Generating sets for powers of finite algebras and the complexity of quantified constraints

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Let us study the growth rate of generating sets for direct powers of an algebra $\mathbb{A}$.

For $\mathbb{A}$ we have a function $f_{\mathbb{A}} : \mathbb{N} \to \mathbb{N}$, giving the cardinality of the minimal generating sets of the sequence

- $\mathbb{A}, \mathbb{A}^2, \mathbb{A}^3, \ldots$ as
- $f(1), f(2), f(3), \ldots$.

We say $\mathbb{A}$ has the XGP with:

(PGP) polynomial, when $f_{\mathbb{A}} = O(i^c)$, for some c; and

(EGP) exponential, when exists b so that $f_{\mathbb{A}} = \Omega(b^i)$.

History

Theorem (Wiegold 1987)

Let $\mathbb{B}$ be a finite semigroup. If $\mathbb{B}$ is a monoid then $\mathbb{B}$ has the (linear) PGP. Otherwise, $\mathbb{B}$ has the EGP.

Proof of PGP.

If $\mathbb{B}$ is a monoid with identity 1 and $|B| = n$, then

$$\begin{array}{c}(B, 1, \ldots, 1, 1)\\(1, B, \ldots, 1, 1)\\\vdots\\(1, 1, \ldots, B, 1)\\(1, 1, \ldots, 1, B)\end{array}$$

is a generating set for $\mathbb{B}^m$ of size mn.

Theorem (Wiegold 1987)

Let $\mathbb{B}$ be a finite semigroup. If $\mathbb{B}$ is a monoid then $\mathbb{B}$ has the (linear) PGP. Otherwise, $\mathbb{B}$ has the EGP.

Proof of EGP.

Otherwise, without an identity, $\mathbb{B}$ and $\mathbb{B}^m$ have the properties that

$$|x \cdot B| \leq n - 1, \text{ for each } x \in B.$$
$$|z \cdot B^m| \leq (n-1)^m, \text{ for each } z \in B^m.$$

Thus, a subset of B^m of size r can generate no more $r + r(n-1)^m$ elements in $\mathbb{B}^m$. Thus, a generating set must be of size $\geq \left(\frac{2n}{2n-1}\right)^m$.

Constraint Satisfaction Problems

The *constraint satisfaction problem* (CSP) is a popular formalism in Artificial Intelligence in which one is given

- a triple $(V, D, \mathcal{C})$ of variables, domain, constraints

and in which one asks for an assignment of the variables to the domain that satisfies the constraints.

A popular parameterisation involves fixing D and restricting

- the constraint language $\mathcal{C}$.

This can be formulated combinatorially as CSP($\mathcal{C}$) with

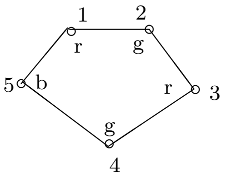
- Input: a structure $\mathcal{A}$.
- Question: does $\mathcal{A}$ have a homomorphism to $\mathcal{C}$?

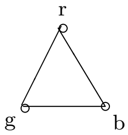
or logically as CSP($\mathcal{C}$) with

- Input: a sentence ϕ of $\{\exists, \wedge, =\}$-FO.
- Question: does $\mathcal{C} \models \phi$?

Example

CSP($\mathcal{K}_3$), or CSP($\{r, g, b\}; \neq$), is *Graph 3-colourability*.





Combinatorially, one looks for a homomorphism from $\mathcal{C}_5$ to $\mathcal{K}_3$.
Logically, one asks if $\mathcal{K}_3 \models \Phi$.

$$\begin{aligned}\Phi := \exists v_1, v_2, v_3, v_4, v_5 \quad & E(v_1, v_2) \wedge E(v_2, v_1) \wedge E(v_2, v_3) \wedge E(v_3, v_2) \\ & E(v_3, v_4) \wedge E(v_4, v_3) \wedge E(v_4, v_5) \\ & E(v_5, v_4) \wedge E(v_5, v_1) \wedge E(v_!, v_5).\end{aligned}$$

Quantified Constraint Satisfaction

The *quantified constraint satisfaction problem* QCSP($\mathcal{B}$) has

- Input: a sentence ϕ of $\{\forall, \exists, \wedge, =\}$-FO.
- Question: does $\mathcal{B} \models \phi$?

It is the CSP with $\forall$ returned.

"The QCSP might be thought of as the dissolute younger brother of its better-studied restriction, the CSP. . . . CSPs are ubiquitous in CS . . . , while QCSPs can not nearly claim to be so important in applications."

useful QCSPs	classified?
relativised ($\forall x \in X$, $\exists y \in Y$)	$\surd$
Boolean (QBF or QSAT)	$\surd$

". . . what is left of the true non-Boolean QCSP is a problem I believe to be mostly of interest to theorists."

Complexity of Model Checking

Fragment	Dual	Classification?
$\{\exists, \vee\}$ $\{\exists, \vee, =\}$ $\{\exists, \vee, \neq\}$	$\{\forall, \wedge\}$ $\{\forall, \wedge, \neq\}$ $\{\forall, \wedge, =\}$	Logspace
$\{\exists, \wedge, \vee\}$ $\{\exists, \wedge, \vee, =\}$ $\{\exists, \wedge, \vee, \neq\}$	$\{\forall, \wedge, \vee\}$ $\{\forall, \wedge, \vee, \neq\}$ $\{\forall, \wedge, \vee, =\}$	Logspace if there is some element a s.t. all relations are a-valid, and NP-complete otherwise
$\{\exists, \wedge\}$ $\{\exists, \wedge, =\}$	$\{\forall, \vee\}$ $\{\forall, \vee, \neq\}$	CSP dichotomy conjecture: P or NP-complete
$\{\exists, \wedge, \neq\}$	$\{\forall, \vee, =\}$	NP-complete for $\vert\mathcal{D}\vert \geq 3$, reduces to Schaefer classes otherwise.
$\{\exists, \forall, \wedge\}$ $\{\exists, \forall, \wedge, =\}$	$\{\exists, \forall, \vee\}$ $\{\exists, \forall, \vee, \neq\}$	QCSP polychotomy: P, NP-complete, or Pspace-complete ?
$\{\exists, \forall, \wedge, \neq\}$	$\{\exists, \forall, \vee, =\}$	Pspace-complete for $\vert\mathcal{D}\vert \geq 3$, reduces to Schaefer classes for Quantified Sat otherwise.
$\{\forall, \exists, \wedge, \vee\}$		Tetrachotomy: P, NP-complete, co-NP-complete or Pspace-complete
$\{\forall, \exists, \wedge, \vee, =\}$ $\{\forall, \exists, \wedge, \vee, \neq\}$ $\{\neg, \exists, \forall, \wedge, \vee, =\}$		Logspace when $\vert\mathcal{D}\vert \leq 1$, Pspace-complete otherwise
$\{\neg, \exists, \forall, \wedge, \vee\}$		Logspace when $\mathcal{D}$ contains only empty or full relations, Pspace-complete otherwise

First-order structures

Relational structures:

$$\mathcal{B} := (B; R_1, R_2, \ldots)$$

Functional structures:

$$\mathbb{B} := (D; f_1, f_2, \ldots)$$

$$\text{functional structures} \;=\; \text{algebras.}$$

What is the interplay between relational and functional structures?

$$\text{Model Theory} \;=\; \text{Logic} \;+\; \text{Universal Algebra}$$

All our structures are finite-domain.

Interplay

Let R be an m-ary relation on $\mathcal{B}$. We say that a k-ary operation $f : B^k \to B$ *preserves* R (or R is *invariant*) under f if:

$$
\begin{array}{llll}
f, & f, & \ldots, & f \\
(x_{11}, & x_{12}, & \ldots, & x_{1m}) \in R \\
(x_{21}, & x_{22}, & \ldots, & x_{2m}) \in R \\
\vdots & \vdots & & \vdots \\
(x_{k1}, & x_{k2}, & \ldots, & x_{km}) \in R \\
\hline
(y_1, & y_2, & \ldots, & y_m) \in R
\end{array}
$$

where each $y_i = f(x_{1i}, x_{2i}, \ldots, x_{ki})$.

- operations that preserve each of the relations of $\mathcal{B}$ are $\mathrm{Pol}(\mathcal{B})$.
- relations invariant under each operation of $\mathbb{B}$ are $\mathrm{Inv}(\mathbb{B})$.

one-side of a Galois Correspondence

Let $\mathcal{B}$ and $\mathbb{B}$ be over the same finite domain B.

$$\mathrm{Inv}(\mathrm{Pol}(\mathcal{B})) = \langle \mathcal{B} \rangle_{\{\exists,\wedge,=\}}$$
$$\mathrm{Inv}(\mathrm{surPol}(\mathcal{B})) = \langle \mathcal{B} \rangle_{\{\forall,\exists,\wedge,=\}}$$

Idempotent operations are surjective! The algebraic definition for QCSP($\mathbb{B}$) has

- Input: a sentence ϕ of $\{\forall, \exists, \wedge\}$-FO with some relations $\mathcal{B} \in \mathrm{Inv}(\mathbb{B})$.
- Question: does $\mathcal{B} \models \phi$?

What if $\mathrm{Inv}(\mathbb{B})$ is infinite?

* Infinite languages on a finite domain *

Each relation R can be given as a list of tuples, but this is far too lengthy! How about a Boolean formula ϕ in atoms

- $v = v'$ and $v = c$,

where c is a domain element. The problem is that recognising, e.g., non-emptiness of the relation can be NP-hard! Following others, e.g. [Bodirsky & Dalmau 2006] we will ask for

- ϕ in DNF,

However, our main result will be a separation NP versus co-NP-hard, so this is not a big deal!

Infinite languages on a finite domain

Example 1.

$$\begin{array}{llll} \{ & (1,2), & (2,1), & \qquad (x \neq y \vee x = 1) \\ & (2,3), & (3,2), & \\ & (1,3), & (3,1), & \\ & (1,1) & \qquad \} & \end{array}$$

Example 2.

$$\begin{array}{lllll} \{ & (1,0,0), & (0,1,0), & (0,0,1), & \qquad (x \neq y \vee y \neq z) \\ & (1,1,0), & (1,0,1), & (1,1,0), \quad \} & \end{array}$$

Back to PGP

Call an algebra $\mathbb{B}$ k-PGP-switchable if $\mathbb{B}^m$ is generated from the set of m-tuples of the form

- $(x_1, \ldots, x_1, x_2, \ldots x_2, \ldots, \ldots, x_{k'}, \ldots, x_{k'})$ for some $k' \leq k$.

switchability were originally introduced in connection with the QCSP by Hubie Chen!

Theorem (Chen 2008)

If $\mathbb{A}$ is switchable then QCSP$(\mathbb{A})$ is in NP.

Theorem (LICS 2015)

$\mathbb{A}$ is PGP-switchable iff it is switchable.

A number of handsome people worked on the PGP-EGP dichotomy conjecture.

Conjecture

Let $\mathbb{B}$ be a finite idempotent algebra, then either $\mathbb{B}$ has PGP or it has EGP.

In 2015, Dmitriy Zhuk solved it.

Theorem (Zhuk 2015)

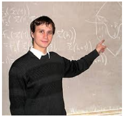
Let $\mathbb{B}$ be a finite algebra, then either $\mathbb{B}$ is PGP-switchable or it has EGP.

In order to prove this result, Zhuk assumes $\mathbb{B}$ is not PGP-switchable and finds the existence of a certain class of relations in $\mathrm{Inv}(\mathbb{B})$.

Church of Switchability

B. M.

switchability



- H. Chen: *Quantified constraint satisfaction and the polynomially generated powers property*. ICALP 2008.
- D. Zhuk: *The Size of Generating Sets of Powers*. Arxiv 2015.

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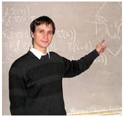

- H. Chen: *Quantified constraint satisfaction and the polynomially generated powers property*. ICALP 2008.
- D. Zhuk: *The Size of Generating Sets of Powers*. Arxiv 2015.
- C. Carvalho, F. Madelaine, B. M.: *From Complexity to Algebra and Back: Digraph Classes, Collapsibility, and the PGP*. LICS 2015.

Results

Henceforth, let $\mathbb{A}$ be an idempotent algebra on a finite domain A.

Conjecture (Chen Conjecture 2012)

Let $\mathcal{B}$ be a finite relational structure expanded with all constants. If Pol$(\mathcal{B})$ has PGP, then QCSP$(\mathcal{B})$ is in NP; otherwise QCSP$(\mathcal{B})$ is Pspace-complete.

Theorem (Revised Chen Conjecture)

If $\mathbb{A}$ satisfies PGP, then QCSP$(\mathrm{Inv}(\mathbb{A}))$ is in NP. Otherwise, if $\mathbb{A}$ satisfies EGP, then QCSP$(\mathrm{Inv}(\mathbb{A}))$ is co-NP-hard.

Conjecture (Alternative Chen Conjecture)

If $\mathbb{A}$ satisfies PGP, then for every finite reduct $\mathcal{B} \subseteq \mathrm{Inv}(\mathbb{A})$, QCSP$(\mathcal{B})$ is in NP. Otherwise, there exists a finite reduct $\mathcal{B} \subseteq \mathrm{Inv}(\mathbb{A})$ so that QCSP$(\mathcal{B})$ is co-NP-hard.

Results

Henceforth, let $\mathbb{A}$ be an idempotent algebra on a finite domain A.

Conjecture (Chen Conjecture 2012)

Let $\mathcal{B}$ be a finite relational structure expanded with all constants. If Pol($\mathcal{B}$) has PGP, then QCSP($\mathcal{B}$) is in NP; otherwise QCSP($\mathcal{B}$) is Pspace-complete.

Theorem (Revised Chen Conjecture)

Either QCSP($\mathrm{Inv}(\mathbb{A})$) is co-NP-hard or QCSP($\mathrm{Inv}(\mathbb{A})$) has the same complexity as CSP($\mathrm{Inv}(\mathbb{A})$).

Conjecture (Alternative Chen Conjecture False)

If $\mathbb{A}$ satisfies PGP, then for every finite reduct $\mathcal{B} \subseteq \mathrm{Inv}(\mathbb{A})$, QCSP($\mathcal{B}$) is in NP. Otherwise, there exists a finite reduct $\mathcal{B} \subseteq \mathrm{Inv}(\mathbb{A})$ so that QCSP($\mathcal{B}$) is co-NP-hard.

Tractability

We know from Zhuk 2015 that

$$\text{PGP} \longrightarrow \text{PGP-switchability}$$

and from [LICS 2015]

$$\text{PGP-switchability} \longrightarrow \text{switchability}$$

whereupon Chen 2008 gives

$$\text{switchability} \longrightarrow \text{QCSP tractability.}$$

Henceforth, α, β be strict subsets of A so that $\alpha \cup \beta = A$.

Theorem (Zhuk 2015)

Algebra $\mathbb{A}$ (idempotent) has EGP iff exists such α, β with

$$\sigma_k(x_1, y_1, \ldots, x_k, y_k) := \rho(x_1, y_1) \vee \ldots \vee \rho(x_k, y_k),$$

where $\rho(x, y) = (\alpha \times \alpha) \cup (\beta \times \beta)$, is in $\mathrm{Inv}(\mathbb{A})$, for each $k \in \mathbb{N}$.

We prefer the relation $\tau_k(x_1, y_1, z_1 \ldots, x_k, y_k, z_k)$ defined by

$$\tau_k(x_1, y_1, z_1 \ldots, x_k, y_k, z_k) := \rho'(x_1, y_1, z_1) \vee \ldots \vee \rho'(x_k, y_k, z_k),$$

where $\rho'(x, y, z) = (\alpha \times \alpha \times \alpha) \cup (\beta \times \beta \times \beta)$.

Corollary

Algebra $\mathbb{A}$ (idempotent) has EGP iff exists such α, β with $\tau_k(x_1, y_1, z_1 \ldots, x_k, y_k, z_k)$ in $\mathrm{Inv}(\mathbb{A})$, for each $k \in \mathbb{N}$.

co-NP-hardness

Theorem

If $\mathrm{Inv}(\mathbb{A})$ *satisfies EGP, then QCSP*$(\mathrm{Inv}(\mathbb{A}))$ *is co-NP-hard.*

Proof.

Reduce from the complement of (monotone) 3-*not-all-equal-sat*.

$$\exists x_1^1, x_1^2, x_1^3, \ldots, \ldots, x_m^1, x_m^2, x_m^3 \ \mathrm{NAE}(x_1^1, x_1^2, x_1^3) \wedge \ldots \wedge \mathrm{NAE}(x_m^1, x_m^2, x_m^3)$$

becomes

$$\forall x_1^1, x_1^2, x_1^3, \ldots, \ldots, x_m^1, x_m^2, x_m^3 \ \rho'(x_1^1, x_1^2, x_1^3) \vee \ldots \vee \rho'(x_m^1, x_m^2, x_m^3)$$

where we note that $\tau_m(x_1, y_1, z_1 \ldots, x_m, y_m, z_m) :=$

$$\rho'(x_1, y_1, z_1) \vee \ldots \vee \rho'(x_m, y_m, z_m)$$

has a DNF representation that is polynomially-sized in m. $\square$

Recall, α, β be strict subsets of A so that $\alpha \cup \beta = A$. Now ask further that $\alpha \cap \beta \neq \emptyset$.

Corollary

$QCSP(A; \{\tau_n : n \in \mathbb{N}\}, \{a : a \in A\})$ is co-NP-hard.

In fact,

Proposition

$QCSP(A; \{\tau_n : n \in \mathbb{N}\}, \{a : a \in A\})$ is in co-NP.

Proof.

Roughly speaking, evaluate all existential variables to something in $\alpha \cap \beta$. But $(A; \{\tau_n : n \in \mathbb{N}\}, \{a : a \in A\})$ is not finitely related. $\square$

Proposition

For every finite reduct $\mathcal{B}$ of $(A; \{\tau_n : n \in \mathbb{N}\}, \{a : a \in A\})$, $QCSP(\mathcal{B})$ is in NL.

Back to * finite domains * and the Chen Conjecture

The conventional definition for QCSP($\mathcal{B}$), where ($\mathcal{B}$) is a finite constraint language, is

- Input: a sentence ϕ of $\{\forall, \exists, \wedge\}$-FO.
- Question: does $\mathcal{B} \models \phi$?

Conjecture (Chen Conjecture + CSP Dichotomy)

Let $\mathcal{B}$ be a finite relational structure expanded with all constants. Either QCSP($\mathcal{B}$) is in P, is NP-complete or is Pspace-complete.

Death of the Chen Conjecture I

Example $R_{\delta,3}$.

$$\begin{array}{llll} \{(1,\_,\_), & (2,\_,\_), & & (x \neq 0 \vee y = z) \\ (0,0,0), & (0,1,1), & (0,2,2), & \end{array}$$

Example $R_{\mathrm{and},2}$.

$$\begin{array}{lllll} \{ & (0,0,0), & (0,1,0), & (1,0,0), & \\ & (1,1,1), & (2,\_,\_), & (\_,2,\_), & \} \end{array}$$

- QCSP($\{0,1,2\}; 0,1,2, R_{\mathrm{and},2}, R_\delta$) is co-NP-complete.

Death of the Chen Conjecture II

Example $R_{\delta,2}$.

$$\left\{ \begin{array}{lll} (0,0), & (1,0), & (2,0), \\ (1,2), & (2,2) & \end{array} \right\}$$

Example $R_{\mathrm{and},2}$.

$$\left\{ \begin{array}{lll} (0,0), & (1,0), & (2,0), \\ (1,2), & (2,2) & \end{array} \right\}$$

- $\mathrm{Pol}(\{0,1,2\};0,1,2,R_{\mathrm{and},2},R_{\delta,3})$ has EGP.
- $\mathrm{QCSP}(\{0,1,2\};0,1,2,R_{\mathrm{and},2},R_{\delta,3})$ is in P.

QCSP Monsters

There are finite $\mathcal{B}$ so that QCSP($\mathcal{B}$) ranges over

- in P.
- NP-complete.
- Pspace-complete.
- co-NP-complete.
- DP-complete.
- Θ_2^P-complete.
- ...

Theorem (Zhuk & M. 2019)

Let $\mathcal{B}$ be a finite 3-element relational structure expanded with all constants. Either QCSP($\mathcal{B}$) is in P, is NP-complete, is co-NP-complete or is Pspace-complete.

Future of the Chen Conjecture

The conservative case is a natural large class on which the Chen Conjecture holds.

Theorem (Zhuk & M. 2019)

Let $\mathcal{B}$ be a finite relational structure expanded with all unary relation. Either QCSP($\mathcal{B}$) is in P, is NP-complete, or is Pspace-complete.

Can PGP and EGP be sensibly modified to make the Chen Conjecture "true"?