Christol’s theorem and its analogue for generalized power series, part 2

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Theorem (Christol, 1979)

Let $\mathbb{F}_q$ be a finite field of characteristic $p$. A formal power series

$$f = \sum_{n=0}^{\infty} f_n t^n \in \mathbb{F}_q[t]$$

is algebraic over the rational function field $\mathbb{F}_q(t)$ if and only if it is \textbf{automatic}: for all $c \in \mathbb{F}_q$, the set of base-$p$ expansions of those $n \geq 0$ with $f_n = c$ form a regular language on the alphabet $\{0, \ldots, p-1\}$. 
Christol’s theorem is not enough

Why Christol’s theorem is not enough

Theorem (Puiseux, 1850 for $K = \mathbb{C}$)

For $K$ a field of characteristic 0, every finite extension of the field $K((t))$ is contained in some extension of the form $L((t^{1/m}))$ for $L$ a finite extension of $K$ and $m$ a positive integer.

This fails in positive characteristic as noted by Chevalley.

Proposition

The polynomial

$$z^p - z - t^{-1} \in \mathbb{F}_q((t))[z]$$

has no root in $\mathbb{F}_{q'}((t^{1/m}))$ for any power $q'$ of $q$ and any positive integer $m$. (Proof on next slide.)
Proof of the Proposition.

Suppose \( z = \sum_n z_n t^n \) were such a root. Then

\[
z^p = \sum_n z_n^p t^{np} = \sum_n z_{n/p}^p t^n
\]

and so

\[
t^{-1} = \sum_n (z_{n/p}^p - z_n) t^n.
\]

Since \( z \) is a (nonzero) formal power series in \( t^{1/m} \) for some \( m \), there must be a smallest index \( i \) for which \( z_i \neq 0 \). If \( i < -1/p \), then \( 0 = z_i^p - z_{pi} \) and so \( z_{pi} \neq 0 \), contradiction. Therefore \( z_{-1} = 0 \), which forces

\[
1 = z_{-1/p} = z_{-1/p^2} = \ldots
\]

and precludes \( z \in F_{q'}((t^{1/m})) \) for any \( m \), contradiction. \( \square \)
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2. Generalized power series

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4. Proof of Christol’s theorem for generalized power series

5. Final questions
Definition (Hahn, 1905)

A *generalized power series* over a field $K$ is a formal expression

$$f = \sum_{n \in \mathbb{Q}} f_n t^n$$

with $f_n \in K$ whose *support*

$$\text{Supp}(f) = \{ n \in \mathbb{Q} : f_n \neq 0 \}$$

is a well-ordered subset of $\mathbb{Q}$, i.e., one containing no infinite decreasing sequence. (Equivalently, every nonempty subset has a least element.)

We will write $K((t^\mathbb{Q}))$ for the set of generalized power series. To be precise, these are really generalized Laurent series; we write $K[[t^\mathbb{Q}]]$ to pick out those series whose supports are contained in $[0, +\infty)$.

Variants: Hahn allows $\mathbb{Q}$ to be replaced by a totally ordered abelian group. There is even a noncommutative version due to Mal’cev and Neumann (independently).
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It is easy to see that generalized power series can be added formally: the point is that the union of two well-ordered sets is again well-ordered.

Multiplication is less clear: given \( f = \sum_{n \in \mathbb{Q}} f_n t^n \), \( g = \sum_{n \in \mathbb{Q}} g_n t^n \), note first that for any \( n \in \mathbb{Q} \) the formal sum

\[
\sum_{i, j \in \mathbb{Q} : i + j = n} f_i g_j
\]

only contains finitely many nonzero terms. Then check that the support of \( f + g = \sum_{n \in \mathbb{Q}} \left( \sum_{i, j \in \mathbb{Q} : i + j = n} f_i g_j \right) t^n \) is well-ordered.
Arithmetic for generalized power series

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$$f + g = \sum_{n \in \mathbb{Q}} \left( \sum_{i,j \in \mathbb{Q} : i+j=n} f_i g_j \right) t^n$$

is well-ordered.
It follows that $K[[t^\mathbb{Q}]]$ and $K((t^\mathbb{Q}))$ are both rings under formal addition and multiplication. The ring $K((t^\mathbb{Q}))$ is also a field: any nonzero element can be written as $at^m(1 - f)$ where $a \in K^*$, $m \in \mathbb{Q}$, $f \in K[[t^\mathbb{Q}]]$, and $f_0 = 0$. But then the sum

$$\sum_{n=0}^{\infty} f^n$$

makes sense and defines an inverse of $1 - f$.

What “the sum makes sense” really means here is that $K((t^\mathbb{Q}))$ is complete for the $t$-adic valuation

$$v_t(f) = \min \text{Supp}(f).$$
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Algebraic closures

Theorem (Hahn, 1905)

*If* $K$ *is an algebraically closed field, then so is* $K(((t^Q)))$.

Sketch of proof.

Given a nonconstant polynomial $P$ over $K(((t^Q)))$, one can build a root by a *transfinite* sequence of successive approximations (one indexed by some countable ordinal).

In particular, if $K$ is an algebraic closure of $\mathbb{F}_q$, then $K(((t^Q)))$ contains an algebraic closure of $\mathbb{F}_q(t)$. Our goal (inspired by a suggestion of Abhyankar) is to identify this algebraic closure explicitly.
More on algebraic closures

Let $\mathbb{Z}[p^{-1}]$ denote the subring of $\mathbb{Q}$ generated by $p^{-1}$, i.e., the ring of rational numbers with only powers of $p$ in their denominators.

**Proposition (easy)**

Let $K$ be an algebraic closure of $\mathbb{F}_q$. Then every element $f$ of the algebraic closure of $\mathbb{F}_q((t))$ within $\mathbb{F}_q((t^Q))$ has the following properties.

(a) We have $\text{Supp}(f) \subset m^{-1}\mathbb{Z}[p^{-1}]$ for some positive integer $m$ coprime to $p$ (depending on $f$).

(b) The coefficients of $f$ belong to some finite subfield $\mathbb{F}_{q'}$ of $K$.

The same is then true of the algebraic closure of $\mathbb{F}_q(t)$ within $\mathbb{F}_q((t^Q))$. 
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Elements of $\mathbb{Q}_{\geq 0}$ have well-defined base-$p$ expansions, but only elements of $\mathbb{Z}[p^{-1}]_{\geq 0}$ have finite expansions. Such expansions are words on the alphabet $\{0, \ldots, p-1, .\}$, where the last symbol is the *radix point*.

We will allow arbitrary leading and trailing zeroes, but we will insist that to be *valid*, expansions must have exactly one radix point.

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Automatic generalized power series

Suppose $f \in \mathbb{F}_q((t^Q))$ has support in $\mathbb{Z}[p^{-1}] \geq 0$. We say that $f$ is automatic if the function $n \mapsto f_n$ is induced by some finite automaton on the alphabet $\{0, \ldots, p-1, .\}$ by identifying $n$ with its base-$p$ expansion.

Lemma (relatively easy)

For $m$ a positive integer and $a \in \mathbb{Z}[p^{-1}] \geq 0$, $\sum_n f_n t^n$ is automatic if and only if $\sum_n f_n t^{mn+a}$ is.

For a general $f \in \mathbb{F}_q((t^Q))$, we say that $f$ is automatic if there exist a positive integer $m$ and some $a \in \mathbb{Z}[p^{-1}] \geq 0$ such that $\sum_n f_n t^{mn+a}$ has support in $\mathbb{Z}[p^{-1}] \geq 0$ and is automatic in the above sense. By the lemma, this specializes back to the previous definition. (In the paper, the second condition is called quasi-automatic.)
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For any automatic $f \in \mathbb{F}_q((t^Q))$ with support in $\mathbb{Z}[p^{-1}]_{\geq 0}$, the function $f : \mathbb{Z}[p^{-1}]_{\geq 0} \to \mathbb{F}_q$ has the form $h \circ g_{\Delta}$ for some finite automaton $\Delta = (S, s_0, \delta)$ and some function $h : S \to \mathbb{F}_q$. We may also ensure that $h \circ g_{\Delta}$ sends all invalid strings to 0 and is constant over all expansions of a given $n$ (with varying leading and trailing zeroes).

But the converse fails: such data do not in general define a generalized power series! The trouble is that $\text{Supp}(h \circ g_{\Delta})$ is usually not well-ordered.

However, one can interpret the condition that $\text{Supp}(h \circ g_{\Delta})$ be well-ordered in graph-theoretical terms. See next slide.
Constraints on automata

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However, one can interpret the condition that $\text{Supp}(h \circ g_\Delta)$ be well-ordered in graph-theoretical terms. See next slide.
Graph-theoretic constraints

Form the directed multigraph $\tilde{\Gamma}$ on $S$ with an edge from $s$ to $s'$ labeled $i$ whenever $\delta(s, i) = s'$. We say a vertex or edge is essential if it occurs along a path from $s_0$ to a state in $h^{-1}(0)$, otherwise inessential.

Let $\Gamma$ be obtained from $\tilde{\Gamma}$ by removing all inessential vertices and edges. Each state in $\Gamma$ can be described as preradix and postradix depending on whether it occurs before or after a radix point along some (hence any) path from $s_0$. Every state in $h^{-1}(0)$ is postradix.

For $\text{Supp}(f)$ to be well-ordered, it is necessary and sufficient that for each postradix state $s \in \Gamma$,

- there is at most one directed cycle passing through $s$;
- if so, then the edge on this cycle from $s$ has a larger label than any other edge from $s$. 
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An example

Take \( p = 3 \). All unlabeled transitions map to a dummy state labeled 0 which only transitions to itself (and is hence inessential).

In base 3, the support consists of

\[ 0.1, 0.21, 0.221, \ldots \]

(omitting leading and trailing zeroes). If the 1 and 2 were reversed we would instead get a decreasing sequence

\[ 0.2, 0.12, 0.112, \ldots \]
An extension of Christol’s theorem

Theorem (Kedlaya, 2006)

An element \( f \in \mathbb{F}_q((t^\mathbb{Q})) \) is algebraic over \( \mathbb{F}_q(t) \) if and only if it is automatic.

Some sample corollaries:

Corollary

If \( f = \sum_{n \in \mathbb{Q}} f_n t^n, g = \sum_{n \in \mathbb{Q}} g_n t^n \in \mathbb{F}_q((t^\mathbb{Q})) \) are algebraic over \( \mathbb{F}_q(t) \), then so is the Hadamard product \( f \odot g = \sum_{n \in \mathbb{Q}} f_n g_n t^n \).

Corollary

If \( f = \sum_{n \in \mathbb{Q}} f_n t^n \) is algebraic over \( \mathbb{F}_q(t) \), then so is \( \sum_{n \in \mathbb{Q} \cap I} f_n t^n \) for any interval \( I \) in \( \mathbb{R} \).
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If \( f = \sum_{n \in \mathbb{Q}} f_n t^n \) and \( g = \sum_{n \in \mathbb{Q}} g_n t^n \) are algebraic over \( \mathbb{F}_q(t) \), then so is the Hadamard product \( f \odot g = \sum_{n \in \mathbb{Q}} f_n g_n t^n \).

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The example of Chevalley

The polynomial

\[ z^p - z - t^{-1} \]

over \( \mathbb{F}_q(t) \) has in \( \mathbb{F}_q((t^\mathbb{Q})) \) the root

\[ f = t^{-1/p} + t^{-1/p^2} + t^{-1/p^3} + \ldots. \]

Note that \( tf \) has support in \( \mathbb{Z}[p^{-1}] \) which is accepted by the regular expression

\[ 0^*.@*0^* \]

where @ represents the digit \( p - 1 \). Hence \( f \) is automatic.
Proof of Christol’s theorem for generalized power series

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$$e_s = \sum_{n \in \mathbb{Z}, g_\Delta(n) = s} t^n, \quad g_s = \sum_{n \in \mathbb{Z}[p^{-1}] \cap [0,1), g_\Delta(n) = s} t^n.$$ 

Note that $e_s \neq 0$ (resp. $g_s \neq 0$) only if $s$ is essential and preradix (resp. postradix). Moreover, $f = \sum_s e_s g_{\delta(s,\cdot)}$ and

$$e_s = \sum_{s' : i : \delta(s',i) = s} e_{s'}^p t^i, \quad g_s = \sum_{i=0}^{p-1} g_{\delta(s,i)}^{1/p} t^{i/p}.$$ 

For $m \geq 0$, $g_s^p^m$ belongs to the $\mathbb{F}_q(t)$-span of the $g_s$, so the $g_s$ are algebraic. Similarly (as before) the $e_s$ are algebraic. Hence $f$ is algebraic.
Proof of Christol’s theorem for generalized power series

Automatic implies algebraic

Suppose \( f \in \mathbb{F}_q((t^\mathbb{Q})) \) is automatic. To check that \( f \) is algebraic, we may assume \( \text{Supp}(f) \subseteq \mathbb{Z}[p^{-1}]_{\geq 0} \). Write \( f = h \circ g_\Delta \) for some finite automaton \( \Delta = (S, s_0, \delta) \) and some function \( h : S \to \mathbb{F}_q \). Put

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e_s = \sum_{s', i : \delta(s', i) = s} e_{s'}^p t^i, \quad g_s = \sum_{i=0}^{p-1} g_\delta^{1/p}(s,i) t^i/p.
\]

For \( m \geq 0 \), \( g_s^p \) belongs to the \( \mathbb{F}_q(t) \)-span of the \( g_s \), so the \( g_s \) are algebraic. Similarly (as before) the \( e_s \) are algebraic. Hence \( f \) is algebraic.
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Automaticity and arithmetic operations

For “algebraic implies automatic,” we can’t use decimations because Frobenius is bijective on $\mathbb{F}_q((t^Q))$. Instead, we use field theory.

Lemma

The set of automatic elements of $\mathbb{F}_q((t^Q))$ is a subfield.

Sketch of proof.

We check that automatic elements form a subring using some explicit constructions of automata. For $f \in \mathbb{F}_q((t^Q))$ nonzero automatic, we know $f$ is algebraic:

$$f^d + h_{d-1}f^{d-1} + \cdots + h_0 = 0$$

for some $h_0, \ldots, h_{d-1} \in \mathbb{F}_q(t)$ with $h_0 \neq 0$. Then

$$f^{-1} = -h_0^{-1}(f^{d-1} + h_{d-1}f^{d-2} + \cdots + h_1)$$

belongs to the subring of automatic elements, which is thus a subfield.
Automaticity and arithmetic operations

For “algebraic implies automatic,” we can’t use decimations because Frobenius is bijective on $\mathbb{F}_q((t^Q))$. Instead, we use field theory.

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Lemma (standard)

Let $F$ be a field of characteristic $p$. Then the $\mathbb{Z}/p\mathbb{Z}$-extensions of $F$ coincide with the Artin-Schreier extensions, i.e., those generated by roots of polynomials of the form

$$z^p - z - c \quad (c \in F).$$

Note that the Galois action is generated by $z \mapsto z + 1$.

Proposition (standard)

Let $K$ be a finite extension of $\mathbb{F}_q(t)$. Then there exist a power $q'$ of $q$, a positive integer $m$, and a finite extension $L$ of $\mathbb{F}_{q'}(t^{1/m})$ containing $K$ such that $L/\mathbb{F}_q(t)$ can be written as a tower of Artin-Schreier field extensions.
Lemma

If \( f \in \mathbb{F}_q((t^Q)) \) is automatic and

\[ g^p - g = f, \]

then \( g \) is automatic.

Sketch of proof.

We may separate the cases where \( f \) is supported in \((-\infty, 0)\) and \((0, \infty)\). In these cases we have respectively

\[ g = c + f^{-1/p} + f^{-1/p^2} + \ldots \]
\[ g = c - f - f^p - \ldots \]

for some \( c \in \mathbb{F}_p \). In both cases, we may explicitly construct an automaton producing \( g \) from one that produces \( f \).
Automaticity and Artin-Schreier extensions

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We now know that for $K$ an algebraic closure of $\mathbb{F}_q$, 

- for $q'$ varying over powers of $q$, the automatic elements of $\bigcup_{q'} \mathbb{F}_{q'}((t^Q))$ form a subfield of the algebraic closure of $\mathbb{F}_q(t)$ in $K((t^Q))$;
- this subfield contains $\mathbb{F}_{q'}(t^{1/m})$ for any power $q'$ of $q$ and any positive integer $m$;
- this subfield is closed under extraction of roots of Artin-Schreier polynomials.

It therefore is the whole algebraic closure of $\mathbb{F}_q(t)$. The theorem follows.
Algebraicity implies automaticity

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2. Generalized power series
3. Christol’s theorem for generalized power series
4. Proof of Christol’s theorem for generalized power series
5. Final questions
Automata and explicit computations

When making machine computations in an algebraic closure of \( \mathbb{Q} \), it is often inefficient to work exactly because one is forced to keep track of algebraic number fields of large degree. It is sometimes more practical to keep track of approximations in \( \mathbb{C} \) of sufficient accuracy, i.e., to do *interval arithmetic*.

It should be possible to similarly compute in an algebraic closure of \( \mathbb{F}_q(t) \) using automata. The tricky part is to describe a sensible notion of *approximation*; this is needed because exact computation is usually infeasible.
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Relative algebraicity

For $K$ an algebraic closure of $\mathbb{F}_q$, it makes sense to ask whether $x_1, \ldots, x_n \in K((t^\mathbb{Q}))$ are algebraically dependent over $\mathbb{F}_q(t)$, i.e., whether $P(x_1, \ldots, x_n) = 0$ for some nonzero $n$-variate polynomial $P$ over $\mathbb{F}_q(t)$.

**Problem**

*Is there an automata-theoretic characterization of algebraic dependence?*

Already the case of ordinary power series is of interest.
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