ON THE THEORY OF QUEUES WITH MANY SERVERS

BY

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1. Introduction. The physical original of the mathematical problem to which this paper is devoted is a system of $s$ "servers," who can be machines in a factory, ticket windows at a railroad station, salespeople in a store, or the like. Individuals (clients) who are to be served by these servers arrive at random and the duration of anyone's service (e.g., stay at the ticket window) is a chance variable whose distribution function may be arbitrary. The phrase "at random" used above is not to be interpreted to mean that the interval between successive arrivals is to have an exponential distribution. The assumption of an exponential or other special distribution for either the interval between arrivals or the service time of an individual or both usually makes the problem much easier. We also allow the distribution of the interval between arrivals to be arbitrary. The queue discipline is "first come, first served." The system is described precisely in §2.

In this system the waiting time of the individual who is $i$th in order of arrival, i.e., the time which elapses between his arrival and the beginning of his service, is a chance variable whose distribution function depends upon $i$. In §3 we prove that this distribution function approaches a limit as $i \to \infty$. This limit may not be a distribution function because its variation may be less than one. We assume that the expected value of the time interval between the arrivals of successive clients and the expected value of the service time of an individual both exist. In terms of these one defines a quantity $\rho$ in §6. The situation may then be classified according as $\rho < 1$ or $\rho \geq 1$. In the former and interesting case the limiting function is a distribution function (§6), in the latter case it is not a distribution function (§7). The limiting function is (a marginal function) obtained from a function which satisfies an integral equation derived in §3. This integral equation is satisfied by a unique distribution function on $s$-space when $\rho < 1$, and by no distribution function when $\rho \geq 1$ (§8). These results for the case of one server were obtained by Lindley [1]. The problem when there are many servers offers many difficulties not present when there is only one server. The methods of the present paper are different from those of [1]. The proof of the result of §7, that the limit is not a distribution function when $\rho \geq 1$, is obtained by reducing the problem to the case $s = 1$ by using our lemma of §4, and then employing the corresponding result of [1]; except for this argument our paper is self-contained. For special distributions of the time between successive arrivals

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and of the service time the results of the present paper have been obtained by various authors (we refer the reader to [5] and [6] which contain extensive bibliographies). The methods of these authors make use of their special assumptions in an essential way. The novelty of the results of the present paper lies in the fact that no restrictions are imposed on the distributions, with the exception of the assumption of finite first moment(2). Thus the results of the present paper include the corresponding ones of previous papers as special cases(3).

Mathematically speaking, our study is one of the ergodic character of the waiting time in our system, and the conditions under which the distribution of the latter approaches stability. Our problem can be reduced, and actually is so reduced by us, to studying a random walk in $s$-space with certain impassable but not absorbing barriers. We actually show that, when $\rho < 1$, the distribution function of the particle engaged in the random walk approaches a limiting distribution which is the same no matter what the original starting point of the particle ($\S 8$).

Perhaps our principal device is to dominate the stochastic process to be studied by a lattice process to which we then apply available theorems from the theory of Markoff processes with discrete time parameter and denumerably many states. This device makes possible the argument of $\S 6$ and is also employed in $\S 8$. We are of the opinion that this device could be applied to other ergodic problems connected with random walks.

When the original process is a lattice process, i.e., when the chance variables $R_i$ and $g_i$ (defined in $\S 2$) take, with probability one, only values which are integral multiples of some positive number $c$, and when $\rho < 1$, the limiting probabilities (which are shown to exist in $\S 6$) are reciprocals of certain mean recurrence times (this follows from the application of Theorem 2 of Chapter 15 of [3] to the argument of $\S 6$). Monte Carlo methods (see, e.g., [4]) may perhaps then be profitably employed to solve the integral equation (3.8).

It would be very desirable and interesting to solve the integral equation (3.8), at least for interesting or important functions $G$ and $H$ (see $\S 2$). This, however, is likely to be very difficult. Even in the simplest case, when $s = 1$, the equation becomes the Wiener-Hopf equation, which has been of considerable interest to physicists but has been solved only in special cases. Some special cases of the equation (3.8) are discussed in [5], [6], and [1]. It may also interest the pure analyst that one can, by probabilistic methods

(2) Under stronger assumptions (e.g., existence of all moments), F. Pollaczek in recent notes (C. R. Acad. Sci. Paris vol. 236 (1953) pp. 578–580, 1469–1470) gives formally an integral equation for the Laplace transform of $F$ (to be defined below), but does not consider the questions of the present paper.

(3) In a paper to be published elsewhere which makes extensive use of the present paper, the authors obtain, under minimal conditions, theorems on convergence of the mean of various variables connected with the queueing process.
like ours, prove the existence or non-existence of distribution function solutions of (3.8).

Finally, in §9 we discuss the limiting distribution (as \(i \to \infty\)) of the queue size, i.e., of the number waiting to be served when the service of the \(i\)th customer begins.

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2. Description of the system. The system consists of \(s\) (\(\geq 1\)) machines, \(M_1, \ldots, M_s\). The \(i\)th individual arrives at time \(t_i\) (\(\geq 0\)), with, of course, \(t_i \leq t_{i+1}\). If all machines are in service at his arrival he takes his place in the queue. His service begins as soon as at least one machine is unoccupied, and all individuals with smaller indices have been or are being served. If more than one machine becomes unoccupied at the time when it is the \(i\)th individual’s turn to be served, we shall assume, for definiteness, that he takes his place at the unoccupied machine with smallest index.

Let \(t_0 = 0\), \(g_i = t_i - t_{i-1}\) for all \(i \geq 1\). We assume that the \(g_i\) are independently and identically distributed chance variables; let \(G(z) = P\{g_i \leq z\}\), where \(P\{\}\) is the probability of the relation in braces. Throughout the paper we assume that \(G(0) < 1\); the case \(G(0) = 1\) is too trivial to discuss. We assume \(\mathbb{E}g_i < \infty\).

Let \(R_i\) be the length of time the \(i\)th person spends being serviced by a machine. We assume that the \(R_i\) are independently and identically distributed chance variables, distributed independently of the \(g_i\); let \(H(z) = P\{R_i \leq z\}\). We assume \(\mathbb{E}R_i < \infty\). We also assume \(H(0) < 1\), the case \(H(0) = 1\) being trivial.

Let \(w_{i+1} + t_i\) be the time at which service of the \(i\)th individual begins; \(w_{i+1}\) is his waiting time. Then the \(i\)th individual leaves his machine at the time \(w_{i+1} + t_i + R_i\).

Let \(u_{i+1} + t_i\) be the time at which the \(j\)th machine finishes serving the last of those among the first \((i-1)\) individuals which it serves. Let \(u'_j = \max(0, u_{i+1})\). Let \(w_{i+1}, \ldots, w_{i+s}\) be the quantities \(u'_{i+1}, \ldots, u'_s\) arranged in order of increasing size. It is easy to see that this definition of \(w_{i+1}\) coincides with the former.

Let

\[
F_i(x_1, \ldots, x_s) = P\{w_{i+1} \leq x_1, \ldots, w_{i+s} \leq x_s\}.
\]

If ever \(x_j > x_{j+1}\) we may, since \(w_{i+1} \leq w_{i+(j+1)}\), replace \(x_j\) by \(x_{j+1}\) in both members of (2.1) without changing the value of either.

Write \(w_i = (w_{i+1}, \ldots, w_{i+s})\). The earliest times at which the various machines could attend to the \((i+1)\)st individual are \(t_i + w_{i+1} + R_i\), \(t_i + w_{i+2}, \ldots, t_i + w_{i+s}\). If \(t_{i+1}\) is greater than or equal to any of these quantities the \((i+1)\)st individual finds at least one machine unoccupied at his arrival and does not have to wait at all. If \(t_{i+1}\) is less than all these quantities the \((i+1)\)st individual has to wait for the first machine to be unoccupied. Since \(t_{i+1} = t_i + g_i + t_{i+1}\), \(w_{i+1}\) is obtained from \(w_i\) as follows: Subtract \(g_i + t_{i+1}\) from every component
of \((w_{i1}+R_i, w_{i2}, w_{i3}, \ldots, w_{iu})\). Rearrange the resulting quantities in ascending order and replace all negative quantities by zero. The ensuing result is \(w_{i+1}\).

3. Recursion formula for \(F_i\). Existence of the limit of \(F_i\) as \(i \to \infty\). Let 
\[\phi_j(a, b, c), j=1, \ldots, s,\]
be the value of \(w_{(i+1),j}\) when \(w_i = a, R_i = b, g_{i+1} = c\). If \(d\) is a point in \(s\)-space we shall say that \(a \leq d\) if every coordinate of \(a\) is not greater than the corresponding coordinate of \(d\). If now \(a \leq d\) then obviously
\[\phi_j(a, b, c) \leq \phi_j(d, b, c)\]
for \(1 \leq j \leq s\). Applying this argument \(k\) times we obtain the following result:
Let \(R_{i+j} = b_{i+j}, g_{i+j} = c_{i+j}, j=1, \ldots, k\). Let \(w_{i+k} = e_1\) when \(w_i = a_1\), and let \(w_{i+k} = e_2\) when \(w_i = a_2\). Then \(a_1 \leq a_2\) implies \(e_1 \leq e_2\).

Let \(S\) be the totality of points \((x_1, x_2, \ldots, x_s)\) of Euclidean \(s\)-space such that \(0 \leq x_1 \leq x_2 \leq \cdots \leq x_s\). Let \(x\) and \(y\) be generic points of \(S\). For \(i \geq 1\), let
\[F_i(x \mid y) = P\{w_i \leq x \mid w_1 = y\}\]
Let 0 be the origin in \(s\)-space. Then
\[F_i(x \mid 0) = F_i(x)\]
and
\[(3.1) \quad F_{i+1}(x) = \int F_i(x \mid y)dF(y)\]
The conclusion of the preceding paragraph enables us to conclude that \(y_1 \in S, y_2 \in S, y_1 \leq y_2\), imply
\[F_i(x \mid y_1) \geq F_i(x \mid y_2)\]
for every \(x\) and every \(i\). Now
\[(3.2) \quad F_{i+1}(x) - F_i(x) = \int \{F_i(x \mid y) - F_i(x \mid 0)\}dF(y)\]
Since the integrand is never positive we have that
\[(3.3) \quad F_{i+1}(x) \leq F_i(x)\]
for all \(x\) and \(i\). From (3.3) it follows that \(F_i(x)\) approaches a limit, say \(F(x)\), which is nondecreasing in every component of \(x\), continuous to the right, and assigns non-negative measure to all rectangles. It need not, however, be a distribution function, i.e., its variation over \(S\) (hence over all of \(s\)-space) may be less than one.

Write
\[(3.4) \quad \phi(a, b, c) = (\phi_1(a, b, c), \cdots, \phi_s(a, b, c))\]
For given \(x \in S, b, c\), let \(\psi(x, b, c)\) be the totality of points \(y \in S\) such that
\( \phi(y, b, c) \leq x \) and \( \in S \). Obviously

\[
F_{(i+1)}(x) = \int P_i \{ \psi(x, b, c) \} dH(b)dG(c)
\]

where \( P_i \) is the measure according to \( F_i \). This equation determines each \( F_i \) uniquely by recursion, since of course \( F_1(0) = 1 \). For \( s = 1 \) and \( x \geq 0 \), \( \psi(x, b, c) \) is \( \{ y \mid 0 \leq y \leq x - b + c \} \). Hence (3.5) becomes, for \( x \geq 0 \),

\[
F_{(i+1)}(x) = \int F_i(x - b + c) dH(b)dG(c),
\]

an equation due to Lindley [1]. (In (3.6) it is understood that \( F_i(x - b + c) = 0 \) whenever \( x - b + c < 0 \).) For \( s = 2 \) and \( x = (x_1, x_2) \in S \) we have that \( \psi(x, b, c) \) is the set of points \( y \in S \) such that \( y \leq (x_1 - b + c, x_2 + c) \), together with the set of points \( y \in S \) such that \( y \leq (\min (x_2 - b + c, x_1 + c), x_1 + c) \). We extend the definition of \( F_i(y_1, y_2) \) to all of \( S \)-space in the natural way as follows: \( F_i(y_1, y_2) = 0 \) if either \( y_1 \) or \( y_2 < 0 \), \( F_i(y_1, y_2) = F_i(y_2, y_2) \) if \( y_1 > y_2 \). Then for all \( (x_1, x_2) \) in \( S \) and \( s = 2 \), (3.5) becomes

\[
F_{(i+1)}(x_1, x_2) = \int \left[ F_i(x_1 - b + c, x_2 + c) + F_i(x_2 - b + c, x_1 + c) \right] dH(b)dG(c).
\]

In general, when (3.5) is written in the form of (3.6) and (3.7) the integrand contains \( (2^s - 1) \) terms. With the integrand in this form let \( i \to \infty \) in (3.5). By Lebesgue’s bounded convergence theorem we obtain for \( x \in S \),

\[
F(x) = \int P_\infty \{ \psi(x, b, c) \} dH(b)dG(c)
\]

where \( P_\infty \) is the measure according to \( F(x) \). (When \( s = 1 \) or 2 equation (3.8) becomes (3.6) and (3.7) with the subscripts of \( F \) deleted.) This is an integral equation satisfied by \( F(x) \). We shall later prove that, when \( \rho < 1 \), \( F(x) \) is a distribution function (d.f.), and the only d.f. over \( S \) which satisfies (3.8). Moreover, we shall prove that, when \( \rho \geq 1 \), \( F(x) \) is not a d.f., and (3.8) has no solution which is a d.f. over \( S \).

We remark that (3.8) implies that if \( F(x) \) is a d.f., the latter defines a stationary absolute probability distribution for our (Markoff) stochastic process, i.e., if \( w_i \) is distributed according to \( F(x) \) then \( w_i \) has this distribution for every value of \( i \).

Write \( \bar{x}_1 = (x_1, \infty, \cdots, \infty) \), \( F^*_i(x_1) = F_i(\bar{x}_1) \). Then, from (3.5), the Lebesgue bounded convergence theorem, and the structure of \( \psi \), it follows that

\[
F^*_i(x_1) = \int P_i \{ \psi(\bar{x}_1, b, c) \} dH(b)dG(c).
\]
We proved earlier that

\[(3.10) \quad F_i(x) \geq F_{(i+1)}(x)\]

for every \(i\) and \(x\). In (3.10) let the last \((s-1)\) coordinates of \(x\) approach infinity. We obtain

\[(3.11) \quad F^*_i(x_1) \geq F^*_{(i+1)}(x_1).\]

We conclude that \(\lim_{i \to \infty} F^*_i(x_1)\) exists; call it \(F^*(x_1)\), say. Clearly we have

\[(3.12) \quad F^*(x_1) \geq F(\bar{x}_1).\]

We shall prove in §5 that equality holds in (3.12). It will then follow from (3.8) that

\[(3.13) \quad F^*(x_1) = \int P\{\psi(\bar{x}_1, b, c)\} dH(b) dG(c).\]

4. An essential lemma. In this section we shall prove the following lemma.

\[
\lim_{y' \to \infty} \lim_{i \to \infty} \inf P\{w_{i,s} - w_{i,1} \leq y'\} = 1
\]

for \(s > 1\).

Proof. Let

\[(4.1) \quad B_i = (s - 1)w_{i,s} - \sum_{j=1}^{i-1} w_{i,j}\]

for \(i \geq 1\). It follows easily from the way in which \(w_{(i+1)}\) is obtained from \(w_i\) that

\[(4.2) \quad B_{(i+1)} \leq \begin{cases} B_i - R_i & \text{when } R_i \leq w_{is} - w_{i1}, \\ B_i - s(w_{is} - w_{i1}) + (s - 1)R_i & \text{when } R_i \geq w_{is} - w_{i1}. \end{cases}\]

In either case we have

\[(4.3) \quad B_{(i+1)} \leq \max (B_i - R_i, (s - 1)R_i).\]

Applying (4.3) to \(B_i\) we obtain

\[(4.4) \quad B_{(i+1)} \leq \max (B_{i-1} - R_{i-1} - R_i, (s - 1)R_{i-1} - R_i, (s - 1)R_i).\]

Continuing in this manner and noting that \(B_1 = 0\) we obtain

\[(4.5) \quad B_{i+1} \leq \max [(s - 1)R_i, (s - 1)R_{i-1} - R_i, (s - 1)R_{i-2} - R_{i-1} - R_i, \ldots, (s - 1)R_1 - R_2 - \cdots - R_i] = Y_i \text{ (say)}.\]
Since the $R_j$ are independently and identically distributed, we may interchange indices $j$ and $i-j+1$, $j=1, \ldots, i$, in the middle member of (4.5) without altering its distribution. Hence, setting $h = (s-1)^{-1}$, we have

$$P\{Y_n \leq y'\} = P\{R_1 \leq hy', R_2 \leq h(R_1 + y')$, \ldots ,
R_n \leq h(R_1 + \cdots + R_{n-1} + y')\}$$

(4.6)

(where, for $n=1$, we replace $R_1 + \cdots + R_{n-1}$ by 0). Since $B_i \equiv w_{i+1} - w_i$, our proof will be complete if we show that

$$\lim_{y' \to \infty} \liminf_{n \to \infty} P\{Y_n \leq y'\} = 1.$$  
(4.7)

From the strong law of large numbers we have

$$P\left\{ \lim_{n \to \infty} \frac{1}{n} \sum_{i=1}^{n} R_i = ER_1, \lim_{n \to \infty} \frac{R_n}{n} = 0 \right\} = 1.$$  
(4.8)

Now, for $y' \geq 0$,

$$P\{Y_n \leq y'\} \geq P\{R_n \leq h(R_1 + \cdots + R_{n-1} + y') \text{ for } n = 1, 2, \ldots, \text{ad inf.}\} = P\left\{ \frac{R_n}{hn} \leq \frac{R_1 + \cdots + R_{n-1}}{n} + \frac{y'}{n} \text{ for } n = 1, 2, \ldots, \text{ad inf.}\right\}.$$  
(4.9)

Because of (4.8), for any $\epsilon > 0$ there exists an integer $N$ such that

$$P\left\{ \frac{R_n}{hn} \leq \frac{R_1 + \cdots + R_{n-1}}{n} \text{ for } n > N \right\} > 1 - \epsilon.$$  

Clearly, there is a value $y_0'$ such that for $y' > y_0'$

$$P\left\{ \frac{R_n}{hn} \leq \frac{R_1 + \cdots + R_{n-1}}{n} + \frac{y'}{n} \text{ for } n \leq N \right\} > 1 - \epsilon.$$  

Equation (4.7) is an immediate consequence.

5. Certain immediate consequences of the lemma.

(A) $F^*(x_1) = F(\hat{x}_1)$.

**Proof.** Let $x(x_1, y')$ be the point $x_1, y', \ldots, y'$. From the lemma it follows at once that for any $\epsilon > 0$ and $i$ and $y'$ sufficiently large we have

$$| P\{w_{i1} \leq x_1\} - P\{w_{i1} \leq x_1, w_{i2} \leq y', \ldots, w_{is} \leq y'\} | < \epsilon.$$  
(5.1)

Let $i \to \infty$. We obtain

$$| F^*(x_1) - F(x(x_1, y')) | \leq \epsilon.$$  
(5.2)

Let $y' \to \infty$. We obtain

$$| F^*(x_1) - F(\hat{x}_1) | \leq \epsilon.$$  
(5.3)
Since \( \epsilon \) was arbitrary the desired result follows.

(B) Either \( F \) and \( F^* \) are both distribution functions or neither is a distribution function.

This follows from the fact that (A) above implies that \( \lim F(x) \) as all coordinates of \( x \) approach infinity is the same as \( \lim F^*(x_1) \) as \( x_1 \) approaches infinity.

6. Proof that \( F \) is a distribution function when \( \rho < 1 \). We define

\[
\rho = (ER_l)(sEg_i)^{-1}.
\]

We shall now prove that, if \( \rho < 1 \), \( F(x) \to 1 \) as all coordinates of \( x \) approach infinity. Then, by (3.12), we have \( \lim F^*(x_1) = 1 \) as \( x_1 \to \infty \).

I. We show that it is sufficient to prove this result in a “dominating” case where, for some \( c > 0 \),

\[
\sum_{i=0}^{\infty} P \{ R_1 = c \} = \sum_{i=0}^{\infty} P \{ g_1 = c \} = 1.
\]

Let \( [a] \) be the largest integer \( \leq a \) and for some one \( c > 0 \) define, for all \( i \),

\[
g_i' = c \left[ \frac{g_i}{c} \right], \quad R_i' = c \left[ \frac{R_i}{c} \right] + c.
\]

Then \( g_i' \leq g_i \) and \( R_i' \geq R_i \). Let \( w_i' \) be the same function of \( \{g_i'\} \) and \( \{R_i'\} \) that \( w_i \) is of \( \{g_i\} \) and \( \{R_i\} \). It follows from an argument like that of §3 that \( w_i' \geq w_i \) for all \( i \). Hence if we can show that

\[
\lim_{y' \to \infty} \lim \inf_{i \to \infty} P \{ w_{i_1}' \leq y', \ldots, w_{i_n}' \leq y' \} = 1
\]

it will follow that

\[
\lim_{y' \to \infty} F(y', y', \ldots, y') = 1
\]

which is the desired result.

We have

\[
Eg_j' \geq Eg_j - c, \quad ER_j' \leq ER_j + c.
\]

Hence, if \( c \) is sufficiently small, \((ER_j') (sEg_i)^{-1} < 1\).

In the remainder of this section we assume that (6.2) is satisfied with \( \rho < 1 \), and we shall prove (6.3) for this process.

II. We show that (6.3) is valid if \( P \{ R_1 = 0 \} > 0 \). We recall that \( P \{ g_1 = 0 \} < 1 \). Hence, for any \( i \) and integral \( a_1, \ldots, a_n \), with \( 0 \leq a_1 \leq a_2 \leq \ldots \leq a_s \),

\[
P \{ w_{(i+j)} = 0 \mid w_{i,1} = a_1 c, w_{i,2} = a_2 c, \ldots, w_{i,s} = a_s c \}
\]

is positive. Let \( Z \) be the totality of all points \((a_1 c, a_2 c, \ldots, a_s c)\) with integral
a's such that \(0 \leq a_1 \leq a_2 \leq \cdots \leq a_s\). Let \(z\) be a generic point of \(Z\). The points \(z\) are the states of our Markoff process \(\{w_i\}\). The preceding argument shows that the origin \(0\) and all the points \(z\) which can be reached by the process \(\{w_i\}\) with positive probability form a chain \(C\) which is irreducible. \(C\) is aperiodic, since
\[
P\{w_{i+1} = 0 \mid w_i = 0\} \geq P\{R_1 = 0\} > 0.
\]
The desired result then follows by III below.

III. We shall show that, if \(C\) is aperiodic and irreducible, (6.3) holds. From §3 or [3, Chap. 15, Theorems 1 and 2], it follows that
\[
\lim_{t \to \infty} P\{w_i = z\}
\]
exists for all \(z\) in \(C\); call it \(f(z)\). From the theorems of [3] cited above it follows that
\[
\sum_{z \in C} f(z) = 0 \quad \text{or} \quad 1.
\]
Our result is proved if we show that the sum in (6.6) is 1. Suppose it were 0; every \(f(z)\) is then zero. We would then have
\[
F(y', y', \ldots, y') = 0
\]
for every \(y'\). Hence from (A), §5, we obtain, using (6.7),
\[
F*(x_i) = 0
\]
for every \(x_i\). From the definition of \(w_i\) and the fact that \(\rho < 1\) we obtain that there exists an \(M > 0\) such that, whenever
\[
M \leq a_1 \leq a_2 \leq \cdots \leq a_s,
\]
we have
\[
E\left\{ \sum_{j=1}^{s} w_{(i+1)j} \mid w_{ij} = a_j, j = 1, \ldots, s \right\} < \sum_{j=1}^{s} a_j - \delta
\]
for some \(\delta > 0\). It is to be noted that, whether (6.9) holds or not, the left member of (6.10) is never greater than
\[
\sum_{j=1}^{s} a_j + ER_1.
\]
Since \(F*(x_i) = 0\) we can find an \(N > 0\) such that for \(i \geq N\) we have
\[
P\{w_{i,1} < M\} < \frac{\delta}{\delta + ER_1}.
\]
Then, for \(i \geq N\), we have
\[
E \left\{ \sum_{i=1}^{s} w_{i+1,i} - \sum_{i=1}^{s} w_{i,i} \right\}
\]

(6.13)

\[
= E \left\{ E \left\{ \sum_{i=1}^{s} w_{i+1,i} - \sum_{i=1}^{s} w_{i,i} \mid w_{i,j} = 1, \cdots, s \right\} \right\}
\]

\[
< \frac{\delta}{\delta + ER_1} (ER_1) + \frac{ER_1}{\delta + ER_1} (-\delta) = 0.
\]

Hence, for \(i > 0\),

(6.14)

\[
E \sum_{i=1}^{s} w_{i+N,i} < E \sum_{i=1}^{s} w_{N,i}
\]

so that \(E \sum_{j=1}^{s} w_{i,j}\) is bounded uniformly in \(i\). This contradicts (6.7) and proves III.

IV. We now suppose \(P\{R_1 = 0\} = 0\), and we construct a suitable "dominating" process for which we can prove results analogous to II and III.

Let \(k\) be a positive integer such that \((sk - 1)^{>0}\),

(6.15)

\[
P\{R_1 \geq (sk - 1)c\} = 1,
\]

and

(6.16)

\[
P\{R_1 = (sk - 1)c\} > 0.
\]

If necessary, we can decrease the \(c\) of (6.2) so that such a \(k\) can always be found. If now

(6.17)

\[
P\{g_1 \geq sc\} > 0,
\]

then it is clear that

(6.18)

\[
P \{w_{i+j} = 0 \text{ for some } j > 0 \mid w_i = z\} > 0
\]

for every \(z\) in \(C\). Hence \(C\) is irreducible. It is also aperiodic, because

(6.19)

\[
P \{w_{i+1} = 0 \mid w_i = 0\} > 0.
\]

Hence the desired result follows by III. We therefore assume that (6.17) does not hold, i.e., that

(6.20)

\[
P\{g_1 \leq (sk - 1)c\} = 1.
\]

Let \(m\) be the largest integer for which

\[
P\{g_1 = mc\} > 0.
\]

Let \(A_1\) be the set of \(\alpha\) (say) non-negative integers \(j < m\) such that

\[
P\{g_1 = jc\} = 0, \quad j \in A_1.
\]

Let \(\{g^i\}\) be independently and identically distributed chance variables with
the following distribution:

\[ P\{g'_1 = jc \} = \lambda, \quad j \in A_1, \]
\[ P\{g'_1 = mc \} = P\{g_1 = mc \} - \alpha \lambda, \]
\[ P\{g'_1 = jc \} = P\{g_1 = jc \}, \quad j \neq m, j \in A_1. \]

Here \( \lambda \) is a small positive number, whose choice will be more fully described shortly, but which should in any case be such that \( P\{g_1 = mc \} - \alpha \lambda > 0 \) and \( \lambda < P\{R_1 = (sk - 1)c\} \).

Let \( A_2 \) be the totality of integers \( j > (sk - 1) \) such that

\[ P\{R_1 = jc \} = 0, \quad j \in A_2. \]

Let \( \{R'_1\} \) be independently and identically distributed chance variables, independent of \( \{g'_1\} \) and with the following distribution:

\[ P\{R'_1 = jc \} = \frac{\lambda}{2i}, \quad j \in A_2, \]
\[ P\{R'_1 = jc \} = P\{R_1 = jc \}, \quad j \neq (sk - 1), j \in A_2, \]
\[ P\{R'_1 \geq (sk - 1)c\} = 1. \]

We choose \( \lambda > 0 \) so small that

\[ (ER'_1)(sEg'_1)^{-1} < 1. \]

Any such \( \lambda \) will suffice.

Let \( \{w'_i\} \) be the same functions of \( \{R'_i, g'_i\} \) as \( w_i \) are of \( \{R_i, g_i\} \). Let \( F'_i \) and \( F' \) be the corresponding functions for the primed \( w_i \). Comparing corresponding sequences in the manner of §3 we obtain that

\[ F_i(x) \leq F_i(x) \quad \text{for every } x. \]

Hence

\[ F'(x) = \lim F'_i(x) \leq F(x) \quad \text{for every } x. \]

If, therefore, we prove the desired result for the system \( \{w'_i\} \) we have a fortiori proved the desired result for the system \( \{w_i\} \). We may therefore drop the accents and henceforth assume that

\[ P\{g_1 = jc \} > 0, \quad j = 0, \ldots, (sk - 1), \]
\[ P\{g_1 \leq (sk - 1)c\} = 1, \]
\[ P\{R_1 = jc \} > 0, j = (sk - 1), (sk), (sk + 1), \ldots, \]
\[ P\{R_1 \geq (sk - 1)c\} = 1. \]

(We note that these imply that we are in the case \( s > 1 \), for \( s = 1 \) would
violate the requirement that $\rho < 1$.

Let

$$z^* = (skc, skc, \ldots, skc).$$

Let

$$z = (a_1c, a_2c, \ldots, a_rc)$$

with $0 \leq a_1 \leq a_2 \leq \cdots \leq a_r$ be any point in $Z$. Let

$$L = w_{i*} + skc.$$ 

If $R_{i+j-1} = L - w_{ij}$ and $g_{i+j} = 0, j = 1, \ldots, s$, an event of positive probability, we have

$$w_{i+j} = (L, L, \ldots, L).$$

If $R_{i+i+j-1} = (sk - 1)c$ and $g_{i+i+j} = kc, j = 1, \ldots, s$, again an event of positive probability, we have, since $L \geq skc$, that

$$w_{i+2s} = (L - c, L - c, \ldots, L - c).$$

Applying the above argument $a_r$ times we conclude that, for any $z$ and $i$, $P\{w_{i+j} = z^* \text{ for some } j \geq 0 | w_i = z\} > 0$. Let $D$ be the set of all points in $Z$ which can be reached from $z^*$ with positive probability. The above argument shows that the states of $D$ form an irreducible Markoff chain. This chain is aperiodic, because a modification of the above argument shows (using (6.23)) that there exists a number $N$ such that, whatever be $n \geq N$, there is a positive probability of moving from $z^*$ back to $z^*$ in exactly $n$ steps.

If now, with probability one, $w_i \in D$ for some $i$, an argument similar to that of III applies and the desired result is proved.

V. We now prove that, with probability one, $w_i \in D$ for some $i$.

From (6.23) and the fact that $P\{g_1 = 0\} > 0$ it follows that any point $z = (a_1c, \ldots, a_rc) \in Z$ such that $(2sk - 1) \leq a_1$ is a member of $D$. We now note that the probability of entering $D$ in at most $s$ steps from any point $z$ not in $D$ bounded below by a number (say) $\mu > 0$, independently of $z$ (not in $D$). To see this, we note that this can be accomplished in at most $s$ steps where each $R = 2skc$ and each $g = 0$. From this it follows that the probability of entering $D$ for some $i$ is one.

The proof of the result of this section is now complete.

7. **Proof that $F$ is not a distribution function when $\rho \geq 1$.** To prove this result we must in addition assume that, when $\rho = 1$,

$$P\{R_i - sg_i = 0\} < 1. \quad (7.1)$$

For if (7.1) does not hold we have, for some $\epsilon > 0$,

$$P\{g_1 = \epsilon\} = P\{R_1 = s\epsilon\} = 1. \quad (7.2)$$
(Hence $\rho = 1$ here.) Therefore, with probability one,
\[
\begin{align*}
    w_1 &= (0, 0, \ldots, 0), \\
    w_2 &= (0, 0, \ldots, 0, (s - 1)e), \\
    w_3 &= (0, 0, \ldots, 0, (s - 2)e, (s - 1)e), \\
    \vdots \\
    w_s &= (0, e, 2e, \ldots, (s - 1)e), \\
    w_i &= w_s, \quad i > s.
\end{align*}
\]
Hence a limiting distribution function $F$ does exist.

We therefore assume that $\rho \geq 1$ and (7.1) holds. We shall show that $F(x) = 0$, and hence (see §5, A) that $F^*(x_1) = 0$.

Let $\{L_i\}$ be a sequence of chance variables defined as follows: $L_1 = 0$ with probability one. For $i \geq 1$
\[
L_{i+1} = \max (0, L_i + R_i - sg_{i+1}).
\]
Thus $L_i$ is the waiting time of the $i$th individual in a system such as described in §2 where $s = 1$, the service time of the $i$th individual is $R_i$, and the interval between the $i$th arrival and $(i+1)$st arrival is $sg_{i+1}$. In this system $\rho \geq 1$, so that the theorem of Lindley (which treats the case $s = 1$) is applicable, i.e.,
\[
\lim_{z' \to \infty} \lim_{t \to \infty} P\{L_i \leq x'\} = 0. \tag{7.3}
\]

Now, if $0 \leq a_1 \leq a_2 \leq \ldots \leq a_s$, and $b, c, d$ are non-negative numbers with $b \leq \sum_{j=1}^{s} a_j$, we clearly have $\max (0, a_1 + c - d) + \sum_{j=2}^{s} \max (0, a_j - d) \geq \max (0, b + c - sd)$. We conclude, using induction, that for all $i \geq 1$,
\[
\lim_{z' \to \infty} \lim_{t \to \infty} P\{w_i \leq x', \ldots \leq x'\} = 0,
\]
with probability one. It follows from (7.3) and (7.4) that
\[
\lim_{z' \to \infty} F(x', x', \ldots, x') = \lim_{z' \to \infty} \lim_{t \to \infty} P\{w_i \leq x', j = 1, \ldots, s\} \leq \lim_{z' \to \infty} \lim_{t \to \infty} P\{\sum_{j=1}^{s} w_i \leq sx'\} = 0,
\]
which proves the desired result.

8. Proof that $\lim_{z' \to \infty} F_i(x|y)$ exists and is independent of $y$. Uniqueness of the solution of the integral equation (3.8). Suppose first that $\rho \geq 1$. Since $F_i(x|y) \leq F_i(x)$ for every $i$ and every $x$ and $y \in S$, it follows from the results
of §7 that
\[ \lim_{t \to \infty} F_i(x \mid y) = 0 \]
when \( \rho \geq 1 \). We shall shortly show that, when \( \rho \geq 1 \), (3.8) has no solution which is a distribution function over \( S \).

Assume, therefore, that \( \rho < 1 \), which is the interesting case. We shall show that, for all \( x \) and \( y \) in \( S \), the ergodic property
\[ \lim_{t \to \infty} F_i(x \mid y) = F(x) \]
holds. From this it follows easily that (3.8) has at most one solution which is a distribution function over \( S \) (thus, by §6, it has exactly one such solution). For, suppose, to the contrary, that there were another such distribution function, say \( V(x) \). It is clear then that, if \( w_t \) is distributed according to \( V(x) \), so are \( w_{2t}, w_{3t}, \ldots \), so that \( V(x) \) is the limiting distribution. On the other hand, it follows from (8.1) and the Lebesgue bounded convergence theorem applied to
\[ V(x) = \int F_i(x \mid y)dV(y) \]
that
\[ V(x) = \int F(x)dV(y) = F(x) \]
which is the desired result. (Thus we have proved that, when \( \rho < 1 \), \( F(x) \) is the unique stationary absolute probability distribution; see the paragraph following equation (3.8).)

Conversely, if (3.8) has a solution \( V \) which is a distribution function over \( S \), then
\[ F(x) = \lim_{t \to \infty} F_i(x) \geq \lim_{t \to \infty} \int F_i(x \mid y)dV(y) = V(x), \]
so that (from the result of §7) \( \rho < 1 \) and hence \( V(x) = \lim_{t \to \infty} F_i(x) \) is the unique solution of (3.8).

Denote by \([a, b]\) and \([c, d]\) the smallest closed intervals for which
\[ P\{a \leq R_1 \leq b\} = P\{c \leq g_1 \leq d\} = 1. \]
We shall conduct the proof separately for several cases.

Case 1: \( b > sc \). Let \( b - sc = 2\nu > 0 \). Then, for any positive integer \( n \),
\[ P\{w_{en,1} > \nu n\} = q_n > 0. \]
Fix \( n \). For any \( x \) and \( \delta > 0 \) there exists an integer \( M \) such that, for all \( j \geq M \)
and \( k > 0 \), we have
\[
| F_j(x) - F_{j+k}(x) | < q_n \delta.
\]
We recall that, if \( y_1 \leq y_2, y_1 \in S, y_2 \in S \), we have, for all \( i \),
\[
F_i(x \mid y_1) \geq F_i(x \mid y_2).
\]
Hence, for \( j \geq M \), we have
\[
0 = q_n \left[ F_j(x) - F_j(x \mid (nv, nv, \ldots, nv)) \right]
\leq \int [F_j(x) - F_j(x \mid y)] dF_n(y)
\leq q_n \delta + \int [F_{j+n}(x) - F_j(x \mid y)] dF_n(y) = q_n \delta.
\]
Therefore
\[
0 \leq [F_j(x) - F_j(x \mid y)] < \delta
\]
for all \( y \leq (nv, nv, \ldots, nv) \), \( y \in S \), and all \( j \geq M \). Since \( x, n, \) and \( \delta \) were arbitrary this proves (8.1) for Case 1.

**Case 2:** \( a < d \). Let \( y \) be any point in \( S \), and
\[
P_n(y) = P \{ w_n = 0; w_i \neq 0, i < n \mid w_1 = y \}.
\]
We shall show that, for all \( y \) in \( S \),
\[
\sum_{n=1}^{\infty} P_n(y) = 1.
\]
This is sufficient to prove the desired result, because
\[
F_i(x \mid y) - \sum_{n \geq i} P_n(y) F_{i-n}(x)
\]
then approaches zero as \( i \to \infty \).

To prove (8.4) we proceed as in §6 to construct a "dominating" random walk on a lattice. The walk begins at a point on the lattice all of whose coordinates are no less than the corresponding ones of \( y \). As in §6 one proves that with probability one the walk enters an irreducible aperiodic chain. Since \( a < d \) this chain contains the origin. Since \( \rho < 1 \) and \( F(x) \) is a distribution function this chain constitutes a positive recurrent class. For an irreducible, recurrent class (8.4) must hold for all \( y \) in the class. Since the walk enters the class with probability one, (8.4) holds for all \( y \) in \( S \).

**Case 3:** \( c = d \leq a = b \leq sc \). In this case we have \( P \{ R_1 = b \} = P \{ g_1 = c \} = 1 \). Since \( \rho < 1 \), we also have \( b < sc \).

Let \( y^* = (y_1, \ldots, y_s) \) be any point in \( S \), and let \( y'' = (y_s, \ldots, y_s) \). Given the process \( \{ R_i, g_i \} \), let \( w_i \) be the position of \( w_i \) if \( w_i = y^* \), let \( w_i \) be the posi-
tion of \( w_i \) if \( w_i = 0 \), and let \( w_i' \) be the position of \( w_i \) if \( w_i = y' \). Clearly, \( w_i \leq w_i^* \leq w_i'' \) for all \( i \) with probability one, and for \( i \geq s \) we have \( w_i' = \bar{w} \), where \( \bar{w} \) is defined by

\[
(8.6) \quad \bar{w} = (0, u_{s-1}, \ldots, u_2, u_1),
\]

where

\[
u_j = \max (b - jc, 0).
\]

We shall show that \( w_i'' = \bar{w} \) with probability one for \( i \) sufficiently large, which implies that for sufficiently large \( i \) with probability one, \( w_i^* = \bar{w} \), and proves the desired result.

It is clear that, for all \( i \),

\[
w_i'' = \max (0, w_i' - c) \quad \text{for } 1 \leq j < s,
\]

\[
w_i'' = w_i' + b - c.
\]

For \( n \geq 0 \) and \( 0 \leq i \leq s - 1 \), we evidently have

\[
w_i'' = w_{i+n,s+i,1} \leq w_{n+1,1}.
\]

Let \( N \) be a positive integer such that \( y_s - N(sc - b) \leq 0 \). Then \( w_{ns+1,1}'' = 0 \) for \( n \geq N \), and hence from (8.8) we have \( w_i'' = 0 \) for \( i \geq Ns + 1 \). It follows from (8.7) that \( w_i'' = \bar{w} \) for \( i \geq (N + 1)s \).

Case 4: \( d \leq a, b \leq sc \), and either \( a < b \) or \( c < d \). Let \( u_j \) be as in (8.6) and for \( \epsilon > 0 \) define \( \bar{w} = (0, u_{s-1}, \ldots, u_2, u_1) \), where \( u_j = \max (0, u_j - \epsilon) \). From the definition of \( b \) and \( c \) we have that, for every \( \epsilon > 0 \),

\[
P\{w_{s,j} \geq u_{s-j+1}, j = 1, \ldots, s\} = \gamma > 0.
\]

An argument like that of Case 1 (with \( \gamma \) for \( q_n \) and \( F_s \) for \( F_{sn} \)) then shows that

\[
\lim_{t \to \infty} F_t(x \mid y) = F(x)
\]

for all \( y \in \Gamma^* = \{y \mid y \in S, y \leq \bar{w} \} \) and all \( x \).

Let \( y \) be any point in \( S \), and

\[
\rho_n^*(y) = P\{w_n \in \Gamma^*, w_i \in \Gamma^*, i < n \mid w_1 = y\}.
\]

We shall show that, for some \( \epsilon > 0 \) and all \( y \in S \), we have

\[
(8.9) \quad \sum_{n=1}^{\infty} \rho_n^*(y) = 1;
\]

from this and the result of the previous paragraph, the desired result is proved in the manner of the first paragraph of Case 2.

Let
In order to prove (8.9) for some $\epsilon > 0$ and for all $\theta \in S$, it clearly suffices to show that
\begin{equation}
P\{w_i \in E \text{ for infinitely many } i \mid w_1 = \theta\} = 1
\end{equation}
for all $\theta \in S$, and that there exists a positive integer $M$ and positive numbers $\alpha$ and $\epsilon$ such that
\begin{equation}
P\{w_M \in \Gamma^\epsilon \mid w_1 = \theta\} > \alpha
\end{equation}
for all $\theta \in E$.

We first prove (8.11). To this end, let $\theta = (\theta_1, \ldots, \theta_n)$ be any fixed point in $S$. Since we have always assumed $d > 0$, we have in Case 4 that $a > 0$. It follows from equation (4.3) that for $n > (s - 1)\theta/d$ we have
\begin{equation}
P\{\theta_i = \theta\} = 1.
\end{equation}
Let $\{e_i\}$, $\{f_i\}$ be any sequences of non-negative numbers, and let $\{v_i\}$ be the corresponding sequence of values of $\{w_i\}$ when $w_1 = \theta$, $R_i = e_i$, and $g_i = f_i$. Then, if $v_i = 0$ for only finitely many $i$, it would follow that $\lim \inf_{n \to \infty} (1/n) \sum_{i=1}^n (e_i - sf_{i+1}) \geq 0$. However, since $\rho < 1$, the strong law of large numbers implies that
\begin{equation}
P\left\{\lim_{n \to \infty} \frac{1}{n} \sum_{i=1}^n (R_i - sg_{i+1}) = ER_1 - sEg_1 < 0\right\} = 1.
\end{equation}
Hence
\begin{equation}
P\{w_{i,1} = 0 \text{ for infinitely many } i \mid w_1 = \theta\} = 1
\end{equation}
for all $\theta \in S$. Equation (8.14) is a fortiori true for the original process, and (8.11) is an immediate consequence of (4.1), (8.13), and (8.14).

It remains to prove (8.12). We recall that in Case 4 we have $c < b \leq sc$ and that there are numbers $b'$, $c'$ such that $P\{R_i \leq b'\} = p > 0$, $P\{g_i \geq c'\} = q > 0$, and $b' - c' = b - c - \epsilon$ for some $\epsilon > 0$. An obvious modification of the argument of Case 3 (put $b'$, $c'$ for $b$, $c$) shows that if $w_1 = \theta \in E$ and if $R_j = b'$ and $g_{j+1} = c'$ for $1 \leq j < M$ where $M/s$ is the greatest integer contained in $2 + (s - 1)b/(sc' - b')$, then
\begin{equation}
w_{M,i} \leq \max\left(0, b' - (s + 1 - i)c'\right) \leq u_{s-i+1}^i.
\end{equation}
Equation (8.15) is a fortiori true if $R_j \leq b'$ and $g_{j+1} \geq c'$ for $1 \leq j < M$ (the argument being similar to that of §3). We conclude that (8.12) is satisfied for $\epsilon$ and $M$ as defined here and for $\alpha = (pq)^{M-1}$.

9. Distribution of the number of individuals waiting in the queue. In order to avoid trivial cases and the circumlocutions required to dispose of them, we shall assume in this section that $G(0) = 0$. This means that the prob-
ability is zero that two or more individuals arrive simultaneously.

Let \( Q_i \) be the number of arrivals in the open time interval \((t_i, t_i+w_{ii})\); i.e., \( Q_i \) is the number of individuals in the queue waiting to be served, just before the service of the \( i \)th individual begins.

Since \( g_{i+1}, g_{i+2}, \ldots \) are independent of \( t_i \), we have

\[
P\left\{ Q_i \geq n \right\} = \int P\left\{ g_1 + g_2 + \cdots + g_n < a \right\} dF_i^*(a)
\]

(9.1)

\[
= \int G^*(a-1) dF_i^*(a),
\]

where \( G^*(a) \) denotes the \( n \)-fold convolution of \( G(a) \) with itself. Since \( F_i^*(a) \) tends nonincreasingly to \( F^*(a) \) as \( i \to \infty \) for all \( a \), and since \( G^*(a-) \) is continuous from the left, we obtain, in the case \( \rho < 1 \),

\[
\lim_{i \to \infty} P\left\{ Q_i \geq n \right\} = \int G^*(a-) dF^*(a).
\]

(9.2)

If \( \rho \geq 1 \), equation (9.1) shows that \( \lim_{i \to \infty} P\left\{ Q_i \geq n \right\} = 1 \) for all \( n \), except in the trivial case where \( P\left\{ R_1 = s_1 = 0 \right\} = 1 \).

References


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