Generalized Frobenius numbers: bounds and average behavior via geometric techniques

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Integer Knapsack Problem

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This problem is known to be NP-complete.

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For $s \in \mathbb{Z}_{\geq 0}$, the s-**Frobenius number** of $\boldsymbol{a}$ is defined to be

$$g_s(\boldsymbol{a}) = \max\left\{ b \in \mathbb{Z}_{>0} : \left| P(\boldsymbol{a}, b) \cap \mathbb{Z}^N \right| = s \right\}.$$

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Frobenius problem is NP-hard.

Theorem 2 (Kannan, 1992)

For each fixed N, the problem of finding the Frobenius number of a given N-tuple is P.

In terms of numerical semigroups...

For an integer $N \geq 2$ and $\boldsymbol{a} \in \mathbb{Z}_{>0}^N$ with

$$a_1 < \cdots < a_N, \quad \gcd(a_1, \ldots, a_N) = 1,$$

the sub-semigroup of $\mathbb{N}$ generated by $\boldsymbol{a} := (a_1, \ldots, a_N)$ is

$$S(\boldsymbol{a}) := \left\{ \sum_{i=1}^{N} a_i x_i : x_1, \ldots, x_N \in \mathbb{Z}_{\geq 0} \right\}.$$

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Set of gaps of $S(\boldsymbol{a})$ is $\mathbb{N} \setminus S(\boldsymbol{a})$, so $g_0(\boldsymbol{a})$ is the largest gap of $S(\boldsymbol{a})$. More generally, $g_s(\boldsymbol{a})$ is the largest $t \in S(\boldsymbol{a})$ that has *precisely* s different representations of the form

$$t = \sum_{i=1}^{N} a_i x_i \text{ for some } x_1, \ldots, x_N \in \mathbb{Z}_{\geq 0}.$$

Research Directions

When $N = 2$,

$$g_s(a_1, a_2) = (s+1)a_1a_2 - a_1 - a_2.$$

This formula was obtained in 1884 for $s = 0$ and for $s \geq 1$ by M. Beck & S. Robins (2003).

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The literature on FP is vast, including a book by Ramirez-Alfonsin; FP has numerous applications in graph theory, computer science, group theory, coding theory, tilings, etc. Current research on FP includes algorithmic results, formulas for special sequences, theory of numerical semigroups, connections to operations research and discrete geometry, and many other directions.

Some Bounds

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Lower bounds on g_1: Davison (1994) for $N = 3$ (sharp - $\sqrt{3}$ cannot be improved):

$$g_0(\boldsymbol{a}) \geq \sqrt{3a_1a_2a_3} - a_1 - a_2 - a_3$$

Aliev & Gruber (2007) for any N:

$$g_0(\boldsymbol{a}) > \left((N-1)! \prod_{i=1}^{N} a_i\right)^{\frac{1}{N-1}} - \sum_{i=1}^{N} a_i .$$

Upper bounds on g_0 for $N \geq 3$

Erdös, Graham (1972):

$$g_0(\boldsymbol{a}) \leq 2a_N \left[\frac{a_1}{N}\right] - a_1.$$

Vitek (1975):

$$g_0(\boldsymbol{a}) \leq \left[\frac{(a_2 - 1)(a_N - 2)}{2}\right] - 1.$$

Selmer (1977):

$$g_0(\boldsymbol{a}) \leq 2a_{N-1} \left[\frac{a_N}{N}\right] - a_N.$$

Beck, Diaz, Robins (2002):

$$g_0(\boldsymbol{a}) \leq \frac{\sqrt{a_1 a_2 a_3 (a_1 + a_2 + a_3)} - a_1 - a_2 - a_3}{2}.$$

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Lattice: $\mathcal{L}_{\boldsymbol{a}} = \left\{ \boldsymbol{x} \in \mathbb{Z}^{N-1} : \sum_{i=1}^{N-1} a_i x_i \equiv 0 \pmod{a_N} \right\}$.

Convex body: $\mathcal{S}_{\boldsymbol{a}} = \left\{ \boldsymbol{x} \in \mathbb{R}_{\geq 0}^{N-1} : \sum_{i=1}^{N-1} a_i x_i \leq 1 \right\}$.

Covering radius: $\mu(\mathcal{S}_{\boldsymbol{a}}, \mathcal{L}_{\boldsymbol{a}}) = \inf \left\{ t \in \mathbb{R}_{>0} : t\mathcal{S}_{\boldsymbol{a}} + \mathcal{L}_{\boldsymbol{a}} = \mathbb{R}^{N-1} \right\}$.

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Kannan (1992): $g_0(\boldsymbol{a}) = \mu(\mathcal{S}_{\boldsymbol{a}}, \mathcal{L}_{\boldsymbol{a}}) - \sum_{i=1}^{N} a_i.$

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Kannan (1992): $g_0(\boldsymbol{a}) = \mu(\mathcal{S}_{\boldsymbol{a}}, \mathcal{L}_{\boldsymbol{a}}) - \sum_{i=1}^{N} a_i.$

The simplex $\mathcal{S}_{\boldsymbol{a}}$ is not 0-symmetric, which makes explicit bounds on $\mu(\mathcal{S}_{\boldsymbol{a}}, \mathcal{L}_{\boldsymbol{a}})$ difficult to produce.

A related geometric approach

Lattice: $\Lambda_{\boldsymbol{a}} = \left\{ \boldsymbol{x} \in \mathbb{Z}^N : \sum_{i=1}^{N} a_i x_i = 0 \right\}$.

Convex body: $B(R)$ = ball of radius $R > 0$ centered at the origin in $V_{\boldsymbol{a}} = \operatorname{span}_{\mathbb{R}} \Lambda_{\boldsymbol{a}}$.

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Theorem 3 (F., Robins, 2007)

$$g_0(\boldsymbol{a}) \leq \frac{(N-1)R_{\boldsymbol{a}}}{\|\boldsymbol{a}\|} \sum_{i=1}^N a_i \sqrt{\|\boldsymbol{a}\|^2 - a_i^2}.$$

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This bound is symmetric in all $a_1, \ldots, a_N$, unlike the previously known ones. The covering radius $R_{\boldsymbol{a}}$ can be bounded by standard techniques in the geometry of numbers.

Bounds on g_s for $s \geq 1$

Extending our previous method, we obtain:

Theorem 4 (F., Schürmann, 2011)

$$g_s(\boldsymbol{a}) \gg_N \left(s \prod_{i=1}^{N-1} a_i \right)^{\frac{1}{N-1}},$$

$$g_s(\boldsymbol{a}) \ll_N \max \left\{ \frac{R_{\boldsymbol{a}} \sum_{i=1}^{N} a_i \sqrt{\|\boldsymbol{a}\|^2 - a_i^2}}{\|\boldsymbol{a}\|}, \left(s \prod_{i=1}^{N-1} a_i \right)^{\frac{1}{N-2}} \right\},$$

where the lower bound holds for sufficiently large s.

Another s-Frobenius number g_s^*

Beck & Kifer (2011) defined a related generalized Frobenius number: $g_s^*(\boldsymbol{a})$ is the largest t that has *at most s* different representations of the form

$$t = \sum_{i=1}^{N} a_i x_i \text{ for some } x_1, \ldots, x_N \in \mathbb{Z}_{\geq 0}.$$

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This may be a more convenient definition of an s-Frobenius number – we will focus on it for the rest of the talk.

Bounds on g_s^*

We now present bounds on g_s^*, which have very similar order of magnitude as our previous bounds on g_s.

Theorem 5 (Aliev, F., Henk (2012))

Let $N \geq 3$, $s \geq 0$. *Then*

$$g_s^*(\boldsymbol{a}) \geq \left((s+1)(N-1)! \prod_{i=1}^{N-1} a_i\right)^{\frac{1}{N-1}} - \sum_{i=1}^{N-1} a_i$$

and

$$g_s^*(\boldsymbol{a}) \leq g_0(\boldsymbol{a}) + \left(s\ (N-1)! \prod_{i=1}^{N-1} a_i\right)^{\frac{1}{N-1}} .$$

What should we typically expect?

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In particular, let Ω^1_N be an ensemble of relatively prime positive integer N-tuples $\boldsymbol{a} = (a_1, \ldots, a_N)$ with

$$\Sigma(\boldsymbol{a}) := a_1 + \cdots + a_N \to \infty.$$

Arnold conjectured that for a “typical” N-tuple $\boldsymbol{a}$ from Ω^1_N,

$$g_0(\boldsymbol{a}) \text{ grows like } \Sigma(\boldsymbol{a})^{1+\frac{1}{N-1}} \text{ as } \Sigma(\boldsymbol{a}) \to \infty.$$

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The investigation of asymptotic behavior of the Frobenius number for a “typical” N-tuple $(a_1, \dots, a_N)$ was initiated by V. I. Arnold in a series of papers (1999 - 2007).
In particular, let Ω_N^1 be an ensemble of relatively prime positive integer N-tuples $\boldsymbol{a} = (a_1, \dots, a_N)$ with

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Variants of Arnold’s conjecture have been considered by a number of authors, including I. Aliev, J. Bourgain, M. Henk, A. Hinrichs, H. Li, J. Marklof, V. Shchur, W. M. Schmidt, Y. Sinai, A. Strömbergson, C. Ulcigrai, A. Ustinov.

Average value estimate for g_s^*

Theorem 6 (Aliev, F., Henk (2012))

Let $N \geq 3$, $s \geq 0$, *and let*

$$\mathrm{G}(T) = \left\{ \boldsymbol{a} \in \mathbb{Z}_{>0}^N : \mathrm{gcd}(\boldsymbol{a}) = 1, |\boldsymbol{a}|_\infty \leq T \right\}.$$

Let $D > 0$. *Then there exists* $T_0(D)$ *such that for all* $T \geq T_0(D)$, *with respect to the uniform probability distribution on* $\mathrm{G}(T)$,

$$\mathrm{Prob}\left(\frac{g_s^*(\boldsymbol{a})}{\left((s+1) \prod_{i=1}^{N-1} a_i \right)^{\frac{1}{N-1}}} \geq D \right) \ll_N \frac{1}{D^{N-1}}.$$

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In case of the classical Frobenius number, i.e. when $s = 0$, this probability estimate has been obtained by H. Li (2011). Our method uses his result.

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- To prove Theorems 3 and 4, we relate Frobenius numbers to the number of integer lattice points in a certain simplex, and then apply techniques from the geometry of numbers to produce counting estimates.

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- To prove Theorem 6, we use the bounds of Theorem 5 along with H. Li's result for g_0 and the fact that "reverse" arithmetic-geometric mean inequality holds with high probability.

Thank you!