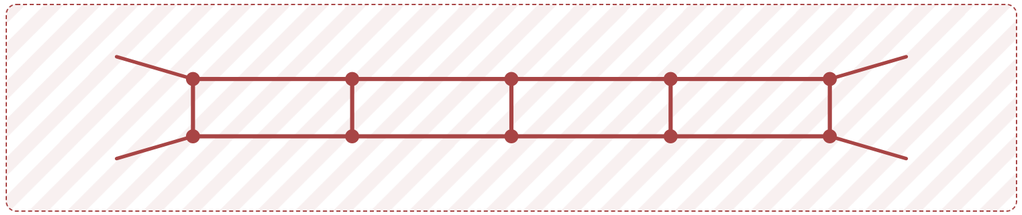

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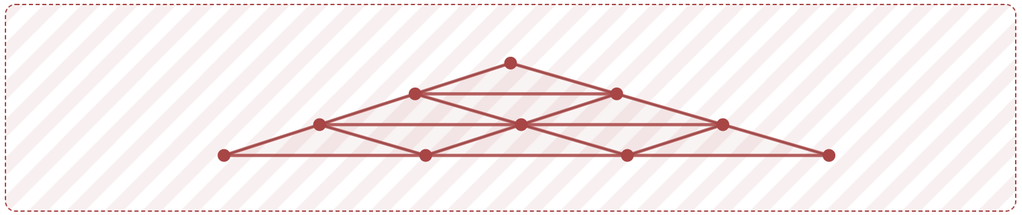

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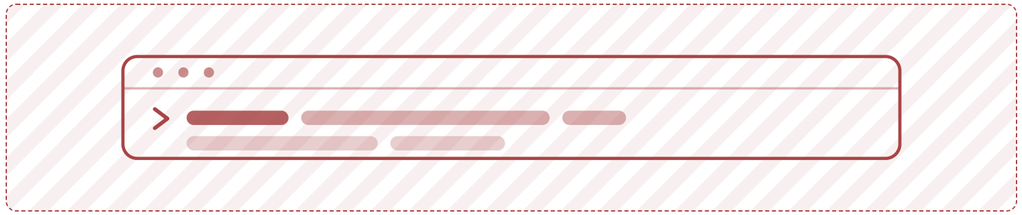

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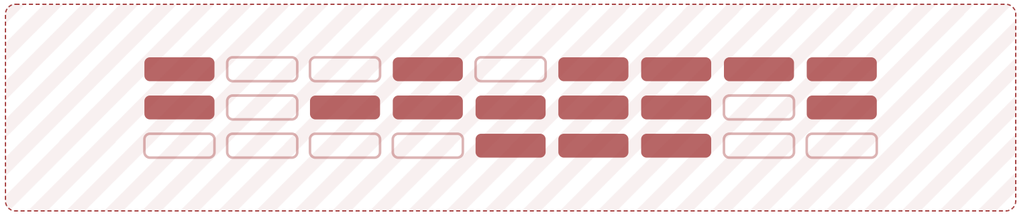

Community library

Database of papers

Database of results

Community library

Database of papers

- AI agent scraping all of arXiv

Database of results

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- 1298 relevant papers so far

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Database of results

- After a successful integration, users can submit the result

Community library

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Community library

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Database of results

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- Needs to pass automatic verification
- 195 results so far

Community library

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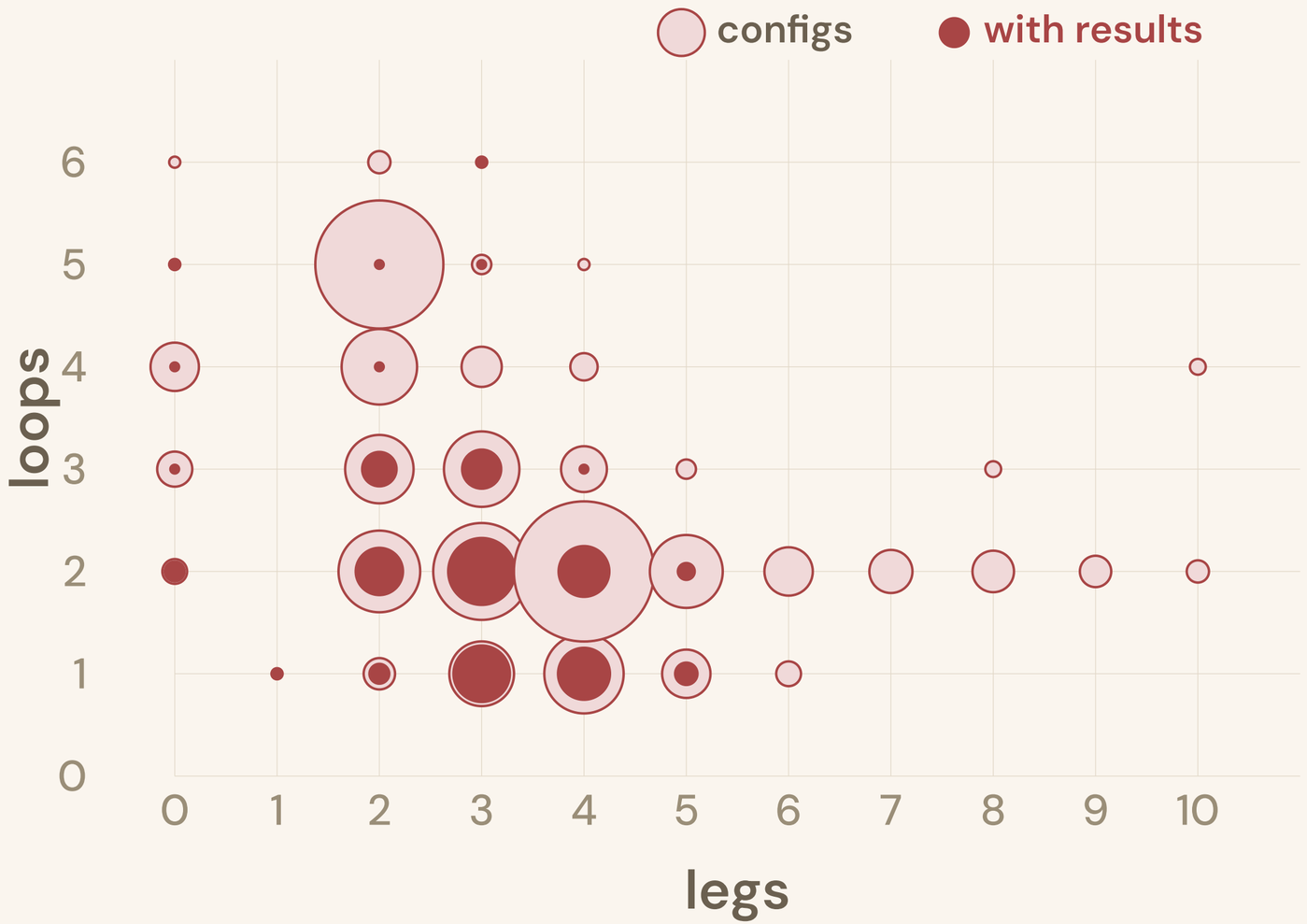
Database of results

- After a successful integration, users can submit the result
- Needs to pass automatic verification
- 195 results so far
- Submissions welcome!
  UI or `STSubmitResult[]`

Library coverage



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Try it yourself!

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1. Individual Registrant Types

- Canadian Citizen
- Permanent Resident of Canada
- Aboriginal Peoples (individuals or groups) indigenous to Canada
- Legal Representative of a Canadian Citizen or Permanent Resident

2. Non-Individual Registrant Types

- Corporation (Canada or Canadian province or territory)
- Government or government entity in Canada
- Canadian Educational institution
- Canadian Unincorporated Association
- Canadian Hospital
- Partnership Registered in Canada
- Domain contains Trade-mark registered in Canada (by a non-Canadian owner)

Try it yourself!

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- Canadian Educational institution
- Canadian Unincorporated Association
- Canadian Hospital
- Partnership Registered in Canada
- Domain contains Trade-mark registered in Canada (by a non-Canadian owner)
- Canadian Trade union
- Canadian Political party
- Canadian Library, Archive or Museum
- Trust established in Canada
- Indian Band recognized by the Indian act of Canada
- Official mark registered in Canada
- Her Majesty the Queen

Click to play

Outlook

Outlook

- Further speed/memory optimizations

Outlook

- Further speed/memory optimizations
- Automatic rationalization

Outlook

- Further speed/memory optimizations
- Automatic rationalization
- Method of regions

Outlook

- Further speed/memory optimizations
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- Extending the library and applications

Outlook

- Further speed/memory optimizations
- Automatic rationalization
- Method of regions
- Extending the library and applications
- **Everyone is welcome to contribute!**

Thank you to the organizers

Sally Dawson

Clara Del Pio

Fernando Febres Cordero

Bernhard Mistlberger

George Sterman

Robert Szafron

Ciaran Williams

Thank you

subtropi.ca

arXiv:2604.20954

github.com/SubTropica

```
PacletInstall["subtropi.ca/SubTropica.paclet"]
```

with **Mathieu Giroux** & **Giulio Salvatori**