HEAT KERNELS AND GREEN FUNCTIONS ON METRIC MEASURE SPACES

ALEXANDER GRIGOR’YAN AND JIAxin hu

Abstract. We prove that, in a setting of local Dirichlet forms on metric measure spaces, a two-sided sub-Gaussian estimate of the heat kernel is equivalent to the conjunction of the volume doubling property, the elliptic Harnack inequality and a certain estimate of the capacity between concentric balls. The main technical tool is the equivalence between the capacity estimate and the estimate of a mean exit time in a ball, that uses two-sided estimates of a Green function in a ball.

Contents

1. Introduction 2
2. Heat semigroups 3
3. Description of the results 5
4. Maximum principles 10
5. Green operator and Green function 14
5.1. Green operator 14
5.2. Harnack inequality and existence of Green function 15
6. Some Potential theory 26
6.1. Riesz measures associated with superharmonic functions 26
6.2. Reduced function 30
6.3. Capacitary measure 32
7. Resistance 34
7.1. Green function and resistance 34
7.2. Estimates of the Green function 38
7.3. Continuity of $G^\Delta f$ 40
8. Proof of Theorem 3.10 44
8.1. Implication $(H) + (R_F) \Rightarrow (G_F)$ 44
8.2. Equivalence $(HG') \iff (H)$ 46
8.3. Implication $(G_F) \Rightarrow (H) + (E_F)$ 48
8.4. Implication $(H) + (E_F) \Rightarrow (H) + (R_F)$ 49
9. Appendix 51
9.1. Capacity 51
9.2. Functions in $\mathcal{F}(\Omega \setminus A)$ 53
References 55

Date: September 2012.

Key words and phrases. Dirichlet form, heat kernel, Green function, capacity.

AG was supported by SFB 701 of the German Research Council(DFG).
JH was supported by NSFC (Grant No. 11071138) and SFB 701.

2010 Mathematics Subject Classification. Primary: 35K08 Secondary: 28A80, 31B05, 35J08, 46E35, 47D07.
1. Introduction

We are concerned with the heat kernel estimates for any regular Dirichlet form on a metric measure space. The heat kernel is the surprising source of many phenomena in various scientific areas. There are a vast literature to devote to some of these questions, for example, in [2, 6, 13, 14, 15, 17, 32, 33, 34, 36, 37, 38, 39] for the Euclidean spaces or Riemannian manifolds, in [8, 10, 24, 25] for torus or infinite graphs, in [3, 5, 9, 27] for certain classes of fractals and in [12, 26, 28, 30, 31, 41, 19, 20] for metric spaces.

In this paper we are concerned with certain conditions that are equivalent to sub-Gaussian two-sided estimates of the heat kernel for all range of time and space variables. In the simplest case the sub-Gaussian estimate has the following form

\[ p_t(x, y) \cong \frac{C}{V(x, t^{1/\beta})} \exp \left( -c \left( \frac{d^\beta(x, y)}{t} \right)^{\frac{1}{\beta-1}} \right) \]

where \( p_t(x, y) \) is the heat kernel in question, \( d(x, y) \) is a metric, \( V(x, r) \) is the volume function of a metric ball, and \( \beta > 1 \) is a parameter that is called the walk dimension. One of our main results – Theorem 3.12, ensures that, under some simple assumptions about the volume function, such an estimate of the heat kernel is equivalent to the following two conditions: the uniform Harnack inequality for harmonic functions and the following estimate of the resistance between two concentric balls \( B = B(x, r) \) and \( KB = B(x, Kr) \):

\[ \text{res} (B, KB) \cong \frac{r^\beta}{V(x, r)}, \quad (1.1) \]

where \( K \) is a large fixed constant. On the other hand, such a sub-Gaussian estimate of the heat kernel is equivalent to a certain two-sided estimate of the Green function.

The main technical result of the paper is Theorem 3.10 that ensures the equivalence of the resistance condition (1.1) to a certain mean exit time estimate from a metric ball. To obtain Theorem 3.12, we then combine Theorem 3.10 with the results of [26] and [20].

In Section 2 we give necessary background material about abstract heat semigroups. In Section 3 we state the two above mentioned theorems, and prove Theorem 3.12 by using Theorem 3.10. The proof of Theorem 3.10 is postponed to Section 8 after we develop necessary tools for that.

In Section 5 we prove some properties of the Green operator, in particular, the existence of its kernel – the Green function, under the Harnack inequality. The most challenging result in this section is to obtain an annulus Harnack inequality for the Green function, without assuming any specific properties of the metric \( d \), unlike previously known similar results [4], [25] where the geodesic property of the distance function was used. A desire to have the results for a general metric \( d \) is motivated by a number of applications. For example, the proof of the uniqueness of Brownian motion on Sierpinski carpet in [7] uses Theorem 3.12. Another possible application could be on self-similar fractals with a resistance metric.

In Section 6 we prove a representation formula for superharmonic functions via Riesz measures. This type of results is known in abstract Potential Theory [11], but
in our setting those results are not directly applicable, and so we give an independent proof based on the heat semigroup.

In Section 7 we prove the pointwise estimates of the Green function using Harnack inequality and the resistance estimate. This type of estimates was known on graphs [25] and on smooth manifolds [17], but the present singular setting imposes certain difficulties that we overcome using the potential-theoretic tools from the previous sections.

In Section 8 we give the proof of Theorem 3.10 using all the machinery developed in the previous sections.

Appendix 9 contains some auxiliary properties of capacities and Dirichlet forms.

Acknowledgement. The authors thank Wolfhard Hansen for valuable conversations on the topics of this paper.

Notation. The sign \( \simeq \) below means that the ratio of the two sides is bounded from above and below by positive constants. The letters \( C, C', c, c' \) will always refer to positive constants, whose values are unimportant and may change at each occurrence. The sign \( U \Subset \Omega \) means that \( U \) is precompact and \( \overline{U} \subset \Omega \). For any bilinear form \( \mathcal{E}(f,g) \) set \( \mathcal{E}(f) := \mathcal{E}(f,f) \). If \( B \) is a ball of radius \( r \) then \( \lambda B \) is the concentric ball with radius \( \lambda r \).

2. Heat semigroups

Throughout the paper, we assume that \((M,d)\) is a locally compact separable metric space and \(\mu\) is a Radon measure on \(M\) with full support. We refer to such a triple \((M,d,\mu)\) as a metric measure space.

Denote by
\[
B(x,r) = \{ y \in M : d(x,y) < r \}
\]
the open metric ball of radius \( r > 0 \) centered at \( x \). We always assume that every ball \( B(x,r) \) is precompact. In particular, the volume function
\[
V(x,r) := \mu(B(x,r))
\]
is finite and positive for all \( x \in M \) and \( r > 0 \).

Let \((\mathcal{E},\mathcal{F})\) be a Dirichlet form in \(L^2(M,\mu)\). Recall that \((\mathcal{E},\mathcal{F})\) is regular if \(\mathcal{F} \cap C_0(M)\) is dense both in \(\mathcal{F}\) and in \(C_0(M)\), where \(C_0(M)\) is the space of all continuous functions with compact support in \(M\), endowed with sup-norm. The form \((\mathcal{E},\mathcal{F})\) is strongly local if \(\mathcal{E}(f,g) = 0\) for any \(f,g \in \mathcal{F}\) with compact supports, such that \(f \equiv \text{const}\) in an open neighborhood of \(\text{supp } g\).

Let \(\mathcal{L}\) be the generator of \(\mathcal{E}\), that is, \(\mathcal{L}\) is a self-adjoint and non-positive definite operator in \(L^2(M,\mu)\) with the domain \(\text{dom}(\mathcal{L})\) that is dense in \(\mathcal{F}\) and such that, for all \(f \in \text{dom}(\mathcal{L})\) and \(g \in \mathcal{F}\),
\[
\mathcal{E}(f,g) = -(\mathcal{L}f,g),
\]
where \((\cdot,\cdot)\) is the inner product in \(L^2(M,\mu)\). The associated heat semigroup
\[
P_t = e^{t\mathcal{L}}, \quad t \geq 0,
\]
is a family of contractive, strongly continuous, self-adjoint operators in \(L^2(M,\mu)\) that satisfies the Markovian property (cf. [16]).
Recall that for any $f \in L^2(M, \mu)$, the function
\[ t \mapsto \frac{1}{t} (f - P_t f, f) \]
is increasing as $t$ is decreasing, and for any $f \in \mathcal{F}$,
\[ \lim_{t \to 0^+} \frac{1}{t} (f - P_t f, f) = \mathcal{E}(f). \]  
(2.1)

The form $(\mathcal{E}, \mathcal{F})$ is called conservative if $P_t 1 = 1$ for every $t > 0$.

A family $\{p_t\}_{t > 0}$ of non-negative $\mu \times \mu$-measurable functions on $M \times M$ is called the heat kernel of the form $(\mathcal{E}, \mathcal{F})$ if $p_t$ is the integral kernel of the operator $P_t$, that is, for any $t > 0$ and for any $f \in L^2(M, \mu)$,
\[ P_t f(x) = \int_M p_t(x, y) f(y) \, d\mu(y) \] 
(2.2)
for $\mu$-almost all $x \in M$.

For a non-empty open $\Omega \subset M$, let $\mathcal{F}(\Omega)$ be the closure of $\mathcal{F} \cap C_0(\Omega)$ in the norm of $\mathcal{F}$. It is known that if $(\mathcal{E}, \mathcal{F})$ is regular, then $(\mathcal{E}, \mathcal{F}(\Omega))$ is also a regular Dirichlet form in $L^2(\Omega, \mu)$. Denote by $P^\Omega_t$ the heat semigroup of $(\mathcal{E}, \mathcal{F}(\Omega))$, and $\mathcal{L}^\Omega$ the generator of $(\mathcal{E}, \mathcal{F}(\Omega))$.

Recall that for any regular Dirichlet form $(\mathcal{E}, \mathcal{F})$, there is an associated Hunt process\(^1\). Denote by $X_t, t \geq 0$, the trajectories of a process and by $\mathbb{P}_x, x \in M$, the probability measure in the space of trajectories emanating from the point $x$. Denote by $\mathbb{E}_x$ the expectation of the probability measure $\mathbb{P}_x$. Then the relation between the Dirichlet form and the associated Hunt process is given by the following identity:
\[ P_t f(x) = \mathbb{E}_x f(X_t), \] 
(2.3)
which holds for any bounded Borel function $f$, for every $t > 0$, and for $\mu$-almost all $x \in M$ (note that $P_t f$ is a function from $L^\infty$ and, hence, is defined up to a set of measure zero, whereas $\mathbb{E}_x f(X_t)$ is defined pointwise for all $x \in M$). By [16, Theorem 7.2.1, p.380], such a process always exists but, in general, is not unique. Let us fix one of such processes once and for all. If $(\mathcal{E}, \mathcal{F})$ is local, then the Hunt process $X_t$ is a diffusion, that is, the sample path $t \mapsto X_t$ is continuous almost surely.

**Example 2.1.** Let $M$ be a connected Riemannian manifold, $d$ be the geodesic distance on $M$, $\mu$ be the Riemannian volume. Define the space
\[ W^1 = \{ f \in L^2 : \nabla f \in L^2 \} \]
where $L^2 = L^2(M, \mu)$ and $\nabla f$ is the Riemannian gradient of $f$ understood in the weak sense. For all $f, g \in W^1$, one defines the energy form
\[ \mathcal{E}(f, g) = \int_M (\nabla f, \nabla g) \, d\mu. \]

Let $\mathcal{F}$ be the closure of $C_0^\infty(M)$ in $W^1$. Then $(\mathcal{E}, \mathcal{F})$ is a regular strongly local Dirichlet form in $L^2(M, \mu)$. The heat kernel admits (cf. [2]) the two-sided Gaussian\(^1\) form.

---

\(^1\)Loosely speaking, a Hunt process is a strong Markov process whose sample paths are right continuous and have left limit almost surely.
bounds
\[ p_t(x, y) \asymp \frac{C}{t^{n/2}} \exp \left( -\frac{|x - y|^2}{ct} \right). \]

Similar bounds hold also on some classes of Riemannian manifolds (see [18], [32]). Note that in the above examples the Dirichlet form is \textit{local} and, hence, the corresponding Hunt process is a diffusion.

\textbf{Example 2.2.} On some classes of fractals the heat kernel is known to exist and to satisfy the following \textit{sub-Gaussian} estimate:
\[ p_t(x, y) \asymp \frac{C}{t^{\alpha/\beta}} \exp \left( -\left( \frac{d(x, y)}{ct^{1/\beta}} \right)^{\beta/(\beta-1)} \right), \]
for all \( t > 0 \) and \( \mu \times \mu \)-almost all \( x, y \in M \). Here \( d(x, y) \) is an appropriate distance function, and \( \alpha > 0 \) and \( \beta > 1 \) are some parameters that characterize the underlying space in question.

3. Description of the results

Let us introduce some definitions needed in this paper.

\textbf{Definition 3.1.} Let \( \Omega \) be an open subset of \( M \). We say that a function \( u \in \mathcal{F} \) is \textit{harmonic} in \( \Omega \) if
\[ \mathcal{E}(u, v) = 0 \text{ for any } v \in \mathcal{F}(\Omega). \]
A function \( u \in \mathcal{F} \) is \textit{superharmonic} in \( \Omega \) if
\[ \mathcal{E}(u, v) \geq 0 \text{ for any nonnegative } v \in \mathcal{F}(\Omega), \]
and is \textit{subharmonic} in \( \Omega \) if
\[ \mathcal{E}(u, v) \leq 0 \text{ for any nonnegative } v \in \mathcal{F}(\Omega). \]

\textbf{Definition 3.2.} We say that the \textit{elliptic Harnack inequality} \((H)\) holds on \( M \) if, there exist constants \( C_H > 1 \) and \( \delta \in (0, 1) \) such that, for any ball \( B(x_0, r) \) in \( M \) and for any function \( u \in \mathcal{F} \) that is harmonic and non-negative in \( B(x_0, r) \), the following inequality is satisfied:
\[ \text{esup}_{B(x_0, \delta r)} u \leq C_H \text{ einf}_{B(x_0, r)} u. \quad (H) \]
Let us emphasize that the constants \( C_H \) and \( \delta \) are independent of the ball \( B(x_0, r) \) and the function \( u \).

\textbf{Definition 3.3.} We say that the \textit{volume doubling} property \((VD)\) holds if there exists a constant \( C_D \) such that, for all \( x \in M \) and all \( r > 0 \)
\[ V(x, 2r) \leq C_D V(x, r). \quad (VD) \]
It is known that \((VD)\) implies that, for all \( x, y \in M \) and \( 0 < r \leq R \),
\[ \frac{V(x, R)}{V(y, r)} \leq C_D \left( \frac{R + d(x, y)}{r} \right)^{\alpha}, \quad (3.1) \]
for some \( \alpha > 0 \) (see for example [20]).
Definition 3.4. We say that the reverse volume doubling property (RVD) holds if, there exist positive constants $\alpha'$ and $c$ such that, for all $x \in M$ and $0 < r \leq R$,
\[
V(x, R) \geq c \left( \frac{R}{r} \right)^{\alpha'}.
\] (3.2)

Recall that (VD) implies (RVD) if $M$ is connected and unbounded (cf. [20]). Let $F$ be a continuous increasing bijection of $(0, \infty)$ onto itself, such that, for all $0 < r \leq R$,
\[
C^{-1} \left( \frac{R}{r} \right)^{\beta} \leq \frac{F(R)}{F(r)} \leq C \left( \frac{R}{r} \right)^{\beta'},
\] (3.3)
for some constants $1 < \beta \leq \beta'$ and $C > 1$. Consider the inverse function $R = F^{-1}$. Obviously (3.3) implies that
\[
C^{-1} \left( \frac{T}{t} \right)^{1/\beta'} \leq \frac{R(T)}{R(t)} \leq C \left( \frac{T}{t} \right)^{1/\beta},
\] (3.4)
for all $0 < t \leq T$.

Definition 3.5. Let $\Omega$ be an open set and $A$ be a Borel subset of $\Omega$. Define the capacity $\text{cap}(A, \Omega)$ by
\[
\text{cap}(A, \Omega) := \inf \{ \mathcal{E}(\varphi) : \varphi \text{ is a cutoff function of } (A, \Omega) \}.
\] (3.5)
For simplicity, denote by
\[
\text{cap}(A) := \text{cap}(A, M).
\]

Recall that a cutoff function $\phi$ of $(A, \Omega)$ means that $\phi \in \mathcal{F} \cap C_0(\Omega)$, $0 \leq \phi \leq 1$ in $M$, and $\phi = 1$ in a neighborhood of $A$. It is known that if $(\mathcal{E}, \mathcal{F})$ is regular, then for any open set $\Omega \subset M$ and any set $A \subset \Omega$, there is a cutoff function of $(A, \Omega)$ (see [16, Lemma 1.4.2(ii), p.29]).

Note that $\text{cap}(A)$ here is different than the 0-order capacity $\text{Cap}_0(A)$ defined as in [16, p.74] where
\[
\text{Cap}_0(A) := \inf \{ \mathcal{E}(\varphi) : \varphi \in \mathcal{F}_c, \varphi \geq 1 \text{ on } A \},
\]
where $\mathcal{F}_c$ consists of all functions $u$ (cf. [16, p.40]) such that $|u(x)| < \infty$, $u_k(x) \to u(x)$ for $\mu$-a.e. $x \in M$, where the sequence $\{u_k\} \subset \mathcal{F}$ satisfies
\[
\mathcal{E}(u_k - u_m) \to 0 \quad (n, m \to \infty).
\]
Clearly, for any Borel set $A$,
\[
\text{cap}(A) \geq \text{Cap}_0(A).
\] (3.6)

Recall that each $u \in \mathcal{F}$ admits a quasi-continuous version $\tilde{u}$ with respect to 0-order capacity $\text{Cap}_0(A)$ [16, Theorems 2.1.3 (p.71) and 2.1.6 (p.74)]. In Appendix, we shall show a similar result but with respect to our capacity $\text{cap}(A)$. Precisely, a function $u$ is cap-quasi-continuous if, for every $\varepsilon > 0$, there exists an open set $U \subset M$ such that $u$ is continuous on $M \setminus U$, and
\[
\text{cap}(U) < \varepsilon.
\] (3.7)

Then any function $u \in \mathcal{F}$ admits a cap-quasi-continuous version $\tilde{u}$ (see Lemma 9.1 in Appendix). Note that, thanks to (3.6), if $u$ is cap-quasi-continuous, then it is also quasi-continuous in the sense of [16, p.69].
By definition, the capacity $\text{cap}(A, \Omega)$ is increasing in $A$, and decreasing in $\Omega$, namely, if $A_1 \subset A_2, \Omega_1 \subset \Omega_2$, then $\text{cap}(A_1, \Omega) \leq \text{cap}(A_2, \Omega)$, and $\text{cap}(A, \Omega_1) \geq \text{cap}(A, \Omega_2)$.

We define the \textit{resistance} $\text{res}(A, \Omega)$ by

$$\text{res}(A, \Omega) = \frac{1}{\text{cap}(A, \Omega)}.$$  \hspace{1cm} (3.8)

\textbf{Definition 3.6.} We say that the \textit{resistance condition} $(R_F)$ is satisfied if, there exist constants $K, C > 1$ such that, for any ball $B$ of radius $r > 0$,

$$C^{-1} \frac{F(r)}{\mu(B)} \leq \text{res}(B, KB) \leq C \frac{F(r)}{\mu(B)}, \hspace{1cm} (3.9)$$

where constants $K$ and $C$ are independent of the ball $B$. Equivalently, (3.9) can be written in the form

$$\text{res}(B, KB) \simeq \frac{F(r)}{\mu(B)}. \hspace{1.5cm} (R_F)$$

We introduce the notions of the Green operator and the Green function.

\textbf{Definition 3.7.} For an open $\Omega \subset M$, a linear operator $G^\Omega : L^2(\Omega) \rightarrow \mathcal{F}(\Omega)$ is called a \textit{Green operator} if, for any $\varphi \in \mathcal{F}(\Omega)$ and any $f \in L^2(\Omega)$,

$$E(G^\Omega f, \varphi) = (f, \varphi). \hspace{1cm} (3.10)$$

If $G^\Omega$ admits an integral kernel $g^\Omega$, that is,

$$G^\Omega f(x) = \int_\Omega g^\Omega(x, y)f(y)d\mu(y) \text{ for any } f \in L^2(\Omega), \hspace{1cm} (3.11)$$

then $g^\Omega$ is called a \textit{Green function}.

We will address the existence and the properties of the Green operator $G^\Omega$ in Lemma 5.1. The issue of the Green function $g^\Omega$ is much more involved, and is one of the key topics in this paper (cf. Lemmas 5.2, 5.3, and 5.7).

For an open set $\Omega \subset M$, the function $E^\Omega$ is defined by

$$E^\Omega(x) := G^\Omega 1(x) \ (x \in M), \hspace{1cm} (3.12)$$

namely, the function $E^\Omega$ is a unique weak solution of the following Poisson-type equation

$$-L^\Omega E^\Omega = 1, \hspace{1cm} (3.13)$$

provided that $\lambda_{\text{min}}(\Omega) > 0$.

It is known that

$$E^\Omega(x) = E_x(\tau_\Omega) \text{ for } \mu\text{-a.a. } x \in M, \hspace{1cm} (3.14)$$

where $\tau_\Omega$ is the \textit{first exit time} of the Hunt process $\{(X_t)_{t \geq 0}, \{\mathbb{P}_x\}_{x \in M}\}$ associated with $(\mathcal{E}, \mathcal{F})$, that is

$$\tau_\Omega = \inf \{t > 0 : X_t \notin \Omega \}, \hspace{1cm} (3.15)$$

where $X_t \notin \Omega$ means that either $X_t \in M \setminus \Omega$, or $X_t = \infty$. Clearly, if the Green function $g^\Omega$ exists, then

$$E^\Omega(x) = G^\Omega 1(x) = \int_\Omega g^\Omega(x, y) d\mu(y) \hspace{1cm} (3.16)$$

for $\mu$-almost all $x \in M$. 

Definition 3.8. We say that condition $(E_F)$ holds if, there exist two constants $C > 1$ and $\delta_1 \in (0, 1)$ such that, for any ball $B$ of radius $r > 0$,
\[
esup_B E^B \leq CF(r), \quad (E_F \leq)
\]
\[
\inf_B E^B \geq C^{-1} F(r). \quad (E_F \geq)
\]

Next we introduce condition $(G_F)$.

Definition 3.9. We say that condition $(G_F)$ holds if, there exist constants $K > 1$ and $\check{C} > 0$ such that, for any ball $B := B(x_0, R)$, the Green kernel $g^B$ exists and is jointly continuous off the diagonal, and satisfies
\[
g^B(x_0, y) \leq C \int_{K^{-1}d(x_0, y)}^R F(s) \frac{ds}{sV(x, s)} \text{ for all } y \in B \setminus \{x_0\}, \quad (G_F \leq)
\]
\[
g^B(x_0, y) \geq C^{-1} \int_{K^{-1}d(x_0, y)}^R F(s) \frac{ds}{sV(x, s)} \text{ for all } y \in K^{-1}B \setminus \{x_0\}. \quad (G_F \geq)
\]

The following theorem is a key in our paper.

Theorem 3.10. Let $(M, d, \mu)$ be a metric measure space where all metric balls are precompact. Assume that $(\mathcal{E}, \mathcal{F})$ is a regular, strongly local Dirichlet form in $L^2(M, \mu)$. If $(VD)$ and $(RVD)$ are satisfied, then the following equivalences take place:

\[(H) + (R_F) \iff (G_F) \iff (H) + (E_F) .\]

Remark 3.11. Condition $(RVD)$ is required only for proving the implication $(H) + (E_F) \Rightarrow (R_F \geq)$.

The proof of this theorem is quite involved, including numerous lemmas and propositions. We give the flowchart of the proof on the following diagram:

Before stating the second theorem of this paper, we introduce more conditions.

$(UE)$ Upper estimate: the heat kernel $p_t(x, y)$ exists, has a Hölder continuous in $x, y \in M$ version, and satisfies the following upper estimate
\[
p_t(x, y) \leq \frac{C}{V(x, R(t))} \exp \left( -\frac{1}{2} t \Phi \left( c \frac{d(x, y)}{t} \right) \right) \quad (UE)
\]
for all $t > 0$ and all $x, y \in M$. Here $c, C$ are positive constants, $R := F^{-1}$, and
\[
\Phi(s) := \sup_{r > 0} \left\{ \frac{s}{r} - \frac{1}{F(r)} \right\}.
\]
Near-diagonal lower estimate: the heat kernel $p_t(x,y)$ exists, has a Hölder continuous in $x,y \in M$ version, and satisfies the lower estimate

$$p_t(x,y) \geq \frac{c}{V(x, R(t))}, \quad (NLE)$$

for all $t > 0$ and all $x,y \in M$ such that $d(x,y) \leq \eta R(t)$, where $\eta > 0$ is a sufficiently small constant.

Denote by $(UE_{weak})$ a modification of condition $(UE)$ that is obtained by removing the Hölder continuity of $p_t(x,y)$ and by relaxing inequality $(UE)$ to $\mu \times \mu$-almost all $x,y \in M$. In a similar way, we can define condition $(NLE_{weak})$.

Theorem 3.12. Let $(M, d, \mu)$ be a metric measure space where all metric balls are precompact. Assume that $(\mathcal{E}, \mathcal{F})$ is a regular, strongly local Dirichlet form in $L^2(M, \mu)$. Assume also that $(VD)$ and $(RVD)$ are satisfied. Then the following sets of conditions are equivalent:

$$(H) + (E_F) \iff (G_F) \iff (H) + (R_F)$$

$$(UE) + (NLE) \iff (UE_{weak}) + (NLE_{weak}).$$

Proof. The first line of equivalences is contained in Theorem 3.10. Denote by $(\tilde{E}_F)$ the following condition:

$$\mathbb{E}_x \tau_{B(x,r)} \simeq F(r) \quad (\tilde{E}_F)$$

for all $r > 0$ and $x \in M \setminus \mathcal{N}$, where $\mathcal{N}$ is a properly exceptional set\footnote{A set $\mathcal{N} \subset M$ is called properly exceptional if it is Borel, $\mu(\mathcal{N}) = 0$ and $\mathbb{P}_x(X_t \in \mathcal{N} \text{ or } X_{t-} \in \mathcal{N} \text{ for some } t \geq 0) = 0$ for all $x \in M \setminus \mathcal{N}$ (see [16, p.152 and Theorem 4.1.1 on p.155]).}. Let us show that the following implications take place:

$$
\begin{array}{c}
(UE) + (NLE) \\
\downarrow \\
(U_E_{weak}) + (NLE_{weak}) \\
\downarrow \\
(H) + (\tilde{E}_F) \\
\uparrow \\
(H) + (E_F)
\end{array}
$$

which contains the remaining equivalences in the statement of Theorem 3.12. Indeed, by [26, Theorem 7.4] we have the equivalences

$$(H) + (\tilde{E}_F) \iff (UE_{weak}) + (NLE_{weak}) \iff (UE) + (NLE). \quad (3.17)$$

Let us verify that

$$(\tilde{E}_F) \Rightarrow (E_F). \quad (3.18)$$

Indeed, let $B := B(x_0, r)$ be any metric ball in $M$. For any $x \in B \setminus \mathcal{N}$ we have, using $(\tilde{E}_F)$ and $B \subset B(x, 2r)$, that

$$\mathbb{E}_x \tau_B \leq \mathbb{E}_x \tau_{B(x, 2r)} \leq CF(2r) \leq C'F(r).$$
Hence, it follows from (3.14) that
\[ \text{esup}_B E^B = \text{esup}_{x \in B} \mathbb{E}_x \tau_B \leq C' F(r), \]
thus proving \((E_F \leq\)). On the other hand, for any \(x \in \frac{1}{2} B \setminus \mathcal{N}\), we have, using \(\tilde{E}_F\) and \(B(x, r/2) \subset B\), that
\[ \mathbb{E}_x \tau_B \geq \mathbb{E}_x \tau_{B(x,r/2)} \geq C^{-1} F(r/2) \geq CF(r), \]
and thus,
\[ \text{einf}_{B/2} E^B = \text{einf}_{x \in B/2} \mathbb{E}_x \tau_B \geq CF(r), \]
hence, proving \((E_F \geq\)) and as well as (3.18).

It remains to prove that
\[ (H) + (E_F) \Rightarrow (UE_{\text{weak}}) + (NLE_{\text{weak}}). \]

For that we use the proof of (3.17) in [26] and verify that the condition \(\tilde{E}_F\) in that proof can be replaced by a priori weaker condition \((E_F)\). By [26, Theorem 3.11] we have
\[ (H) + (E_F) \Rightarrow (FK), \]
where \((FK)\) denotes a certain \textit{Faber-Krahn type inequality} (see [26, Definition 3.9]).

It follows from the inequality [22, (6.34)] that
\[ (E_F) \Rightarrow (S_F), \]
where \((S_F)\) stands for a \textit{survival estimate} defined by [20, (5.23)]. By [20, Theorem 2.1] we have
\[ (FK) + (S_F) \Rightarrow (UE_{\text{weak}}), \]
which implies
\[ (H) + (E_F) \Rightarrow (UE_{\text{weak}}). \]

Arguing as in [26, Section 5.4], one obtains
\[ (H) + (E_F) \Rightarrow (NLE_{\text{weak}}), \]
which finishes the proof. \(\square\)

4. Maximum principles

We give three maximum principles, and the first two are for a subharmonic function on one open set, and the third is for a subharmonic function on the difference of two open sets. All of them will be used later on.

\textbf{Lemma 4.1} (Maximum principle). Assume that \((\mathcal{E}, \mathcal{F})\) is a regular Dirichlet form in \(L^2(M, \mu)\). Let \(\Omega \subset M\) be open such that \(\lambda_{\min}(\Omega) > 0\), and let \(\Omega_1 \Subset \Omega\) be open. Assume that \(u \geq 0\) in \(M\).

\(1\) If \(u\) is subharmonic in \(\Omega\), then (see Fig. 1 below)
\[ \text{esup}_\Omega u \leq \text{esup}_{M \setminus \Omega_1} u. \]

Consequently, if in addition \(u\) vanishes outside \(\Omega\), then
\[ \text{esup}_\Omega u = \text{esup}_{\Omega \setminus \Omega_1} u. \]
(2) Assume in addition that $(\mathcal{E}, \mathcal{F})$ is strongly local, $\Omega$ is precompact, and that $u \in L^\infty(M)$. If $u$ is subharmonic (resp. superharmonic) in $\Omega$, then for any open $\Omega_2 \supseteq \Omega$,

$$
esup_{\Omega} u \leq \sup_{\Omega_2 \setminus \Omega_1} u,$$

(resp. $\inf_{\Omega} u \geq \inf_{\Omega_2 \setminus \Omega_1} u$).

Moreover, if $u$ is continuous in a neighborhood of $\partial \Omega$, the above inequalities can be replaced by

$$
esup_{\Omega} u = \sup_{\partial \Omega} u$$

(resp. $\inf_{\Omega} u = \inf_{\partial \Omega} u$),

where $\partial \Omega = \overline{\Omega} \setminus \Omega$, the boundary of $\Omega$.

Proof. (1). Assume that $\esup_{M \setminus \Omega_1} u$ is finite; otherwise (4.1) is automatically true. If (4.1) fails, there would have a finite positive number $c$ such that $\esup_{\Omega} u > c > \esup_{M \setminus \Omega_1} u$. Since $c \geq 0$, the function $\varphi := (u-c)_+$ is a normal contraction of $u$ ([16, p.5]), and thus, $\varphi \in \mathcal{F}$. Moreover, $\varphi \in \mathcal{F}(\Omega)$ since $(u-c)_+ = 0$ outside $\Omega_1$. Using the subharmonicity of $u$ and the Markov property of $(\mathcal{E}, \mathcal{F})$ (cf. [19, Lemma 4.3]), it follows that

$$
0 \geq \mathcal{E}(u, \varphi) = \mathcal{E}(u, (u-c)_+)
\geq \mathcal{E}((u-c)_+) \geq \lambda_{\min}(\Omega) \| (u-c)_+ \|^2 > 0,
$$

a contradiction, thus proving (4.1).

If in addition $u = 0$ in $M \setminus \Omega$, we have

$$
esup_{M \setminus \Omega_1} u = \esup_{\Omega \setminus \Omega_1} u.$$
Hence, it follows from (4.1) that
\[
\text{esup}_\Omega u \leq \text{esup}_\Omega u \leq \text{esup}_{\Omega \setminus \Omega_1} u,
\]
showing (4.2).

(2). Let \( \psi \) be a cut-off function of \( (\Omega, \Omega_2) \). Since \( u, \psi \in \mathcal{F} \cap L^\infty \), we see that \( w \psi \in \mathcal{F} \cap L^\infty \). For any \( \varphi \in \mathcal{F}(\Omega) \), observe that the product of the two functions \( u(\psi - 1) \) and \( \varphi \) is equal to zero, and so (cf. \cite[Prop. 4.1]{[40]})
\[
\mathcal{E}(u(\psi - 1), \varphi) = 0.
\]

We first assume that \( u \) is subharmonic in \( \Omega \). It follows that
\[
\mathcal{E}(u \psi, \varphi) = \mathcal{E}(u, \varphi) + \mathcal{E}(u(\psi - 1), \varphi) = \mathcal{E}(u, \varphi) \leq 0,
\]

namely, the function \( u \psi \) is also subharmonic in \( \Omega \). By (4.1), we have
\[
\text{esup}_\Omega u = \text{esup}_M (u \psi) \leq \text{esup}_{\Omega \setminus \Omega_1} (u \psi) \leq \text{esup}_{\Omega_2 \setminus \Omega_1} u,
\]
proving (4.3).

We next assume that \( u \) is superharmonic in \( \Omega \). Similar to (4.8), the function \( u \psi \) is also superharmonic in \( \Omega \). To show (4.4), consider the function \( v := (a - u) \psi \), where \( a := \text{esup}_M u \). Then \( v \geq 0 \) in \( M \), and is subharmonic in \( \Omega \) since for any \( \varphi \in \mathcal{F}(\Omega) \), using the strong locality of \( (\mathcal{E}, \mathcal{F}) \),
\[
\mathcal{E}(v, \varphi) = a \mathcal{E}(\psi, \varphi) - \mathcal{E}(u \psi, \varphi) = -\mathcal{E}(u \psi, \varphi) \leq 0.
\]

Hence, we see from (4.1) that
\[
\text{esup}_\Omega (a - u) = \text{esup}_\Omega v \leq \text{esup}_{M \setminus \Omega_1} v \leq \text{esup}_{\Omega_2 \setminus \Omega_1} (a - u),
\]
proving (4.4).

Finally, if \( u \) is continuous in a neighborhood of \( \partial \Omega \), we have that, letting \( \Omega_2 \downarrow \Omega \),
\[
\text{esup}_{\Omega_2 \setminus \Omega_1} u \to \text{sup}_{\partial \Omega} u.
\]
Similarly, letting \( \Omega_1 \uparrow \Omega \), we have
\[
\text{sup}_{\Omega \setminus \Omega_1} u \to \text{sup}_{\Omega \setminus \partial \Omega} = \text{sup}_{\partial \Omega} u.
\]
Therefore, it follows from (4.3) that
\[
\text{esup}_\Omega u \leq \text{sup}_{\partial \Omega} u,
\]
which gives (4.5), by using the fact that \( \text{sup}_{\partial \Omega} u \leq \text{esup}_{\partial \Omega} u \) as \( \partial \Omega \subset \overline{\Omega} \). The equality (4.6) can be proved similarly.

The second maximum principle is for a subharmonic function \( u \) where we do not know a-priori whether or not \( u \) keeps the same sign in the whole domain \( M \), as required in the first maximum principle, although this function \( u \) turns out to be non-positive hereafter. This maximum principle will be used in the proof of Lemma 6.4 (b).

For an open \( U \subset M \) and \( u, v \in \mathcal{F} \), denote by
\[
u \leq v \mod \mathcal{F}(U), \quad (\text{resp. } u = v \mod \mathcal{F}(U))
\]
if there exists some \( h \in \mathcal{F}(U) \) such that \( u - v \leq h \) in \( M \) (resp. \( u - v = h \) in \( M \)).

**Proposition 4.2.** Assume that \((\mathcal{E}, \mathcal{F})\) is a regular Dirichlet form. Let \( U \) be open such that \( \lambda_{\min}(U) > 0 \). If

\[
\begin{cases}
  u \text{ is subharmonic in } U, \\
  u \leq 0 \mod \mathcal{F}(U),
\end{cases}
\]

then \( u \leq 0 \) in \( U \) (and thus also in \( M \)).

**Proof.** Since \( u \leq 0 \mod \mathcal{F}(U) \), we have that \( u + \in \mathcal{F}(U) \) (cf. [19, Lemma 4.4, p.114]). Since \( u \) is subharmonic in \( U \), we have that, for any non-negative \( \varphi \in \mathcal{F}(U) \),

\[
\mathcal{E}(u, \varphi) \leq 0.
\]

Letting \( \varphi = u + \) and noting that

\[
\mathcal{E}(u_+, u_-) = \lim_{t \to 0} \frac{1}{t} (u_+ - P_t u_+, u_-) = -\lim_{t \to 0} \frac{1}{t} (P_t u_+, u_-) \leq 0,
\]

we obtain that

\[
0 \geq \mathcal{E}(u, u_+) = \mathcal{E}(u_+) - \mathcal{E}(u_+, u_-) \geq \mathcal{E}(u_+) \geq 0,
\]

and thus, \( \mathcal{E}(u_+) = 0 \). Therefore,

\[
\|u_+\|^2_{L^2(U)} \leq \frac{\mathcal{E}(u_+)}{\lambda_{\min}(U)} = 0,
\]

which implies that \( u \leq 0 \) in \( U \). \( \square \)

Finally, we present a third maximum principle where the domain is the difference of two open sets. It will be used in the proofs of Lemmas 5.3 and 7.4.

**Proposition 4.3.** Assume that \((\mathcal{E}, \mathcal{F})\) is regular, local. Let \( \Omega \) be open such that \( \lambda_{\min}(\Omega) > 0 \), and let \( A \subset \Omega \) be compact. Let \( 0 \leq u \in \mathcal{F}(\Omega) \cap L^\infty \) and is subharmonic in \( \Omega \setminus A \), and is continuous in some neighborhood of \( \partial U \), for any open \( U \) with \( A \subset U \subset \Omega \). Then,

\[
esup_{\Omega \setminus U} u = \sup_{\partial U} u.
\]

**Proof.** Since we always have that \( \esup_{\Omega \setminus U} u \geq \sup_{\partial U} u \), assume on the contrary that

\[
m := \sup_{\partial U} u < \esup_{\Omega \setminus U} u,
\]

and we will deduce a contradiction.

Choose a small \( \varepsilon > 0 \) such that

\[
esup_{\Omega \setminus U} u \geq m + \varepsilon.
\]

Choose an open set \( V \) such that \( A \subset V \subset U \), and

\[
\sup_{U \setminus V} u \leq m + \varepsilon/2.
\]

Let \( \varphi \) be a cutoff function of \((V, U)\). Consider the function

\[
u^* := u - u \varphi.
\]
Clearly, \( u^* \in \mathcal{F} \cap L^\infty, u^*|_V = 0 \), and
\[
u^* \leq u \leq m + \varepsilon/2 \text{ in } U \setminus V.
\]
Hence, the function \( v := (u^* - (m + \varepsilon/2))_+ \) satisfies that \( v|_U = 0 \). Since \( v \in \mathcal{F}(\Omega) \), by Proposition 9.3 in Appendix, we have that \( v \in \mathcal{F}(\Omega \setminus A) \).

On the other hand, using the locality of \((\mathcal{E}, \mathcal{F})\) and the fact that \( \varphi v = 0 \), we have
\[
\mathcal{E}(u^* \varphi, v) = 0.
\]
Therefore, by the subharmonicity of \( u \), we obtain
\[
\mathcal{E}(u^*, v) = \mathcal{E}(u, v) - \mathcal{E}(u \varphi, v) \leq 0.
\]
It follows that
\[
0 \geq \mathcal{E}(u^*, v) \geq \mathcal{E}(v) \geq \lambda_{\text{min}}(\Omega) ||v||^2_{L^2(\Omega \setminus A)},
\]
showing that \( v = 0 \) in \( \Omega \setminus A \). Hence,
\[
u^* \leq m + \varepsilon/2 \text{ in } \Omega \setminus A,
\]
in particular, we have that \( u^* \leq m + \varepsilon/2 \) in \( \Omega \setminus U \). But this is a contradiction by noting that \( u^* = u \) in \( \Omega \setminus U \) and using (4.11). \( \square \)

### 5. Green operator and Green function

#### 5.1. Green operator.
We give the existence of the Green operator, and present its properties.

**Lemma 5.1.** Let \((\mathcal{E}, \mathcal{F})\) be a regular Dirichlet form in \( L^2(M, \mu) \), and let \( \Omega \subset M \) be open such that \( \lambda_{\text{min}}(\Omega) > 0 \). Let \( \mathcal{L}^\Omega \) be the generator of \((\mathcal{E}, \mathcal{F}(\Omega))\), and set \( G^\Omega = (-\mathcal{L}^\Omega)^{-1} \), the inverse\(^3\) of \(-\mathcal{L}^\Omega\). Then the following statements are true.

1. \[ ||G^\Omega|| \leq \lambda_{\text{min}}(\Omega)^{-1}, \text{ that is, for any } f \in L^2(\Omega) \]
\[
||G^\Omega f||_{L^2(\Omega)} \leq \lambda_{\text{min}}(\Omega)^{-1} ||f||_{L^2(\Omega)}. \tag{5.1}
\]
2. For any \( f \in L^2(\Omega) \), we have that \( G^\Omega f \in \mathcal{F}(\Omega) \), and
\[ \mathcal{E}(G^\Omega f, \varphi) = (f, \varphi) \text{ for any } \varphi \in \mathcal{F}(\Omega). \tag{5.2} \]
3. For any \( f \in L^2(\Omega) \),
\[ G^\Omega f = \int_0^\infty P^\Omega_s f \, ds. \tag{5.3} \]
4. \( G^\Omega \) is non-negative definite: \( G^\Omega f \geq 0 \text{ if } f \geq 0 \).

**Proof.**
1. It is trivial since \( \text{spec}(G^\Omega) \subset [0, \lambda_{\text{min}}(\Omega)^{-1}] \), and so \( ||G^\Omega|| \leq \lambda_{\text{min}}(\Omega)^{-1} \).
2. Let \( u = G^\Omega f \). Then \( u \) lies in the domain of \( \mathcal{L}^\Omega \), and hence, for any \( \varphi \in \mathcal{F}(\Omega) \),
\[ \mathcal{E}(G^\Omega f, \varphi) = \mathcal{E}(u, \varphi) = - \left( \mathcal{L}^\Omega u, \varphi \right) = (f, \varphi). \]
3. Using the spectral resolution, we see that
\[ P^\Omega_s f = \int_{\lambda_{\text{min}}(\Omega)}^\infty e^{-s\lambda} dE^\Omega_\lambda f, \]
\(^3\)Since \( \lambda_1(\Omega) > 0 \), the operator \(-\mathcal{L}^\Omega\) has a bounded inverse in \( L^2(\Omega, \mu) \).
and hence,
\[ \int_0^\infty P_\Omega^s f \, ds = \int_0^\infty \left( \int_{\lambda_{\min}(\Omega)}^\infty e^{-s\lambda} \, dE_\lambda^f \right) \, ds \]
\[ = \int_{\lambda_{\min}(\Omega)}^\infty \left( \int_0^\infty e^{-s\lambda} \, ds \right) \, dE_\lambda^f \]
\[ = \int_{\lambda_{\min}(\Omega)}^\infty \lambda^{-1} \, dE_\lambda^f = (-L_\Omega)^{-1} f, \]
showing (5.3).

(4). Finally, since \( P_\Omega^s f \geq 0 \) if \( f \geq 0 \) for any \( s \geq 0 \), we see from (5.3) that \( G_\Omega \) is non-negative definite. \( \square \)

5.2. Harnack inequality and existence of Green function. If condition \((H)\) holds, we will show that the Green function \( g_\Omega \) exists and is jointly continuous off diagonal.

**Lemma 5.2.** Assume that \((\mathcal{E}, \mathcal{F})\) is strongly local, regular, and that conditions \((H)\) and \((VD)\) hold. Let \( \Omega \subset M \) be open such that \( \lambda_{\min}(\Omega) > 0 \). Then there exists a function \( g_\Omega(x, y) \) defined for \((x, y) \in \Omega \times \Omega \setminus \text{diag}\) with the following properties:

1. \( G_\Omega f(x) = \int_\Omega g_\Omega(x, z) f(z) \, d\mu(z) \) for any \( f \in L^2(\Omega) \) and a.e. \( x \in \Omega \).
2. \( g_\Omega(x, y) = g_\Omega(y, x) \geq 0 \).
3. \( g_\Omega(x, y) \) is jointly continuous in \((x, y) \in \Omega \times \Omega \setminus \text{diag}\).
4. For any ball \( B \) with \( \overline{B} \subset \Omega \) and any \( y \in \Omega \setminus B \),
\[
\sup_{x \in \delta B} g_\Omega(x, y) \leq C_H \inf_{x \in \delta B} g_\Omega(x, y),
\]  
where constants \( C_H, \delta \) are the same as in condition \((H)\).

**Proof.** The proof is quite long. We first show the existence of \( g_\Omega(x, y) \) for \((x, y) \in \Omega \times \Omega \setminus \text{diag}\).

Fix a point \( x \in \Omega \), a ball \( B := B(x, R) \Subset \Omega \), and set \( U = \Omega \setminus \overline{B} \). Let \( f \) be any non-negative function in \( L^2(\Omega) \) that vanishes outside \( U \). Then \( G_\Omega f \) is harmonic in \( B \) because for any \( \varphi \in \mathcal{F}(B) \),
\[
\mathcal{E}(G_\Omega f, \varphi) = (f, \varphi) = 0.
\]
Hence, by condition \((H)\) and (5.1),
\[
esup_{\delta B} G_\Omega f \leq C_H \inf_{\delta B} G_\Omega f \]
\[
\leq C_H \left( \frac{1}{\mu(\delta B)} \int_{\delta B} (G_\Omega f)^2 \, d\mu \right)^{1/2}
\]
\[
\leq C_H \mu(\delta B)^{-1/2} \| G_\Omega f \|_{L^2(\Omega)}
\]
\[
\leq C_H \mu(\delta B)^{-1/2} \lambda_{\min}(\Omega)^{-1} \| f \|_{L^2(\Omega)} = C_1(\Omega, B) \| f \|_{L^2(U)},
\]
where the constant \( C_1(\Omega, B) \) is given by
\[
C_1(\Omega, B) = \frac{C_H}{\lambda_{\min}(\Omega) \sqrt{\mu(\delta B)}}.
\]
Since \((\mathcal{E}, \mathcal{F})\) is strongly local, using (5.5) and the fact that \(G^\Omega f \geq 0\), the harmonic function \(G^\Omega f\) satisfies the following oscillation property: for any ball \(B(z, \rho) \subset \delta B\) and any \(0 < r \leq \rho\),

\[
\text{Osc}_{B(z,r)} \frac{G^\Omega f}{B(z,r)} : = \sup_{B(z,r)} G^\Omega f - \inf_{B(z,r)} G^\Omega f \\
\leq 2 \left(\frac{r}{\rho}\right)^\theta \text{Osc}_{B(z,\rho)} G^\Omega f \\
\leq 2 \left(\frac{r}{\rho}\right)^\theta \text{esup}_{\delta B} G^\Omega f \\
\leq 2C_1(\Omega, B) \left(\frac{r}{\rho}\right)^\theta \|f\|_{L^2(U)},
\]

where \(\theta > 0\) is a constant depending only on constants \(C, \delta\) in condition (H), see [26, Lemma 5.2]. Thus the function \(G^\Omega f\) admits a Hölder continuous version in \(\delta B\), that will also be denoted by \(G^\Omega f\).

It follows from (5.5) that

\[G^\Omega f(x) \leq C_1(\Omega, B) \|f\|_{L^2(U)}\]

so that the mapping \(f \mapsto G^\Omega f(x)\) is a bounded linear functional on \(L^2(U)\). By the Riesz representation theorem, there exists a unique \(g_{x, U}^\Omega(\cdot) \in L^2(U)\) that is non-negative in \(U\) and such that

\[G^\Omega f(x) = \int_U g_{x, U}^\Omega(z) f(z) d\mu(z) \text{ for any } f \in L^2(U).\]

Let \(\{B_k\}_{k \geq 1}\) be a shrinking sequence of balls centered at \(x\) such that \(\cap B_k = \{x\}\), and let \(U_k = \Omega \setminus \overline{B_k}\). Then we obtain a sequence of the functions \(g_{x, U_k}^\Omega\) that is consistent in the sense that

\[g_{x, U_{k+1}}^\Omega|_{U_k} = g_{x, U_k}^\Omega.\]

This allows us to define a function \(g_x^\Omega\) on \(\Omega \setminus \{x\}\) by

\[g_x^\Omega = g_{x, U_k}^\Omega\text{ on } U_k.\]

By construction, \(g_x^\Omega \in L^2_{\text{loc}}(\Omega \setminus \{x\})\), is non-negative in \(\Omega \setminus \{x\}\) and satisfies

\[G^\Omega f(x) = \int_\Omega g_x^\Omega(z) f(z) d\mu(z) \quad (5.8)\]

for any \(f \in L^2(U_k)\) and \(k \geq 1\).

We claim that (5.8) also holds for any \(f \in L^2(\Omega)\), that is,

\[G^\Omega f(x) = \int_\Omega g_x^\Omega(z) f(z) d\mu(z) \text{ for any } f \in L^2(\Omega). \quad (5.9)\]

Indeed, set \(f_k = f1_{U_k}\) for any non-negative \(f \in L^2(\Omega)\). Since (5.8) holds for \(f_k:\)

\[G^\Omega f_k(x) = \int_\Omega g_x^\Omega(z) f_k(z) d\mu(z), \quad (5.10)\]

we let \(k \to \infty\) and obtain that

\[G^\Omega f_k \to G^\Omega f \text{ in } L^2(\Omega)\]
by using the monotone convergence theorem, because
\[ f_k \to f \text{ in } L^2(\Omega) \]
and \( G^\Omega \) is bounded in \( L^2(\Omega) \) by (5.1). This proves our claim.

Observe that for any ball \( A \Subset U \),
\[
\| G^\Omega 1_{\delta A} \|_{L^\infty(\delta B)} \leq \frac{C_H \sqrt{\mu(\delta A)}}{\lambda_{\min}(\Omega) \sqrt{\mu(\delta B)}} \cdot (5.11)
\]
since, taking \( f = 1_{\delta A} \) in (5.5), we see that
\[
\| G^\Omega 1_{\delta A} \|_{L^\infty(\delta B)} \leq C H \sqrt{\mu(\delta B)} \mu(\delta A)^{1/2}.
\]

Let us show that \( G^\Omega : L^1(\delta A) \to L^\infty(\delta B) \) is bounded, that is, for any \( f \in L^1(\delta A) \),
\[
\max_{\delta B} G^\Omega f \leq \frac{(C_H)^2}{\lambda_{\min}(\Omega) \sqrt{\mu(\delta B)} \mu(\delta A)} \| f \|_{L^1(\delta A)} \cdot (5.12)
\]
Indeed, interchanging the balls \( A \) and \( B \) in (5.11), we obtain that
\[
\| G^\Omega 1_{\delta B} \|_{L^\infty(\delta A)} \leq \frac{C_H \sqrt{\mu(\delta B)}}{\lambda_{\min}(\Omega) \sqrt{\mu(\delta A)}} \cdot (5.13)
\]
Hence, for any non-negative \( f \in L^1(\delta A) \),
\[
\| G^\Omega f \|_{L^1(\delta B)} = (G^\Omega f, 1_{\delta B}) = (f, G^\Omega 1_{\delta B}) \leq \| f \|_{L^1(\delta A)} \| G^\Omega 1_{\delta B} \|_{L^\infty(\delta A)} \leq \frac{C_H \sqrt{\mu(\delta B)}}{\lambda_{\min}(\Omega) \sqrt{\mu(\delta A)}} \| f \|_{L^1(\delta A)}.
\]
Therefore, using condition \((H)\),
\[
\max_{\delta B} G^\Omega f \leq C_H \min_{\delta B} G^\Omega f \leq C_H \left( \frac{1}{\mu(\delta B)} \| G^\Omega f \|_{L^1(\delta B)} \right) \leq \frac{(C_H)^2}{\lambda_{\min}(\Omega) \sqrt{\mu(\delta B)} \mu(\delta A)} \| f \|_{L^1(\delta A)} \cdot (5.14)
\]
proving (5.12).

Now for \( y \in U \), let \( \{\varepsilon_n\}_{n \geq 1} \) be a decreasing sequence of positive numbers shrinking to 0 such that \( A := B(y, \varepsilon_1) \subset U \), see Figure 2.

Let \( u_{n,y} := G^\Omega f_{n,y} \), where
\[
f_{n,y} = \frac{1}{\mu(B(y, \varepsilon_n))} 1_{B(y, \varepsilon_n)},
\]
such that \( f_{n,y} \to \delta_y \) weakly in \( C_0(M) \) as \( n \to \infty \), where \( \delta_y \) is the usual Dirac function concentrated at point \( y \). It follows from (5.6) and (5.12) that for \( B(z, \rho) \subset \delta B \) and
\[ \begin{align*}
0 < r < \rho,

\text{Osc}_{B(z,r)} u_{n,y} & \leq 2 \left( \frac{r}{\rho} \right)^{\theta} \sup_{\delta B} u_{n,y} \\
& \leq 2 \left( \frac{r}{\rho} \right)^{\theta} \frac{(C_H)^2}{\lambda_{\min}(\Omega) \sqrt{\mu(\delta B) \mu(\delta A)}} \| f_{n,y} \|_{L^1(\delta A)} \\
& = 2 \left( \frac{r}{\rho} \right)^{\theta} \frac{(C_H)^2}{\lambda_{\min}(\Omega) \sqrt{\mu(\delta B) \mu(\delta A)}}. \tag{5.15}
\end{align*} \]

Therefore, the sequence \( \{u_{n,y}\} \) is uniformly bounded and equicontinuous in \( \delta B \). By the Arzelà-Ascoli theorem, there exists a subsequence \( \{u_{n_k,y}\} \) that is uniformly convergent in \( \delta B \). In fact, the limit is \( g_\Omega^{\Omega} \), that is,

\[ g_\Omega^{\Omega}(z) = \lim_{k \to \infty} G_\Omega f_{n_k,y}(z) \text{ uniformly for } z \in \delta B, \tag{5.16} \]

because, for any \( \varphi \in C_0(\delta B) \), using (5.9),

\[ \langle u_{n_k,y}, \varphi \rangle = \langle G_\Omega f_{n_k,y}, \varphi \rangle = \langle f_{n_k,y}, G_\Omega \varphi \rangle \to G_\Omega \varphi(y) = \langle g_\Omega^{\Omega}, \varphi \rangle, \]

and hence,

\[ u_{n_k,y} \rightharpoonup g_\Omega^{\Omega} \text{ weakly in } C_0(\delta B) \text{ as } k \to \infty. \]

We now define the function \( g^\Omega(y, x) \) by

\[ g^\Omega(y, x) := g_\Omega^{\Omega}(x) = \lim_{k \to \infty} G^\Omega f_{n_k,y}(x) \geq 0 \]

for almost all \( (x, y) \in \Omega \times \Omega \setminus \text{diag} \).

We next show that such \( g^\Omega(y, x) \) satisfies all the properties (1)-(4).

Indeed, property (1) is clear by (5.9). Property (2) follows by using (5.9),

\[ g^\Omega(y, x) = \lim_{k \to \infty} G^\Omega f_{n_k,y}(x) = \lim_{k \to \infty} \int_{\Omega} g^\Omega_z(z) f_{n_k,y}(z) d\mu(z) \\
= g^\Omega_z(y) = g^\Omega(x, y). \]
To show property (3), we have from (5.15) that, for any $0 < r < \delta R$,
\[
\frac{\text{Osc}}{B(x,r)} G^\Omega f_{n_k,y} \leq 2 \left( \frac{r}{\delta R} \right)^{\theta} \frac{(C_H)^2}{\lambda_{\text{min}}(\Omega) \sqrt{\mu(\delta B) \mu(\delta A)}},
\]
and hence, passing to the limit as $k \to \infty$,
\[
\frac{\text{Osc}}{B(x,r)} g^\Omega(y, \cdot) \leq 2 \left( \frac{r}{\delta R} \right)^{\theta} \frac{(C_H)^2}{\lambda_{\text{min}}(\Omega) \sqrt{\mu(\delta B) \mu(\delta A)}},
\]
It follows that $g^\Omega(\cdot, y)$ is Hölder continuous in $\delta B$ locally uniformly for $y \in U$, and thus, the function $g^\Omega$ is jointly continuous away from the diagonal.

More precisely, for any $x_1, y_1 \in \Omega$ and any $r_1, r_2 > 0$ such that $B(x_1, r_1) \cap B(y_1, r_2) = \emptyset$, and $B(x_1, r_1) \subset \Omega$, $B(y_1, r_2) \subset \Omega$, we have that
\[
\left| g^\Omega(x_1, y_1) - g^\Omega(x_2, y_2) \right| \leq \frac{2\delta^{-\theta}(C_H)^2}{\lambda_{\text{min}}(\Omega) \sqrt{V(x_1, \delta r_1)V(y_1, \delta r_2)}} \left[ \left( \frac{d(x_1, x_2)}{\delta r_1} \right)^{\theta} + \left( \frac{d(y_1, y_2)}{\delta r_2} \right)^{\theta} \right],
\]
where $x_2 \in B(x_1, \delta r_1)$ and $y_2 \in B(y_1, \delta r_2)$.

Finally, to show the property (4), let $B$ be an arbitrary ball with $\overline{B} \subset \Omega$, and let $y \in B^c$. Note that $u_{n,y}$ satisfies condition (H) in $\delta B$ uniformly for $n \geq 1$, that is,
\[
\max_{\delta B} G^\Omega f_{n_k,y} \leq C_H \min_{\delta B} G^\Omega f_{n_k,y}.
\]
Passing to the limit as $k \to \infty$, we obtain (5.4). \qed

The next is the maximum-minimum principle for the Green function $g^\Omega(x_0, \cdot)$. Since we do not know whether or not the function $g^\Omega(x_0, \cdot)$ belongs to $\mathcal{F}$, making it harmonic in $\Omega \setminus \{x_0\}$, we are not able to apply directly the maximum principles established before, as often did when $M$ is a graph or a manifold.

**Lemma 5.3.** Assume that all the hypotheses of Lemma 5.2 hold. If $x_0 \in U \subset \Omega$, then
\[
\inf_{\Omega \setminus \{x_0\}} g^\Omega(x_0, \cdot) = \inf_{\partial U} g^\Omega(x_0, \cdot), \quad (5.19)
\]
\[
\sup_{\Omega \setminus U} g^\Omega(x_0, \cdot) = \sup_{\partial U} g^\Omega(x_0, \cdot). \quad (5.20)
\]

**Proof.** Let $\Omega_n \uparrow \Omega$ such that $\Omega_n$ is precompact open, $\Omega_n \supset U$ for each $n$. Let $U_k \downarrow \{x_0\}$ such that each $U_k$ is open, and $U_k \subset U$. Let
\[
U_k := G^\Omega f_{k,x_0}
\]
where $f_{k,x_0} \to \delta_{x_0}$ weakly in $C(M)$ as $k \to \infty$, for example $f_{k,x_0} = \frac{1}{\mu(U_k)} 1_{U_k}$. By the proof of Lemma 5.2, the sequence $\{u_k\}_{k=1}^\infty$ converges uniformly to $g^\Omega(x_0, \cdot)$ on each compact subset of $\Omega \setminus \{x_0\}$, as $k \to \infty$.

We first prove (5.19). To do this, note that each $u_k = G^\Omega f_{k,x_0}$ is superharmonic in $\Omega$ (and in particular in $U$), since for any non-negative $\varphi \in \mathcal{F}(\Omega)$,
\[
\mathcal{E}(u_k, \varphi) = (f_{k,x_0}, \varphi) \geq 0.
\]
As $U$ is precompact, we have from (4.6) that, for each $k$,

$$\inf_{\partial U} u_k = \inf_{\partial U} u_k.$$  \hfill (5.21)

Clearly, for each $n$, we have that $\partial U \subset \overline{U} \setminus U_n \subset \overline{U}$, and thus

$$\inf u_k \leq \inf_{\partial U \setminus U_n} u_k \leq \inf u_k$$

for each $k$. Combining this with (5.21), we see

$$\inf_{\partial U \setminus U_n} u_k = \inf_{\partial U} u_k.$$  \hfill (5.21)

Letting $k \to \infty$, we obtain that

$$\inf_{\partial U \setminus U_n} g_{x_0, \cdot} \Omega = \inf_{\partial U} g_{x_0, \cdot} \Omega,$$

and then letting $n \to \infty$, we conclude that (5.19) holds.

We next show (5.20). In fact, since each $u_k$ is harmonic in $\Omega \setminus U_1$, it follows from Proposition 4.3 that

$$\sup_{\Omega_n \setminus U} u_k = \sup_{\partial U} u_k$$

for each $n$. Letting $k \to \infty$, we have that

$$\sup_{\Omega_n \setminus U} g_{x_0, \cdot} \Omega = \sup_{\partial U} g_{x_0, \cdot} \Omega,$$

and then letting $n \to \infty$ and using the continuity of $g_{x_0, \cdot} \Omega$ off diagonal, we conclude that (5.20) holds.  \hfill $\blacksquare$

It is not hard to see that (5.4) is equivalent to the following; if

$$d(z_1, z_2) < \delta [d(x_0, z_1) \wedge d(x_0, z_2)]$$

for any points $x_0, z_1, z_2 \in \Omega$, then $g_{x_0, \cdot} \Omega$ satisfies (5.22) that is,

$$C^{-1} g_{x_0, z_2} \Omega \leq g_{x_0, z_1} \Omega \leq C g_{x_0, z_2} \Omega$$

for some $C > 0$.

We introduce the Harnack inequality for the Green function $g_{x_0, \cdot} \Omega$.

**Definition 5.4.** We say that the Green function $g_{x_0, \cdot} \Omega$ satisfies the Harnack inequality if $g_{x_0, \cdot} \Omega$ is jointly continuous off diagonal, and if there exist some (large) constants $K, C$ such that for any ball $B = B(x_0, R)$ and for any precompact open set $\Omega \supset KB$,

$$\sup_{\partial B} g_{x_0, \cdot} \Omega \leq C \inf_{\partial B} g_{x_0, \cdot} \Omega,$$

where $C$ may depend on $K$, but both $K$ and $C$ are independent of the ball $B$ and the set $\Omega$.

We will show that (HG) is true if conditions (H) and (VD) hold. For doing this, we need the relatively connected property of balls.
Definition 5.5. A metric space $(M,d)$ is relatively $(\varepsilon,K)$-ball-connected if, for constants $\varepsilon \in (0,1)$ and $K > 1$, there exists an integer $N = N(\varepsilon,K)$ such that for any ball $B(x_0,KR)$ and for any two points $x,y \in B(x_0,R)$, there is a chain of balls $\{B_i\}_{i=0}^N$ of the same radius $\varepsilon R$ inside $B(x_0,KR)$ connecting $x$ and $y$, that is,

$$x \in B_0 \sim B_1 \sim B_2 \sim \cdots \sim B_N \ni y,$$

where $B_i \sim B_j$ means that $B_i \cap B_j \neq \emptyset$, see Figure 3.

![Figure 3. Balls $\{B_i\}_{i=0}^N$ connecting two points $x$ and $y.$](image)

We give a sufficient condition for the ball-connectedness.

Proposition 5.6. Assume that $(E,F)$ is a strongly local, regular Dirichlet form, and that conditions $(H)$ and $(VD)$ hold. Then $(M,d)$ is relatively $(\varepsilon,K)$-ball-connected for any $\varepsilon \in (0,1)$ and any $K > \delta^{-1}$, with the same $\delta$ as in condition $(H)$.

Proof. Fix $\varepsilon \in (0,1)$ and $K > \delta^{-1}$, and let $B := B(x_0,R)$. For the ball $B(x_0,KR)$, by condition $(VD)$, there exists a finite number of balls $\{B_i\}_{i=0}^N$ of the same radius $\varepsilon R$ that covers $B(x_0,KR)$, where $N$ depends only on $K, \varepsilon$ (cf. [29, Theorem 1.16, p.8]). It suffices to show that if $X_1,X_2 \in \{B_i\}$ and $X_j \cap B \neq \emptyset$ ($j = 1,2$), then $X_1$ and $X_2$ can be connected by a chain of balls from $\{B_i\}$.

To see this, denote by $\Omega$ the union of all the balls in $\{B_i\}$ that can be connected to $X_1$. Clearly, the set $\Omega$ is open. We claim that $\Omega$ is also closed in $B(x_0,KR)$.

Indeed, for any point $y \in B(x_0,KR) \setminus \Omega$, there exists a ball $Y$ in $\{B_i\}$ such that $y \in Y$. If $Y$ intersects one of the balls in $\Omega$, then $X \subset \Omega$, which contradicts the fact that $y \notin \Omega$. Thus, $Y$ does not intersect any ball from $\Omega$, that is $\Omega \cap Y = \emptyset$, and $Y$ has an open neighborhood $X \cap B(x_0,KR)$ outside $\Omega$. Therefore, the set $B(x_0,KR) \setminus \Omega$ is open, showing that $\Omega$ is closed in $B(x_0,KR)$.

Let $Y := B(x_0,\delta^{-1}R)$ so that $B \subset Y \subset B(x_0,KR)$, and let

$$A = \Omega \cap \overline{Y} = \overline{\Omega} \cap \overline{Y}.$$

Then $A$ is compact. Let $u$ be a cut-off function of $(A,\Omega)$. We will show that $u$ is harmonic in $Y$. In fact, for any $\varphi \in F \cap C_0(Y)$, we have that $\text{supp}(u \varphi) \subset \Omega \cap \overline{Y} = A$.
whilst $u \equiv 1$ in a neighborhood of $A$, see Figure 4. Hence, using the strong locality, we have that $\mathcal{E}(u, u\varphi) = 0$. Similarly, $\mathcal{E}(u, \varphi(1-u)) = 0$ because $\text{supp}(\varphi(1-u)) \subset \overline{Y \cap A^c} \subset \overline{Y \cap \Omega^c}$ whilst $u = 0$ in $\Omega^c$. Therefore,

$$\mathcal{E}(u, \varphi) = \mathcal{E}(u, u\varphi) + \mathcal{E}(u, \varphi(1-u)) = 0,$$

proving that $u$ is harmonic in $Y$.

Hence, we can apply condition (H) for the non-negative harmonic function $u$ for the pair $(B, Y)$.

Let $x \in X_1 \cap \overline{B} \subset \Omega \cap \overline{Y} = A$. For any $y \in X_2 \cap \overline{B}$, we obtain

$$1 = u(x) \leq C_H u(y),$$

which gives that $u(y) > 0$. Thus, $y \in \Omega$ since $u$ is a cut-off function of $(A, \Omega)$ and $u = 0$ in $\Omega^c$. Hence, $X_2 \cap \overline{B} \subset \Omega$, showing that $X_2$ can be connected to $X_1$ by a chain of balls in $\{B_i\}$. The proof is complete. \hfill $\square$

The last part of the above proof was motivated by that in [26, Theorem 7.3(a)].

We next show that condition (HG) holds.

**Lemma 5.7.** Assume that all the hypotheses in Lemma 5.2 are satisfied, then condition (HG) is true where $K > \delta^{-1}$. Consequently, for any ball $KB \subset \Omega$ with center $x_0$,

$$\sup_{\Omega \setminus B} g^\Omega(x_0, \cdot) \leq C \inf_B g^\Omega(x_0, \cdot)$$

for some $C > 0$ independent of the ball $B$ and $\Omega$.

**Proof.** First observe that $(M, d)$ is relatively ball-connected by using Proposition 5.6. Fix a ball $B := B(x_0, R)$, and let $\Omega$ be open such that $B(x_0, KR) \subset \Omega$. Since $g^\Omega(x_0, \cdot)$ is continuous on $\partial B$, let $x$ and $y$ be two points on $\partial B$ such that

$$g^\Omega(x_0, x) = \sup_{\partial B} g^\Omega(x_0, \cdot),$$

$$g^\Omega(x_0, y) = \inf_{\partial B} g^\Omega(x_0, \cdot).$$
We need to show that
\[ g^\Omega(x_0, x) \leq C g^\Omega(x_0, y). \] (5.24)

Clearly, if \( d(x, y) < \delta R \), then (5.24) with \( C = C_H \) follows from (5.4). In the sequel, we assume that \( d(x, y) \geq \delta R \).

Let \( \varepsilon = \delta^3/4 \), and let \( \{B_i\}_{i=0}^N \) be any fixed chain of balls with the same radius \( \varepsilon R \) in \( B(x_0, KR) \) connecting \( x \) and \( y \). Denote by \( B_i := B(\xi_i, \varepsilon R) \), and note that
\[ x \in B_0 \sim B_1 \sim B_2 \sim \cdots \sim B_N \ni y. \]

We will prove (5.24) according to the whereabouts of the centers \( \{\xi_0, \xi_1, \xi_2, \cdots, \xi_N\} \) of the balls \( \{B_i\}_{i=0}^N \). We distinguish two cases.

**Case 1:** \( d(x_0, \xi_i) > \delta R \) for each \( i \) (see Figure 5).

Consider the function \( g^\Omega(x_0, \cdot). \) For \( i = 0, \cdots, N - 1 \), note that
\[
d(\xi_i, \xi_{i+1}) = 2\varepsilon R = \delta^3 R/2 < \delta R < \delta \min\{d(x_0, \xi_i), d(x_0, \xi_{i+1})\}.
\]

Applying (5.23), we obtain that \( g^\Omega(x_0, \xi_i) \simeq g^\Omega(x_0, \xi_{i+1}) \), and thus,
\[ g^\Omega(x_0, \xi_0) \simeq g^\Omega(x_0, \xi_N). \]

Also we have
\[
g^\Omega(x_0, x) \simeq g^\Omega(x_0, \xi_0),
g^\Omega(x_0, \xi_N) \simeq g^\Omega(x_0, y).
\]

Therefore, we conclude that
\[ g^\Omega(x_0, x) \simeq g^\Omega(x_0, y), \]
proving (5.24).

**Case 2:** \( d(x_0, \xi_i) \leq \delta R \) for some \( i \).
Let \( x' := \xi_k \) be the point from \( \{ \xi_0, \xi_1, \cdots, \xi_N \} \) such that all the centers \( \xi_0, \xi_1, \xi_2, \cdots, \xi_k \) lie outside \( B(x_0, \delta R) \) whilst the next center \( \xi_{k+1} \) lies inside \( B(x_0, \delta R) \). Denote by \( x'' := \xi_{k+1} \) (see Fig. 6).

![Figure 6. The points \( x', x'' \) and \( y', y'' \).](image)

At the same time, let \( y' := \xi_j \) be the point from \( \{ \xi_0, \xi_1, \cdots, \xi_N \} \) such that \( \xi_{j-1} \) lies inside \( B(x_0, \delta R) \) whilst all the next centers \( \xi_j, \xi_{j+1}, \cdots, \xi_N \) lie outside \( B(x_0, \delta R) \). Denote by \( y'' := \xi_{j-1} \). At this stage, we do not care about any ball with the center in \( \{ \xi_{k+2}, \xi_{k+3}, \cdots, \xi_{j-2} \} \) if any.

We further distinguish three cases.

Case (2a): There exists a point \( \eta \) from \( \{ y', \xi_{j+1}, \cdots, \xi_N \} \) such that
\[
\frac{2}{3} \delta R < \min \{ d(x_0, x'), d(x_0, \eta) \}.
\]

(See Fig 7).

By Case 1, we have already proved that
\[
\begin{align*}
g^\Omega(x_0, x') &\simeq g^\Omega(x_0, x), \\
g^\Omega(x_0, \eta) &\simeq g^\Omega(x_0, y).
\end{align*}
\]

(5.25)

On the other hand, consider the function \( g^\Omega(x_0, \cdot) \). Since
\[
d(x', \eta) \leq \frac{2}{3} \delta R < \delta^2 R < \delta \min \{ d(x_0, x'), d(x_0, \eta) \},
\]
we see by (5.23) that
\[
g^\Omega(x_0, x') \simeq g^\Omega(x_0, \eta),
\]
which combines with (5.25) to show that (5.24) also holds.

Case (2b): There exists a point \( \xi \) from \( \{ \xi_0, \xi_1, \xi_2, \cdots, \xi_{k-1}, x' \} \) such that
\[
d(y', \xi) \leq \frac{2}{3} \delta R.
\]
In this case, we can similarly prove that (5.24) holds, as we did in Case (2a).

**Case (2c):** $d(x', z) > \frac{2\delta}{3} R$ for all $z \in \{y', \xi_{j+1}, \cdots, \xi_N\}$, and $d(y', z) > \frac{2\delta}{3} R$ for all $z \in \{\xi_0, \xi_1, \xi_2, \cdots, \xi_{k-1}, x'\}$ (see Fig. 6).

Consider the function $g^\Omega(x', \cdot)$. For each $k = j, j + 1, \cdots, N - 1$, we see that

\[
\begin{align*}
  d(\xi_k, \xi_{k+1}) &\leq 2\varepsilon R < \frac{\delta^3 R}{2} < \delta \left( \frac{2\delta^2}{3} R \right) \\
 &< \delta \min \{d(x', \xi_k), d(x', \xi_{k+1})\}.
\end{align*}
\]

Applying (5.23), we have that $g^\Omega(x', \xi_k) \simeq g^\Omega(x', \xi_{k+1})$, and so

\[
g^\Omega(x', y') \simeq g^\Omega(x', y). \tag{5.26}
\]

On the other hand, consider the function $g^\Omega(y, \cdot)$. Since

\[
\begin{align*}
  d(y, x'') &> d(y, x_0) - d(x_0, x'') > R - \delta R > \delta^2 R, \\
  d(y, x') &> d(y, x_0) - d(x_0, x'') - d(x'', x') \\
 &> R - \delta R - 2\varepsilon R > \delta^2 R,
\end{align*}
\]

we see that

\[
\begin{align*}
  d(x'', x') &< 2\varepsilon R = \frac{\delta^3 R}{2} < \delta (\delta^2 R) \\
 &< \delta \min \{d(y, x'), d(y, x'')\}.
\end{align*}
\]

Thus, we have by (5.23) that

\[
g^\Omega(y, x') \simeq g^\Omega(y, x''). \tag{5.27}
\]

Also noting that $d(x'', x_0) < \delta R$, and $d(y, x_0) = R$, we apply (5.4) to obtain that

\[
g^\Omega(y, x'') \simeq g^\Omega(y, x_0). \tag{5.28}
\]
Therefore, as \( g^\Omega(x', y) = g^\Omega(y, x') \), it follows from (5.26)-(5.28) that
\[
g^\Omega(x', y') \simeq g^\Omega(y, x_0).
\]
Similarly, we obtain that
\[
g^\Omega(x', y') \simeq g^\Omega(x, x_0).
\]
Therefore, we conclude that (5.24) also holds. \( \square \)

6. Some Potential theory

6.1. Riesz measures associated with superharmonic functions. For any open \( \Omega \subset M \), we show that any non-negative superharmonic function \( f \in \mathcal{F}(\Omega) \) admits a regular Borel measure \( \nu_f \) such that \( f \) can be expressed as an integral of the Green function \( g^\Omega \) with respect to \( \nu_f \). This measure \( \nu_f \) is called a Riesz measure associated with \( f \). Recall that for the classical case, F. Riesz proved this theorem, now called the Riesz decomposition theorem (cf. [1, T.4.4.1, p.105, and Def. 4.3.4, p.102]).

Lemma 6.1. Assume that \((E, \mathcal{F})\) is a regular Dirichlet form. Let \( \Omega \subset M \) be non-empty open, and let \( f \in \mathcal{F} \) in \( M \).

(a) If \( f \) is superharmonic in \( \Omega \) and if either one of the following two conditions is satisfied:

1. \( f \geq 0 \) in \( M \);
2. \( f \in \mathcal{F}(\Omega) \) \( (f \) being not necessarily non-negative in \( M \));
then \( P_t^\Omega f \leq f \) in \( \Omega \) for all \( t > 0 \).

(b) If \( P_t^\Omega f \leq f \) in \( \Omega \) for all \( t > 0 \) and \( f \in \mathcal{F}(\Omega) \), then \( f \) is superharmonic in \( \Omega \).

Consequently, when \( \Omega = M \), any non-negative function \( f \) is superharmonic in \( M \) if and only if \( P_t^\Omega f \leq f \) for all \( t > 0 \).

Proof. (a). The function \( u(t, \cdot) := P_t^\Omega f - f \) is a weak subsolution of the heat equation in \( \mathbb{R}_+ \times \Omega \) (cf. [19, Example 4.10, p.117]), and satisfies the initial condition
\[
u_+(t, \cdot) \rightarrow 0 \quad \text{as} \quad t \rightarrow 0.
\]
We need to verify the boundary condition
\[
u_+(t, \cdot) \in \mathcal{F}(\Omega).
\] (6.1)

If \( f \geq 0 \) in \( M \), then \( u(t, \cdot) = P_t^\Omega f - f \leq P_t^\Omega f \) in \( M \), and thus, by [19, Lemma 4.4], condition (6.1) is true. If \( f \in \mathcal{F}(\Omega) \), so is \( u(t, \cdot) \), and (6.1) is also true. In both cases, using the parabolic maximum principle (see [19, Prop. 4.11, p.117]), we obtain that \( u \leq 0 \) in \((0, \infty) \times \Omega \), that is, \( P_t^\Omega f \leq f \) in \( \Omega \) for all \( t > 0 \).

(b). Assume now that \( P_t^\Omega f \leq f \in \mathcal{F}(\Omega) \). Then, for any non-negative function \( \varphi \in \mathcal{F}(\Omega) \),
\[
\mathcal{E}(f, \varphi) = \lim_{t \to 0} \left( \frac{f - P_t^\Omega f}{t}, \varphi \right) \geq 0,
\]
which means that \( f \) is superharmonic in \( \Omega \). \( \square \)

We will show that the Riesz measure exists for any non-negative superharmonic function.

Lemma 6.2. Assume that \((\mathcal{E}, \mathcal{F})\) is regular, and let \( \Omega \subset M \) be open. Assume that \( 0 \leq f \in \mathcal{F}(\Omega) \) is superharmonic in \( \Omega \).
(a) Then, there is a regular Borel measure $\nu_f$ on $\Omega$ such that

$$\frac{f - P_t^\Omega f}{t} \rightharpoonup \nu_f \text{ as } t \to 0,$$

(6.2)

where the convergence is weak in $C_0(\Omega)$. Moreover, measure $\nu_f$ does not charge any open set where $f$ is harmonic.

(b) Assume further that $\lambda_{\text{min}}(\Omega) > 0$, and $f \in L^\infty$ is harmonic in $U = \Omega \setminus S$ for a compact set $S$. Assume also that $g^\Omega(x,y)$ exists, and is jointly continuous off diagonal. Then

$$f(x) = \int_S g^\Omega(x,y) \, d\nu_f(y)$$

(6.3)

for all $x \in U$ and $\mu$-a.a. $x \in S$.

It follows from (6.2) that, for any $\varphi \in \mathcal{F} \cap C_0(\Omega)$,

$$\mathcal{E}(f, \varphi) = \int_{\Omega} \varphi \, d\nu_f.$$

(6.4)

Recall that if $f \in \text{dom} \mathcal{L}^\Omega$, then $\mathcal{E}(f, \varphi) = (-\mathcal{L}^\Omega f, \varphi)$. Hence, the identity (6.4) allows to define

$$-\mathcal{L}^\Omega f := \nu_f$$

(6.5)

for any non-negative superharmonic function $f \in \mathcal{F}(\Omega)$.

**Proof.** (a) For any $t > 0$ and $\varphi \in C_0(\Omega)$, set

$$\mathcal{E}_t(f, \varphi) := \left( \frac{f - P_t^\Omega f}{t}, \varphi \right)$$

so that $\varphi \mapsto \mathcal{E}_t(f, \varphi)$ is a linear functional in $C_0(\Omega)$. Let us show that $\lim_{t \to 0} \mathcal{E}_t(f, \varphi)$ exists for all $\varphi \in C_0(\Omega)$. Fix a precompact open set $V \subset \Omega$ and we shall prove that $\lim_{t \to 0} \mathcal{E}_t(f, \varphi)$ exists for all $\varphi \in C_0(V)$ (which will imply the same for all $\varphi \in C_0(\Omega)$). Let $\psi$ be a cutoff function of $(V, \Omega)$. Then, as $t \to 0$,

$$\left\| \frac{f - P_t^\Omega f}{t} \right\|_{L^1(V)} \leq \int_{\Omega} \frac{f - P_t^\Omega f}{t} \psi \, d\mu = \mathcal{E}_t(f, \psi) \rightharpoonup \mathcal{E}(f, \psi).$$

It follows that, for sufficiently small $t > 0$ and for all $\varphi \in C_0(V)$,

$$|\mathcal{E}_t(f, \varphi)| \leq \left\| \frac{f - P_t^\Omega f}{t} \right\|_{L^1(V)} \sup |\varphi| \leq [\mathcal{E}(f, \psi) + 1] \sup |\varphi|,$$

that is, $\mathcal{E}_t(f, \varphi)$ is a bounded linear functional of $\varphi \in C_0(V)$, and the norm of this functional is bounded uniformly in $t$. Since $\lim_{t \to 0} \mathcal{E}_t(f, \varphi)$ exists (and is equal to $\mathcal{E}(f, \varphi)$) for all $\varphi \in \mathcal{F}$, in particular, for $\varphi \in \mathcal{F} \cap C_0(V)$, and the latter set is dense in $C_0(V)$ by the regularity of $(\mathcal{E}, \mathcal{F})$, it follows that $\lim_{t \to 0} \mathcal{E}_t(f, \varphi)$ exists for all $\varphi \in C_0(V)$. 

Since $E_t(f, \varphi) \geq 0$ for non-negative $\varphi$, the $\lim_{t \to 0} E_t(f, \varphi)$ is a non-negative linear functional on $C_0(\Omega)$. By the Riesz representation theorem, the functional $\lim_{t \to 0} E_t(f, \varphi)$ determines a regular Borel measure $\nu_f$ on $\Omega$, so that

$$\lim_{t \to 0} E_t(f, \varphi) = \int_{\Omega} \varphi d\nu_f$$

for all $\varphi$. Since $\mathcal{F} \cap C_0(U)$ is dense in $C_0(U)$, we conclude that $\nu_f = 0$ on $U$.

(b) Since $g^\Omega$ is jointly continuous off diagonal and measure $\mu$ is non-atomic, we see that $g^\Omega(x, y)$ is measurable with respect to $d\nu_f(y) d\mu(x)$, as the measure of the diagonal is zero. Then the integral

$$\int_M \int_M g^\Omega(x, y) \varphi(x) d\nu_f(y) d\mu(x)$$

is defined for all $\varphi \in C_0(M)$, and hence, by Fubini’s theorem, the integral

$$\int_M \left[ \int_M g^\Omega(x, y) \varphi(x) d\mu(x) \right] d\nu_f(y)$$

is also defined. Therefore, the function

$$G^\Omega \varphi = \int_M g^\Omega(x, y) \varphi(x) d\mu(x)$$

is $\nu_f$-measurable.

We claim that, for any fixed non-negative $\varphi \in C_0(\Omega)$,

$$E(f, G^\Omega \varphi) = \int_S G^\Omega \varphi d\nu_f.$$  \hspace{1cm} (6.7)

Indeed, note that

$$\|G^\Omega f\|_{\infty} \leq \frac{1}{\lambda_{\min}(\Omega)} \|f\|_{\infty},$$

that is, $G^\Omega$ is a bounded operator in $L^\infty(\Omega)$ (see (8.20) below, or [26, Lemma 3.2]). Hence, the function $u := G^\Omega \varphi$ is a non-negative bounded function on $\Omega$. Recall that, by (5.2),

$$E(f, u) = E(f, G^\Omega \varphi) = (f, \varphi).$$  \hspace{1cm} (6.8)

Let $\psi_1$ be a cutoff function of $(S, A)$, where $A$ is some neighborhood of $S$. Let $V$ be a precompact open neighborhood of $\text{supp} \psi_1$. By Lemma 9.1 in Appendix, for any $\varepsilon > 0$, the function $u$ is cap-quasi-continuous in $\Omega$ (in particular, in $V$), that is, there is an open set $E \subset V$ such that $\text{cap}(E) < \varepsilon/2$, and $u$ is continuous in $V \setminus E$. Let $\psi_2$ be a cutoff function of $E$ such that $E(\psi_2) < \varepsilon$ (see Fig. 8).

That $u \in \mathcal{F} \cap L^\infty$ implies that the following three functions are also in $\mathcal{F} \cap L^\infty$:

$$u_1 := u \psi_1 (1 - \psi_2), \quad u_2 = u \psi_1 \psi_2, \quad u_3 = u (1 - \psi_1).$$

Note that $u_1 + u_2 + u_3 = u$ in $M$. Let us investigate the terms in (6.7) separately for each of the functions $u_i$. 
By construction, \( u_1 \) has compact support and is continuous in \( \Omega \) (indeed, \( u_1 \) vanishes in an open neighborhood of the closure of the set where \( u \) is discontinuous). By (6.4), we have
\[
\mathcal{E}(f, u_1) = \int_{\Omega} u_1 d\nu_f = \int_S u (1 - \psi_2) d\nu_f,
\]
where we have used the fact that \( \nu_f(S^c) = 0 \) and \( \psi_1 \equiv 1 \) on \( S \). It follows that
\[
\left| \mathcal{E}(f, u_1) - \int_S u d\nu_f \right| \leq \|u\|_\infty \int_S \psi_2 d\nu_f = \|u\|_\infty \mathcal{E}(f, \psi_2).
\]
Next, we have
\[
|\mathcal{E}(f, u_2)| = \lim_{t \to 0} \left( \frac{f - P_t^f u}{t}, u_1 \psi_2 \right) \\
\leq \|u\|_\infty \lim_{t \to 0} \left( \frac{f - P_t^f u}{t}, \psi_2 \right) = \|u\|_\infty \mathcal{E}(f, \psi_2).
\]
The function \( u_3 \) vanishes in an open neighborhood \( W \) of \( S \) (where \( \psi_1 = 1 \)), we have that \( u_3 \in \mathcal{F}(U) \) by using Proposition 9.3 in Appendix. Since \( f \) is harmonic in \( U \), we obtain
\[
\mathcal{E}(f, u_3) = 0.
\]
Adding up the above estimates of \( \mathcal{E}(f, u_i) \) and using the fact that
\[
\mathcal{E}(f, \psi_2) \leq \mathcal{E}(f)^{1/2} \mathcal{E}(\psi_2)^{1/2} \leq \mathcal{E}(f)^{1/2} \varepsilon^{1/2},
\]
we obtain
\[
\left| \mathcal{E}(f, u) - \int_S u d\nu_f \right| \leq 2 \|u\|_\infty \mathcal{E}(f)^{1/2} \varepsilon^{1/2}.
\]
Since \( \varepsilon > 0 \) is arbitrary, we conclude that (6.7) holds.
Finally, for any \( 0 \leq \varphi \in C_0(\Omega) \), we have that, using (6.8) and (6.7),
\[
\int_{\Omega} f(x) \varphi(x) \, d\mu(x) = \mathcal{E}(f,u) = \int_S G^\Omega(y) \, d\nu_f(y)
\]
\[
= \int_S \left( \int_{\Omega} g^\Omega(y,x) \varphi(x) \, d\mu(x) \right) \, d\nu_f(y)
\]
\[
= \int_{\Omega} \left( \int_S g^\Omega(x,y) \, d\nu_f(y) \right) \varphi(x) \, d\mu(x),
\]
showing that (6.3) holds for \( \mu \)-a.a. \( x \in \Omega \). Using the joint continuity of \( g^\Omega \) off diagonal and the dominated convergence theorem, we see that (6.3) holds pointwise in \( S^c = U \).

The following example says that for some superharmonic function \( f \), the associated Riesz measure \( \nu_f \) may coincide with the measure \( \mu \), that is, \( \nu_f = \mu \).

**Example 6.3.** Let \( f = E^\Omega 1_\Omega \) be the weak solution of (3.13). Then \( 0 \leq f \in \mathcal{F}(\Omega) \), and is superharmonic in \( \Omega \) since for any \( 0 \leq \varphi \in \mathcal{F}(\Omega) \),
\[
\mathcal{E}(f,\varphi) = \mathcal{E}(E^\Omega 1_\Omega,\varphi) = \int_{\Omega} \varphi d\mu \geq 0.
\]
Hence, this function admits a Riesz measure \( \nu_f \), which actually is equal to \( \mu \), since for any \( \varphi \in \mathcal{F} \cap C_0(\Omega) \),
\[
\int_{\Omega} \varphi d\mu = \mathcal{E}(f,\varphi) = \int_{\Omega} \varphi d\nu_f,
\]
and then use the fact that the space \( \mathcal{F} \cap C_0(\Omega) \) is dense in \( C_0(\Omega) \).

**6.2. Reduced function.** We introduce a reduced function \( \hat{u} \) of \( u \in \mathcal{F} \cap L^\infty \) with respect to \( (A,\Omega) \). Roughly speaking, a reduced function \( \hat{u} \) of \( (A,\Omega) \) is the one that is obtained by cutting off \( u \) such that \( \hat{u} = u \) in \( A \), and \( \hat{u} \) is harmonic in \( \Omega \setminus A \), and \( \hat{u} \in \mathcal{F}(\Omega) \) (so that \( \hat{u} \) vanishes outside \( \Omega \)).

**Lemma 6.4.** Assume that \( (\mathcal{E},\mathcal{F}) \) is regular, and let \( \Omega \subset M \) be precompact with \( \lambda_{\text{min}}(\Omega) > 0 \). Let \( A \) be a compact subset of \( \Omega \) and set \( U = \Omega \setminus A \). Fix a function \( u \in \mathcal{F} \cap L^\infty \) and fix a cutoff function \( \psi \) of \( (A,\Omega) \), and let \( f \in \mathcal{F} \) be the solution to the weak Dirichlet problem in \( U \):
\[
\begin{align*}
\{ & f \text{ is harmonic in } U, \\
& f = u\psi \mod \mathcal{F}(U). \\
\end{align*}
\]
(6.9)

Define the function \( \hat{u} \) on \( M \) (see Fig. 9) by
\[
\hat{u} = \begin{cases} 
u & \text{in } A, \\
f & \text{in } A^c.
\end{cases}
\]
(6.10)

(a) Then \( \hat{u} \in \mathcal{F}(\Omega) \).
(b) If in addition \( u \geq 0 \) in \( M \) and \( u \) is superharmonic in \( \Omega \), then \( \hat{u} \) is also superharmonic in \( \Omega \), and \( 0 \leq \hat{u} \leq u \) in \( M \).

The above function \( \hat{u} \) is called a reduced function of \( u \) with respect to \( (A,\Omega) \). For example, the capacitory potential of \( (A,\Omega) \) is a reduced function of any cutoff function of \( (\Omega, M) \), see Proposition 9.2 in Appendix.
Proof. (a) We have $w\psi \in \mathcal{F} \cap L^\infty$, and the Dirichlet problem (6.9) has a unique weak solution (cf. [26, Lemma 7.1]). It follows from (6.9) that
\[ v := w\psi - f \in \mathcal{F}(U). \]
Let us verify that $\hat{u} = f$ in $M$, that is,
\[ \hat{u} = u\psi - v \in M. \] (6.11)
Indeed, in $A$ we have
\[ \hat{u} = u = w\psi - v \]
because $\psi \equiv 1$ and $v \equiv 0$ in $A$, and in $A^c$ we have
\[ \hat{u} = f = w\psi - v \]
by the definition of $v$. Since $w\psi \in \mathcal{F}(\Omega)$ and $v \in \mathcal{F}(U) \subset \mathcal{F}(\Omega)$, it follows from (6.11) that $\hat{u} \in \mathcal{F}(\Omega)$.
(b) Since $w\psi \geq 0$ and $\lambda_{\text{min}}(U) \geq \lambda_{\text{min}}(\Omega) > 0$, we have by the maximum principle (cf. Proposition 4.2) that $f \geq 0$ in $M$ and, hence, $\hat{u} \geq 0$ in $M$. The function $f - u$ is obviously subharmonic in $U$. Since $f - u \leq f - w\psi$ in $M$ and $f - w\psi = 0 \mod \mathcal{F}(U)$, we have
\[ f - u \leq 0 \mod \mathcal{F}(U). \]
Hence, using the maximum principle again, we obtain that $f - u \leq 0$ in $M$. Therefore, $\hat{u} \leq u$ in $M$.

It remains to show that $\hat{u}$ is superharmonic in $\Omega$. By Lemma 6.1(b), we need to show that
\[ P^\Omega_t \hat{u} \leq \hat{u} \text{ for any } t > 0. \] (6.12)
Indeed, we have that in $A$,
\[ P^\Omega_t \hat{u} \leq P^\Omega_t u \leq u = \hat{u}. \] (6.13)
To prove (6.12) in $U$, observe that $w(t, \cdot) := P_t^\Omega \tilde{u} - \tilde{u}$ obviously is a weak subsolution of the heat equation in $\mathbb{R}_+ \times U$, and satisfies the initial condition

$$w_+(t, \cdot) \xrightarrow{L^2(U)} 0 \text{ as } t \to 0.$$  

We claim that the boundary condition

$$w_+(t, \cdot) \in \mathcal{F}(U)$$

also holds. To see this, note that, using part (a) and (6.11),

$$P_t^\Omega \tilde{u} - \tilde{u} \leq P_t^\Omega u - \tilde{u} \leq u - (u\psi - v)$$

$$= (1 - \psi) u + v \text{ in } M.$$  

(6.15)

The function $h := (1 - \psi) u$ vanishes in an open neighborhood of $A$, and thus, by Proposition 9.3 in Appendix, we see that $h \in \mathcal{F}(U)$. As $v \in \mathcal{F}(U)$, it follows from (6.15) that

$$w(t, \cdot) \leq h + v \in \mathcal{F}(U),$$

thus proving our claim (6.14) by using Lemma 4.4 in [19].

Finally, using the parabolic maximum principle (see [19, Prop. 4.11, p.117]), we conclude that $w \leq 0$ in $\mathbb{R}_+ \times U$. This finishes the proof. \qed

6.3. Capacitory measure. We give some properties for the capacitory measure (also called the equilibrium measure).

Lemma 6.5. Assume that $(\mathcal{E}, \mathcal{F})$ is strongly local, regular. Let $\Omega \subset M$ be precompact open such that $\lambda_{\min}(\Omega) > 0$, and let $U$ be open such that $U \Subset \Omega$. Then there exists a regular Borel measure $\nu_p$ supported on $\partial U$ such that

$$\nu_p(\partial U) = \text{cap}(U, \Omega).$$

(6.16)

If in addition the Green function $g^\Omega$ exists and is jointly continuous off diagonal, then the capacitory potential $u_p$ can be written as

$$u_p(x) = \int_{\partial U} g^\Omega(x, y) d\nu_p(y) \text{ for all } x \in \Omega \setminus \partial U,$$

(6.17)

In particular, we have

$$\int_{\partial U} g^\Omega(x, y) d\nu_p(y) = 1 \text{ for all } x \in U.$$  

(6.18)

Proof. Let $u_p$ be the capacitory potential of $(U, \Omega)$, then $u_p \in \mathcal{F}(\Omega), 0 \leq u_p \leq 1$ in $\Omega$, $u_p|_U = 1$, and

$$\mathcal{E}(u_p) = \text{cap}(U, \Omega),$$

(6.19)

and $u_p$ is harmonic in $\Omega \setminus \overline{U}$. Note that $u_p$ is a reduced function of any cutoff function of $(\overline{\Omega}, M)$, and is superharmonic in $\Omega$ (cf. Proposition 9.2 in Appendix).

We claim that, for any two open subsets $U_1, U_2$ of $\Omega$ with $U_1 \Subset U \Subset U_2$, the potential function $u_p$ is harmonic in $\Omega \setminus S$ where $S := \overline{U_2} \setminus U_1$.

Indeed, for any $0 \leq \varphi \in \mathcal{F}(\Omega \setminus S)$, by Proposition 9.4 in Appendix, we can decompose $\varphi = \varphi_1 + \varphi_2$, where $\varphi_1 \in \mathcal{F}(U), \varphi_2 \in \mathcal{F}(\Omega \setminus \overline{U})$. Therefore, as $u_p$ is harmonic in $\Omega \setminus \overline{U}$ and $(\mathcal{E}, \mathcal{F})$ is strongly local, it follows that

$$\mathcal{E}(u_p, \varphi) = \mathcal{E}(u_p, \varphi_1 + \varphi_2) = \mathcal{E}(u_p, \varphi_1) + \mathcal{E}(u_p, \varphi_2)$$

$$= \mathcal{E}(u_p, \varphi_1) = 0,$$
thus proving our claim.

Therefore, by Lemma 6.2, there exists a regular Borel measure \( \nu_p \) associated with \( u_p \) as in (6.2), and \( \nu_p \) is supported on \( S = \overline{U}_2 \setminus U_1 \) for any \( U_1 \subseteq U \subseteq U_2 \).

On the other hand, let \( \{u_k\}_{k=1}^{\infty} \) be a minimizing sequence of \( u_p \), that is, each \( u_k \) is a cutoff function of \( (\overline{U}, \Omega) \), and \( \mathcal{E}(u_k) \to \mathcal{E}(u_p) \). By (6.4),

\[
\mathcal{E}(u_p, u_k) = \int_S u_k d\nu_p.
\]

Since \( u_k = 1 \) in a neighborhood of \( \overline{U} \), and \( 0 \leq u_p \leq 1 \) in \( M \), we see that

\[
\nu_p(\partial U) \leq \nu_p(\overline{U} \setminus U_1) \leq \int_S u_k d\nu_p \leq \nu_p(\overline{U}_2 \setminus U_1),
\]

and hence,

\[
\nu_p(\partial U) \leq \mathcal{E}(u_p, u_k) \leq \nu_p(\overline{U}_2 \setminus U_1).
\]

Letting \( k \to \infty \) and then using (6.19), it follows that, for any \( U_1 \subseteq U \subseteq U_2 \),

\[
\nu_p(\partial U) \leq \text{cap}(U, \Omega) \leq \nu_p(\overline{U}_2 \setminus U_1).
\]

By the regularity of \( \nu_p \), the measure \( \nu_p(\overline{U}_2 \setminus U_1) \to \nu_p(\partial U) \) as \( U_1 \uparrow U \) and \( U_2 \downarrow U \). Therefore, we conclude that

\[
\text{cap}(U, \Omega) = \mathcal{E}(u_p) = \nu_p(\partial U),
\]

thus proving (6.16).

Finally, if \( g^\Omega \) exists and is jointly continuous off diagonal, then (6.17) follows directly from (6.3). \( \square \)

For any point \( x_0 \in \Omega \) and any \( c > 0 \), consider the set

\[
A_c(x_0) := \{ y \in \Omega : g^\Omega(x_0, y) > c \}.
\]

We look at the capacity \( \text{cap}(A_c(x_0), \Omega) \).

**Proposition 6.6.** Assume that \( (\mathcal{E}, \mathcal{F}) \) is regular, strongly local, and let \( \Omega \subset M \) be precompact open such that \( \lambda_{\text{min}}(\Omega) > 0 \). Assume that the Green function \( g^\Omega \) exists and is jointly continuous off diagonal. For any \( c > 0 \), if \( x_0 \in A_c(x_0) \) and if \( A_c(x_0) \subseteq \Omega \), then

\[
\text{cap}(A_c(x_0), \Omega) = \frac{1}{c}.
\]  

**Proof.** Since \( g^\Omega \) is jointly continuous off diagonal, the set \( U := A_c(x_0) \) is an open subset of \( \Omega \), and the boundary

\[
\partial U = \partial A_c(x_0) = \{ y \in \Omega : g^\Omega(x_0, y) = c \}.
\]

As \( x_0 \in U \), it follows from (6.18) that

\[
1 = \int_{\partial U} g^\Omega(x_0, y) d\nu_p(y) = c\nu_p(\partial U).
\]

Combines this with (6.16), we obtain

\[
\text{cap}(U, \Omega) = \nu_p(\partial U) = \frac{1}{c}.
\]

This finishes the proof. \( \square \)
7. Resistance

7.1. Green function and resistance. The following lemma gives a two-sided estimate of the resistance \( \text{res} (U, \Omega) \) in terms of the values of the Green function \( g^\Omega \) on the boundary \( \partial U \).

**Lemma 7.1.** Assume that \((E, F)\) is regular and strongly local, and that conditions \((H)\) and \((VD)\) hold. Let \( \Omega \subset M \) be open such that \( \lambda_{\min} (\Omega) > 0 \). If \( x_0 \in U \Subset \Omega \), we have that

\[
\inf_{\partial U} g^\Omega (x_0, \cdot) \leq \text{res} (U, \Omega) \leq \sup_{\partial U} g^\Omega (x_0, \cdot).
\]  

(7.1)

**Proof.** Let \( A_c(x_0) \) be defined as in (6.20), and let

- \( a := \sup_{\partial U} g^\Omega (x_0, \cdot) \),
- \( b := \inf_{\partial U} g^\Omega (x_0, \cdot) \).

Since \( g^\Omega (x_0, \cdot) \) is non-negative and jointly continuous off diagonal, we see that

\[ 0 \leq b \leq a < \infty. \]

Note that \( a > 0 \); otherwise \( g^\Omega (x_0, \cdot) \equiv 0 \) on \( \partial U \), and thus, using (6.18), we have

\[ 1 = \int_{\partial U} g^\Omega (x_0, y) \, d\nu_p (y) = 0, \]

where \( \nu_p \) is the capacitory measure for \( \text{cap} (U, \Omega) \), leading to a contradiction.

Note that if \( b = 0 \), the first inequality in (7.1) is clear, and the second one can be proved in a similar way as below. In the sequel, assume that \( b > 0 \). Let \( \varepsilon > 0 \) be arbitrarily small.

We first show

\[ \inf_{\partial U} g^\Omega (x_0, \cdot) \leq \text{res} (U, \Omega). \]  

(7.2)

Indeed, by Lemma 5.3, we see that

\[ \inf_U g^\Omega (x_0, \cdot) = \inf_{\partial U} g^\Omega (x_0, \cdot) = b > b - \varepsilon > 0, \]

and thus \( U \subset A_{b-\varepsilon}(x_0) \). Since \( g^\Omega (x_0, \cdot) \) is continuous in \( \Omega \setminus \{x_0\} \), we can choose an open set \( U_1 \) such that \( U \subset U_1 \Subset \Omega \), and

\[ g^\Omega (x_0, x) \geq b - \varepsilon \text{ for any } x \in \partial U_1 \]

where \( \partial U_1 \) is contained in a neighborhood of \( \partial U \). Let

\[ A_{b-\varepsilon}'(x_0) = U_1 \cap A_{b-\varepsilon}(x_0). \]

Then, we see that \( x_0 \in U \subset A_{b-\varepsilon}'(x_0) \Subset \Omega \), and for any \( y \in \partial (A_{b-\varepsilon}'(x_0)) \),

\[ g^\Omega (x_0, y) \geq b - \varepsilon. \]

It follows from (6.18) and (6.16) that

\[ 1 = \int_{\partial (A_{b-\varepsilon}'(x_0))} g^\Omega (x_0, y) \, d\nu_b (y) \]

\[ \geq (b - \varepsilon) \nu_b \left( \partial (A_{b-\varepsilon}'(x_0)) \right) = (b - \varepsilon) \text{cap} (A_{b-\varepsilon}'(x_0), \Omega), \]
where $\nu_b$ is the capacitory measure for $\text{cap}(A'_b(x_0), \Omega)$. Therefore,

$$\text{cap}(U, \Omega) \leq \text{cap}(A'_b(x_0), \Omega) \leq \frac{1}{b - \varepsilon},$$

that is, $b - \varepsilon \leq \text{res}(U, \Omega)$, proving (7.2).

We next show the second inequality in (7.1), namely,

$$\text{res}(U, \Omega) \leq \sup_{\partial U} g^\Omega(x_0, \cdot). \tag{7.3}$$

Indeed, by Lemma 5.3, we see that

$$\sup_{\Omega \setminus U} g^\Omega(x_0, \cdot) = \sup_{\partial U} g^\Omega(x_0, \cdot) = a,$$

and thus $A_a(x_0) \subset \overline{U}$, and

$$\text{cap}(A_a(x_0), \Omega) \leq \text{cap}(\overline{U}, \Omega).$$

If $x_0 \in A_a(x_0) \subset \overline{U} \Subset \Omega$, using Proposition 6.6, we have

$$\text{cap}(A_a(x_0), \Omega) = \frac{1}{a}, \tag{7.4}$$

thus proving (7.3).

If $x_0 \notin A_a(x_0)$, by definition of $A_a(x_0)$, we have that

$$g^\Omega(x_0, x) \leq a < a + \varepsilon.$$

Using the continuity of $g^\Omega(x_0, \cdot)$, we can choose a neighborhood $N_{x_0}$ of $x_0$ such that $N_{x_0} \subset U$, and

$$g^\Omega(x_0, x) \leq a + \varepsilon \text{ for any } x \in N_{x_0}.$$

Denote by the set

$$A'_a(x_0) := A_a(x_0) \cup N_{x_0}.$$

Then, we see that $x_0 \in N_{x_0} \subset A'_a(x_0) \subset \overline{U} \Subset \Omega$, and for any $y \in \partial A'_a(x_0)$,

$$g^\Omega(x_0, y) \leq a + \varepsilon.$$

It follows from (6.18) and (6.16) that

$$1 = \int_{\partial A'_a(x_0)} g^\Omega(x_0, y) \, d\nu_a(y)$$

$$\leq (a + \varepsilon) \nu_a(\partial A'_a(x_0)) = (a + \varepsilon) \text{cap}(A'_{a}(x_0), \Omega),$$

where $\nu_a$ is the capacitory measure for $\text{cap}(A'_a(x_0), \Omega)$. Therefore,

$$\text{cap}(U, \Omega) = \text{cap}(\overline{U}, \Omega) \geq \text{cap}(A'_a(x_0), \Omega) \geq \frac{1}{a + \varepsilon},$$

that is, $a + \varepsilon \geq \text{res}(U, \Omega)$, thus proving (7.3).

Finally, combining (7.2) and (7.3), we finish the proof.

As a consequence of Lemma 7.1, we have the following.
Lemma 7.2. Assume that \((E, F)\) is regular and strongly local, and that conditions \((H)\) and \((VD)\) hold. If \(\Omega\) is a precompact open set containing a ball \(K B\) where \(B = B(x_0, R)\) and \(K > \delta^{-1}\), and such that \(\lambda_{\min}(\Omega) > 0\), then
\[
\inf_{\partial B} g^\Omega(x_0, \cdot) \simeq \text{res}(B, \Omega) \simeq \sup_{\partial B} g^\Omega(x_0, \cdot). \tag{7.5}
\]

Proof. Since condition \((HG)\) holds, we see that
\[
\inf_{\partial B} g^\Omega(x_0, \cdot) \simeq \sup_{\partial B} g^\Omega(x_0, \cdot).
\]
Using (7.1), we obtain the desired. \(\Box\)

We next estimate the sum of a finite number of resistances. For this, we need the following lemma.

Lemma 7.3. Assume that \((E, F)\) is regular. For any two open sets \(\Omega_1, \Omega_2\) in \(M\) such that \(\Omega_1 \subset \Omega_2\) and \(\lambda_{\min}(\Omega_1) > 0\), and for any non-negative \(f \in L^2(\Omega_2)\), we have
\[
\sup_{\Omega_2} (G^{\Omega_2} f - G^{\Omega_1} f) \leq \sup_{\Omega_2 \setminus U} G^{\Omega_2} f \tag{7.6}
\]
where \(U\) is any open subset with \(U \subset \Omega_1\). If \(G^{\Omega_2} f\) is continuous in a neighborhood of \(\partial \Omega_1\), then
\[
\sup_{\Omega_2} (G^{\Omega_2} f - G^{\Omega_1} f) = \sup_{\Omega_2 \setminus \Omega_1} G^{\Omega_2} f. \tag{7.7}
\]

Proof. Let \(u := G^{\Omega_2} f - G^{\Omega_1} f\). Then \(u \geq 0\) in \(M\), and is harmonic in \(\Omega_1\) since for any \(\varphi \in F(\Omega_1)\),
\[
E(u, \varphi) = E(G^{\Omega_2} f - G^{\Omega_1} f, \varphi) = (f, \varphi) - (f, \varphi) = 0.
\]
Therefore, for any \(U \subset \Omega_1\), by the maximum principle (4.1), we have
\[
\sup_{\Omega_2 \setminus U} u \leq \sup_{\Omega_2 \setminus \Omega_1} G^{\Omega_2} f.
\]
As \(u \leq G^{\Omega_2} f\) in \(M\), we see that
\[
\sup_{\Omega_2 \setminus U} u \leq \sup_{\Omega_2 \setminus \Omega_1} G^{\Omega_2} f. \tag{7.8}
\]
Hence, it follows that
\[
\sup_{\Omega_2 \setminus U} u \leq \sup_{\Omega_2 \setminus \Omega_1} G^{\Omega_2} f,
\]
which implies that, using the fact that \(\Omega_2 \setminus \Omega_1 \subset \Omega_2 \setminus U\),
\[
\sup_{\Omega_2} u = \sup_{\Omega_1} u \vee \sup_{\Omega_2 \setminus \Omega_1} u = \sup_{\Omega_2 \setminus U} G^{\Omega_2} f \leq \sup_{\Omega_2 \setminus U} G^{\Omega_2} f \vee \sup_{\Omega_2 \setminus \Omega_1} G^{\Omega_2} f = \sup_{\Omega_2 \setminus \Omega_1} G^{\Omega_2} f,
\]
proving (7.6).
If \(G^{\Omega_2} f\) is continuous in a neighborhood of \(\partial \Omega_1\), we let \(U \uparrow \Omega_1\) in (7.6) and obtain
\[
\sup_{\Omega_2} u \leq \sup_{\Omega_2 \setminus \Omega_1} G^{\Omega_2} f.
\]
On the other hand, it is obvious that
\[ \operatorname{esup}_{\{x_0\}} u \geq \operatorname{esup}_{\mathcal{O}_2 \setminus \mathcal{O}_1} u = \operatorname{esup}_{\mathcal{O}_2 \setminus \mathcal{O}_1} G_{\Omega^2} f. \]

Thus, we conclude that (7.7) holds. \(\square\)

**Lemma 7.4.** Assume that \((E, \mathcal{F})\) is regular and strongly local, and that conditions \((H)\) and \((VD)\) hold. Fix a ball \(B(x_0, R)\) and set \(B_n = K^n B\) for \(n = 0, 1, 2, \ldots\), where \(K > \delta^{-1}\). For all \(n > m \geq 0\), if \(\lambda_{\min}(B_n) > 0\) then
\[ \sup_{\partial B_m} g^{B_n}(x_0, \cdot) \simeq \sum_{k=m}^{n-1} \operatorname{res}(B_k, B_{k+1}) \simeq \inf_{\partial B_m} g^{B_n}(x_0, \cdot). \] (7.9)

**Proof.** For each \(k \geq 0\), let us show that for any \(y \in M \setminus \{x_0\},\)
\[ g^{B_{k+1}}(x_0, y) - g^{B_k}(x_0, y) \leq \sup_{B_{k+1} \setminus B_k} g^{B_{k+1}}(x_0, \cdot). \] (7.10)

Indeed, note that (7.10) trivially holds for any \(y \notin B_k\). We will prove (7.10) for any \(y \in B_k \setminus \{x_0\}\).

To do this, we have from (7.6) that, for any concentric ball \(B' \subset B_k,\)
\[ \operatorname{esup}_{B_{k+1}} (G^{B_{k+1}} f - G^{B_k} f) \leq \operatorname{esup}_{B_{k+1} \setminus B'} G^{B_{k+1}} f, \] (7.11)
and thus for any fixed point \(y \in B_k \setminus \{x_0\},\)
\[ G^{B_{k+1}} f(y) - G^{B_k} f(y) \leq \operatorname{esup}_{B_{k+1} \setminus B'} G^{B_{k+1}} f. \] (7.12)

Choose \(f = f_{n,x_0} \rightharpoonup \delta_{x_0}\) weakly in \(C(M)\) as \(n \to \infty\). The function \(G^{B_{k+1}} f_{n,x_0}\) is harmonic in \(B_{k+1} \setminus B'\) since \(f_{n,x_0}\) vanishes in a small neighborhood of \(x_0\). Hence, using the maximum principle (4.10),
\[ \operatorname{esup}_{B_{k+1} \setminus B'} G^{B_{k+1}} f_{n,x_0} = \operatorname{esup}_{\partial B'} G^{B_{k+1}} f_{n,x_0}. \]

As \(G^{B_{k+1}} f_{n,x_0}\) is continuous in \(B_{k+1} \setminus B'\), letting \(B' \uparrow B_k\), we obtain from (7.12) that
\[ G^{B_{k+1}} f_{n,x_0}(y) - G^{B_k} f_{n,x_0}(y) \leq \operatorname{sup}_{\partial B_k} G^{B_{k+1}} f_{n,x_0} \] (7.13)

By (5.16), we have already shown that, as \(n \to \infty,\)
\[ G^{B_k} f_{n,x_0}(y) \to g^{B_k}(x_0, y), \]
\[ G^{B_{k+1}} f_{n,x_0}(y) \to g^{B_{k+1}}(x_0, y), \]
and at the same time,
\[ G^{B_{k+1}} f_{n,x_0}(\cdot) \to g^{B_{k+1}}(x_0, \cdot) \]
uniformly in the compact subset \(\partial B_k\).

Therefore, passing to the limit as \(n \to \infty\) in (7.13), we obtain that
\[ g^{B_{k+1}}(x_0, y) - g^{B_k}(x_0, y) \leq \operatorname{sup}_{\partial B_k} G^{B_{k+1}}(x_0, \cdot) \leq \operatorname{sup}_{B_{k+1} \setminus B_k} G^{B_{k+1}}(x_0, \cdot), \]
thus showing that (7.10) holds for any \(y \in B_k \setminus \{x_0\}\).
It follows from (7.10) that, using (5.20) and (7.5),
\[ g^{B_{k+1}}(x_0, y) - g^{B_k}(x_0, y) \leq \sup_{B_{k+1} \setminus B_k} g^{B_{k+1}}(x_0, \cdot) \leq C_1 \text{res}(B_k, B_{k+1}), \]
for some $C_1 > 0$. Adding up $k$ from $m+1$ to $n-1$, we obtain that for all $y \in M \setminus \{x_0\}$,
\[ g^{B_n}(x_0, y) - g^{B_{m+1}}(x_0, y) \leq C_1 \sum_{k=m+1}^{n-1} \text{res}(B_k, B_{k+1}). \tag{7.14} \]

On the other hand, using (7.5) again, we have
\[ \sup_{\partial B_m} g^{B_{m+1}}(x_0, \cdot) \simeq \text{res}(B_m, B_{m+1}). \tag{7.15} \]
Therefore, combining (7.14) and (7.15), we conclude that
\[ \sup_{\partial B_m} g^{B_n}(x_0, \cdot) \leq C_1 \sum_{k=m}^{n-1} \text{res}(B_k, B_{k+1}). \tag{7.16} \]

We next show that
\[ \sum_{k=m}^{n-1} \text{res}(B_k, B_{k+1}) \leq C_2 \inf_{\partial B_m} g^{B_n}(x_0, \cdot), \tag{7.17} \]
for some $C_2 > 0$. Indeed, since $(\mathcal{E}, \mathcal{F})$ is strongly local, we have (cf. [23, Lemma 2.5, p.157]) that
\[ \sum_{k=m}^{n-1} \text{res}(B_k, B_{k+1}) \leq \text{res}(B_m, B_n). \]

Using (7.5), we have
\[ \text{res}(B_m, B_n) \simeq \inf_{\partial B_m} g^{B_n}(x_0, \cdot). \]
Therefore, we obtain (7.17).

Finally, combining (7.16) and (7.17), we obtain (7.9).

\[ \square \]

7.2. Estimates of the Green function. We give upper estimate of the Green function under conditions (H) and $(E_F \leq \cdot)$.

**Theorem 7.5.** Assume that $(\mathcal{E}, \mathcal{F})$ is regular and strongly local, and that conditions (H), $(VD)$ and $(E_F \leq \cdot)$ all hold. Then, for any ball $B := B(x_0, R)$, the Green kernel $g^B$ exists and satisfies the following estimate: for all $y \in B \setminus \{x_0\}$,
\[ g^B(x_0, y) \leq C \int_{r/4}^{R} \frac{F(s)}{sV(x_0, s)} ds, \quad (G_F \leq \cdot) \]
where $r = d(x_0, y)$ and constant $C > 0$ is independent of the ball $B$.

**Proof.** Fix a point $y \in B \setminus \{x_0\}$. Let $r := d(x_0, y)$, and let $n$ be an integer such that
\[ 2^{-n}R \leq r < 2^{-(n-1)}R. \]
For $k = 0, 1, \ldots, n$, let
\[ r_k := 2^{-k}R \quad \text{and} \quad B_k := B(x_0, r_k). \]
Let $0 \leq f \in L^2$. Note that for $U \subset \Omega$,

\[
\inf_U G^\Omega f \leq \frac{1}{\mu(U)} \int_U G^\Omega f \, d\mu \\
= \frac{1}{\mu(U)} \int_U \left( \int_\Omega g^\Omega(x,y) f(y) \, d\mu(y) \right) \, d\mu(x) \\
= \frac{1}{\mu(U)} \int_\Omega \left( \int_U g^\Omega(x,y) \, d\mu(x) \right) f(y) \, d\mu(y) \\
\leq \frac{\|E^\Omega\|_{L^\infty(\Omega)}}{\mu(U)} \|f\|_{L^1(\Omega)}.
\]

(7.18)

Since the function $G^{B_k} f - G^{B_{k+1}} f$ is harmonic in $B_{k+1}$ for each $k$, we have by $(H)$ that it is Hölder continuous in $\delta B_{k+1}$ and, using (7.18), $(VD)$ and $(E_F \leq)$,

\[
\sup_{\delta B_{k+1}} (G^{B_k} f - G^{B_{k+1}} f) \leq C_H \inf_{\delta B_{k+1}} (G^{B_k} f - G^{B_{k+1}} f) \\
\leq C_H \inf_{\delta B_{k+1}} G^{B_k} f \\
\leq C_H \frac{\|E^{B_k}\|_{L^\infty(B_k)}}{\mu(\delta B_{k+1})} \|f\|_1 \\
\leq C \frac{F(r_k)}{\mu(B_k)} \|f\|_1.
\]

Therefore, for $k = 0, 1, \cdots, n$,

\[
G^{B_k} f(x_0) - G^{B_{k+1}} f(x_0) \leq C \frac{F(r_k)}{\mu(B_k)} \|f\|_1.
\]

Choosing $f = f_{n,y} \rightharpoonup \delta_y$ weakly in $C_0(M)$, and using the facts that $G^{B_{n+1}} f_{n,y} \equiv 0$ and $\|f_{n,y}\|_1 = 1$, we obtain that

\[
G^B f_{n,y}(x_0) = \sum_{k=0}^n \left[ G^{B_k} f_{n,y}(x_0) - G^{B_{k+1}} f_{n,y}(x_0) \right] \\
\leq C \sum_{k=0}^n \frac{F(r_k)}{\mu(B_k)}.
\]

Hence, letting $n \to \infty$ and using (5.16), we have

\[
g^B(x_0, y) \leq C \sum_{k=0}^n \frac{F(r_k)}{\mu(B_k)}.
\]

(7.19)
On the other hand, as both \( F \) and \( V(x_0, \cdot) \) are non-decreasing and \( r/4 < 2^{-(n+1)}R = r_{n+1} \), the integral

\[
\int_{r/4}^R \frac{F(s)}{sV(x_0, s)} \, ds \geq \sum_{k=0}^{n} \int_{r_{k+1}}^{r_k} \frac{F(s)}{sV(x_0, s)} \, ds \\
\geq \sum_{k=0}^{n} \frac{F(r_{k+1})}{V(x_0, r_k)} \int_{r_{k+1}}^{r_k} \frac{ds}{s} = \ln 2 \sum_{k=0}^{n} \frac{F(r_{k+1})}{V(x_0, r_k)} \quad (7.20)
\]

\[
\geq C' \sum_{k=0}^{n} \frac{F(r_k)}{V(x_0, r_k)} \quad \text{(using (3.3))} \quad (7.21)
\]

Combining (7.19) and (7.21), we obtain \((G_F \leq \cdot)\).

7.3. **Continuity of \( G^{\Omega} f \).** We investigate the continuity of the function \( G^{\Omega} f \). Before doing this, we need the following general result.

**Proposition 7.6.** Assume that conditions (3.3) and \((VD)\) hold, and let \(0 < \lambda, \lambda_1 \leq 1\) and \(B := B(x_0, R)\). For any \(t \geq 0\), let

\[
f(t) := \int_{\lambda t}^R \frac{F(s)}{sV(x_0, s)} \, ds.
\]

Then, we have

\[
C_1 F(R) \leq \int_{\lambda t}^R f(d(x_0, y)) \, d\mu(y) \leq C_2 F(R), \quad (7.22)
\]

where constants \(C_1, C_2\) are independent of the ball \(B\), but may depend on \(\lambda, \lambda_1\). If further condition (3.2) holds, then

\[
\int_{\lambda_1 B} f(d(x_0, y)) \, d\mu(y) \leq C(\lambda) \left[ \lambda_1^{\alpha'} \ln \frac{1}{\lambda_1} + \lambda_1^{\alpha'} + \lambda_1^\beta \right] F(R), \quad (7.23)
\]

where \(C(\lambda)\) is independent of \(\lambda_1\) and \(R\).

**Proof.** Since \(f\) is non-increasing, we have that

\[
\int_{\lambda_1 B} f(d(x_0, y)) \, d\mu(y) \geq f(\lambda_1 R)V(x_0, \lambda_1 R). \quad (7.24)
\]

As the functions \(F\) and \(V(x_0, \cdot)\) are non-decreasing, we see that, using (3.3),

\[
f(\lambda_1 R) = \int_{\lambda_1 R}^R \frac{F(s)}{sV(x_0, s)} \, ds \geq \frac{F(\lambda_1 R)}{V(x_0, R)} \int_{\lambda_1 R}^R \frac{ds}{s} \geq C'(\lambda, \lambda_1) \frac{F(R)}{V(x_0, R)}. \quad (7.25)
\]

Therefore, it follows from (7.24), (7.25) that, using \((VD)\) again,

\[
\int_{\lambda_1 B} f(d(x_0, y)) \, d\mu(y) \geq f(\lambda_1 R)V(x_0, \lambda_1 R) \geq C'(\lambda, \lambda_1) \frac{V(x_0, \lambda_1 R) F(R)}{V(x_0, R)} \geq C^{-1} F(R),
\]
Thus proving the first inequality in (7.22).

We next show the second inequality in (7.22). Indeed, we have that

$$\int_{\lambda_1 B} f(d(x_0, y))d\mu(y) = \int_0^{\lambda_1 R} f(t)dV(x_0, t)$$

$$= f(t)V(x_0, t)|_{0}^{\lambda_1 R} - \int_0^{\lambda_1 R} V(x_0, t)f'(t)dt$$

$$\leq f(\lambda_1 R)V(x_0, \lambda_1 R) - \int_0^{\lambda_1 R} V(x_0, t)f'(t)dt. \quad (7.26)$$

By (3.1), we see that

$$\frac{1}{V(x_0, \lambda_1 R)} = \frac{1}{V(x_0, R)} \frac{V(x_0, \lambda_1 R)}{V(x_0, R)}$$

$$\leq C_D \left( \frac{1}{\lambda \lambda_1} \right)^{\alpha} \frac{1}{V(x_0, R)},$$

and hence,

$$f(\lambda_1 R) = \int_{\lambda \lambda_1 R}^{R} \frac{F(s)ds}{sV(x_0, s)} \leq \frac{F(R)}{V(x_0, \lambda_1 R)} \int_{\lambda \lambda_1 R}^{R} \frac{ds}{s}$$

$$= \frac{F(R)}{V(x_0, \lambda_1 R)} \ln \frac{1}{\lambda \lambda_1}$$

$$\leq C_D \left( \frac{1}{\lambda \lambda_1} \right)^{\alpha} \left( \ln \frac{1}{\lambda \lambda_1} \right) \frac{F(R)}{V(x_0, R)}. \quad (7.27)$$

On the other hand, using (3.1) and (3.3),

$$0 \leq -\int_0^{\lambda_1 R} V(x_0, t)f'(t)dt = \int_0^{\lambda_1 R} V(x_0, t)\frac{F(\lambda t)}{tV(x_0, \lambda t)}dt$$

$$\leq C(\lambda) \int_0^{\lambda_1 R} \frac{F(\lambda t)}{t}dt = C(\lambda)F(R) \int_0^{\lambda_1 R} \frac{F(\lambda t)}{F(R)} \frac{dt}{t}$$

$$\leq C'(\lambda)F(R) \int_0^{\lambda_1 R} \left( \frac{\lambda t}{R} \right)^{\beta} \frac{dt}{t} = C(\lambda)\lambda^{\beta}_1 F(R). \quad (7.28)$$

Therefore, it follows from (7.26), (7.27) and (7.28) that

$$\int_{\lambda_1 B} f(d(x_0, y))d\mu(y) \leq C_D \left( \frac{1}{\lambda \lambda_1} \right)^{\alpha} \left( \ln \frac{1}{\lambda \lambda_1} \right) \frac{V(x_0, \lambda_1 R) F(R)}{V(x_0, R)}$$

$$+ C(\lambda)\lambda^{\beta}_1 F(R) \quad (7.29)$$

Finally, it remains to show (7.23). Note that

$$f(\lambda_1 R)V(x_0, \lambda_1 R) = V(x_0, \lambda_1 R) \int_{\lambda \lambda_1 R}^{R} \frac{F(s)ds}{sV(x_0, s)}$$

$$= V(x_0, \lambda_1 R) \left\{ \int_{\lambda \lambda_1 R}^{\lambda_1 R} \frac{F(s)ds}{sV(x_0, s)} + \int_{\lambda_1 R}^{R} \frac{F(s)ds}{sV(x_0, s)} \right\}. \quad (7.30)$$
By the monotonicity of $F$ and $V(x_0, \cdot)$, the first term
\[
V(x_0, \lambda_1 R) \int_{\lambda_1 R}^{\lambda_1 R} \frac{F(s) \, ds}{sV(x_0, s)} \leq F(\lambda_1 R) \frac{V(x_0, \lambda_1 R)}{V(x_0, \lambda_1 R)} \int_{\lambda_1 R}^{\lambda_1 R} \frac{ds}{s} \\
\leq C(\lambda) F(\lambda_1 R) = C(\lambda) F(R) \frac{F(\lambda_1 R)}{F(R)} \\
\leq C'(\lambda) F(R) (\lambda_1)^{\beta} \quad \text{(using (3.3) ).} \quad (7.31)
\]

Similarly, using (3.3) and (3.2), the second term
\[
V(x_0, \lambda_1 R) \int_{\lambda_1 R}^{R} \frac{F(s) \, ds}{sV(x_0, s)} = F(R) \int_{\lambda_1 R}^{R} \frac{F(s) \, V(x_0, \lambda_1 R) \, ds}{sV(x_0, s)} \\
\leq cF(R) \int_{\lambda_1 R}^{R} \left( \frac{s}{R} \right)^{\beta} \left( \frac{\lambda_1 R}{s} \right)^{\alpha'} \frac{ds}{s} \\
= cF(R) (\lambda_1)^{\alpha'} \int_{\lambda_1}^{1} s^{\beta-\alpha'-1} ds.
\]

If $\beta = \alpha'$, we have
\[
\int_{\lambda_1}^{1} s^{\beta-\alpha'-1} ds = \ln \frac{1}{\lambda_1},
\]
and if $\beta \neq \alpha'$, we have
\[
\int_{\lambda_1}^{1} s^{\beta-\alpha'-1} ds = \frac{1}{\beta - \alpha'} \left( 1 - (\lambda_1)^{\beta-\alpha'} \right).
\]

Hence, the second term
\[
V(x_0, \lambda_1 R) \int_{\lambda_1 R}^{R} \frac{F(s) \, ds}{sV(x_0, s)} \leq cF(R) \left( \lambda_1^{\alpha'} \ln \frac{1}{\lambda_1} + \lambda_1^{\alpha'} + \lambda_1^{\beta} \right). \quad (7.32)
\]

Therefore, it follows from (7.30), (7.31), (7.32) that
\[
f(\lambda_1 R) V(x_0, \lambda_1 R) \leq C'(\lambda) F(R) \left( \lambda_1^{\alpha'} \ln \frac{1}{\lambda_1} + \lambda_1^{\alpha'} + \lambda_1^{\beta} \right). \quad (7.33)
\]

Combining (7.26), (7.33), and (7.28), we arrive at (7.23). \hfill \Box

**Lemma 7.7.** Assume that $(\mathcal{E}, \mathcal{F})$ is regular and strongly local, and that conditions $(H)$, $(VD)$, $(RV\ D)$ and $(E_F \leq \cdot)$ all hold. Let $\Omega$ be a bounded open subset of $M$ with $\lambda_{\min}(\Omega) > 0$, and let $f \in L^\infty(\Omega)$. Then, the function
\[
G^\Omega f(x) = \int_\Omega g^\Omega(x, y) f(y) d\mu(y)
\]
is continuous for $x \in \Omega$. In particular, the function $E^\Omega = G^\Omega 1_\Omega$ is continuous in $\Omega$.

**Proof.** Without loss of generality, assume that $\|f\|_\infty \leq 1$. Fix a point $x_0 \in \Omega$, and let $R > 0, \rho \geq 1$ such that
\[
B := B(x_0, R) \subseteq \Omega \subseteq B(x_0, \rho R).
\]
Let \( \{x_k\}_{k=1}^\infty \subset B \) such that \( x_k \to x_0 \) as \( k \to \infty \). Let \( \eta > 0 \) be small, and let \( d(x_k, x_0) < \delta(\eta R) \) for any \( k \geq 1 \), where \( \delta \) is the same as in \((H)\). Then,

\[
|G^\Omega f(x_k) - G^\Omega f(x_0)| = \left| \int_{\Omega} g^\Omega(x_k, y)f(y) d\mu(y) - \int_{\Omega} g^\Omega(x_0, y)f(y) d\mu(y) \right|
\]

\[
\leq \int_{B(x_0, \eta R)} g^\Omega(x_k, y) d\mu(y) + \int_{B(x_0, \eta R)} g^\Omega(x_0, y) d\mu(y) + \int_{\Omega \setminus B(x_0, \eta R)} |g^\Omega(x_k, y) - g^\Omega(x_0, y)| d\mu(y). \tag{7.34}
\]

We claim that

\[
\lim_{k \to \infty} \int_{\Omega \setminus B(x_0, \eta R)} |g^\Omega(x_k, y) - g^\Omega(x_0, y)| d\mu(y) = 0. \tag{7.36}
\]

Indeed, as \( g^\Omega \) is jointly continuous off diagonal, we have that, for any \( y \in \Omega \setminus B(x_0, \eta R) \),

\[
\lim_{k \to \infty} g^\Omega(x_k, y) = g^\Omega(x_0, y).
\]

Noting that \( x_k \in B(x_0, \delta(\eta R)) \) for all \( k \geq 1 \), it follows from \((5.4)\) that, for any \( y \in \Omega \setminus B(x_0, \eta R) \),

\[
g^\Omega(x_k, y) \leq C_H g^\Omega(x_0, y).
\]

By condition \((E_F \leq)\), the function \( g^\Omega(x_0, \cdot) \) is integrable in \( \Omega \), that is,

\[
\int_{\Omega} g^\Omega(x_0, y) d\mu(y) = E^\Omega(x_0) \leq CF(R).
\]

Therefore, applying the dominated convergence theorem,

\[
\lim_{k \to \infty} \int_{\Omega \setminus B(x_0, \eta R)} g^\Omega(x_k, y) d\mu(y) = \int_{\Omega \setminus B(x_0, \eta R)} g^\Omega(x_0, y) d\mu(y),
\]

proving our claim.

We next estimate the two terms in \((7.34)\). It is enough to consider the first term. The second one is treated similarly. Now fix \( k \geq 1 \), and let

\[
f(t) = \int_{1/4}^{2\rho R} \frac{F(s) ds}{s V(x_k, s)}.
\]

By Theorem \(7.5\), we have that, using that fact that \( \Omega \subset B(x_0, \rho R) \subset B_1 := B(x_k, 2\rho R) \),

\[
\int_{B(x_0, \eta R)} g^\Omega(x_k, y) d\mu(y) \leq \int_{B(x_k, 2\eta R)} g^{B_1}(x_k, y) d\mu(y)
\]

\[
\leq C \int_{B(x_k, 2\eta R)} f(d(x_k, y)) d\mu(y).
\]

Using \((7.23)\) with \( \lambda_1 = \eta/\rho, \lambda = \frac{1}{4} \) and with \( R, x_0 \) being replaced by \( 2\rho R, x_k \) respectively, we obtain that

\[
\int_{B(x_k, 2\eta R)} f(d(x_k, y)) d\mu(y) \leq C \left( \eta^\rho \ln \frac{1}{\eta} + \eta^\rho + \eta^\beta \right) F(2\rho R)
\]

\[
= o(\eta). \tag{7.37}
\]
Therefore, it follows from (7.34), (7.35), (7.36) and (7.37) that
\[
\lim_{k \to \infty} \left| G^\Omega f(x_k) - G^\Omega f(x_0) \right| \leq 2 \omega(\eta),
\]
thus proving the continuity of \( G^\Omega f \).

\[\Box\]

**Remark 7.8.** Under the hypotheses of Lemma 7.7, the essential supremum and essential infimum in conditions \((E_F \leq)\) and \((E_F \geq)\) in Definition 3.8 can be replaced by supremum and infimum, respectively.

### 8. Proof of Theorem 3.10

#### 8.1. Implication \((H) + (R_F) \Rightarrow (G_F)\).

**Proof.** Let \( B := B(x_0, R) \) and choose \( K > 4 \vee \delta^{-1} \). We split the proof into two steps.

**Step 1.** We prove the lower bound \((G_F \geq)\): there exists some \( C > 0 \) such that
\[
g^B(x_0, y) \geq C^{-1} \int_{K^{-1}r}^R \frac{F(s)}{sV(x_0, s)} \, ds, \quad r = d(x_0, y). \tag{8.1}
\]

Indeed, choose the integer \( n > 1 \) such that
\[
K^{-n-1}R \leq r < K^{-n}R, \tag{8.2}
\]
and for \( i \geq 0 \), set
\[
r_i := K^{-i}R \quad \text{and} \quad B_i := B(x_0, r_i).
\]

As \( K^{-1}r \geq K^{-n-2}R \), similar to (7.20), we have that
\[
\int_{K^{-1}r}^R \frac{F(s)}{sV(x_0, s)} \, ds \leq \sum_{i=0}^{n+1} \int_{r_{i+1}}^{r_i} \frac{F(s)}{sV(x_0, s)} \, ds \leq \ln K \sum_{i=0}^{n+1} \frac{F(r_i)}{V(x_0, r_{i+1})} \tag{8.3}
\]

The last two terms for \( i = n \) and \( i = n + 1 \) in the sum can be bounded by the term \( \frac{F(r_n)}{V(x_0, r_n)} \), since we have that, using (3.3) and (VD),
\[
\frac{F(r_{n+1})}{V(x_0, r_{n+1})} = \frac{F(r_n)}{V(x_0, r_n)} \cdot \frac{F(r_{n+1})}{F(r_n)} \cdot \frac{V(x_0, r_n)}{V(x_0, r_{n+1})} \leq C \frac{F(r_n)}{V(x_0, r_n)},
\]
and a similar bound for the other term:
\[
\frac{F(r_{n+2})}{V(x_0, r_{n+2})} \leq C \frac{F(r_n)}{V(x_0, r_n)}.
\]

...
Hence, it follows from (8.3) that
\[
\int_{R_{K-1}}^{R} F(s) \frac{ds}{sV(x_0, s)} \leq C' \sum_{i=0}^{n-1} \frac{F(r_{i+1})}{V(x_0, r_{i+1})} \\
\leq C' \sum_{i=0}^{n-1} \text{res}(B_{i+1}, B_i) \quad \text{(by condition } (R_F \geq )) \\
\leq C'' \inf_{\partial B_n} g^B(x_0, \cdot) \quad \text{(by (7.9))}. \tag{8.4}
\]

On the other hand, using the fact that $y \in B_n \backslash B_{n+1}$, we have from (5.19) that
\[
g^B(x_0, y) \geq \inf_{B_n} g^B(x_0, \cdot) = \inf_{\partial B_n} g^B(x_0, \cdot).
\]

This combines with (8.4) to prove that $(G_F \geq)$ holds.

**Step 2.** We prove the upper bound $(G_F \leq)$: there exists some $C > 0$ such that for all $y \in B \backslash \{x_0\}$,
\[
g^B(x_0, y) \leq C \int_{R_{K-1}}^{R} F(s) \frac{ds}{sV(x_0, s)}, \quad r = d(x_0, y). \tag{G_F \leq}
\]

Fix $y \in B \backslash \{x_0\}$, and set $r = d(x_0, y)$ as before.

**Case (a)** when $y \in K^{-1}B \backslash \{x_0\}$. Let $n, r_i$ and $B_i$ be respectively defined as in (8.1), (8.2). It follows that
\[
g^B(x_0, y) \leq \sup_{B \backslash B_{n+1}} g^B(x_0, \cdot) = \sup_{\partial B_{n+1}} g^B(x_0, \cdot) \quad \text{(by (5.20))}
\]
\[
\leq C \sum_{i=0}^{n} \text{res}(B_{i+1}, B_i) \quad \text{(by (7.9))}
\]
\[
\leq C' \sum_{i=0}^{n} \frac{F(r_{i+1})}{V(x_0, r_{i+1})} \quad \text{(by condition } (R_F \leq)). \tag{8.5}
\]

Therefore, using (7.20), we obtain $(G_F \leq)$.

**Case (b)** when $y \in B \backslash K^{-1}B$. We want to derive $(E_F \leq)$. If so, we are done by using Theorem 7.5.

Let $x \in B$. We see that
\[
B \subset B(x, 2R) := B'.
\]

It follows that, using (5.20),
\[
E^B(x) = \int_B g^B(x, y) \, d\mu(y) \leq \int_{B'} g^{B'}(x, y) \, d\mu(y)
\]
\[
= \int_{\delta B'} g^{B'}(x, y) \, d\mu(y) + \int_{B' \backslash \delta B'} g^{B'}(x, y) \, d\mu(y)
\]
\[
\leq \int_{\delta B'} g^{B'}(x, y) \, d\mu(y) + \sup_{\partial(\delta B')} g^{B'}(x, \cdot) \mu(B'). \tag{8.6}
\]

By (7.5) and (3.3),
\[
\sup_{\partial(\delta B')} g^{B'}(x, \cdot) \simeq \text{res}(\delta B', B') \leq C \frac{F(2\delta R)}{\mu(\delta B')} \leq C' \frac{F(R)}{\mu(B')}.
\]
and hence,
\[
\sup_{\partial(\delta B')} g^{B'}(x, \cdot) \mu(B') \leq C' F(R).
\] (8.7)

It remains to estimate the integral on the right-hand side of (8.6). Indeed, by Case (a), we have that for \( y \in \delta B' \),
\[
g^{B'}(x, y) \leq C \int_{K^{-1} r}^{2R} \frac{F(s)}{sV(x, s)} ds.
\]

Therefore, by Proposition 7.6 where \( f(t) = \int_{K^{-1} r}^{2R} \frac{F(s) ds}{sV(x, s)} \), we obtain
\[
\int_{\delta B'} g^{B'}(x, y) d\mu(y) \leq C \int_{\delta B'} f(d(x, y)) d\mu(y) \leq C' F(2R) \leq CF(R).
\] (8.8)

Finally, adding up (8.8) and (8.7), we prove that condition \((E_F \leq C)\) holds.

This finishes the proof. □

8.2. Equivalence \((HG') \iff (H)\). We introduce an alternative Harnack inequality, denoted by \((HG')\), for the Green function \(g^B\) on a ball \(B\), and will show that \((HG') \iff (H)\) by using Lemmas 6.4 and 6.2.

Definition 8.1 (Condition \((HG')\)). We say that condition \((HG')\) holds if, for any ball \(B\) in \(M\), the Green function \(g^B\) exists and is jointly continuous off diagonal, and for any \(y \in \overline{B_1} \setminus B_2\) with some balls \(B_1 = \rho_1 B, B_2 = \rho_2 B\) \((0 < \rho_2 < \rho_1 < 1)\),
\[
esup_{\delta' B_2} g^B(\cdot, y) \leq C'_H \inf_{\delta' B_2} g^B(\cdot, y), \tag{HG'}
\]
where \(C'_H \geq 1\) and \(\delta' \in (0, 1)\) are independent of \(B\) and \(y\), but \(\delta'\) may depend on \(\rho_2, \rho_1\), and \(C'_H\) on \(\delta', \rho_2, \rho_1\).

We now show the implication \((HG') \iff (H)\).

Lemma 8.2. Assume that \((\mathcal{E}, \mathcal{F})\) is a local, regular Dirichlet form, and that \(\lambda_{\min}(B) > 0\) for any ball \(B\) in \(M\). Then,
\[
(HG') \Rightarrow (H).
\]

Consequently, if in addition that \((\mathcal{E}, \mathcal{F})\) is strongly local and \((VD)\) holds, then
\[
(HG') \iff (H). \tag{8.9}
\]

Proof. Fix a ball \(B\) in \(M\), and let \(u \in L^\infty(M)\) be non-negative in \(B\) and be harmonic in \(B\). We need to show that
\[
esup_{\delta B} u \leq C_H \inf_{\delta B} u \tag{8.10}
\]
for some constants \(C_H \geq 1\) and \(\delta \in (0, 1)\), which will imply condition \((H)\). It suffices to prove (8.10) assuming in addition that \(u \in L^\infty(M)\), because then the Harnack inequality for arbitrary \(u\) follows by the argument in [26, p.1280 (proof of Theorem 7.4)].

Assuming in the sequel that \(u \in L^\infty\), we split the proof into four steps. Let \(B_1\) and \(B_2\) be the same as in condition \((HG')\).
Step 1. We cut off the function \( u \) such that it becomes non-negative globally in \( M \), but still in \( \mathcal{F} \). For doing this, let \( \phi \) be a cutoff function of \((B_1, B)\). Let
\[
1 := u \phi.
\]
This function \( u_1 \) will do. Indeed, it is easy to see that \( u_1 \geq 0 \) in \( M \) (noting that \( u_1 \) vanishes outside \( B \)), and \( u_1 \in \mathcal{F} \cap L^\infty \).

Let us further show that \( u_1 \) is harmonic in \( B_1 \). Indeed, let \( \varphi \in \mathcal{F}(B_1) \). We have that \( \mathcal{E}(u, \varphi) = 0 \) by the harmonicity of \( u \). Noting that \( u(\phi - 1) \equiv 0 \) in a neighborhood of \( B_1 \), we see that \( \mathcal{E}(u(\phi - 1), \varphi) = 0 \) by the locality of \((\mathcal{E}, \mathcal{F})\). Hence,
\[
\mathcal{E}(u_1, \varphi) = \mathcal{E}(u \phi, \varphi) = \mathcal{E}(u(\phi - 1), \varphi) + \mathcal{E}(u, \varphi) = 0,
\]
showing that \( u_1 \) is harmonic in \( B_1 \).

Step 2. We will work on the function \( u_1 \), and want to modify it such that it is superharmonic in \( B_1 \). This can be done by using a reduced function. Let \( \hat{u}_1 \) be a reduced function of \( u_1 \) with respect to \((\overline{B_2}, B_1)\), as we did in Lemma 6.4. Note that
\[
\begin{cases}
\hat{u}_1 \in \mathcal{F}(B_1), \\
\hat{u}_1 \text{ is superharmonic in } B_1,
\end{cases}
\]
\((8.11)\)

Step 3. We further show that \( \hat{u}_1 \) is harmonic in \( B_2 \). Indeed, let \( \varphi \in \mathcal{F}(B_2) \). By Step 1, the function \( u_1 \) is harmonic in \( B_1 \), and thus, \( \mathcal{E}(u_1, \varphi) = 0 \). Since the function \( \hat{u}_1 - u_1 \) vanishes in \( B_2 \), by the locality of \((\mathcal{E}, \mathcal{F})\),
\[
\mathcal{E}(\hat{u}_1 - u_1, \varphi) = 0.
\]
Hence, we conclude that
\[
\mathcal{E}(\hat{u}_1, \varphi) = \mathcal{E}(u_1, \varphi) + \mathcal{E}(\hat{u}_1 - u_1, \varphi) = 0,
\]
proving that \( \hat{u}_1 \) is harmonic in \( B_2 \).

Step 4. Let \( S = \overline{B_1} \setminus B_2 \). By Step 3, the function \( \hat{u}_1 \) is harmonic in \( B_2 = B_1 \setminus S \). Since \( \lambda_{\min}(B_1) > 0 \), it follows by Lemma 6.2 that
\[
\hat{u}_1(x) = \int_S g^{B_1}(x, y) d\nu(y) \text{ for all } x \in B_2,
\]
where \( \nu := \nu_{\hat{u}_1} \) is a regular Borel measure determined as in (6.2) whose support is contained in \( S \). By condition \((GH')\), for any \( x_1, x_2 \in \delta B_2 \) and for any \( y \in \overline{B_1} \setminus B_2 = S \),
\[
g^{B_1}(x_1, y) \leq C'_{H} g^{B_1}(x_2, y).
\]
Therefore, we conclude that
\[
u(x_1) = \hat{u}_1(x_1) = \int_S g^{B_1}(x_1, y) d\nu(y) \leq C'_{H} \int_S g^{B_1}(x_2, y) d\nu(y) = C'_{H} \hat{u}_1(x_2) = C'_{H} u(x_2).
\]
Let \( C_H = C'_{H} \), and choose \( \delta > 0 \) such that \( \delta B = \delta' B_2 \), that is, \( \delta = \rho_2 \delta' \). Therefore, we obtain \((8.10)\).

Finally, by Lemma 5.2, the opposite implication \((H) \Rightarrow (HG')\) is clear. Indeed, we may choose \( \rho_1 = \frac{3}{4}, \rho_2 = \frac{1}{2} \) and \( \delta' = \delta, C'_H = C_H \), and then apply (5.4). Hence,
the equivalence (8.9) does hold. This finishes the proof of (8.10) for bounded \( u \) and, hence, the entire proof. \( \square \)

8.3. Implication \((G_F) \Rightarrow (H) + (E_F)\).

**Proof.** Fix a ball \( B := B(x_0, R) \). Let \( K \) be the same as in condition \((G_F)\). We split the proof into three steps.

**Step 1.** \((G_F) \Rightarrow (H)\). By Lemma 8.2, it suffices to prove that \((G_F) \Rightarrow (HG')\).

Choose \( \delta' = \frac{3}{4} \) and

\[
B_1 := (4K)^{-1}B \quad \text{and} \quad B_2 := (6K)^{-1}B. 
\]

We need to show that there exists a constant \( C = C(K) > 0 \) such that, for all \( x_1, x_2 \in \delta'B_2 = (8K)^{-1}B \) and all \( y \in B_1 \setminus B_2 \),

\[
C^{-1}g^B(x_1, y) \leq g^B(x_2, y) \leq Cg^B(x_1, y). 
\]

(8.12)

Let us prove the first inequality in (8.12).

For \( i = 1, 2 \), we have that

\[
d(y, x_i) \leq d(y, x_0) + d(x_0, x_i) < (4K)^{-1}R + (8K)^{-1}R = 3(8K)^{-1}R, 
\]

and that

\[
d(y, x_i) \geq d(y, x_0) - d(x_0, x_i) > (6K)^{-1}R - (8K)^{-1}R = (24K)^{-1}R. 
\]

As \( B \subset B(y, 2R) \), we have by \((G_F \leq)\) that

\[
g^B(x_1, y) \leq g^{B(y,2R)}(x_1, y) = g^{B(y,2R)}(y, x_1) 
\]

\[
\leq C_1 \int_{K^{-1}d(y, x_1)}^{2R} \frac{F(s)}{sV(y, s)} ds 
\]

\[
\leq C_1 \int_{K^{-1}(24K)^{-1}R}^{2R} \frac{F(s)}{sV(y, s)} ds 
\]

\[
\leq C_2 \frac{F(R)}{V(y, R)} \quad \text{(similar to (7.27) ).} \quad (8.13)
\]

On the other hand, as \( B(y, R/2) \subset B \), we have by \((G_F \geq)\) that, using the fact that \( d(y, x_2) \leq 3(8K)^{-1}R < K^{-1}(R/2) \),

\[
g^B(x_2, y) \geq g^{B(y,R/2)}(x_2, y) = g^{B(y,R/2)}(y, x_2) 
\]

\[
\geq C_3 \int_{K^{-1}d(y, x_2)}^{R/2} \frac{F(s)}{sV(y, s)} ds 
\]

\[
\geq C_3 \int_{K^{-2}R/2}^{R/2} \frac{F(s)}{sV(y, s)} ds 
\]

\[
\geq C_4 \frac{F(R)}{V(y, R)} \quad \text{(similar to (7.25) ).} \quad (8.14)
\]

Combining (8.13) and (8.14), we obtain the the first inequality in (8.12).

The second inequality also holds by interchanging \( x_1 \) and \( x_2 \). Hence, condition \((HG')\) holds.
Step 2. \((G_F) \Rightarrow (E_F)\). We first show that, for some \(C_2 > 0\),
\[
\sup_{x \in B} E^B(x) \leq C_2 F(R) .
\]  
(8.15)
Indeed, for \(x \in B\), we have that \(B \subset B(x, 2R)\), and thus
\[
E^B(x) = \int_B g^B(x, y) \, d\mu(y) \\
\leq \int_B g^{B(x, 2R)}(x, y) \, d\mu(y) \\
\leq \int_B \left[ C \int_{K^{-1}d(x,y)}^{2R} \frac{F(s) \, ds}{sV(x,s)} \right] \, d\mu(y) \quad \text{(using } (G_F \leq )) \\
\leq C_2 F(R) \quad \text{(using } (7.22) ),
\]
thus proving (8.15).

We next show the opposite inequality, that is, for some \(C_1 > 0\),
\[
\inf_{x \in \delta B} E^B(x) \geq C_1 F(R) ,
\]  
(8.16)
where \(\delta = K^{-1}\). Indeed, fix \(x \in \delta B\), and let \(B' := B(x, (1-\delta)R)\). Then \(B' \subset B\), and thus
\[
E^B(x) = \int_B g^B(x, y) \, d\mu(y) \\
\geq \int_B g^{B'}(x, y) \, d\mu(y) \\
\geq \int_{K^{-1}B'} \left[ C^{-1} \int_{K^{-1}d(x,y)}^{(1-\delta)R} \frac{F(s) \, ds}{sV(x,s)} \right] \, d\mu(y) \quad \text{(using } (G_F \geq )) \\
\geq C_1 F(R) \quad \text{(using } (7.22) ),
\]
thus proving (8.16).

\[\square\]

8.4. Implication \((H) + (E_F) \Rightarrow (H) + (R_F)\). We need the following two lemmas.

**Lemma 8.3.** Assume that \((\mathcal{E}, \mathcal{F})\) is regular. Then, for any two open subsets \(U \Subset \Omega\) of \(M\) such that \(\lambda_{\min}(\Omega) > 0\), we have
\[
\text{res} (U, \Omega) \leq \frac{\|E^\Omega\|_\infty}{\mu(U)} .
\]  
(8.17)

**Proof.** Let \(u_p\) be the capacitory potential of \((U, \Omega)\), that is, \(u_p \in \mathcal{F}(\Omega), u_p|_U = 1\), and \(\mathcal{E}(u_p) = \text{cap}(U, \Omega)\).

It follows that \(\|u_p\|_2^2 \geq \mu(U)\), and
\[
\lambda_{\min}(\Omega) \leq \frac{\mathcal{E}(u_p)}{\|u_p\|_2^2} \leq \frac{\text{cap}(U, \Omega)}{\mu(U)} ,
\]  
(8.18)

showing that
\[
\text{res} (U, \Omega) \leq \frac{1}{\mu(U) \lambda_{\min}(\Omega)} .
\]  
(8.19)
On the other hand, we claim that
\[
\frac{1}{\lambda_{\min}(\Omega)} \leq \|E^\Omega\|_\infty. \tag{8.20}
\]

Let \( u_e \) be a non-negative minimizing function for the first eigenvalue
\[
\lambda_{\min}(\Omega) = \inf_{u \in F(\Omega) \setminus \{0\}} \frac{\mathcal{E}(u)}{\|u\|_2^2},
\]
(such a function \( u_e \) exists since \( \lambda_{\min}(\Omega) > 0 \)), that is, \( 0 \leq u_e \in F(\Omega) \) and
\[
\mathcal{E}(u_e, \varphi) = \lambda_{\min}(\Omega) \int_\Omega u_e \varphi d\mu \text{ for any } \varphi \in F(\Omega).
\]
In particular, taking \( \varphi = G^\Omega 1_\Omega = E^\Omega \), we have
\[
\mathcal{E}(u_e, G^\Omega 1_\Omega) = \lambda_{\min}(\Omega) \int_\Omega u_e (G^\Omega 1_\Omega) d\mu.
\]
Observing that
\[
\mathcal{E}(u_e, G^\Omega 1_\Omega) = \int_\Omega u_e d\mu,
\]
it follows that
\[
\lambda_{\min}(\Omega) = \frac{\int_\Omega u_e d\mu}{\int_\Omega u_e (G^\Omega 1_\Omega) d\mu} \geq \frac{\int_\Omega u_e d\mu}{\|G^\Omega 1_\Omega\|_\infty \int_\Omega u_e d\mu} = \frac{1}{\|G^\Omega 1_\Omega\|_\infty},
\]
proving our claim.

Finally, combining (8.19) and (8.20), we finish the proof. \( \square \)

**Lemma 8.4.** Assume that \((\mathcal{E}, F)\) is regular, strongly local. Let \( \Omega \subset M \) be open with \( \lambda_{\min}(\Omega) > 0 \), and assume that the Green function \( g^\Omega \) exists and is jointly continuous off diagonal. Then, for any open set \( U \subset \Omega \),
\[
\text{res}(U, \Omega) \geq \left( \inf_{\partial U} E^\Omega \right)^2 / \mu(\Omega) \|E^\Omega\|_\infty. \tag{8.21}
\]

**Proof.** Let \( u_p \) be the capacitory potential of \((U, \Omega)\). By (8.18),
\[
\lambda_{\min}(\Omega) \leq \frac{\text{cap}(U, \Omega)}{\|u_p\|_2^2}.
\]
We see that, using the Cauchy-Schwarz inequality,
\[
\|u_p\|_2^2 = \int_\Omega u_p^2 d\mu \geq \left( \int_\Omega u_p d\mu \right)^2 / \mu(\Omega).
\]
Note that by Lemma 6.5, for all \( x \in \Omega \setminus \partial U \),
\[
u_p(x) = \int_{\partial U} g^\Omega(x, y) d\nu_p(y)
\]
where $\nu_p$ is the equilibrium measure of $(U, \Omega)$ supported on $\partial U$. Hence,
\begin{align*}
\int_{\Omega} u_p(x) \, d\mu(x) &= \int_{\partial U} \int_{\Omega} g^\Omega(x, y) \, d\mu(x) \, d\nu_p(y) \\
&= \int_{\partial U} E^\Omega(y) d\nu_p(y) \geq \nu_p(\partial U) \inf_{\partial U} E^\Omega \\
&= \text{cap}(U, \Omega) \inf_{\partial U} E^\Omega,
\end{align*}
whence, it follows that
\[ \lambda_{\text{min}}(\Omega) \leq \frac{\text{cap}(U, \Omega) \mu(\Omega)}{[\text{cap}(U, \Omega) \inf_{\partial U} E^\Omega]^2} \leq \frac{\text{res}(U, \Omega) \mu(\Omega)}{(\inf_{\partial U} E^\Omega)^2}. \]
Substituting (8.20) into this inequality, we obtain (8.21).

We now turn to the proof.

Proof of $(H) + (E_F) \Rightarrow (H) + (R_F)$. Fix a ball $B := B(x_0, R)$. We split the proof into two steps.

**Step 1.** $(H) + (E_F) \Rightarrow (R_F \leq)$.

Indeed, this easily follows from (8.17): for any $\delta \in (0, 1)$,
\[ \text{res}(\delta B, B) \leq \frac{\| E^\Omega \|_{\infty}}{\mu(\delta B)} \leq C \frac{F(R)}{\mu(B)}. \]

**Step 2.** $(H) + (E_F) \Rightarrow (R_F \geq)$.

Let $0 < \delta < \delta_1$ where $\delta_1$ is the same as in condition $(E_F \geq)$, and let
\[ U = \delta B \text{ and } \Omega = B. \]
Note that by Lemma 7.7, the function $E^B$ is continuous in $B$. Hence, by condition $(E_F \geq)$, we have that
\[ \inf_{\partial U} E^\Omega \geq \inf_{U} E^\Omega = \inf_{U} E^\Omega \geq C^{-1} F(R). \]
Therefore, using (8.21) and condition $(E_F \leq)$, we conclude that
\[ \text{res}(\delta B, B) \geq \frac{\left( \inf_{\partial U} E^\Omega \right)^2}{\mu(U) \| E^\Omega \|_{\infty}} \geq \frac{\left[ C^{-1} F(R) \right]^2}{\mu(U) \left[ C F(R) \right]} \geq C'' \frac{F(R)}{\mu(B)}, \]
thus proving condition $(R_F \geq)$, as desired. $\square$

9. **Appendix**

9.1. **Capacity.** Recall that the capacity $\text{cap}(A)$ is defined by (3.5), and the definition of $\text{cap}$-$\text{quasi-continuous}$ is given by around (3.7). Observe that for any Borel sets $A, B \subset M$,
\[ \text{cap}(A \cup B) + \text{cap}(A \cap B) \leq \text{cap}(A) + \text{cap}(B), \]
and hence, for any Borel subsets \( \{A_i\}_{i=1}^\infty \) of \( M \),
\[
\text{cap}(\bigcup_{i=1}^\infty A_i) \leq \sum_{i=1}^\infty \text{cap}(A_i).
\] (9.1)

**Lemma 9.1.** Assume that \((\mathcal{E}, \mathcal{F})\) is a regular Dirichlet form. Then, each \( u \in \mathcal{F} \) admits a cap-quasi-continuous version.

**Proof.** We modify the proof given for [16, Thm 2.1.3 (p.71)] to our capacity.

We first show that, for each \( u \in \mathcal{F} \cap C_0(M) \) and each \( \lambda > 0 \),
\[
\text{cap}(\{x \in M : |u(x)| > \lambda\}) \leq \frac{4}{\lambda^2} \mathcal{E}(u).
\] (9.2)

Indeed, consider the sets
\[
G := \{x \in M : |u(x)| > \lambda\}, \quad G' := \{x \in M : |u(x)| > \frac{\lambda}{2}\},
\]
both of which are open as \( u \) is continuous in \( M \). Then \( G \subset G' \). Set
\[
\varphi := \frac{u}{\lambda/2} \wedge 1.
\]
Clearly, \( \varphi \in \mathcal{F} \cap C_0(M) \), and \( \varphi = 1 \) on \( G' \), and hence, it is a test function for \( \text{cap}(G) \), that is
\[
\text{cap}(G) \leq \mathcal{E}(\varphi) \leq \frac{4}{\lambda^2} \mathcal{E}(u),
\]
proving (9.2).

For each \( u \in \mathcal{F} \), by the regularity of \((\mathcal{E}, \mathcal{F})\), there exists a sequence \( \{u_n\}_{n=1}^\infty \subset \mathcal{F} \cap C_0(M) \) such that \( u_n \xrightarrow{\mathcal{F}} u \) as \( n \to \infty \). Without loss of generality, assume that
\[
\mathcal{E}(u_{l+1} - u_l) \leq 2^{-3l}, \ l \geq 1.
\] (9.3)

Let
\[
G_l = \{x \in M : |u_{l+1}(x) - u_l(x)| > 2^{-l}\}, \\
F_k = (\bigcup_{l=k}^\infty G_l)^c = \bigcap_{l=k}^\infty (G_l)^c.
\]

For \( x \in F_k \), \( k \geq 1 \), we see that
\[
|u_{l+1}(x) - u_l(x)| \leq 2^{-l} \text{ for any } l \geq k,
\]
and hence, the sequence \( \{u_l(x)\} \) is a Cauchy, and it converges uniformly to a continuous function on \( F_k \). Let
\[
\tilde{u}(x) = \lim_{l \to \infty} u_l(x).
\]
Then \( \tilde{u} \) is defined on \( \bigcup_{k=1}^\infty F_k \), and \( \tilde{u}|_{F_k} \) is continuous for each \( k \geq 1 \). Moreover, using (9.1), (9.2) and (9.3), we have
\[
\text{cap}(F_k^c) \leq \sum_{l=k}^\infty \text{cap}(G_l) \leq \sum_{l=k}^\infty \frac{4}{2^{-2l}} \mathcal{E}(u_{l+1} - u_l)
\leq \sum_{l=k}^\infty \frac{4}{2^{-2l}} \cdot 2^{-3l} = 8 \cdot 2^{-k}.
\]
We conclude that $\tilde{u}$ is continuous on $F_k$, and $M \setminus F_k = F_k^c$ is open, and $\cap (F_k^c) \leq 8 \cdot 2^{-k}$. Therefore, noting that $\tilde{u} = u$ $\mu$-a.e., we obtain that $\tilde{u}$ is a cap-quasi-continuous version of $u$.

The next proposition shows that the capacitory potential $u_p$ of $(A, \Omega)$ exists for any compact subset $A$. In the classical potential theory, this issue is called the equilibrium problem or the Robin problem (cf. [35, p.189]). It turns out that the capacitory potential $u_p$ of $(A, \Omega)$ is a reduced function of any cutoff function of $(\overline{\Omega}, M)$ for any precompact open $\Omega$ with $\lambda_{\min}(\Omega) > 0$.

**Proposition 9.2.** Assume that $(\mathcal{E}, \mathcal{F})$ is a regular Dirichlet form. Let $\Omega \subset M$ be precompact open such that $\lambda_{\min}(\Omega) > 0$, and let $\psi$ be any cutoff function of $(\overline{\Omega}, M)$ and let $A$ be a compact subset of $\Omega$. Then the capacitory potential $u_p$ of $(A, \Omega)$ is a reduced function of $\psi$ w.r.t. $(A, \Omega)$. If in addition $(\mathcal{E}, \mathcal{F})$ is strongly local, then $u_p$ is superharmonic in $\Omega$.

**Proof.** Let $u_p$ be the capacitory potential of $(A, \Omega)$. By the standard approach, there exists a minimizing sequence $\{u_k\}_{k=1}^{\infty}$ of cutoff functions of $(A, \Omega)$ such that $u_k \xrightarrow{F} u_p$ as $k \to \infty$, and

$$\mathcal{E}(u_p) = \cap (A, \Omega),$$

and moreover, the function $u_p \in \mathcal{F}(\Omega), 0 \leq u_p \leq 1$ in $\Omega$, and $u_p|_A = 1$. Note that this potential $u_p$ is unique. Also $u_p$ is harmonic in $U = \Omega \setminus A$, since for any $\varphi \in \mathcal{F} \cap C_b(U)$ and any number $a$, each function $u_k + a \varphi$ for $k \geq 1$ is a cutoff function of $(A, \Omega)$, and thus

$$\cap (A, \Omega) \leq \mathcal{E}(u_k + a \varphi) = \mathcal{E}(u_k) + 2a \mathcal{E}(u_k, \varphi) + a^2 \mathcal{E}(\varphi) \to \mathcal{E}(u_p) + 2a \mathcal{E}(u_p, \varphi) + a^2 \mathcal{E}(\varphi),$$

which implies that $2a \mathcal{E}(u_p, \varphi) + a^2 \mathcal{E}(\varphi) \geq 0$, showing that $\mathcal{E}(u_p, \varphi) = 0$.

Since $\psi$ is a cutoff function of $(\overline{\Omega}, M)$, it is straightforward to verify that $u_p$ is a reduced function of $\psi$.

Finally, if $(\mathcal{E}, \mathcal{F})$ is strongly local, the cutoff function $\psi$ is harmonic (in particular superharmonic) in $\Omega$. Therefore, we obtain from Lemma 6.4 that $u_p$ is superharmonic in $\Omega$.

### 9.2. Functions in $\mathcal{F}(\Omega \setminus A)$.

The following give a sufficient condition for a function belonging to the space $\mathcal{F}(\Omega \setminus A)$, and it can be viewed as a supplement of Proposition 2.8 in [21].

**Proposition 9.3.** Assume that $(\mathcal{E}, \mathcal{F})$ is a regular Dirichlet form. Let $\Omega \subset M$ be open, and let $S \subset \Omega$ be compact. If $v \in \mathcal{F}(\Omega)$ vanishes in a neighborhood $V$ of $A$, then $v \in \mathcal{F}(\Omega \setminus A)$.

**Proof.** Note that $v = v_+ - v_-$, and $v_+ = v_- = 0$ in $V$, and that $v_+, v_- \in \mathcal{F}$. It suffices to assume that $v \geq 0$ in $V$. We can also assume that $v$ is bounded because otherwise consider a sequence $v_k := v \wedge k$ that tends to $v$ in $\mathcal{F}$-norm as $k \to \infty$ by [16, Theorem 1.4.2(iii), p.28]; if we already know that $v_k \in \mathcal{F}(\Omega \setminus A)$ then we can conclude that also $v \in \mathcal{F}(\Omega \setminus A)$.

Hence, we can assume in the sequel that $v$ is non-negative and bounded in $M$, say $0 \leq v \leq 1$. 


Let $\varphi$ be a cut-off function of $(A, V)$. Let $\{v_k\}_{k=1}^{\infty}$ be a sequence of functions from $\mathcal{F} \cap C_0(\Omega)$ such that $v_k \xrightarrow{\mathcal{F}} v$ as $k \to \infty$. Consider

$$u_k := v_k - v_k \wedge \varphi.$$ 

Note that each $u_k \in \mathcal{F} \cap C_0(\Omega)$, $u_k = 0$ in $A$, and hence, the support of $u_k$ is outside a neighborhood of $A$, that is,

$$u_k \in \mathcal{F} \cap C_0(\Omega \setminus A).$$

We claim that $\{u_k\}$ converges to $v$ weakly in $\mathcal{F}$:

$$u_k \xrightarrow{\mathcal{F}} v \text{ as } k \to \infty.$$ 

Indeed, as $v \geq 0$ and $v_k \xrightarrow{\mathcal{F}} v$, we have by [16, Theorem 1.4.2(v), p.28] that

$$|v_k - \varphi| \xrightarrow{\mathcal{F}} |v - \varphi|,$$

as $k \to \infty$. It follows that

$$v_k \wedge \varphi = \frac{1}{2} [v_k + \varphi - |v_k - \varphi|] \xrightarrow{\mathcal{F}} \frac{1}{2} [v + \varphi - |v - \varphi|] = v \wedge \varphi,$$

and hence, $u_k = v_k - v_k \wedge \varphi \xrightarrow{\mathcal{F}} v - v \wedge \varphi = v$, proving our claim.

Since $u_k \in \mathcal{F} \cap C_0(\Omega \setminus A)$, we conclude that $v \in \mathcal{F}(\Omega \setminus A)$.

Proposition 9.4. Assume that $(\mathcal{E}, \mathcal{F})$ is a regular Dirichlet form. Let $U, V$ be two precompact open subsets of $M$ such that their closures $\overline{U}, \overline{V}$ are disjoint. If $u \in \mathcal{F}(U \cup V) \cap L^\infty(M)$, we can decompose $u = u_1 + u_2$, where $u_1 \in \mathcal{F}(U_1), u_2 \in \mathcal{F}(V_1)$, and where $U_1, V_1$ are any respective neighborhoods of $U, V$ with disjoint closures $\overline{U_1}, \overline{V_1}$.

Proof. Let $\phi$ be a cutoff function of $(U, U_1)$. Since $u \in \mathcal{F} \cap L^\infty$, we see also that $u_1 := u \phi \in \mathcal{F} \cap L^\infty$. We show that $u_1 \in \mathcal{F}(U_1)$. In fact, since the support of $u_1$ is contained in the set

$$\text{supp } (u) \cap \text{supp } (\phi) \subseteq U \cup V \cap U_1 = U \subset U_1.$$ 

Hence, as $U$ is precompact, we obtain by [21, Prop. 2.8, p.2620] that $u_1 \in \mathcal{F}(U_1)$.

To show that $u_2 := (1 - \phi)u \in \mathcal{F}(V_1)$, observe that the support of $u_2$ is contained in the set

$$\text{supp } (u) \cap \text{supp } (1 - \phi) \subseteq U \cup V \cap M \setminus U = V \subset V_1.$$ 

Hence, using [21, Prop. 2.8, p.2620] again, we have that $u_2 \in \mathcal{F}(V_1)$.

Finally, note that

$$u = u \phi + (1 - \phi)u = u_1 + u_2.$$ 

We finish the proof.
References


Fakultät für Mathematik, Universität Bielefeld, Postfach 100131, 33501 Bielefeld, Germany.
E-mail address: grigor@math.uni-bielefeld.de

Department of Mathematical Sciences, and Mathematical Sciences Center, Tsinghua University, Beijing 100084, China.
E-mail address: hujiaxin@mail.tsinghua.edu.cn