Computer Algebra for Lattice Path Combinatorics

Alin Bostan

Inria informatics mathematics

HDR defense — Univ. Paris 13

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Research context

Computer algebra = effective mathematics + algebraic complexity

- effective mathematics: what can be computed?
- algebraic complexity: how fast?

Efficient computer algebra for functional equations

- equations as data structures — $\pm\sqrt{5}$ as $t^2 - 5 = 0$
- algorithmic proofs of identities — $\sum_{k=0}^{n} \binom{n}{k} = 2^n$
- complexity-driven algorithms — 3^N in $\tilde{O}(N)$

Ultimate goals

- automatic computations on functional equations
- computer-driven resolution of difficult problems

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Ultimate goals

- automatic computations on functional equations
- computer-driven resolution of difficult problems e.g., in combinatorics

An (innocent looking) combinatorial question

Let $\mathfrak{S} = \{\uparrow, \leftarrow, \searrow\}$. A $\mathfrak{S}$-walk is a path in $\mathbb{Z}^2$ using only steps from $\mathfrak{S}$. Show that, for any integer n, the following quantities are equal:

(i) the number a_n of $\mathfrak{S}$-walks of length n confined to the upper half plane $\mathbb{Z} \times \mathbb{N}$ that start and end at the origin $(0,0)$;

(ii) the number b_n of $\mathfrak{S}$-walks of length n confined to the quarter plane $\mathbb{N}^2$ that start at the origin $(0,0)$ and finish on the diagonal $x = y$.

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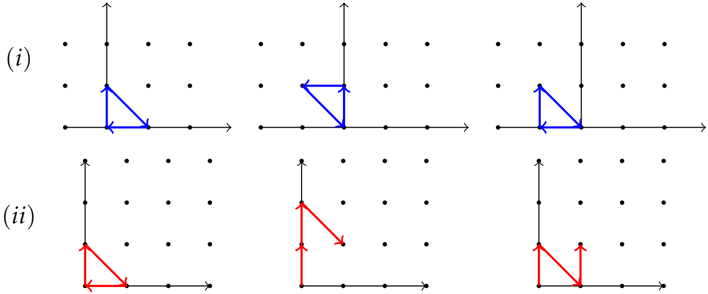
For instance, for $n = 3$, this common value is $a_3 = b_3 = 3$:



Teasers

Teaser 1: This problem can be solved using computer algebra!

Teaser 2: The answer has a nice closed form!

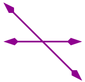
$$a_{3n} = b_{3n} = \frac{(3n)!}{n!^2 \cdot (n+1)!}, \qquad \text{and} \quad a_m = b_m = 0 \quad \text{if 3 does not divide } m.$$

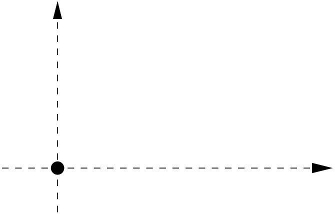
Teaser 3: A certain group attached to the step set $\{\uparrow, \leftarrow, \searrow\}$ is finite!

Combinatorial context: lattice paths confined to cones

Let $\mathfrak{S}$ be a subset of $\mathbb{Z}^d$ (step set, or model) and $p_0 \in \mathbb{Z}^d$ (starting point).

Example: $\mathfrak{S} = \{(1,0),(-1,0),(1,-1),(-1,1)\}$, $p_0 = (0,0)$





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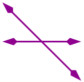

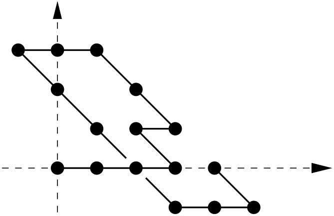

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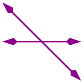
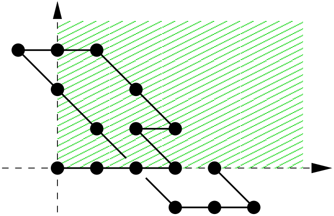
Let $\mathfrak{C}$ be a cone of $\mathbb{R}^d$ (if $x \in \mathfrak{C}$ and $r \geq 0$ then $r \cdot x \in \mathfrak{C}$).

Example: $\mathfrak{S} = \{(1,0), (-1,0), (1,-1), (-1,1)\}$, $p_0 = (0,0)$ and $\mathfrak{C} = \mathbb{R}_+^2$





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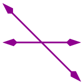

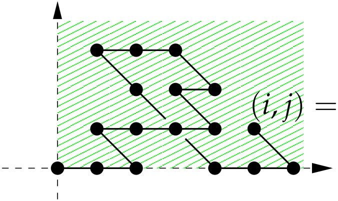

$(i,j) = (5,1)$

Questions

- What is the number a_n of n-step walks contained in $\mathfrak{C}$?
- For $\boldsymbol{i} \in \mathfrak{C}$, what is the number $a_{n;\boldsymbol{i}}$ of such walks that end at $\boldsymbol{i}$?
- What about their GF's $A(t) = \sum_n a_n t^n$ and $A(t;\boldsymbol{x}) = \sum_{n,\boldsymbol{i}} a_{n;\boldsymbol{i}} \boldsymbol{x}^{\boldsymbol{i}} t^n$?

Why count walks in cones?

Many discrete objects can be encoded in that way:

- discrete mathematics (permutations, trees, words, urns, ...)
- statistical physics (Ising model, ...)
- probability theory (branching processes, games of chance, ...)
- operations research (queueing theory, ...)

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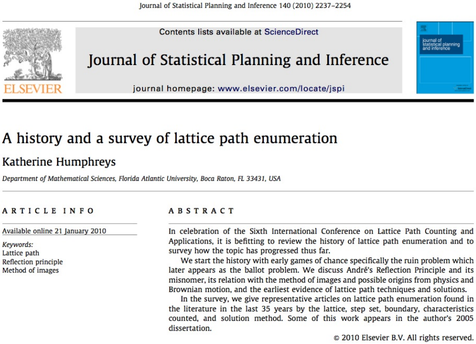
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A history and a survey of lattice path enumeration

Katherine Humphreys

Department of Mathematical Sciences, Florida Atlantic University, Boca Raton, FL 33431, USA

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ABSTRACT

In celebration of the Sixth International Conference on Lattice Path Counting and Applications, it is befitting to review the history of lattice path enumeration and to survey how the topic has progressed thus far.

We start the history with early games of chance specifically the ruin problem which later appears as the ballot problem. We discuss André's Reflection Principle and its misnomer, its relation with the method of images and possible origins from physics and Brownian motion, and the earliest evidence of lattice path techniques and solutions.

In the survey, we give representative articles on lattice path enumeration found in the literature in the last 35 years by the lattice, step set, boundary, characteristics counted, and solution method. Some of this work appears in the author's 2005 dissertation.

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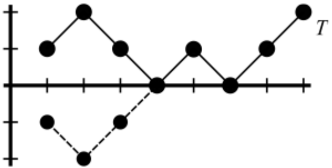
An old topic: ballot problem [Bertrand, 1887]

Suppose that candidates A and B are running in an election. If a votes are cast for A and b votes are cast for B, where $a > b$, then the probability that A stays ahead of B throughout the counting of the ballots is $(a-b)/(a+b)$.

Lattice path reformulation: find the number of paths that start at the origin and never touch the x-axis, consisting of a upsteps $\nearrow$ and b downsteps $\searrow$

Reflection principle [Aebly, 1923]: *paths in* $\mathbb{N}^2$ *from* $(1,1)$ *to* $T(a+b, a-b)$ *that do touch the x-axis* are in bijection with *paths in* $\mathbb{Z}^2$ *from* $(1,-1)$ *to* T



Answer: (*paths in* $\mathbb{Z}^2$ *from* $(1,1)$ *to* T) − (*paths in* $\mathbb{Z}^2$ *from* $(1,-1)$ *to* T)

$$\binom{a+b-1}{a-1} - \binom{a+b-1}{b-1} = \frac{a-b}{a+b}\binom{a+b}{a}$$

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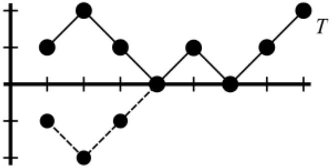
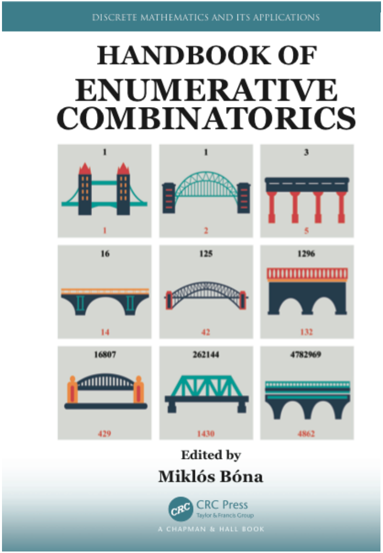


Answer: when $a = n+1$ and $b = n$, this is the Catalan number

$$C_n = \frac{1}{2n+1}\binom{2n+1}{n+1} = \frac{1}{n+1}\binom{2n}{n}$$

. . . but still a topical issue



Chapter 10

Lattice Path Enumeration

Christian Krattenthaler
Universität Wien

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A (very) basic cone: the full space

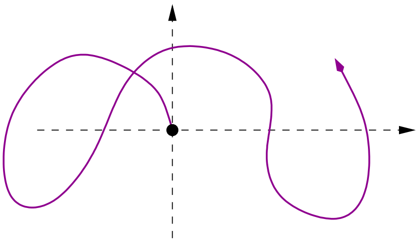
Rational series [folklore]

If $\mathfrak{S} \subset \mathbb{Z}^d$ is finite and $\mathfrak{C} = \mathbb{R}^d$, then

$$a_n = |\mathfrak{S}|^n, \text{ i.e. } \quad A(t) = \sum_{n \geq 0} a_n t^n = \frac{1}{1 - |\mathfrak{S}|\, t}.$$

More generally:

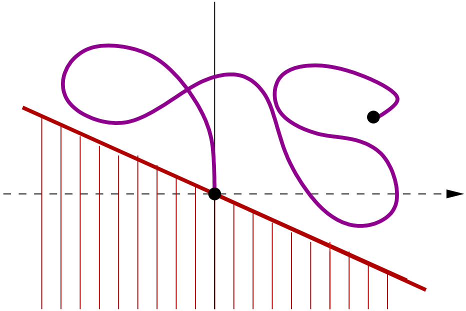
$$A(t; \boldsymbol{x}) = \sum_{n, \boldsymbol{i}} a_{n;\boldsymbol{i}} \boldsymbol{x}^{\boldsymbol{i}} t^n = \frac{1}{1 - t \sum_{\boldsymbol{s} \in \mathfrak{S}} \boldsymbol{x}^{\boldsymbol{s}}}.$$



Also well-known: a (rational) half-space

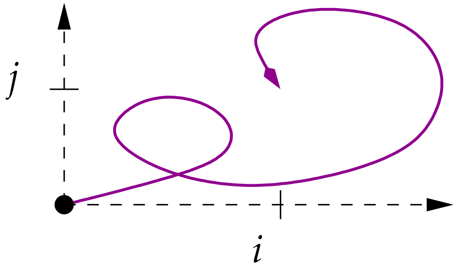
Algebraic series [Bousquet-Mélou, Petkovšek, 2000]

If $\mathfrak{S} \subset \mathbb{Z}^d$ is finite and $\mathfrak{C}$ is a rational half-space, then $A(t; \boldsymbol{x})$ is algebraic, given by an explicit system of polynomial equations.



Example: For Dyck paths (ballot problem), $A(t;1) = \sum_{n \geq 0} C_n t^n = \dfrac{1-\sqrt{1-4t}}{2t}$

The “next” case: intersection of two half-spaces



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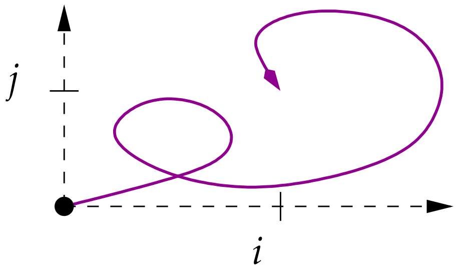

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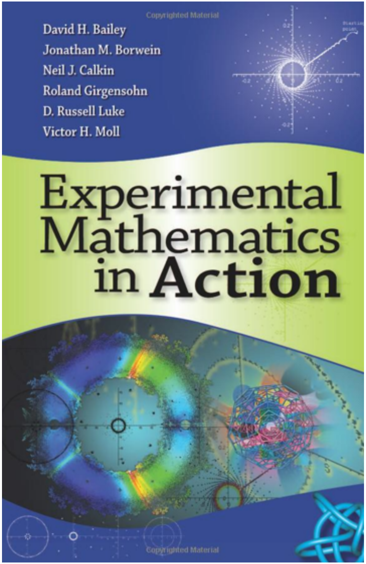
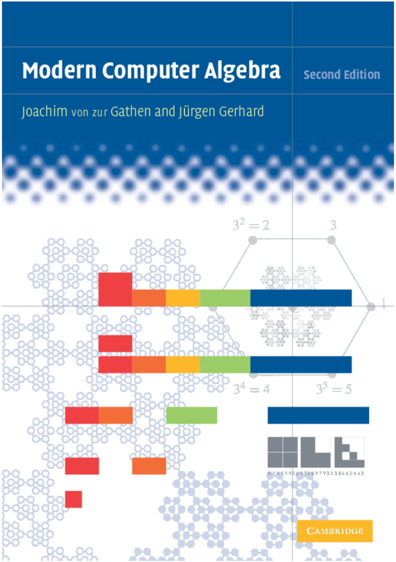
Approach: Experimental Mathematics using Computer Algebra





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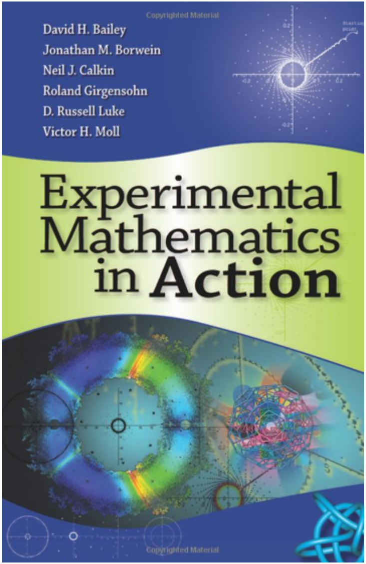
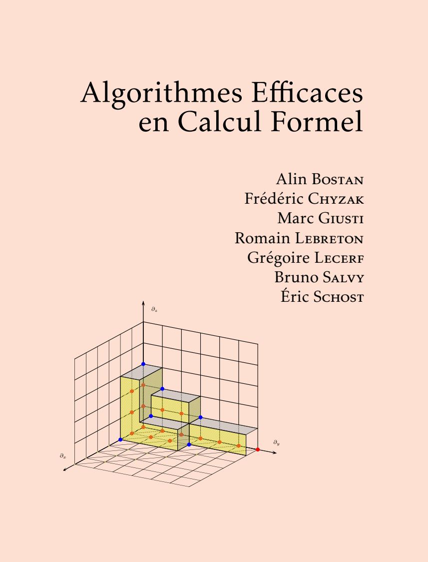


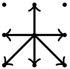


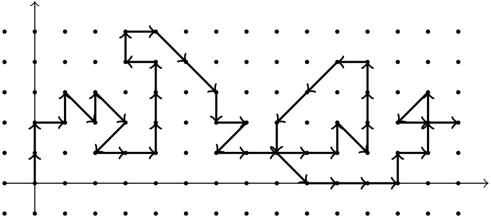
Lattice walks with small steps in the quarter plane

▷ From now on: we focus on nearest-neighbor walks in the quarter plane, i.e. walks in $\mathbb{N}^2$ starting at $(0,0)$ and using steps in a *fixed* subset $\mathfrak{S}$ of

$$\{\swarrow, \leftarrow, \nwarrow, \uparrow, \nearrow, \rightarrow, \searrow, \downarrow\}.$$

▷ Example with $n = 45$, $i = 14$, $j = 2$ for:

$\mathfrak{S} =$ 



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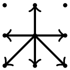
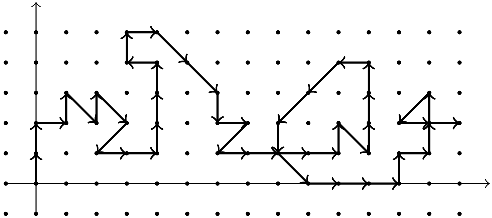
$\mathfrak{S} =$ 



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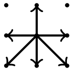
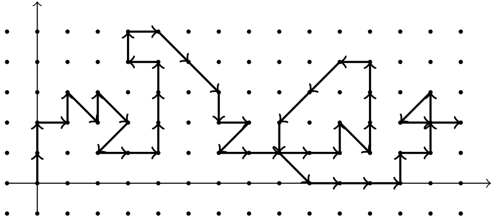
$\mathfrak{S} =$ 



▷ Counting sequence: $f_{n;i,j}$ = number of walks of length n ending at (i,j).

▷ Specializations:

- $f_{n;0,0}$ = number of walks of length n returning to origin ("excursions");
- $f_n = \sum_{i,j\geq 0} f_{n;i,j}$ = number of walks with prescribed length n.

Generating functions and combinatorial problems

▷ Complete generating function:

$$F(t;x,y) = \sum_{n=0}^{\infty} \left(\sum_{i,j=0}^{\infty} f_{n;i,j} x^i y^j \right) t^n \ \in \mathbb{Q}[x,y][[t]].$$

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- GF of walks: $F(t;1,1) = \sum_{n \geq 0} f_n t^n$;
- GF of horizontal returns: $F(t;1,0)$;
- GF of diagonal returns: "$F(t;0,\infty)$" $:= \left[x^0\right] F(t;x,1/x)$.

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Combinatorial questions:
Given $\mathfrak{S}$, what can be said about $F(t;x,y)$, resp. $f_{n;i,j}$, and their variants?

- Structure of F: algebraic? transcendental? solution of ODE?
- Explicit form: of F? of $f_{n;i,j}$?
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Our goal: Use computer algebra to give computational answers.

Small-step models of interest

Among the 2^8 step sets $\mathfrak{S} \subseteq \{-1,0,1\}^2 \setminus \{(0,0)\}$, some are:

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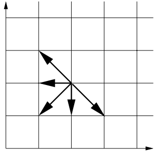

trivial,

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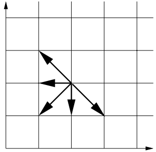

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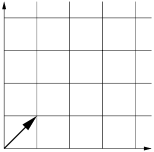

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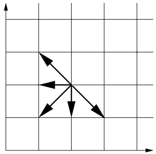

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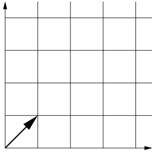

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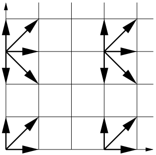

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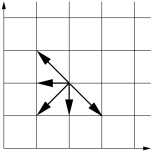

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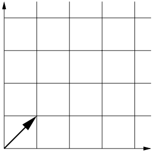

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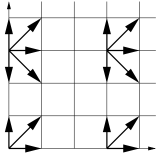

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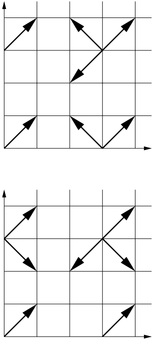

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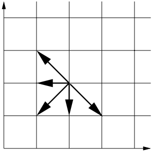

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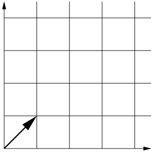

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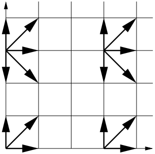

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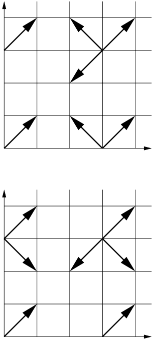

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One is left with 79 interesting distinct models.

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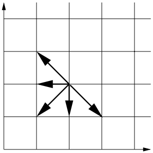

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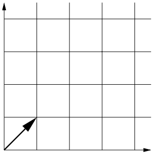

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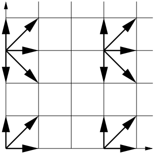

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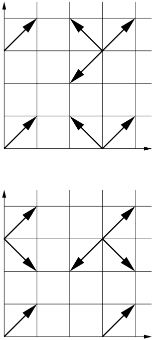

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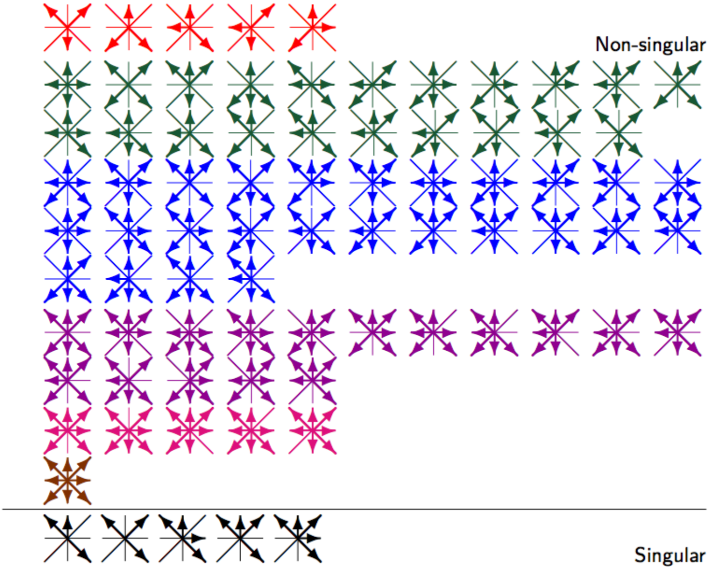
One is left with 79 interesting distinct models.

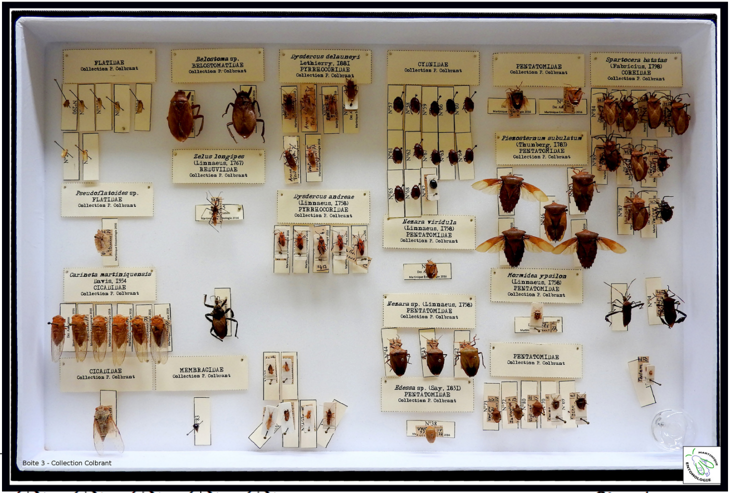
Is any further classification possible?

The 79 models



The 79 models

Non-singular

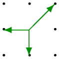


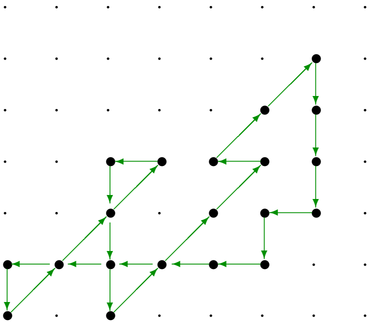
Singular

Two important models: Kreweras and Gessel walks

$\mathfrak{S} = \{\downarrow, \leftarrow, \nearrow\}$ $\qquad F_{\mathfrak{S}}(t;x,y) \equiv K(t;x,y)$

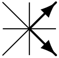
$\mathfrak{S} = \{\nearrow, \swarrow, \leftarrow, \rightarrow\}$ $\qquad F_{\mathfrak{S}}(t;x,y) \equiv G(t;x,y)$

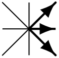




Example: A Kreweras excursion.

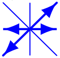
“Special” models

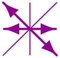
Dyck: 

Motzkin: 

Pólya: 

Kreweras: 

Gessel: 

Gouyou-Beauchamps: 

King walks: 

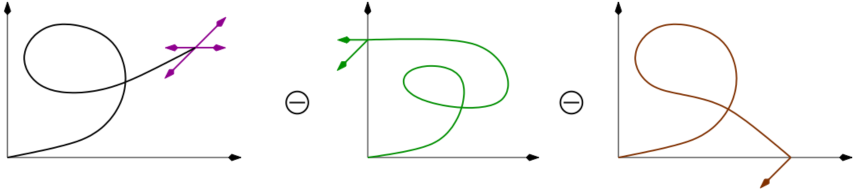
Tandem walks: 

Algebraic reformulation: solving a functional equation

Generating function: $G(t;x,y) = \sum_{n=0}^{\infty} \sum_{i=0}^{n} \sum_{j=0}^{n} g_{n;i,j} t^n x^i y^j \in \mathbb{Q}[x,y][[t]]$

"Kernel equation":

$$G(t;x,y) = 1 + t\left(xy + x + \frac{1}{xy} + \frac{1}{x}\right) G(t;x,y) - t\left(\frac{1}{x} + \frac{1}{x}\frac{1}{y}\right) G(t;0,y) - t\frac{1}{xy}\left(G(t;x,0) - G(t;0,0)\right)$$



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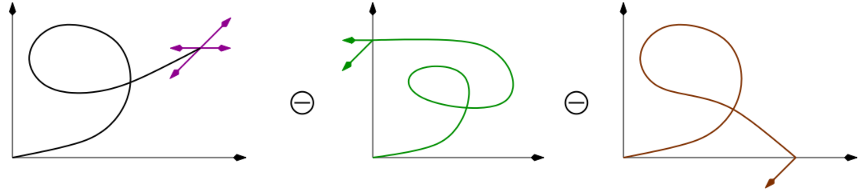

Task: Solve this functional equation!

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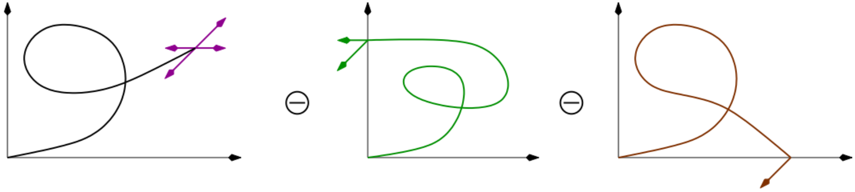
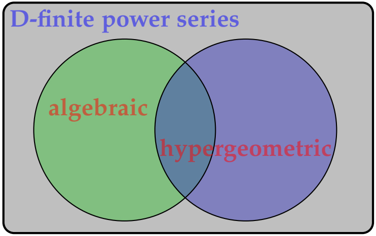


Task: For the other models – solve 78 similar equations!

Classification of univariate power series



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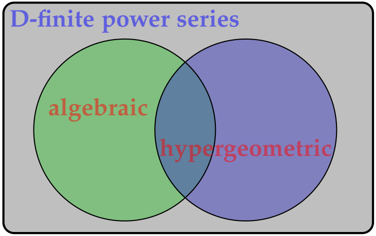

$$S(t) = \sum_{n=0}^{\infty} s_n t^n \in \mathbb{Q}[[t]] \quad \text{is}$$

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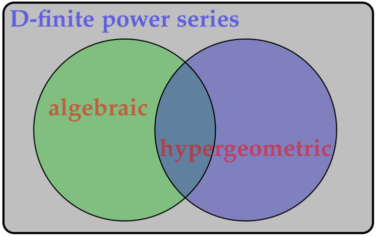

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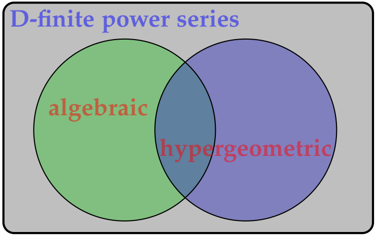

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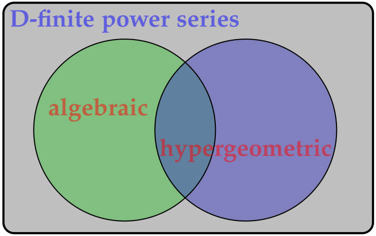

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$$\ln(1-t); \quad \frac{\arcsin(\sqrt{t})}{\sqrt{t}}; \quad (1-t)^{\alpha}, \alpha \in \mathbb{Q}$$

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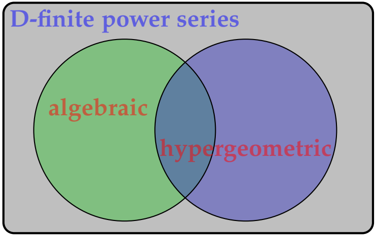

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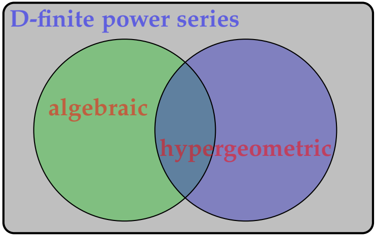

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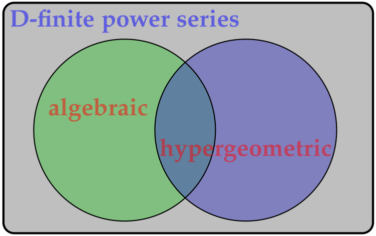

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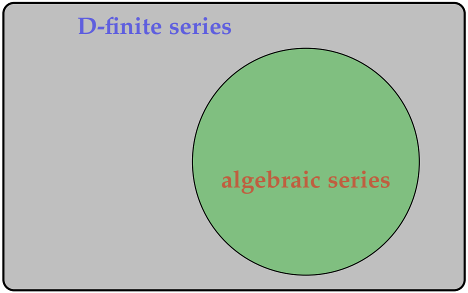
Theorem [Schwarz, 1873; Beukers, Heckman, 1989]

Characterization of { *hypergeometric* } ∩ { *algebraic* }.

Classification of multivariate power series



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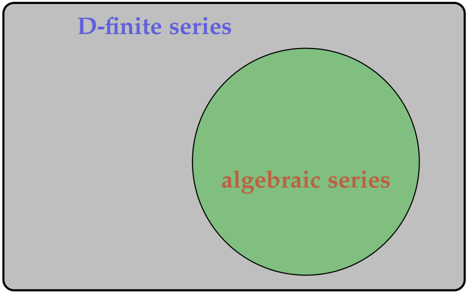

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▷ $S \in \mathbb{Q}[[x, y, t]]$ is *D-finite* if it satisfies a system of linear partial differential equations with polynomial coefficients

$$\sum_i a_i(t, x, y) \frac{\partial^i S}{\partial x^i} = 0, \quad \sum_i b_i(t, x, y) \frac{\partial^i S}{\partial y^i} = 0, \quad \sum_i c_i(t, x, y) \frac{\partial^i S}{\partial t^i} = 0.$$

Main results (I): algebraicity of Gessel walks

Theorem [Kreweras, 1965; 100 pages long combinatorial proof!]

$$K(t;0,0) = {}_3F_2\left(\begin{matrix}1/3 & 2/3 & 1\\ & 3/2 & 2\end{matrix}\,\middle|\, 27\,t^3\right) = \sum_{n=0}^{\infty} \frac{4^n \binom{3n}{n}}{(n+1)(2n+1)} t^{3n}.$$

Theorem [Kauers, Koutschan, Zeilberger, 2009: former Gessel's conj. 1]

$$G(t;0,0) = {}_3F_2\left(\begin{matrix}5/6 & 1/2 & 1\\ & 5/3 & 2\end{matrix}\,\middle|\, 16t^2\right) = \sum_{n=0}^{\infty} \frac{(5/6)_n (1/2)_n}{(5/3)_n (2)_n} (4t)^{2n}.$$

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▷ Computer-driven discovery and proof.
▷ Guess'n'Prove method, using Hermite-Padé approximants†

† Minimal polynomial $P(x,y,t,G(t;x,y)) = 0$ has $> 10^{11}$ terms; $\approx 30\,$Gb (!)

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Question: What about the structure of $K(t;x,y)$ and $G(t;x,y)$?

Theorem [Gessel, 1986; Bousquet-Mélou, 2005] $K(t;x,y)$ is algebraic.

Theorem [B., Kauers, 2010: former Gessel's conj. 2] $G(t;x,y)$ is algebraic.

▷ Computer-driven discovery and proof.
▷ Guess'n'Prove method, using Hermite-Padé approximants†

▷ Recent (human) proofs [B., Kurkova, Raschel, 2013; Bousquet-Mélou, 2015]

---

† Minimal polynomial $P(x,y,t,G(t;x,y)) = 0$ has $> 10^{11}$ terms; ≈ 30 Gb (!)

Main results (II): Explicit form for $G(t;x,y)$

Theorem [B., Kauers, van Hoeij, 2010]

Let $V = 1 + 4t^2 + 36t^4 + 396t^6 + \cdots$ be a root of

$$(V-1)(1+3/V)^3 = (16t)^2,$$

let $U = 1 + 2t^2 + 16t^4 + 2xt^5 + 2(x^2+83)t^6 + \cdots$ be a root of

$$x(V-1)(V+1)U^3 - 2V(3x+5xV-8Vt)U^2$$
$$-xV(V^2-24V-9)U + 2V^2(xV-9x-8Vt) = 0,$$

let $W = t^2 + (y+8)t^4 + 2(y^2+8y+41)t^6 + \cdots$ be a root of

$$y(1-V)W^3 + y(V+3)W^2 - (V+3)W + V - 1 = 0.$$

Then $G(t;x,y)$ is equal to

$$\frac{\frac{64(U(V+1)-2V)V^{3/2}}{x(U^2-V(U^2-8U+9-V))^2} - \frac{y(W-1)^4(1-Wy)V^{-3/2}}{t(y+1)(1-W)(W^2y+1)^2}}{(1+y+x^2y+x^2y^2)t-xy} - \frac{1}{tx(y+1)}.$$

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▷ Computer-driven discovery and proof.
▷ Proof uses guessed minimal polynomials for $G(t; x, 0)$ and $G(t; 0, y)$.

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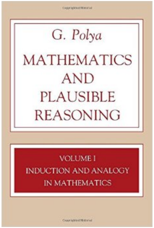
▷ Recent (human) proofs [B., Kurkova, Raschel, 2013; Bousquet-Mélou, 2015]

First guess, then prove [Pólya, 1954]



Guessing and Proving

George Pólya

What is "scientific method"? Philosophers and non-philosophers have discussed this question and have not yet finished discussing it. Yet as a first introduction it can be described in three syllables:

Guess and test.

Mathematicians too follow this advice in their research although they sometimes refuse to confess it. They have, however, something which the other scientists cannot really have. For mathematicians the advice is

First guess, then prove.

A typical *guess'n'prove* algorithmic proof

Theorem

$$g(t) := G(\sqrt{t}; 0, 0) = \sum_{n=0}^{\infty} \frac{(5/6)_n (1/2)_n}{(5/3)_n (2)_n} (16t)^n \quad \text{is algebraic.}$$

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Proof: First guess a polynomial $P(t,T)$ in $\mathbb{Q}[t,T]$, then prove that P admits the power series $g(t) = \sum_{n=0}^{\infty} g_n t^n$ as a root.

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1. Find P such that $P(t, g(t)) = 0 \bmod t^{100}$ by (structured) linear algebra.

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1. Find P such that $P(t, g(t)) = 0 \bmod t^{100}$ by (structured) linear algebra.
2. Implicit function theorem: $\exists!$ root $r(t) \in \mathbb{Q}[[t]]$ of P.
3. $r(t) = \sum_{n=0}^{\infty} r_n t^n$ being algebraic, it is D-finite, and so is (r_n):

$$(n+2)(3n+5)r_{n+1} - 4(6n+5)(2n+1)r_n = 0, \qquad r_0 = 1$$

$\Rightarrow$ solution $r_n = \frac{(5/6)_n (1/2)_n}{(5/3)_n (2)_n} 16^n = g_n$, thus $g(t) = r(t)$ is algebraic.

Main results (III): Models with D-Finite $F(t;1,1)$

	OEIS	$\mathfrak{S}$	Pol size	LDE size	Rec size		OEIS	$\mathfrak{S}$	Pol size	LDE size	Rec size
1	A005566		—	(3, 4)	(2, 2)	13	A151275		—	(5, 24)	(9, 18)
2	A018224		—	(3, 5)	(2, 3)	14	A151314		—	(5, 24)	(9, 18)
3	A151312		—	(3, 8)	(4, 5)	15	A151255		—	(4, 16)	(6, 8)
4	A151331		—	(3, 6)	(3, 4)	16	A151287		—	(5, 19)	(7, 11)
5	A151266		—	(5, 16)	(7, 10)	17	A001006		(2, 2)	(2, 3)	(2, 1)
6	A151307		—	(5, 20)	(8, 15)	18	A129400		(2, 2)	(2, 3)	(2, 1)
7	A151291		—	(5, 15)	(6, 10)	19	A005558		—	(3, 5)	(2, 3)
8	A151326		—	(5, 18)	(7, 14)						
9	A151302		—	(5, 24)	(9, 18)	20	A151265		(6, 8)	(4, 9)	(6, 4)
10	A151329		—	(5, 24)	(9, 18)	21	A151278		(6, 8)	(4, 12)	(7, 4)
11	A151261		—	(4, 15)	(5, 8)	22	A151323		(4, 4)	(2, 3)	(2, 1)
12	A151297		—	(5, 18)	(7, 11)	23	A060900		(8, 9)	(3, 5)	(2, 3)

Equation sizes = (order, degree)

- ▷ Computerized discovery: enumeration + guessing [B., Kauers, 2009]
- ▷ 1–22: Confirmed by human proofs in [Bousquet-Mélou, Mishna, 2010]
- ▷ 23: Confirmed by a human proof in [B., Kurkova, Raschel, 2013]

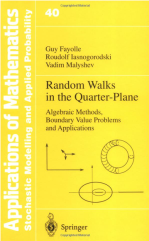
Main results (III): Models with D-Finite $F(t;1,1)$

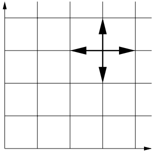
	OEIS	$\mathfrak{S}$	algebraic?	asymptotics		OEIS	$\mathfrak{S}$	algebraic?	asymptotics
1	A005566		N	$\frac{4}{\pi}\frac{4^n}{n}$	13	A151275		N	$\frac{12\sqrt{30}}{\pi}\frac{(2\sqrt{6})^n}{n^2}$
2	A018224		N	$\frac{2}{\pi}\frac{4^n}{n}$	14	A151314		N	$\frac{\sqrt{6}\lambda\mu C^{5/2}}{5\pi}\frac{(2C)^n}{n^2}$
3	A151312		N	$\frac{\sqrt{6}}{\pi}\frac{6^n}{n}$	15	A151255		N	$\frac{24\sqrt{2}}{\pi}\frac{(2\sqrt{2})^n}{n^2}$
4	A151331		N	$\frac{8}{3\pi}\frac{8^n}{n}$	16	A151287		N	$\frac{2\sqrt{2}A^{7/2}}{\pi}\frac{(2A)^n}{n^2}$
5	A151266		N	$\frac{1}{2}\sqrt{\frac{3}{\pi}}\frac{3^n}{n^{1/2}}$	17	A001006		Y	$\frac{3}{2}\sqrt{\frac{3}{\pi}}\frac{3^n}{n^{3/2}}$
6	A151307		N	$\frac{1}{2}\sqrt{\frac{5}{2\pi}}\frac{5^n}{n^{1/2}}$	18	A129400		Y	$\frac{3}{2}\sqrt{\frac{3}{\pi}}\frac{6^n}{n^{3/2}}$
7	A151291		N	$\frac{4}{3\sqrt{\pi}}\frac{4^n}{n^{1/2}}$	19	A005558		N	$\frac{8}{\pi}\frac{4^n}{n^2}$
8	A151326		N	$\frac{2}{\sqrt{3\pi}}\frac{6^n}{n^{1/2}}$					
9	A151302		N	$\frac{1}{3}\sqrt{\frac{5}{2\pi}}\frac{5^n}{n^{1/2}}$	20	A151265		Y	$\frac{2\sqrt{2}}{\Gamma(1/4)}\frac{3^n}{n^{3/4}}$
10	A151329		N	$\frac{1}{3}\sqrt{\frac{7}{3\pi}}\frac{7^n}{n^{1/2}}$	21	A151278		Y	$\frac{3\sqrt{3}}{\sqrt{2}\Gamma(1/4)}\frac{3^n}{n^{3/4}}$
11	A151261		N	$\frac{12\sqrt{3}}{\pi}\frac{(2\sqrt{3})^n}{n^2}$	22	A151323		Y	$\frac{\sqrt{2}3^{3/4}}{\Gamma(1/4)}\frac{6^n}{n^{3/4}}$
12	A151297		N	$\frac{\sqrt{3}B^{7/2}}{2\pi}\frac{(2B)^n}{n^2}$	23	A060900		Y	$\frac{4\sqrt{3}}{3\Gamma(1/3)}\frac{4^n}{n^{2/3}}$

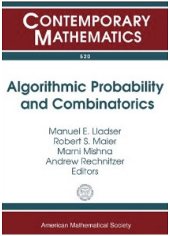
$$A = 1+\sqrt{2},\ B = 1+\sqrt{3},\ C = 1+\sqrt{6},\ \lambda = 7+3\sqrt{6},\ \mu = \sqrt{\frac{4\sqrt{6}-1}{19}}$$

- ▷ Computerized discovery: conv. acc. + LLL/PSLQ [B., Kauers, 2009]
- ▷ Confirmed by human proofs using ACSV in [Melczer, Wilson, 2015]

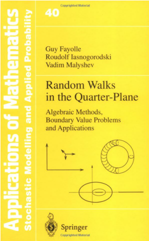
The group of a model: the simple walk case

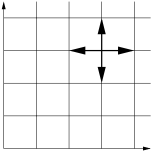


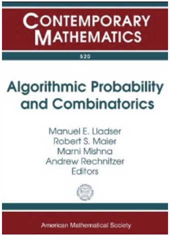




The characteristic polynomial $\chi_{\mathfrak{S}} := x + \frac{1}{x} + y + \frac{1}{y}$



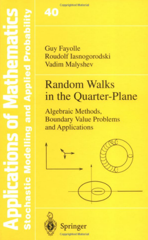


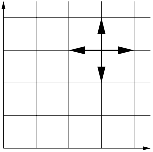


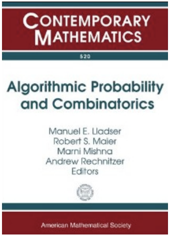
The characteristic polynomial $\chi_{\mathfrak{S}} := x + \frac{1}{x} + y + \frac{1}{y}$ is left invariant under

$$\psi(x,y) = \left(x, \frac{1}{y}\right), \quad \phi(x,y) = \left(\frac{1}{x}, y\right),$$

The group of a model: the simple walk case







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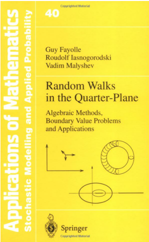
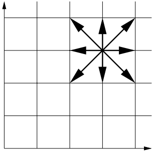
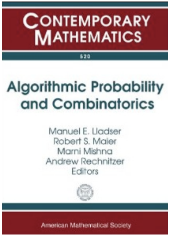
and thus under any element of the group

$$\langle \psi, \phi \rangle = \left\{ (x,y), \left(x, \frac{1}{y}\right), \left(\frac{1}{x}, \frac{1}{y}\right), \left(\frac{1}{x}, y\right) \right\}.$$

The group of a model: the general case

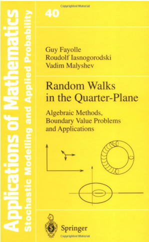


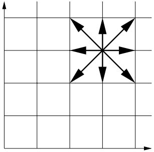


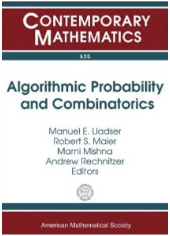


The polynomial $\chi_{\mathfrak{S}} := \sum_{(i,j)\in\mathfrak{S}} x^i y^j = \sum_{i=-1}^{1} B_i(y) x^i = \sum_{j=-1}^{1} A_j(x) y^j$

The group of a model: the general case







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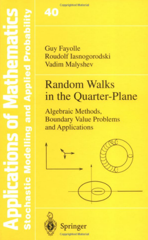
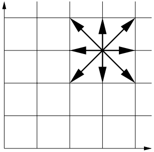
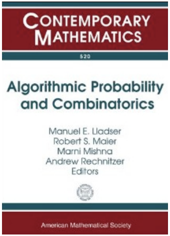
The group of a model: the general case







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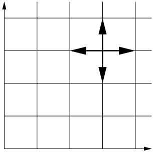
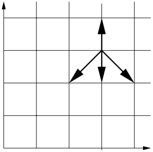
$$\mathcal{G}_{\mathfrak{S}} := \langle \psi, \phi \rangle.$$

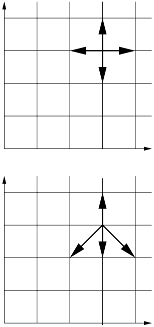
Examples of groups





Order 4,

Examples of groups



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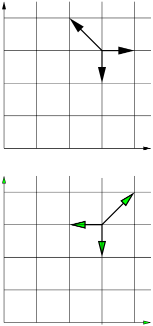
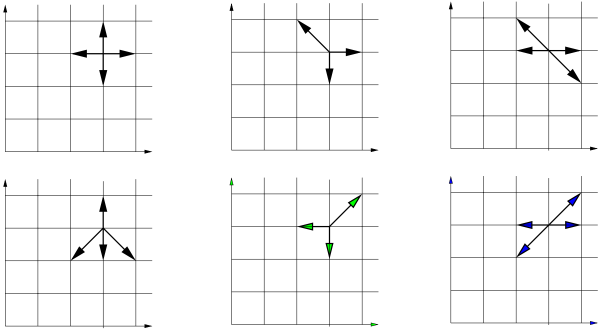


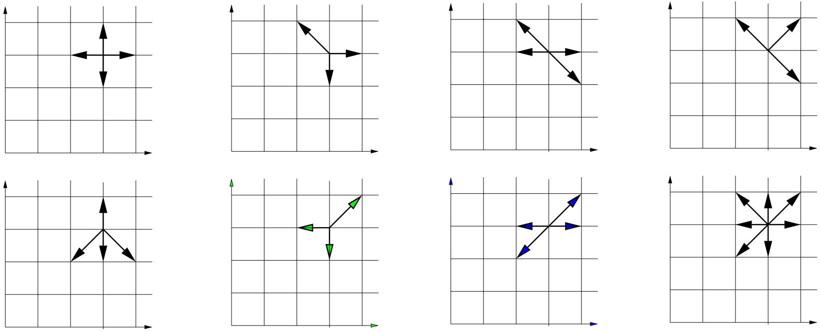
order 6,

Examples of groups



Order 4, order 6, order 8,

Examples of groups



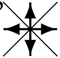
Order 4, order 6, order 8, order ∞.

An important concept: the orbit sum (OS)

When $\mathcal{G}_{\mathfrak{S}}$ is finite, the orbit sum of $\mathfrak{S}$ is the polynomial in $\mathbb{Q}[x, x^{-1}, y, y^{-1}]$:

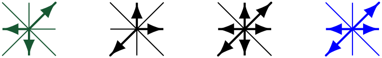
$$\mathrm{OS}_{\mathfrak{S}} := \sum_{\theta \in \mathcal{G}_{\mathfrak{S}}} (-1)^{\theta} \theta(xy)$$

▷ E.g., for the simple walk, with $\mathcal{G}_{\mathfrak{S}} = \left\{ (x,y), \left(x, \frac{1}{y}\right), \left(\frac{1}{x}, \frac{1}{y}\right), \left(\frac{1}{x}, y\right) \right\}$:

OS 

$$= x \cdot y - \frac{1}{x} \cdot y + \frac{1}{x} \cdot \frac{1}{y} - x \cdot \frac{1}{y}$$

▷ For 4 models, the orbit sum is zero:



E.g., for the Kreweras model:

OS 

$$= x \cdot y - \frac{1}{xy} \cdot y + \frac{1}{xy} \cdot x - y \cdot x + y \cdot \frac{1}{xy} - x \cdot \frac{1}{xy} \quad = 0$$

The 79 models: finite and infinite groups

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23 admit a finite group

[Mishna'07]

56 have an infinite group

[Bousquet-Mélou, Mishna'10]

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all $F(t;x,y)$ D-finite

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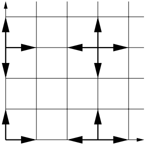
$\longrightarrow$ all non-D-finite

- [Mishna, Rechnitzer'07] and [Melczer, Mishna'13] for 5 singular models
- [Kurkova, Raschel'13] and [B., Raschel, Salvy'13] for all others

D-Finiteness via the finite group [Bousquet-Mélou, Mishna, 2010]



The kernel $J = 1 - t \cdot \sum_{(i,j)\in\mathfrak{S}} x^i y^j = 1 - t\left(x + \frac{1}{x} + y + \frac{1}{y}\right)$ is invariant under the change of (x, y) into, respectively:

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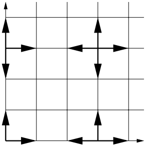

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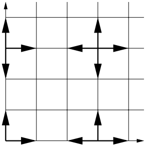

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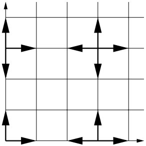

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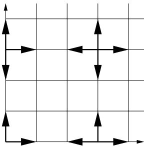

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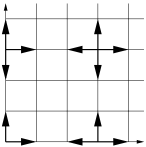

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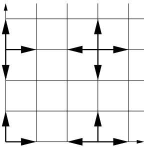
\end{aligned}$$

Summing up yields the orbit equation:

$$\sum_{\theta\in\mathcal{G}} (-1)^\theta \theta\big(xy\,F(t;x,y)\big) = \frac{xy - \frac{1}{x}y + \frac{1}{x}\frac{1}{y} - x\frac{1}{y}}{J(t;x,y)}$$



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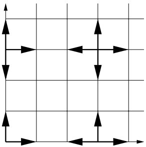
Taking positive parts yields:

$$[x^> y^>] \sum_{\theta\in\mathcal{G}} (-1)^\theta \theta\big(xy\,F(t;x,y)\big) = [x^> y^>] \frac{xy - \frac{1}{x}y + \frac{1}{x}\frac{1}{y} - x\frac{1}{y}}{J(t;x,y)}$$

D-Finiteness via the finite group [Bousquet-Mélou, Mishna, 2010]



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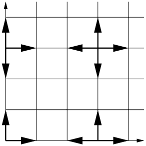

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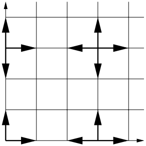
$$\mathsf{GF} = \mathsf{PosPart}\left(\frac{\mathsf{OS}}{\mathsf{kernel}}\right)$$



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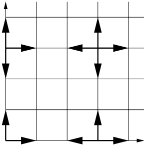

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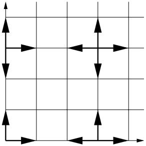
▷ Argument works if $\mathsf{OS} \neq 0$: algebraic version of the reflection principle

D-Finiteness via the finite group [Bousquet-Mélou, Mishna, 2010]



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▷ Creative Telescoping finds a differential equation for PosPart(OS/ker)

Main results (IV): explicit expressions for models 1–19

Theorem [B., Chyzak, van Hoeij, Kauers, Pech, 2016]

Let $\mathfrak{S}$ be one of the 19 models with finite group $\mathcal{G}_{\mathfrak{S}}$, and non-zero orbit sum. Then

- $F_{\mathfrak{S}}$ is expressible using iterated integrals of ${}_2F_1$ expressions.
- Among the 19×4 specializations of $F_{\mathfrak{S}}(t; x, y)$ at $(x, y) \in \{0, 1\}^2$, only 4 are algebraic: for $\mathfrak{S} =$  at $(1, 1)$, and $\mathfrak{S} =$  at $(1, 0), (0, 1), (1, 1)$

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Example (King walks in the quarter plane, A025595)

F 

$$F_{\text{king}}(t; 1, 1) = \frac{1}{t} \int_0^t \frac{1}{(1+4x)^3} \cdot {}_2F_1\left(\left. \begin{matrix} \frac{3}{2} \ \frac{3}{2} \\ 2 \end{matrix} \right| \frac{16x(1+x)}{(1+4x)^2} \right) dx$$

$$= 1 + 3t + 18t^2 + 105t^3 + 684t^4 + 4550t^5 + 31340t^6 + 219555t^7 + \cdots$$

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▷ Computer-driven discovery and proof; no human proof yet.
▷ Proof uses creative telescoping, ODE factorization, ODE solving.

Hypergeometric Series Occurring in Explicit Expressions for $F(t;x,y)$

	$\mathfrak{S}$	occurring ${}_2F_1$	w		$\mathfrak{S}$	occurring ${}_2F_1$	w
1		${}_2F_1\left(\begin{matrix}\frac{1}{2} & \frac{1}{2}\\ & 1\end{matrix}\middle\| w\right)$	$16t^2$	11		${}_2F_1\left(\begin{matrix}\frac{1}{2} & \frac{1}{2}\\ & 1\end{matrix}\middle\| w\right)$	$\frac{16t^2}{4t^2+1}$
2		${}_2F_1\left(\begin{matrix}\frac{1}{2} & \frac{1}{2}\\ & 1\end{matrix}\middle\| w\right)$	$16t^2$	12		${}_2F_1\left(\begin{matrix}\frac{1}{4} & \frac{3}{4}\\ & 1\end{matrix}\middle\| w\right)$	$\frac{64t^3(2t+1)}{(8t^2-1)^2}$
3		${}_2F_1\left(\begin{matrix}\frac{1}{4} & \frac{3}{4}\\ & 1\end{matrix}\middle\| w\right)$	$\frac{64t^2}{(12t^2+1)^2}$	13		${}_2F_1\left(\begin{matrix}\frac{1}{4} & \frac{3}{4}\\ & 1\end{matrix}\middle\| w\right)$	$\frac{64t^2(t^2+1)}{(16t^2+1)^2}$
4		${}_2F_1\left(\begin{matrix}\frac{1}{2} & \frac{1}{2}\\ & 1\end{matrix}\middle\| w\right)$	$\frac{16t(t+1)}{(4t+1)^2}$	14		${}_2F_1\left(\begin{matrix}\frac{1}{4} & \frac{3}{4}\\ & 1\end{matrix}\middle\| w\right)$	$\frac{64t^2(t^2+t+1)}{(12t^2+1)^2}$
5		${}_2F_1\left(\begin{matrix}\frac{1}{4} & \frac{3}{4}\\ & 1\end{matrix}\middle\| w\right)$	$64t^4$	15		${}_2F_1\left(\begin{matrix}\frac{1}{4} & \frac{3}{4}\\ & 1\end{matrix}\middle\| w\right)$	$64t^4$
6		${}_2F_1\left(\begin{matrix}\frac{1}{4} & \frac{3}{4}\\ & 1\end{matrix}\middle\| w\right)$	$\frac{64t^3(t+1)}{(1-4t^2)^2}$	16		${}_2F_1\left(\begin{matrix}\frac{1}{4} & \frac{3}{4}\\ & 1\end{matrix}\middle\| w\right)$	$\frac{64t^3(t+1)}{(1-4t^2)^2}$
7		${}_2F_1\left(\begin{matrix}\frac{1}{2} & \frac{1}{2}\\ & 1\end{matrix}\middle\| w\right)$	$\frac{16t^2}{4t^2+1}$	17		${}_2F_1\left(\begin{matrix}\frac{1}{3} & \frac{2}{3}\\ & 1\end{matrix}\middle\| w\right)$	$27t^3$
8		${}_2F_1\left(\begin{matrix}\frac{1}{4} & \frac{3}{4}\\ & 1\end{matrix}\middle\| w\right)$	$\frac{64t^3(2t+1)}{(8t^2-1)^2}$	18		${}_2F_1\left(\begin{matrix}\frac{1}{3} & \frac{2}{3}\\ & 1\end{matrix}\middle\| w\right)$	$27t^2(2t+1)$
9		${}_2F_1\left(\begin{matrix}\frac{1}{4} & \frac{3}{4}\\ & 1\end{matrix}\middle\| w\right)$	$\frac{64t^2(t^2+1)}{(16t^2+1)^2}$	19		${}_2F_1\left(\begin{matrix}\frac{1}{2} & \frac{1}{2}\\ & 1\end{matrix}\middle\| w\right)$	$16t^2$
10		${}_2F_1\left(\begin{matrix}\frac{1}{4} & \frac{3}{4}\\ & 1\end{matrix}\middle\| w\right)$	$\frac{64t^2(t^2+t+1)}{(12t^2+1)^2}$				

▷ All related to the complete elliptic integrals $\int_0^{\pi/2}(1-k^2\sin^2\theta)^{\pm\frac{1}{2}}\,d\theta$

Main results (V): non-D-finiteness for models with an infinite group

Theorem [B., Raschel, Salvy, 2013]

Let $\mathfrak{S}$ be one of the 51 non-singular models with infinite group $\mathcal{G}_{\mathfrak{S}}$.
Then $F_{\mathfrak{S}}(t; 0, 0)$, and in particular $F_{\mathfrak{S}}(t; x, y)$, are non-D-finite.

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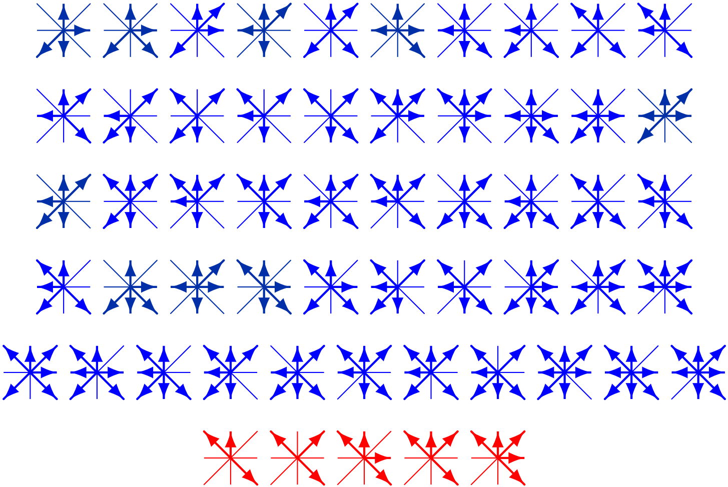
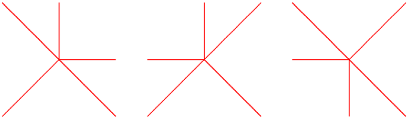
▷ [Bernardi, Bousquet-Mélou, Raschel, 2016] For 9 of these 51 models, $F_{\mathfrak{S}}(t;x,y)$ is nevertheless D-algebraic!
▷ [Dreyfus, Hardouin, Roques, Singer, 2017]: hypertranscendence of the remaining 42 models.



In blue, non-singular models, solved by [B., Raschel, Salvy, 2013]
In red, singular models, solved by [Melczer, Mishna, 2013]

Example: the scarecrows

[B., Raschel, Salvy, 2013]: $F_{\mathfrak{S}}(t;0,0)$ is not D-finite for the models



For the 1st and the 3rd, the excursions sequence $[t^n]\, F_{\mathfrak{S}}(t;0,0)$

$$1, 0, 0, 2, 4, 8, 28, 108, 372, \ldots$$

is $\sim K \cdot 5^n \cdot n^{-\alpha}$, with $\alpha = 1 + \pi / \arccos(1/4) = 3.383396\ldots$

[Denisov, Wachtel, 2013]

The irrationality of α prevents $F_{\mathfrak{S}}(t;0,0)$ from being D-finite.

[Katz, 1970; Chudnovsky, 1985; André, 1989]

Summary: Classification of 2D non-singular walks

The Main Theorem Let $\mathfrak{S}$ be one of the 74 non-singular models. The following assertions are equivalent:

(1) The full generating function $F_{\mathfrak{S}}(t;x,y)$ is D-finite

(2) the excursions generating function $F_{\mathfrak{S}}(t;0,0)$ is D-finite

(3) the excursions sequence $[t^n]\, F_{\mathfrak{S}}(t;0,0)$ is $\sim K \cdot \rho^n \cdot n^\alpha$, with $\alpha \in \mathbb{Q}$

(4) the group $\mathcal{G}_{\mathfrak{S}}$ is finite (and $|\mathcal{G}_{\mathfrak{S}}| = 2 \cdot \min\{\ell \in \mathbb{N}^\star \mid \frac{\ell}{\alpha+1} \in \mathbb{Z}\}$)

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Moreover, under (1)–(5), $F_{\mathfrak{S}}(t;x,y)$ is algebraic if and only if the model $\mathfrak{S}$ has positive covariance $\sum_{(i,j)\in\mathfrak{S}} ij - \sum_{(i,j)\in\mathfrak{S}} i \cdot \sum_{(i,j)\in\mathfrak{S}} j > 0$, and iff it has $\mathrm{OS} = 0$.

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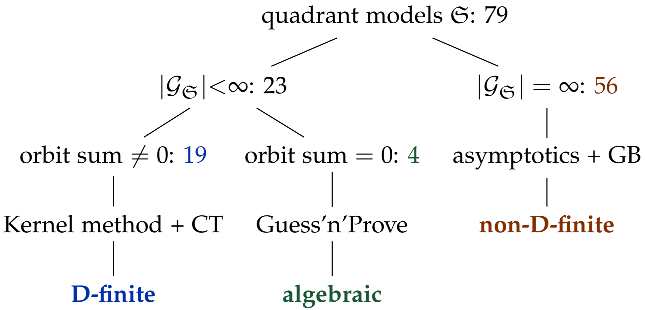
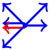
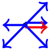
In this case, $F_{\mathfrak{S}}(t;x,y)$ is expressible using nested radicals.
If not, $F_{\mathfrak{S}}(t;x,y)$ is expressible using iterated integrals of ${}_2F_1$ expressions.

Summary: Walks with small steps in $\mathbb{N}^2$



Extensions: Walks in $\mathbb{N}^2$ with small repeated steps

- 2D quadrant models: 527
  - $|\mathcal{G}_{\mathfrak{S}}| < \infty$: 118
    - orbit sum $\neq 0$: 95
      - kernel method: 94 — **D-finite**
      - CA:  — **D-finite**
    - orbit sum $= 0$: 23
      - 22: reducible to Kreweras/Gessel — **D-finite**
      - CA:  — **algebraic**
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    - **non-D-finite?**

[B., Bousquet-Mélou, Kauers, Melczer, 2015]

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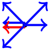
    - CA:  — **D-finite**
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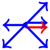
    - CA:  — **algebraic**
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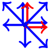
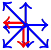
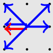
[B., Bousquet-Mélou, Kauers, Melczer, 2015]

▷ [Du, Hou, Wang, 2015]: proofs that groups are infinite in the 409 cases, and GF are non-D-finite in 366 cases.

▷ [Kauers, Yatchak, 2015]: extension to $4^8 = 65536$ models with mult. ≤ 3. 1457 **D-finite**, 79 **algebraic**, 3 pearls:   

A pearl among models in $\mathbb{N}^2$ with small but repeated steps

Theorem [B., Bousquet-Mélou, Kauers, Melczer, 2015]

Let $e_n = \#\Big\{$  – walks of length n in $\mathbb{N}^2$ from $(0,0)$ to $(0,0)\Big\}$

$$(e_n)_{n\geq 0} = (1,\ 0,\ 3,\ 0,\ 26,\ 0,\ 323,\ 0,\ 4830,\ 0,\ 80910, \ldots)$$

Then

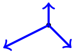
$$e_{2n} = \frac{6(6n+1)!(2n+1)!}{(3n)!(4n+3)!(n+1)!}.$$

- ▷ Current proof is computer-driven.
- ▷ Open problem: find a *human proof*.

quadrant models with steps in $\{-2,-1,0,1\}^2$: 13 110

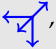
- $|\text{orbit}| < \infty$: 240
  - $\text{OS} \neq 0$: 431 — **D-finite**
  - $\text{OS} = 0$: 9 — **D-finite?**
- $|\text{orbit}| = \infty$: 12 870
  - α rational: 16 — **non-D-finite?**
  - α irrational: 12 854 — **non-D-finite**

[B., Bousquet-Mélou, Melczer, 2017]

- Example: For the model 

$$xyF(t;x,y) = [x^{>0}y^{>0}]\,\frac{(x-2x^{-2})(y-(x-x^{-2})y^{-1})}{1-t(xy^{-1}+y+x^{-2}y^{-1})}$$

Conjecture 1 [B., Bousquet-Mélou, Melczer, 2017]

For the model , writing $\phi(t) = \frac{108\,t(1+4t)^2}{(12t-1)^3}$, then $F(t^{1/2};0,0)$ is equal to

$$\frac{1}{3t} - \frac{\sqrt{1-12t}}{6t}\left({}_2F_1\left(\begin{matrix}\frac{1}{6} & \frac{1}{3}\\ & 1\end{matrix}\,\middle|\,\phi(t)\right) + {}_2F_1\left(\begin{matrix}-\frac{1}{6} & \frac{2}{3}\\ & 1\end{matrix}\,\middle|\,\phi(t)\right)\right).$$

Conjecture 2 [B., Bousquet-Mélou, Melczer, 2017]

For the model , $F(t;0,0)$ is equal to

$$\frac{(1-24\,U+120\,U^2-144\,U^3)\,(1-4\,U)}{(1-3\,U)\,(1-2\,U)^{3/2}\,(1-6\,U)^{9/2}},$$

where $U = t^4 + 53\,t^8 + 4363\,t^{12} + \cdots$ is the unique series in $\mathbb{Q}[[t]]$ satisfying

$$U\,(1-2\,U)^3\,(1-3\,U)^3\,(1-6\,U)^9 = t^4\,(1-4\,U)^4.$$

Extensions: Walks with small steps in $\mathbb{N}^3$

$2^{3^3-1} \approx 67$ million models, of which ≈ 11 million inherently 3D

3D octant models $\mathfrak{S}$ with ≤ 6 steps: 20804

$|\mathcal{G}_{\mathfrak{S}}| < \infty$: 170

$|\mathcal{G}_{\mathfrak{S}}| = \infty$?: 20634

orbit sum $\neq 0$: 108

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non-D-finite?

kernel method

2D-reducible: 43

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[B., Bousquet-Mélou, Kauers, Melczer, 2015]

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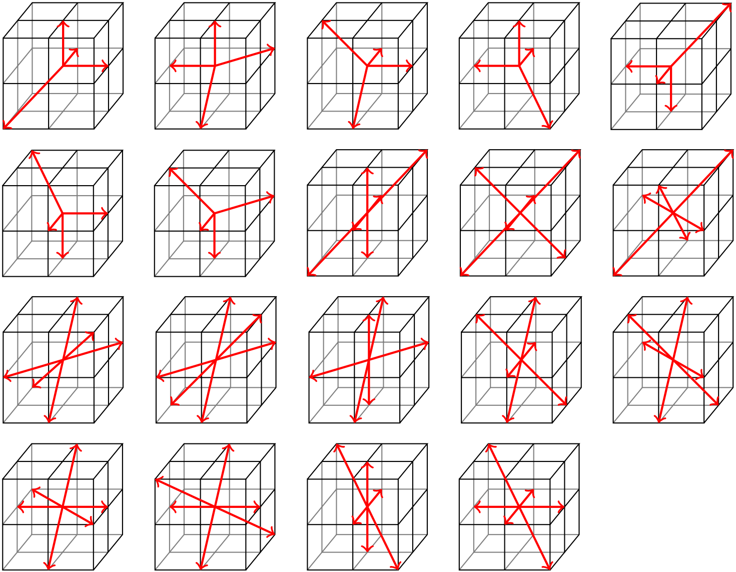
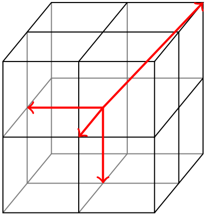
▷ Open question: are there non-D-finite models with a finite group?

▷ [Du, Hou, Wang, 2015]: proofs that groups are infinite in the 20634 cases

▷ [Bacher, Kauers, Yatchak, 2016]: extension to all 3D models; 170 models found with $|\mathcal{G}_{\mathfrak{S}}| < \infty$ and orbit sum 0 (instead of 19)

19 mysterious 3D-models





Two different computations suggest:

$$k_{4n} \approx C \cdot 256^n / n^{3.3257570041744\ldots},$$

so excursions are very probably transcendental (and even non-D-finite)

Conclusion

- Computer algebra may solve difficult combinatorial problems
- Classification of $F(t;x,y)$ fully completed for 2D small step walks
- Robust algorithmic methods, based on efficient algorithms:
  - Guess'n'Prove
  - Creative Telescoping
- Brute-force and/or use of naive algorithms = hopeless.
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Lack of "purely human" proofs for some results.

Open: is $F(t; 1, 1)$ non-D-finite for all 56 models with infinite group?

Many beautiful open questions for 2D models with repeated or large steps, and in dimension > 2.

Future reasearch

Fundamental computer algebra

- structured power series and matrices — Hermite-Padé approximants
- basic operations on operators (mod p) — $\times$ and Hadamard $\odot$
- factorization of operators (mod p) — p-curvature

Computer algebra for functional equations

- minimality of operators (order vs. total size) — desingularisation
- faster guessing — structured and certified
- faster Creative Telescoping — 4G, reduction-based

Applications

- Combinatorics — solving discrete PDEs
  - lattice walks — symmetries, various groups
  - algorithmic hyper-transcendence — diff. Galois and Tutte invariants
  - other classes of combinatorial objects — urns, maps
- Number theory — transcendence of values of E- and G-functions

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- Hypergeometric expressions for generating functions of walks with small steps in the quarter plane, with F. Chyzak, M. van Hoeij, M. Kauers and L. Pech, European Journal of Combinatorics, 2017.
- Computer Algebra for Lattice Path Combinatorics, preprint, 2017.

Thanks for your attention!