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Harnack inequalities for supersolutions of fully nonlinear elliptic difference and differential equations

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Abstract

We present a new Harnack inequality for non-negative discrete supersolutions of fully nonlinear uniformly elliptic difference equations on rectangular lattices. This estimate applies to all supersolutions; instead the Harnack constant depends on the graph distance on lattices. For the proof we modify the proof of the weak Harnack inequality. Applying the same idea to elliptic equations in a Euclidean space, we also derive a Harnack type inequality for non-negative viscosity supersolutions.

Key words: Harnack inequality, Fully nonlinear elliptic equations, Discrete solutions, Viscosity solutions

Mathematics Subject Classification 2010: 35B05, 35J60, 65N22, 35D40

1 Introduction

We consider fully nonlinear, non-homogeneous second order equations of the form

$$F(D^2u) = f(x) \tag{1.1}$$

with a uniformly elliptic operator F . A typical statement of the Harnack inequality is that there exists a constant $C > 0$ such that the inequality

$$\max_U u \leq C \left\{ \min_U u + \|f\|_{L^n(V)} \right\} \tag{1.2}$$

holds for every non-negative solution u of (1.1) in V . Here V is a set which is (enough) larger than U , and n represents the dimension of space. One of well-known proofs of the Harnack inequality is a combination of a *weak Harnack inequality*, which asserts that, for some $p > 0$,

$$\|u\|_{L^p(U)} \leq C \left\{ \min_U u + \|f\|_{L^n(V)} \right\}$$

holds for every non-negative supersolution u , and a *local maximum principle* (or a *mean value inequality*):

$$\max_U u \leq C \left\{ \|u\|_{L^q(U)} + \|f\|_{L^n(V)} \right\}$$

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for subsolutions u , where $q > 0$ is arbitrary. These estimates are well-known in the continuum case where (1.1) is studied as a partial differential equation in $\mathbf{R}^n$; for instance, the reader is referred to [9, Chapter 9] for linear equations and [3, Chapter 4] for fully nonlinear equations. The corresponding results are also obtained in the discrete case when we study (1.1) as a difference equation on lattices. In [13] the Harnack inequality for elliptic difference equations is derived via the weak Harnack inequality and the local maximum principle. See also [14] for the parabolic case and [15, 16] for general meshes.

The main goal of this paper is to show that, in the discrete case, a modified proof of the weak Harnack inequality implies a new type of the Harnack inequality for discrete supersolutions to (1.1) on rectangular lattices (Theorem 4.1). Our proof is direct and simple in the sense that we do not need the local maximum principle. The resulting estimate is different from the literature in that it holds for supersolutions which are not necessarily subsolutions; instead the Harnack constant, C in (1.2), depends on the graph distance on lattices. Due to this, passing to limits in our Harnack inequality does not imply the continuum Harnack inequality since the Harnack constant C goes to infinity when the mesh size tends to 0 (Remark 3.4 and 4.2). Here it is worth to mention that such reconstruction of the continuum Harnack inequality should not be possible since (1.2) does not hold even for the Laplace equation if we do not require u to be a subsolution; see Example 5.3 for the counter-example. We can say that our Harnack inequality is an interesting estimate which comes at the expense of convergence of discrete schemes.

In the proof of the weak Harnack inequality for fully nonlinear equations of the continuum case ([2, 3]), we take a radially symmetric and increasing supersolution ϕ of the Pucci equation

$$\mathcal{P}^-(D^2\phi) = -\xi(x). \quad (1.3)$$

Here $\mathcal{P}^-$ is a Pucci operator (see (5.2) or (2.2) for definition) and ξ is a non-negative, continuous function whose support is contained in a small ball centered at the origin. Such a function ϕ is often called a *barrier function*. In the discrete case, we are able to construct the barrier function so that ξ is non-zero only at the origin (Lemma 3.1 and Remark 3.2). In other words, its support is only one point. This is a crucial difference from the continuous case, and this enables a pointwise estimate for supersolutions of difference equations. In our proof of the Harnack inequality, we translate the barrier function so that its minimum point, which originally lies at the origin, comes to a maximum point of the supersolution u of (1.1). As a result, we obtain the Harnack inequality without discussing the local maximum principle.

We apply the same idea involving translation of the barrier function to partial differential equations in $\mathbf{R}^n$. This gives our another result in this paper (Theorem 5.7). To describe the result, we first note that (1.2) can be stated equivalently as

$$u(z) \leq C \left\{ \min_U u + \|f\|_{L^n(V)} \right\} \quad \text{for all } z \in U, \quad (1.4)$$

which is a pointwise estimate and does not hold for supersolutions. Employing the theory of viscosity solutions, we prove that, for a fixed $\varepsilon > 0$, there exists a constant $C > 0$ depending on ε such that, for every $z \in U$, the minimum value of u over $\{|x - z| \leq \varepsilon\}$ is dominated by the right-hand side of (1.4). In other words, our Harnack inequality needs further information of u around z . The barrier function ϕ which we will use in the proof is chosen so that the support of ξ appearing in (1.3) is contained in $\{|x| \leq \varepsilon\}$. Also, around the origin, ϕ is defined by using a modulus of continuity (from below) of u near z . The resulting estimate can be said to be a “very weak Harnack inequality” since the minimum of u over

$\{|x - z| \leq \varepsilon\}$ is controlled by its L^p -norm on U . Thus the method in this paper presents how a simple estimate is established by a simple argument without the Calderón-Zygmund decomposition appearing in the literature ([2, 3]).

This paper is organized as follows: Section 2 is devoted to preparation for studies of difference equations on rectangular lattices. In Section 3 we construct a barrier function ϕ in (1.3) so that the support of ξ lies only at the origin. Then, in Section 4 we give a proof of the Harnack inequality for non-negative discrete supersolutions. Section 5 is concerned with the Harnack inequality in $\mathbf{R}^n$ for viscosity supersolutions. We use a similar idea to the one presented in Section 4. In Appendix A we establish a unique existence of discrete solutions to Dirichlet problems of fully nonlinear uniformly elliptic difference equations. This unique solution is needed in Section 4 to derive the Harnack inequality with non-zero f .

2 Preliminaries

In this paper we consider an n -dimensional weighted lattice $h\mathbf{Z}^n$ defined as

$$h\mathbf{Z}^n := \{(h_1 m_1, \dots, h_n m_n) \in \mathbf{R}^n \mid (m_1, \dots, m_n) \in \mathbf{Z}^n\}.$$

Here h_i is a fixed positive constant which represents a mesh size in the direction of x_i . We set $h_{\max} := \max\{h_1, \dots, h_n\}$ and $h_{\min} := \min\{h_1, \dots, h_n\}$. For $\Omega \subset h\mathbf{Z}^n$ we define its closure $\overline{\Omega} \subset h\mathbf{Z}^n$ and its boundary $\partial\Omega \subset h\mathbf{Z}^n$ as

$$\overline{\Omega} := \Omega \cup \{x \pm h_i e_i \mid x \in \Omega, i \in \{1, \dots, n\}\}, \quad \partial\Omega := \overline{\Omega} \setminus \Omega,$$

where $\{e_i\}_{i=1}^n \subset \mathbf{R}^n$ is the standard orthogonal basis of $\mathbf{R}^n$, e.g., $e_1 = (1, 0, \dots, 0)$.

We next introduce difference operators. Let $u : h\mathbf{Z}^n \rightarrow \mathbf{R}$, $x \in h\mathbf{Z}^n$ and $i \in \{1, \dots, n\}$. We define the second order difference operators as follows:

$$\begin{aligned} \delta_i^2 u(x) &:= \frac{u(x + h_i e_i) + u(x - h_i e_i) - 2u(x)}{h_i^2}, \\ \vec{\delta}^2 u(x) &:= (\delta_1^2 u(x), \dots, \delta_n^2 u(x)). \end{aligned}$$

The difference equation we consider is

$$F(\vec{\delta}^2 u(x)) = f(x), \tag{2.1}$$

where $F : \mathbf{R}^n \rightarrow \mathbf{R}$ is uniformly elliptic (Definition 2.2), $F(0) = 0$ and $f : h\mathbf{Z}^n \rightarrow \mathbf{R}$.

Definition 2.1. Let $\Omega \subset h\mathbf{Z}^n$. We say $u : \overline{\Omega} \rightarrow \mathbf{R}$ is a *discrete subsolution* (resp. *supersolution*) of (2.1) in Ω if $F(\vec{\delta}^2 u(x)) \leq f(x)$ (resp. $\geq f(x)$) for all $x \in \Omega$. If u is both a discrete sub- and supersolution, it is called a *discrete solution*.

Throughout this paper we fix ellipticity constants $0 < \lambda \leq \Lambda$. To describe the uniform ellipticity of F in (2.1) we introduce *Pucci operators* $\mathcal{P}^\pm : \mathbf{R}^n \rightarrow \mathbf{R}$, which are defined as

$$\mathcal{P}^+(\vec{X}) := -\lambda \sum_{X_i > 0} X_i - \Lambda \sum_{X_i < 0} X_i, \quad \mathcal{P}^-(\vec{X}) := -\lambda \sum_{X_i < 0} X_i - \Lambda \sum_{X_i > 0} X_i \tag{2.2}$$

for $\vec{X} = (X_1, \dots, X_n) \in \mathbf{R}^n$. An easy computation shows that the Pucci operators satisfy $\mathcal{P}^-(\vec{X} + \vec{Y}) \leq \mathcal{P}^+(\vec{X}) + \mathcal{P}^-(\vec{Y}) \leq \mathcal{P}^+(\vec{X} + \vec{Y})$ for all $\vec{X}, \vec{Y} \in \mathbf{R}^n$.

Definition 2.2. We say $F : \mathbf{R}^n \rightarrow \mathbf{R}$ is *uniformly elliptic* if $\mathcal{P}^-(\vec{X} - \vec{Y}) \leq F(\vec{X}) - F(\vec{Y}) \leq \mathcal{P}^+(\vec{X} - \vec{Y})$ for all $\vec{X}, \vec{Y} \in \mathbf{R}^n$.

Putting $\vec{Y} = 0$, we see that $\mathcal{P}^-(\vec{X}) \leq F(\vec{X}) \leq \mathcal{P}^+(\vec{X})$ since $F(0) = 0$.

We next state the ABP maximum principle (ABP estimate). This is a pointwise estimate for subsolutions and supersolutions of elliptic equations, and it will be used in the proof of the Harnack inequality. We prepare some notations before stating the estimate. For $a \in \mathbf{R}$ we set $a^\pm := \max\{\pm a, 0\}$ (≥ 0). Let $\Omega \subset h\mathbf{Z}^n$ and $u : \bar{\Omega} \rightarrow \mathbf{R}$. We define $\Gamma_\Omega[u]$, an *upper contact set* of u on Ω , as

$$\Gamma_\Omega[u] := \left\{ x \in \Omega \mid \begin{array}{l} \text{there exists some } p \in \mathbf{R}^n \text{ such that} \\ u(y) \leq \langle p, y - x \rangle + u(x) \text{ for all } y \in \bar{\Omega} \end{array} \right\}, \quad (2.3)$$

where $\langle \cdot, \cdot \rangle$ is the standard Euclidean inner product in $\mathbf{R}^n$. The p -norm ($p \in [1, \infty)$) of u over Ω is given as $\|u\|_{\ell^p(\Omega)} := (\sum_{x \in \Omega} h^n |u(x)|^p)^{1/p}$, where $h^n := h_1 \times \cdots \times h_n$. We only use the case $p = n$ in this paper. The diameter of Ω is $\text{diam}(\Omega) := \max_{x, y \in \partial\Omega} |x - y|$. Here $|\cdot|$ stands for the standard Euclidean norm in $\mathbf{R}^n$.

Theorem 2.3 (ABP maximum principle). *Let $\Omega \subset h\mathbf{Z}^n$ be bounded. There exists a constant $C_A = C_A(n, \lambda) > 0$ such that, for every discrete subsolution (resp. supersolution) u of (2.1) in Ω , the estimate*

$$\max_{\bar{\Omega}} u \leq \max_{\partial\Omega} u^+ + C_A \text{diam}(\Omega) \|f^+\|_{\ell^n(\Gamma_\Omega[u^+])} \quad (2.4)$$

$$\text{(resp. } \min_{\bar{\Omega}} u \geq \min_{\partial\Omega} (-u^-) - C_A \text{diam}(\Omega) \|f^-\|_{\ell^n(\Gamma_\Omega[u^-])}) \quad (2.5)$$

holds.

We do not give a proof of Theorem 2.3; see [13, Theorem 2.1], [10, Theorem 4.1].

3 Barrier function

In the proof of the Harnack inequality we use a barrier function, which is a radially increasing supersolution of $\mathcal{P}^- = 0$ except at the origin. (See [3, Lemma 4.1] for the continuum case.)

For $x \in h\mathbf{Z}^n$ given as $x = (h_1 m_1, \dots, h_n m_n)$ with $(m_1, \dots, m_n) \in \mathbf{Z}^n$, we define $\rho(x) := |m_1| + \cdots + |m_n|$. This represents the graph distance on $h\mathbf{Z}^n$ between 0 and x , i.e., the number of edges in a shortest path connecting them. Let $k \in \mathbf{N} \cup \{0\}$. We define a ball $B_k \subset h\mathbf{Z}^n$ as $B_k := \{x \in h\mathbf{Z}^n \mid \rho(x) \leq k\}$, which is a diamond-shaped set. Note that the index k is not the Euclidean distance but the graph distance.

Lemma 3.1 (Barrier function). *Let $k \in \mathbf{N}$. There exists a function $\phi : \bar{B}_k \rightarrow \mathbf{R}$ such that*

$$\begin{cases} \mathcal{P}^-(\delta^2 \phi) \geq 0 & \text{in } B_k \setminus \{0\}, \end{cases} \quad (3.1)$$

$$\begin{cases} \phi = 0 & \text{on } \partial B_k, \end{cases} \quad (3.2)$$

$$\begin{cases} \phi \leq -1 & \text{in } B_k. \end{cases} \quad (3.3)$$

Proof. Let $\{a_m\}_{m=0}^{k+1} \subset \mathbf{R}$. We define $\phi(x) := a_m$ if $\rho(x) = m \in \{0, 1, \dots, k+1\}$ and set $a_{k+1} = 0$, $a_k = -1$. We show that, for given a_{m+1} and a_m such that $a_{m+1} > a_m$, we have $\mathcal{P}^-(\delta^2 \phi(x)) \geq 0$ for x with $\rho(x) = m$ if we take a_{m-1} sufficiently small (i.e., $a_{m-1} \ll -1$).

Fix $m \in \{1, \dots, k\}$ and $x = (x_1, \dots, x_n) \in B_k \setminus \{0\}$ such that $\rho(x) = m$. Let us calculate $\delta_i^2 \phi(x)$. If $x_i = 0$, we observe

$$\delta_i^2 \phi(x) = \frac{a_{m+1} + a_{m+1} - 2a_m}{h_i^2} = \frac{2(a_{m+1} - a_m)}{h_i^2} > 0.$$

On the other hand, if $x_i \neq 0$, then

$$\delta_i^2 \phi(x) = \frac{a_{m+1} + a_{m-1} - 2a_m}{h_i^2},$$

which is negative when $a_{m-1} \ll -1$. Thus the definition of $\mathcal{P}^-$ implies that

$$\mathcal{P}^-(\delta^2 \phi(x)) = -\lambda \sum_{x_i \neq 0} \delta_i^2 \phi(x) - \Lambda \sum_{x_i = 0} \delta_i^2 \phi(x).$$

Now, there exists at least one index i such that $x_i \neq 0$ since $x \neq 0$. Therefore

$$\begin{aligned} \mathcal{P}^-(\delta^2 \phi(x)) &\geq -\lambda \frac{a_{m+1} + a_{m-1} - 2a_m}{h_{\max}^2} - \Lambda \frac{2(a_{m+1} - a_m)}{h_{\min}^2} (n-1) \\ &= -\frac{\lambda}{h_{\max}^2} \left(a_{m+1} + a_{m-1} - 2a_m + \frac{2\Lambda h_{\max}^2 (n-1)(a_{m+1} - a_m)}{\lambda h_{\min}^2} \right). \end{aligned} \quad (3.4)$$

This is non-negative if $a_{m-1} \ll -1$, and hence (3.1) holds. The conditions (3.2) and (3.3) are clear by construction. $\square$

Remark 3.2. Using the barrier function ϕ in Lemma 3.1, we define

$$\xi(x) := \begin{cases} -\mathcal{P}^-(\delta^2 \phi(0)) & \text{if } x = 0, \\ 0 & \text{if } x \neq 0. \end{cases}$$

Then ϕ is a supersolution of $\mathcal{P}^- = -\xi$ in B_k . We also note that $\xi(0) > 0$ since $\delta_i^2 \phi(0) = 2(a_1 - a_0)/h_i^2 > 0$ for all $i = 1, \dots, n$.

Remark 3.3. In view of the proof, we notice that $\phi(0)$ depends on $k, n, \Lambda/\lambda$ and $h_{\max}/h_{\min}$. The positive constant $-\phi(0)$ will appear as the Harnack constant C_H in (4.2).

Remark 3.4. The quantity in parentheses of (3.4) is chosen to be non-positive, and so we have $a_{m+1} - a_m < a_m - a_{m-1}$ for $m \in \{1, \dots, k\}$. This yields $a_0 < -k-1$ since $a_{k+1} - a_k = 1$. It thus follows that the value $\phi(0) = a_0$ goes to $-\infty$ as $k \rightarrow \infty$. This implies that we cannot obtain the continuum Harnack inequality as the limit of our discrete Harnack inequality; see Remark 4.2.

4 Harnack inequality

We show the Harnack inequality for non-negative discrete supersolutions of

$$\mathcal{P}^+(\delta^2 u) = -f^-(x). \quad (4.1)$$

Note that a supersolution of (2.1) is also a supersolution of (4.1).

Theorem 4.1 (Harnack inequality). *Let $r \in \mathbf{N}$. Then there exists a constant $C_H = C_H(r, n, \Lambda/\lambda, h_{\max}/h_{\min}) > 0$ such that, for every non-negative discrete supersolution $u : \overline{B_{3r}} \rightarrow [0, \infty)$ of (4.1) in B_{3r} , the estimate*

$$\max_{B_r} u \leq C_H \left\{ \min_{B_r} u + C_A \text{diam}(B_{3r}) \|f^-\|_{\ell^n(B_{3r})} \right\} \quad (4.2)$$

holds, where C_A is the constant in Theorem 2.3.

We first prove (4.2) in the case when $f^- \equiv 0$; a crucial difference between the discrete case and the continuum case appears in this part. We translate ξ in Remark 3.2 so that its support comes to a maximum point of u and derive the estimate for u at the point. The proof for a general f is similar to the proof in the continuum case; see, e.g., [1, Proof of Theorem 1.11]. We employ a solution v of a Pucci equation and study $u + v$ to apply (4.2) with $f^- \equiv 0$.

Proof. Case: $f^- \equiv 0$. 1. We take $x_M, x_m \in B_r$ such that $u(x_M) = \max_{B_r} u$ and $u(x_m) = \min_{B_r} u$. Our goal is to derive $u(x_M) \leq C_H u(x_m)$. Let ϕ be the barrier function in Lemma 3.1 with $k = 2r$. Let $\beta > u(x_m) (\geq 0)$. We define $\tilde{\phi}(x) := \beta\phi(x - x_M)$ and

$$\tilde{\xi}(x) := \begin{cases} -\mathcal{P}^-(\delta^2 \tilde{\phi}(x_M)) & \text{if } x = x_M, \\ 0 & \text{if } x \neq x_M. \end{cases}$$

Set $B := x_M + B_{2r}$. Then $B_r \subset B \subset B_{3r}$ since $x_M \in B_r$. By virtue of Lemma 3.1 and Remark 3.2, we have

$$\begin{cases} \mathcal{P}^-(\delta^2 \tilde{\phi}) \geq -\tilde{\xi} & \text{in } B, \\ \tilde{\phi} = 0 & \text{on } \partial B, \\ \tilde{\phi} \leq -\beta & \text{in } B. \end{cases} \quad \begin{matrix} (4.3) \\ (4.4) \\ (4.5) \end{matrix}$$

2. Let us study a function $u + \tilde{\phi}$. For every $x \in B$ we deduce from (4.3) that

$$\mathcal{P}^+(\delta^2 u(x) + \delta^2 \tilde{\phi}(x)) \geq \mathcal{P}^+(\delta^2 u(x)) + \mathcal{P}^-(\delta^2 \tilde{\phi}(x)) \geq 0 - \tilde{\xi}(x).$$

Namely, $u + \tilde{\phi}$ is a supersolution of $\mathcal{P}^+ = -\tilde{\xi}$ in B . Applying the ABP maximum principle (2.5) to $u + \tilde{\phi}$, we obtain

$$\min_B (u + \tilde{\phi}) \geq \min_{\partial B} \{-(u + \tilde{\phi})^-\} - C_A \text{diam}(B) \|\tilde{\xi}\|_{\ell^n(\Gamma_B[(u + \tilde{\phi})^-])}. \quad (4.6)$$

Since u is non-negative and (4.4) holds, we have $u + \tilde{\phi} \geq 0$ on ∂B , and thus $\min_{\partial B} \{-(u + \tilde{\phi})^-\} = 0$. As for the left-hand side of (4.6), using (4.5), we compute

$$\min_B (u + \tilde{\phi}) \leq \min_B u - \beta \leq \min_{B_r} u - \beta < 0.$$

Therefore it follows from (4.6) that $0 > -\|\tilde{\xi}\|_{\ell^n(\Gamma_B[(u + \tilde{\phi})^-])}$. Since $\tilde{\xi}$ is nonzero only at x_M by its definition, we must have

$$x_M \in \Gamma_B[(u + \tilde{\phi})^-]. \quad (4.7)$$

3. We claim $(u + \tilde{\phi})(x_M) < 0$. Suppose by contradiction that $(u + \tilde{\phi})(x_M) \geq 0$, i.e., $(u + \tilde{\phi})^-(x_M) = 0$. Then, since $(u + \tilde{\phi})^- = 0$ on ∂B , (4.7) implies

$$(u + \tilde{\phi})^- = 0 \quad \text{on } \overline{B}. \quad (4.8)$$

Indeed, by (4.7) there exists some $p = (p_1, \dots, p_n) \in \mathbf{R}^n$ such that

$$0 \leq (u + \tilde{\phi})^-(y) \leq (u + \tilde{\phi})^-(x_M) + \langle p, y - x_M \rangle = \langle p, y - x_M \rangle \quad (4.9)$$

for all $y \in \overline{B}$. Fix $i \in \{1, \dots, n\}$ and choose $k_+, k_- \in \mathbf{N}$ such that $x_M \pm k_{\pm} h_i e_i \in \partial B$. (Such numbers $k_{\pm}$ exist since B is bounded.) Taking $y = x_M \pm k_{\pm} h_i e_i$ in (4.9), we observe

$$0 \leq \langle p, k_+ h_i e_i \rangle = k_+ h_i p_i, \quad 0 \leq \langle p, -k_- h_i e_i \rangle = -k_- h_i p_i,$$

which imply $p_i = 0$. Finally, applying $p = 0$ to (4.9) yields (4.8). However, at a minimum point x_m we have $(u + \tilde{\phi})(x_m) \leq u(x_m) - \beta < 0$. This contradicts to (4.8).

By the claim we have $u(x_M) < -\tilde{\phi}(x_M) = -\beta\phi(0)$, and sending $\beta \rightarrow u(x_m)$ yields $u(x_M) \leq C_H u(x_m)$ with $C_H = -\phi(0)$.

Case: $f^- \not\equiv 0$. 1. Let v be the discrete solution of

$$\begin{cases} \mathcal{P}^-(\tilde{\delta}^2 v) = f^- & \text{in } B_{3r}, \\ v = 0 & \text{on } \partial B_{3r}. \end{cases}$$

We will prove a unique existence of solutions in Appendix A (Theorem A.4) for more general Dirichlet problems. By the ABP maximum principles we see that v satisfies

$$\begin{aligned} \max_{\overline{B_{3r}}} v &\leq \max_{\partial B_{3r}} v^+ + C_A \text{diam}(B_{3r}) \| (f^-)^+ \|_{\ell^n(\Gamma_{B_{3r}}[v^+])} \\ &\leq 0 + C_A \text{diam}(B_{3r}) \| f^- \|_{\ell^n(B_{3r})} \end{aligned} \quad (4.10)$$

and

$$\begin{aligned} \min_{\overline{B_{3r}}} v &\geq \min_{\partial B_{3r}} (-v^-) - C_A \text{diam}(B_{3r}) \| (f^-)^- \|_{\ell^n(\Gamma_{B_{3r}}[v^-])} \\ &= 0 - 0. \end{aligned} \quad (4.11)$$

2. We now consider a function $u + v$. By the non-negativity of u and (4.11), we have $u + v \geq 0$ in $\overline{B_{3r}}$. Next, for $x \in B_{3r}$ we compute

$$\mathcal{P}^+(\tilde{\delta}^2 u(x) + \tilde{\delta}^2 v(x)) \geq \mathcal{P}^+(\tilde{\delta}^2 u(x)) + \mathcal{P}^-(\tilde{\delta}^2 v(x)) \geq -f^-(x) + f^-(x) = 0.$$

Thus $u + v$ is a non-negative supersolution of $\mathcal{P}^+ = 0$ in B_{3r} . From the Harnack inequality of the case $f^- \equiv 0$ it follows that

$$\max_{B_r} (u + v) \leq C_H \min_{B_r} (u + v).$$

Finally, applying the estimates (4.10) and (4.11) to the right- and the left-hand side respectively, we obtain (4.2). $\square$

Remark 4.2. Passing to limits in (4.2) as $h \rightarrow 0$ does not imply the Harnack inequality in the continuum case. Indeed, to derive the continuum Harnack inequality on a bounded set $K \subset \mathbf{R}^n$, one needs to “cover” K by a discrete ball $B_r \subset h\mathbf{Z}^n$. When the mesh size goes to 0, the radius $r \in \mathbf{N}$ must tend to infinity, and thus the value $C_H = -\phi(0)$ goes to infinity as we observed in Remark 3.4.

5 Continuum case

We consider elliptic partial differential equations of the form

$$F(D^2u(x)) = f(x), \quad (5.1)$$

where $D^2u(x) = (\partial_{ij}^2 u(x))_{ij}$ denotes the Hessian matrix, $F \in C(\mathbf{S}^n)$ is uniformly elliptic (Definition 5.2), $F(O) = 0$ and $f \in C(\mathbf{R}^n)$. Here $\mathbf{S}^n$ is the set of real $n \times n$ symmetric matrices. In this section, applying the idea of the proof of Theorem 4.1, we deduce a Hanack type inequality for supersolutions of (5.1).

We employ a notion of viscosity solutions to solve (5.1) since it is fully nonlinear.

Definition 5.1. Let $\Omega \subset \mathbf{R}^n$ be open. We say that $u \in C(\Omega)$ is a *viscosity subsolution* (resp. *supersolution*) of (5.1) in Ω if $F(D^2\phi(x)) \leq f(x)$ (resp. $\geq f(x)$) for all $(x, \phi) \in \Omega \times C^2(\Omega)$ such that $u - \phi$ attains a local maximum (resp. minimum) at x .

For given ellipticity constants $0 < \lambda \leq \Lambda$ we define *Pucci operators* $\mathcal{P}^\pm : \mathbf{S}^n \rightarrow \mathbf{R}$ as

$$\mathcal{P}^+(X) := -\lambda \sum_{\mu_i > 0} \mu_i - \Lambda \sum_{\mu_i < 0} \mu_i, \quad \mathcal{P}^-(X) := -\lambda \sum_{\mu_i < 0} \mu_i - \Lambda \sum_{\mu_i > 0} \mu_i, \quad (5.2)$$

where μ_i ($i = 1, \dots, n$) are the eigenvalues of $X \in \mathbf{S}^n$. It is easily seen that these operators satisfy $\mathcal{P}^-(X + Y) \leq \mathcal{P}^+(X) + \mathcal{P}^-(Y) \leq \mathcal{P}^+(X + Y)$ for all $X, Y \in \mathbf{S}^n$. We also have

$$\begin{aligned} \mathcal{P}^+(X) &= \sup\{-\text{trace}(AX) \mid A \in \mathbf{S}^n, \lambda I \leq A \leq \Lambda I\}, \\ \mathcal{P}^-(X) &= \inf\{-\text{trace}(AX) \mid A \in \mathbf{S}^n, \lambda I \leq A \leq \Lambda I\}, \end{aligned}$$

i.e., $\mathcal{P}^\pm$ are Bellman type operators. Here I is the identity matrix, and for $X, Y \in \mathbf{S}^n$ we write $X \leq Y$ if $\langle (Y - X)\xi, \xi \rangle \geq 0$ for all $\xi \in \mathbf{R}^n$.

Definition 5.2. We say $F : \mathbf{S}^n \rightarrow \mathbf{R}$ is *uniformly elliptic* if $\mathcal{P}^-(X - Y) \leq F(X) - F(Y) \leq \mathcal{P}^+(X - Y)$ for all $X, Y \in \mathbf{S}^n$.

Now, we shall give examples showing that the usual Harnack inequality does not hold in the continuum case if we require u to be only a non-negative supersolution. In this section B_r stands for the open ball $\{|x| < r\}$ in $\mathbf{R}^n$. The closure of it in $\mathbf{R}^n$ is denoted by $\overline{B_r}$. Also, set $B_r(z) := \{|x - z| < r\}$.

Example 5.3. We consider the Laplace equation $-\Delta u = 0$ in $\mathbf{R}^n$ when $n \geq 3$. Set $u(x) = \min\{c|x|^{2-n}, 1\}$ with $c > 0$. As is known, $|x|^{2-n}$ is the fundamental solution of the Laplace equation while any constant is trivially a solution. Since the minimum of two supersolutions is still a supersolution ([5, Lemma 4.2]), u is a viscosity supersolution. On the other hand, u is not a viscosity subsolution. Indeed, letting $\phi(x) = -\varepsilon|x|^2$ for $\varepsilon > 0$ small, we see that $u - \phi$ takes a maximum at a point z such that $c|z|^{2-n} = 1$, but $-\Delta\phi(z) = 2n\varepsilon > 0$. Now, let us fix $r > 0$. We then have $\max_{\overline{B_r}} u = 1$ and $\min_{\overline{B_r}} u = cr^{2-n}$ for c small. Thus the ratio $(\max_{\overline{B_r}} u)/(\min_{\overline{B_r}} u)$ tends to ∞ as $c \rightarrow 0$. This implies that the Harnack inequality does not hold.

The functions $u(x) = \min\{|x|^{2-n}, M\}$ with $M > 0$ also show that the Harnack inequality does not hold by letting $M \rightarrow 0$.

We state the ABP maximum principle for viscosity solutions. Let $\Omega \subset \mathbf{R}^n$ be an open set and $u : \overline{\Omega} \rightarrow \mathbf{R}$. Similarly to the discrete case, we define a upper contact set $\Gamma_\Omega[u]$ by (2.3). Set $\|u\|_{L^n(\Omega)} := (\int_\Omega |u(x)|^n dx)^{1/n}$.

Theorem 5.4 (ABP maximum principle). *Let $\Omega \subset \mathbf{R}^n$ be a bounded open set. There exists a constant $C_A = C_A(n, \lambda) > 0$ such that, for every viscosity subsolution (resp. supersolution) $u \in C(\overline{\Omega})$ of (5.1) in Ω , the estimate*

$$\max_{\overline{\Omega}} u \leq \max_{\partial\Omega} u^+ + C_A \text{diam}(\Omega) \|f^+\|_{L^n(\Gamma_\Omega[u^+])} \quad (5.3)$$

$$\text{(resp. } \min_{\overline{\Omega}} u \geq \min_{\partial\Omega} (-u^-) - C_A \text{diam}(\Omega) \|f^-\|_{L^n(\Gamma_\Omega[u^-])}) \quad (5.4)$$

holds.

For the proof see [4, Proposition 2.12, Appendix A] or [11, Proposition 6.2, Section 7.2]. To present a barrier function in the continuum case, we first prepare

Lemma 5.5. *Let $0 < \rho < R$ and define $\psi(x) := M_1 - M_2|x|^{-\alpha}$ with*

$$M_1 = \frac{R^{-\alpha}}{\rho^{-\alpha} - R^{-\alpha}}, \quad M_2 = \frac{1}{\rho^{-\alpha} - R^{-\alpha}}, \quad \alpha = \max \left\{ 1, \frac{(n-1)\Lambda}{\lambda} - 1 \right\}.$$

Then

$$\begin{cases} \mathcal{P}^-(D^2\psi) \geq 0 & \text{in } \mathbf{R}^n \setminus \{0\}, \\ \psi \geq 0 & \text{in } \mathbf{R}^n \setminus B_R, \\ \psi \leq -1 & \text{in } B_\rho. \end{cases} \quad (5.5)$$

Proof. See [3, Lemma 4.1]. □

Let $\varepsilon > 0$. We say that a function $\omega : [0, \varepsilon] \rightarrow [0, \infty)$ is a *modulus* on $[0, \varepsilon]$ if $\omega(0) = 0$, $\lim_{r \rightarrow 0} \omega(r) = 0$ and ω is non-decreasing on $[0, \varepsilon]$.

Lemma 5.6. *Let ω be a modulus on $[0, \varepsilon]$. Let $\delta > 0$. Then there exists a modulus ω_0 on $[0, \varepsilon]$ such that $\omega_0 \in C^2(0, \varepsilon)$, $\omega_0 > \omega$ on $(0, \varepsilon]$ and $\omega_0(r) = \omega(\varepsilon) + \delta$ for all $r \in [\varepsilon/2, \varepsilon]$.*

Proof. We set $\omega_1(0) := 0$, $\omega_1(\varepsilon) = \omega_1(\varepsilon/2) := \omega(\varepsilon) + \delta$ and $\omega_1(\varepsilon/2^{j+1}) := \omega(\varepsilon/2^j)$ for $j \in \mathbf{N}$. On each interval $[\varepsilon/2^j, \varepsilon/2^{j-1}]$ we interpolate ω_1 by a linear function. Then ω_1 is a modulus such that $\omega_1 \geq \omega$ on $[0, \varepsilon]$. We next define $\omega_2(r) := \min\{2\omega_1(r), \omega(\varepsilon) + \delta\}$, which is again a piecewise linear modulus satisfying $\omega_2 > \omega$ on $(0, \varepsilon]$ and $\omega_0(r) = \omega(\varepsilon) + \delta$ for all $r \in [\varepsilon/2, \varepsilon]$. Finally, mollifying ω_2 near each corner of the graph, we obtain the desired C^2 -function ω_0 . □

A similar technique to make a smooth modulus can be found in [8, Lemma 2.1.9]. Using the above functions, let us construct a barrier function which will be used in the proof of our Harnack inequality. Let $0 < \varepsilon < \rho < R$ and ω be a modulus on $[0, \varepsilon]$. We also give positive constants $\beta, \delta > 0$. Set $K_\varepsilon := -(M_1 - M_2\varepsilon^{-\alpha}) > 0$, which will appear as the Harnack constant C_H in (5.9). We define

$$\phi(x) := \begin{cases} \beta\psi(x) & \text{if } |x| \geq \varepsilon, \\ \omega_0(|x|) - \beta K_\varepsilon - 2\delta - \omega(\varepsilon) & \text{if } |x| \leq \varepsilon/2. \end{cases}$$

On $\{\varepsilon/2 \leq |x| \leq \varepsilon\}$ we extend ϕ smoothly so that $\phi \in C^2(\mathbf{R}^n \setminus \{0\})$ and $-\beta K_\varepsilon - \delta \leq \phi(x) \leq -\beta K_\varepsilon$ if $\varepsilon/2 \leq |x| \leq \varepsilon$; see Figure 1. Then, by Lemma 5.5 and 5.6, the function ϕ possesses

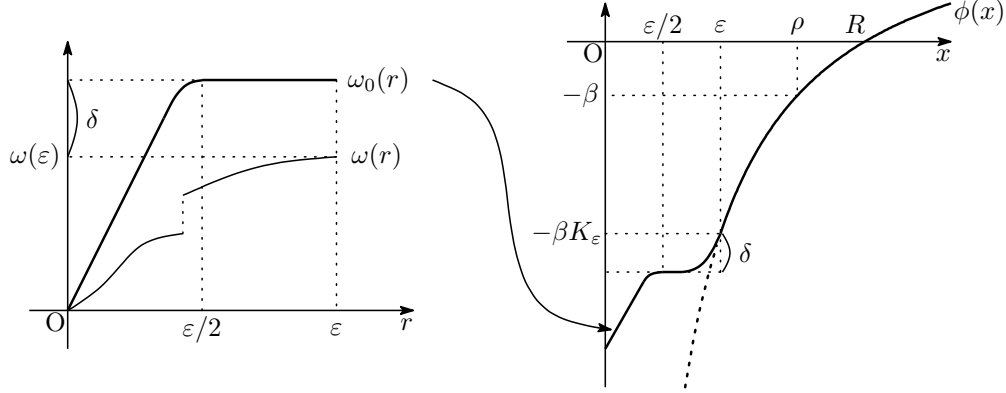


Figure 1: The graphs of ω_0 and ϕ .

the following properties:

$$\begin{cases} \mathcal{P}^-(D^2\phi) \geq 0 & \text{in } \mathbf{R}^n \setminus \overline{B_\varepsilon}, \\ \phi \geq 0 & \text{in } \mathbf{R}^n \setminus B_R, \\ \phi \leq -\beta & \text{in } B_\rho \end{cases} \quad (5.6)$$

and

$$\phi(x) - \phi(0) > \omega(|x|) \quad \text{if } 0 < |x| \leq \varepsilon. \quad (5.7)$$

Since ϕ is not necessarily a C^2 -function on the whole space, we next mollify it near the origin. For $j \in \mathbf{N}$ we mollify ϕ in $B_{\varepsilon/2^j}$ so that $\phi_j \in C^2(\mathbf{R}^n)$, $\phi_j \leq -\beta$ in B_ρ and ϕ_j converges to ϕ uniformly in $\mathbf{R}^n$ as $j \rightarrow \infty$. Then each ϕ_j satisfies the three properties in (5.6). We next define $\xi_j(x) := |\mathcal{P}^-(D^2\phi_j(x))|$. It then follows that

$$\mathcal{P}^-(D^2\phi_j) \geq -\xi_j(x) \quad \text{in } \mathbf{R}^n, \quad \text{supp}(\xi_j) \subset \overline{B_\varepsilon}.$$

Here $\text{supp}(\xi_j) := \overline{\{x \in \mathbf{R}^n \mid \xi_j(x) \neq 0\}}$.

We now derive the Harnack inequality for viscosity supersolutions of

$$\mathcal{P}^+(D^2u) = -f^-(x). \quad (5.8)$$

A viscosity supersolution of (5.1) is always a supersolution of (5.8).

Theorem 5.7 (Harnack inequality). *Let $r > 0$ and $0 < \varepsilon < 2r$. Then there exists a constant $C_H = C_H(r, \varepsilon, n, \Lambda/\lambda) > 0$ such that, for every non-negative viscosity supersolution $u \in C(\overline{B_{4r}})$ of (5.8) in B_{4r} , the estimate*

$$\min_{\overline{B_\varepsilon}(z)} u \leq C_H \left\{ \min_{\overline{B_r}} u + C_A \text{diam}(\Omega) \|f^-\|_{L^n(B_{4r})} \right\} \quad (5.9)$$

holds for all $z \in \overline{B_r}$, where C_A is the constant in Theorem 5.4.

Proof. Case: $f^- \equiv 0$. 1. Fix any $z \in \overline{B_r}$. For $t \in [0, \varepsilon]$ we define $\omega(t) := u(z) - \min_{\overline{B_t}(z)} u$. It is easily seen that ω is a modulus on $[0, \varepsilon]$. Choose x_m as a minimum point of u over

$\overline{B_r}$, i.e., $u(x_m) = \min_{\overline{B_r}} u$, and let $\beta > u(x_m)$ (≥ 0). We take ϕ, ϕ_j and ξ_j as the functions given after Lemma 5.6 with $\rho = 2r$ and $R = 3r$, where ω and β are chosen as above. Define $\tilde{\phi}(x) := \phi(x - z)$, $\tilde{\phi}_j(x) := \phi_j(x - z)$ and $\tilde{\xi}(x) := \xi(x - z)$. We furthermore set $B' := B_{2r}(z)$ and $B := B_{3r}(z)$, so that we have $B_r \subset B' \subset B \subset B_{4r}$.

By (5.7) we see that $u + \tilde{\phi}$ attains its strict minimum at z over $\overline{B_\varepsilon(z)}$. Indeed, if $0 < |x - z| \leq \varepsilon$, we compute

$$u(x) + \tilde{\phi}(x) > \{u(z) - \omega(|x - z|)\} + \{\tilde{\phi}(z) + \omega(|x - z|)\} = u(z) + \tilde{\phi}(z).$$

We let z_j be a minimum point of $u + \tilde{\phi}_j$ over $\overline{B_\varepsilon(z)}$. Then, since $\tilde{\phi}_j$ uniformly converges to $\tilde{\phi}$, it follows that $z_j \rightarrow z$ as $j \rightarrow \infty$.

2. We show that $u + \tilde{\phi}_j$ is a viscosity supersolution of $\mathcal{P}^+ = -\tilde{\xi}_j$ in B . Assume that $u + \tilde{\phi}_j - \psi$ attains a local minimum at $x \in B$ for $\psi \in C^2(B)$. Since $u + \tilde{\phi}_j - \psi = u - (\psi - \tilde{\phi}_j)$ and u is a viscosity supersolution of (5.8), we observe

$$\begin{aligned} 0 &\leq \mathcal{P}^+(D^2\psi(x) - D^2\tilde{\phi}_j(x)) \leq \mathcal{P}^+(D^2\psi(x)) - \mathcal{P}^-(D^2\tilde{\phi}_j(x)) \\ &\leq \mathcal{P}^+(D^2\psi(x)) + \tilde{\xi}_j(x), \end{aligned}$$

which implies the assertion. Therefore the ABP maximum principle (5.4) implies

$$\min_{\overline{B}}(u + \tilde{\phi}_j) \geq \min_{\partial B} \{-(u + \tilde{\phi}_j)^-\} - C_A \text{diam}(B) \|\tilde{\xi}_j\|_{L^n(\Gamma_B[(u + \tilde{\phi}_j)^-])}.$$

Similarly to the discrete case, we have $\min_{\partial B} \{-(u + \tilde{\phi}_j)^-\} = 0$ and $\min_{\overline{B}}(u + \tilde{\phi}_j) < 0$ by the properties of $\tilde{\phi}_j$, and hence $\|\tilde{\xi}_j\|_{L^n(\Gamma_B[(u + \tilde{\phi}_j)^-])} > 0$. Since $\text{supp}(\tilde{\xi}_j) \subset \overline{B_\varepsilon(z)}$, we see that the set $\overline{B_\varepsilon(z)} \cap \Gamma_B[(u + \tilde{\phi}_j)^-]$ is not empty.

3. Choose an arbitrary $y \in \overline{B_\varepsilon(z)} \cap \Gamma_B[(u + \tilde{\phi}_j)^-]$. Then we see $(u + \tilde{\phi}_j)(y) < 0$ by a similar argument to the discrete case. Since $u + \tilde{\phi}_j$ attains its minimum at z_j over $\overline{B_\varepsilon(z)}$, it follows that

$$u(z_j) + \tilde{\phi}_j(z_j) \leq u(y) + \tilde{\phi}_j(y) < 0.$$

Letting $j \rightarrow \infty$, we have

$$u(z) \leq -\tilde{\phi}(z) = -\phi(0) = \beta K_\varepsilon + 2\delta + \omega(\varepsilon).$$

By the definition of ω , this gives

$$\min_{\overline{B_\varepsilon(z)}} u \leq \beta K_\varepsilon + 2\delta.$$

Finally, sending $\beta \rightarrow u(x_m)$ and $\delta \rightarrow 0$ yield $\min_{\overline{B_\varepsilon(z)}} u \leq C_H u(x_m)$ with $C_H = K_\varepsilon$.

Case: $f^- \not\equiv 0$. 1. Let $\{f_j\}_{j=1}^\infty \subset C^\infty(\mathbf{R}^n)$ be a sequence of smooth functions such that $f_j \geq f^-$ in $\overline{B_{4r}}$ for all $j \in \mathbf{N}$ and that f_j converges to f^- uniformly on $\overline{B_{4r}}$ as $j \rightarrow \infty$. We consider the Dirichlet problem

$$\begin{cases} \mathcal{P}^-(D^2v_j) = f_j & \text{in } B_{4r}, \\ v_j = 0 & \text{on } \partial B_{4r} \end{cases} \quad (5.10)$$

and denote by $v_j \in C^2(B_{4r}) \cap C(\overline{B_{4r}})$ the solution of (5.10). The existence of smooth solutions is due to the classical results by Evans-Krylov for convex/concave (or Bellman

type) equations. See [6, 7, 12] or [11, Section 7.3]. The ABP maximum principles, (5.3) and (5.4), yield

$$0 \leq v_j \leq C_A \text{diam}(\Omega) \|f_j\|_{L^n(B_{4r})} \quad \text{on } \overline{B_{4r}}. \quad (5.11)$$

2. Now, it is easy to see that $u + v_j$ is a viscosity solution of $\mathcal{P}^+ = 0$ in B_{4r} . Since $u + v_j$ is non-negative on $\overline{B_{4r}}$ by (5.11), the Harnack inequality (5.9) with $f^- \equiv 0$ implies

$$\frac{\min}{\overline{B_\varepsilon(z)}}(u + v_j) \leq C_H \frac{\min}{\overline{B_r}}(u + v_j).$$

Applying the first and the second inequality in (5.11) to the left- and the right-hand side of the above estimate respectively, we obtain

$$\frac{\min}{\overline{B_\varepsilon(z)}} u \leq C_H \left\{ \min_{\overline{B_r}} u + C_A \text{diam}(\Omega) \|f_j\|_{L^n(B_{4r})} \right\}.$$

Sending $j \rightarrow \infty$ gives (5.9). □

Remark 5.8. The estimate (5.9) we established can be written as

$$u(z) \leq C_H \left\{ \min_{\overline{B_r}} u + C_A \text{diam}(\Omega) \|f^-\|_{L^n(B_{4r})} \right\} + \omega(\varepsilon),$$

which gives a pointwise estimate for u , but the right-hand side involves a modulus of continuity from below of u around z .

Remark 5.9. The functions in Example 5.3 shows that the Harnack constant C_H in (5.9) must go to infinity when $\varepsilon \rightarrow 0$. Indeed, the Harnack constant which we selected in the proof is $C_H = K_\varepsilon = -(M_1 - M_2 \varepsilon^{-\alpha})$ and this tends to infinity as $\varepsilon \rightarrow 0$.

As a byproduct of this observation, we see non-existence of a radially symmetric function $\psi \in C(\mathbf{R}^n) \cap C^2(\mathbf{R}^n \setminus \{0\})$ satisfying the three conditions in (5.5). (Note that the function ψ in Lemma 5.5 does not belong to $C(\mathbf{R}^n)$.) If there were such a ψ , by a similar argument to the proof of Theorem 5.7 we would have the Harnack inequality (5.9) with C_H which is less than $-\psi(0)$, a contradiction.

Remark 5.10. The result in Theorem 5.7 still holds for L^p -viscosity solutions, although we do not give the details in this paper. In the theory of L^p -viscosity solutions, f is just assumed to be in $L^p(\Omega)$ and solutions are defined by test functions belonging to $W_{\text{loc}}^{2,p}$. In this case, we do not need to approximate f^- by smooth functions f_j in the proof of the Harnack inequality because the Dirichlet problem (5.10) with f^- instead of f_j admits a solution in $W_{\text{loc}}^{2,p}$. Also, it is not difficult to extend the result to more general equations of the form

$$\mathcal{P}^+(D^2u) + \mu |Du| = -f^-(x)$$

with $\mu \geq 0$. See [4] and [11, Section 6 and 7] for the theory of L^p -viscosity solutions and the above generalized equation.

A A well-posedness of uniformly elliptic equations

We prove that the Dirichlet problem

$$F(\delta^2 u(x)) = f(x) \quad \text{in } \Omega, \quad (A.1)$$

$$u(x) = g(x) \quad \text{on } \partial\Omega \quad (A.2)$$

has a unique discrete solution. Here $\Omega \subset h\mathbf{Z}^n$ is a bounded set, $F : \mathbf{R}^n \rightarrow \mathbf{R}$ is uniformly elliptic, $F(0) = 0$, $f : \Omega \rightarrow \mathbf{R}$ and $g : \partial\Omega \rightarrow \mathbf{R}$ is a given boundary datum. The uniqueness easily follows from the ABP maximum principle. The existence of solutions to elliptic difference equations is more or less known even when the equation is degenerate; for example, the fixed point theorem is one of powerful tools to show the existence. However, we present it here to make the paper self-contained and to give the proof based on *Perron's method*, which cannot be found much in discrete problems.

For $\vec{X}, \vec{Y} \in \mathbf{R}^n$ given as $\vec{X} = (X_1, \dots, X_n)$ and $\vec{Y} = (Y_1, \dots, Y_n)$, we write $\vec{X} \leq \vec{Y}$ if $X_i \leq Y_i$ for all $i \in \{1, \dots, n\}$. By the uniform ellipticity of F , we have $F(\vec{X}) \geq F(\vec{Y})$ if $\vec{X} \leq \vec{Y}$. This is a degenerate ellipticity ([5, (0.3)]).

From the ABP maximum principle (Theorem 2.3) we immediately deduce a comparison principle for a discrete sub- and supersolution of (A.1). This implies a uniqueness of solutions.

Corollary A.1 (Comparison principle). *Let u and v be, respectively, a discrete subsolution and supersolution of (A.1). If $u \leq v$ on $\partial\Omega$, then $u \leq v$ in Ω .*

Proof. Since F is uniformly elliptic, we observe

$$\mathcal{P}^-(\delta^2 u(x) - \delta^2 v(x)) \leq F(\delta^2 u(x)) - F(\delta^2 v(x)) \leq f(x) - f(x) = 0$$

for all $x \in \Omega$. Therefore $u - v$ is a discrete subsolution of the Pucci equation $\mathcal{P}^- = 0$ in Ω . We now apply the ABP maximum principle to obtain $\max_{\bar{\Omega}}(u - v) \leq \max_{\partial\Omega}(u - v) \leq 0$. $\square$

We turn to an existence problem. To construct discrete solutions, we employ the idea of Perron's method for viscosity solutions ([5, Section 4]).

Proposition A.2 (Perron's method). *Let v and V be, respectively, a discrete sub- and supersolution of (A.1) such that $v \leq V$ on $\bar{\Omega}$. Let*

$$\mathcal{S} := \left\{ w : \bar{\Omega} \rightarrow \mathbf{R} \left| \begin{array}{l} w \text{ is a discrete subsolution of (A.1)} \\ \text{such that } v \leq w \leq V \text{ on } \bar{\Omega} \end{array} \right. \right\}.$$

Then $u(x) := \sup_{w \in \mathcal{S}} w(x)$ is a discrete solution of (A.1).

Proof. 1. We first prove that u is a discrete subsolution. Fix $x \in \Omega$ and $\varepsilon > 0$. By the definition of u there exists some $w_\varepsilon \in \mathcal{S}$ such that $u(x) - \varepsilon \leq w_\varepsilon(x) \leq u(x)$. We then observe

$$\begin{aligned} \delta_i^2 u(x) &= \frac{u(x + h_i e_i) + u(x - h_i e_i) - 2u(x)}{h_i^2} \\ &\geq \frac{w_\varepsilon(x + h_i e_i) + w_\varepsilon(x - h_i e_i) - 2(w_\varepsilon(x) + \varepsilon)}{h_i^2} = \delta_i^2 w_\varepsilon(x) - \frac{2\varepsilon}{h_i^2} \end{aligned}$$

for each $i \in \{1, \dots, n\}$. Thus

$$\vec{\delta}^2 u(x) \geq \vec{\delta}^2 w_\varepsilon(x) - \frac{2\varepsilon}{h_{\min}^2} (1, \dots, 1).$$

From the uniform ellipticity of F it follows that

$$\begin{aligned}
F(\vec{\delta}^2 u(x)) &\leq F\left(\vec{\delta}^2 w_\varepsilon(x) - \frac{2\varepsilon}{h_{\min}^2}(1, \dots, 1)\right) \\
&\leq F(\vec{\delta}^2 w_\varepsilon(x)) - \mathcal{P}^-\left(\frac{2\varepsilon}{h_{\min}^2}(1, \dots, 1)\right) \\
&= F(\vec{\delta}^2 w_\varepsilon(x)) + \Lambda \frac{2\varepsilon n}{h_{\min}^2}.
\end{aligned} \tag{A.3}$$

We now have $F(\vec{\delta}^2 w_\varepsilon(x)) \leq f(x)$ since $w_\varepsilon \in \mathcal{S}$. Applying this to (A.3) and then letting $\varepsilon \rightarrow 0$, we obtain $F(\vec{\delta}^2 u(x)) \leq f(x)$. This implies that u is a discrete subsolution.

2. We next show that u is a discrete supersolution. Suppose that this were false. Then we could find some $y \in \Omega$ such that

$$F(\vec{\delta}^2 u(y)) < f(y). \tag{A.4}$$

For such y and $\delta > 0$ we define

$$U(x) := \begin{cases} u(y) + \delta & \text{if } x = y, \\ u(x) & \text{if } x \neq y. \end{cases}$$

We claim that $U \in \mathcal{S}$ for a sufficiently small $\delta > 0$. Showing this claim yields a contradiction since U is strictly larger than u at y .

We first prove $u(y) < V(y)$. Suppose $u(y) = V(y)$. Then, noting that $u(x) \leq V(x)$ for $x \neq y$, we would have $\vec{\delta}^2 u(y) \leq \vec{\delta}^2 V(y)$. Since V is a supersolution, it would follow that $F(\vec{\delta}^2 u(y)) \geq F(\vec{\delta}^2 V(y)) \geq f(y)$, a contradiction to (A.4). Thus $v \leq U \leq V$ on $\bar{\Omega}$ if we take $\delta \leq V(y) - u(y)$.

Let us show that U is a subsolution. Let $x \in \Omega$. It is easily seen that $\vec{\delta}^2 U(x) = \vec{\delta}^2 u(x)$ if $x \notin \{y\}$ and that $\vec{\delta}^2 U(x) \geq \vec{\delta}^2 u(x)$ if $x \in \{y\}$. Therefore the ellipticity of F implies that $F(\vec{\delta}^2 U(x)) \leq F(\vec{\delta}^2 u(x)) \leq f(x)$ for $x \neq y$. We next consider the case $x = y$. Then

$$\delta_i^2 U(y) = \frac{u(y + h_i e_i) + u(y - h_i e_i) - 2(u(y) + \delta)}{h_i^2} = \delta_i^2 u(y) - \frac{2\delta}{h_i^2},$$

and so the same calculation as in Step 1 yields

$$F(\vec{\delta}^2 U(y)) \leq F(\vec{\delta}^2 u(y)) + \Lambda \frac{2\delta n}{h_{\min}^2} = f(y) + \Lambda \frac{2\delta n}{h_{\min}^2} - \{f(y) - F(\vec{\delta}^2 u(y))\}.$$

In view of (A.4), it follows that $F(\vec{\delta}^2 U(y)) \leq f(y)$ if $\delta \leq h_{\min}^2 \{f(y) - F(\vec{\delta}^2 u(y))\} / (2\Lambda n)$. Summarizing the above argument, we conclude that $U \in \mathcal{S}$, and hence u is a discrete supersolution. $\square$

The remaining thing is to construct v and V in Proposition A.2 which attain a given boundary datum on $\partial\Omega$. For this purpose, we prepare quadratic functions on lattices. We will use these functions to make such v and V .

Example A.3. Let $A = (A_1, \dots, A_n) \in \mathbf{R}^n$. We define a *quadratic function* $q = q_A : h\mathbf{Z}^n \rightarrow \mathbf{R}$ as $q(x) := \sum_{j=1}^n A_j x_j^2$ for $x = (x_1, \dots, x_n) \in h\mathbf{Z}^n$. Then $\delta_i^2 q$ is a constant for each $i \in \{1, \dots, n\}$. Indeed, we observe

$$\begin{aligned} \delta_i^2 q(x) &= \frac{q(x + h_i e_i) + q(x - h_i e_i) - 2q(x)}{h_i^2} \\ &= \frac{A_i(x_i + h_i)^2 + A_i(x_i - h_i)^2 - 2A_i x_i^2}{h_i^2} = 2A_i \end{aligned}$$

for all $x \in h\mathbf{Z}^n$. In particular, if we take $A_i = -c/(2\lambda n)$ with $c \geq 0$, then

$$\mathcal{P}^-(\bar{\delta}^2 q(x)) = -\lambda \cdot \frac{-c}{\lambda n} \cdot n = c,$$

i.e., q is a discrete solution of the above Pucci equation in $h\mathbf{Z}^n$.

Theorem A.4 (Unique solvability). *The Dirichlet problem (A.1) and (A.2) admits a unique discrete solution.*

Proof. The uniqueness is a consequence of the comparison principle, Corollary A.1. To show the existence we construct v and V in the statement of Proposition A.2 such that $v = V = g$ on $\partial\Omega$; then Proposition A.2 ensures that $u := \sup_{w \in \mathcal{S}} w$ is a discrete solution of (A.1) and (A.2). To construct such v and V we use quadratic functions in Example A.3. Let q_A be the quadratic function in Example A.3 with $A_i = -(\max_{\Omega} |f|)/(2\lambda n)$, so that

$$\mathcal{P}^-(\bar{\delta}^2 q_A(x)) = \max_{\Omega} |f| \quad \text{in } \Omega. \quad (\text{A.5})$$

Choose $k \geq 0$ such that $q_A + k \geq \max_{\partial\Omega} g$ on $\bar{\Omega}$, and define

$$V(x) := \begin{cases} q_A(x) + k & \text{if } x \in \Omega, \\ g(x) & \text{if } x \in \partial\Omega. \end{cases}$$

Then V is a discrete supersolution of (A.1). Indeed, since $V \leq q_A + k$ on $\partial\Omega$, we have $\bar{\delta}^2 V(x) \leq \bar{\delta}^2(q_A + k)(x) = \bar{\delta}^2 q_A(x)$ for $x \in \Omega$. Therefore it follows from ellipticity that $F(\bar{\delta}^2 V(x)) \geq F(\bar{\delta}^2 q_A(x)) \geq \mathcal{P}^-(\bar{\delta}^2 q_A(x))$. By virtue of (A.5) we conclude that V is a discrete supersolution of (A.1).

Similarly, using a suitable quadratic function, we are able to construct a discrete subsolution v which satisfies $v = g$ on $\partial\Omega$ and $v \leq \min_{\partial\Omega} g$ in Ω . The proof is now complete since $v \leq \min_{\partial\Omega} g \leq \max_{\partial\Omega} g \leq V$ in Ω . $\square$

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References

- [1] X. Cabré, On the Alexandroff-Bakel'man-Pucci estimate and the reversed Hölder inequality for solutions of elliptic and parabolic equations, *Comm. Pure Appl. Math.* 48 (1995), no. 5, 539–570.

- [2] L. A. Caffarelli, Interior a priori estimates for solutions of fully nonlinear equations, *Ann. of Math. (2)* 130 (1989), no. 1, 189–213.
- [3] L. A. Caffarelli, X. Cabré, Fully nonlinear elliptic equations, American Mathematical Society Colloquium Publications, vol. 43, American Mathematical Society, Providence, RI, 1995.
- [4] L. A. Caffarelli, M. G. Crandall, M. Kocan, A. Święch, On viscosity solutions of fully nonlinear equations with measurable ingredients, *Comm. Pure Appl. Math.* 49 (1996), no. 4, 365–397.
- [5] M. G. Crandall, H. Ishii, P. L. Lions, User’s guide to viscosity solutions of second order partial differential equations, *Bull. Amer. Math. Soc. (N.S.)* 27 (1992), no. 1, 1–67.
- [6] L. C. Evans, Classical solutions of fully nonlinear, convex, second-order elliptic equations, *Comm. Pure Appl. Math.* 35 (1982), no. 3, 333–363.
- [7] L. C. Evans, Classical solutions of the Hamilton-Jacobi-Bellman equation for uniformly elliptic operators, *Trans. Amer. Math. Soc.* 275 (1983), no. 1, 245–255.
- [8] Y. Giga, Surface evolution equations: A level set approach, *Monographs in Mathematics*, 99, Birkhauser Verlag, Basel, 2006, xii+264 pp.
- [9] D. Gilbarg, N. S. Trudinger, Elliptic partial differential equations of second order, Reprint of the 1998 edition, *Classics in Mathematics*, Springer-Verlag, Berlin, 2001.
- [10] N. Hamamuki, A discrete isoperimetric inequality on lattices, *Discrete Comput. Geom.* 52 (2014), no. 2, 221–239.
- [11] S. Koike, A beginner’s guide to the theory of viscosity solutions, *MSJ Memoirs*, 13, Mathematical Society of Japan, Tokyo, 2004, viii+123 pp.
- [12] N. V. Krylov, Boundedly nonhomogeneous elliptic and parabolic equations, *Izv. Akad. Nauk SSSR Ser. Mat.* 46 (1982), 487–523 (Russian); English translation in *Math. USSR Izv.* 20 (1983), 459–492.
- [13] H.-J. Kuo, N. S. Trudinger, Linear elliptic difference inequalities with random coefficients, *Math. Comp.* 55 (1990), no. 191, 37–53.
- [14] H.-J. Kuo, N. S. Trudinger, Local estimates for parabolic difference operators, *J. Differential Equations* 122 (1995), no. 2, 398–413.
- [15] H.-J. Kuo, N. S. Trudinger, Positive difference operators on general meshes, *Duke Math. J.* 83 (1996), no. 2, 415–433.
- [16] H.-J. Kuo, N. S. Trudinger, Evolving monotone difference operators on general space-time meshes, *Duke Math. J.* 91 (1998), no. 3, 587–607.