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WIENER-HOPF FACTORIZATION FOR MATRICES

by

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1. The main results. Let  $E$  be a finite set. Let  $\mathcal{Q}(E)$  denote the set of (real)  $E \times E$  matrices  $Q$  such that, for  $i, j \in E$ ,

$$Q(i, j) \geq 0 \quad (i \neq j), \quad \sum_{k \in E} Q(i, k) \leq 0.$$

Let  $Q$  now denote some fixed element of  $\mathcal{Q}(E)$ . Let  $v$  be a function from  $E$  to  $\mathbb{R} \setminus \{0\}$ , and let  $V$  be the diagonal  $E \times E$  matrix  $\text{diag}\{v(i) : i \in E\}$ . Let  $E^+ = \{i \in E : v(i) > 0\}$ , and  $E^- = \{i \in E : v(i) < 0\}$ . Let  $I$  denote the identity  $E \times E$  matrix,  $I^+$  the identity  $E^+ \times E^+$  matrix, and  $I^-$  the identity  $E^- \times E^-$  matrix.

Let  $c$  be a strictly positive real number.

THEOREM I. There exists a unique pair  $(\Pi_c^+, \Pi_c^-)$ , where  $\Pi_c^+$  is an  $E^- \times E^+$  matrix and  $\Pi_c^-$  is an  $E^+ \times E^-$  matrix, such that, if

$$(1) \quad S = \begin{pmatrix} I^+ & \Pi_c^- \\ \Pi_c^+ & I^- \end{pmatrix},$$

then  $S$  is invertible and

$$(2) \quad S^{-1}[V^{-1}(Q - cI)]S = \begin{pmatrix} \tilde{Q}_c^+ & 0 \\ 0 & -\tilde{Q}_c^- \end{pmatrix},$$

where  $\tilde{Q}_c^+ \in \mathcal{Q}(E^+)$  and  $\tilde{Q}_c^- \in \mathcal{Q}(E^-)$ . Moreover,  $\Pi_c^+$  and  $\Pi_c^-$  are strictly substochastic: thus, for  $i \in E^-$ ,  $j \in E^+$ ,

$$\Pi_c^+(i, j) \geq 0, \quad \sum_{k \in E^+} \Pi_c^+(i, k) < 1.$$

Theorem I will be said to yield the 'Wiener-Hopf factorization' of the matrix  $V^{-1}(Q - cI)$ .

Now let  $X$  be a Markov chain on  $E \cup \{\partial\}$  ( $\partial$  is the cemetery state) with  $Q$ -matrix  $Q$ . Thus the transition matrix function of  $X$  is  $P(t) = \exp(tQ)$ . For  $t \geq 0$ , define:

$$\phi(t) = \int_0^t v(X_s) ds, \quad \tau^+(t) = \inf\{s : \phi(s) > t\}.$$

As usual, we shall (for example) write  $\tau_t^+$  for  $\tau^+(t)$  when more convenient. Note that  $X(\tau_t^+) \in E^+ \cup \{\partial\}$ .

THEOREM II. For  $i \in E^-$  and  $j \in E^+$ ,

$$(3) \quad E_{\mathbb{W}}^i[\exp(-c\tau_0^+); X(\tau_0^+) = j] = \Pi_c^+(i, j).$$

For  $i \in E^+$ ,  $j \in E^+$ , and  $t \geq 0$ ,

$$(4) \quad E_{\mathbb{W}}^i[\exp(-c\tau_t^+); X(\tau_t^+) = j] = [\exp(t\tilde{Q}_c^+)](i, j).$$

The corresponding 'minus' results follow, on replacing  $\phi$  by  $(-\phi)$ .

The problem of finding the joint distribution of  $\tau_t^+$  and  $X(\tau_t^+)$  is of course solved by Theorems I and II. The way in which  $\Pi_c^+$  and  $\Pi_c^-$  may be calculated will be clear from the proofs.

Comment. The reader may feel that the martingale techniques used in this paper are more sophisticated than those required for this Markov chain problem. The following two statements are therefore apposite. First, we do not know how to prove the purely algebraic Theorem I without appealing to probability theory (and ultimately to martingale theory). Second, the martingale technique generalises to other (more interesting) cases, though the problem of obtaining explicit answers proves to be very difficult. First thoughts on the 'continuous' state-space case appear in the following article by Rogers and Williams.

2. Basic martingales. It is important to regard the strictly positive number  $c$  as fixed throughout the remainder of the paper, except in section 7.

Let  $f$  be a function on  $(E \cup \{\partial\}) \times \mathbf{R} \times [0, \infty)$  such that  $f(\partial, \cdot, \cdot) = 0$ .

A natural extension of Dynkin's formula shows that (for every initial distribution)

$$f(X_t, \phi_t, t) - \int_0^t \mathcal{A}f(X_s, \phi_s, s) ds$$

is a local martingale, where

$$\mathcal{A}f(x, \phi, t) = Qf + v \frac{\partial f}{\partial \phi} + \frac{\partial f}{\partial t}.$$

Here, of course,

$$Qf(x, \phi, t) = \sum_{y \in E} Q(x, y) f(y, \phi, t).$$

In particular, if  $g$  is any vector on  $E$ , and

$$(5) \quad f(x, \phi, t) = \{\exp[-ctI - \phi V^{-1}(Q - cI)]g\}(x) \text{ on } E,$$

then  $f(X_t, \phi_t, t)$  is a local martingale (in fact, a martingale, because it is bounded on every finite interval).

3. Definition of  $\mathcal{N}$ . Before recalling part of the theory of the Jordan form, we recall the proof of the well-known fact that  $V^{-1}(Q - cI)$  cannot have an eigenvalue on the imaginary axis. For suppose that  $\mu$  lies on the imaginary axis and that

$$(6) \quad (Q - cI)g = \mu Vg$$

for some non-zero vector  $g$ . Choose  $i$  in  $E$  with  $|g(i)| \geq |g(j)|$  for all  $j$  in  $E$ . The  $i$ -th coordinate of (6) reads:

$$[Q(i, i) - c - \mu v(i)]g(i) = - \sum_{j \neq i} Q(i, j)g(j).$$

But the left-hand side has modulus at least equal to  $(|Q(i, i)| + c)|g(i)|$ , while the right-hand side has modulus at most equal to  $|Q(i, i)||g(i)|$ . The contradiction establishes the 'well-known fact'.

One of the main steps in Jordan-form theory shows that the space of complex vectors on  $E$  has a basis  $\mathcal{L}$  such that every  $g$  in  $\mathcal{L}$  solves an equation

$$(7) \quad [V^{-1}(Q - cI) - \mu I]^k g = 0,$$

where  $\mu$  is an eigenvalue of  $V^{-1}(Q - cI)$  and  $k$  is a positive integer.

Fix  $g$ , and let  $\mathcal{N}$  [respectively,  $\mathcal{P}$ ] denote the set of those vectors  $g$  in  $\mathcal{L}$  for which the associated  $\mu$ -value has (strictly) negative [respectively, positive] real part.

4. The structure of  $\mathcal{N}$ . Let  $g \in \mathcal{N}$ , so that  $g$  satisfies (7) for some  $k$  and some  $\mu$  with negative real part. Then the function  $f$  at (5) may be written

$$f(\cdot, \phi, t) = \exp(-ct - \mu\phi) \exp\{-\phi[V^{-1}(Q - cI) - \mu I]\}g,$$

and the second exponential may be expanded in a power series in which all terms after the  $(k-1)$ -th annihilate  $g$ . Hence, since  $\mu$  has negative real part,

(8) for  $g \in \mathcal{N}$  and  $f$  as at (5),  $f(X_s, \phi_s, s)$  is bounded on  $[0, \tau_t^+]$  for every  $t$ .

In particular, on applying the optional stopping theorem at time  $\tau_0^+$ , we find that (for all  $i \in E$ )

$$E^i[\exp(-c\tau_0^+)g \circ X(\tau_0^+)] = g(i).$$

Now define  $\Pi_c^+$  via the probabilistic formula (3). We have just shown that

(9) if  $g \in \mathcal{N}$ , then  $g = \begin{pmatrix} I^+ \\ \Pi_c^+ \end{pmatrix} g^+$  where  $g^+$  denotes the restriction of  $g$  to  $E^+$ .

Hence  $\mathcal{N}$  has at most  $|E^+|$  elements, and, by a similar argument,  $\mathcal{P}$  has at most  $|E^-|$  elements. The only explanation is that

(10)  $\mathcal{N}$  has precisely  $|E^+|$  elements and the elements  $g^+$  where  $g \in \mathcal{N}$  form a basis for the space of vectors on  $E^+$ .

5. Proof of the uniqueness of Wiener-Hopf factorization. Suppose that for some  $E^- \times E^+$  matrix  $K_c^+$ , some  $E^+ \times E^-$  matrix  $K_c^-$ , some  $\hat{Q}_c^+$  in  $\hat{Q}(E^+)$ ,

and some  $\hat{Q}_c^-$  in  $\mathcal{Q}(E^-)$ , we have that  $\begin{pmatrix} I^+ & K_c^- \\ K_c^+ & I^- \end{pmatrix}$  is invertible, and

$$\begin{pmatrix} I^+ & K_c^- \\ K_c^+ & I^- \end{pmatrix}^{-1} V^{-1}(Q - cI) \begin{pmatrix} I^+ & K_c^- \\ K_c^+ & I^- \end{pmatrix} = \begin{pmatrix} \hat{Q}_c^+ & 0 \\ 0 & -\hat{Q}_c^- \end{pmatrix}.$$

Then the eigenvalues of  $V^{-1}(Q - cI)$  with negative real part must coincide with the eigenvalues of  $\hat{Q}_c^+$ . Moreover, if

$$(11) \quad (\hat{Q}_c^+ - \mu I^+)^k u^+ = 0$$

for some positive integer  $k$ , some  $\mu$  (with negative real part) and some vector  $u^+$  on  $E^+$ , then

$$\{V^{-1}(Q - cI) - \mu I\}^k \begin{pmatrix} I^+ \\ K_c^+ \end{pmatrix} u^+ = 0,$$

so that, from the argument leading to (9),

$$(12) \quad \begin{pmatrix} I^+ \\ K_c^+ \end{pmatrix} u^+ = \begin{pmatrix} I^+ \\ \Pi_c^+ \end{pmatrix} u^+.$$

By the theory of the Jordan canonical form for  $\hat{Q}_c^+$ , equation (11) holds for a set of vectors  $u^+$  spanning the vectors on  $E^+$ , and so therefore does equation (12). Hence

$$K_c^+ = \Pi_c^+$$

and the required uniqueness follows from this fact and its 'minus' analogue.

6. Existence of the Wiener-Hopf factorization. For the moment, regard  $t \geq 0$  as fixed. Let  $g \in \mathcal{N}$ , define  $f$  as at (5), and recall that  $f(X_s, \phi_s, s)$  is a martingale. Using (8) as justification, apply the optional stopping theorem at time  $\tau_t^+$  to obtain

$$E[\exp(-c\tau_t^+) h \circ X(\tau_t^+)] = g = \exp[tV^{-1}(Q - cI)]h,$$

where  $h = \exp[-tV^{-1}(Q - cI)]g$ . Note that  $h$  will automatically satisfy the same version of (7) as does  $g$ , so that  $h$ , like  $g$ , has property (9). Hence, since  $X(\tau_t^+) \in E^+$ , we have

$$(13) \quad \begin{pmatrix} I^+ \\ \Pi_c^+ \end{pmatrix} \mathbb{E}^+ [\exp(-c\tau_t^+) h^+ \circ X(\tau_t^+)] = \exp[tV^{-1}(Q - cI)] \begin{pmatrix} I^+ \\ \Pi_c^+ \end{pmatrix} h^+.$$

We have obtained (13) for a class of vectors  $h^+$  which clearly spans the space of all vectors on  $E^+$ , so that (13) holds for all vectors  $h^+$  on  $E^+$ .

It is almost immediate from the strong Markov property of  $X$  that

$$\tilde{P}_c^+(t; i, j) = \mathbb{E}^i [\exp(-c\tau_t^+); X(\tau_t^+) = j] \quad (i, j \in E^+)$$

defines a subMarkovian transition function on  $E^+$ , so that

$$\tilde{P}_c^+(t) = \exp(t\tilde{Q}_c^+)$$

for some  $\tilde{Q}_c^+$  in  $\mathcal{Q}(E^+)$ . (One can alternatively deduce this from (13).)

On differentiating (13) with respect to  $t$  and setting  $t = 0$ , we obtain

$$(14) \quad \begin{pmatrix} I^+ \\ \Pi_c^+ \end{pmatrix} \tilde{Q}_c^+ = V^{-1}(Q - cI) \begin{pmatrix} I^+ \\ \Pi_c^+ \end{pmatrix}.$$

Theorems I and II now follow from (14) and its 'minus' analogue.

7. The case  $c = 0$ . As has already been noted, Theorems I and II solve the problem of calculating the joint distribution of  $\tau_t^+$  and  $X(\tau_t^+)$ , but the involvement of the positive parameter  $c$  complicates the formulae, and is irrelevant if only the law of  $X(\tau_t^+)$  is sought. This corresponds to the case  $c = 0$ , in which case we have the following result.

**THEOREM III.** There exists a unique pair  $(\Pi^+, \Pi^-)$ , where  $\Pi^+$  is an  $E^- \times E^+$  matrix, and  $\Pi^-$  is an  $E^+ \times E^-$  matrix, such that, for some  $Q^+ \in \mathcal{Q}(E^+)$  and  $Q^- \in \mathcal{Q}(E^-)$ ,

$$(15) \quad V^{-1}QS = S \begin{pmatrix} Q^+ & 0 \\ 0 & -Q^- \end{pmatrix}$$

where

$$(16) \quad S = \begin{pmatrix} I^+ & \Pi^- \\ \Pi^+ & I^- \end{pmatrix}.$$

Moreover,  $\Pi^+$  and  $\Pi^-$  are substochastic, and for  $i \in E^-, j \in E^+, k \in E^+$ ,

$$(17) \quad P^i[X(\tau_0^+) = j] = \Pi^+(i, j)$$

and

$$(18) \quad P^k[X(\tau_t^+) = j] = [\exp(tQ^+)](k, j)$$

for each  $t \geq 0$ .

Remarks. The matrix  $S$  need no longer be invertible, and it is also possible that both  $Q^+$  and  $Q^-$  may be conservative.

Proof. The existence of such a decomposition follows easily from Theorem I: by considering a sequence  $(c_n : n \geq 0)$  of reals decreasing to 0, we may suppose, by taking a subsequence if necessary, that  $\Pi_{c_n}^+, \Pi_{c_n}^-, \tilde{Q}_{c_n}^+$ , and  $\tilde{Q}_{c_n}^-$  each converge entry by entry to  $\Pi^+, \Pi^-, Q^+$ , and  $Q^-$  respectively. Thus (15) follows immediately from (2), (17) follows from (3), and (18) follows from (4).

As to the uniqueness of the decomposition (15), the argument of section 5 serves again with minor modification. Suppose that there exists  $\hat{Q}^+ \in \mathcal{Q}(E^+)$  and an  $E^- \times E^+$  matrix  $K^+$  such that

$$V^{-1}Q \begin{pmatrix} I^+ \\ K^+ \end{pmatrix} = \begin{pmatrix} I^+ \\ K^+ \end{pmatrix} \hat{Q}^+.$$

Consider a basis  $\mathcal{B}$  for the space of complex vectors on  $E^+$  such that for each  $u^+ \in \mathcal{B}$  there exists an integer  $k \geq 1$  and an eigenvalue  $\mu$  of  $\hat{Q}^+$  such that

$$(19) \quad (\hat{Q}^+ - \mu I^+)^{k-1} u^+ \neq 0, (\hat{Q}^+ - \mu I^+)^k u^+ = 0.$$

(Such a basis is guaranteed by the theory of the Jordan form.)

As the argument of section 3 shows, the non-zero eigenvalues of  $\hat{Q}^+$  have strictly negative real part, so if  $u^+ \in \mathcal{B}$  is associated through (19) with a non-zero eigenvalue, the argument of section 5 leads to

$$(20) \quad \begin{pmatrix} I^+ \\ K^+ \end{pmatrix} u^+ = \begin{pmatrix} I^+ \\ \Pi^+ \end{pmatrix} u^+.$$



To complete the proof, we must notice that if  $a^+ \in \mathcal{B}$  is associated through (19) with a zero eigenvalue, then  $\hat{Q}^+ a^+ = 0$ . [Indeed, were this not so, then  $\hat{P}^+(t) a^+ \equiv \exp(t \hat{Q}^+) a^+$  would not remain bounded as  $t \rightarrow \infty$ .]

Accordingly, if  $a$  is defined by

$$a \equiv \begin{pmatrix} I^+ \\ K^+ \end{pmatrix} a^+,$$

then  $a \in \ker(Q)$  and so  $a(X_t)$  is a martingale, whence (20) is satisfied by  $a$ , and we conclude as before that  $K^+ = \Pi^+$ .

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Correction. The uniqueness assertion for the case when  $c = 0$  is obviously false, as can be seen by taking

$$Q = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}.$$

The error occurs in the last two lines of the paper. The treatment of the 'c = 0' case in the following Rogers-Williams paper is correct, and points to the way in which Section 7 above can be redeemed.