Computing Solutions of Linear Mahler Equations

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Inria informatiques mathématiques

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Joint work with Th. Dreyfus, Ph. Dumas, and M. Mezzarobba

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Mahler operator of radix b ($b \in \mathbb{N},\ b \geq 2,\ y$ a function or series):

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- partition theory
- enumeration of words
- transcendence theory
- complexity analysis of divide-and-conquer algorithms

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In contrast, if $b = \operatorname{char} \mathbb{K}$ and is prime, all solutions y are algebraic: $y(x^b) = y(x)^b$.

Our Goal in this Work: Solutions in Closed Form When char $\mathbb{K} = 0$

Targeted classes

Given L of order r, with polynomial coefficients of degree $\leq d$, find algorithms of reasonable complexity for:

- (power/Puiseux) series solutions,
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Challenge

- $L(x^n)$ has degree $d + b^r n$,
- similarly, change of unknowns $y = \dfrac{\tilde{y}}{q} \to \deg M^r q = b^r \deg q$.

Series Solutions: Understanding the Linear System

For $b = 3$, look for a solution $y = \sum_{n \geq 0} y_n x^n$ of

$$\begin{aligned} L = x^3(1 - x^3 + x^6)(1 - x^7 - x^{10})\, M^2 \\ -(1 - x^{28} - x^{31} - x^{37} - x^{40})\, M \\ + x^6(1 + x)(1 - x^{21} - x^{30}). \end{aligned}$$

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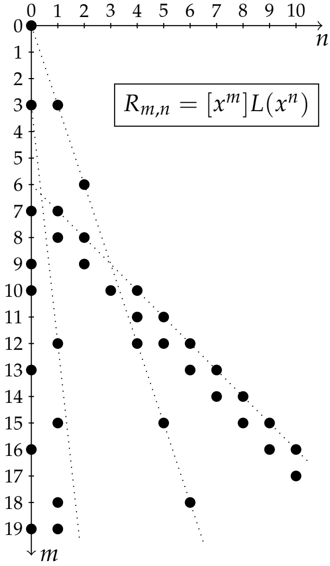
$L \longleftrightarrow$ infinite matrix $R = (R_{m,n})$



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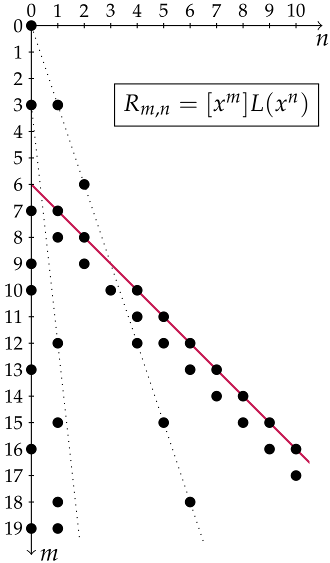
$$x^n \xrightarrow{x^6} x^{n+6}$$



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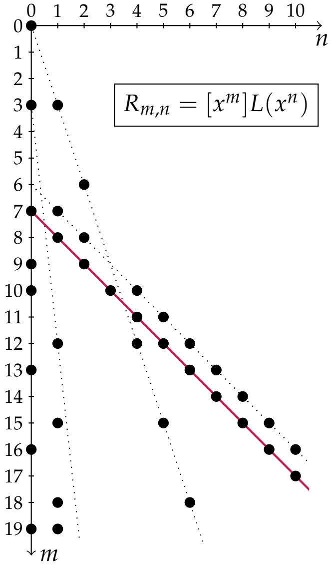

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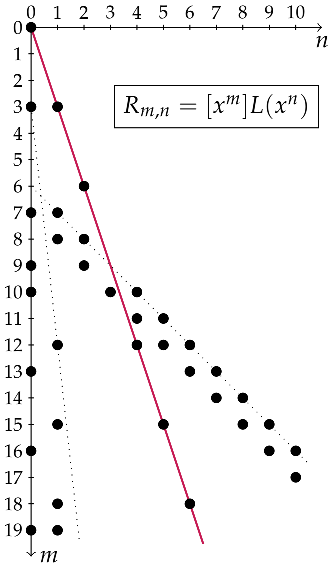
$$x^n \xrightarrow{M} x^{3n}$$



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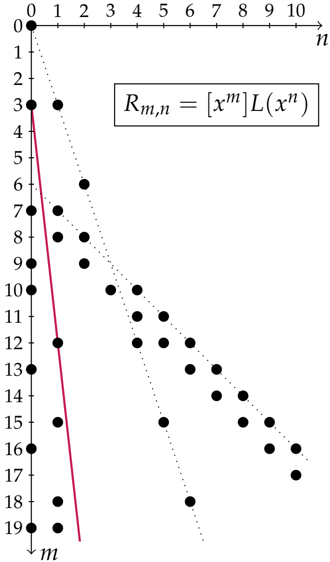

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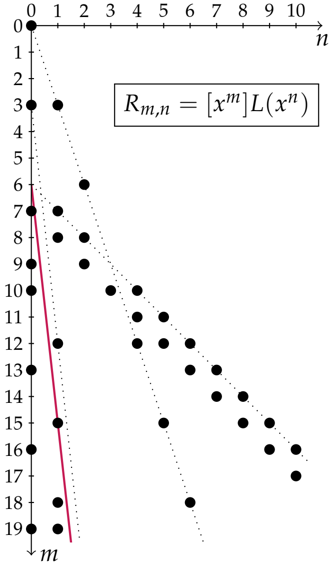

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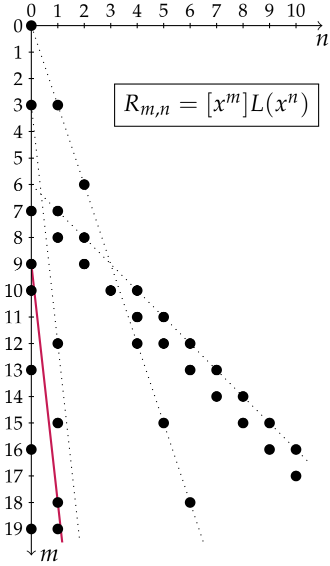

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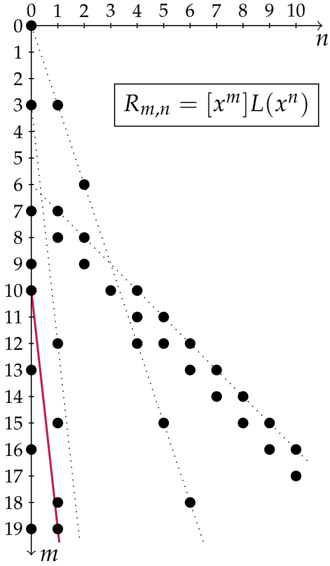

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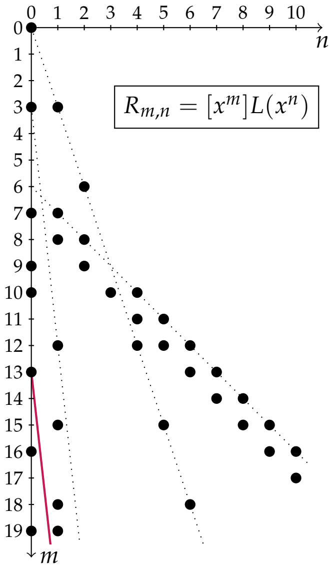

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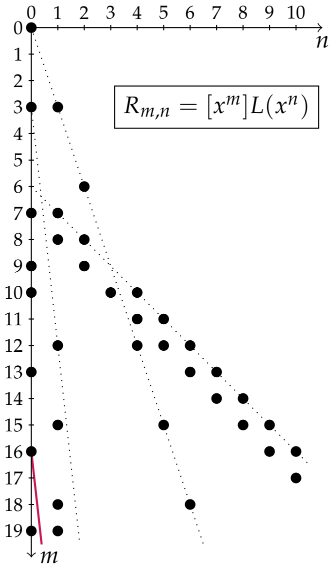

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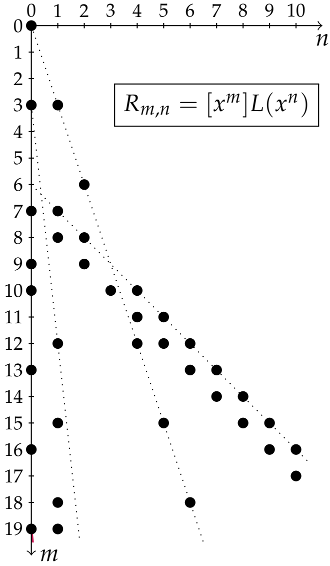

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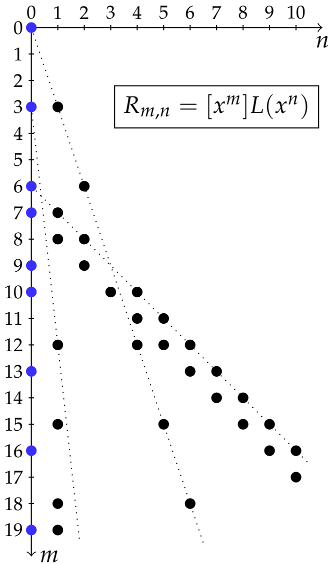
$x^0 \xrightarrow{L}$ span of the •'s



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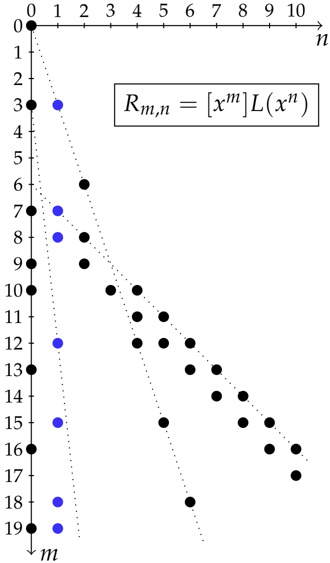

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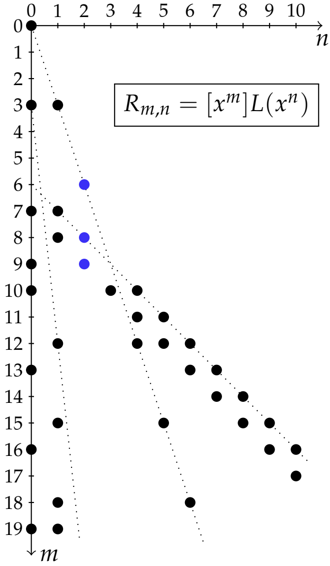

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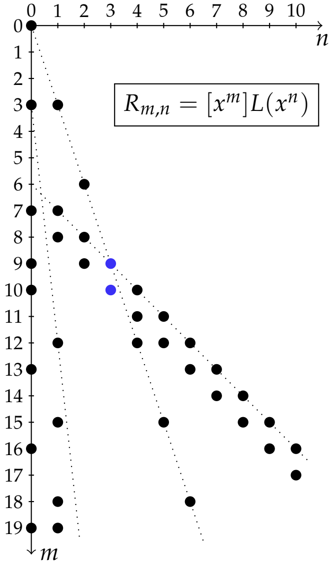

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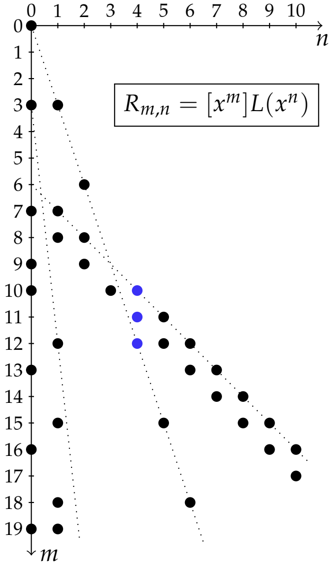

$R_{m,n} = [x^m] L(x^n)$

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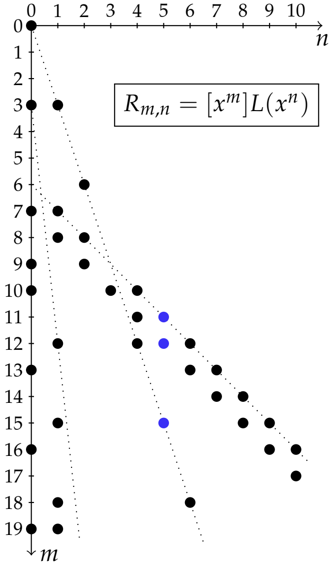

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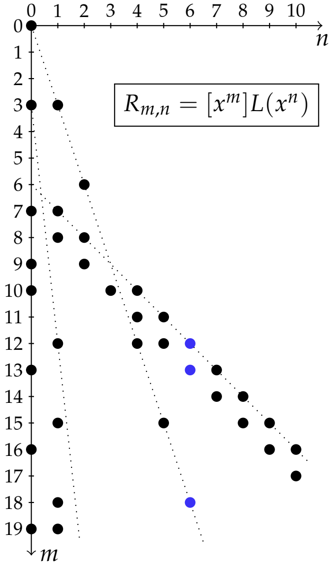
$x^6 \xrightarrow{L}$ span of the •'s



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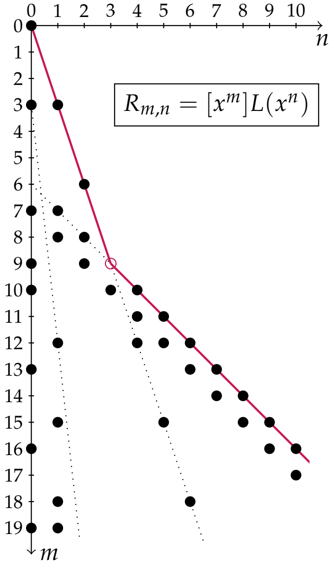
$$x^n \xrightarrow{L} \circ\, x^{\min(n+6,3n)} + \cdots$$



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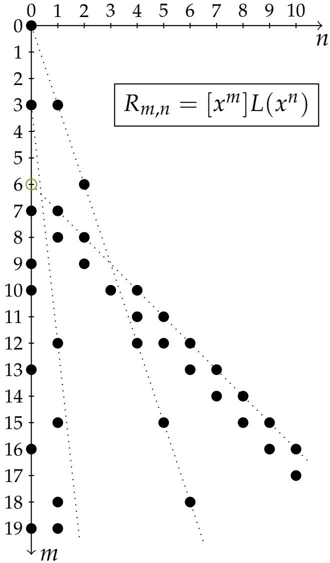
$$x^0 \xrightarrow{L} x^{\neq 6}$$



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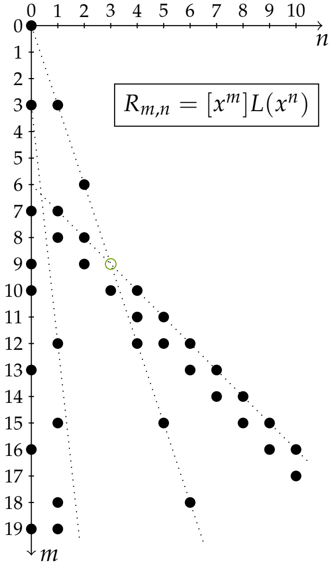
$$x^3 \xrightarrow{L} x^{>9}$$



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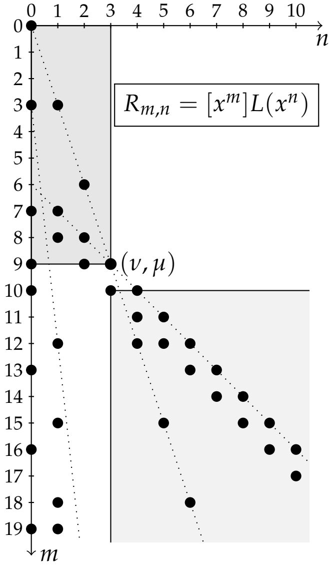

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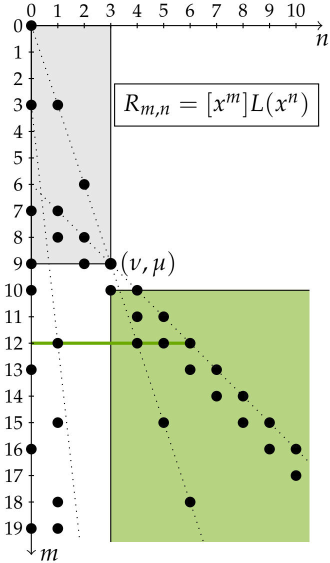
$m = 12 \longrightarrow y_6$ in terms of y_5, y_4, y_1



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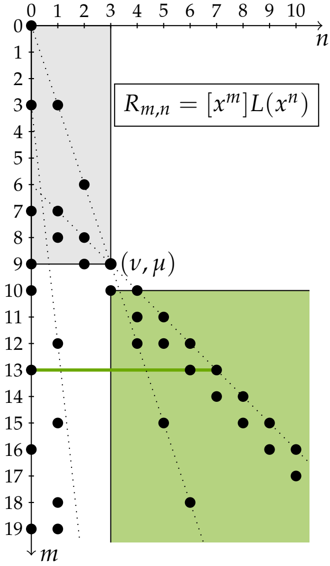
$m = 13 \longrightarrow y_7$ in terms of y_6, y_5, y_0



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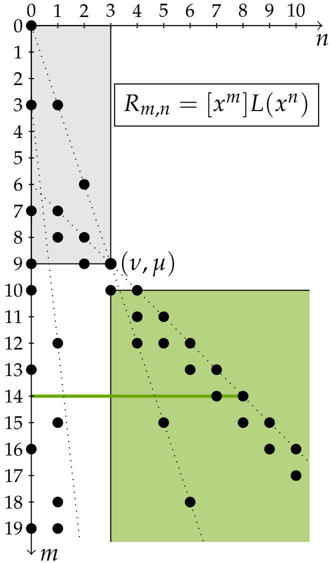
$m = 14 \longrightarrow y_8$ in terms of y_7



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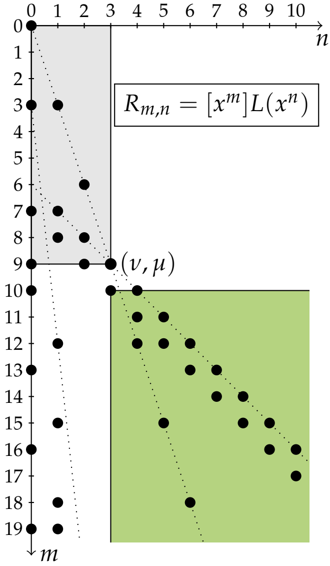
$m \geq 10 \longrightarrow y_{m-6}$ in terms of lower indices



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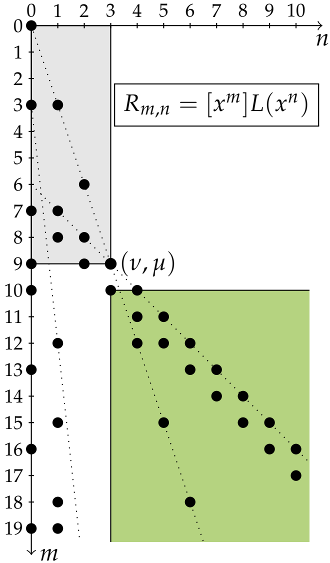
For $m \geq 10$, y_{m-6} can be determined uniquely by

$$\left(y_{\frac{m-3}{9}} - y_{\frac{m-6}{9}} + y_{\frac{m-9}{9}} - y_{\frac{m-10}{9}} - y_{\frac{m-19}{9}}\right) - \left(y_{\frac{m}{3}} - y_{\frac{m-28}{3}} - y_{\frac{m-31}{3}} - y_{\frac{m-37}{3}} - y_{\frac{m-40}{3}}\right) + \left(y_{m-6} + y_{m-7} - y_{m-27} - y_{m-28} - y_{m-36} - y_{m-37}\right) = 0$$

where $y_s = 0$ if $s \notin \mathbb{N}$.



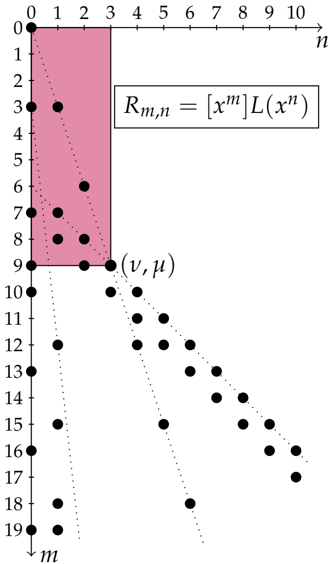
For $b = 3$, look for a solution $y = \sum_{n \geq 0} y_n x^n$ of

$$L = (x^3 - x^6 + x^9 - x^{10} + 2x^{13} - 2x^{16} + x^{19})\, M^2 \\ -(1 - x^{28} - x^{31} - x^{37} - x^{40})\, M \\ +(x^6 + x^7 - x^{27} - x^{28} - x^{36} - x^{37}).$$

$y_0, \dots, y_3$ can be determined uniquely by

$$\left(y_{\frac{m-3}{9}} - y_{\frac{m-6}{9}} + y_{\frac{m-9}{9}} - y_{\frac{m-10}{9}} - y_{\frac{m-19}{9}}\right) \\ - \left(y_{\frac{m}{3}} - y_{\frac{m-28}{3}} - y_{\frac{m-31}{3}} - y_{\frac{m-37}{3}} - y_{\frac{m-40}{3}}\right) \\ + \left(y_{m-6} + y_{m-7} - y_{m-27} - y_{m-28} - y_{m-36} - y_{m-37}\right) = 0$$

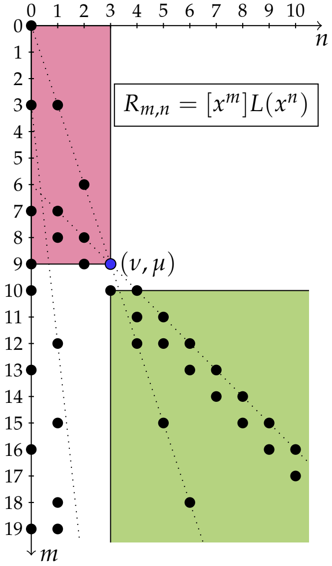
for $0 \leq m \leq 9$, where $y_s = 0$ if $s \notin \mathbb{N}$.



Series Solutions: Understanding the Linear System

For $b = 3$, look for a solution $y = \sum_{n \geq 0} y_n x^n$ of

$$L = (x^3 - x^6 + x^9 - x^{10} + 2x^{13} - 2x^{16} + x^{19})\, M^2$$
$$-(1 - x^{28} - x^{31} - x^{37} - x^{40})\, M$$
$$+(x^6 + x^7 - x^{27} - x^{28} - x^{36} - x^{37}).$$



$y_0, \ldots, y_\nu \longleftrightarrow$ eqns for $0 \leq m \leq \mu$

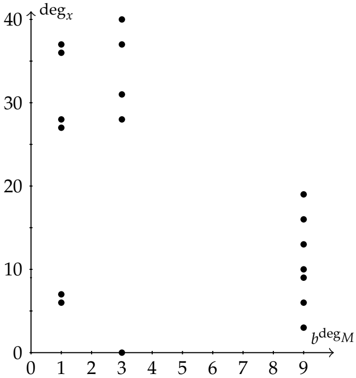
y_ν is free $\longleftrightarrow$ coeff. at $(\nu, \mu) = 0$

y_n for $n > \nu \longleftrightarrow$ eqns for $m > \mu$

Newton diagram

collection of points (b^k, j) associated with the monomials $x^j M^k$ of L

$$L = (x^3 - x^6 + x^9 - x^{10} + 2x^{13} - 2x^{16} + x^{19})\, M^2 - (1 - x^{28} - x^{31} - x^{37} - x^{40})\, M + (x^6 + x^7 - x^{27} - x^{28} - x^{36} - x^{37}).$$



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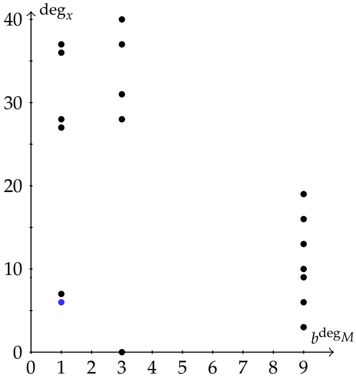
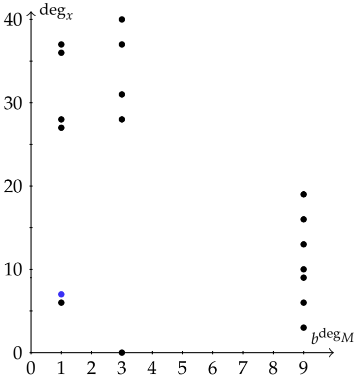


Newton Diagrams, Newton Polygons

Newton diagram

collection of points (b^k, j) associated with the monomials $x^j M^k$ of L

$$L = (x^3 - x^6 + x^9 - x^{10} + 2x^{13} - 2x^{16} + x^{19})\, M^2$$
$$- (1 - x^{28} - x^{31} - x^{37} - x^{40})\, M$$
$$+ (x^6 + x^7 - x^{27} - x^{28} - x^{36} - x^{37}).$$



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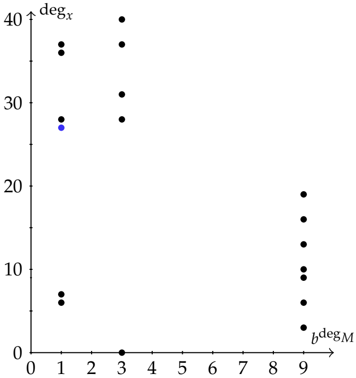

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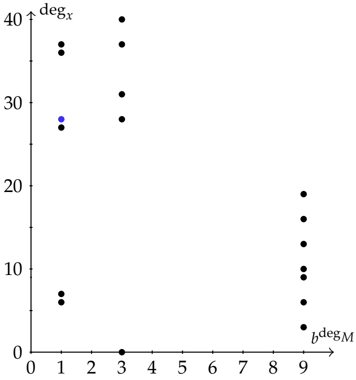

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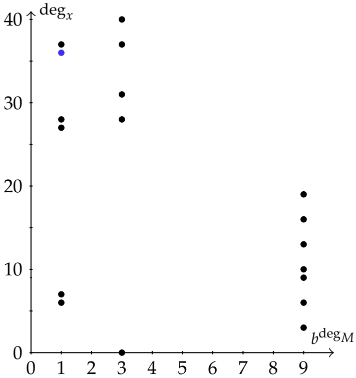

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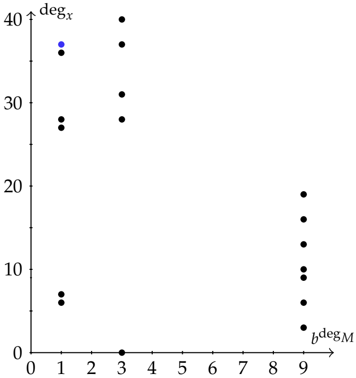

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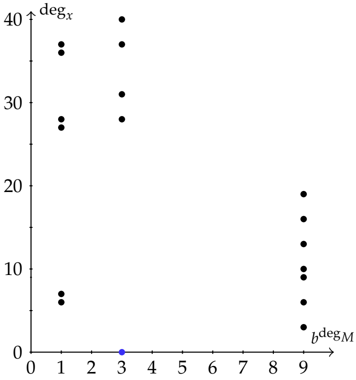

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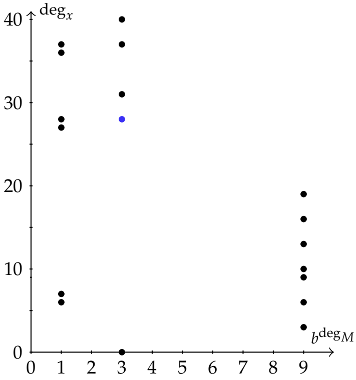

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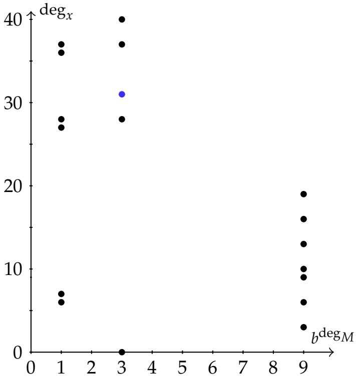

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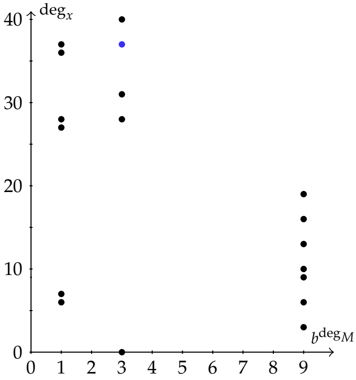

Newton Diagrams, Newton Polygons

Newton diagram

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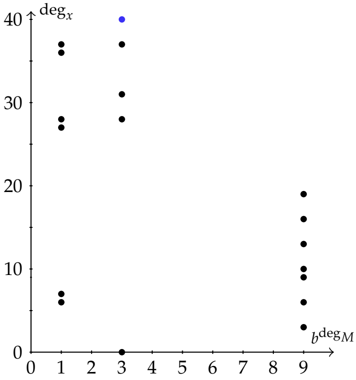

Newton Diagrams, Newton Polygons

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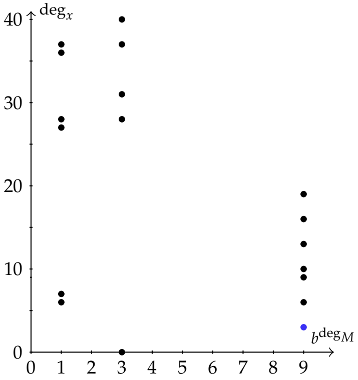

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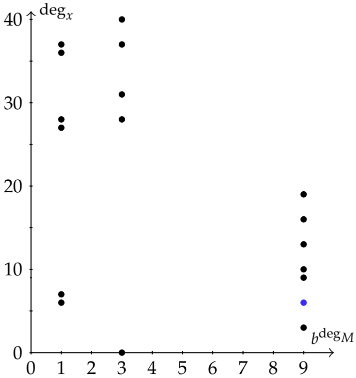

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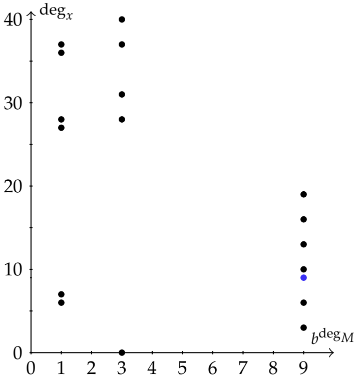

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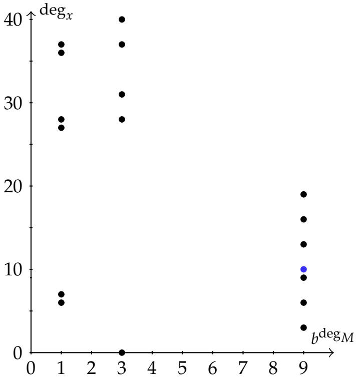

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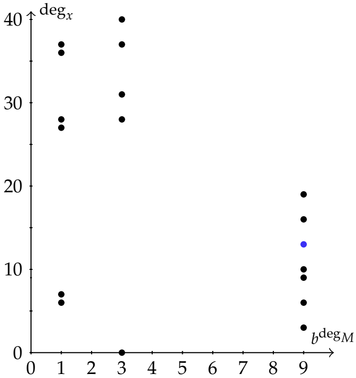

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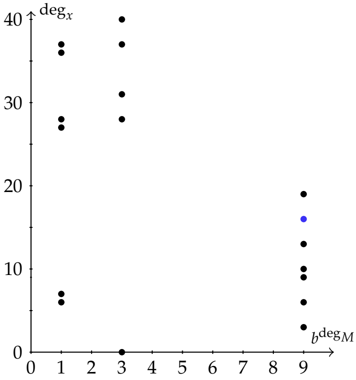

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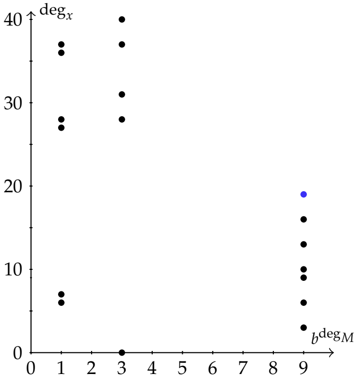

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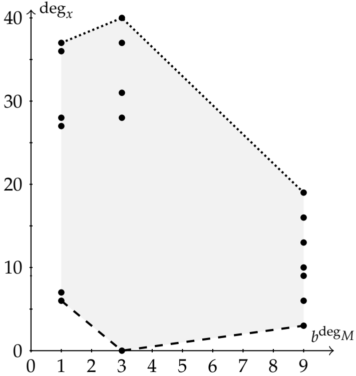

Newton polygons = boundary of convex hull

- lower Newton polygon $\longleftrightarrow$ valuations,
- upper Newton polygon $\longleftrightarrow$ degrees.

Newton diagram

collection of points (b^k, j) associated with the monomials $x^j M^k$ of L

$$L = (x^3 - x^6 + x^9 - x^{10} + 2x^{13} - 2x^{16} + x^{19})\, M^2 - (1 - x^{28} - x^{31} - x^{37} - x^{40})\, M + (x^6 + x^7 - x^{27} - x^{28} - x^{36} - x^{37}).$$

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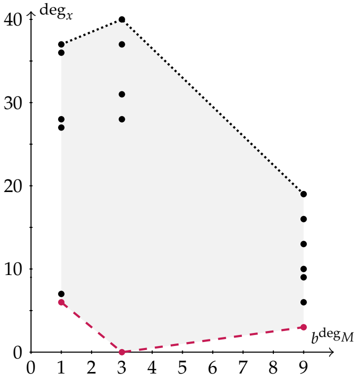

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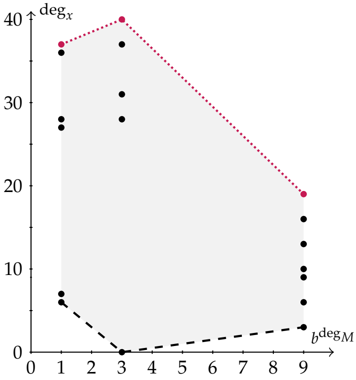

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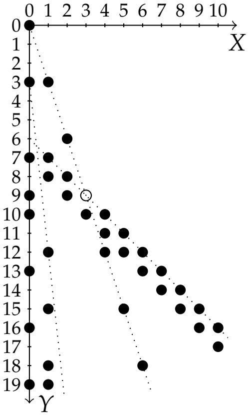
Link between the Linear System and the Newton Polygon

Linear system



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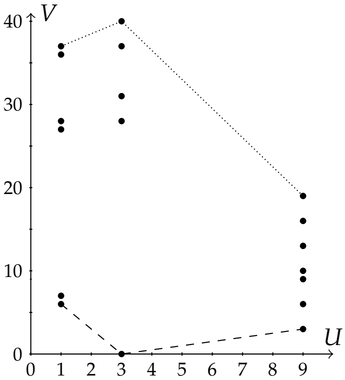
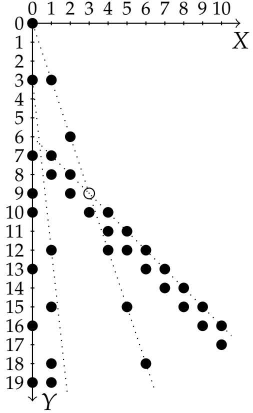


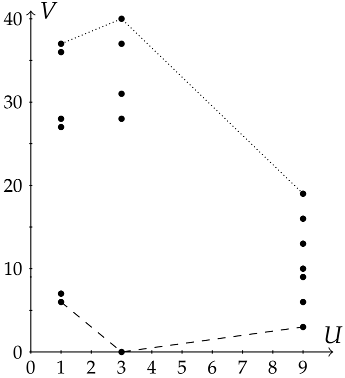
Linear system

line $Y = j + b^k X$



Newton diagram

point (b^k, j)



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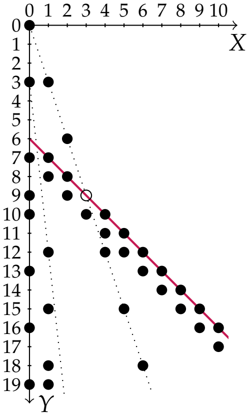

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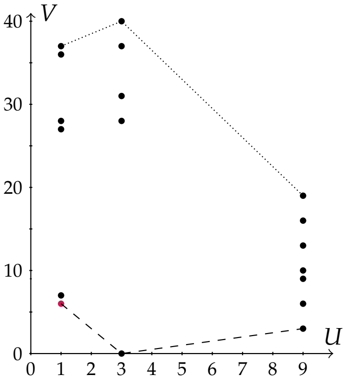
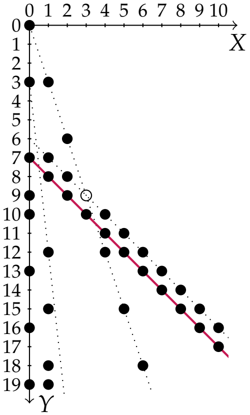
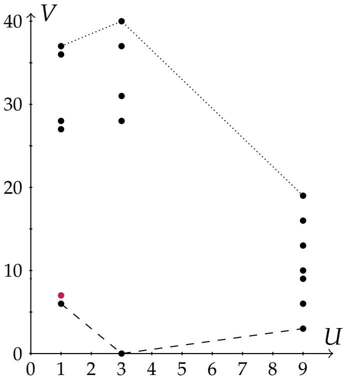


Link between the Linear System and the Newton Polygon

Linear system	Newton diagram
line $Y = j + b^k X$	point (b^k, j)





Link between the Linear System and the Newton Polygon

Linear system	Newton diagram
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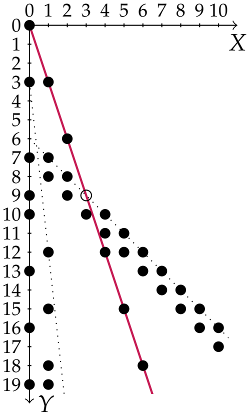

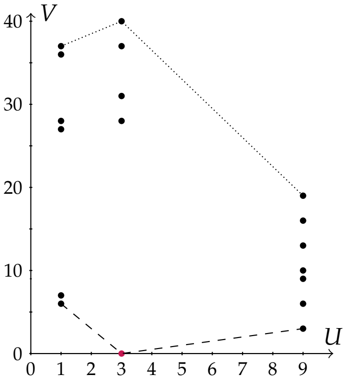

Link between the Linear System and the Newton Polygon

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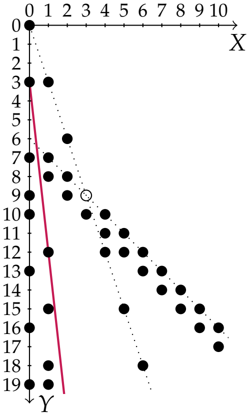

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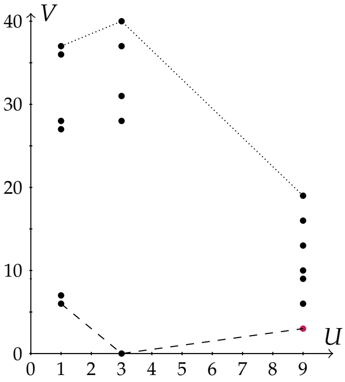

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Linear system

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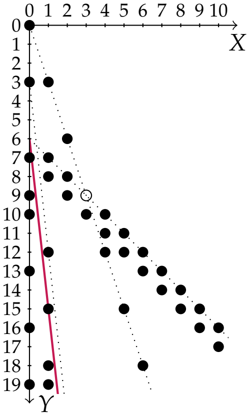

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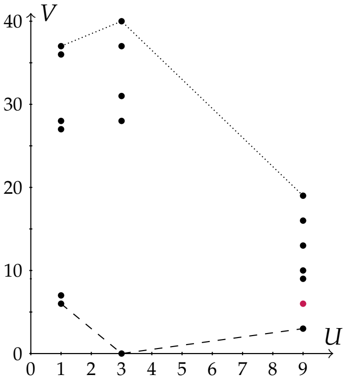
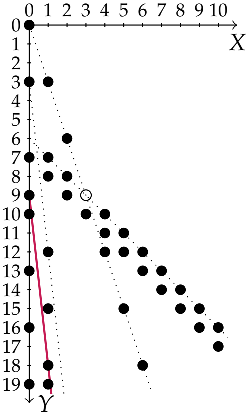


Link between the Linear System and the Newton Polygon

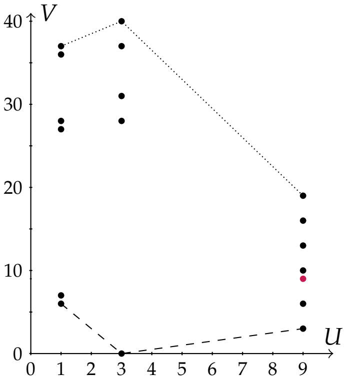
Linear system

line $Y = j + b^k X$



Newton diagram

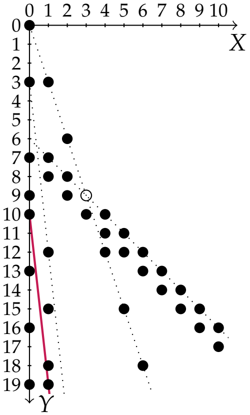
point (b^k, j)



Link between the Linear System and the Newton Polygon

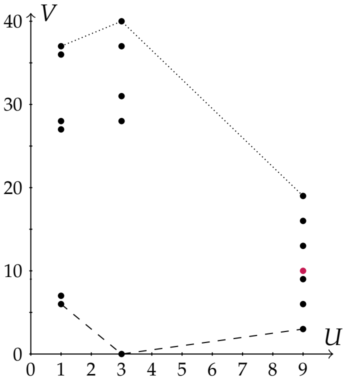
Linear system

line $Y = j + b^k X$



Newton diagram

point (b^k, j)



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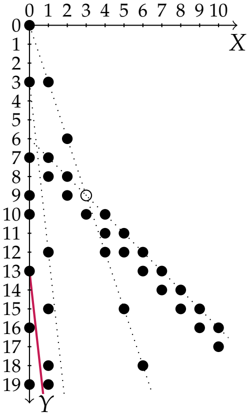

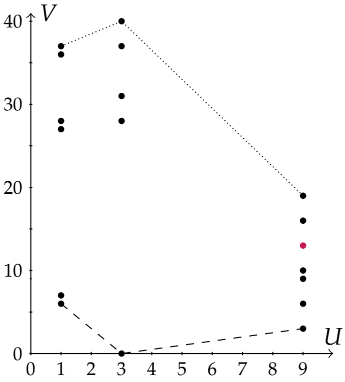

Link between the Linear System and the Newton Polygon

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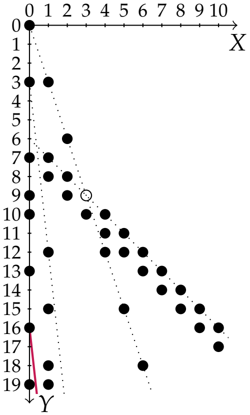

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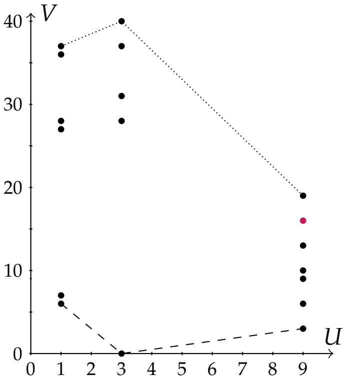

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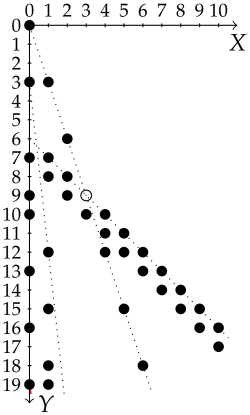

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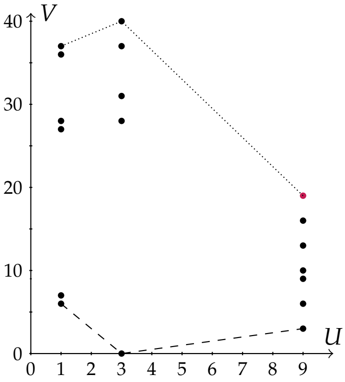

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Linear system

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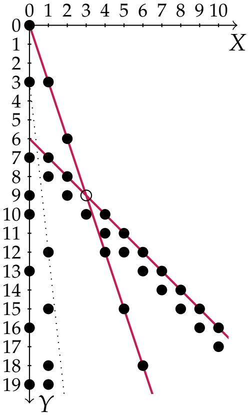
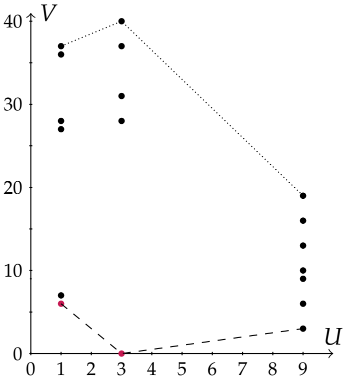


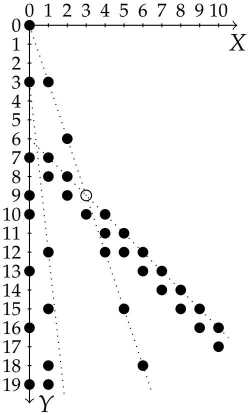
Newton diagram

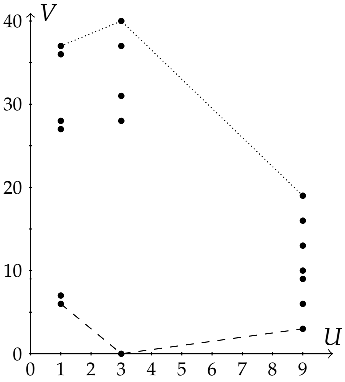
point (b^k, j)



Link between the Linear System and the Newton Polygon

Linear system	Newton diagram
line $Y = j + b^k X$	point (b^k, j)
point (n, m)	line $V = m - nU$



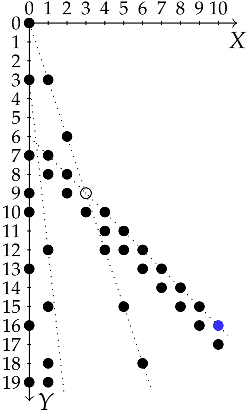


Link between the Linear System and the Newton Polygon

Linear system

line $Y = j + b^k X$

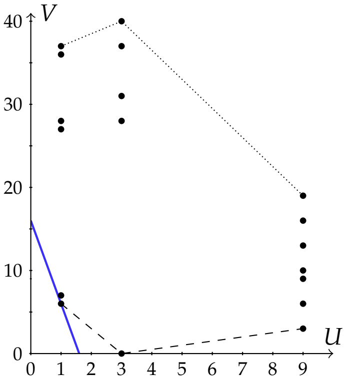
point (n, m)



Newton diagram

point (b^k, j)

line $V = m - nU$



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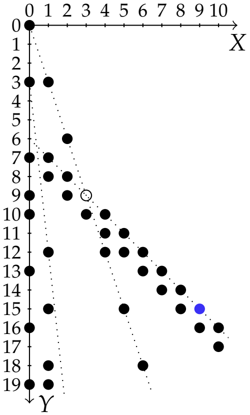

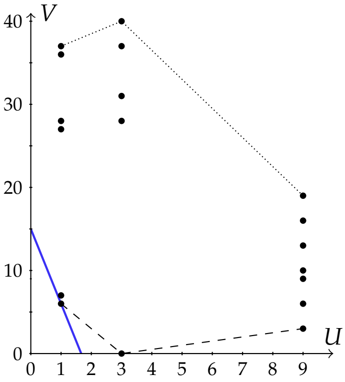

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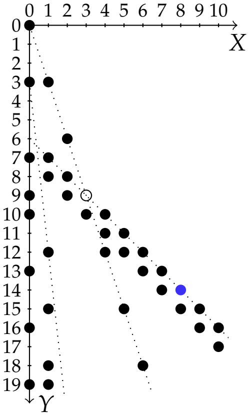
Linear system

line $Y = j + b^k X$

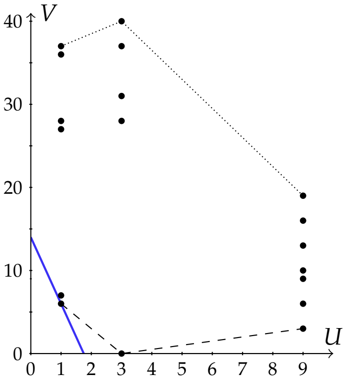
point (n, m)



Newton diagram

point (b^k, j)

line $V = m - nU$



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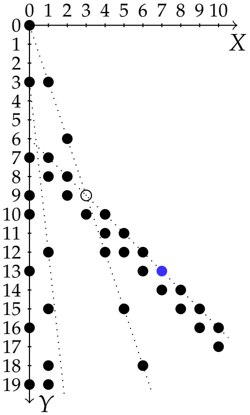

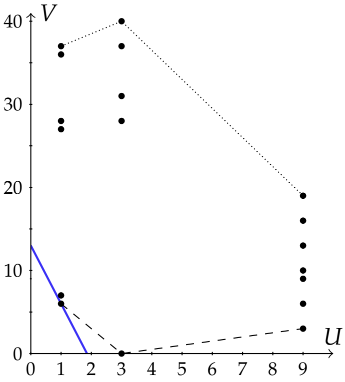

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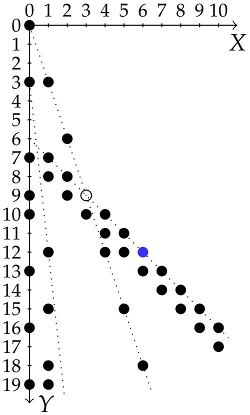

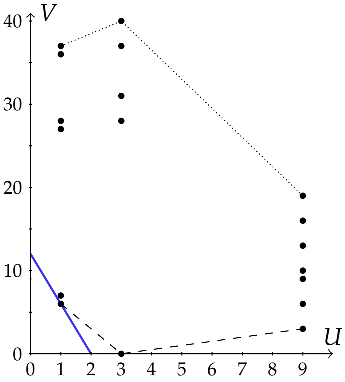

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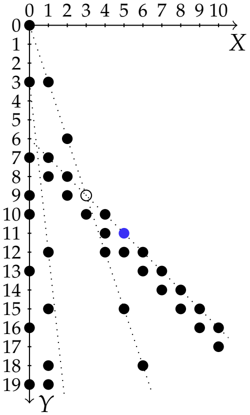
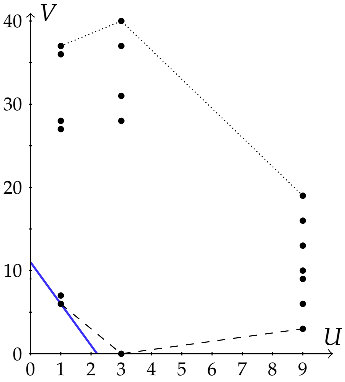




Link between the Linear System and the Newton Polygon

Linear system

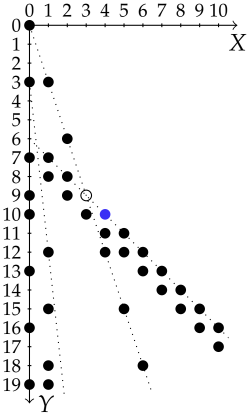
line $Y = j + b^k X$

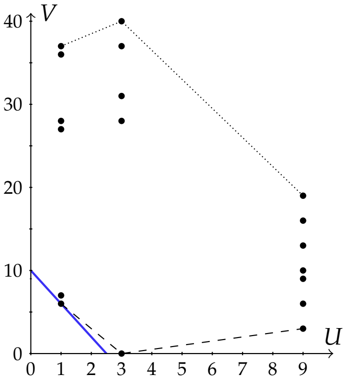
point (n, m)

Newton diagram

point (b^k, j)

line $V = m - nU$

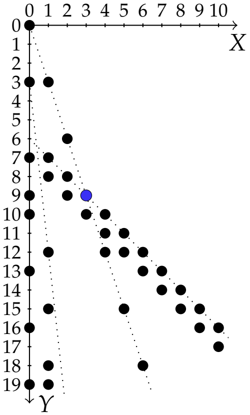




Linear system

line $Y = j + b^k X$

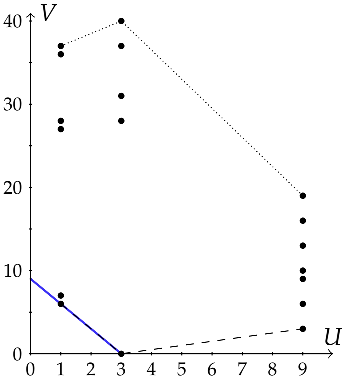
point (n, m)



Newton diagram

point (b^k, j)

line $V = m - nU$



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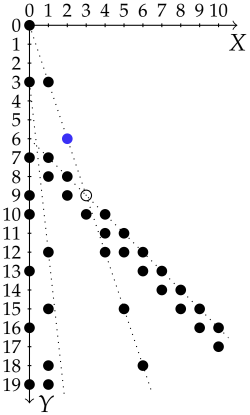

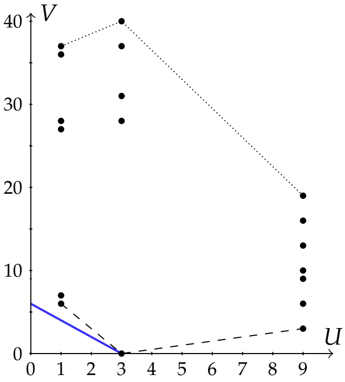

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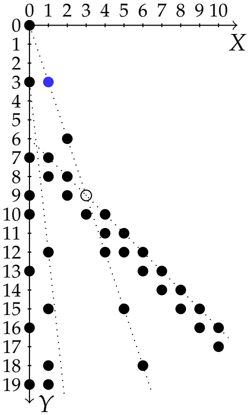

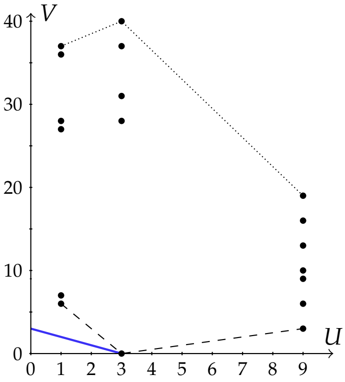

Link between the Linear System and the Newton Polygon

Linear system

line $Y = j + b^k X$

point (n, m)

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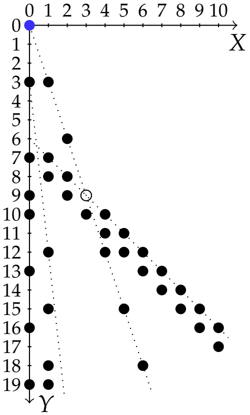

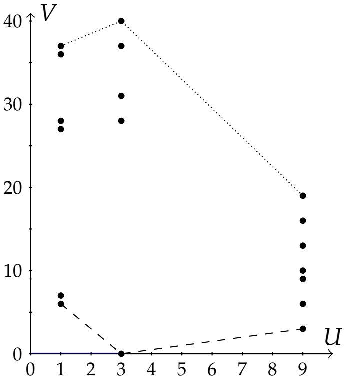

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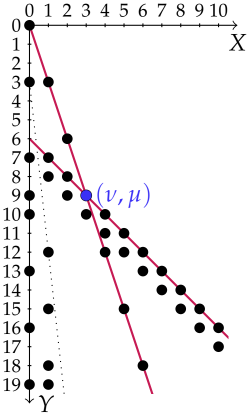
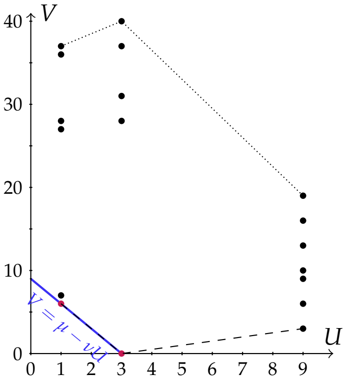




Bounds for Series and Polynomial Solutions

$$L = \ell_r(x)M^r + \cdots + \ell_0(x), \quad \ell_0\ell_r \neq 0, \quad 0 \leq v_k = \operatorname{val}\ell_k, \quad d_k = \deg \ell_k \leq d.$$

Size of singular system ("approximate series solutions")

$$\nu = \max_{k\geq 1} \frac{v_0 - v_k}{b^k - 1}, \qquad \mu = v_0 + \nu.$$

Any series solution to order $\mathrm{O}(x^\nu + 1)$ can be prolonged uniquely.

Bound on valuation v of a series solution

$$-\frac{v_r}{b^{r-1}(b-1)} \leq v = -\frac{v_{k_2} - v_{k_1}}{b^{k_2} - b^{k_1}} \leq \frac{v_0}{b-1},$$

where $v = -$ slope of edge $\left[(b^{k_1}, v_{k_1}), (b^{k_2}, v_{k_2})\right]$ in lower Newton polygon.

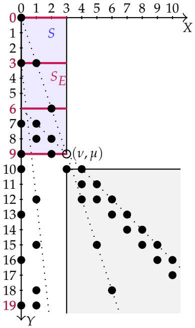
Bound on degree δ of any polynomial solution

$$\delta = -\frac{d_{k_1} - d_{k_2}}{b^{k_1} - b^{k_2}} \leq \frac{d}{b^{r-1}(b-1)},$$

where $\delta = -$ slope of edge $\left[(b^{k_1}, v_{k_1}), (b^{k_2}, v_{k_2})\right]$ in upper Newton polygon.

Algorithm

1. $h := \lfloor \mu \rfloor + 1$, $w := \lfloor \nu \rfloor + 1$, $E := \left(\min_k \left(v_k + nb^k\right)\right)_{0 \le n < w}$.
2. $S :=$ upper left subsystem $\in \mathbb{K}^{h \times w}$.
3. $S_E :=$ submatrix of S given by the rows of index in E.
4. $G := \ker S_E \in \mathbb{K}^{w \times \rho}$ with $\rho = \dim \ker S_E \le r$.
   (forward substitution)
5. For $1 \le j \le \rho$,
   1. $g_j := G_{0,j} + G_{1,j}x + \cdots + G_{w-1,j}x^{w-1} \in \mathbb{K}[x]$,
   2. $\sum_{0 \le i < h} s'_{i,j} x^i := Lg_j(x) \bmod x^h$.
6. $S' := (s'_{i,j}) \in \mathbb{K}^{h \times \rho}$.
7. $K := \ker S' \in \mathbb{K}^{\rho \times \sigma}$ with $\sigma = \dim \ker S' \le r$.
   (Ibarra, Moran, Hui, 1982)
8. $F := GK \in \mathbb{K}^{w \times \sigma}$.
9. Return $(f_1, \dots, f_\sigma)$ where $f_j = F_{0,j} + \cdots + F_{w-1,j}x^{w-1}$.



Algorithm

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2. $S :=$ upper left subsystem $\in \mathbb{K}^{h \times w}$. $O(rwh)$
3. $S_E :=$ submatrix of S given by the rows of index in E.
4. $G := \ker S_E \in \mathbb{K}^{w \times \rho}$ with $\rho = \dim \ker S_E \le r$.
   (forward substitution) $O(rw^2)$
5. For $1 \le j \le \rho$, $O(r^2\,\mathrm{M}(h))$
   1. $g_j := G_{0,j} + G_{1,j}x + \cdots + G_{w-1,j}x^{w-1} \in \mathbb{K}[x]$,
   2. $\sum_{0 \le i < h} s'_{i,j} x^i := Lg_j(x) \bmod x^h$.
6. $S' := (s'_{i,j}) \in \mathbb{K}^{h \times \rho}$.
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   (Ibarra, Moran, Hui, 1982) $O(r^{\omega-1}h)$
8. $F := GK \in \mathbb{K}^{w \times \sigma}$. $O(r^{\omega-1}w)$
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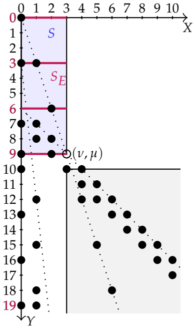

Theorem (correctness and complexity) [cf. naive $O(v_0^\omega)$]

Returns a basis of approximate series solutions in $O(rv_0^2 + r^2\,\mathrm{M}(v_0))$ ops.

Solving the Singular System. Series and Polynomial Solutions

Algorithm

1. $h := 3d + 1$, $w := \lfloor \frac{d}{b^r - b^{r-1}} \rfloor + 1$, $E := \left(\max_k (d_k + nb^k) \right)_{0 \le n < w}$.
2. $S :=$ upper left subsystem $\in \mathbb{K}^{h \times w}$. $\quad O(rwh)$
3. $S_E :=$ submatrix of S given by the rows of index in E.
4. $G := \ker S_E \in \mathbb{K}^{w \times \rho}$ with $\rho = \dim \ker S_E \le r$.
   (backward substitution) $\quad O(rw^2)$
5. For $1 \le j \le \rho$, $\quad O(r^2 \, M(h))$
   1. $g_j := G_{0,j} + G_{1,j}x + \cdots + G_{w-1,j}x^{w-1} \in \mathbb{K}[x]$,
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   (Ibarra, Moran, Hui, 1982) $\quad O(r^{\omega - 1} h)$
8. $F := GK \in \mathbb{K}^{w \times \sigma}$. $\quad O(r^{\omega-1} w)$
9. Return $(f_1, \ldots, f_\sigma)$ where $f_j = F_{0,j} + \cdots + F_{w-1,j} x^{w-1}$.

Theorem (correctness and complexity) [cf. naive $O(d^\omega)$]

Returns a basis of polynomial solutions in $\tilde{O}(d^2/b^r + M(d))$ ops.

Initiating the Quest for Denominator Bounds

$$\sum_{k=0}^{r} \ell_k M^k \left(\frac{p}{q} \right) = 0, \qquad p \wedge q = 1,\ q(0) \neq 0.$$

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$$M^r q \mid \ell_r \bigvee_{i=0}^{r-1} M^i q$$

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$$M^r q \mid \ell_r \bigvee_{i=0}^{r-1} M^i q$$

$$q(\alpha) = 0 \text{ and } \beta^{b^r} = \alpha \implies \ell_r(\beta) = 0 \text{ or } \left(q(\alpha') = 0 \text{ for } \alpha' = \beta^{b^i},\ i < r\right)$$

Initiating the Quest for Denominator Bounds

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$$\sum_{k=0}^{r-1} \ell_k (M^r q) \underbrace{\left((M^k q)^{-1} \bigvee_{i=0}^{r-1} M^i q\right)}_{\text{polynomial}} (M^k p) + \underbrace{\ell_r \left(\bigvee_{i=0}^{r-1} M^i q\right)}_{\text{dividable by } M^r q} (M^r p) = 0.$$

$$M^r q \mid \ell_r \bigvee_{i=0}^{r-1} M^i q$$

$$q(\alpha) = 0 \rightsquigarrow \left(\ell_r(\beta) = 0 \text{ for } \beta^{b^r} = \alpha\right) \text{ or } \left(q(\alpha') = 0 \text{ for } (\alpha')^{b^k} = \alpha,\ k > 0\right)$$

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Geometric intuition

If α, not a root of unity, is a root of q, it generates:

- a finite sequence $\alpha_0 = \alpha, \alpha_1, \ldots, \alpha_n$ of two by two distinct roots of q,
- then, a b^rth root β_n of α_n that is a root of ℓ_r.

The Graeffe Operator: a Quasi-Inverse for the Mahler Operator

$$\begin{array}{ccc}
\gamma = \alpha^b & (Gp)(\gamma) = 0 & Gp = \mathrm{Res}_y(y^b - x, p(y)) \\
\uparrow & \uparrow & \uparrow \\
\alpha \in \mathbb{C} & p(\alpha) = 0 & p \in \mathbb{K}[x] \\
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Key lemma

Given $\ell \in \mathbb{K}[x]$:

$$\begin{cases} q \in \mathbb{K}[x] \setminus \mathbb{K} \\ x \nmid q \\ M^r q \mid \ell \bigvee_{i=0}^{r-1} M^i q \end{cases} \implies \exists u \in \mathbb{K}[x] \setminus \mathbb{K}, \quad M^r u \mid \ell \quad \text{or} \quad \begin{cases} M^{r-1} u \mid \ell \\ q \mid Gu \end{cases}$$

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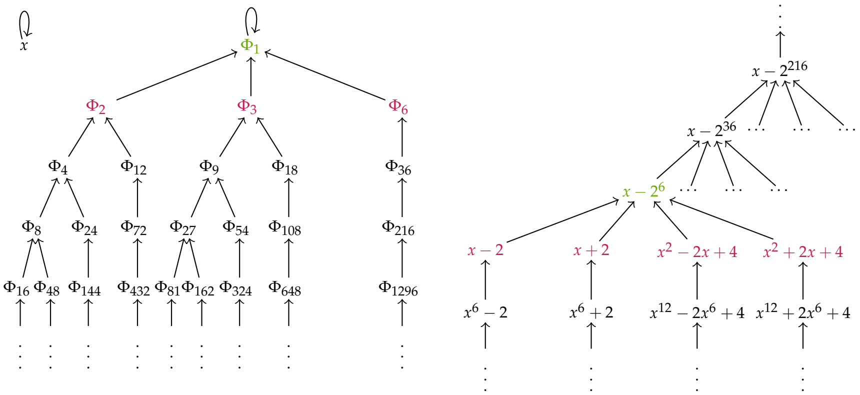
Remark: left case impossible $\implies$ q is a product of cyclotomic polynomials.

Graph of (Radical of) Graeffe Operator for $b = 6$ in $\mathbb{Q}[x]$

$$Mp = \prod_{q \text{ s.t. } \sqrt{G}(q)=p} q$$

$$M\Phi_1 = \Phi_1\Phi_2\ \Phi_3\ \Phi_6$$

$$M(x - 2^6) = (x-2)(x+2)(x^2-2x+4)(x^2+2x+4)$$



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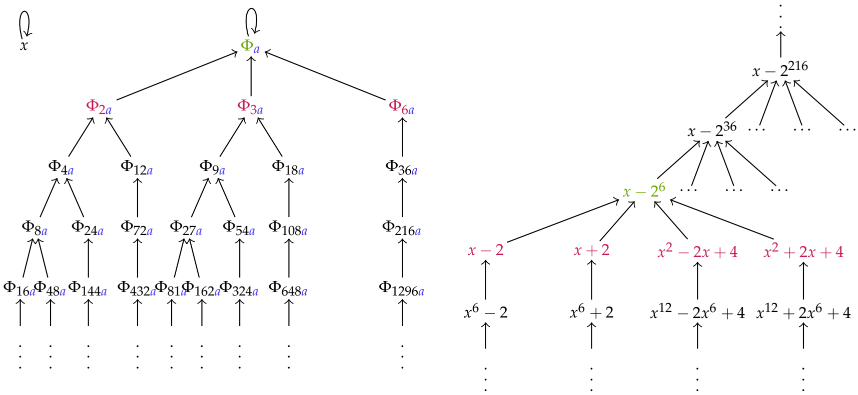
$$M\Phi_a = \Phi_a \Phi_{2a} \Phi_{3a} \Phi_{6a}, \quad a \wedge 6 = 1$$

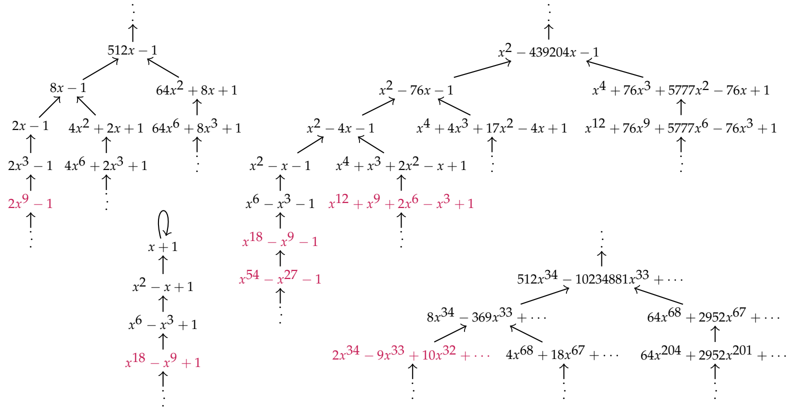
$$M(x - 2^6) = (x-2)(x+2)(x^2 - 2x + 4)(x^2 + 2x + 4)$$



Looking for a Denominator: an Example When $b = 3$

$$L = (2x^9-1)(x^{18}-x^9-1)(x^{12}+x^9+2x^6-x^3+1)(x^{18}-x^9+1)(2x^{34}-9x^{33}+10x^{32}+\cdots)(x^{54}-x^{27}-1)\,M^2 + \cdots$$

$$L\left(\frac{p}{q}\right) = 0, \qquad M^2 q \mid \ell_2\,(q \vee Mq).$$



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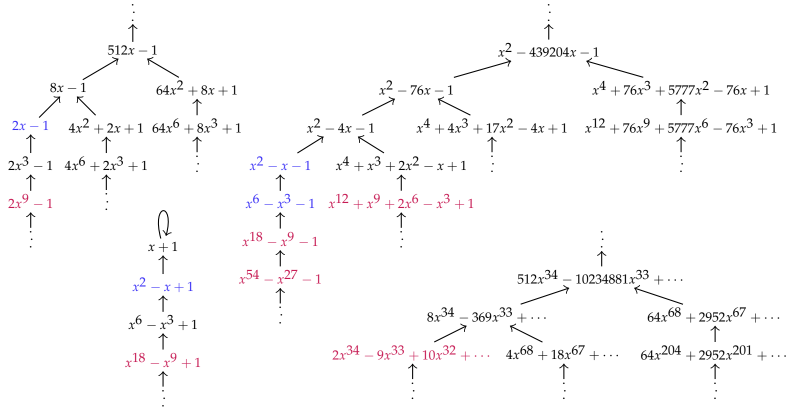

$$u_1=(2x-1)(x^2-x+1)(x^2-x-1)(x^6-x^3-1) \implies M^2u_1 \mid \ell_2$$

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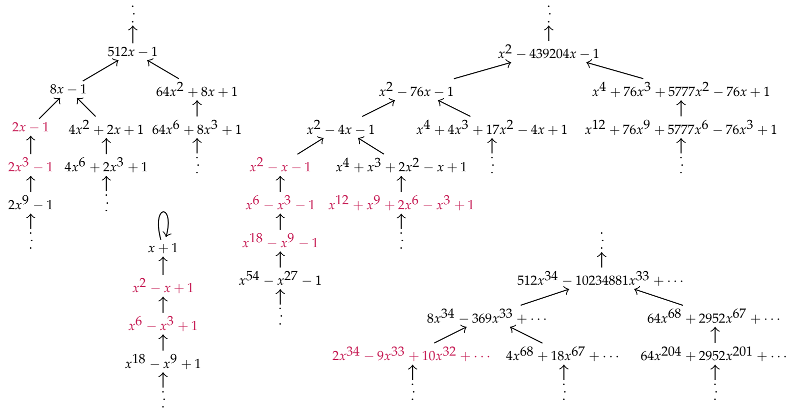

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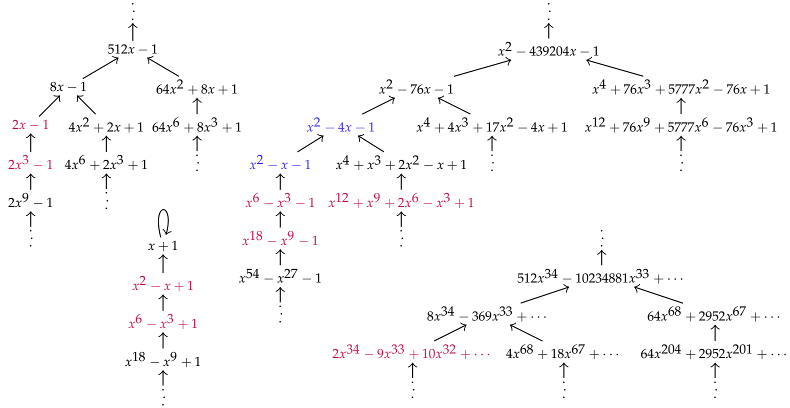

$$u_2 = (x^2 - x - 1)(x^2 - 4x - 1) \implies M^2 u_2 \mid \ell_2$$

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$L[u_1 u_2] = (2x-1)(x^2-x+1)(x^2-x-1)^2(x^2-4x-1)(2x^3-1)(x^4+x^3+2x^2-x+1)(x^6-x^3+1)(x^6-x^3-1)(2x^{34}-9x^{33}+\cdots)\,M^2+\cdots$

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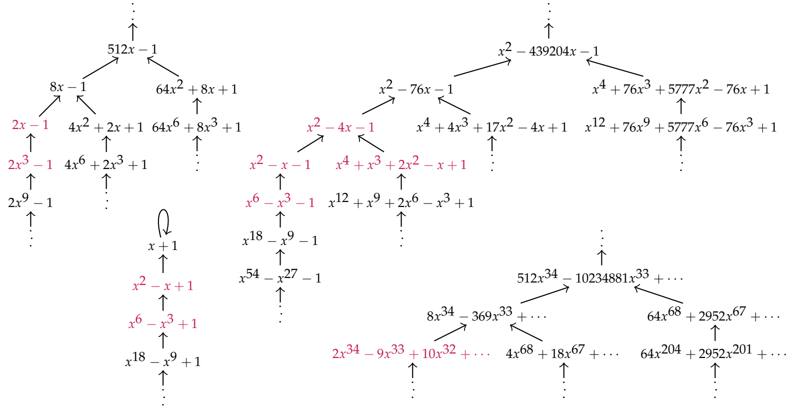

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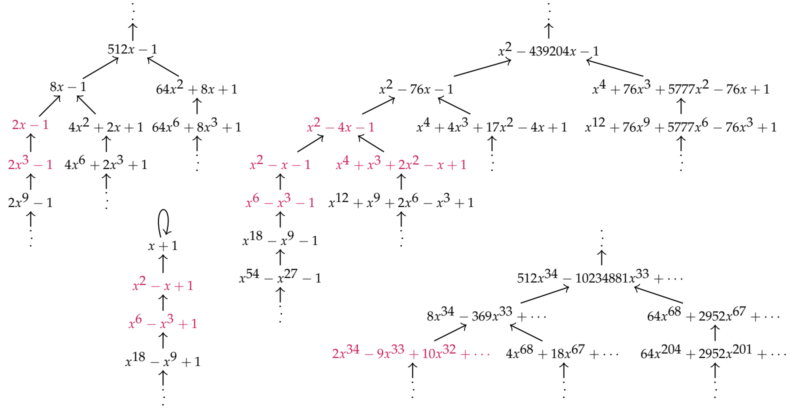

$u_3 = 1$

$L[u_1u_2u_3] = (2x-1)(x^2-x+1)(x^2-x-1)^2(x^2-4x-1)(2x^3-1)(x^4+x^3+2x^2-x+1)(x^6-x^3+1)(x^6-x^3-1)(2x^{34}-9x^{33}+\cdots)\,M^2+\cdot$

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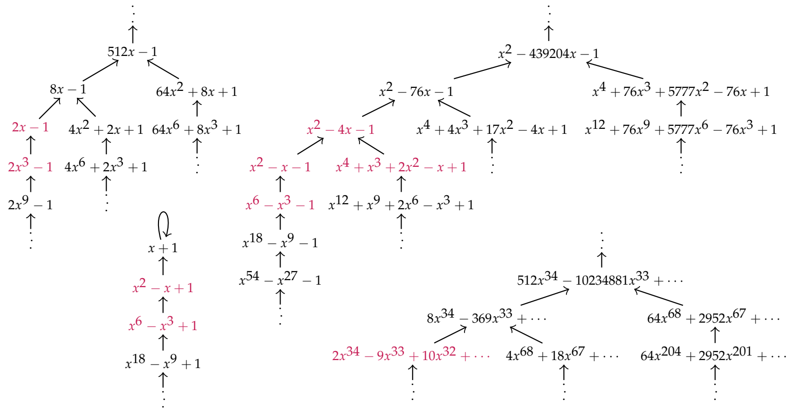

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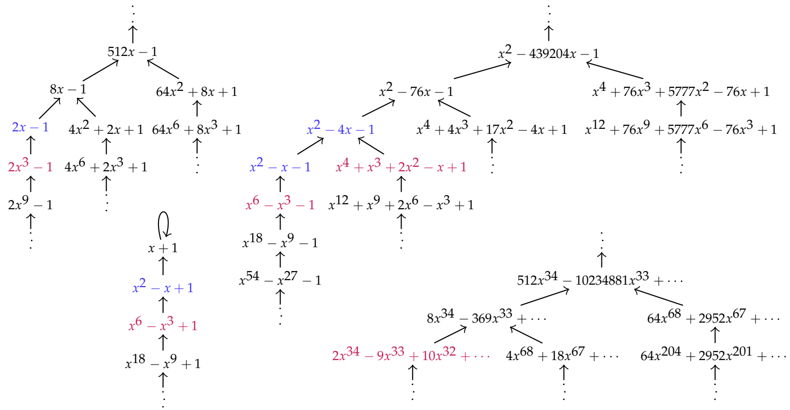

$$\tilde{u} = (2x-1)(x^2-x+1)(x^2-x-1)(x^2-4x-1) \implies M\tilde{u} \mid \ell_2 \text{ and } q \mid G\tilde{u}$$

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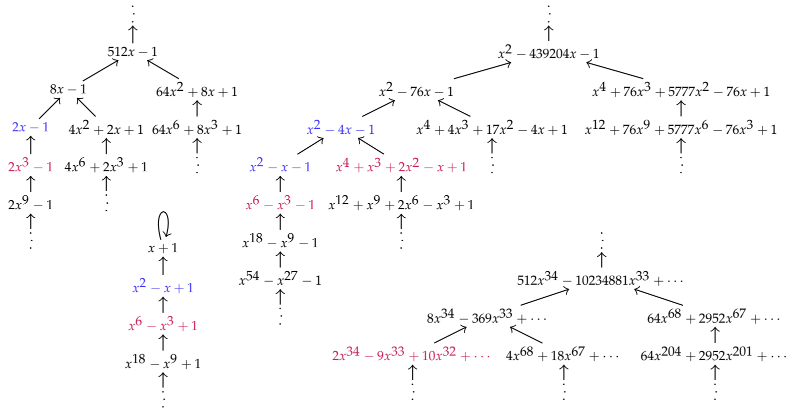

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Looking for a Denominator: an Example (Conclusion)

Operator to solve:

$$L = (2x^9 - 1)(x^{18} - x^9 - 1)(x^{12} + x^9 + 2x^6 - x^3 + 1)(x^{18} - x^9 + 1)(2x^{34} - 9x^{33} + 10x^{32} + \cdots)(x^{54} - x^{27} - 1)\,M^2$$
$$- (x^2+1)(x^2-x-1)(2x^3-1)(x^4+1)(x^4+x^3+2x^2-x+1)(x^6-x^3+1)(x^6-x^3-1)(x^{18}-x^9-1)(2x^{88}-9x^{87}+8x^{86}+\cdots)M$$
$$+ x^2(2x-1)(x^2-x+1)^2(x^2-x-1)(x^2+x+1)(x^2-4x-1)(2x^{102}-9x^{99}+10x^{96}+\cdots)$$

Denominator bound found:

$$q^\star = u_1 u_2 G \tilde{u} = (2x-1)(x^2-x+1)^2(x^2-x-1)^2(x^2-4x-1)(x^6-x^3-1)$$

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Explicit rational solutions:

$$\frac{2x}{(2x-1)(x^2-x-1)} \quad \text{and} \quad \frac{x-3}{(x^2-x+1)(x^2-4x-1)(x^6-x^3-1)}$$

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Remark: $\deg \ell_2 = 145 > \deg \ell_2[u_1] = 84 > \deg \ell_2[u_1u_2] = 62$.

Computing Denominator Bounds

$$\ell = \sum_{n \geq 0} c_n x^n \xrightarrow{i\text{th section in radix } b} \sum_{n \geq 0} c_{b^r n + i} x^n =: f_i$$

Algorithm

1. Set $\ell = \ell_r$, then repeat for $k = 1, 2, \ldots$:
   1. set $u_k = \bigwedge_{i=0}^{b^r - 1} f_i$ where $\ell = \sum_{i=0}^{b^r - 1} x^i M^r f_i$ with $f_i \in \mathbb{K}[x]$;
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Theorem (correctness)

Assume $Ly = 0$ with $y = \frac{p}{x^{\bar{v}} q}$ and $q(0) \neq 0$. Then, $q \mid q^\star$.

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Theorem (complexity and degree bounds)

- algorithm runs in $\mathrm{O}(d\ \mathrm{M}(d) \log d)$ ops
- $\deg q^\star \leq d$ if $b = 2$, $\quad \deg q^\star \leq d / b^{r-1}$ if $b \geq 3$

Conclusions

Summary

- theory of Newton polygons
- algorithms for formal series solutions, polynomial solutions, and rational-function solutions.
- algorithms for denominator bounds:
  - good: complexity is polynomial in r and d,
  - bad: quadratic in output size.

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Ongoing/Future work

- algorithms for Puiseux-series solutions,
- the case $\ell_0 = 0$,
- infinite-product solutions,
- rational solutions of Riccati-type equation.