A SOLUTION TO A COUNTABLE SYSTEM OF EQUATIONS ARISING IN MARKOVIAN DECISION PROCESSES

by

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Nontechnical Summary

Let $X_o, X_1, \ldots$ be a sequence of non-negative integer valued random variables with the property that

$$\Pr(X_{n+1} = j | X_o = x_o, \ldots, X_{n-1} = x_{n-1}, X_n = i) = p_{ij}$$

for all i, j, $x_o, \ldots, x_n$, n. The collection of random variables $\{X_n\}$ is called a Markov chain and the p_{ij} are called transition probabilities. We refer to X_n as the state of the process at time n. Let w_i be the cost incurred at time n if the process is in state i at that time. Consider the system of equations

(1) $$g + v_i = w_i + \sum_{j=o}^{\infty} p_{ij} v_j, \quad i = 0, 1, \ldots$$

in the unknown variables $g, v_o, v_1, \ldots$. Such a system arises in connection with constructing optimal rules for controlling Markovian decision processes. Also the numbers $g, v_o, v_1, \ldots$ are of interest in their own right. Often g is the long run expected average cost and $v_i - v_j$ is the limit, as $n \to \infty$, of the difference between expected total cost during times $0, 1, \ldots, n$ given that the process starts in states i and j respectively.

We show in this paper that one solution to the system (1) is given by

(2) $$g = \frac{c_{oo}}{m_{oo}} \quad \text{and} \quad v_i = c_{io} - g m_{io}, \quad i = 0, 1, \ldots$$

provided that the expected time m_{io} required to go from state i to state 0 is finite and that the expected cost c_{io} incurred during that time is also finite, $i = 0, 1, \ldots$. Notice that $v_o = 0$.

As an illustration of the above ideas, consider a single item inventory model in which the demands in periods $1, 2, \ldots$ are independent. A demand of size one occurs with probability p, $0 < p < 1$, and a demand of size zero occurs with probability $1 - p$. Let X_n denote the stock on hand at the beginning of period n. An order for one unit is placed in period n with immediate delivery if $X_n = 0$; otherwise, no order is placed in period n. There is a unit cost h for each unit of stock on hand after ordering in a period. There is a cost K for placing an order in a period. Under these assumptions the nonzero transition probabilities are $p_{oo} = p$, $p_{o1} = 1 - p$, $p_{ii} = 1 - p$, and $p_{i,i-1} = p$, $i = 1, 2, \ldots$. Also $w_o = K + h$ and $w_i = hi$, $i = 1,2,\ldots$. Thus the system (1) becomes

$$g + v_o = K + h + pv_o + (1 - p)v_1$$

$$g + v_i = ih + pv_{i-1} + (1 - p)v_i, \; i = 1, 2, \ldots .$$

The solution given in (2) is

$$g = pK + h ,$$

$$v_i = \frac{hi(i-1)}{2p} - Ki, \; i = 0, 1, \ldots .$$

Thus g is here the long run expected average cost under the indicated ordering policy. Also v_i is the limit, as $n \to \infty$, of the amount by which the expected cost in periods $0, 1, \ldots, n$ starting with i units of stock on hand exceeds that starting with no stock on hand.

A SOLUTION TO A COUNTABLE SYSTEM OF EQUATIONS

ARISING IN MARKOVIAN DECISION PROCESSES

by

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Let $\{X_n\}$, $n = 0, 1, \ldots$, be a Markov chain having a state space consisting of the non-negative integers and having stationary transition probabilities $\{p_{ij}\}$. Let $\{w_i\}$, $i = 0, 1, \ldots$, be a sequence of real numbers. Consider the system of equations

$$(1) \qquad g + v_i = w_i + \sum_{j=0}^{\infty} p_{ij} v_j, \quad i = 0, 1, \ldots,$$

in the unknown variables $\{g, v_0, v_1, \ldots\}$. In [2], the system (1) arises in connection with conditions for the existence and construction of optimal rules for controlling a Markovian decision process. For a finite state space existence of solutions to (1) is guaranteed by the condition that the Markov chain have at most one ergodic class of states. (See [3].) In this note we give conditions ensuring the existence (Theorem 1) and uniqueness (Theorem 2) of solutions to (1).

Let

$$Z_n(j) = \begin{cases} 1, & \text{if } X_n = j \text{ and if } X_m \neq 0 \text{ for } 0 < m \leq n \\ 0, & \text{otherwise} \end{cases}$$

$$j, n = 0, 1, \ldots,$$

$${}_0p^*_{ij} = E\left(\sum_{n=0}^{\infty} Z_n(j) \,\middle|\, X_0 = i\right), \quad i, j = 0, 1, \ldots,$$

and

$$m_{io} = \sum_{j=o}^{\infty} {}_{o}p^{*}_{ij}, \quad i = 0, 1, \ldots .$$

If the last series converges absolutely, then m_{io} is the mean first passage time from i to 0 and we say m_{io} is finite. If the m_{io} are all finite, as we assume throughout, then state 0 is positive recurrent and there is only one recurrent class.

$$\text{Let} \quad Y_n = \sum_{j=o}^{\infty} w_j Z_n(j) \quad \text{and} \quad c_{io} = E\left(\sum_{n=o}^{\infty} Y_n \middle| X_o = i\right) .$$

By an obvious generalization of Theorem 5 in [1, p. 81] we get $c_{io} = \sum_{j=o}^{\infty} {}_{o}p^{*}_{ij} w_j$ provided the series is absolutely convergent. If the series is absolutely convergent we say c_{io} is finite. In applications w_i is often the cost incurred when in state i so c_{io} is then the expected cost during a first passage from i to o.

Theorem 1 (Existence)

If the numbers m_{io} and c_{io}, $i = 0, 1, \ldots$, are finite, then the numbers

$$(2) \qquad g = \frac{c_{oo}}{m_{oo}} \quad \text{and} \quad v_i = c_{io} - gm_{io}, \quad i = 0, 1, \ldots$$

satisfy (1) and $\sum_{j=o}^{\infty} p_{ij} v_j$ converges absolutely, $i = 0, 1, \ldots$.

Proof:

Let $w^{*}_{i} = w_i - g$ and $Y^{*}_{n} = \sum_{j=o}^{\infty} w^{*}_{j} Z_n(j)$. Then for $i = 0, 1, \ldots$

$$v_i = E\left(\sum_{n=o}^{\infty} Y_n^* | X_o = i\right)$$

$$= w_i^* + \sum_{n=1}^{\infty} \sum_{j=o}^{\infty} E(Y_n^* | X_o = i, X_1 = j) p_{ij}$$

$$= w_i^* + \sum_{j=o}^{\infty} \sum_{n=1}^{\infty} E(Y_n^* | X_o = i, X_1 = j) p_{ij}$$

$$= w_i^* + \sum_{j=o}^{\infty} p_{ij} v_j$$

so (1) holds. The interchange of expectation and summation is justified since the finiteness of the m_{io} and c_{io} imply that $\sum_{n=o}^{\infty} E(|Y_n^*| \, | X_o = i) < \infty$. This in turn implies that the series above are absolutely convergent so the interchange of summations is also justified.

<u>Theorem 2</u> (Uniqueness)

If the numbers m_{io} and c_{io}, $i = 0, 1, \ldots$, are finite, if $\sum_{j=o}^{\infty} {}_o p_{ij}^* \left(c_{jo} - \frac{c_{oo}}{m_{oo}} m_{jo}\right)$, $i = 0, 1, \ldots$ converges absolutely, and if $\{g, v_o, v_1, \ldots\}$ is a sequence with $\sum_{j=o}^{\infty} {}_o p_{ij}^* v_j$, $i = 0, 1, \ldots$, converging absolutely, then $\{g, v_o, v_1, \ldots\}$ satisfies (1) if and only if there is a real number r such that

$$(3) \qquad g = \frac{c_{oo}}{m_{oo}} \quad \text{and} \quad v_i = c_{io} - g m_{io} + r, \; i = 0, 1, \ldots .$$

<u>Proof</u>:

It is immediate from the hypotheses and Theorem 1 that $\{g, v_o, v_1, \ldots\}$ defined in (3) satisfies (1) and $\sum_{j=o}^{\infty} {}_o p_{ij}^* v_j$ converges absolutely as well as $\sum_{j=o}^{\infty} p_{ij} v_j$. Let $\{g', v_o', v_1', \ldots\}$ be any other solution to (1) with $\sum_{j=0}^{\infty} {}_0p^*_{ij}v'_j$ converging absolutely for $i = 0, 1, \ldots$. Hence $\sum_{k=0}^{\infty} p_{ik}v'_k$ is absolutely convergent. Now pre-multiplying both sides of (1) by $\pi_i \equiv \frac{{}_0p^*_{0i}}{m_{00}}$, summing over $i = 0, 1, \ldots$, using the relations $\sum_{i=0}^{\infty} \pi_i = 1$ and $\pi_j = \sum_{k=0}^{\infty} p_{kj}\pi_k$, $j = 0, 1, \ldots$, and the fact that the interchange of summations is justified, we get $g' = \sum_{i=0}^{\infty} \pi_i w_i$ which is independent of $\{v'_0, v'_1, \ldots\}$. Thus since $\{g, v_0, v_1, \ldots\}$ satisfies (1) we must have $g = g'$.

Letting $\Delta_i = v'_i - v_i$, $i = 0, 1, \ldots$, we get from (1) on subtracting one system from the other that

$$\Delta_i = \sum_{j=0}^{\infty} p_{ij}\Delta_j, \quad i = 0, 1, \ldots . \tag{4}$$

Let $p^n_{ij} = \Pr(X_n = j | X_0 = i)$. Evidently for $N = 1, 2, \ldots$,

$$\sum_{n=1}^{N} p^n_{ij} \le {}_0p^*_{ij} + (N-1)\,{}_0p^*_{0j}, \quad j = 0, 1, \ldots$$

so

$$\frac{1}{N}\sum_{n=1}^{N} p^n_{ij}\,|\Delta_j| \le [{}_0p^*_{ij} + {}_0p^*_{0j}]|\Delta_j|, \qquad j = 0, 1, \ldots . \tag{5}$$

Since the series on the right side of (5) converges absolutely by hypothesis, and $\lim_{N\to\infty} \frac{1}{N}\sum_{n=1}^{\infty} p^n_{ij} = \pi_j$, we get from the dominated convergence theorem that

$$(6) \qquad \lim_{N \to \infty} \sum_{j=0}^{\infty} \frac{1}{N} \sum_{n=1}^{\infty} p_{ij}^{n} \Delta_j = \sum_{j=0}^{\infty} \pi_j \Delta_j .$$

Since from (5), $\sum_{j=0}^{\infty} p_{ij}^{n} \Delta_j$ converges absolutely we can iterate (4), yielding

$$(7) \qquad \Delta_i = \sum_{j=0}^{\infty} p_{ij}^{n} \Delta_j, \quad i = 0, 1, \ldots ; \quad n = 1, 2, \ldots .$$

Hence on substituting (7) into (6)

$$\Delta_i = \sum_{j=0}^{\infty} \pi_j \Delta_j, \quad i = 0, 1, \ldots .$$

Thus Δ_i is independent of i, which completes the proof.

Example:

If the sequences $\{m_{io}\}$ and $\{w_i\}$, $i = 0, 1, \ldots$, are bounded, then so is the sequence $\{c_{io}\}$, $i = 0, 1, \ldots$, since $|c_{io}| \leq \sup_{k,j} m_{ko} |w_j|$. Thus Theorem 1 applies and in addition the solution to (1) given in (2) is bounded. This result is used in [2].

We remark that since

$$\sum_{j=0}^{\infty} {}_{o}p_{oj}^{*} |u| \geq {}_{o}f_{ok} \sum_{j=0}^{\infty} {}_{o}p_{kj}^{*} |u_j|$$

where

$${}_{o}f_{ok} = \Pr\left(\sum_{n=0}^{\infty} Z_n(k) > 0 | X_o = 0 \right) > 0 ,$$

$\sum_{j=o}^{\infty} {}_{o}p^{*}_{kj} |u_j|$ is absolutely convergent for every recurrent state k provided that $\sum_{j=o}^{\infty} {}_{o}p^{*}_{oj} |u_j|$ is absolutely convergent. Thus the hypotheses of Theorems 1 and 2 could have been stated only for state 0 and the transient states.

References

[1] Chung, K. L. (1960), Markov Chains with Stationary Transition Probabilities, Springer, Berlin.

[2] Derman, Cyrus (1966), "Denumerable State Markovian Decision Processes - Average Cost Criterion," (To Appear in Ann. Math. Stat.).

[3] Howard, Ronald (1960), Dynamic Programming and Markov Processes, John Wiley, New York.

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