

**q -deformed binomial
coefficients of words**

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Overview



1. Definition and examples
2. Combinatorial interpretation
3. p -group languages
4. q -Parikh matrices

The background of the slide is composed of two large, overlapping geometric shapes. A teal-colored shape occupies the top-left corner, while a light gray shape occupies the bottom-left corner. The rest of the slide is white. The text is centered in the white area.

Definition and examples



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q -deformations

A *q -deformation* or *q -analog* is a generalisation of some mathematical object involving a new parameter q , such that the limit for $q \rightarrow 1$ gives back the original object.



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Ex:

- ▶ q -natural numbers: $[n]_q = \frac{1 - q^n}{1 - q} = 1 + q + \cdots + q^{n-1}$,
- ▶ q -factorial: $[n]_q! = [n]_q [n-1]_q \cdots [2]_q [1]_q$,
- ▶ q -binomial coefficients: $\binom{n}{k}_q = \frac{[n]_q!}{[n-k]_q! [k]_q!}$



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But also: q -rational numbers, q -derivative, Gaussian q -distribution, etc.



Definition and examples

Basics for COW

In this talk, all considered words are *finite words* over a finite alphabet A , and a, b will denote two (distinct) *letters* of A .

The *empty word* is denoted by ε and is the identity element of the free monoid A^* .

The *length* of a word u is denoted by $|u|$.

If there exist some finite words p, f, s such that $u = pfs$, we say that

- ▶ p is a *prefix* of u ($p \in \text{Pref}(u)$),
- ▶ f is a *factor* of u ($f \in \text{Fac}(u)$),
- ▶ s is a *suffix* of u ($s \in \text{Suff}(u)$).



Definition and examples

Binomial coefficients

The *binomial coefficient* $\binom{u}{v}$ of two words counts the number of occurrences of v as a subword of u .

Ex:

$$\binom{abbab}{ab} = 4$$

abbab *abbab*

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Gaussian binomial coefficient $\binom{n}{k}_q$ of two positive integers:

$$\binom{n}{k}_q = \frac{(1 - q^n) \cdots (1 - q^{n-k+1})}{(1 - q^k) \cdots (1 - q)}$$

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→ counts the number of subspaces of dimension k in a vector space of dimension n over $\mathbb{F}_q$.

→ ***What if we merge these two objects?***



Definition and examples

q -deformed binomial coefficients of words

Two recursive definitions for the “classical” coefficients:



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Coefficients on words:

$$\binom{ua}{vb} = \binom{u}{vb} + \delta_{a,b} \binom{u}{v}$$

Gaussian coefficients:

$$\binom{n+1}{k+1}_q = \binom{n}{k+1}_q \cdot q^{k+1} + \binom{n}{k}_q$$



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→ ***We are going to mix these two!***



Definition and examples

q -deformed binomial coefficients of words

The *q -deformation* $\binom{\cdot}{\cdot}_q$ of binomial coefficients of words is a polynomial in $\mathbb{N}[q]$ defined as follows: for all $u, v \in A^*$ and $a, b \in A$ (where A is a finite alphabet),

$$\binom{u}{\varepsilon}_q = 1, \quad \binom{\varepsilon}{v}_q = 0 \text{ if } v \neq \varepsilon,$$

$$\binom{ua}{vb}_q = \binom{u}{vb}_q \cdot q^{|vb|} + \delta_{a,b} \binom{u}{v}_q.$$



Definition and examples

Basic properties

Directly from definition, we can show that for all $u, v \in A^*$,

- ▶ $\binom{u}{u}_q = 1$,
- ▶ $\binom{u}{v}_q = 0 \Leftrightarrow v$ does not occur as a subword of u .

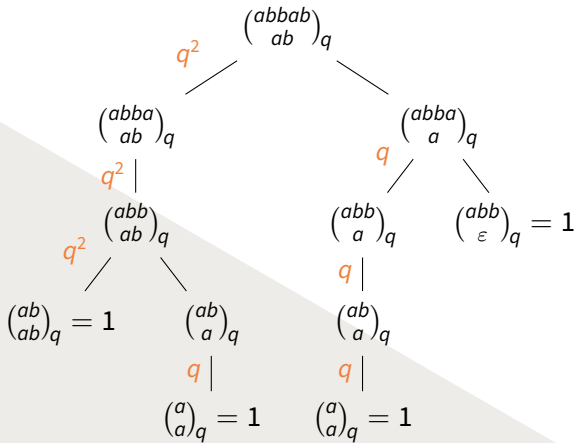
We can also link our q -coefficients to the classical ones: for all $u, v \in A^*, k, l \in \mathbb{N}$

- ▶ $\binom{u}{v}_q(1) = \binom{u}{v}$,
- ▶ $\binom{a^k}{a^\ell}_q = \binom{k}{\ell}_q$.



Definition and examples

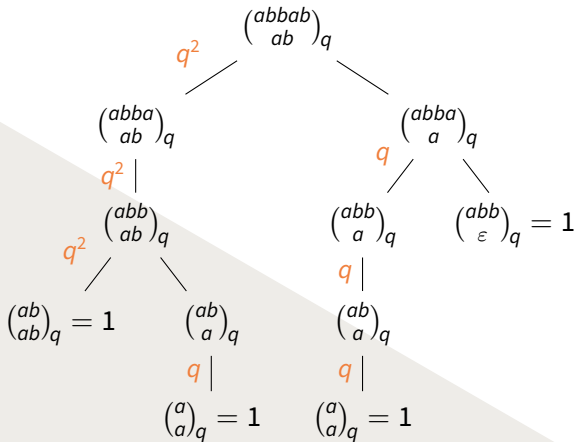
Example: an easy way to compute q -binomials



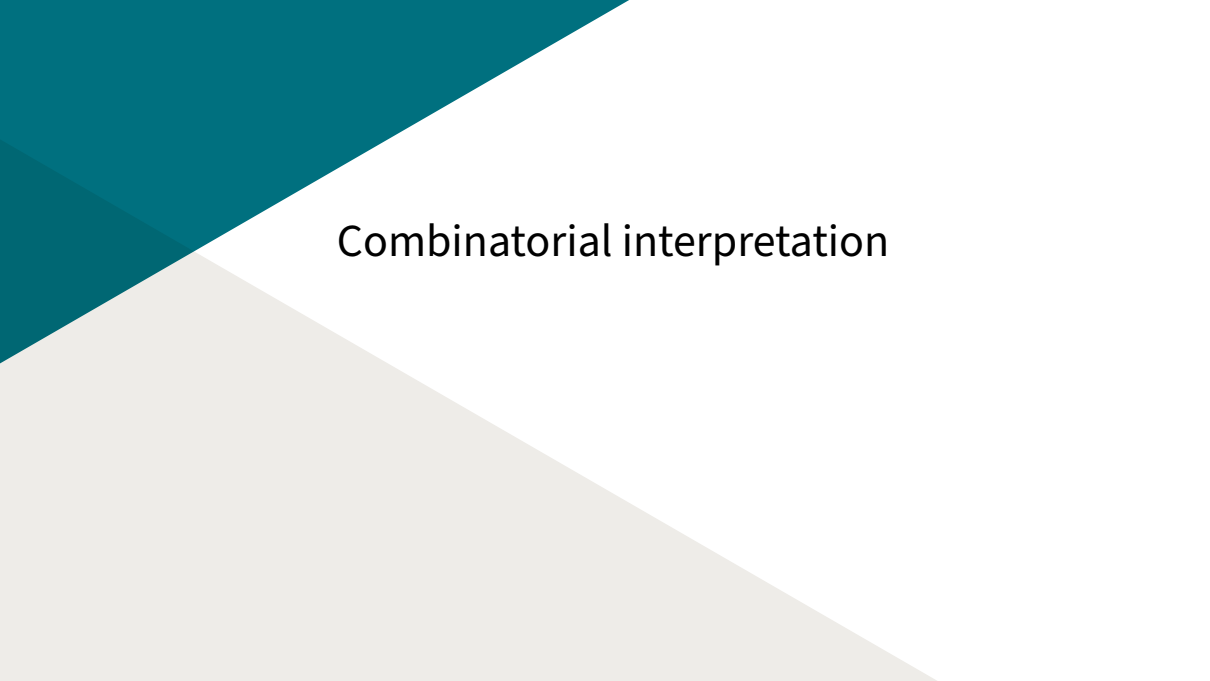


Definition and examples

Example: an easy way to compute q -binomials



$$\binom{abbab}{ab}_q = q^6 + q^5 + q^3 + 1$$

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Combinatorial interpretation



Combinatorial interpretation

Main result

Theorem (R., Rigo, Whiteland, 2024+)

Let u be a word over A , $k \geq 0$, and $a_1, \dots, a_k \in A$. Then

$$\binom{u}{a_1 \cdots a_k}_q = \sum_{\substack{u_0, u_1, \dots, u_k \in A^* \\ u = u_0 a_1 \cdots u_{k-1} a_k u_k}} q^{\sum_{i=1}^k i|u_i|}.$$



Combinatorial interpretation

Main result

If we take back our favourite example

$$\binom{abbab}{ab}_q = q^6 + q^5 + q^3 + 1,$$

we have to consider all factorisations of $abbab$ of the form $u_0 a u_1 b u_2$:

	$abbab$	$abbab$	$abbab$	$abbab$
(u_1, u_2)	(ε, bab)	(b, ab)	(bba, ε)	$(\varepsilon, \varepsilon)$
$ u_1 + 2 u_2 $	6	5	3	0

Combinatorial interpretation



Main result

In other words, for a fixed occurrence of v in u , one has to count, for each letter of v , the number of letters of u that are at its right and not part of this specific occurrence.

Summing these numbers gives the corresponding power of q .



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Here we go again:

$$\begin{array}{ccccccc} \text{a}\text{b}\overline{\text{b}}\text{a}\overline{\text{b}} & & \text{a}\text{b}\overline{\text{b}}\underline{\text{a}}\overline{\text{b}} & & \text{a}\text{b}\underline{\text{b}}\text{a}\text{b} & & \text{a}\text{b}\text{b}\text{a}\text{b} \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \\ q^{3+3} & + & q^{3+2} & + & q^{3+0} & + & q^{0+0} = \binom{\text{abbab}}{\text{ab}}_q \end{array}$$



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→ **the powers of q encode the positions of the letters of v in its occurrences in u**



Combinatorial interpretation

Information within the coefficients

From the combinatorial interpretation, we get some information about coefficients.

Corollary (R., Rigo, Whiteland, 2024+)

For all words u, v , the polynomial $\binom{u}{v}_q$ is monic, and the non-zero coefficient of the monomial of least degree is 1. In particular,

- ▶ $\binom{u}{v}_q(0) = \begin{cases} 1, & \text{if } v \text{ is a suffix of } u, \\ 0, & \text{otherwise.} \end{cases}$
- ▶ $\binom{u}{v}_q [q^{|v|(|u|-|v|)}] = \begin{cases} 1, & \text{if } v \text{ is a prefix of } u, \\ 0, & \text{otherwise.} \end{cases}$

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p -group languages



p -group languages

Definitions

Recall that a language L is *recognised* by a monoid M if there exist

- ▶ a subset $S \subset M$,
- ▶ a monoid morphism $\varphi : A^* \rightarrow M$,

such that $L = \varphi^{-1}(S)$.



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Finally, a language recognised by a p -group (*i.e.* a group whose elements have order which is a power of p) is a **p -group language**, where p is a prime.



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N.B.: Regular languages = recognisable languages



p -group languages

Characterising p -group languages

Theorem (Eilenberg, 1976)

Let p be a prime. A language is a p -group language if and only if it is a Boolean combination of languages of the form

$$L_{v,r,p} := \{u \in A^* \mid \binom{u}{v} \equiv r \pmod{p}\}.$$



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Theorem (R., Rigo, Whiteland, 2024+)

Let p be a prime and $\mathfrak{M} = a(q-1)^d$ with $d \geq 1$ an integer and a non-zero $a \in \mathbb{F}_p$. A language is a p -group language if and only if it is a Boolean combination of languages of the form

$$L_{v,\mathfrak{R},\mathfrak{M}} = \left\{ u \in A^* \mid \binom{u}{v}_q \equiv \mathfrak{R} \pmod{\mathfrak{M}} \right\}.$$



p -group languages

Preliminaries

Let p be a prime, $\mathbb{F}_p = \mathbb{Z}/p\mathbb{Z}$ be the field of integers modulo p and $\mathfrak{M}$ be a non-zero polynomial in $\mathbb{F}_p[q]$. We denote $\mathbb{K} = \mathbb{F}_p[q]/\langle \mathfrak{M} \rangle$.

Quite naturally, we will consider languages of the form

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Idea: To prove the theorem, we are going to define a congruence $\cong$, so that $A^*/\cong$ is a finite monoid, and thus have regular languages.



p -group languages

Preliminaries

Let $u \in A^*$ and $\mathfrak{M} \in \mathbb{F}_p[q]$. Two finite words $w_1, w_2 \in A^*$ are $(u, \mathfrak{M})$ -*binomially equivalent* and we write $w_1 \sim_{u, \mathfrak{M}} w_2$ whenever

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→ # classes $\leq \#\mathbb{K}(\#\text{Fac}(u)-1)$

→ $A^* / \sim_{u, \mathfrak{M}}$ is finite



p -group languages

Preliminaries

Problem: $\sim_{u,\mathfrak{M}}$ is not always a congruence...

Ex: For $p = 2$, $\mathfrak{M} = q^2 + 1$, $A = \{a, b\}$ and $u = a$, we have $a \sim_{u,\mathfrak{M}} abbbbaa$ and $b \sim_{u,\mathfrak{M}} bb$:

$$\binom{a}{a}_q \equiv 1 \equiv \binom{abbbbaa}{a}_q \pmod{\mathfrak{M}} \quad \text{and} \quad \binom{b}{a}_q \equiv 0 \equiv \binom{bb}{a}_q \pmod{\mathfrak{M}}$$

but $ab \not\sim_{u,\mathfrak{M}} abbbbaabb$:

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We will consider a congruence $\cong$ which is a **refinement** of $\sim_{u,\mathfrak{M}}$, i.e.

$$w_1 \cong w_2 \Rightarrow w_1 \sim_{u,\mathfrak{M}} w_2.$$

We also say that $\sim_{u,\mathfrak{M}}$ is **coarser** than $\cong$.

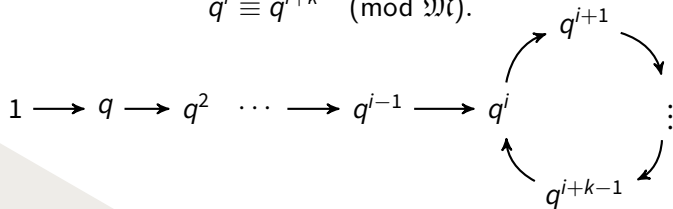


p -group languages

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As $\mathbb{K} = \mathbb{F}_p[q]/\langle \mathfrak{M} \rangle$ is finite, there exist $i \geq 0, k \geq 1$ such that

$$q^i \equiv q^{i+k} \pmod{\mathfrak{M}}.$$



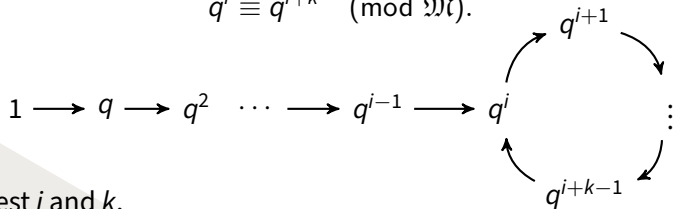


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Taking the smallest i and k ,

- ▶ i is the **index** of q ,
- ▶ k is the **period** of q .

Notice that, if q is invertible in $\mathbb{K}$, then $i = 0$ and $k = \text{ord}(q)$.



p -group languages

Results

If q is not a unit of $\mathbb{K}$, we have the following:

Proposition (R., Rigo, Whiteland, 2024)

Let $u \in A^*$, $\mathfrak{M} \in \mathbb{F}_p[q]$ and $\cong$ be a congruence that refines $\sim_{u,\mathfrak{M}}$. If q is not a unit of $\mathbb{K}$, then the monoid $A^* / \cong$ is not a group. In particular, no element except for the identity is invertible.



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Why? We managed to show that for any congruence $\cong$ refining $\sim_{u,\mathfrak{M}}$, we have

$$w_1 \cong w_2 \Rightarrow |w_1| = |w_2| \text{ or } (|w_1|, |w_2| \geq \text{ind}(q) \wedge \dots)$$

So when q is not a unit of $\mathbb{K}$, $\text{ind}(q) \geq 1$, and $[\varepsilon]$ is a singleton, so that $[w] \cdot [x] = [wx] \neq [\varepsilon]$ for all $w, x \in A^+$.



p -group languages

Results

If q is a unit of $\mathbb{K}$, we can look for the *coarsest* congruence refining $\sim_{u, \mathfrak{M}}$.

We showed that $\sim_{u, \mathfrak{M}} \cap \sim_{\text{ord}(p)}$, where

$$w_1 \sim_{\text{ord}(q)} w_2 \Leftrightarrow |w_1| \equiv |w_2| \pmod{\text{ord}(q)},$$

and denoted $\equiv_{u, \mathfrak{M}}$ is the coarsest congruence refining $\sim_{u, \mathfrak{M}}$.



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If q is a unit of $\mathbb{K}$, we can look for the **coarsest** congruence refining $\sim_{u, \mathfrak{M}}$.

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Theorem (R., Rigo, Whiteland, 2024)

Let $u \in A^$, $\mathfrak{M} \in \mathbb{F}_p[q]$. If q is a unit in $\mathbb{K}$, $A^* / \equiv_{u, \mathfrak{M}}$ is a group whose order divides $\text{ord}(q) \cdot p^{|u|}$.*



p -group languages

Results

Corollary (R., Rigo, Whiteland, 2024+)

Let v be a word and $\mathfrak{M} = a(q-1)^d$ for some integer $d \geq 1$. The language

$$L_{v, \mathfrak{R}, \mathfrak{M}} = \left\{ u \in A^* \mid \binom{u}{v}_q \equiv \mathfrak{R} \pmod{\mathfrak{M}} \right\}$$

is a p -group language.

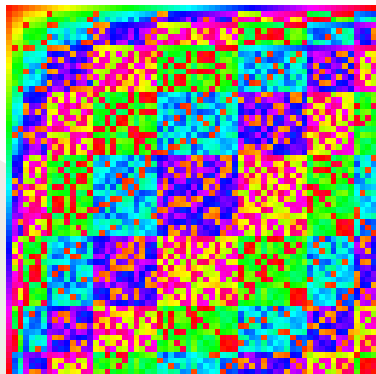
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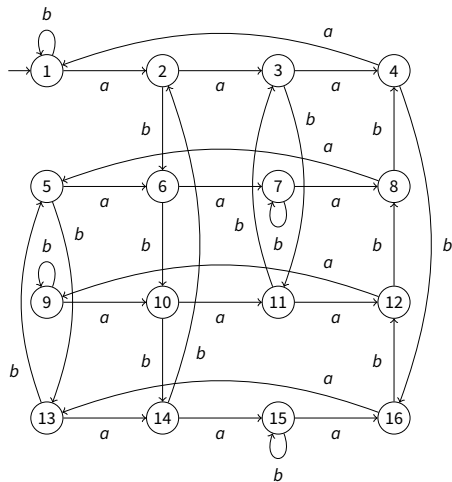
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p -group languages

Nice examples



$$\{a, b\}^* / \sim_{ab, q^2+1}$$



$$L_{ab, \mathfrak{A}, q^2+1}$$

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q -Parikh matrices



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“Classical” Parikh matrices

Introduced by Șerbănuță in 2004, the *Parikh matrix induced by a word* $z = z_1 \cdots z_n$ and associated to a word u is an upper triangular matrix of size $(n + 1) \times (n + 1)$, containing elements of the form $\binom{u}{v}$ for words v of the form $z_i z_{i+1} \cdots z_j$, $1 \leq i \leq j \leq |z|$.



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The Parikh matrix mapping is a monoid morphism $\Psi_{A,z} : A^* \rightarrow \mathbb{N}^{(n+1) \times (n+1)}$ defined by

$$[\Psi_{A,z}(a)]_{i,j} = \begin{cases} 1 & j = i \\ \delta_{a,z_i} & j = i + 1 \\ 0 & \text{otherwise} \end{cases} \quad \text{for all } a \in A.$$



q -Parikh matrices

An example

Fix $z = aba$ and $u = abbaba$. We have

$$\psi_{A,z}(a) = \begin{pmatrix} 1 & \color{red}{1} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & \color{red}{1} \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad \text{and} \quad \psi_{A,z}(b) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & \color{red}{1} & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

so that $\psi_{A,z}(u) = \psi_{A,z}(a)\psi_{A,z}(b)\psi_{A,z}(b)\psi_{A,z}(a)\psi_{A,z}(b)\psi_{A,z}(a)$, i.e.

$$\psi_{A,z}(u) = \begin{pmatrix} 1 & 3 & 4 & 6 \\ 0 & 1 & 3 & 5 \\ 0 & 0 & 1 & 3 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & \binom{u}{a} & \binom{u}{ab} & \binom{u}{aba} \\ 0 & 1 & \binom{u}{b} & \binom{u}{ba} \\ 0 & 0 & 1 & \binom{u}{a} \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$



q -Parikh matrices

q -deformed Parikh matrices

Let $z = z_1 \cdots z_n$ be a word and A be the alphabet of z , i.e. the set of letters occurring in z .

For $a \in A$ and $\ell \geq 0$, we let $\mathcal{M}_{a,\ell}$ denote the upper triangular matrix defined by

$$[\mathcal{M}_{a,\ell}]_{i,j} = \begin{cases} 1 & j = i \\ \delta_{a,z_i} q^\ell & j = i + 1 \\ 0 & \text{otherwise} \end{cases}.$$

We now define the map

$$\mathcal{P}_z : A^* \rightarrow (\mathbb{N}[q])^{(n+1) \times (n+1)} : u_k u_{k-1} \cdots u_1 u_0 \mapsto \mathcal{M}_{u_k,k} \cdots \mathcal{M}_{u_0,0}.$$



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q -deformed Parikh matrices

Let $z = z_1 \cdots z_n$ be a word and A be the alphabet of z , i.e. the set of letters occurring in z .

For $a \in A$ and $\ell \geq 0$, we let $\mathcal{M}_{a,\ell}$ denote the upper triangular matrix defined by

$$[\mathcal{M}_{a,\ell}]_{i,j} = \begin{cases} 1 & j = i \\ \delta_{a,z_i} q^\ell & j = i + 1 \\ 0 & \text{otherwise} \end{cases}.$$

We now define the map

$$\mathcal{P}_z : A^* \rightarrow (\mathbb{N}[q])^{(n+1) \times (n+1)} : u_k u_{k-1} \cdots u_1 u_0 \mapsto \mathcal{M}_{u_k,k} \cdots \mathcal{M}_{u_0,0}.$$

Unfortunately, **this is not a monoid morphism anymore.**



q -Parikh matrices

q -deformed Parikh matrices

Here, we have the following:

Theorem (R., Rigo, Whiteland, 2024+)

Let z be a word of length $n \geq 1$ whose alphabet is A . Let $u \in A^$. The corresponding $(n + 1) \times (n + 1)$ q -Parikh matrix is such that*

- ▶ $[\mathcal{P}_z(u)]_{i,j} = 0$, for all $1 \leq j < i \leq n + 1$,
- ▶ $[\mathcal{P}_z(u)]_{i,i} = 1$, for all $1 \leq i \leq n + 1$.
- ▶ Let $r \in \{1, \dots, n\}$. For all $1 \leq i \leq n - r + 1$, $[\mathcal{P}_z(u)]_{i,i+r} = q^{s(r-1)} \binom{u}{z_i z_{i+1} \dots z_{i+r-1}}_q$,
where $s(\ell) = \sum_{k=1}^{\ell} k$.



q -Parikh matrices

An example (again)

Back with our friends $z = aba$ and $u = abbaba$, we have

$$\mathcal{M}_{a,\ell} = \begin{pmatrix} 1 & q^\ell & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & q^\ell \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad \text{and} \quad \mathcal{M}_{b,\ell} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & q^\ell & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$



q -Parikh matrices

An example (again)

Thus,

$$\begin{aligned}\mathcal{P}_z(u) &= \mathcal{M}_{a,5}\mathcal{M}_{b,4}\mathcal{M}_{b,3}\mathcal{M}_{a,2}\mathcal{M}_{b,1}\mathcal{M}_{a,0} \\ &= \begin{pmatrix} 1 & q^5 + q^2 + 1 & q^9 + q^8 + q^6 + q^3 & q^{11} + q^{10} + q^9 + q^8 + q^6 + q^3 \\ 0 & 1 & q^4 + q^3 + q & q^6 + q^5 + q^4 + q^3 + q \\ 0 & 0 & 1 & q^5 + q^2 + 1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \\ &= \begin{pmatrix} 1 & \binom{u}{a}_q & q\binom{u}{ab}_q & q^3\binom{u}{aba}_q \\ 0 & 1 & \binom{u}{b}_q & q\binom{u}{ba}_q \\ 0 & 0 & 1 & \binom{u}{a}_q \\ 0 & 0 & 0 & 1 \end{pmatrix}.\end{aligned}$$



q -Parikh matrices

Some consequences

- ▶ Alternative way to compute q -binomials;
- ▶ New identities, e.g.

$$\sum_{\substack{z=xy \\ x,y \in A^*}} (-1)^{|y|} q^{s(|x|-1)+s(|y|-1)} \binom{u}{x}_q \binom{u}{\widetilde{y}}_q = 0$$

for words z with no equal consecutive letters;

- ▶ etc.



q -Parikh matrices

Convergence to formal power series

Theorem (R., Rigo, Whiteland, 2024+)

The q -binomial $\binom{u^n}{z}_q$ can be expressed as

$$\frac{1}{q^{s(|z|-1)}} \sum_{k=1}^m R_k(q) \frac{1 - q^{c_k n |u|}}{1 - q^{c_k |u|}},$$

where m and c_k are positive integers, and R_k are rational functions whose denominators only have factors of the form $(1 - q^{t|u|})$ for some integer t . Moreover, these quantities c_k and R_k can be effectively computed. In particular, the sequence $(\binom{u^n}{z}_q)_{n \geq 0}$ converges in $\mathbb{N}[[q]]$ to the formal power series $\mathfrak{s}_{\mathbf{u},z}(q)$ expressed by the rational function

$$\frac{1}{q^{s(|z|-1)}} \sum_{k=1}^m R_k(q) \frac{1}{1 - q^{c_k |u|}}.$$



q -Parikh matrices

Convergence to formal power series

Ex:

The sequence $\left(\binom{(abba)^n}{ab}_q \right)_{n \geq 0}$ converges to the series

$$q^3 + 2q^4 + q^5 + q^7 + 2q^8 + q^9 + 2q^{11} + 4q^{12} + 2q^{13} + 2q^{15} + 4q^{16} + 2q^{17} + 3q^{19} + 6q^{20} + \dots,$$

which corresponds to the rational function

$$R(q) = \frac{q^3}{(q-1)^2 (q^2+1)^2 (q^4+1)}.$$



q -Parikh matrices

Convergence to formal power series

We generalise a result from Salomaa (2008), which we can recover by taking $q = 1$:

Corollary (R., Rigo, Whiteland, 2024+)

The sequence of q -binomials $(\binom{u^n}{z}_q)_{n \geq 0}$ satisfies a linear recurrence relation with polynomial coefficients. In particular, the sequence of binomials $(\binom{u^n}{z})_{n \geq 0}$ satisfies a linear recurrence relation with constant coefficients.



q -Parikh matrices

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Ex: The sequence $\left(\binom{(abba)^n}{ab}_q\right)_{n \geq 0}$ satisfies the relation

$$p_{n+3} = (1 + q^4 + q^8)p_{n+2} - (q^4 + q^8 + q^{12})p_{n+1} + q^{12}p_n,$$

so that the integer sequence $\left(\binom{(abba)^n}{ab}\right)_{n \geq 0}$ satisfies $p_{n+3} = 3p_{n+2} - 3p_{n+1} + p_n$.



q -Parikh matrices

Convergence to formal power series

Finally, we know exactly the behaviour of the coefficients appearing in the formal series:

Theorem

Let $s_{\mathbf{u},z}(q) = \sum_{i \geq 0} c_i q^i$. Let $r \in \{0, \dots, |u| - 1\}$. Either $c_{r+i|u|}$ is zero for all large enough i , or the growth order of the function $r + i|u| \mapsto c_{r+i|u|}$ is in $\Theta(i^{|z|-1})$. Moreover, the two kinds of behavior are completely determined by the words u and z .



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Ex: With $z = ab$ and $u = abba$, we have

$$\langle \mathfrak{s}_{(abba)^\omega, ab}, q^{2+4n} \rangle = 0 \text{ for all } n.$$



Thank you for your attention!



Another example

Of course, other coefficients may be different than 1. For instance,

$$\binom{aabaaa}{aa}_q = q^8 + q^6 + 2q^5 + 2q^4 + q^3 + q^2 + q + 1.$$

Here, the 2's mean that there exist two occurrences of aa in $aabaaa$ such that the sum of positions equals 7 (resp. 8):

$$aaabaaa \text{ and } aaba\textcolor{brown}{aa} \longrightarrow 2q^4$$

$$\textcolor{brown}{aa}abaaa \text{ and } aaba\textcolor{brown}{aa} \longrightarrow 2q^5$$



Reconstructing words

Theorem (R., Rigo, Whiteland, 2024+)

Let k be an integer, u, x words such that $|u| \geq k \geq |x|$. We have

$$\binom{|u| - |x|}{k - |x|}_q \binom{u}{x}_q = \sum_{t \in A^k} \binom{u}{t}_q \binom{t}{x}_q.$$

Corollary (R., Rigo, Whiteland, 2024+)

Let $u \in A^*$ and $1 \leq k \leq |u|$. The sequence $\left(\binom{u}{x}_q \right)_{x \in A^k}$ uniquely determines the word u .