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## **The Wiener test for degenerate elliptic equations**

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# THE WIENER TEST FOR DEGENERATE ELLIPTIC EQUATIONS

by E. FABES(\*), D. JERISON(\*), C. KENIG(\*)

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## Introduction.

This is the second in a series of three articles examining solutions to degenerate elliptic equations in divergence form

$$Lu = - \partial_j (a_{ij}(x) \partial_i u(x)) = 0 (**).$$

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(\*\*) Here and elsewhere  $\partial_j$  denotes  $\partial/\partial x_j$ ,  $j = 1, \dots, n$  and repeated indices are summed.

In the first article, two of the present authors and R. Serapioni established a Harnack inequality, Hölder continuity of solutions and certain other basic estimates that we will use here. Our main purpose in this article is to prove a Wiener test for regular points in the Dirichlet problem for  $L$ . We will suppose that the coefficients  $a_{ij}(x)$  are real-valued, measurable, symmetric, and satisfy

$$c^{-1} |\xi|^2 w(x) \leq a_{ij}(x) \xi_i \xi_j \leq C |\xi|^2 w(x)$$

for all  $x$  and  $\xi$  in  $\mathbf{R}^n$  and some constant  $c \geq 1$ . The weight  $w(x)$  will be a non-negative, measurable function satisfying either Muckenhoupt's condition  $(A_2)$  or the condition (QC). These conditions are defined as follows:

$$(A_2) \quad \sup_B \left( \frac{1}{|B|} \int_B w(x) dx \right) \left( \frac{1}{|B|} \int_B w(x)^{-1} dx \right) \leq C$$

where the supremum is taken over all Euclidean balls  $B$  and  $|B| = \int_B dx$ .

$$(QC) \quad w(x) = |f'(x)|^{1-2/n},$$

where  $f$  is a global quasiconformal mapping  $f: \mathbf{R}^n \rightarrow \mathbf{R}^n$  and  $|f'(x)|$  denotes the absolute value of the Jacobian determinant of  $f$ . For example, all functions  $w(x)$  of the form  $|x|^\alpha$ ,  $\alpha > -n$  satisfy either  $(A_2)$  or (QC). For more details on the nature of these conditions see [2, 5], and [6].

Denote  $w(E) = \int_E w(x) dx$  and  $B(x, r) = \{y \in \mathbf{R}^n : |x - y| \leq r\}$ . Fix a large ball  $\Sigma$  of radius  $R$ . The first main result is an approximate formula for the Green function in  $\Sigma$ ,

$$g(x, y) \approx \int_{|x-y|}^R \frac{s^2}{w(B(x, s))} \frac{ds}{s}, \quad \text{for } x, y \in \frac{1}{4} \Sigma.$$

(For a precise statement, see Theorem 3.3.) This formula shows that locally the Green function for  $L$  exhibits essentially the same simple radial behavior as the classical Green function. (The third article is devoted in part to estimates of the Green function near the boundary.)

The formula reveals an amusing difference from classical Green functions. The limit on  $y \rightarrow x$  of  $g(x, y)$  need not be infinite. The following properties are equivalent:

- (i)  $\limsup_{y \rightarrow x} g(x, y) < \infty$ . (We will see that the limit exists.)

(ii) the punctured ball  $\Sigma \setminus \{x\}$  is regular for the Dirichlet problem.

(iii) The capacity (1.19) of  $\{x\}$  is positive.

$$(iv) \int_0^R \frac{s^2}{w(B(x, s))} \frac{ds}{s} < \infty.$$

At first glance property (ii) seems to contradict the maximum principle, since we can assign boundary values 1 at  $x$  and 0 on  $\partial\Sigma$ . However, as property (iii) indicates, the set  $\{x\}$  is not removable in any appropriate sense, so the maximum principle remains intact. The extra phenomenon of (i)-(iv) is reflected in the Wiener test (Theorem 5.1(a)). A corollary of the Wiener test is that regular points depend only on  $w(x)$  and not on the particular operator  $L$ . Another by-product of the argument is that the capacity we are considering has the usual equivalent descriptions (Theorem 4.7, 4.10). These descriptions coupled with the formula for the Green function above give a convenient way to calculate capacities and hence the Wiener criterion 5.1 (b).

If  $w(x)$  satisfies (QC), then a change of variable by the quasi-conformal map  $f$  transforms the problem into one for  $w \equiv 1$ , that is a uniformly elliptic equation with bounded, measurable coefficients such as was treated by Littman, Stampacchia, and Weinberger [8]. In that case our results follow from theirs. The point is to prove the results directly so that they apply to weights that satisfy conditions (like  $A_2$ ) that are more easily verified. In fact, our proof will apply to a wider class of weights satisfying six properties listed in [5]. The single most important of these is

$$(*) \int_{\Omega} |\varphi(x)|^2 \varphi(x) dx \leq C \int_{\Omega} |\nabla \varphi(x)|^2 w(x) dx, \text{ all } \varphi \in C_0^\infty(\Omega),$$

where  $C$  depends only on  $w$  and  $\Omega$ .

We will follow the outline of the paper of Littman et al. [8]. The main differences are in Section 3.

## 1. Preliminaries.

Recall that  $w(x)$  is a non-negative function satisfying either  $(A_2)$  or  $(QC)$ . Two well-known facts are

(1.1)  $w(x) dx$  and  $dx$  are mutually absolutely continuous

(1.2)  $w(B(x, 2r)) \leq Cw(B(x, r))$ . (*Doubling condition.*)

$\Omega$  will always denote a bounded, open connected subset of  $\mathbf{R}^n$ .

*Function Spaces.* Denote by  $L^p(\Omega, w)$  the Lebesgue class with norm  $\|f\|_p^p = \int_{\Omega} |f(x)|^p w(x) dx$ .  $\text{Lip}(\bar{\Omega})$  is the restriction to  $\bar{\Omega}$  of functions  $\Psi$  on  $\mathbf{R}^n$  satisfying the Lipschitz condition  $|\Psi(x) - \Psi(y)| \leq M|x - y|$  for some  $M$ .  $\text{Lip}_0(\Omega)$  denotes the class of functions of  $\text{Lip}(\bar{\Omega})$  with compact support in  $\Omega$ . (All functions are real valued.) Consider the inclusion

$$\text{Lip}(\bar{\Omega}) \longrightarrow [L^p(\Omega, w)]^{n+1}$$

given by  $\varphi \longrightarrow (\varphi, \nabla \varphi) = (\varphi, \partial_1 \varphi, \dots, \partial_n \varphi)$ .  $H^{1,p}(\Omega)$  denotes the closure of the image of  $\text{Lip}(\bar{\Omega})$  in  $[L^p(\Omega, w)]^{n+1}$ . Similarly,  $H_0^{1,p}(\Omega)$  denotes the closure of the image of  $\text{Lip}_0(\Omega)$  in  $[L^p(\Omega, w)]^{n+1}$ . When  $p \geq 2$ , an  $(n+1)$ -tuple  $\underline{u} = (u_0, u_1, \dots, u_n)$  in  $H^{1,p}(\Omega)$  is uniquely determined by its first component  $u_0$  (see [5] 2.1). If  $w^{-1} \in L^1(dx)$  and  $\underline{u} \in H^{1,2}(\Omega)$ , then  $u_0$  is a distribution and  $(u_1, \dots, u_n) = \nabla u_0$  in the sense of distributions, but this is not true in general. But since  $(u_1, \dots, u_n)$  are determined by  $u_0$ , we can use the symbol  $\nabla u_0$  for  $(u_1, \dots, u_n)$ . We will also shift notation and refer to  $u_0$  as an element of  $H^{1,2}(\Omega)$ . The *Dirichlet form*  $D : H^{1,2}(\Omega) \times H^{1,2}(\Omega) \longrightarrow \mathbf{R}$  is defined by  $D(u, v) = \int_{\Omega} a_{ij}(x) u_i(x) v_j(x) dx$ , where  $(u_1, \dots, u_n) = \nabla u$  and  $(v_1, \dots, v_n) = \nabla v$ . (We will use this notation consistently).

Let  $\frac{1}{p} + \frac{1}{p'} = 1$ . The dual space of  $H_0^{1,p'}(\Omega)$  for  $p' < \infty$  is the space

$$H^{-1,p}(\Omega) = \{f_0 - \text{div } \vec{f} : \vec{f} = (f_1, \dots, f_n), \\ f_j/w \in L^p(\Omega, w) \quad j = 0, 1, \dots, n\}.$$

To see this, observe first that since  $w \in L^1(\Omega, dx)$ , a function  $f$  satisfying  $f/w \in L^p(\Omega, w)$  belongs to  $L^1(\Omega, dx)$ . Hence, an element  $T = f_0 - \text{div } \vec{f}$  of  $H^{-1,p}(\Omega)$  is a distribution and acts on  $\text{Lip}_0(\Omega)$  by

$$\langle T, \varphi \rangle = \int_{\Omega} f_0(x) dx + \int_{\Omega} \vec{f} \cdot \nabla \varphi dx.$$

This action extends in a unique way to all  $u$  in  $H_0^{1,p'}(\Omega)$

$$\langle T, \underline{u} \rangle = \sum_{j=0}^n \int_{\Omega} f_j(x) u_j(x) dx.$$

DEFINITION 1.3. — Let  $T \in H^{-1,2}(\Omega)$ . We say that  $Lu = T$  in the  $H^{1,2}(\Omega)$  sense if  $u \in H^{1,2}(\Omega)$  and  $D(u, v) = \langle T, v \rangle$  for every  $v \in H_0^{1,2}(\Omega)$ .

THEOREM 1.4. — For every  $T$  in  $H^{-1,2}(\Omega)$  and every  $h$  in  $H^{1,2}(\Omega)$  there is a unique  $u$  in  $H^{1,2}(\Omega)$  satisfying  $Lu = T$  in the  $H^{1,2}(\Omega)$  sense and  $u - h \in H_0^{1,2}(\Omega)$ .

Property (\*) of the introduction says that the inner product  $D(u, v)$  is non-degenerate when restricted to  $H_0^{1,2}(\Omega)$ . Thus the proof of 1.4 consists of the usual Hilbert space argument. (See, for example, [7].)

*Fundamental Inequalities.* We recall now the results from [5] needed. The constants  $C$ ,  $k > 1$ ,  $\alpha > 0$ , and  $p_0 < \infty$  below depend only on the  $(A_2)$  or  $(QC)$  constants of  $w(x)$ . In particular, they are independent of  $r$  and  $p$ . Denote

$$B = B_1 = \{y : |x - y| < r\} \text{ and } B_2 = \{y : |x - y| < 2r\}.$$

The basic inequality (\*) of the introduction is the consequence of a stronger inequality ([5], 2.3, 4))

$$\left( \frac{1}{w(B)} \int_B |\varphi|^{2k} w \right)^{1/2k} \leq Cr \left( \frac{1}{w(B)} \int_B |\nabla \varphi|^2 w \right)^{1/2} \quad \text{for all} \\ (1.5) \quad \varphi \in H_0^{1,2}(B).$$

A slight variant ([5], 2.3, 5)) is

$$\left( \frac{1}{w(B)} \int_B |\varphi - \varphi_B|^{2k} w \right)^{1/2k} \leq Cr \left( \frac{1}{w(B)} \int_B |\nabla \varphi|^2 w \right)^{1/2}, \quad \text{for all} \\ (1.6) \quad \varphi \in H^{1,2}(B), \quad \varphi_B = \frac{1}{w(B)} \int_B \varphi w.$$

Let  $u$  satisfy  $Lu = 0$  in the  $H^{1,2}(B_2)$  sense. Then  $u$  is Hölder continuous and ([5], 2.3.1, 2.3.12)

$$(1.7) \quad \max_{B_1} |u| \leq C \left( \frac{1}{w(B_2)} \int_{B_2} u^2 w \right)^{1/2},$$

$$(1.8) \quad \sup_{|z-x|<\rho} |u(z) - u(x)| \leq C \left( \frac{1}{w(B_2)} \int_{B_2} u^2 w \right)^{1/2} (\rho/r)^\alpha, \text{ for } \rho < r.$$

If  $u$  is also non-negative, then Harnack's inequality says ([5], 2.3.8).

$$(1.9) \quad \max_{y \in B_1} u(y) \leq C \min_{y \in B_1} u(y)$$

(1.10) *Notations.* — Let  $\Sigma = \{y : |y| < R\}$  be fixed from now on. The mapping  $G : H^{-1,2}(\Sigma) \longrightarrow H_0^{1,2}(\Sigma)$  is uniquely defined by the conditions  $u = G(T) \in H_0^{1,2}(\Sigma)$  and  $Lu = T$  in the  $H^{1,2}(\Sigma)$  sense. (See 1.4).

The proof of 1.4 shows that

$$(1.11) \quad G : H^{-1,2}(\Sigma) \longrightarrow H_0^{1,2}(\Sigma) \text{ is an isomorphism.}$$

If  $T \in H^{-1,p}(\Sigma)$  for  $p \geq p_0$ , then  $u = G(T)$  is Hölder continuous in  $\bar{\Sigma}$  and ([5], 2.4.8).

$$(1.12) \quad \sup_{\Sigma} |u| \leq C \|T\|_{H^{-1,p}(\Sigma)}$$

$$(1.13) \quad \sup_{\substack{x,y \in \Sigma \\ |x-y|<\rho}} |u(x) - u(y)| \leq C \rho^\alpha \|T\|_{H^{-1,p}(\Sigma)}.$$

Note that since  $u \in H_0^{1,2}(\Sigma)$ ,  $u$  vanishes on  $\partial\Sigma$ .

Finally, we have the standard lemma ([8], 2.1): If  $Lu = 0$  in the  $H^{1,2}(B_2)$  sense, then

$$(1.14) \quad \int_{B_1} |\nabla u|^2 w \leq C r^{-2} \int_{B_2} |u|^2 w.$$

The boundary variant says ([5], 2.4.2) that if  $Lu = 0$  in the  $H^{1,2}(\Sigma \cap B_2)$  sense and  $u = 0$  on  $\partial\Sigma \cap B_2$  in the  $H^{1,2}(\Sigma \cap B_2)$  sense, then

$$(1.14)' \quad \int_{B_1} |\nabla u|^2 w \leq C r^{-2} \int_{B_2} |u|^2 w.$$

*Truncation.* Let  $\underline{u} = (u, u_1, \dots, u_n)$  be an element of  $H_0^{1,2}(\Omega)$ . For  $\mathcal{E} \geq 0$ , denote  $u^{(\mathcal{E})}(x) = \min \{u(x), \mathcal{E}\}$ . Let  $\varphi_j \in \text{Lip}_0(\Omega)$  be a sequence tending to  $\underline{u}$  in  $H_0^{1,2}(\Omega)$  norm. Then  $\varphi_j^{(\mathcal{E})}$  tends to  $u^{(\mathcal{E})}$  in  $L^2(\Omega, w)$  norm and  $\varphi_j^{(\mathcal{E})}$  tends weakly to some  $\underline{v} = (v, v_1, \dots, v_n)$  in  $H_0^{1,2}(\Omega)$ . But then  $u^{(\mathcal{E})} = v$ , and as remarked above,  $v$  uniquely determines  $\underline{v}$ . Hence  $\underline{v}$  is unique and we have proved

LEMMA 1.15. — If  $\underline{u}$  belongs to  $H_0^{1,2}(\Omega)$  &  $\geq 0$ , then there is a unique  $\underline{u}^{(\epsilon)}$  such that for every sequence  $\varphi_j \in \text{Lip}_0(\Omega)$  with  $\varphi_j \rightarrow \underline{u}$  in  $H_0^{1,2}(\Omega)$ ,  $\varphi_j^{(\epsilon)}$  tends weakly to  $\underline{u}^{(\epsilon)}$  in  $H_0^{1,2}(\Omega)$ . Moreover, the first component of  $\underline{u}^{(\epsilon)}$  is  $u^{(\epsilon)}$ .

Notice also that replacing  $\varphi_j^{(\epsilon)}$  by the arithmetic means of a subsequence, we can suppose (by the theorem of Banach and Saks) that  $\varphi_j^{(\epsilon)} \rightarrow u^{(\epsilon)}$  in  $H_0^{1,2}(\Omega)$  norm.

We will have no further need in the remainder of the section to distinguish between  $\underline{u}$  and its first component. Similar considerations to 1.15 yield

PROPOSITION 1.16. — If  $u$  belongs to  $H_0^{1,2}(\Omega)$ , then  $|u|$ ,  $u^+ = \max(u, 0)$  and  $u^{(\epsilon)}$  &  $\geq 0$  belong to  $H_0^{1,2}(\Omega)$ . Furthermore,  $\|u^{(\epsilon)}\|_{H_0^{1,2}(\Omega)} \leq \|u\|_{H_0^{1,2}(\Omega)}$  and other analogous norm inequalities hold.

DEFINITION 1.17. — Let  $K \subset \bar{\Omega}$ . We say that  $u \geq c$  on  $K$  in the  $H^{1,2}(\Omega)$  sense if there exist  $\varphi_j \in \text{Lip}(\bar{\Omega})$  such that  $\varphi_j(x) \geq c$  for all  $x \in K$  and  $\varphi_j \rightarrow u$  in  $H^{1,2}(\Omega)$ . (There is a similar definition for  $u \leq c$  on  $K$ , and  $u = c$  on  $K$  means  $u \leq c$  and  $u \geq c$  on  $K$ .)

The weak maximum principle of Stampacchia says

THEOREM 1.18. — If  $u \in H^{1,2}(\Omega)$ ,  $u \geq 0$  on  $\partial\Omega$  in the  $H^{1,2}(\Omega)$  sense, and  $D(u, v) \geq 0$  for every  $v$  in  $H_0^{1,2}(\Omega)$  such that  $v \geq 0$  on  $\Omega$  in the  $H^{1,2}(\Omega)$  sense, then  $u(x) \geq 0$  a.e.  $x$  in  $\Omega$ .

The proof is well-known and uses truncation. (See [7] or [8]).

Capacity. — Let  $K$  be a compact subset of  $\Sigma$ . (1.10).

DEFINITION 1.19. — The capacity of  $K$  in  $\Sigma$  is

$$\text{cap}(K) = \inf \{D(u, u) : u \in H_0^{1,2}(\Sigma)$$

and  $u \geq 1$  on  $K$  in the  $H^{1,2}(\Sigma)$  sense\}.

THEOREM 1.20. — There exist a unique  $u$  in  $H_0^{1,2}(\Sigma)$  satisfying  $D(u, u) = \text{cap}(K)$  and  $u \geq 1$  on  $K$  in the  $H^{1,2}(\Sigma)$  sense. Moreover,  $u = 1$  on  $K$  in the  $H^{1,2}(\Sigma)$  sense and  $D(u, v) \geq 0$  for every  $v \in H_0^{1,2}(\Sigma)$  such that  $v \geq 0$  on  $K$  in the  $H^{1,2}(\Sigma)$  sense.



*Proof.* — One can easily check that the infimum is taken over a closed convex set in  $H_0^{1,2}(\Sigma)$ . As we observed in 1.4,  $D(u, v)$  is an inner product for the Hilbert space, so the extremal function  $u$  exists and is unique. A limiting argument using truncation shows that  $u = u^{(1)} = 1$  on  $K$  in the  $H^{1,2}(\Sigma)$  sense. Finally, if  $v \in H_0^{1,2}(\Sigma)$  and  $v \geq 0$  on  $K$  in the  $H_0^{1,2}(\Sigma)$  sense, then

$$D(u + \varepsilon v, u + \varepsilon v) \geq D(u, u)$$

for all  $\varepsilon > 0$ . Hence,  $2\varepsilon D(u, v) + \varepsilon^2 D(v, v) \geq 0$ , which implies  $D(u, v) \geq 0$ .

The function  $u$  is the *capacitary potential* of  $K$  in  $\Sigma$ . It follows from 1.20 that  $Lu = 0$  in the  $H^{1,2}(\Sigma \setminus K)$  sense. Also,  $u = 1$  on  $K$  and  $u = 0$  on  $\partial\Sigma$  in the  $H^{1,2}(\Sigma)$  sense. Therefore, by 1.18,

COROLLARY 1.21. — *A capacitary potential  $u$  satisfies  $0 \leq u(x) \leq 1$  a.e.  $x$  in  $\Sigma$ .*

Next, for any  $\varphi \in C_0^\infty(\Sigma)$  satisfying  $\varphi \geq 0$  on  $K$ , we have  $D(u, \varphi) \geq 0$ . By L. Schwartz' theorem, there exists a positive measure  $\mu$  supported on  $K$  such that  $D(u, \varphi) = \int \varphi d\mu$  for all  $\varphi \in C_0^\infty(\Sigma)$ . It is easy to see that the previous equality also holds for all  $\varphi \in \text{Lip}_0(\Sigma)$ . The measure  $\mu$  is known as the *capacitary distribution* of  $K$  in  $\Sigma$ .

PROPOSITION 1.22. — *The capacitary distribution  $\mu$  defined above is supported on  $\partial K$  and  $\mu(K) = \text{cap}(K)$ .*

*Proof.* — We can arrange using truncation that  $u$  is the limit of  $\Psi_j \in \text{Lip}_0(\Sigma)$  such that  $\Psi_j = 1$  on  $K$ . If  $\varphi \in C_0^\infty(\Sigma)$  is supported in the interior of  $K$ , then  $D(u, \varphi) = \lim_{j \rightarrow \infty} D(\Psi_j, \varphi) = 0$ , because  $\nabla \Psi_j = 0$  in the interior of  $K$ . Hence  $\mu$  is supported on  $\partial K$ . Also,  $\mu(K) = \lim_{j \rightarrow \infty} \int \Psi_j d\mu = \lim_{j \rightarrow \infty} D(\Psi_j, u) = D(u, u) = \text{cap}(K)$ .

DEFINITION 1.23. — *A measure  $\mu$  is said to belong to  $H^{-1,2}(\Sigma)$  if  $|\int \varphi d\mu| \leq C \|\varphi\|_{H_0^{1,2}(\Sigma)}$  for all  $\varphi \in C_0^\infty(\Sigma)$ . It is then clear that there exists a unique  $T \in H^{-1,2}(\Sigma)$  so that  $\int \varphi d\mu = \langle T, \varphi \rangle$  for all  $\varphi \in C_0^\infty(\Sigma)$ . This equality immediately extends to all  $\varphi \in \text{Lip}_0(\Sigma)$ .*

Remark 1.24. — If  $\mu$  is the capacitary distribution of  $K \subset \Sigma$ , then  $\mu \in H^{-1,2}(\Sigma)$ , and if  $u$  is the corresponding capacitary potential,  $Lu = \mu$  in the  $H^{1,2}(\Sigma)$  sense.

Before proceeding with our development, we need to take a closer look at capacity and at continuity properties of elements of  $H_0^{1,2}(\Sigma)$ . The results will be applied in the forthcoming sections. Most of the material that follows is known in one form or another. Unfortunately, we have been unable to find any reference in the literature where these results are stated in the precise form we need them.

For an open set  $\mathcal{O}$  in  $\Sigma$ , and an arbitrary set  $E$  in  $\Sigma$ , denote

$$\text{cap}(\mathcal{O}) = \sup \{ \text{cap}(K) : K \text{ compact, } K \subset \mathcal{O} \}$$

$$\text{cap}^*(E) = \inf \{ \text{cap}(U) : U \text{ open, } U \supset E \}.$$

We will say that an equality holds *quasi-everywhere* (abbreviated *q.e.*) on a set  $S \subset \Sigma$  if it holds on  $S \setminus E$ , where  $\text{cap}^*(E) = 0$ .

**PROPOSITION 1.25.** — *If the non-negative measure  $\mu$  belongs to  $H^{-1,2}(\Sigma)$  then, if  $E$  is a Borel set and  $\text{cap}^*(E) = 0$ ,  $\mu(E) = 0$ .*

*Proof.* — Given  $\mathcal{E} > 0$ , there exists an open set  $U$ ,  $E \subset U$  such that  $\text{cap}(U) \leq \mathcal{E}$ . Let  $K$  be any compact subset of  $U$ . Then,  $\text{cap}(K) \leq \mathcal{E}$ . It is easy to see that  $\text{cap}(K) = \inf \{ D(\varphi, \varphi) : \varphi \geq 1 \text{ on } K, \varphi \in \text{Lip}_0(\Sigma) \}$ . Replacing  $\varphi$  by  $\varphi^+$ , we can choose  $\varphi \geq 0$  in  $\Sigma$ ,  $\varphi \geq 1$  on  $K$ ,  $\varphi \in \text{Lip}_0(\Sigma)$  such that  $D(\varphi, \varphi) \leq 2\mathcal{E}$ . Then,  $\mu(K) \leq \int \varphi d\mu = \langle T, \varphi \rangle \leq CD(\varphi, \varphi) \leq C\mathcal{E}$ . Thus,  $\mu(U) \leq C\mathcal{E}$ , and as  $\mathcal{E} > 0$  is arbitrary,  $\mu(E) = 0$ .

**DEFINITION 1.26.** — *A function  $u$  defined q.e. in  $\Sigma$  is called quasi-continuous, if given  $\mathcal{E} > 0$ , there exists an open set  $U \subset \Sigma$ , with  $\text{cap}(U) < \mathcal{E}$  so that  $u$  is continuous on  $\Sigma \setminus U$ . Our main goal is to prove the following two propositions.*

**PROPOSITION 1.27.** — *Given  $u \in H_0^{1,2}(\Sigma)$ , there exists a sequence  $\{\varphi_j\} \in \text{Lip}_0(\Sigma)$ , and a sequence of open sets  $\mathcal{O}_k$ , such that  $\text{cap}(\mathcal{O}_k) \rightarrow 0$ ,  $\varphi_j \rightarrow u$  in  $H_0^{1,2}(\Sigma)$ , and  $\{\varphi_j\}$  converges uniformly in  $\Sigma \setminus \mathcal{O}_k$  for each  $k$ . Moreover, if  $u$  is bounded, the  $\varphi_j$  can be taken to be uniformly bounded, and if  $u = 1$  on  $K$  in the  $H^{1,2}(\Sigma)$  sense, the  $\varphi_j$  can be taken to be  $\equiv 1$  on  $K$ .*

As a consequence of the proposition we see that given  $u \in H_0^{1,2}(\Sigma)$ , there exists  $\tilde{u}$  in  $H_0^{1,2}(\Sigma)$  with  $u = \tilde{u}$  a.e., and  $\tilde{u}$  quasi continuous.

PROPOSITION 1.28. — *If  $\tilde{u}_1$  and  $\tilde{u}_2$  belong to  $H_0^{1,2}(\Sigma)$ , are quasi-continuous, and agree almost everywhere, they agree quasi-everywhere.*

The following corollary is the main application of 1.27 and 1.28 that will be needed in the sequel.

COROLLARY 1.29. — *Let  $\mu$  be a positive measure in  $H^{-1,2}(\Sigma)$ . Then, if  $u \in H_0^{1,2}(\Sigma)$ , is Borel measurable, bounded and quasi-continuous we have  $\int u d\mu = \langle T, u \rangle$ , where  $T$  is as in definition 1.23.*

*Proof of corollary 1.29.* — Pick a sequence  $\{\varphi_j\}$  of  $\text{Lip}_0(\Sigma)$  functions and a sequence of open sets  $\{\mathcal{O}_k\}$  as in 1.27. Let  $E = \bigcap \mathcal{O}_k$ . Then  $E$  is a Borel set, and  $\text{cap}(E) = 0$ . Let  $\tilde{u} = \lim \varphi_j$ , where the limit is taken in the pointwise sense. Clearly  $\tilde{u}$  is defined everywhere in  $\Sigma \setminus E$ , and as  $\mu(E) = 0$ , it is  $\mu$ -measurable. Also, as  $|E| = 0$ ,  $\tilde{u}$  is in  $H_0^{1,2}(\Sigma)$ , and  $\tilde{u} = u$  almost everywhere. Because of the uniform convergence of  $\{\varphi_j\}$  in  $\Sigma \setminus \mathcal{O}_k$ , we see that  $\tilde{u}$  is quasi-continuous. But then,  $\tilde{u} = u$  quasi-everywhere by 1.28. Thus, there exists a  $G_\delta$  set  $\tilde{E}$  so that  $\tilde{u} = u$  for every point in  $\Sigma \setminus \tilde{E}$ . By 1.25,  $\mu(E \cup \tilde{E}) = 0$ . Thus,

$$\begin{aligned} \int u d\mu &= \int_{\Sigma \setminus E \cup \tilde{E}} u d\mu = \int_{\Sigma \setminus E \cup \tilde{E}} \tilde{u} d\mu = \int_{\Sigma \setminus E \cup \tilde{E}} \lim \varphi_j d\mu \\ &= \lim_j \int_{\Sigma \setminus E \cup \tilde{E}} \varphi_j d\mu = \lim_j \int_{\Sigma} \varphi_j d\mu = \lim_j \langle T, \varphi_j \rangle = \langle T, u \rangle. \end{aligned}$$

The interchange of  $\lim$  and integration is justified by the uniform boundedness of  $\{\varphi_j\}$ .

We now turn to the proof of propositions 1.27 and 1.28.

*Proof of proposition 1.27.* — We first note that

$$\text{cap}(K_1 \cup K_2) \leq \text{cap}(K_1) + \text{cap}(K_2)$$

for any two compact sets  $K_1$  and  $K_2$ . This follows easily by considering the test function  $u = \max(u_1, u_2)$  where the  $u_i$  are the capacitary potentials of  $K_i$ . From this it easily follows that  $\text{cap}\left(\bigcup_i \mathcal{O}_i\right) \leq \sum_i \text{cap}(\mathcal{O}_i)$  for any sequence of open sets  $\mathcal{O}_i$ . Pick now a sequence  $\varphi_j \in C_0^\infty(\Sigma)$ ,  $\varphi_j \longrightarrow u$  in  $H_0^{1,2}(\Sigma)$  so fast that

$\sum_j 4^j \|\varphi_{j+1} - \varphi_j\|_{H_0^{1,2}(\Sigma)}^2 < \infty$ . Let now

$$U_j = \left\{ x \in \Sigma : |\varphi_{j+1}(x) - \varphi_j(x)| > \frac{1}{2^j} \right\},$$

and  $\mathcal{O}_k = \bigcup_{j=k}^{\infty} U_j$ . We know that  $\text{cap}(\mathcal{O}_k) \leq \sum_{j=k}^{\infty} \text{cap}(U_j)$ . On the other hand,  $2^j |\varphi_{j+1}(x) - \varphi_j(x)| \geq 1$  on  $U_j$ , and so

$$\begin{aligned} \text{cap}(U_j) &\leq D(2^j |\varphi_{j+1} - \varphi_j|, 2^j |\varphi_{j+1} - \varphi_j|) \\ &\leq 4^j D(\varphi_{j+1} - \varphi_j, \varphi_{j+1} - \varphi_j). \end{aligned}$$

Thus,  $\text{cap}(\mathcal{O}_k) \rightarrow 0$  as  $k \rightarrow \infty$ , and the proposition follows. Proposition 1.28 follows immediately from Theorem 5 in [3], once we show that our definition of capacity of an open set  $\mathcal{O}$  coincides with the encombremment of an open set  $\mathcal{O}$  as defined in [3]. We recall the definition of  $\text{enc}(\mathcal{O})$ . For an open set  $\mathcal{O} \subset \Sigma$ , let  $U_{\mathcal{O}} = \{u \in H_0^{1,2}(\Sigma) : u \geq 1 \text{ almost everywhere on } \mathcal{O}\}$ . Then,

$$\begin{aligned} &+\infty \quad \text{if } U_{\mathcal{O}} = \emptyset \\ \text{enc}(\mathcal{O}) &= \inf_{u \in U_{\mathcal{O}}} D(u, u) \quad \text{if } U_{\mathcal{O}} \neq \emptyset \end{aligned}$$

We then have

PROPOSITION 1.30. — *For any open set  $\mathcal{O} \subset \Sigma$ ,  $\text{enc}(\mathcal{O}) = \text{cap}(\mathcal{O})$ .*

*Proof.* — We first claim that if  $K \subset \Sigma$ ,

$$K_{\rho} = \{x \in \Sigma : \text{dist}(x, K) \leq \rho\},$$

and  $u \in H_0^{1,2}(\Sigma)$  is non-negative a.e. in  $K_{\rho}$ , then  $u \geq 0$  in  $K$  in the  $H_0^{1,2}(\Sigma)$  sense. To see this, pick  $\varphi \equiv 1$  in  $K$ ,  $\text{supp } \varphi \subset K_{\rho}$ ,  $\varphi \in C_0^{\infty}(\Sigma)$ . Then,  $\varphi u \in H_0^{1,2}(\Sigma)$ ,  $\varphi u \geq 0$  in  $\Sigma$ . Thus, using truncation we can find a sequence  $g_j$ ,  $g_j \geq 0$  in  $\Sigma$ ,  $g_j \in \text{Lip}_0(\Sigma)$ , such that  $g_j \rightarrow \varphi u$  in  $H_0^{1,2}(\Sigma)$ . Pick  $h_j \in C_0^{\infty}(\Sigma)$ ,  $h_j \rightarrow u$  in  $H_0^{1,2}(\Sigma)$ . Then,  $(1 - \varphi)h_j + g_j \rightarrow u$  in  $H_0^{1,2}(\Sigma)$ , and on  $K$ ,  $(1 - \varphi)h_j + g_j = g_j \geq 0$ , and the claim follows. Now, assume  $\text{enc}(\mathcal{O}) < +\infty$ ,  $\text{cap}(\mathcal{O}) < +\infty$ . Then, there exists a  $u \in U_{\mathcal{O}}$ . Let  $K \subset \subset \mathcal{O}$ . By the claim,  $u \geq 1$  on  $K$  in the  $H_0^{1,2}(\Sigma)$  sense. Thus,  $\text{cap}(\mathcal{O}) \leq D(u, u)$ , and so  $\text{cap}(\mathcal{O}) \leq \text{enc}(\mathcal{O})$ . Pick now a sequence of compact sets  $\{K_j\}$ ,  $K_j \subset K_{j+1}$ ,  $K_j \subset \mathcal{O}$ ,  $K_j \nearrow \mathcal{O}$ . Let  $u_j$  be the capacity potential of  $K_j$ . Since  $\text{cap}(\mathcal{O}) < +\infty$ ,  $D(u_j, u_j) \leq C$ .

Thus, there exists a subsequence  $u_{j_k}$  and  $u \in H_0^{1,2}(\Sigma)$  so that  $u_{j_k} \rightharpoonup u$  weakly. Because of the Banach Saks theorem, it is easy to see that  $u \geq 1$  a.e. on  $\mathcal{O}$ . But, then,

$$\begin{aligned} D(u, u) &= \lim_{k \rightarrow \infty} D(u, u_{j_k}) \leq \overline{\lim}_k D(u_{j_k}, u_{j_k})^{1/2} \cdot D(u, u)^{1/2} \\ &\leq \overline{\lim}_k \text{cap}(K_{j_k})^{1/2} \cdot D(u, u)^{1/2} \\ &\leq \text{cap}(\mathcal{O})^{1/2} D(u, u)^{1/2}, \end{aligned}$$

and so,  $D(u, u) \leq \text{cap}(\mathcal{O})$ . Hence,  $\text{enc}(\mathcal{O}) \leq \text{cap}(\mathcal{O})$ . As it is easy to see that  $\text{enc}(\mathcal{O}) = +\infty$  iff  $\text{cap}(\mathcal{O}) = +\infty$ , the proposition follows.

As mentioned before, proposition 1.28 follows from 1.30 by the results in [3].

## 2. Weak solutions and the Green function.

Recall from 1.12 and 1.13 that if  $p \geq p_0$ ,  $G$  maps  $H^{-1,p}(\Sigma)$  into  $C_0(\Sigma)$ , the class of continuous functions in  $\bar{\Sigma}$  that vanish on  $\partial\Sigma$ . Denote by  $M(\Sigma)$  the class of finite measures supported in  $\Sigma$ . A function  $u$  in  $L^1(\Sigma, w)$  is called a *weak solution vanishing on  $\partial\Sigma$*  to  $Lu = \mu$  provided

$$\int_{\Sigma} u(x) \Psi(x) w(x) dx = \int_{\Sigma} G(\Psi w) d\mu,$$

for every  $\Psi \in L^\infty(\Sigma, \vec{w})$ . Notice that  $\Psi w \in H^{-1,p}(\Sigma)$  for all  $p$ , since  $\Psi w = f_0 - \text{div } \vec{f}$ , where  $\vec{f} = 0$  and  $f_0/w = \Psi \in L^p(\Sigma, w)$  for all  $p$ . Consequently,  $G(\Psi w)$  is continuous in  $\bar{\Sigma}$  and the right hand integral makes sense.

**PROPOSITION 2.1.** — *For every  $\mu \in M(\Sigma)$ , there exists a unique weak solution  $u$  to  $Lu = \mu$ . Moreover, there exists  $\underline{u} \in H_0^{1,p'}(\Sigma)$  so that  $\underline{u} = (u, u_1, \dots, u_n)$  and  $\|\underline{u}\|_{H_0^{1,p'}(\Sigma)} \leq C \|\mu\|_{M(\Sigma)}$  for  $1 \leq p' \leq p'_0$ .*

*Proof.* — The existence of  $u$  follows from the fact that the adjoint of  $G$ ,  $G^*$ , is bounded from  $M(\Sigma)$  to  $H_0^{1,p'}(\Sigma)$ . Put  $\underline{u} = G^*(\mu)$ , then by definition (using the representation  $\Psi w = f_0 - \text{div } \vec{f}$  with  $\vec{f} = 0$  above)

$$\int_{\Sigma} u \Psi w = \langle \underline{u}, \Psi w \rangle = \langle G^*(\mu), \Psi w \rangle = \langle \mu, G(\Psi w) \rangle = \int_{\Sigma} G(\Psi w) d\mu.$$

The function  $u$  is unique in  $L^1(\Sigma, w)$  because it is determined by  $\int_{\Sigma} u \Psi w$  for all  $\Psi \in L^\infty(\Sigma, w)$ .

PROPOSITION 2.2. — *If  $\mu \geq 0$ , then the weak solution  $u$  to  $Lu = \mu$  is non-negative a.e. in  $\Sigma$ .*

*Proof.* — It is enough to show that  $\int_{\Sigma} u \Psi w \geq 0$  for all non-negative  $\Psi \in L^\infty(\Sigma, w)$ . But  $\Psi w \geq 0$  implies  $G(\Psi w) \geq 0$  by the weak maximum principle 1.18. Hence,

$$\int_{\Sigma} u \Psi w = \int_{\Sigma} G(\Psi w) d\mu \geq 0.$$

PROPOSITION 2.3. — *Assume that  $\mu \geq 0$ , and  $\mu \in H^{-1,2}(\Sigma)$ . Then, the weak solution  $u$  of  $Lu = \mu$  belongs to  $H_0^{1,2}(\Sigma)$ . Moreover,  $Lu = \mu$  in the  $H_0^{1,2}(\Sigma)$  sense.*

*Proof.* — Since  $\mu \in H^{-1,2}(\Sigma)$ , by 1.4 and 1.29 there exists a  $v \in H_0^{1,2}(\Sigma)$  such that  $D(v, \varphi) = \langle \mu, \varphi \rangle$  for all  $\varphi \in C(\bar{\Sigma}) \cap H_0^{1,2}(\Sigma)$ . For  $\Psi \in L^\infty(\Sigma, w)$ ,  $G(\Psi w) \in C(\bar{\Sigma}) \cap H_0^{1,2}(\Sigma)$ , and thus by definition of  $G$ ,  $\langle v, \Psi w \rangle = D(G(\Psi w), v) = D(v, G(\Psi w)) = \langle \mu, G(\Psi w) \rangle$ . Hence,  $v$  is the weak solution to  $Lv = \mu$ , and the proposition follows.

Note that because of remark 1.24 and 2.3, if  $\mu$  is a capacity distribution and  $u$  is the corresponding capacity potential, then  $u$  is the weak solution to  $Lu = \mu$ .

Fix  $y \in \Sigma$ . Denote by  $g(x, y)$  the weak solution of  $Lg = \delta_y$  as a function of  $x$ . ( $\delta_y$  is the unit mass at  $y$ .) By Proposition 2.2  $g(x, y) \geq 0$  for a.e.  $x$  in  $\Sigma$ .

PROPOSITION 2.4. —  *$g(\cdot, y) \in H^{1,2}(\Sigma \setminus B(y, r))$  for any  $r > 0$ . Moreover,  $g(\cdot, y)$  can be modified on a set of measure zero so that it is Hölder continuous in  $\Sigma \setminus \{y\}$  and vanishes on  $\partial\Sigma$ .*

*Proof.* — Define a measure  $d\mu_j = \Psi_j w dx$ , where

$$\Psi_j(x) = \begin{cases} 1/w(B(y, j^{-1})) & x \in B(y, j^{-1}) \\ 0 & \text{elsewhere.} \end{cases}$$

Then  $\mu_j$  tends to  $\delta_y$  weakly, and  $\mu_j \in H^{-1,p}(\Sigma)$  for every  $p$ . Let  $u_j$  be the weak solution to  $Lu_j = \mu_j$ . Since  $G^*$  is bounded from

$M(\Sigma)$  to  $L^{p'}(\Sigma, w)$ ,  $p \geq p_0$ ,  $\|u_j\|_{L^{p'}(\Sigma, w)} \leq C$  is independent of  $j$  and  $u_j$  tends to  $g(\cdot, y)$  weakly in  $L^{p'}(\Sigma, w)$ .

By 2.3, we see that  $u_j \in H_0^{1,2}(\Sigma)$ . Moreover,  $Lu_j = 0$  in the  $H^{1,2}(\Sigma \setminus B(y, j^{-1}))$  sense. Thus we can choose the Hölder continuous representative of  $u_j$  (1.8). Also by 2.2,  $u_j$  is non-negative, so Harnack's principle applies (1.9). Thus

$$u_j(x) \leq C \left( \frac{1}{w(B)} \int_B u_j(z) w(z) dz \right) \leq \frac{C}{w(B)} \|u_j\|_{L^{p'}(\Sigma, w)},$$

where  $x \in \partial B(y, r)$ ,  $B = B(x, r/2)$ ,  $j^{-1} < r/4$ . Thus by the maximum principle,  $0 \leq u_j(x) \leq C_r$  for all  $x \in \Sigma \setminus B(y, r)$ ,  $j^{-1} < r/4$ . Next, by 1.14 and 1.14' we also have

$$\int_{\Sigma \setminus B(y, r)} |\nabla u_j(z)|^2 w(z) dz \leq C_r,$$

and thus the sequence  $u_j$  is uniformly bounded in  $H^{1,2}(\Sigma \setminus B(y, r))$  norm. Thus a subsequence converges weakly and it follows that  $g(\cdot, y) \in H^{1,2}(\Sigma \setminus B(y, r))$ . Finally, it also follows that  $Lg(\cdot, y) = 0$  in the  $H^{1,2}(\Sigma \setminus B(y, r))$  sense, and  $g(\cdot, y)$  vanishes on  $\partial\Sigma$  in the  $H^{1,2}(\Sigma \setminus B(y, r))$  sense. Therefore  $g(\cdot, y)$  is Hölder continuous in  $\bar{\Sigma} \setminus \{y\}$  and vanishes on  $\partial\Sigma$ . (See 1.12 and 1.13).

LEMMA 2.5. — Let  $\Psi \in L^\infty(\Sigma, w)$ . Then

$$G(\Psi w)(y) = \int_\Sigma g(x, y) \Psi(x) w(x) dx.$$

*Proof.* —

$$\begin{aligned} \int_\Sigma g(x, y) \Psi(x) w(x) dx &= \langle g(\cdot, y), \Psi w \rangle \\ &= \langle \delta_y, G(\Psi w) \rangle = G(\Psi w)(y). \end{aligned}$$

From now on we will only use the representative of  $g(x, y)$  that is continuous in  $x$  for  $x \in \bar{\Sigma} \setminus \{y\}$ .

PROPOSITION 2.6. —  $g(x, y)$  is jointly continuous in  $\Sigma \times \Sigma \setminus \Delta$ , where  $\Delta = \{(y, y) : y \in \Sigma\}$ .

*Proof.* — Fix  $x$  and let

$$\Psi_j^{(x)}(z) = \begin{cases} 1/w(B(x, j^{-1})) & z \in B(x, j^{-1}) \\ 0 & \text{elsewhere.} \end{cases}$$

From 2.5, the solution  $\Phi_j^{(x)} \in H_0^{1,2}(\Sigma) \cap C(\bar{\Sigma})$  of  $L\Phi_j^{(x)} = \Psi_j^{(x)}w$  is given by  $\Phi_j^{(x)}(y) = \int_{\Sigma} g(z, y) \Psi_j^{(x)}(z) w(z) dz$ . If  $x \neq y$ , then  $\Phi_j^{(x)}(y)$  tends to  $g(x, y)$ . Even better, if  $J$  and  $K$  are disjoint compact sets in  $\Sigma$ , then  $\Phi_j^{(x)}(y) \rightarrow g(x, y)$  uniformly for  $x \in J$ ,  $y \in K$ . In fact, 1.8 implies for  $z \in J^* = \{z: \text{dist}(z, J) < j^{-1}\}$  and  $j$  large,

$$|g(z, y) - g(x, y)| \leq C |z - x|^\alpha \left( \int_{J^{**}} g(z', y)^2 w(z') dz' \right)^{1/2}.$$

By the proof of Proposition 2.4, the integral is bounded independent of  $y \in K$ . Hence, for sufficiently large  $j$ ,

$$\begin{aligned} |\Phi_j^{(x)}(y) - g(x, y)| \\ = \left| \int_{\Sigma} (g(z, y) - g(x, y)) \Psi_j^{(x)}(z) w(z) dz \right| \leq C j^{-\alpha}. \end{aligned}$$

On the other hand,  $\Phi_j^{(x)}(y)$  is continuous in  $J \times K$  for large  $j$ . This is because (1.12) implies

$$\sup_{y \in K} |\Phi_j^{(x)}(y) - \Phi_j^{(z)}(y)| \leq C \|\Psi_j^{(x)} - \Psi_j^{(z)}\|_{L^p(\Sigma, w)}$$

for  $p \geq p_0$ . Clearly the right hand side tends to zero as  $z \rightarrow x$ . Finally, for  $x \in J$ ,

$$|\Phi_j^{(x)}(y) - \Phi_j^{(x)}(y')| \leq C |y - y'|^\alpha \|\Psi_j^{(x)}\|_{L^p(\Sigma, w)}.$$

LEMMA 2.7. — For every  $\mu \in M(\Sigma)$ ,  $u(x) = \int g(x, y) d\mu(y)$  exists for a.e.  $x$  and  $u$  is the weak solution to  $Lu = \mu$ .

*Proof.* — Assume that  $\mu \geq 0$ . Since  $g(x, y)$  is continuous in  $\Sigma \times \Sigma \setminus \Delta$  and  $dx \times d\mu(\Delta) = 0$ ,  $g(x, y)$  is  $dx \times d\mu(y)$  measurable on  $\Sigma \times \Sigma$ . Let  $\Psi \geq 0$ ,  $\Psi \in L^\infty(\Sigma, w)$ . Then by Fubini's theorem, and 2.5,

$$\begin{aligned} \langle G(\Psi w), \mu \rangle &= \iint g(x, y) \Psi(x) w(x) dx d\mu(y) \\ &= \int \Psi(x) w(x) u(x) dx \end{aligned}$$

because  $g(x, y) \geq 0$  for  $(x, y) \notin \Delta$ . These integrals are always finite because  $G(\Psi w)$  is continuous. Thus  $u(x)$  exists a.e.  $x$ , and we can drop the restrictions  $\Psi \geq 0$  and  $\mu \geq 0$ .

PROPOSITION 2.8. —  $g(x, y) = g(y, x)$ .

*Proof.* — Fix  $x_0 \neq y_0$ . Let  $\Psi \in L^\infty(\Sigma, w)$  be supported near



$y_0$  and disjoint from  $x_0$ . By 2.7 and 2.3,

$$\Phi_1(x) = \int g(x, y) \Psi(y) w(y) dy$$

represents the  $H_0^{1,2}(\Sigma)$  solution to  $L\Phi = \Psi w$ . By 2.5

$$\Phi_2(x) = \int g(y, x) \Psi(y) w(y) dy$$

also represents this solution. But since  $g(x, y)$  is continuous near  $(x_0, y_0)$ , both  $\Phi_1$  and  $\Phi_2$  are continuous near  $x_0$ . Therefore,  $\Phi_1(x_0) = \Phi_2(x_0)$ . Now using arbitrary  $\Psi$  and continuity of  $g$  we see that  $g(x_0, y_0) = g(y_0, x_0)$ .

### 3. The size of the Green function.

We will say that  $A_1(x) \simeq A_2(x)$  if there exist positive constants  $c_1$  and  $c_2$  such that  $c_1 < A_1(x)/A_2(x) < c_2$ . The constants depend only on the  $(A_2)$  or (QC) constants of  $w$  and not on  $x$ , whose range will be specified.

LEMMA 3.1. — *If  $B(x, 2r) \subset \Sigma$  and  $y \in \partial B(x, r)$ , then  $g(x, y) \cong 1/\text{cap}(B(x, r))$ .*

*Proof.* — Let  $\mu$  be the capacitary distribution of  $B(x, r)$  and  $\hat{u}(z) = \int g(z, y) d\mu(y)$  a representative of its capacitary potential (see 2.3 and 2.7). Since  $\mu$  is supported on  $\partial B(x, r)$  and  $\hat{u}(z) = 1$  on  $B(x, r)$  in the  $H^{1,2}(\Sigma)$  sense,  $\hat{u}$  is continuous in the interior of  $B(x, r)$  and  $1 = \hat{u}(x) = \int_{\partial B(x, r)} g(x, y) d\mu(y)$  (see 1.20 and 1.22). Therefore,

$$\min_{y \in \partial B(x, r)} g(x, y) \text{cap}(B(x, r)) \leq 1 \leq \max_{y \in \partial B(x, r)} g(x, y) \text{cap}(B(x, r)).$$

By 2.4 and 2.8,  $g(x, \cdot) \in H^{1,2} \Sigma \setminus \left( B\left(x, \frac{r}{2}\right) \right)$  and  $g(x, \cdot) \geq 0$  there. Thus Harnack's principle applies, giving

$$\max_{y \in \partial B(x, r)} g(x, y) \simeq \min_{y \in \partial B(x, r)} g(x, y),$$

and 3.1 is proved.

LEMMA 3.2. — *If  $x \in \Sigma$  and  $\frac{3}{2}r \leq \text{dist}(x, \partial\Sigma) \leq 8r$ , then  $\text{cap}(B(x, r)) \simeq w(B(x, r))/r^2$ .*

*Proof.* — Choose  $\Psi \in \text{Lip}_0(\Sigma)$  with  $\Psi = 1$  on

$B(x, r)$ ,  $\text{supp } \Psi \subset B(x, 2r)$ ,  $0 \leq \Psi \leq 1$ , and  $|\nabla \Psi| \leq Cr^{-1}$ .

Then  $\text{cap}(B(x, r)) \leq D(\Psi, \Psi) \leq C \int |\nabla \Psi|^2 w \cong w(B(x, r))/r^2$ , by (1.2). Conversely, let  $u$  be the capacitary potential of  $B(x, r)$ . Let  $\bar{x}$  be the point of  $\partial\Sigma$  closest to  $x$ . By Hölder continuity at the boundary (1.13), for  $\rho < r$

$$\max_{z \in B(\bar{x}, \rho) \cap \bar{\Sigma}} u(z) \leq C(\rho/r)^\alpha \left( \frac{1}{w(B(\bar{x}, r))} \int_{B(\bar{x}, r) \cap \Sigma} u(z)^2 w(z) dz \right)^{1/2} \leq C(\rho/r)^\alpha.$$

The last expression is less than  $\frac{1}{2}$  if  $\rho = \mathcal{E}r$  for some  $\mathcal{E} > 0$  (independent of  $r$ ). Now applying Harnack's principle on a chain of balls connecting the point of  $\partial B(\bar{x}, \mathcal{E}r) \cap \Sigma$  on the ray between  $\bar{x}$  and  $x$  to  $\partial B(x, (1 + \mathcal{E})r)$  to the (non-negative) function  $1 - u(z)$ , we find that  $1 - u(z) \geq c > 0$  for all

$$z \in B(x, (1 + 2\mathcal{E})r) \setminus B(x, (1 + \mathcal{E})r) = A.$$

By the doubling condition (1.2),  $w(A) \simeq w(B(x, 2r))$ . Also,  $u \leq 1$  almost everywhere. Hence,

$$\bar{u} = \frac{1}{w(B(x, (1 + 2\mathcal{E})r))} \int_{B(x, (1 + 2\mathcal{E})r)} u(z) w(z) dz \leq 1 - \mathcal{E}',$$

where  $\mathcal{E}' > 0$ , and  $\mathcal{E}'$  depends only on  $c$ ,  $\mathcal{E}$  and the constant in (1.2). Define  $\varphi(z) = \Psi(z)(u(z) - \bar{u})$ . Then  $\varphi \geq \mathcal{E}'$  in  $B(x, r)$  and by 1.6,

$$\begin{aligned} (\mathcal{E}')^2 w(B(x, r)) &\leq c \int_{B(x, r)} |\varphi|^2 w \leq c \int_{B(x, 2r)} \Psi^2 |u - \bar{u}|^2 w \\ &\leq cr^2 \int_{\Sigma} |\nabla u|^2 w \simeq r^2 D(u, u) = r^2 \text{cap}(B(x, r)). \end{aligned}$$

**THEOREM 3.3.** — Let  $x$  and  $y$  belong to  $\Sigma' = \left\{ z : |z| < \frac{1}{4} R \right\}$ . Denote  $r = |x - y|$ . Then

$$g(x, y) \simeq \int_r^R \frac{s^2}{w(B(x, s))} \frac{ds}{s}.$$

*Proof.* — Denote by  $g_j(x, y)$  the Green function for  $B(x, 2^j r)$ ,  $j = 0, 1, \dots, N$ , with  $2^{N+1} r \leq R < 2^{N+2} r$ . Lemmas 3.1 and 3.2 show that  $g_j(x, y) \simeq (2^j r)^2 / w(B(x, 2^j r))$  for  $y \in \partial B(x, 2^{j-1} r)$ .

Denote  $u_j(y) = g_j(x, y) - g_{j-1}(x, y)$  for  $y \in B(x, 2^{j-1}r)$ . A limiting procedure like the one in the proof of 2.4 shows that  $u_j(y)$  solves  $Lu_j = 0$  in the  $H^{1,2}(\overset{\circ}{B}(x, 2^{j-1}r))$  sense. Also, by (2.4)  $u_j$  is continuous in the closed ball  $B(x, 2^{j-1}r)$  with  $u_j(y) = g_j(x, y)$  on  $\partial B(x, 2^{j-1}r)$  continuously and in the  $H^{1,2}(\overset{\circ}{B}(x, 2^{j-1}r))$  sense. Thus by the maximum principle  $u_j(y) \simeq (2^j r)^2 / w(B(x, 2^{j-1}r))$  for all  $y \in B(x, 2^{j-1}r)$ . Let  $u(y) = g(x, y) - g_N(x, y)$ . A similar argument shows that  $u(y) \simeq (2^N r)^2 / w(B(x, 2^N r))$  for  $y \in B(x, 2^N r)$ . In all, by 1.2

$$g(x, y) = u(y) + \sum_{j=1}^N u_j(y) \simeq \sum_{j=1}^{N+1} (2^j r)^2 / w(B(x, 2^j r)) \simeq \int_r^R \frac{s^2}{w(B(x, s))} \frac{ds}{s}.$$

We will now define  $g(y, y)$  as follows. If  $\text{cap}(\{y\}) = 0$ , then let  $g(y, y) = \infty$ . If  $\text{cap}(\{y\}) > 0$ , then let  $g(y, y) = 1/\text{cap}(\{y\})$ . This definition is justified by

PROPOSITION 3.4. — *If  $\text{cap}(\{y\}) = 0$ , then  $\lim_{x \rightarrow y} g(x, y) = \infty$ . If  $\text{cap}(\{y\}) > 0$ , then  $\lim_{x \rightarrow y} g(x, y) = 1/\text{cap}(\{y\})$ .*

*Proof.* — We first claim that  $\text{cap}(\{y\}) = \lim_{r \rightarrow 0} \text{cap}(B(y, r))$ . Clearly  $\text{cap}(B(y, r))$  decreases as  $r$  decreases and

$$\lim_{r \rightarrow 0} \text{cap}(B(y, r)) \geq \text{cap}(\{y\}).$$

Let  $u_r$  denote the capacitary potential of  $B(y, r)$ . Then for  $r \leq r_0$ ,  $D(u_r, u_r) = \text{cap}(B(y, r)) \leq \text{cap}(B(y, r_0))$ , so that  $u_r$  is uniformly bounded in  $H_0^{1,2}(\Sigma)$  norm as  $r \rightarrow 0$ . Choose a sequence  $r_j \downarrow 0$  so that  $u_{r_j}$  converges weakly to  $u$  in  $H_0^{1,2}(\Sigma)$ . Then  $u$  is the capacitary potential of  $\{y\}$ . By the Banach-Saks theorem we can pass to a sub-sequence (still denoted  $r_j$ ) such that the means  $\Psi_j = j^{-1}(u_{r_1} + \cdots + u_{r_j})$  converge to  $u$  in  $H_0^{1,2}(\Sigma)$  norm. Thus  $\text{cap}(\{y\}) = D(u, u) = \lim_{j \rightarrow \infty} D(\Psi_j, \Psi_j)$ . But  $\Psi_j = 1$  in the  $H^{1,2}(\Sigma)$  sense on  $B(y, r_j)$ , so  $D(\Psi_j, \Psi_j) \geq \text{cap}(B(y, r_j))$  and the claim follows. Lemma 3.1 and the claim imply that if  $\text{cap}(\{y\}) = 0$ , then  $\lim_{x \rightarrow y} g(x, y) = \infty$ .

Now suppose that  $\text{cap}(\{y\}) > 0$ . Recall from the proof of 3.1 that

$$\min_{x \in \partial B(y, r)} g(x, y) \operatorname{cap}(B(y, r)) \leq 1 \leq \max_{x \in \partial B(y, r)} g(x, y) \operatorname{cap}(B(y, r)) .$$

Thus it suffices to show that

$$\lim_{r \rightarrow 0} \sup_{\substack{|x-y|=r \\ |x'-y|=r}} |g(x, y) - g(x', y)| = 0 .$$

Since  $\operatorname{cap}(\{y\}) > 0$ , the claim and 3.1 imply that  $g(x, y) \leq c$  for all  $x \neq y$ . Hence by Theorem 3.3,  $\int_0^R \frac{s^2}{w(B(y, s))} \frac{ds}{s} < \infty$ . Recalling 1.2, we have in particular,  $\lim_{s \rightarrow 0} \frac{s^2}{w(B(y, s))} = 0$ . The capacitary potentiel  $u$  for  $\{y\}$  mentioned above satisfies  $Lu = \mu$  for a measure  $\mu$  supported on  $\{y\}$ . Also,  $\mu(\{y\}) = \operatorname{cap}(\{y\})$ . Thus

$$g(x, y) = u(x) / \operatorname{cap}(\{y\}) .$$

There is a dimensional constant  $N$  such that every two points  $x$  and  $x'$  of  $\partial B(y, r)$  can be connected by points

$$x = x_1, x_2, \dots, x_{N-1},$$

$x_N = x'$  such that  $x_j \in \partial B(y, r)$  and  $|x_{j+1} - x_j| < \frac{1}{100} r$ . Then 1.6 and 1.7 imply

$$\begin{aligned} |u(x_{j+1}) - u(x_j)| &\leq Cr \left( \frac{1}{w(B(x_j, r/2))} \int_{B(x_j, r/2)} |\nabla u|^2 w \right)^{1/2} \\ &\leq C \left( \frac{r^2}{w(B(x, r))} \right)^{1/2} \|u\|_{H_0^{1,2}(\Sigma)}, \end{aligned}$$

which tends to zero as  $r \rightarrow 0$ .

From 3.4, and 2.6 it follows that

COROLLARY 3.5. —  $g(x, y)$  is Borel measurable.

Another consequence of 3.4 is

LEMMA 3.6. — If  $\mu$  is a positive measure, then

$$\hat{u}(x) = \int g(x, y) d\mu(y)$$

is lower semicontinuous, that is,  $\liminf_{y \rightarrow x} \hat{u}(y) \geq \hat{u}(x)$ .

Henceforth we will always use the lower semicontinuous representative given above of the weak solution to  $Lu = \mu$ .

*Proof.* — Fix a point  $x_0 \in \Sigma$ , and write  $\mu = \mu_1 + \mu_2$ , where  $\mu_1(\{x_0\}) = 0$ , and  $\mu_2 = \mu(\{x_0\}) \delta_{x_0}$ . Then,

$$\hat{u}(x) = \int g(x, y) d\mu_1(y) + \mu(\{x_0\}) g(x, x_0).$$

(We use the convention  $0 \cdot \infty = 0$ ). Hence,

$$\liminf_{x \rightarrow x_0} \hat{u}(x) \geq \liminf_{x \rightarrow x_0} \int g(x, y) d\mu_1(y) + \mu\{x_0\} g(x_0, x_0),$$

by 3.4. Pick now a sequence of functions  $\varphi_j \in \text{Lip}(\mathbf{R})$ ,  $\varphi_j \leq \varphi_{j+1}$ ,  $\varphi_j \equiv 0$  near 0,  $\varphi_j(t) \equiv 1$  for  $t \geq \frac{1}{j}$ , so that  $\varphi_j(t) \rightarrow \begin{cases} 1 & \text{for } t > 0 \\ 0 & \text{for } t = 0 \end{cases}$ .

Let  $g_j(x, y) = g(x, y) \varphi_j(|x - y|)$ . Then  $g_j(x, y) \leq g_{j+1}(x, y)$ ,  $g_j(x, y) \nearrow g(x, y)$  except at  $x = y$ . Since  $\mu_1(\{x_0\}) = 0$ ,  $\int g(x_0, y) d\mu_1(y) = \lim_{j \rightarrow \infty} \int g_j(x_0, y) d\mu_1(y)$ . But,  $\int g_j(x, y) d\mu(y)$  is a continuous function by 2.8, and so,

$$\int g_j(x_0, y) d\mu_1(y) = \liminf_{x \rightarrow x_0} \int g_j(x, y) d\mu_1(y) \leq \liminf_{x \rightarrow x_0} \int g(x, y) d\mu_1(y).$$

Thus,  $\int g(x_0, y) d\mu_1(y) \leq \liminf_{x \rightarrow x_0} \int g(x, y) d\mu_1(y)$ , and the proposition follows.

#### 4. Capacitary potentials and distributions.

In this section we will prove basic results on capacitary potentials needed in the proof of the Wiener test. These results are easily deduced from the properties of the Green function of Section 3.

LEMMA 4.1. — Suppose that  $\text{cap}(\{y\}) = 0$  and  $\mu$  is a capacitary distribution. Then  $\lim_{r \rightarrow 0} \int_{|x-y| < r} g(y, x) d\mu(x) = 0$ .

*Proof.* — By 1.24 and 1.25,  $\mu(\{y\}) = 0$ . Also,

$$\int g(y, x) d\mu(x) \leq 1$$

because the capacitary potential of a set  $K$ ,  $u(y) = \int g(y, x) d\mu(x)$ , is continuous in  $\Sigma \setminus K$  and  $\overset{\circ}{K}$ ,  $\leq 1$  a.e., (and hence everywhere on  $\Sigma \setminus K$  and  $\overset{\circ}{K}$ ) and is lower semicontinuous. The result now follows from the dominated convergence theorem.

LEMMA 4.2. — *Let  $\mu_1$  and  $\mu_2$  be positive measures, and  $u_j(x) = \int g(x, y) d\mu_j(y)$ ,  $j = 1, 2$ . Then,*

$$\int u_1(y) d\mu_2(y) = \int u_2(x) d\mu_1(x) = \iint g(x, y) d\mu_1(x) d\mu_2(y).$$

The lemma follows from 2.8, 3.5, 3.6 and Fubini's Theorem.

LEMMA 4.3. — *Let  $K \subset \Sigma$  be a compact set. Let*

$$u(y) = \int g(x, y) d\mu(x)$$

*be the lower semicontinuous representative of its capacitary potential. Then  $u$  is quasi-continuous in  $\Sigma$ .*

*Proof.* — The proof follows very closely the one of Lemma 6, section III of [1]. Some modifications are needed to take care of the points  $y$  such that  $\text{cap}\{y\} > 0$ .

Let  $E_1 = \{x \in \partial K : \text{cap}\{x\} = 0\}$ ,  $E_2 = \{x \in \partial K : \text{cap}\{x\} > 0\}$ . By 3.4 and 3.5  $E_1$  and  $E_2$  are Borel sets. We first claim that given  $\mathcal{E} > 0$ , there exists a closed set  $F_2 \subset E_2$ , with  $\mu(E_2/F_2) < \mathcal{E}$  such that if  $\mu_2(E) = \mu(E \cap F_2)$ , and  $u_2(x) = \int g(x, y) d\mu_2(y)$ , then  $u_2$  is continuous in  $\Sigma$ . (Note that as  $\mu_2(E) \leq \mu(E)$ ,  $\mu_2 \in H_0^{1,2}(\Sigma)$ , and therefore by 2.7 and 2.3,  $u_2 \in H_0^{1,2}(\Sigma)$ ). Given  $y \in E_2$ , define  $\omega(m, y) = \sup_{\substack{x_0 \in \bar{\Sigma} \\ x \in \bar{\Sigma}, |x - x_0| \leq 1/m}} |g(x, y) - g(x_0, y)|$ . By the definition of  $E_2$ ,

and 2.6 and 3.4,  $g(-, y)$  is continuous in  $\bar{\Sigma}$ . Thus,  $\omega(m, y)$  is a Borel function of  $y$ . Let  $E_{m,n} = \left\{ y \in E_2 : \omega(m, y) < \frac{1}{n} \right\}$ .

$E_{mn}$  are Borel sets, and for every fixed  $n$ ,  $E_{m,n} \nearrow E_2$ . Thus, given  $\mathcal{E} > 0$ , and  $n$ , we can find a closed set  $F_n$ ,  $F_n \subset E_{m,n}$ , so that  $\mu(E_2 \setminus F_n) < \frac{\mathcal{E}}{2^n}$ . Let now  $F_2 = \bigcap_n F_n$ , so that  $\mu(E_2 \setminus F_2) \leq \mathcal{E}$ .

Also, given  $\eta > 0$ , we can choose  $\delta = \delta(\eta)$  so that, for any  $y \in F_2$  and, for all  $x_0 \in \bar{\Sigma}$ ,  $x \in \bar{\Sigma}$ ,  $|x - x_0| \leq \delta$  implies that

$$|g(x, y) - g(x_0, y)| \leq \eta.$$

Thus,  $u_2(x)$  is continuous in  $\Sigma$ . For further reference, define  $\nu_2(E) = \mu(E \cap (E_2 \setminus F_2))$ , so that  $\nu_2(\Sigma) \leq \mathcal{E}$ , and

$$v_2(x) = \int g(x, y) d\nu_2(y).$$

By lemma 4.1, we know that for each  $x \in E_1$ , we have  $\lim_{r \rightarrow 0} \int_{|x-y| < r} g(x, y) d\mu(y) = 0$ . By standard measure theoretic arguments, given  $\mathcal{E} > 0$ , we can find a closed set  $F_1 \subset E_1$ , with  $\mu(E_1 \setminus F_1) \leq \mathcal{E}$ , so that given  $\delta > 0$ , there exists  $\eta = \eta(\delta)$  so that for all  $x \in F_1$ ,  $\int_{|x-y| < \eta} g(x, y) d\mu(y) < \delta$ . Let

$$\mu_1(E) = \mu(E \cap F_1), \text{ and } u_1(x) = \int g(x, y) d\mu_1(y).$$

We claim that  $u_1$  is continuous in  $\Sigma$ . It is enough to check it for  $x \in F_1$ . Let  $\{x_n\}$  be any sequence,  $x_n \rightarrow x_0 \in F_1$ . Then,

$$\begin{aligned} \overline{\lim}_n u_1(x_n) &= \overline{\lim}_n \int g(x_n, y) d\mu_1(y) \leq \int_{|x_0-y| > \eta} g(x_0, y) d\mu_1(y) \\ &\quad + \overline{\lim}_n \int_{|x_n-y| < \eta} g(x_n, y) d\mu_1(y). \end{aligned}$$

To analyze the last term, note that there exists a number  $N$ , depending only on the dimension of the space, such that for any  $x$  there exist  $N$  overlapping closed cases  $Q_v$ , with vertices at  $x$ , such that if  $\xi_v$  is the point of  $Q_v \cap F_1$  which is closest to  $x$ , any other point  $y \in F_1$  is closer to some  $\xi_v$  then to  $x$ . Because of 3.3, if the  $\xi_v$  are chosen for  $x = x_n$ ,  $g(x_n, y) \leq C \left( \sum_{v=1}^N g(\xi_v, y) \right)$  for all  $y \in F_1$ . Thus,

$$\begin{aligned} \overline{\lim}_n u_1(x_n) &\leq \int_{|y-x_0| > \eta} g(x_0, y) d\mu_1(y) \\ &\quad + C \overline{\lim}_n \sum_1^N \int_{|\xi_v-y| < \eta} g(\xi_v, y) d\mu_1(y) \\ &\leq \int_{|y-x_0| > \eta} g(x_0, y) d\mu_1(y) + CN\delta. \end{aligned}$$

Hence,  $\overline{\lim}_n u_1(x_n) \leq u_1(x_0)$ , and so from 3.6 we see that  $u_1$  is continuous at  $x_0$ .

Let  $\nu_1(E) = \mu(E \cap (E_1 \setminus F_1))$  so that

$$\nu_1(\Sigma) \leq \mathcal{E}, \text{ and } v_1(x) = \int g(x, y) d\nu_1(y).$$

Then,  $u(x) = u_1(x) + v_1(x) + u_2(x) + v_2(x)$ , and the  $u_i$  are continuous. Let  $S_n^1 = \{v_1 > 1/n\}$ ,  $S_n^2 = \{v_2 > 1/n\}$ . By 3.6 these sets are open. Let  $K \subset S_n^1$ ,  $K$  compact, and  $u_K$  its lower-semi-continuous capacitary potential.  $\frac{1}{n} \mu_K(K) \leq \int v_1 d\mu_K = \int u_K dv_1$  by 4.2. By the remarks in the proof of 4.1,  $u_K \leq 1$ , and so  $\text{cap}(S_n^1) \leq n\mathcal{E}$ . Similarly,  $\text{cap}(S_n^2) \leq n\mathcal{E}$ . Let  $\eta > 0$  be given, and

choose  $n_i \nearrow \infty$ ,  $\mathcal{E}_i \searrow 0$  so that  $\sum_i n_i \mathcal{E}_i \leq \eta/2$ . Let  $\mathcal{O} = \bigcup_i S_{n_i}^1 \cup \bigcup_i S_{n_i}^2$ . Then,  $\mathcal{O}$  is open, and  $\text{cap}(\mathcal{O}) \leq \eta$ . Also, it is easy to see that  $u$  is continuous in  $\Sigma \setminus \mathcal{O}$ , and thus the lemma follows.

We now turn to an alternative definition of capacity.

Let  $K$  be a compact subset of  $\Sigma$ . Then define

$$\text{cap}_1(K) = \sup \left\{ \nu(K) : \int g(x, y) d\nu(y) \leq 1 \text{ for all } x \in K, \right. \\ \left. \nu \text{ is a positive measure} \right\}.$$

Let  $\mu$  be the capacitary distribution of  $K$  and  $u$  the (lower semicontinuous representative of the) capacitary potential. By lower semicontinuity  $u(x) \leq 1$  for all  $x$ . Moreover,  $\mu(K) = \text{cap}(K)$ . Therefore,

$$(4.4) \quad \text{cap}_1(K) \geq \text{cap}(K).$$

We will say that an equality or inequality holds *p.p.* if it holds except on a set of  $\text{cap}_1$  size zero. The capacity  $\text{cap}_1$  is treated for instance in Carleson's book [1]. Although the hypotheses are slightly more restricted there, the same proofs hold with some modifications to take care of  $y$  with  $g(y, y) < +\infty$ , as in 3.6 and 4.3. In particular, we have ([1] Theorems 4 and 7, Chapter III.)

THEOREM 4.5. — *All analytic sets are capacitable for  $\text{cap}_1$ .*

THEOREM 4.6. — *For any compact set  $K \subset \Sigma$ , there exists a positive measure  $\nu$  supported on  $K$  such that*

$$v(x) = \int g(x, y) d\nu(y) \leq 1 \text{ everywhere } v(x) = 1 \text{ p.p. on } K \\ \text{and } \nu(K) = \text{cap}_1(K).$$

Our goal is to prove

THEOREM 4.7. — *With the notations above,  $\text{cap}_1(K) = \text{cap}(K)$ ,  $v = u$ ,  $\nu = \mu$ , and p.p. and q.e. are equivalent.*

THEOREM 4.8. —  $\nu$  belongs to  $H^{-1,2}(\Sigma)$ .

By 4.2,  $\iint g(x, y) d\nu(x) d\nu(y) = \int v(x) d\nu(x) \leq \nu(K) < \infty$ . Recall that  $G$  is an isomorphism  $G: H^{-1,2}(\Sigma) \cong H_0^{1,2}(\Sigma)$  and the norm on  $H_0^{1,2}(\Sigma)$  can be taken to be  $\|u\|_{H_0^{1,2}(\Sigma)} = D(u, u)^{1/2}$ . Let  $\Psi \in L^\infty(\Sigma, w)$ , then



$$\begin{aligned} \|\Psi w\|_{H^{-1,2}(\Sigma)}^2 &\cong D(G(\Psi w), G(\Psi w)) = \langle G(\Psi w), \Psi w \rangle \\ &= \iint g(x, y) \Psi(x) w(x) dx \Psi(y) w(y) dy. \end{aligned}$$

Let  $Q_{j,k}$  be a grid of non-overlapping cubes of side  $2^{-k}$  covering  $\Sigma$ . Let  $c_{j,k} = \nu(Q_{j,k})/w(Q_{j,k})$  and  $d\nu_k(x) = \sum_j c_{j,k} w(x) \chi_{Q_{j,k}}(x) dx$ . The measures  $\nu_k$  tend to  $\nu$  weakly (and hence in the sense of distributions). It therefore suffices to show that  $\|\nu_k\|_{H^{-1,2}(\Sigma)}$  is uniformly bounded as  $k \rightarrow \infty$ . Since  $\text{supp } \nu = K \subset \subset \Sigma$ , we can assume  $k$  is so small that all the cubes  $Q_{j,k}$  for which  $c_{j,k} \neq 0$ , have the property that their doubles are still contained in  $\Sigma$ .

$$\iint g(x, y) d\nu_k(x) d\nu_k(y) = \sum_{i,j} \iint g(x, y) w(x) dx w(y) dy c_{i,k} c_{j,k}.$$

By Harnack's inequality,  $g(x, y)$  is essentially constant for  $(x, y)$  in  $Q_{i,k} \times Q_{j,k}$  provided  $Q_{i,k}$  and  $Q_{j,k}$  are neither adjacent nor equal. Thus it is easy to dominate this part of the sum by the corresponding integral for  $\nu$ . To handle the case of pairs of nearby cubes, consider a ball  $B = B(x_0, 2^{-k+2})$ . Let  $\lambda = g(x_0, y)$  for some  $y \in \partial B$ . By Harnack's principle, if  $x, y \in B$  and  $|x - y| > \frac{1}{100} 2^{-k}$ , then  $g(x, y) \simeq \lambda$ . Furthermore, by 3.3, if  $x$  and  $y$  are any points of  $B$ , then  $Cg(x, y) \geq \lambda$ . Therefore,

$$C \int_B \int_B g(x, y) d\nu(x) d\nu(y) \geq \lambda \nu(B)^2.$$

Suppose that we can show for any  $x \in B$

$$\int_B g(x, y) w(y) dy \leq C \int_{2^{-k+1} < |x-y| < 2^{-k+2} \atop y \in B} g(x, y) w(y) dy. \quad (4.9)$$

Then the proof of 4.8 is concluded as follows. If  $Q_1$  and  $Q_2$  are cubes of side  $2^{-k}$  in  $B$ , then (recalling 1.2),

$$\begin{aligned} \int_{Q_1} \int_{Q_2} g(x, y) w(x) dx w(y) dy &\frac{\nu(Q_1)}{w(Q_1)} \frac{\nu(Q_2)}{w(Q_2)} \\ &\leq C \int_B \int_B g(x, y) w(x) dx w(y) dy \frac{\nu(Q_1)}{w(Q_1)} \frac{\nu(Q_2)}{w(Q_2)} \\ &\leq C \lambda w(B)^2 \frac{\nu(Q_1)}{w(Q_1)} \frac{\nu(Q_2)}{w(Q_2)} \\ &\leq C \lambda \nu(B)^2 \end{aligned}$$

$$\leq C \int_B \int_B g(x, y) dv(x) dv(y).$$

This shows that  $\iint g(x, y) dv_k(x) dv_k(y)$  is uniformly bounded.

To prove 4.9, note first that we can assume (for simplicity) that  $x = x_0$ . Denote  $w_i = w(B(x_0, 2^{-i}))$ ,  $L_i = \int_{2^{-i}}^R \frac{s^2}{w(B(x_0, s))} \frac{ds}{s}$ . Then the left hand side of 4.9 is equivalent to

$$\sum_{i=k}^{\infty} (w_i - w_{i+1}) L_i = w_k L_k + \sum_{i=k+1}^{\infty} w_i (L_i - L_{i-1}).$$

But  $w_i (L_i - L_{i-1}) = w(B(x_0, 2^{-i})) \int_{2^{-i}}^{2^{-i+1}} \frac{s^2}{w(B(x_0, s))} \frac{ds}{s} \simeq 2^{-2i}$ . In particular,  $w_i L_i \geq c 2^{-2i}$ . Hence

$$w_k L_k + \sum_{i=k+1}^{\infty} w_i (L_i - L_{i-1}) \simeq w_k L_k + 2^{-2k} \simeq w_k L_k,$$

and  $w_k L_k$  is comparable to the right hand side of 4.9.

*Proof of 4.7.* — By 4.4 and 4.6,  $v = 1$  q.e. on  $K$ . Hence, by 1.24, 1.25 and 4.2,  $\mu(K) = \int v d\mu = \int u dv$ . By the proof of 4.1,  $u \leq 1$ . Recall that  $u = 1$  on  $K$  in the  $H_0^{1,2}(\Sigma)$  sense. Thus, there exists a sequence  $\varphi_j \in \text{Lip}_0(\Sigma)$  such that  $\varphi_j \equiv 1$  on  $K$ , and  $\varphi_j \rightarrow u$  in  $H_0^{1,2}(\Sigma)$  norm. By 4.8, 4.3 and 1.29,

$$\int u dv = \lim_{j \rightarrow \infty} \int \varphi_j dv = \nu(K).$$

Thus,  $\text{cap}_1(K) = \text{cap}(K)$  and q.e. and p.p. are equivalent. By the proof of 4.3,  $v$  is quasi-continuous in  $\Sigma$ , and is also 1 q.e. on  $K$ . By 4.8, 1.29 and 2.3,  $D(v, v) = \int v dv = \nu(K) = \text{cap}(K)$ , so that  $D(v, v) = D(u, u)$ . By a similar argument,

$$D(v, u) = \int v d\mu = \mu(K) = \text{cap}(K).$$

Hence,  $u = v$  as elements of  $H_0^{1,2}(\Sigma)$  and by 2.3,  $\mu = \nu$ . But then,  $u = v$  pointwise.

THEOREM 4.10. — *The extremal problems*

$$A^{-1} = \inf \left\{ \iint g(x, y) dv(x) dv(y) : \nu(K) = 1, \nu \text{ a positive measure} \right\}$$

$$B = \inf \{ \nu(K) : \int g(x, y) d\nu(y) \geq 1 \text{ p.p. on } K \}$$

$$C = \sup \{ \nu(K) : \int g(x, y) d\nu(y) \leq 1 \text{ p.p. on } K \}$$

are equivalent so that  $A = B = C = \text{cap}(K)$ .

This is an easy consequence of 4.5, 4.6, and 4.7. (See [1], Theorem 5, Chapter III.) The pair of characterizations  $B$  and  $C$  and the formula for the Green function 3.3 make calculation of capacity up to a bounded factor as easy as in the classical case.

### 5. Regular points.

Let  $\Omega \subset \Sigma' = \left\{ z : |z| < \frac{1}{4} R \right\}$ . Denote by  $H$  the quotient space  $H^{1,2}(\Omega)/H_0^{1,2}(\Omega)$ . By Theorem 1.4, there is a bounded linear map  $B : H \rightarrow H^{1,2}(\Omega)$  such that if  $\bar{h} \in H^{1,2}(\Omega)$  represents an element  $h$  of  $H$ ,  $u = Bh$  satisfies  $Lu = 0$  in the  $H^{1,2}(\Omega)$  sense and  $u - \bar{h} \in H_0^{1,2}(\Omega)$ . Notice that by 1.8,  $Bh$  is Hölder continuous in  $\Omega$ . If  $\bar{h}$  is bounded on  $\partial\Omega$  in the  $H^{1,2}(\Omega)$  sense, then

$$\sup_{\Omega} |Bh| \leq \max_{\partial\Omega} |\bar{h}|,$$

where  $\max_{\partial\Omega} |\bar{h}|$  means the smallest number  $c$  such that  $\bar{h} \leq c$  and  $-\bar{h} \leq c$  on  $\partial\Omega$  in the  $H^{1,2}(\Omega)$  sense. In fact,  $\|Bh\| \leq C \max_{\partial\Omega} |\bar{h}|$ , where

$$\|g\| = \sup_{\Omega} |g| + \sup \left\{ r^M \frac{|g(x) - g(y)|}{|x - y|} : |x - y| < \frac{1}{2} r, \text{dist}(x, \partial\Omega) = r \right\}$$

for some large value of  $M$ . Since the restriction of  $C^\infty(\mathbb{R}^n)$  to  $\partial\Omega$  is dense in the space of continuous functions with the supremum norm,  $B$  extends uniquely to a mapping from continuous functions  $h$  on  $\partial\Omega$  to functions  $Bh$  that are Hölder continuous in  $\Omega$ . (It is also easy to see that  $LBh = 0$  in the  $H^{1,2}(\Omega')$  sense for any  $\Omega' \subset\subset \Omega$ ).

A point  $y \in \partial\Omega$  is *regular* if for every continuous function  $h$  on  $\partial\Omega$ , the solution  $u = Bh$  to the Dirichlet problem satisfies  $\lim_{\substack{x \rightarrow y \\ x \in \Omega}} u(x) = h(y)$ .

THEOREM 5.1 (Wiener test). —  $y \in \partial\Omega$  is regular if and only if

$$\begin{aligned} \text{a) } & \int_0^R \frac{s^2}{w(B(y, s))} \frac{ds}{s} < \infty, \text{ or} \\ \text{b) } & \int_0^R \text{cap}(K_\rho) \frac{\rho^2}{w(B(y, \rho))} \frac{d\rho}{\rho} = \infty, \end{aligned}$$

where  $K_\rho = (\Sigma \setminus \Omega) \cap B(y, \rho)$ .

COROLLARY 5.2. — The set of regular points of  $\partial\Omega$  depends only on  $w(x)$  and not on the particular operator  $L$ .

Conditions a) and b) are mutually exclusive. Condition a) does not depend on  $\Omega$ , so in case a)  $y$  is regular for any domain. (See (i)-(iv) of the introduction.)

Denote the capacitary distribution of  $K_\rho$  by  $\mu_\rho$ . Denote  $u_\rho(x) = \int g(x, y) d\mu_\rho(y)$  the lower semicontinuous representative of the capacitary potential of  $K_\rho$ . The following lemma is proved in the same way as the remark at the end of section 3 of [8].

LEMMA 5.3. —  $y$  is regular if and only if  $\lim_{\substack{x \rightarrow y \\ x \in \Sigma \setminus K_\rho}} u_\rho(x) = 1$  for all  $\rho > 0$ .

LEMMA 5.4. — Suppose that  $\text{cap}(\{y\}) = 0$ . Let  $\mu$  be a positive  $H^{-1,2}$  measure and  $u(x) = \int g(x, z) d\mu(z)$ . Then,

$$u(y) \geq \liminf_{x \rightarrow y} u(x).$$

*Proof.* — The proof follows closely the one of Lemma 8.1 of [8]. Let

$$F_a(t) = \begin{cases} t & t \leq a \\ t - \frac{1}{4a} (t - a)^2 & a \leq t \leq 3a \\ 2a & t \geq 3a \end{cases}$$

By monotone convergence,  $u(y) = \lim_{a \rightarrow \infty} \int F_a(g(y, z)) d\mu(z)$ . Since  $g(y, y) = +\infty$ ,  $F_a(g(y, -)) \in H_0^{1,2}(\Sigma) \cap C(\bar{\Sigma})$ , and is the weak solution of

$LF_a(g(y, -))$

$$= \begin{cases} \frac{1}{2a} a_{ij} \partial_i g(y, x) \partial_j g(y, x) & \text{on } a \leq g(y, -) \leq 3a \\ 0 & \text{elsewhere} \end{cases} = f(x) dx,$$

where  $f \in L^1(dx)$ . By 1.28,  $F_a(g(y, -)) = \int g(x, z) f(z) dz$  q.e., and so, because of 1.25, and 4.2

$$\int F_a(g(y, z)) d\mu(z) = \frac{1}{2a} \int u(x) a_{ij} \partial_i g(y, x) \partial_j g(y, x) dx.$$

By our assumption on  $y$ ,  $\{x : a \leq g(y, x) \leq 3a\}$  shrinks to  $y$  as  $a \rightarrow \infty$ . Also,  $y \in \text{int } J_a$ , where  $J_a = \{x : g(y, x) \geq a\}$ , by 3.4, and by 2.6.  $\partial J_a = \{x : g(y, x) = a\}$ . Let  $\nu$  be the capacitary distribution of  $J_a$ ,  $\nu(x) = \int g(x, z) d\nu(z)$ . Then,

$$1 = \nu(y) = \int_{\partial J_a} g(y, z) d\nu(z) = a \text{ cap}(J_a),$$

so that  $\text{cap}(J_a) = \frac{1}{a}$ . By the remarks prior to 1.21, we see that  $\nu$  equals 1 on  $J_a$ , and  $\frac{g(y, x)}{a}$  on  $\Sigma \setminus J_a$ , so that

$$\frac{1}{a} = \text{cap}(J_a) = \frac{1}{a^2} \int_{\Sigma \setminus J_a} a_{ij} \partial_i g(y, x) \partial_j g(y, x) dx.$$

(Here we used the fact that  $\nabla h = 0$  a.e. on the set where  $h = 0$ , for  $h \in H_0^{1,2}(\Sigma)$ . See the remark prior to Lemma 2.1 in [5].) Therefore,

$$\frac{1}{2a} \int_{a < g < 3a} a_{ij} \partial_i g(y, x) \partial_j g(y, x) dx = 1.$$

Hence,

$$u(y) = \lim_{a \rightarrow \infty} \frac{1}{2a} \int u(x) a_{ij} \partial_i g(y, x) \partial_j g(y, x) dx \geq \liminf_{x \rightarrow y} u(x).$$

LEMMA 5.5. — Suppose that  $\text{cap}\{y\} = 0$ , and that  $u$  is the lower semi-continuous capacitary potential of a compact set  $K$ . Then,

$$u(y) = \liminf_{\substack{x \rightarrow y \\ x \in \Sigma \setminus K}} u(x).$$

*Proof.* — By 3.6,  $u(y) \leq \liminf_{\substack{x \rightarrow y \\ x \in \Sigma \setminus K}} u(x)$ . Let

$$\bar{u}(x) = \begin{cases} u(x) & \text{in } \Sigma \setminus K \\ 1 & \text{in } K \end{cases}.$$

Then,  $u(x) = \bar{u}(x)$  a.e., and the proof of lemma 5.4 shows that

$u(y) \geq \liminf_{x \rightarrow y} \bar{u}(x)$ . Now, by the proof of 4.1,  $u(x) \leq 1$ , and so  $\liminf_{x \rightarrow y} \bar{u}(x) = \liminf_{\substack{x \rightarrow y \\ x \in \Sigma \setminus K}} u(x)$ , and the lemma follows.

**COROLLARY 5.6.** — *Suppose that  $\text{cap}\{y\} = 0$ . Then  $y$  is regular if and only if  $u_\rho(y) = 1$  for all  $\rho > 0$ .*

The corollary follows from 5.3 and 5.5.

The following lemma follows closely 9.8 of [8].

**LEMMA 5.7.** — *Suppose that  $\text{cap}(\{y\}) = 0$ . Then,  $y$  is not regular if and only if  $\lim_{\rho \rightarrow 0} u_\rho(y) = 0$ .*

*Proof.* — If  $u_\rho(y) \rightarrow 0$ , by 5.6  $y$  is irregular. Assume now that  $y$  is irregular. Because  $u_\rho(y) \leq 1$  (see the proof of 4.1), we must have  $u_{\rho_0}(y) < 1$  for some  $\rho_0$ , by 5.6. By 4.1, given  $\mathcal{E} > 0$ , we can find  $\sigma < \rho_0$  such that  $\int_{|z-y|>\sigma} g(y, z) d\mu_{\rho_0}(z) \leq \mathcal{E}$ . Let  $v(x) = \int_{|z-y|>\sigma} g(x, z) d\mu_{\rho_0}(z)$ ,  $u(x) = \int_{|z-y|>\sigma} g(x, z) d\mu_{\rho_0}(z)$ . Then  $u_{\rho_0}(x) = v(x) + u(x)$ ,  $v(y) \leq \mathcal{E}$ , and in view of 2.7 and 2.3,  $v, u \in H^{1,2}_0(\Sigma)$ . Also  $u$  is continuous at  $y$ ,  $u(y) \leq u_{\rho_0}(y) < 1$ . Hence, there is a  $\tau$  with  $2\tau < \sigma$  such that  $u(x) \leq \frac{1}{2}(1 + u_{\rho_0}(y))$  on  $B(y, 2\tau)$ . Therefore, by the claim in the beginning of the proof of 1.30,  $v(x) = 1 - u(x) \geq \frac{1}{2}(1 - u_{\rho_0}(y))$  on  $K_\tau$  in the  $H^{1,2}(\Sigma)$  sense. Since  $u_{\rho_0}(x) \equiv 1$  on  $K_{\rho_0}$ , and hence on  $K_\tau$  in  $H^{1,2}(\Sigma)$  sense,  $v(x) \geq \frac{1}{2}(1 - u_{\rho_0}(y))u_{\rho_0}(x)$  on  $K_\tau$  in the  $H^{1,2}(\Sigma)$  sense. By 1.20, 2.3 and 1.18,  $v(x) \geq \frac{1}{2}(1 - u_{\rho_0}(y))u_\tau(x)$  almost everywhere in  $\Sigma \setminus K_\tau$ . Choose now  $\mathcal{E} < \frac{1}{2}(1 - u_{\rho_0}(y))$ . Then, as  $v(x) \geq \frac{1}{2}(1 - u_{\rho_0}(y))$  a.e. on  $K_\tau$ , and  $v(y) \leq \mathcal{E}$ ,  $v(x)$  is bounded away from  $v(y)$  a.e. on  $K_\tau$ . Because of 3.6,  $v(y) \leq \liminf_{\substack{x \rightarrow y \\ x \in \Sigma \setminus K_\tau}} v(x)$ , and the proof of 5.4 shows that  $v(y) \geq \liminf_{\substack{x \rightarrow y \\ x \in \Sigma \setminus K_\tau}} \bar{v}(x)$ , for any  $\bar{v}$  which equals  $v$  a.e. Thus,  $v(y) = \liminf_{\substack{x \rightarrow y \\ x \in \Sigma \setminus K_\tau}} v(x)$ . On  $\Sigma \setminus K_\sigma$ ,  $u_\tau$

and  $v$  are continuous, and so,  $v(x) \geq \frac{1}{2} (1 - u_{\rho_0}(y)) u_r(x)$  everywhere in  $\Sigma \setminus K_\sigma$ . Moreover, by 5.5,  $u_r(y) = \liminf_{\substack{x \rightarrow y \\ x \in \Sigma \setminus K_r}} u_r(x)$ . Thus,

$$\begin{aligned} \mathcal{E} \geq v(y) &= \liminf_{\substack{x \rightarrow y \\ x \in \Sigma \setminus K_r}} v(x) \geq \frac{1}{2} (1 - u_{\rho_0}(y)) \liminf_{\substack{x \rightarrow y \\ x \in \Sigma \setminus K_r}} u_r(x) \\ &= \frac{1}{2} (1 - u_{\rho_0}(y)) u_r(y). \end{aligned}$$

Therefore, the lemma follows.

LEMMA 5.8. — If  $\rho > r$ , then

$$\mu_r(K_r) = \mu_\rho(K_r) + \int_{K_\rho \setminus K_r} u_r d\mu_\rho.$$

In particular,  $\mu_\rho(K_r) \leq \mu_r(K_r) = \text{cap}(K_r)$ .

*Proof.* — By 1.25, 4.6, 4.7 and 4.2

$$\begin{aligned} \mu_r(K_r) &= \int u_\rho d\mu_r = \int u_r d\mu_\rho = \int_{K_r} u_r d\mu_\rho + \int_{K_\rho \setminus K_r} u_r d\mu_\rho \\ &= \mu_\rho(K_r) + \int_{K_\rho \setminus K_r} u_r d\mu_\rho. \end{aligned}$$

*Proof of 5.1.*

*Case I*  $\text{cap}(\{y\}) > 0$ .

Let  $u$  be the (continuous representative of the) capacitary potential of  $\{y\}$ . (See the proof of 3.4). By the maximum principle,  $u(x) \leq u_\rho(x)$  for  $x \in \Sigma \setminus K_\rho$ . But by 3.4,  $\lim_{x \rightarrow y} u(x) = 1$ , so  $\lim_{x \rightarrow y} u_\rho(x) = 1$  in  $\Sigma \setminus K_\rho$  and  $y$  is regular by Lemma 5.3. Moreover,  $\text{cap}(\{y\}) > 0$  is equivalent to (a).

*Case II*  $\text{cap}(\{y\}) = 0$ .

$$\begin{aligned} u_\rho(y) &= \int_{K_\rho} g(x, y) d\mu_\rho(x) \simeq \sum_{j=0}^{\infty} \int_{2^{-j}\rho}^{2^{-j+1}\rho} \frac{s^2}{w(B(y, s))} \frac{ds}{s} (\mu_\rho(K_{2^{-j}\rho}) \\ &\quad - \mu_\rho(K_{2^{-j-1}\rho})). \end{aligned}$$

Notice that by 4.1,

$$\lim_{r \rightarrow 0} u_\rho(K_r) \int_r^R \frac{s^2}{w(B(y, s))} \frac{ds}{s} \leq c \lim_{r \rightarrow 0} \int_{K_r} g(x, y) d\mu_\rho(x) = 0.$$

Therefore, we can apply summation by parts and obtain

$$(5.9) \quad u_\rho(y) \cong \mu_\rho(K_\rho) \int_\rho^R \frac{s^2}{w(B(y, s))} \frac{ds}{s} + \int_0^\rho \frac{r^2}{w(B(y, r))} \mu_\rho(K_r) \frac{dr}{r}.$$

Denote  $c(\rho) = \text{cap}(K_\rho)$  and  $\theta(s) = s/w(B(y, s))$ . Then by 5.8,  $u_\rho(y) \leq c(\rho) \int_\rho^R \theta(s) ds + \int_0^\rho c(s) \theta(s) ds$ . Suppose that (b) fails, then  $\int_0^R c(s) \theta(s) ds = C < \infty$ . Evidently,  $\int_0^\rho c(s) \theta(s) ds$  tends to zero as  $\rho \rightarrow 0$ . Choose  $\delta_2 > 0$  so that  $\int_0^{\delta_2} c(s) \theta(s) ds < \mathcal{E}$ . Since,  $c(s)$  is increasing and  $\lim_{s \rightarrow 0} c(s) = 0$  (see the proof of 3.4) we can choose  $\delta_1 < \delta_2$  so that for all  $\rho < \delta_1$ ,  $c(\rho) < \mathcal{E} c(\delta_2)$ . Now, for  $\rho < \delta_1$

$$c(\rho) \int_\rho^R \theta(s) ds \leq \int_\rho^{\delta_2} c(s) \theta(s) ds + \mathcal{E} \int_{\delta_2}^R c(s) \theta(s) ds \leq \mathcal{E} + C \mathcal{E}.$$

In all,  $u_\rho(y)$  tends to zero as  $\rho \rightarrow 0$ , so that  $y$  is not regular (Lemma 5.7).

Conversely, suppose that  $y$  is not regular. 5.9 implies that

$\int_0^\rho \frac{r^2}{w(B(y, r))} \mu_\rho(K_r) \frac{dr}{r}$  is finite. To prove (b) fails, it suffices to show that  $c(r/2) \leq 2 \mu_\rho(K_r)$  for  $r \leq \rho$  and  $\rho$  sufficiently small. In fact,

$$c(r/2) = \mu_{r/2}(K_{r/2}) = \mu_\rho(K_{r/2}) + \int_{K_\rho \setminus K_{r/2}} u_{r/2} d\mu_\rho \leq \mu_\rho(K_r) + \int_{K_\rho \setminus K_{r/2}} u_{r/2} d\mu_\rho.$$

By Harnack's principle and 3.3, if  $x \in K_\rho \setminus K_r$  and  $z \in K_{r/2}$ , then  $g(x, z) \leq Cg(x, y)$ . Hence

$$\begin{aligned} \int_{K_\rho \setminus K_r} u_{r/2} d\mu_\rho &= \int_{K_\rho \setminus K_r} \int_{K_{r/2}} g(x, z) d\mu_{r/2}(z) d\mu_\rho(x) \\ &\leq C \int_{K_\rho \setminus K_r} \int_{K_{r/2}} g(x, y) d\mu_{r/2}(z) d\mu_\rho(x) \leq Cu_\rho(y) c(r/2). \end{aligned}$$

Thus,  $c(r/2) \leq \mu_\rho(K_r) + Cu_\rho(y) c(r/2)$ . Since  $u_\rho(y)$  tends to zero as  $\rho \rightarrow 0$ ,  $c(r/2) \leq 2 \mu_\rho(K_r)$  for sufficiently small  $\rho$ .



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