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MATRIX p-NORMS ARE NP-HARD TO APPROXIMATE IF $p \neq 1, 2, \infty$*

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Abstract. We show that, for any rational $p \in [1, \infty)$ except $p = 1, 2$, unless $P = NP$, there is no polynomial time algorithm which approximates the matrix p-norm to arbitrary relative precision. We also show that, for any rational $p \in [1, \infty)$ including $p = 1, 2$, unless $P = NP$, there is no polynomial-time algorithm which approximates the ∞, p mixed norm to some fixed relative precision.

Key words. matrix norms, complexity, NP-hardness

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1. Introduction.

The p-norm of a matrix A is defined as

$$||A||_p = \max_{||x||_p=1} ||Ax||_p.$$

We consider the problem of computing the matrix p-norm to relative error ϵ, defined as follows: given the inputs (i) a matrix $A \in R^{n\times n}$ with rational entries and (ii) an error tolerance ϵ which is a positive rational number, output a rational number r satisfying

$$\big|r - ||A||_p\big| \leq \epsilon ||A||_p.$$

We will use the standard bit model of computation. When $p = \infty$ or $p = 1$, the p-matrix norm is the largest of the row/column sums and thus may be easily computed exactly. When $p = 2$, this problem reduces to computing an eigenvalue of $A^T A$ and thus can be solved in polynomial time in $n, \log \frac{1}{\epsilon}$ and the bit size of the entries of A. Our main result suggests that the case of $p \notin \{1, 2, \infty\}$ may be different.

THEOREM 1.1. *For any rational $p \in [1, \infty)$ except $p = 1, 2$, unless $P = NP$, there is no algorithm which computes the p-norm of a matrix with entries in $\{-1, 0, 1\}$ to relative error ϵ with running time polynomial in n, $\frac{1}{\epsilon}$.*

On the way to our result, we also slightly improve the NP-hardness result for the mixed norm $||A||_{\infty,p} = \max_{||x||_\infty \leq 1} ||Ax||_p$ from [5]. Specifically, we show that, for every rational $p \geq 1$, there exists an error tolerance $\epsilon(p)$ such that, unless $P = NP$, there is no polynomial time algorithm approximating $||A||_{\infty,p}$ with a relative error smaller than $\epsilon(p)$.

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1.1. Previous work. When p is an integer, computing the matrix norm can be recast as solving a polynomial optimization problem. These are known to be hard to solve in general [3]; however, because the matrix norm problem has a special structure, one cannot immediately rule out the possibility of a polynomial time solution. A few hardness results are available in the literature for mixed matrix norms $||A||_{p,q} = \max_{||x||_p \leq 1} ||Ax||_q$. Rohn has shown in [4] that computing the $||A||_{\infty,1}$ norm is NP-hard. In her thesis, Steinberg [5] proved more generally that computing $||A||_{p,q}$ is NP-hard when $1 \leq q < p \leq \infty$. We refer the reader to [5] for a discussion of applications of the mixed matrix norm problems to robust optimization.

It is conjectured in [5] that there are only three cases in which mixed norms are computable in polynomial time: First, $p = 1$, and q is any rational number larger than or equal to 1. Second, $q = \infty$, and p is any rational number larger than or equal to 1. Third, $p = q = 2$. Our work makes progress on this question by settling the "diagonal" case of $p = q$; however, the case of $p < q$, as far as the authors are aware, is open.

1.2. Outline. We begin in section 2 by providing a proof of the NP-hardness of approximating the mixed norm $||\cdot||_{\infty,p}$ within some fixed relative error for any rational $p \geq 1$. The proof may be summarized as follows: observe that, for any matrix M, $\max_{||x||_\infty=1} ||Mx||_p$ is always attained at one of the 2^n points of $\{-1,1\}^n$. So by appropriately choosing M, one can encode an NP-hard problem of maximization over the latter set. This argument will prove that computing the $||\cdot||_{\infty,p}$ norm is NP-hard.

Next, in section 3, we exhibit a class of matrices A such that $\max_{||x||_p=1} ||Ax||_p$ is attained at each of the 2^n points of $\{-1,1\}^n$ (up to scaling) and nowhere else. These two elements are combined in section 4 to prove Theorem 1.1. More precisely, we define the matrix $Z = (M^T \ \alpha A^T)^T$, where we will pick α to be a large number depending on n, p ensuring that the maximum of $||Zx||_p/||x||_p$ occurs very close to vectors $x \in \{-1,1\}^n$. As mentioned several sentences ago, the value of $||Ax||_p$ is the same for every vector $x \in \{-1,1\}^n$; as a result, the maximum of $||Zx||_p/||x||_p$ is determined by the maximum of $||Mx||_p$ on $\{-1,1\}^n$, which is proved in section 2 to be hard to compute. We conclude with some remarks on the proof in section 5.

2. The $||\cdot||_{\infty,p}$ norm. We now describe a simple construction which relates the ∞, p norm to the maximum cut in a graph.

Suppose $G = (\{1,\ldots,n\}, E)$ is an undirected, connected graph. We will use $M(G)$ to denote the edge-vertex incidence matrix of G; that is, $M(G) \in R^{|E|\times n}$. We will think of columns of $M(G)$ as corresponding to nodes of G and of rows of $M(G)$ as corresponding to the edges of G. The entries of $M(G)$ are as follows: orient the edges of G arbitrarily, and let the ith row of $M(G)$ have $+1$ in the column corresponding to the origin of the ith edge, -1 in the column corresponding to the endpoint of the ith edge, and 0 at all other columns.

Given any partition of $\{1,\ldots,n\} = S \cup S^c$, we define $\text{cut}(G,S)$ to be the number of edges with exactly one endpoint in S. Furthermore, we define $\text{maxcut}(G) = \max_{S\subset\{1,\ldots,n\}} \text{cut}(G,S)$. The indicator vector of a cut (S,S^c) is the vector x with $x_i = 1$ when $i \in S$ and $x_i = -1$ when $i \in S^c$. We will use $\text{cut}(x)$ for vectors $x \in \{-1,1\}^n$ to denote the value of the cut whose indicator vector is x.

PROPOSITION 2.1. *For any $p \geq 1$,*

$$\max_{||x||_\infty \leq 1} ||M(G)x||_p = 2\text{maxcut}(G)^{1/p}.$$

Proof. Observe that $||M(G)x||_p$ is a convex function of x, so that the maximum is achieved at the extreme points of the set $||x||_\infty \leq 1$, i.e., vectors x satisfying $x_i = \pm 1$. Suppose we are given such a vector x; define $S = \{i \mid x_i = 1\}$. Clearly, $||M(G)x||_p^p = 2^p \text{cut}(G, S)$. From this the proposition immediately follows. ∎

Next, we introduce an error term into this proposition. Define f^* to be the optimal value $f^* = \max_{||x||_\infty \leq 1} ||M(G)x||_p$; the above proposition implies that $(f^*/2)^p = \text{maxcut}(G)$. We want to argue that if f_{approx} is close enough to f^*, then $(f_{\text{approx}}/2)^p$ is close to $\text{maxcut}(G)$.

PROPOSITION 2.2. *If $p \geq 1$, $|f^* - f_{\text{approx}}| < \epsilon f^*$ with $\epsilon < 1$, then*

$$\left| \left(\frac{f_{\text{approx}}}{2} \right)^p - \text{maxcut}(G) \right| \leq 2^{p-1} p \epsilon \cdot \text{maxcut}(G).$$

Proof. By Proposition 2.1, $\text{maxcut}(G) = (f^*/2)^p$. Using the inequality

$$|a^p - b^p| \leq |a - b| p \max(|a|, |b|)^{p-1},$$

we obtain

$$\left| \left(\frac{f_{\text{approx}}}{2} \right)^p - \text{maxcut}(G) \right| \leq \frac{1}{2} |f^* - f_{\text{approx}}| \, p \max \left(\frac{f^*}{2}, \frac{f_{\text{approx}}}{2} \right)^{p-1}.$$

It follows from $\epsilon < 1$ that $f_{\text{approx}} \leq 2f^*$. We have therefore

$$\left| \left(\frac{f_{\text{approx}}}{2} \right)^p - \text{maxcut}(G) \right| \leq \frac{1}{2} |f^* - f_{\text{approx}}| \cdot p \cdot (f^*)^{p-1} \leq \frac{\epsilon}{2} p (f^*)^p,$$

where we have used the assumption that $|f^* - f_{\text{approx}}| \leq \epsilon f^*$. The result follows then from $\text{maxcut}(G) = (f^*/2)^p$. ∎

We now put together the previous two propositions to prove that approximating the $|| \cdot ||_{\infty,p}$ norm within some fixed relative error is NP-hard.

THEOREM 2.3. *For any rational $p \geq 1$ and $\delta > 0$, unless $P = NP$, there is no algorithm which, given a matrix with entries in $\{-1, 0, 1\}$, computes its p-norm to relative error $\epsilon = ((33 + \delta) p 2^{p-1})^{-1}$ with running time polynomial in the dimensions of the matrix.*

Proof. Suppose there was such an algorithm. Call f^* its output on the $|E| \times n$ matrix $M(G)$ for a given connected graph G on n vertices. It follows from Proposition 2.2 that

$$\left| \left(\frac{f_{\text{approx}}}{2} \right)^p - \text{maxcut}(G) \right| \leq \frac{2^{p-1} p}{(33 + \delta) p 2^{p-1}} \text{maxcut}(G) = \frac{1}{33 + \delta} \text{maxcut}(G).$$

Observing that

$$\frac{32 + \delta}{34 + \delta} \text{maxcut}(G) = \frac{33 + \delta}{34 + \delta} \left(\text{maxcut}(G) - \frac{1}{33 + \delta} \text{maxcut}(G) \right),$$

the former inequality implies

$$\frac{32 + \delta}{34 + \delta} \text{maxcut}(G) \leq \frac{33 + \delta}{34 + \delta} \left(\frac{f_{\text{approx}}}{2} \right)^p \leq \text{maxcut}(G).$$

Since p is rational, one can compute in polynomial time a lower bound V for $\frac{33+\delta}{34+\delta}(f_{\text{approx}}/2)^p$ sufficiently accurate so that $V > \frac{32+\delta/2}{34+\delta/2} \text{maxcut}(G) > \frac{16}{17} \text{maxcut}(G)$.

However, it has been established in [2] that, unless $P = NP$, for any $\delta' > 0$, there is no algorithm producing a quantity V in polynomial time in n such that

$$\left(\frac{16}{17} + \delta'\right) \text{maxcut}(G) \leq V \leq \text{maxcut}(G). \qquad \square$$

Remark. Observe that the matrix $M(G)$ is not square. If one desires to prove hardness of computing the ∞, p-norm for square matrices, one can simply add $|E| - n$ zeros to every row of $M(G)$. The resulting matrix has the same ∞, p-norm as $M(G)$ and is square, and its dimensions are at most $n^2 \times n^2$.

3. A discrete set of exponential size. Let us now fix n and a rational $p > 2$. We denote by X the set $\{-1, 1\}^n$ and use $S(a, r) = \{x \in R^n \mid ||x - a||_p = r\}$ to stand for the sphere of radius r around a in the p-norm. We consider the following matrix in $R^{2n \times n}$:

$$A = \left(\begin{array}{cccccc} 1 & -1 & & & & \\ 1 & 1 & & & & \\ \hline & 1 & -1 & & & \\ & 1 & 1 & & & \\ \hline & & \ddots & \ddots & & \\ & & \ddots & \ddots & & \\ \hline & & & & 1 & -1 \\ & & & & 1 & 1 \\ \hline -1 & & & & & 1 \\ 1 & & & & & 1 \end{array}\right)$$

and show that the maximum of $||Ax||_p$ for $x \in S(0, n^{1/p})$ is attained at the 2^n vectors in X and at no other points. For this, we will need the following lemma.

LEMMA 3.1. *For any real numbers x, y and $p \geq 2$*

$$|x + y|^p + |x - y|^p \leq 2^{p-1} \left(|x|^p + |y|^p\right).$$

In fact, $|x + y|^p + |x - y|^p$ is upper bounded by

$$2^{p-1} \left(|x|^p + |y|^p\right) - \frac{\left(|x| - |y|\right)^2}{4} \left(p(p-1)\big||x| + |y|\big|^{p-2} - 2\big||x| - |y|\big|^{p-2}\right),$$

where the last term on the right is always nonnegative.

Proof. By symmetry we can assume that $x \geq y \geq 0$. In that case, we need to prove

$$(x + y)^p + (x - y)^p \leq 2^{p-1}(x^p + y^p) - \frac{(x - y)^2}{4} \left(p(p-1)(x + y)^{p-2} - 2(x - y)^{p-2}\right).$$

Divide both sides by $(x + y)^p$, and change the variables to $z = (x - y)/(x + y)$:

$$1 + z^p \leq \frac{(1 + z)^p + (1 - z)^p}{2} - \left(\frac{p(p-1)}{4} z^2 - \frac{1}{2} z^p\right).$$

The original inequality holds if this inequality holds for $z \in [0, 1]$. Let's simplify:

$$2 + z^p \leq (1 + z)^p + (1 - z)^p - \frac{p(p-1)}{2} z^2.$$

Observe that we have equality when $z = 0$, so it suffices to show that the right-hand side grows faster than the left-hand side, namely,

$$z^{p-1} \leq (1+z)^{p-1} - (1-z)^{p-1} - (p-1)z,$$

and this follows from

$$(1+z)^{p-1} \geq 1 + (p-1)z \geq (1-z)^{p-1} + z^{p-1} + (p-1)z,$$

where we have used the convexity of $f(a) = a^{p-1}$. ☐

Now we prove that every vector of X optimizes $||Ax||_p/||x||_p$ or, equivalently, optimizes $||Ax||_p^p$ over the sphere $S(0, n^{1/p})$.

Lemma 3.2. *For any $p \geq 2$, the supremum of $||Ax||_p^p$ over $S(0, n^{1/p})$ is achieved by any vector in X.*

Proof. Observe that $||Ax||_p^p = n2^p$ for any $x \in X$. To prove that this is the largest possible value, we write

$$||Ax||_p^p = \sum_{i=1}^{n} |x_i - x_{i+1}|^p + |x_i + x_{i+1}|^p, \tag{3.1}$$

using the convention $n + 1 = 1$ for the indices. Lemma 3.1 implies that

$$|x_i - x_{i+1}|^p + |x_i + x_{i+1}|^p \leq 2^{p-1} \left(|x_i|^p + |x_{i+1}|^p\right).$$

By applying this inequality to each term of (3.1) and by using $||x||_p^p = n$, we obtain

$$||Ax||_p^p \leq \sum_{i=1}^{n} 2^{p-1} \left(|x_i|^p + |x_{i+1}|^p\right) = 2^p \sum_{i=1}^{n} |x_i|^p = 2^p n. \qquad ☐$$

Next we refine the previous lemma by including a bound on how fast $||Ax||_p^p$ decreases as we move a little bit away from the set X while staying on $S(0, n^{1/p})$.

Lemma 3.3. *Let $p \geq 2, c \in (0, 1/2]$, and suppose $y \in S(0, n^{1/p})$ has the property that*

$$\min_{x \in X} ||y - x||_\infty \geq c. \tag{3.2}$$

Then

$$||Ay||_p^p \leq n2^p - \frac{3(p-2)}{2^p n^2} c^2.$$

Proof. We proceed as before in the proof of Lemma 3.2 until the time comes to apply Lemma 3.1, when we include the error term which we had previously ignored:

$$||Ay||_p^p \leq n2^p - \frac{1}{4} \sum_i \left(|y_i| - |y_{i+1}|\right)^2 \left(p(p-1) \left||y_i| + |y_{i+1}|\right|^{p-2} - 2 \left||y_i| - |y_{i+1}|\right|^{p-2}\right),$$

Note that on the right-hand side, we are subtracting a sum of nonnegative terms. The upper bound will still hold if we subtract only one of these terms, so we conclude that, for each k,

$$||Ay||_p^p \leq n2^p - \frac{1}{4} \left(|y_k| - |y_{k+1}|\right)^2 \left(p(p-1) \left||y_k| + |y_{k+1}|\right|^{p-2} - 2 \left||y_i| - |y_{i+1}|\right|^{p-2}\right).$$

By assumption, there is at least one y_k with $\big||y_k| - 1\big| \geq c$. Suppose first that $|y_k| > 1$. Then we have $|y_k| > 1 + c$, and there must be a y_j with $|y_j| < 1$, for otherwise y would not be in $S(0, n^{1/p})$. Similarly, if $|y_k| < 1$, then $|y_k| < 1 - c$ and there is a j for which $|y_j| > 1$. In both cases, this implies the existence of an index m with $|y_m|$ and $|y_{m+1}|$ differing by at least c/n and such that at least one of $|y_m|$ and $|y_{m+1}|$ is larger than or equal to $1 - c$. Therefore,

$$||Ay||_p^p \leq n2^p - \frac{1}{4}\frac{c^2}{n^2}\left[p(p-1)\,\big||y_m| + |y_{m+1}|\big|^{p-2} - 2\,\big||y_m| - |y_{m+1}|\big|^{p-2}\right].$$

Now observe that $\big||y_m| - |y_{m+1}|\big| \leq |y_m| + |y_{m+1}|$ and that $|y_m| + |y_{m+1}| \geq (1-c) \geq 1/2$ because $c \in (0, 1/2]$. These two inequalities suffice to establish that the term in square brackets is at least $(1/2)^{p-2}(p(p-1) - 2) \geq (3/2^p)(p-2)$ so that

$$||Ay||_p^p \leq n2^p - \frac{3(p-2)}{2^p n^2}c^2. \qquad \square$$

4. Proof of Theorem 1.1. We now relate the results of the last two sections to the problem of the p-norm. For a suitably defined matrix Z combining A and $M(G)$, we want to argue that the optimizer of $||Zx||_p/||x||_p$ is very close to satisfying $|x_i| = |x_j|$ for every i, j.

PROPOSITION 4.1. *Let $p > 2$ and G be a graph on n vertices. Consider the matrix*

$$\tilde{Z} = \begin{pmatrix} A \\ \frac{p-2}{64pn^8}M(G) \end{pmatrix}$$

with $M(G)$ and A as in sections 2 and 3, respectively. If x^* is the vector at which the optimization problem $\max_{x \in S(0,n^{1/p})} ||\tilde{Z}x||_p$ achieves its supremum, then

$$\min_{x \in X} ||x^* - x||_\infty \leq \frac{1}{4^p n^6}.$$

Proof. Suppose the conclusion is false. Then using Lemma 3.3 with $c = 1/4^p n^6$, we obtain

$$||Ax^*||_p^p \leq n2^p - \frac{3(p-2)}{2^p 4^{2p} n^{14}} = n2^p - \frac{3(p-2)}{32^p n^{14}}.$$

It follows from Proposition 2.1 that

$$||Mx^*||_p^p \leq 2^p \text{maxcut}(G) \leq 2^p n^2$$

so that

$$||\tilde{Z}x^*||_p^p = ||Ax^*||_p^p + \left(\frac{p-2}{64pn^8}\right)^p ||Mx^*||_p^p \leq 2^p n - \frac{3(p-2)}{32^p n^{14}} + \frac{2^p (p-2)^p n^2}{64^p p^p n^{8p}}.$$

Observe that the last term in this inequality is smaller than the previous one (in absolute value). Indeed, for $p > 2$, we have that $3/32^p > (2/64)^p$, $p - 2 > [(p-2)/p]^p$, and $1/n^{14} > n^2/n^{8p}$. We therefore have $||Zx^*||_p^p < 2^p n$. By contrast, let x be any vector in $\{-1, 1\}^n$. Then $x \in S(0, n^{1/p})$ and

$$||\tilde{Z}x||_p^p \geq ||Ax||_p^p \geq 2^p n,$$

which contradicts the optimality of x^*. ∎

Next we seek to translate the fact that the optimizer x^* is close to X to the fact that the objective value $||Zx||_p/||x||_p$ is close to the largest objective value at X.

PROPOSITION 4.2. *Let $p > 2$, G be a graph on n vertices, and*

$$Z = \begin{pmatrix} \frac{64pn^8}{p-2}A \\ M(G) \end{pmatrix}.$$

If x^* is the vector at which the optimization problem

$$\max_{x \in S(0,n^{1/p})} ||Zx||_p$$

achieves its supremum and $x_{\rm r}$ is the rounded version of x^* in which every component is rounded to the closest of -1 and 1, then

$$\Big|\, ||Zx^*||_p^p - ||Zx_{\rm r}||_p^p \Big| \leq \frac{1}{n^2}.$$

Proof. Observe that x^* is the same as the extremizer of the corresponding problem with $\tilde{Z}$ instead of Z so that x satisfies the conclusion of Proposition 4.1. Consequently every component of x^* is closer to one of ± 1 than to the other, and so $x_{\rm r}$ is well defined. We have,

$$||Zx^*||_p^p - ||Zx_{\rm r}||_p^p = \left(64\frac{p}{p-2}n^8\right)^p (||Ax^*||_p^p - ||Ax_{\rm r}||_p^p) + (||Mx^*||_p^p - ||Mx_{\rm r}||_p^p).$$

This entire quantity is nonnegative since x^* is the maximum of $||Zx||$ on $S(0, n^{1/p})$. Moreover, $||Ax^*||_p^p - ||Ax_{\rm r}||_p^p$ is nonpositive since, by Proposition 3.2, $||Ax||_p$ achieves its maximum over $S(0, n^{1/p})$ on all the elements of X. Consequently,

$$\begin{aligned} ||Zx^*||_p^p - ||Zx_{\rm r}||_p^p &\leq ||Mx^*||_p^p - ||Mx_{\rm r}||_p^p \\ &\leq (||Mx^*||_p - ||Mx_{\rm r}||_p)p \max(||Mx^*||_p, ||Mx_{\rm r}||_p)^{p-1}. \end{aligned} \tag{4.1}$$

We now bound all the terms in the last equation. First

$$||Mx^*||_p - ||Mx_{\rm r}||_p \leq ||M||_2||x^* - x_{\rm r}||_2 \leq ||M||_F\sqrt{n}||x^* - x_{\rm r}||_\infty = \frac{n\sqrt{n}}{4^p n^6}, \tag{4.2}$$

where we have used $||M(G)||_F = \sqrt{2\,|E|} < n$ and Proposition 4.1 for the last inequality. Now that we have a bound on the first term in (4.1), we proceed to the last term. It follows from the definition of M that

$$||Mx_{\rm r}||_p^p \leq 2^p \cdot \binom{n}{2} \leq 2^p n^2.$$

Next we bound $||Mx^*||_p^p$. Observe that a particular case of (4.2) is

$$||Mx^*||_p < ||Mx_{\rm r}||_p + 1. \tag{4.3}$$

Moreover, observe that $||Mx_{\rm r}||_p \geq 1$. (The only way this does not hold is if every entry of $x_{\rm r}$ is the same, i.e., $||Mx_{\rm r}||_p = 0$. But then (4.3) implies that $||Mx^*||_p < 1$, which is impossible since G has at least one edge.), So (4.3) implies that $||Mx^*||_p \leq 2||Mx_{\rm r}||_p$, and so

$$||Mx^*||_p^p \leq 4^p n^2.$$

Thus

$$\max(||Mx^*||_p, ||Mx_{\rm r}||_p)^p \leq 4^p n^2,$$

and therefore $\max(||Mx^*||_p, ||Mx_{\rm r}||_p)^{p-1} \leq 4^p n^2$. Indeed, this bound is trivially valid if $\max(||Mx^*||_p, ||Mx_{\rm r}||_p)^p \leq 1$ and follows from $a^{p-1} < a^p$ for $a \geq 1$ otherwise. Using this bound and the inequality (4.2), we finally obtain

$$||Zx^*||_p^p - ||Zx_{\rm r}||_p^p \leq \frac{n^{1.5}}{4^p n^6} p \cdot 4^p n^2 \leq \frac{1}{n^2}. \qquad \square$$

Finally let us bring it all together by arguing that if we can approximately compute the p-norm of Z, we can approximately compute the maximum cut.

PROPOSITION 4.3. *Let $p > 2$. Consider a graph G on $n > 2$ vertices and the matrix*

$$Z = \begin{pmatrix} 64\frac{p}{p-2} n^8 A \\ M(G) \end{pmatrix},$$

and let $f^* = ||Z||_p$. *If*

$$|f_{\rm approx} - f^*| \leq \frac{(p-2)^p}{132^p p^p n^{8p+3} p},$$

then

$$\left| \left(\frac{n}{2^p} f_{\rm approx}^p - n\left(\frac{64pn^8}{p-2}\right)^p \right) - {\rm maxcut}(G) \right| \leq \frac{1}{n}.$$

Proof. Observe that $n^{\frac{1}{p}} f^* = \max_{x \in S(0,n^{1/p})} ||Zx||_p$. It follows thus from Proposition 4.2 that

$$\left| n f^{*p} - \max_{x \in X} ||Zx||_p^p \right| < \frac{1}{n^2}.$$

Recall that $||Zx||_p^p = ||Mx||_p^p + \left(64\frac{p}{p-2}n^8\right)^p ||Ax||_p^p$ and that $||Ax||_p^p = n2^p$ for every $x \in X$. Therefore,

$$\max_{x \in X} ||Zx||_p^p = \left(\frac{64pn^8}{p-2}\right)^p n2^p + \max_{x \in X} ||Mx||_p^p = \left(\frac{64pn^8}{p-2}\right)^p n2^p + 2^p {\rm maxcut}(G),$$

and by combining the last two equations, we have

$$\left| \left(\frac{n}{2^p} f^{*p} - n\left(\frac{64pn^8}{p-2}\right)^p \right) - {\rm maxcut}(G) \right| \leq \frac{1}{2^p n^2}. \qquad (4.4)$$

Let us now evaluate the error introduced by the approximation $f_{\rm approx}$:

$$\begin{aligned} \left| \left(\frac{n}{2^p} f_{\rm approx}^p - n\left(\frac{64pn^8}{p-2}\right)^p \right) - {\rm maxcut}(G) \right| &\leq \frac{1}{2^p n^2} + \frac{n}{2^p} \left| f_{\rm approx}^p - f^{*p} \right| \\ &\leq \frac{1}{2^p n^2} + \frac{n}{2^p} \left| f_{\rm approx} - f^* \right| p \max(f^*, f_{\rm approx})^{p-1}. \end{aligned}$$

It remains to bound the last term of this inequality. First we use the fact that $f^* \geq 1$ and (4.4) to argue

$$f^{*(p-1)} \leq f^{*p} \leq 2^p \left(\frac{64pn^8}{p-2}\right)^p + \frac{2^p}{n}\text{maxcut}(G) + \frac{1}{n^3} \leq 2^p \left(\frac{66pn^8}{p-2}\right)^p, \tag{4.5}$$

where we have used $\text{maxcut}(G) < n^2$ and $1 \leq p/(p-2)$ for the last inequality. By assumption, $|f_{\text{approx}} - f^*| \leq 1$, and since $f^* \geq 1$,

$$f_{\text{approx}}^{(p-1)} \leq (2f^*)^{p-1} \leq (2f^*)^p \leq 4^p \left(\frac{66pn^8}{p-2}\right)^p.$$

Putting it all together and using the bound on $|f_{\text{approx}} - f^*|$, we obtain (assuming $n > 1$)

$$\begin{aligned}\left|\left(\frac{n}{2^p} f_{\text{approx}}^p - n\left(\frac{64pn^8}{p-2}\right)^p\right) - \text{maxcut}(G)\right| &\leq \frac{1}{2^p n^2} + \frac{(p-2)^p}{132^p p^p n^{8p+3} p} 2^p np \left(\frac{66pn^8}{p-2}\right)^p \\ &\leq \frac{1}{2^p n^2} + \frac{1}{n^2} \\ &\leq \frac{1}{n}. \qquad \square\end{aligned}$$

PROPOSITION 4.4. *Fix a rational $p \in [1, \infty)$ with $p \neq 1, 2$. Unless $P = NP$, there is no algorithm which, given input $\epsilon > 0$ and a matrix Z, computes $||Z||_p$ to a relative accuracy ϵ, in time which is polynomial in $1/\epsilon$, the dimensions of Z, and the bit size of the entries of Z.*

Proof. Suppose first that $p > 2$. We show that such an algorithm could be used to build a polynomial time algorithm solving the maximum cut problem. For a graph G on n vertices, fix

$$\epsilon = \left(132^p \left(\frac{p}{p-2}\right)^p n^{8p+3} p\right)^{-1} \cdot \left(132 \left(\frac{p}{p-2}\right) n^8\right)^{-1},$$

build the matrix Z as in Proposition 4.3, and compute the norm of Z; let f_{approx} be the output of the algorithm. Observe that, by (4.5),

$$||Z||_p \leq \frac{132pn^8}{p-2},$$

so

$$\left|f_{\text{approx}} - ||Z||_p\right| \leq \epsilon \, ||Z||_p \leq \epsilon \left(132 \frac{p}{p-2} n^8\right) \leq \left(132^p \left(\frac{p}{p-2}\right)^p n^{8p+3} p\right)^{-1}.$$

It follows then from Proposition 4.3 that

$$n \left(\frac{f_{\text{approx}}}{2}\right)^p - n \left(64 \cdot \left(\frac{p}{p-2}\right) n^8\right)^p$$

is an approximation of the maximum cut with an additive error at most $1/n$. Once we have f_{approx}, we can approximate this number in polynomial time to an additive accuracy of $1/4$. This gives an additive error $1/4 + 1/n$ approximation algorithm for maximum cut, and since the maximum cut is always an integer, this means we can compute it exactly when $n > 4$. However, maximum cut is an NP-hard problem [1].

For the case of $p \in (1, 2)$, NP-hardness follows from the analysis of the case of $p > 2$ since, for any matrix Z, $||Z||_p = ||Z^T||_{p'}$, where $1/p + 1/p' = 1$. ∎

Remark. In contrast to Theorem 2.3 which proves the NP-hardness of computing the matrix ∞, k-norm to relative accuracy $\epsilon = 1/C(p)$, for some function $C(p)$, Proposition 4.4 proves the NP-hardness of computing the p-norm to accuracy $1/C'(p)n^{8p+11}$ for some function $C'(p)$. In the latter case, ϵ depends on n.

Our final theorem demonstrates that the p-norm is still hard to compute when restricted to matrices with entries in $\{-1, 0, 1\}$.

THEOREM 4.5. *Fix a rational $p \in [1, \infty)$ with $p \neq 1, 2$. Unless $P = NP$, there is no algorithm which, given input ϵ and a matrix M with entries in $\{-1, 0, 1\}$, computes $||M||_p$ to relative accuracy ϵ, in time which is polynomial in ϵ^{-1} and the dimensions of the matrix.*

Proof. As before, it suffices to prove the theorem for the case of $p > 2$; the case of $p \in (1, 2)$ follows because $||Z||_p = ||Z^T||_{p'}$, where $1/p + 1/p' = 1$.

Define

$$Z^* = \begin{pmatrix} \left(\left\lceil \left(64\frac{p}{p-2}n^8\right) \right\rceil\right) A \\ M(G) \end{pmatrix},$$

where $\lceil \cdot \rceil$ refers to rounding up to the closest integer. Observe that, by an argument similar to the proof of the previous proposition, computing $||Z^*||_p$ to an accuracy $\epsilon = (C(p)n^{8p+11})^{-1}$ is NP-hard for some function $C(p)$. But if we define

$$Z^{**} = \begin{pmatrix} A \\ A \\ \vdots \\ A \\ M \end{pmatrix},$$

where A is repeated $\left\lceil \left(64\frac{p}{p-2}n^8\right)^p \right\rceil$ times, then

$$||Z^{**}||_p = ||Z^*||_p.$$

The matrix Z^{**} has entries in $\{-1, 0, 1\}$, and its size is polynomial in n, so it follows that it is NP-hard to compute $||Z^{**}||_p$ within the same ϵ. ∎

Remark. Observe that the argument also suffices to show that computing the p-norm of *square* matrices with entries in $\{-1, 0, 1\}$ is NP-hard: simply pad each row of Z^{**} with enough zeros to make it square. Note that this trick was also used in section 2.

5. Concluding remarks. We have proved the NP-hardness of computing the matrix p-norm approximately with *relative* error $\epsilon = 1/C(p)n^{8p+11}$, where $C(p)$ is some function of p, and the NP-hardness of computing the matrix ∞, p-norm to some fixed relative accuracy depending on p. We finish with some technical remarks about various possible extensions of the theorem:

- Due to the linear property of the norm $||\alpha A|| = |\alpha|\,||A||$, our results also imply the NP-hardness of approximating the matrix p-norm with any fixed or polynomially growing *additive error*.

- Our construction also implies the hardness of computing the matrix p-norm for any irrational number $p > 1$ for which a polynomial time algorithm to approximate x^p is available.
- Our construction may also be used to provide a new proof of the NP-hardness of the $|| \cdot ||_{p,q}$ norm when $p>q$, which has been established in [5]. Indeed, it rests on the matrix A with the property that $\max ||Ax||_p/||x||_p$ occurs at the vectors $x \in \{-1, 1\}^n$. We use this matrix A to construct the matrix $Z = (\alpha A\ M)^T$ for large α and argue that $\max ||Zx||_p/||x||_p$ occurs close to the vectors $x \in \{-1, 1\}^n$. At these vectors, it happens Ax is a constant, so we are effectively maximizing $||Mx||_p$, which is hard as shown in section 2.
  If one could come up with such a matrix for the case of the mixed $||\cdot||_{p,q}$ norm, one could prove NP-hardness by following the same argument. However, when $p > q$, actually the same matrix A works. Indeed, one could simply argue that
  $$||A||_{p,q} = \max_{x \neq 0} \frac{||Ax||_q}{||x||_p} = \max_{x \neq 0} \frac{||Ax||_q}{||x||_q} \frac{||x||_q}{||x||_p},$$
  and since the maximum of $||x||_q/||x||_p$ when $1 \leq q < p \leq \infty$ occurs at the vectors $x \in \{-1, 1\}^n$, we have that both terms on the right are maximized at $x =\in \{-1, 1\}^n$, and that is where $||Ax||_q/||x||_p$ is maximized.
- Finally we note that our goal was only to show the existence of a polynomial time reduction from the maximum cut problem to the problem of matrix p-norm computation. It is possible that more economical reductions which scale more gracefully with n and p exist.

REFERENCES

[1] M. R. Garey and D. S. Johnson, *Computers and Intractability: A Guide to the Theory of NP-Completeness,* W. H. Freeman, San Francisco, 1979.

[2] J. Håstad, *Some optimal inapproximability results*, J. ACM, 48 (2001), pp. 798–859.

[3] K. G. Murty and S. N. Kabadi, *Some NP-complete problems in quadratic and nonlinear programming*, Math. Program., 39 (1987), pp. 117–129.

[4] J. Rohn, *Computing the norm* $\|A\|_{\infty,1}$ *is NP-hard*, Linear Multilinear Algebra, 47 (2000), pp. 195–204.

[5] D. Steinberg, *Computation of Matrix Norms with Applications to Robust Optimization*, M.Sc. thesis, Technion—Israel Institute of Technology, Haifa, Israel, 2005, also available online from http://www2.isye.gatech.edu/∼nemirovs/Daureen.pdf.