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# ON EXISTENCE OF A DUAL SEMIGROUP

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We establish the existence of a sub-Markov semigroup in a Borel state space, which is in duality to a given sub-Markov semigroup with respect to a given excessive measure. The only assumption is that the initial semigroup is normal and separates points.

1. A dual semigroup is a powerful tool in the theory of Markov processes. By means of a dual semigroup one can treat the process in the reversed time. In many papers on potential theory a pair of dual Markov processes with some regularity properties is considered. So the question arises how to construct a dual Markov process with desired properties or at least a dual semigroup. Different approaches to this problem were given in the papers [GM73], [SW73], [Shu77], [J78], [CR78]. As a rule, the existence of a dual semigroup was established only if a "good" Markov process (i.e. at least right continuous and strong Markov) exists for the initial semigroup.

However it happens that the answer to this question is always positive for non-homogeneous Markov processes (see [Kuz80], [Kuz82]). So it is natural to find the widest conditions for the existence of dual semigroup. In the paper [Kuz86] we prove it under stochastic continuity of the original semigroup. Here we improve this result, canceling the stochastic continuity and assuming only that the original semigroup is normal and separates points.

Mainly we use the notation of [Kuz82], [DM75], [BG68], [Ge75], [Sha88], but we shall give all main definitions.

2. Let  $(E, \mathcal{E})$  be a Borel space, i.e. a measurable space isomorphic to a

Borel subset of a Polish space with Borel  $\sigma$ -field. In [DM75] Lousin space stands for such spaces.

We call the function  $p(t, x, \Gamma)$ ,  $t > 0$ ,  $x \in E$ ,  $\Gamma \in \mathcal{E}$ , a *homogeneous transition function*, or a *sub-Markov semigroup*, in the space  $E$  if (i) it is  $\mathcal{B}(0, \infty) \times \mathcal{E}$ -measurable in  $t$ ,  $x$  for any  $\Gamma$ , (ii) it is a sub-Markov measure on  $\Gamma$  for any  $t$ ,  $x$  and (iii) the Kolmogorov-Chapman equation holds, i.e.

$$\int p(s, x, dy)p(t, y, \Gamma) = p(s+t, x, \Gamma).$$

for any  $s, t > 0$ ,  $x \in E$ ,  $\Gamma \in \mathcal{E}$ .

We denote by  $P_t$  the operator corresponding to the kernel  $p(t, \cdot, \cdot)$ .

The semigroup  $p$  is said to be *normal* if  $\lim_{t \downarrow 0} p(t, x, E) = 1$ .

The semigroup  $p$  *separates points*, if the equality  $p(\cdot, x, \cdot) = p(\cdot, y, \cdot)$  implies  $x = y$ .

Two semigroups  $p$  and  $\hat{p}$  with the common space  $E$  are said to be *dual* (or in *duality*) with respect to some  $\sigma$ -finite measure  $m$  on  $E$  if

$$m(dx)p(t, x, dy) = m(dy)\hat{p}(t, y, dx)$$

for any  $t > 0$ .

In turn, let us say that the semigroup  $\hat{p}$  is  $\alpha$ -dual ( $\alpha \geq 0$ ) with respect to  $p$  and  $m$  if the semigroups  $e^{-\alpha t}p(t, \cdot, \cdot)$  and  $\hat{p}$  are in duality with respect to  $m$ , or, which is equivalent, if

$$m(dx)p(t, x, dy) = e^{\alpha t}m(dy)\hat{p}(t, y, dx)$$

for any  $t > 0$ .

It can be easily seen that if  $p$  and  $\hat{p}$  are in duality with respect to  $m$ , then the measure  $m$  is a *supermedian* one with respect to  $p$  (and  $\hat{p}$ ), i.e. that  $mP_t \leq m$  for any  $t > 0$ . Moreover, the normality of  $p$  implies that  $m$  is an *excessive* measure indeed, i.e. that  $mP_t \uparrow m$  as  $t \downarrow 0$  (see [Kuz82], 11.4). In turn, if  $\hat{p}$  is  $\alpha$ -dual with respect to  $p$  and  $m$ , then  $m$  is  $\alpha$ -excessive, i.e.

$$e^{-\alpha t}mP_t \leq m \quad \text{for any } t > 0;$$

$$e^{-\alpha t}mP_t \uparrow m \quad \text{as } t \downarrow 0.$$

Our aim is to prove the following

**Theorem.** *Let  $E$  be a Borel space and  $p$  be a normal semigroup on  $E$ , separating points. Let  $m$  be  $\alpha$ -excessive measure ( $\alpha \geq 0$ ) with respect to  $p$ . Then, there exists a semigroup  $\hat{p}$ , which is  $\alpha$ -dual with respect to  $p$  and  $m$ .*

**Remarks.** 1. Our definition of duality corresponds to the concept of *weak duality* in the potential theory. Remember that *strong* duality also includes the absolute continuity of both resolvents of  $p$  and  $\hat{p}$  with respect to  $m$ .

2. Obviously, we can't expect any regularity properties for  $\hat{p}$  without any additional assumptions. However, one can apply to  $\hat{p}$  the Ray-Knight compactification [Ge75] or Dynkin's regularization procedure [Dy73].

Since the statement is trivial for finite or countable  $E$ , we shall assume that  $E$  is *uncountable*.

The general scheme of the proof is as follows. The original state space  $E$  will be embedded into a new space  $H$  (the space of entrance laws), and the subspace  $E_+$  (the entrance space) will be chosen in  $H$ . We shall consider a Markov process in  $E$  with  $p$  for its semigroup and  $m$  for its one-dimensional distributions. We shall construct in  $E_+$  an auxiliary "good" Markov process which would be stochastic equivalent to the above process. The dual semigroup in  $E_+$  for the auxiliary process will be constructed. Finally, it will be rearranged to the desired semigroup in the original state space  $E$ .

**3. Entrance laws and entrance space.** An *entrance law* is a collection of sub-probability measures  $\nu_t(dx)$ ,  $t > 0$ , satisfying the relation  $\nu_t^P = \nu_{t+s}$  for any  $t, s > 0$ . An entrance law is said to be *normed* if  $\lim_{t \downarrow 0} \nu_t(E) = 1$ .

We assume that all considered entrance laws are normed without special mention.

Let  $H$  be the space of all (normed) entrance laws. Let us denote by  $\mathcal{H}$  a  $\sigma$ -field in  $H$  generated by all the functions  $F(v) = v_t(\Gamma)$ ,  $t > 0$ ,  $\Gamma \in \mathcal{E}$ . Due to [Dy71], [Dy72] the space  $(H, \mathcal{H})$  is Borel.

We shall use characters  $x, y, \dots$  for elements of  $H$ , and shall denote by  $v^x, v^y$  etc. the corresponding entrance laws.

An entrance law  $v$  is said to be *extreme* if the relation  $v = \theta v^1 + (1 - \theta)v^2$  with  $0 < \theta < 1$  and  $v^1$  and  $v^2$  being (normed) entrance laws implies  $v = v^1 = v^2$ . The space  $E_+$  of all extreme entrance laws is measurable in  $H$  and any (normed) entrance law  $v$  can be uniquely represented in an integral form

$$v_t(\Gamma) = \int_{E_+} \bar{v}_t(\Gamma) q(v, d\bar{v}) \quad (1)$$

where  $q(v, d\bar{v})$  is a probability measure on  $E_+$  and a Markov kernel from  $H$  to  $E_+$  with respect to  $v$ . Denote by  $\mathcal{E}_+$  the restriction of  $\mathcal{H}$  to  $E_+$ . The space  $(E_+, \mathcal{E}_+)$  is also Borel. See [Dy71] and [Dy72], or [Kuz82].

To any point  $x \in E$  there corresponds an entrance law  $\mu_t^x(\Gamma) = p(t, x, \Gamma)$ . Since  $p$  separates points, the correspondence  $\pi: x \rightarrow \mu^x$  provides a one-to-one mapping from  $E$  into  $H$ . The set  $\pi(E)$  is a Borel subset of  $H$  as a one-to-one image of a Borel space (see, for example, [Pa67], Chapter I, Corollary 3.3). So we can treat the space  $E$  as a subset of  $H$ , and we shall consider all the measures defined on  $E$  as measures on  $H$ , concentrated on  $E$ . In particular, it concerns the measure  $m$ , all the entrance laws etc.

For  $x \in H$  we put  $q(x, \cdot) = q(v^x, \cdot)$ . We denote by  $Q$  the operator corresponding to the kernel  $q$ .

Define a semigroup  $p^+$  in the space  $H$  by the formula

$$p^+(t, x, \Gamma) = v_t^x Q(\Gamma), \quad x \in H, \Gamma \in \mathcal{H}, t > 0.$$

Obviously the measure  $p^+(t, x, \cdot)$  is concentrated on  $E_+$  for any  $t, x$ , and it is easy to verify that  $p^+$  is a normal semigroup in  $H$  as well as in  $E_+$ , separating points of  $H$ , hence  $E_+$ .

We put  $m_+ = mQ$ . The measure  $m_+$  is  $\alpha$ -excessive with respect to  $p^+$ .

Our local goal is to prove the two following propositions.

**Lemma 1.**  $m = m_+$  and

$$m(dx)p(t,x,dy) = m_+(dx)p^+(t,x,dy)$$

for any  $t > 0$  where the equality is considered as the equality of measures in  $H \times H$ .

**Lemma 2.** One can introduce a metric  $\rho$  in  $E_+$  which generates  $\mathcal{E}_+$  and for which the semigroup  $p^+$  restricted to  $E_+$  would be stochastically continuous with respect to  $\rho$ .

Proofs of these propositions will be given in n<sup>0</sup> 4 - 6. Using them we shall establish the Theorem in n<sup>0</sup> 7.

**4. Processes with random birth and death times.** Let introduce a space  $\Omega$  of all the trajectories  $\omega_t$  defined on open intervals  $(\alpha, \beta)$ ,  $-\infty \leq \alpha(\omega) < \beta(\omega) \leq \infty$ . As usual, we put  $x_t(\omega) = \omega_t$  for  $\alpha < t < \beta$ ,  $\mathcal{F}(\cdot) = \sigma\{x_t, t \in \cdot\}$ ,  $\mathcal{F} = \mathcal{F}(-\infty, \infty)$ ,  $\mathcal{F}(s, t+) = \bigcap_{\varepsilon > 0} \mathcal{F}(s, t+\varepsilon)$  etc. See [Kuz82].

For any real  $t$  we define the shift operator  $\theta_t: \Omega \rightarrow \Omega$  by putting  $(\theta_t \omega)_s = \omega_{s+t}$  with corresponding shift of the life interval  $(\alpha, \beta)$ . We put  $\Omega_t = \Omega \cap \{\alpha \leq t < \beta\}$ . Obviously  $\theta_s(\Omega_t) = \Omega_{s+t}$  and  $\theta_t \mathcal{F}(\cdot) = \mathcal{F}(\cdot + t)$ .

Let  $Q$  be a  $\sigma$ -finite measure on  $\mathcal{F}$ . The pair  $(x_t, Q)$  is said to be a (canonical) Markov process with random birth and death times if its one-dimensional distributions

$$Q\{\alpha < t < \beta, x_t \in dx\}$$

are  $\sigma$ -finite for any  $t$  and the Markov property

$$Q(AB|x_t) = Q(A|x_t)Q(B|x_t) \text{ a.s. } Q \text{ on } \alpha < t < \beta,$$

holds for any  $A \in \mathcal{F}_{<t}$ ,  $B \in \mathcal{F}_{>t}$ . Due to [Kuz73] there exists a unique canonical Markov process  $(x_t, Q)$  with two-dimensional distributions of the form

$$m_{st}(dx, dy) = Q\{\alpha < s, x_s \in dx, x_t \in dy, t < \beta\} \\ = e^{\alpha s} m(dx) p(t-s, x, dy).$$

One can easily verify that

$$Q(\theta_t A) = e^{\alpha t} Q(A). \quad (2)$$

for any  $A \in \mathcal{F}$ .

Introduce a space  $K_s$  of all probability measures  $P$  on the  $\sigma$ -field  $\mathcal{F}_{>s}$  such that  $P(\Omega_s) = 1$  and for any  $t > s$ ,  $\Gamma \in \mathcal{E}$

$$P(x_t \in \Gamma | \mathcal{F}(s, t)) = p(t-s, x_t, \Gamma) \text{ a.s. } P \text{ on } t < \beta. \quad (3)$$

Define a  $\sigma$ -field  $\mathcal{K}_s$  in  $K_s$  as one generated by all the functions  $F(P) = P(A)$ ,  $A \in \mathcal{F}_{>s}$ .

To any measure  $P \in K_s$  there corresponds an entrance law

$$\nu_t(\Gamma) = P(x_{s+t} \in \Gamma), \quad t > 0.$$

It is easy to verify that this relation defines a one-to-one two-sided measurable correspondence  $j_s: K_s \rightarrow H$ . The measure  $P$  corresponding to an entrance law  $\nu^x$ ,  $x \in H$ , will be denoted by  $P_{s,x}$ . In particular, to any  $x \in E$  there corresponds a measure  $P_{s,x} \in K_s$  with the property

$$P_{s,x}(x_t \in \Gamma) = p(t-s, x, \Gamma).$$

By means of the measures  $P_{s,x}$  the equality (3) can be rearranged as follows: for any  $s < t$ ,  $A \in \mathcal{F}_{>t}$

$$P_{s,x}(A | \mathcal{F}(s, t)) = P_{t,x_t}(A) \text{ a.s. } P_{s,x} \text{ on } t < \beta. \quad (4)$$

Moreover from the definition of the measure  $Q$  it follows that

$$Q(A | \mathcal{F}_{\leq t}) = P_{t,x_t}(A) \text{ a.s. } Q \text{ on } \alpha < t < \beta. \quad (5)$$

See [Kuz82].

Note that the operator  $\theta_t$  generates a one-to-one mapping of  $K_s$  to  $K_{s+t}$  which commutes with  $j_s$  and  $j_{s+t}$ .

Denote by  $K_{s,e}$  the set of all  $\mathcal{F}(s, s+)$ -ergodic measures  $P \in K_s$ , i.e. all the measures  $P \in K_s$  with the property  $P(A) = 0$  or  $1$  for any  $A \in \mathcal{F}(s, s+)$ . Due

to [Dy71], [Dy72] an entrance law  $\nu = \nu^x \in H$  is an extreme one if and only if the corresponding measure  $P_{s,x}$  belongs to  $K_{s,e}$ .

**5. Regularization and stochastic equivalence.** Due to Lemma 9.4 of [Kuz82] there exists a stochastic process  $\Pi_{s+} = \Pi_{s+, \omega}$ ,  $\alpha \leq s < \beta$ , taking values in  $K_s$ , with the following properties:

(i)  $\Pi_{s+} \in \mathcal{F}(s, s+)$

(ii) For any  $s \leq u$ ,  $P \in K_s$ ,  $B \in \mathcal{F}_{>u}$

$$P(B; \mathcal{F}(s, u+)) = \Pi_{u+}(B) \text{ a.s. } P \text{ on } u < \beta \quad (6)$$

$$Q(B; \mathcal{F}_{<u+}) = \Pi_{u+}(B) \text{ a.s. } Q \text{ on } \alpha < u < \beta \quad (7)$$

(iii) For any  $s < u$ ,  $P \in K_s$ ,  $B \in \mathcal{F}_{>u}$  the function  $\Pi_{t+}(B)$  is right continuous with respect to  $t$  on  $[s, u \wedge \beta)$  a.s.  $P$  and on  $(\alpha, u \wedge \beta)$  a.s.  $Q$ .

Denote by  $x_{s+} = x_{s+}(\omega)$  very element of  $H$  satisfying  $P_{s, x_{s+}} = \Pi_{s+}$ .

Properties (i) and (ii) are equivalent to the fact that  $\Pi_{s+}$  is a  $(K_s, \mathcal{F}(s, s+))$ -kernel in the sense of [Dy71]. Hence by Lemma 2.2 of [Dy71] we have

$$P(\Pi_{s+} \notin K_{s,e}) = P(x_{s+} \notin E_+) = 0. \quad (8)$$

for any  $P \in K_s$ .

Moreover by virtue force of (6) and (8)

$$\begin{aligned} \nu_t^x(\Gamma) &= P_{s,x}(x_{s+t} \in \Gamma) = P_{s,x}\{P_{s, x_{s+}}(x_{s+t} \in \Gamma)\} \\ &= \int_{E_+} P_{s,x}(x_{s+} \in dy) \nu_t^y(\Gamma). \end{aligned}$$

Combining this equality with the uniqueness of the representation (1), we have

$$q(x, dy) = P_{s,x}(x_{s+} \in dy) \quad (9)$$

for any  $x \in H$ . In particular, from (8), (9) and the characterization of  $E_+$  by means of  $\mathcal{F}(s, s+)$ -ergodic measures it follows that

$$P_{s,x}(x_{s+} = x) = 1 \quad (10)$$

holds for any  $x \in E_+$ .

Using (i), (7), (8) and the implication  $\Pi_{s+} \in K_s$ , one can easily find



that

$$Q(\Pi_{s+} \notin K_{s,e}, \alpha < s < \beta) = Q(\Pi_{s+}(\Pi_{s+} \notin K_{s,e}) I_{\alpha < s < \beta}) = 0.$$

We are ready to establish the connections between the measure  $m_+$  and the semigroup  $p^+$  on the one hand and the process  $x_{t+}$  on the other hand.

**Lemma 3.** (a)  $m_+(\cdot) = Q\{x_{0+} \in \cdot, \alpha < 0 < \beta\}$ ;

(b) For any  $t > 0$ ,  $x \in H$

$$P_{s,x}(x_{(s+t)+} \in \Gamma) = p^+(t, x, \Gamma)$$

*Proof.* From (i) and the Markov property (5) it follows that

$$\begin{aligned} Q\{x_{0+} \in \cdot, \alpha < 0 < \beta\} &= Q\{P_{0,x_0}\{x_{0+} \in \cdot\}\} \\ &= Q\{q(x_0, \cdot)\} = mQ(\cdot) = m_+. \end{aligned}$$

(b) follows from (4) in a similar way.  $\square$

**Lemma 4.** For any  $s$

$$Q\{x_s \neq x_{s+}, \alpha < s < \beta\} = 0$$

(Both processes  $x_s$  and  $x_{s+}$  are considered as processes in  $H$ ).

*Proof.* Similar to [Dy73], [6], basing on Th 11.2 of [Do53] one can find that the value

$$p_s = Q\{P_{s,x_s} \neq P_{s,x_{s+}}, \alpha < s < \beta\}$$

is positive at most for a countable set of moments  $s$ . Since  $p^+$  separates points of  $H$ , by Lemma 3(b) the equality  $P_{s,x_s} = P_{s,x_{s+}}$  is equivalent to the equality  $x_s = x_{s+}$ . But in view of stationary condition (2)  $p_s = e^{\alpha s} p_0$ . Hence  $p_s \equiv 0$ .  $\square$

Using Lemma 3 and Lemma 4 one can easily establish the statement of Lemma 1. Namely, by Lemma 4 we have  $m(dx) = Q\{x_0 \in dx\} = Q\{x_{0+} \in dx\} = m_+(dx)$ , and by (7)

$$m_+(dx)p^+(t,x,dy) = Q(x_{0+} \in dx, x_{t+} \in dy) = m(dx)p(t,x,dy).$$

**6. Metrics in the space  $H$  and stochastic continuity.** Let  $\{\Gamma_n\}$  be a countable system of subsets generating the  $\sigma$ -field  $\mathcal{H}$  and let  $\{\alpha_m\}$  be a countable dense subset of  $(0, \infty)$ . By Lemma 12.1 of [Kuz82] the resolvent  $u_\alpha^+(x, dy) = \int_0^\infty e^{-\alpha t} p^+(t, x, dy) dt$  of the semigroup  $p^+$  separates points of  $H$ . Hence the countable family of functions  $f_{nm}(x) = \alpha_n u_{\alpha_m}^+(x, \Gamma_m)$  also separates points of  $H$  and generates the  $\sigma$ -field  $\mathcal{H}$ . Put

$$\rho(x, y) = \sum_{n, m} \frac{1}{2^{n+m}} |f_{nm}(x) - f_{nm}(y)|. \quad (11)$$

Clearly  $\rho$  generates  $\mathcal{H}$  (and  $\mathcal{E}_+$ ).

Let us now prove that the semigroup  $p^+$  restricted to  $E_+ \subset H$  is stochastically continuous with respect to  $\rho$ . To this end we note that in view of (iii) of n° 5 the process  $x_{t+}$  is regular in the sense of [Dy73], [Kuz82]. Hence the theorem 5.3 of [Kuz82] yields that any function  $f_{nm}(x_{t+})$  is right continuous in  $t$  on  $[s, \beta)$  a.s.  $P_{s, x}$  for any  $x \in H$ . In view of uniform convergence of the sum (11) the function  $\rho(x, x_{t+})$  is also right continuous in  $t$  on  $[s, \beta)$  a.s.  $P_{s, x}$ . Basing on (10), for  $x \in E_+$  we have

$$P_{0, x} \{\rho(x, x_{t+}) < \varepsilon\} = p^+(t, x, V_\varepsilon(x)) \rightarrow 1$$

as  $t \downarrow 0$ , where  $V_\varepsilon(x)$  stands for  $\varepsilon$ -neighborhood of  $x$ . The above relation coincides with the definition of stochastic continuity of  $p^+$  in the space  $E_+$ . This complete the proof of Lemma 2.

**7. Dual semigroup.** Since the metric  $\rho$  is measurable and the space  $(E_+, \mathcal{E}_+)$  is Borel, one can easily find that  $E_+$  is a Borel subset of its closure.

Applying Theorem 3 of [Kuz86], one can construct a semigroup  $\bar{p}$  in  $E_+$ , which is  $\alpha$ -dual with respect to  $p^+$  and  $m = m_+$ . We have only to modify  $\bar{p}$  in such a way as to obtain a semigroup on  $E$ . This will be done similar to Lemma 6 of [Kuz86] (see also Lemma 1 of [Kuz80]).

Since  $E$  is uncountable, by virtue of Corollary A2.1 of [Kuz82] there exists a set  $F \in \mathcal{E}$  for which  $m(F) = 0$  and the measurable space  $(F, \mathcal{E}'_F)$  is isomorphic to  $(E_+, \mathcal{E}_+)$ . Let  $i: F \rightarrow E_+$  be the above isomorphism.

Put  $G = (E \setminus F) \cap E_+$ . Clearly  $G \subset E \cap E_+$  and  $m(E \setminus G) = 0$  because of  $m$  is concentrated on  $E \cap E_+$ . Let us take a point  $x_0 \in E_+$ . Define a mapping  $\kappa_1: E_+ \rightarrow E$  by putting  $\kappa_1(x) = x$  for  $x \in G, \kappa_1(x) = i^{-1}(x)$  for  $x \notin G$ . In turn, define a mapping  $\kappa_2: E \rightarrow E_+$  by putting  $\kappa_2(x) = x$  for  $x \in G, \kappa_2(x) = i(x)$  for  $x \in F, \kappa_2(x) = x_0$  otherwise. Obviously,  $\kappa_2(\kappa_1(x)) = x$ .

Put

$$\hat{p}(t, x, \Gamma) = \bar{p}(t, \kappa_2(x), \kappa_1^{-1}(\Gamma)).$$

for  $x \in E, \Gamma \in \mathcal{E}$ . Simple calculation similar to the proof of Lemma 6 of [Kuz86] shows that  $\hat{p}$  is a semigroup in the space  $E$ . It only remains to verify that

$$\hat{p}(t, x, \cdot) = \bar{p}(t, x, \cdot) \text{ a.e. } m. \quad (12)$$

To obtain it we note that if  $m(A) = 0$  then  $\bar{p}(t, x, A) = 0$  a.e.  $m$ . In turn,  $m(H \setminus G) = 0$  and we have only to verify (12) on  $G$ . But on  $G$

$$\begin{aligned} \hat{p}(t, x, \Gamma) &= \bar{p}(t, x, \kappa_1^{-1}(\Gamma)) = \bar{p}(t, x, \kappa_1^{-1}(\Gamma) \cap G) \\ &= \bar{p}(t, x, \Gamma \cap G) = \bar{p}(t, x, \Gamma) \text{ a.e. } m, \end{aligned}$$

hence (12).

Finally, the desired duality relation follows from (12) and Lemma 1.

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