Lucas congruences and congruence schemes

Seminar
University of Vienna

Armin Straub

June 10, 2022

University of South Alabama

THM Lucas 1878

$$\binom{n}{k} \equiv \binom{n_0}{k_0}\binom{n_1}{k_1}\binom{n_2}{k_2}\cdots \pmod{p}$$

where n_i and k_i are the base p digits of n and k.

includes joint work with:

Joel Henningsen
(Baylor University)

Slides available at:
`http://arminstraub.com/talks`

Some goals for today

- **Lucas congruences** are interesting.
- **Diagonals** and **constant terms** are useful ways of representing integer sequences.
- **Congruence automata** are a powerful device for capturing the mod p^r values of sequences.
- **Lucas congruences** correspond to single-state (linear) congruence automata.
- Larger automata can be translated into **generalized Lucas congruences**.

- (**Apéry-like sequences** are fascinating.)

Lucas congruences

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EG

$$\binom{136}{79} \equiv \binom{3}{2}\binom{5}{4}\binom{2}{1} = 3\cdot 5\cdot 2 \equiv 2 \pmod{7}$$

LHS $= 1009220746942993946271525627285911932800$

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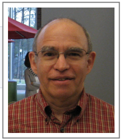
- Interesting sequences like the **Apéry numbers** $1, 5, 73, 1445, \ldots$

$$A(n) = \sum_{k=0}^{n} \binom{n}{k}^2 \binom{n+k}{k}^2$$

satisfy such **Lucas congruences** as well:



THM Gessel '82

$$A(n) \equiv A(n_0)A(n_1)\cdots A(n_r) \pmod{p}$$

Application: Primes not dividing Apéry numbers

CONJ Rowland–Yassawi '15

There are infinitely many primes p such that p does not divide any Apéry number $A(n)$.

Such as $p = 2, 3, 7, 13, 23, 29, 43, 47, \ldots$

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- The values of Apéry numbers $A(0), A(1), \ldots, A(6)$ modulo 7 are $1, 5, 3, 3, 3, 5, 1$.

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The proportion of primes not dividing any Apéry number $A(n)$ is $e^{-1/2} \approx 60.65\%$.

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CONJ Malik–S '16: The proportion of primes not dividing any Apéry number $A(n)$ is $e^{-1/2} \approx 60.65\%$.

- Heuristically, combine Lucas congruences,
- palindromic behavior of Apéry numbers, that is

$$A(n) \equiv A(p-1-n) \pmod{p},$$

- and $e^{-1/2} = \lim_{p\to\infty} \left(1 - \frac{1}{p}\right)^{(p+1)/2}$.

Diagonals

$$\sum_{n_1,\ldots,n_d \geqslant 0} a(n_1,\ldots,n_d)\, x_1^{n_1} \cdots x_d^{n_d} \qquad \sum_{n \geqslant 0} a(n,\ldots,n)\, t^n$$

multivariate series

diagonal

EG

$$\frac{1}{1-x-y}$$

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diagonal: $$\sum_{n=0}^{\infty} \binom{2n}{n} t^n = \frac{1}{\sqrt{1-4t}}$$

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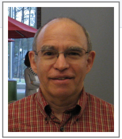
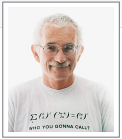
THM Gessel, Zeilberger, Lipshitz 1981–88

The diagonal of a rational function is D-finite.

More generally, the diagonal of a D-finite function is D-finite.

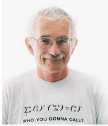
$F \in K[[x_1,\ldots,x_d]]$ is D-finite if its partial derivatives span a finite-dimensional vector space over $K(x_1,\ldots,x_d)$.

Diagonals: an example from positivity

CONJ Kauers-Zeilberger 2008 All Taylor coefficients of the following function are positive:

$$\frac{1}{1-(x+y+z+w)+2(yzw+xzw+xyw+xyz)+4xyzw}.$$



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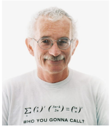

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- Would imply conjectured positivity of Lewy–Askey function

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Non-negativity proved by a very general result of Scott–Sokal ('14)

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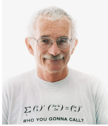

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PROP S-Zudilin 2015

The **diagonal coefficients** of the Kauers–Zeilberger function are

$$D(n)=\sum_{k=0}^{n}\binom{n}{k}^2\binom{2k}{n}^2.$$

- $D(n)$ is an example of an **Apéry-like sequence**.

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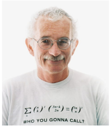

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Q S-Zudilin 2015

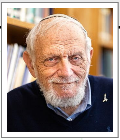
Can we conclude the conjectured positivity from the positivity of $D(n)$ together with the (easy) positivity of $\frac{1}{1-(x+y+z)+2xyz}$?

Characterizations of diagonals

EG Diagonals of rational functions

- $F(x) \quad = \quad C$-finite sequences

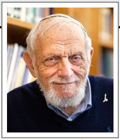
Characterizations of diagonals



EG Diagonals of rational functions

- $F(x)$ $=$ C-finite sequences
- $F(x,y)$ $=$ sequences with algebraic GF (Furstenberg '67)

To see the latter, express the diagonal as $\frac{1}{2\pi i}\int_{|x|=\varepsilon} F\left(x, \frac{z}{x}\right)\frac{\mathrm{d}x}{x}$.



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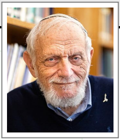
THM Bostan, Lairez, Salvy '17

Diagonals of rational functions = (multiple) binomial sums



Characterizations of diagonals



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THM Bostan, Lairez, Salvy '17 Diagonals of rational functions

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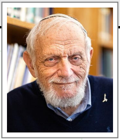
CONJ Christol '90 Diagonals of rational functions over $\mathbb{Q}$ ($\subseteq$ known)

$=$ globally bounded, D-finite sequences

(i.e. $cd^n a_n \in \mathbb{Z}$ for $c, d \in \mathbb{Z}$ and at most exponential growth)



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- Open: example of a diagonal that requires more than 3 variables

Though we have numerous candidates.

Automatic automata

THM Rowland, Yassawi '15: If an integer sequence $A(n)$ is the diagonal of $F(\boldsymbol{x}) \in \mathbb{Z}(\boldsymbol{x})$, then the reductions $A(n) \pmod{p^r}$ are p-**automatic**.

Constructive proof of results by Denef and Lipshitz '87.

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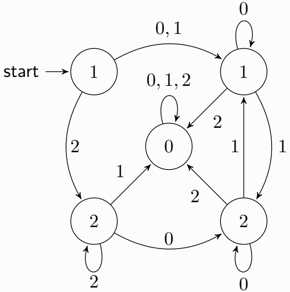
EG Catalan numbers $C(n)$ modulo 3:



$$C(35) = 3{,}116{,}285{,}494{,}907{,}301{,}262$$
$$\equiv 1 \pmod{3}$$

Instead via automaton:

$35 = 1\ 0\ 2\ 2$ in base 3

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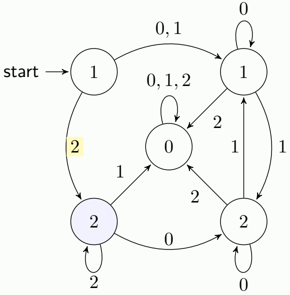

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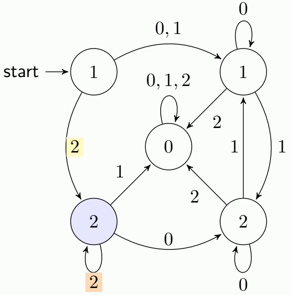

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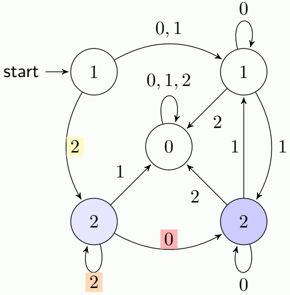

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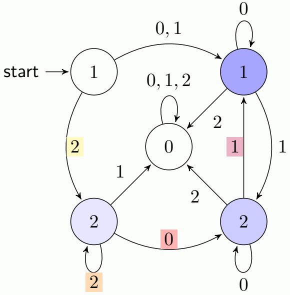

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$C(8)$	$C(2\,2) \equiv 2$
	$C(0\,2\,2) \equiv 2$
$C(35)$	$C(1\,0\,2\,2) \equiv 1$

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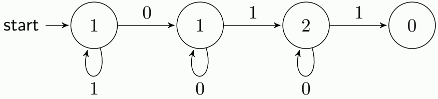

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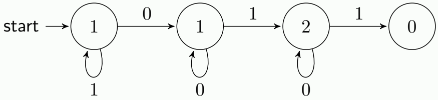
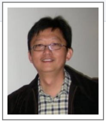


THM Eu, Liu, Yeh '08

$$C(n) \equiv \begin{cases} 1, & \text{if } n = 2^a - 1 \text{ for some } a \geqslant 0, \\ 2, & \text{if } n = 2^b + 2^a - 1 \text{ for some } b > a \geqslant 0, \\ 0, & \text{otherwise,} \end{cases} \pmod{4}.$$



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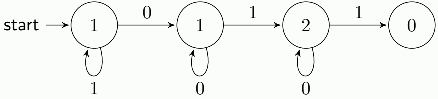

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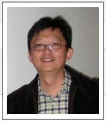


COR $C(n) \not\equiv 3 \pmod{4}$

Things quickly get more complicated

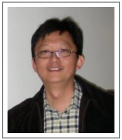
- Liu–Yeh (2010) also determine the Catalan numbers modulo 16 and 64.

Theorem 5.5. *Let c_n be the n-th Catalan number. First of all, $c_n \not\equiv_{16} 3, 7, 9, 11, 15$ for any n. As for the other congruences, we have*

$$c_n \equiv_{16} \begin{cases} \left.\begin{array}{c} 1 \\ 5 \\ 13 \end{array}\right\} & \text{if } \ d(\alpha) = 0 \ \text{ and } \begin{cases} \beta \le 1, \\ \beta = 2, \\ \beta \ge 3, \end{cases} \\ \left.\begin{array}{c} 2 \\ 10 \end{array}\right\} & \text{if } \ d(\alpha) = 1,\ \alpha = 1 \ \text{ and } \begin{cases} \beta = 0 \text{ or } \beta \ge 2, \\ \beta = 1, \end{cases} \\ \left.\begin{array}{c} 6 \\ 14 \end{array}\right\} & \text{if } \ d(\alpha) = 1,\ \alpha \ge 2 \ \text{ and } \begin{cases} (\alpha = 2, \beta \ge 2) \text{ or } (\alpha \ge 3, \beta \le 1), \\ (\alpha = 2, \beta \le 1) \text{ or } (\alpha \ge 3, \beta \ge 2), \end{cases} \\ \left.\begin{array}{c} 4 \\ 12 \end{array}\right\} & \text{if } \ d(\alpha) = 2 \ \text{ and } \begin{cases} zr(\alpha) \equiv_2 0, \\ zr(\alpha) = 1, \end{cases} \\ \ \ 8 & \text{if } \ d(\alpha) = 3, \\ \ \ 0 & \text{if } \ d(\alpha) \ge 4. \end{cases}$$

where $\alpha = (CF_2(n+1) - 1)/2$ and $\beta = \omega_2(n+1)$ (or $\beta = \min\{i \mid n_i = 0\}$).

$$\begin{aligned} \omega_p(n) &= p\text{-adic valuation of } n \\ CF_p(n) &= n \,/\, p^{\omega_p(n)} \\ d(n) &= \text{sum of 2-adic digits of } n \end{aligned}$$



- For comparison: the corresponding minimal automaton has 26 states.

A different approach to congruences

THM Kauers, Krattenthaler, Müller '12

The Catalan numbers modulo 64 are determined by

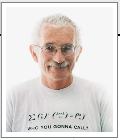
$$\begin{aligned}\sum_{n=0}^{\infty} C(n)x^n \equiv\ & 1+13x+6x^2+16x^4+32x^5 \\ & +(40+44x+20x^2+32x^3+32x^4)\Phi(x) \\ & +(12x^{-1}+52+30x+56x^2+16x^3)\Phi(x)^2 \\ & +(28x^{-1}+60+60x+32x^3)\Phi(x)^3 \\ & +(35x^{-1}+18+48x+16x^2+32x^3)\Phi(x)^4 \\ & +(44+32x^2)\Phi(x)^5+(50x^{-1}+8+48x)\Phi(x)^6 \\ & +(4x^{-1}+32+32x)\Phi(x)^7 \pmod{64}\end{aligned}$$

where

$$\Phi(x)=\sum_{n=0}^{\infty} x^{2^n}.$$

- Such expressions can be automatically obtained modulo any power of 2.
- For comparison: the corresponding minimal automaton has 134 states.

Constant terms and p-schemes



- Rowland and Zeilberger '14 construct congruence automata for **constant terms** $A(n) = \mathrm{ct}[P(\boldsymbol{x})^n Q(\boldsymbol{x})]$.

EG

$$C(n) = \mathrm{ct}[(x^{-1} + 2 + x)^n (1 - x)]$$ Catalan numbers

$$\sum_{k=0}^{n} \binom{n}{k}^2 \binom{n+k}{k} = \mathrm{ct}\left[\frac{(x+1)(x+y)(x+y+1)}{xy}\right]^n$$ Apéry numbers

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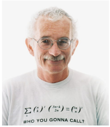

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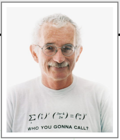

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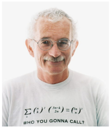

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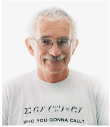

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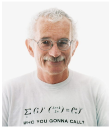

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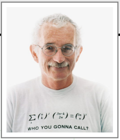

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Hence, this process terminates.

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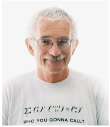

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linear p-scheme:
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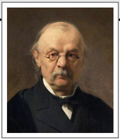

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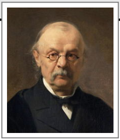

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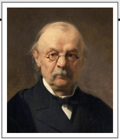

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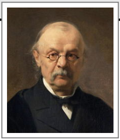

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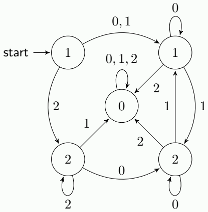
EG
mod 3

automatic 3-scheme



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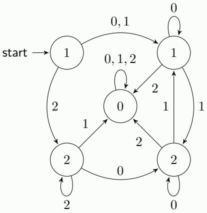

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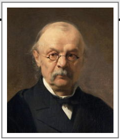

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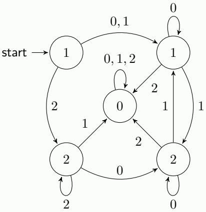

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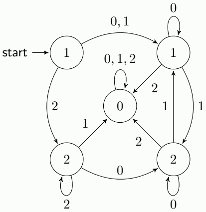

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Lucas congruences correspond to the simplest schemes

PROP Henningsen S '21

Suppose $A(0) = 1$.

$A(n)$ satisfies Lucas congruences modulo p.
$\Longleftrightarrow A(n) \pmod{p}$ can be encoded by a single-state linear p-scheme.

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- This suggests generalizations such as:

  $A(n)$ satisfies **Lucas congruences of order k** modulo p.
  $\iff A(n) \pmod{p}$ can be encoded by a linear p-scheme with k states.

Generalized Lucas congruences

THM Henningsen S '21

Let $A(n) = \mathrm{ct}[P(x,y)^n Q(x,y)]$ where $P, Q \in \mathbb{Z}[x^{\pm 1}, y^{\pm 1}]$ with

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Then, for any $n \in \mathbb{Z}_{\geqslant 0}$ and $k \in \{0, 1, \ldots, p-1\}$,

$$A(pn+k) \equiv B(n) A(k) + \begin{cases} 0, & \text{if } k < p-1, \\ \tilde{A}(n), & \text{if } k = p-1, \end{cases} \pmod{p}.$$

Here, $B(n) = \operatorname{ct}[P(x,y)^n]$ and $\tilde{A}(n) = \operatorname{ct}[P(x,y)^n \tilde{Q}(x,y)]$ with:

Generalized Lucas congruences

THM Henningsen S '21

Let $A(n) = \operatorname{ct}[P(x,y)^n Q(x,y)]$ where $P, Q \in \mathbb{Z}[x^{\pm 1}, y^{\pm 1}]$ with

$$P(x,y) = \sum_{(i,j) \in \{-1,0,1\}^2} a_{i,j} x^i y^j, \quad Q(x,y) = \alpha + \beta x + \gamma y + \delta xy.$$

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- $\sigma_x = \left(\frac{a_{1,0}^2 - 4a_{1,-1}a_{1,1}}{p} \right) \in \{0, \pm 1\}$ $\qquad p \neq 2, p \nmid a_{1,1}$
- $\sigma_y = \left(\frac{a_{0,1}^2 - 4a_{-1,1}a_{1,1}}{p} \right) \in \{0, \pm 1\}$

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$p \neq 2, p \nmid a_{1,1}$

If $Q = 1$, these reduce to the usual Lucas congruences.

Application: Catalan numbers

COR Henningsen S '21

If $\underbrace{p-1,\ldots,p-1}_{s}, n_0, n_1, \ldots, n_r$ is the p-adic expansion of n, then

$$C(n) \equiv \delta(n_0, s) C(n_0) \binom{2n_1}{n_1} \cdots \binom{2n_r}{n_r} \pmod{p}$$

where $\delta(n_0, s) = \begin{cases} 1, & \text{if } s = 0, \\ -(2n_0+1), & \text{if } s \geqslant 1. \end{cases}$

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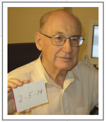
EG Deutsch, Sagan '06

$$C(n) \equiv \begin{cases} (-1)^{\tau(n+1)}, & \text{if } n+1 \in T, \\ 0, & \text{otherwise,} \end{cases} \pmod{3},$$

where $m = m_0 + 3m_1 + 3^2 m_2 + \ldots \in T$ iff $m_1, m_2, \ldots \in \{0, 1\}$.

$\tau(m) = (\#$ of $m_1, m_2, \ldots$ equal to $1)$



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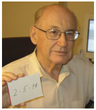

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$$C(n) \equiv \begin{cases} 2^{\lambda(n)}, & \text{if } n \notin Z, \\ 0, & \text{otherwise,} \end{cases} \pmod{5},$$

where $n \in Z$ iff $n_0 = 3$, or $(n_0 = 2,\ s \geqslant 1)$, or one of $n_1, n_2, \ldots \in \{3, 4\}$.

$\lambda(n) = (\#$ of $n_1, n_2, \ldots$ equal to $1) + \begin{cases} 1, & \text{if } n_0 = 2, \text{ or if both } n_0 = 1 \text{ and } s \geqslant 1, \\ 2, & \text{if } n_0 = 0 \text{ and } s \geqslant 1. \end{cases}$

Catalan numbers: forbidden residues

EG Rowland, Yassawi '15

$C(n) \not\equiv 3 \pmod{4}$ Eu–Liu–Yeh '08

$C(n) \not\equiv 9 \pmod{16}$ Liu–Yeh '10

$C(n) \not\equiv 17, 21, 26 \pmod{32}$

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r	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$P(r)$	0	.25	.25	.31	.41	.47	.54	.59	.65	.69	.73	.76	.79	.82
$N(r)$	0	1	2	5	13	30	69	152	332	710	1502	3133	6502	13394
$A(r)$	0	1	0	1	3	4	9	14	28	46	82	129	236	390

$N(r) = \#$ residues not attained mod 2^r

$A(r) = \#$ additional residues not attained mod $2^r = N(r) - 2N(r-1)$

Catalan numbers mod 10

CONJ Bostan '15

$C(n) \not\equiv 3 \pmod{10}$ for all $n \geqslant 0$.

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If true, the last digit of any sufficiently large odd Catalan number is always 5. ($n > 255$?)

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- $C(n)$ is odd iff $n = 2^k - 1$ for some k.
- For such n, the generalized Lucas congruences mod 5 simplify to:

(since the first digit n_0 cannot be 4)

$$C(n) \equiv \begin{cases} 2^{\lambda(n)}, & \text{if } n_0, n_1, \ldots \notin \{3,4\}, \\ 0, & \text{otherwise,} \end{cases} \pmod{5},$$

where $\lambda(n) = (\#$ of $n_0 - 1, n_1, n_2, \ldots$ equal to $1)$.

A victory for the French peasant...*

- The **Apéry numbers** $1, 5, 73, 1445, \ldots$

$$A(n) = \sum_{k=0}^{n} \binom{n}{k}^2 \binom{n+k}{k}^2$$

satisfy

$$(n+1)^3 u_{n+1} = (2n+1)(17n^2 + 17n + 5)u_n - n^3 u_{n-1}.$$

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proof The same recurrence is satisfied by the "near"-integers

$$B(n) = \sum_{k=0}^{n} \binom{n}{k}^2 \binom{n+k}{k}^2 \left(\sum_{j=1}^{n} \frac{1}{j^3} + \sum_{m=1}^{k} \frac{(-1)^{m-1}}{2m^3 \binom{n}{m}\binom{n+m}{m}} \right).$$

Then, $\frac{B(n)}{A(n)} \to \zeta(3)$. But too fast for $\zeta(3)$ to be rational. □

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Nowadays, there are excellent implementations of this **creative telescoping**, including:

- **HolonomicFunctions** by Koutschan (Mathematica)
- **Sigma** by Schneider (Mathematica)
- **ore_algebra** by Kauers, Jaroschek, Johansson, Mezzarobba (Sage)

(These are just the ones I use on a regular basis. . .

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Zagier's search and Apéry-like numbers

- Recurrence for Apéry numbers is the case $(a, b, c) = (17, 5, 1)$ of

$$(n+1)^3 u_{n+1} = (2n+1)(an^2 + an + b)u_n - cn^3 u_{n-1}.$$

Q *Beukers, Zagier*: Are there other tuples (a, b, c) for which the solution defined by $u_{-1} = 0$, $u_0 = 1$ is integral?

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- Essentially, only 14 tuples (a,b,c) found. (Almkvist–Zudilin)
  - 4 hypergeometric and 4 Legendrian solutions (with generating functions

$${}_3F_2\left(\begin{matrix}\frac{1}{2},\alpha,1-\alpha\\1,1\end{matrix}\middle|4C_\alpha z\right), \qquad \frac{1}{1-C_\alpha z}\,{}_2F_1\left(\begin{matrix}\alpha,1-\alpha\\1\end{matrix}\middle|\frac{-C_\alpha z}{1-C_\alpha z}\right)^2,$$

    with $\alpha=\frac{1}{2},\frac{1}{3},\frac{1}{4},\frac{1}{6}$ and $C_\alpha = 2^4,3^3,2^6,2^4\cdot 3^3$)
  - 6 sporadic solutions

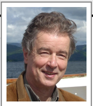
- Similar (and intertwined) story for:
  - $(n+1)^2 u_{n+1} = (an^2+an+b)u_n - cn^2 u_{n-1}$ (Beukers, Zagier)
  - $(n+1)^3 u_{n+1} = (2n+1)(an^2+an+b)u_n - n(cn^2+d)u_{n-1}$ (Cooper)

The six sporadic Apéry-like numbers

$$(n+1)^3 u_{n+1} = (2n+1)(an^2+an+b)u_n - cn^3 u_{n-1}$$

(a,b,c)	$A(n)$	
$(17,5,1)$	$\sum_k \binom{n}{k}^2 \binom{n+k}{n}^2$	Apéry numbers
$(12,4,16)$	$\sum_k \binom{n}{k}^2 \binom{2k}{n}^2$	Kauers–Zeilberger diagonal
$(10,4,64)$	$\sum_k \binom{n}{k}^2 \binom{2k}{k} \binom{2(n-k)}{n-k}$	Domb numbers
$(7,3,81)$	$\sum_k (-1)^k 3^{n-3k} \binom{n}{3k} \binom{n+k}{n} \frac{(3k)!}{k!^3}$	Almkvist–Zudilin numbers
$(11,5,125)$	$\sum_k (-1)^k \binom{n}{k}^3 \binom{4n-5k}{3n}$	
$(9,3,-27)$	$\sum_{k,l} \binom{n}{k}^2 \binom{n}{l} \binom{k}{l} \binom{k+l}{n}$	

Apéry numbers have remarkable properties



THM Beukers '87

$$\underbrace{\frac{\eta^7(2\tau)\eta^7(3\tau)}{\eta^5(\tau)\eta^5(6\tau)}}_{\text{modular form}} = \sum_{n\geqslant 0} A(n) \underbrace{\left(\frac{\eta^{12}(\tau)\eta^{12}(6\tau)}{\eta^{12}(2\tau)\eta^{12}(3\tau)}\right)^n}_{\text{modular function}}$$

$1 + 5q + 13q^2 + 23q^3 + O(q^4)$ $\qquad$ $q - 12q^2 + 66q^3 + O(q^4)$ $\qquad$ $q = e^{2\pi i\tau}$

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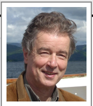

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n_i are the p-adic digits of n

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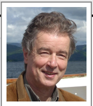

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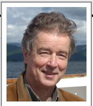
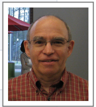
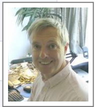

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- These extend to **all other** known Apéry-like numbers!!???

! = proven
? = partially known

Approaches to proving Lucas congruences

- From suitable expressions as a binomial sum. Gessel '82, McIntosh '92

Apéry numbers: $\sum_k \binom{n}{k}^2 \binom{n+k}{n}^2$

Sequence (η): $\sum_k (-1)^k \binom{n}{k}^3 \binom{4n-5k}{3n}$

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Sequence (η): $\sum_k (-1)^k \binom{n}{k}^3 \binom{4n-5k}{3n}$

- From suitable constant term expressions. Samol–van Straten '09, Mellit–Vlasenko '16

THM Samol, van Straten '09: $A(n) = \mathrm{ct}[P(\boldsymbol{x})^n]$ satisfies the Lucas congruences for any p, if the Newton polytope of $P \in \mathbb{Z}[\boldsymbol{x}^{\pm 1}]$ has the origin as its only interior integral point. (In fact, we get the stronger Dwork congruences.)

$$P = \frac{(x+y)(z+1)(x+y+z)(y+z+1)}{xyz}$$

$$\left(1 - \frac{1}{xy(1+z)^5}\right) \frac{(1+x)(1+y)(1+z)^4}{z^3}$$

Approaches to proving Lucas congruences

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- From suitable diagonal expressions. Rowland–Yassawi '15

For instance, diagonals of $1/Q(\boldsymbol{x})$ for $Q(\boldsymbol{x}) \in \mathbb{Z}[\boldsymbol{x}]$ with $Q(\boldsymbol{x})$ linear in each variable and $Q(\mathbf{0}) = 1$.

Challenge: finding constant term expressions

THM Malik–S '16: All of the $6+6+3$ known sporadic sequences satisfy Lucas congruences modulo every prime.

- Proof using binomial sums and McIntosh's technique for all but 2 sequences.
- Proof is long and technical for the sequences (η) and s_{18}.

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EG Gorodetsky '21: (η): $\dfrac{(zx + xy - yz - x - 1)(xy + yz - zx - y - 1)(yz + zx - xy - z - 1)}{xyz}$

$(1, 0, 0)$, $(1, 1, 0)$ and their permutations are interior points.

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Q Algorithmic tools to find useful constant term expressions?

Some goals for today

- **Lucas congruences** are interesting.
- **Diagonals** and **constant terms** are useful ways of representing integer sequences.
- **Congruence automata** are a powerful device for capturing the mod p^r values of sequences.
- **Lucas congruences** correspond to single-state (linear) congruence automata.
- Larger automata can be translated into **generalized Lucas congruences**.

- (**Apéry-like sequences** are fascinating.)

THANK YOU!

Slides for this talk will be available from my website:
`http://arminstraub.com/talks`

J. Henningsen, A. Straub
Generalized Lucas congruences and linear p-schemes
arXiv:2111.08641