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Markov programming by successive approximations
with respect to weighted supremum norms

by

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Eindhoven, December 1974 (revised)

The Netherlands

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Summary. Markovian decision processes are considered in the situation of discrete time, countable state space, and general decision space. By introducing a Banach space with a weighted supremum norm, conditions are derived, which guarantee convergence of successive approximations to the value function. These conditions are weaker than those required by the usual supnorm approach. Several properties of the successive approximations are derived.

1. Introduction. We consider a Markov decision process with a countably infinite or finite state space \mathcal{S} and decision space \mathcal{K} , defined as follows. A system is observed at discrete points of time ($t = 0, 1, 2, \dots$). If at time t the state of the system is $i \in \mathcal{S}$, a decision $k \in \mathcal{K}$ may be chosen, which results in a reward r_i^k . The state i at time t and the decision k determine the probability p_{ij}^k of observing the system in state j at time $t+1$ (regardless of the earlier history of the process). We suppose:

$$\sum_{j \in \mathcal{S}} p_{ij}^k \leq 1 \quad \text{for all } i \in \mathcal{S}, k \in \mathcal{K} .$$

Hence a positive probability for fading of the system is allowed.

A policy f is a function on \mathcal{S} with values in \mathcal{K} . A strategy s is a sequence of policies: $s = (f_0, f_1, f_2, \dots)$. If strategy s is used, we take decision $f_t(i)$, if at time t the state of the system is i , i.e. we introduce only so-called (nonrandomized) Markov strategies.

As optimality criterion we choose total expected reward, which is defined for a strategy $s = (f_0, f_1, \dots)$ as a vector $V(s)$ in the following way

$$V(s) = \sum_{t=0}^{\infty} \left[\prod_{n=0}^{t-1} P(f_n) \right] r(f_t) ,$$

where the sum is supposed to remain convergent when rewards are replaced by their absolute values,

$r(f)$ is interpreted as a (column) vector with i -component $r_i^{f(i)}$ (for $i \in \mathcal{S}$) for any policy f , and

$P(f)$ is interpreted as a matrix with (i,j) -component $p_{ij}^{f(i)}$ (for $i,j \in \mathcal{S}$) for any policy f .

Matrix products, matrix-vector products and sums of vectors are defined in the usual way; an empty matrix product is the identical matrix.

This formulation contains the discounted case ($\beta \leq 1$), since the discount-factor may be supposed to be incorporated in the p_{ij}^k . The same holds for the semi-Markov case, which only requires t to be interpreted as the number of the decision moment rather than as actual time. For semi-Markov decision processes with discounting the resulting discountfactors depend on i,j,k and may again be supposed to be incorporated in the p_{ij}^k .

$V(s)$ converges absolutely and uniformly in its components under the following conditions:

$$\sum_j p_{ij}^k \leq \rho < 1, \quad |r_i^k| \leq M \quad (\text{for all } i \in \mathcal{S}, k \in \mathcal{K}).$$

Under these conditions the total expected reward $V_i(s)$, when the system starts in i and under strategy s , is at most $\frac{M}{1-\rho}$ in absolute value. The value function $V := \sup_s V(s)$ may then be estimated by successive approximations. Upper and lower bounds for V may be given at each step. At the same time, the method produces at each step a stationary strategy $s = (f, f, \dots)$ with $V(s)$ lying between the same bounds. For the finite state, finite decision case this may be found in MacQueen [7], Schellhaas [11], and van Nunen [8]. A more general situation has been treated by Denardo [2].

In this paper we obtain similar results under somewhat weaker conditions, especially the uniformity requirements of the conditions will be weakened. Like Denardo, MacQueen, Schellhaas, and van Nunen, we shall basically apply the contraction operator technique as introduced by Blackwell [1]. However, we shall not use the Banach space of functions on \mathcal{S} with supremum norm as Blackwell does. We shall introduce a Banach space \mathcal{V} of functions on \mathcal{S} with a modified supremum norm. For inventory problems with average costs, Wijngaard [15] introduces a special (exponential) norm of this type. Lippman [6] works

with the same type of norm for the discounted case, however his conditions are more complicated and only guarantee N-stage contraction. Operators in \mathbb{W} are introduced in section 2. Section 3 presents an approximation procedure for the value function of the problem, together with a procedure to find a strategy which is nearly optimal. In section 4 some possibilities for extensions and for weakening of the conditions are suggested.

2. Norms and operators. Let μ be a positive function on \mathcal{S} , and denote by \mathbb{W} the set of all real valued functions v on \mathcal{S} (interpreted as columnvectors) with the property

$$\|v\| := \sup_{i \in \mathcal{S}} \mu(i) |v(i)| < \infty .$$

As one easily verifies, $\|\cdot\|$ is a norm and the set \mathbb{W} is complete with respect to this norm, i.e. \mathbb{W} is a Banach space.

This norm on \mathbb{W} induces a norm on the set of real matrices that represent linear operators on \mathbb{W} , viz.

$$\|A\| := \sup_i \mu(i) \sum_j |a_{ij}| \mu^{-1}(j) .$$

For matrices A, B with $\|A\|, \|B\| < \infty$ and $v \in \mathbb{W}$ we clearly have

$$\|Av\| \leq \|A\| \|v\| \text{ and } \|AB\| \leq \|A\| \|B\| .$$

We now state some assumptions on the reward and probability structure of the system.

Assumptions.

- 1) $r(f) \in \mathbb{W}$ and $\|r(f)\| \leq M < \infty$ for all policies f .
- 2) $\sup_f \|P(f)\| =: \rho < 1$.

Assumption 1 means that

$$|r_i^k| \leq \frac{M}{\mu(i)} \quad \text{for all } k \in K \text{ and } i \in \mathcal{S} .$$

Hence, for fixed $i \in \mathcal{S}$ the rewards for different decisions are bounded, however as a function of i these bounds may increase to infinity. Actually, a function μ exists such that assumption 1 is fulfilled, iff r_i^k is bounded in k for fixed i .

For the probability structure, assumption 2 means, that, given the starting state i and the decision k , the expectation of $\mu^{-1}(X_1)$ is at most $\rho\mu^{-1}(i)$, where X_1 is the random variable denoting the state of the system at time $t = 1$. In the special case $\mu \equiv 1$ these assumptions give the well-known conditions mentioned in section 1.

Lemma 1. For any strategy $s = (f_0, f_1, \dots)$ the total expected reward $V(s)$ exists, i.e.

$$\sum_{t=0}^{\infty} [\prod_{n=0}^{t-1} P(f_n)] |r(f_t)|$$

converges componentwise and in norm (the vector $|r|$ has i -component $|r_i|$),

$$V(s) \in \mathbb{V}, \|V(s)\| \leq \frac{M}{1-\rho} \text{ or } V_i(s) \leq \frac{M}{1-\rho} \mu^{-1}(i) .$$

Proof. The assertion follows from the fact that

$$v_t := [\prod_{n=0}^{t-1} P(f_n)] |r(f_t)| \in \mathbb{V} ,$$

with $\|v_t\| \leq \rho^t M$. □

On \mathbb{V} we define the operators L_f for any policy f and U , by

$$L_f v := r(f) + P(f)v \quad \text{for any } v \in \mathbb{V}$$

$$(Uv)(i) := \sup_{k \in K} \{r_i^k + \sum_j p_{ij}^k v(j)\} \quad \text{for } i \in S, v \in \mathbb{V} ,$$

or in matrix notation:

$$Uv := \sup_f \{r(f) + P(f)v\} ,$$

where the sup is taken componentwise.

Lemma 2.

- a) L_f and U map \mathbb{V} into \mathbb{V} .
- b) L_f and U are monotone mappings.
- c) L_f and U map $\{v \in \mathbb{V} \mid \|v\| \leq \frac{M}{1-\rho}\}$ into itself.
- d) L_f and U are strictly contracting with contraction radii $\|P(f)\|$ and ρ respectively.

- e) L_f and U possess unique fixed points in \mathbb{V} with norms at most $\frac{M}{1-\rho}$.
 f) the fixed point of L_f is $V(f^{(\infty)})$, where $f^{(\infty)}$ denotes the stationary strategy (f, f, f, \dots) .

Proof. The proofs of a), b), c) are straightforward. For the finite state, finite decision case with $\mu \equiv 1$ property c) has been noticed by Shapiro [12]. e) is a direct consequence of d) and assumption 2. f) is proved by direct verification. About d) the following remarks. The proof of the fact that L_f is strictly contracting with contraction radius at most $\|P(f)\|$ is straightforward. The example $v(i) := \mu^{-1}(i)$, $w(i) := 0$ ($i \in \mathcal{S}$) shows that for certain $v, w \in \mathbb{V}$

$$\|L_f v - L_f w\| = \|P(f)\| \|v - w\|.$$

That U has contraction radius at most ρ is proved in the following way. Choose $v \in \mathbb{V}$ and $\varepsilon > 0$. For any $i \in \mathcal{S}$ a decision k is chosen such that

$$r_i^k + \sum_j p_{ij}^k v(j) \geq (Uv)(i) - \varepsilon \mu^{-1}(i).$$

Now for this v and an arbitrary $w \in \mathbb{V}$ we have

$$\begin{aligned} \mu(i)(Uv)(i) - \mu(i)(Uw)(i) &\leq \mu(i)r_i^k + \mu(i) \sum_j p_{ij}^k v_j + \varepsilon + \\ &- \mu(i)r_i^k - \mu(i) \sum_j p_{ij}^k w(j) = \varepsilon + \mu(i) \sum_j p_{ij}^k (v(j) - w(j)) \leq \\ &\leq \varepsilon + \rho \|v - w\|. \end{aligned}$$

In the same way we prove for arbitrary v and w

$$\mu(i)(Uw)(i) - \mu(i)(Uv)(i) \leq \varepsilon + \rho \|v - w\|.$$

Hence

$$\|Uv - Uw\| \leq \varepsilon + \rho \|v - w\| \quad \text{for all } \varepsilon > 0,$$

and therefore

$$\|Uv - Uw\| \leq \rho \|v - w\|.$$

By substituting $w(i) := 0$, $v(j) := \ell \mu^{-1}(j)$ with $\ell > 0$, we verify that

$$\|Uv - Uw\| \geq [-2\varepsilon + \rho] \|v - w\| \quad \text{if } \ell \geq \frac{M}{\varepsilon}.$$

This implies that ρ is the contraction radius. □

3. Approximation procedures. Fixed points of contraction mappings on \mathbb{W} may be approximated by a sequence of points in \mathbb{W} . For the operator U , such a sequence is generated in the following way: choose $v_0 \in \mathbb{W}$, define recursively $v_n := Uv_{n-1}$ for $n = 1, 2, \dots$. Then v_n converges in norm to the fixed point w of U : $\lim_{n \rightarrow \infty} \|v_n - w\| = 0$, or, for $\epsilon > 0$ there exists a number N_ϵ such that for $n \geq N_\epsilon$:

$$|v_n(i) - w(i)| < \epsilon \mu^{-1}(i), \quad \text{for all } i \in \mathbb{S}.$$

As U is monotone, we obtain a nondecreasing sequence, if v_0 is chosen such that $v_0 \leq v_1$.

This can be achieved by taking $v_0 := -\frac{M}{1-\rho} \mu^{-1}$, where $\mu^{-1} \in \mathbb{V}$ with components $\mu^{-1}(i)$. By assumptions 1 and 2 we then have

$$\begin{aligned} v_1 &= \sup_f \{r(f) - P(f) \frac{M}{1-\rho} \mu^{-1}\} \geq -M\mu^{-1} - \frac{M}{1-\rho} \rho \mu^{-1} = \\ &= -\frac{M}{1-\rho} \mu^{-1} = v_0. \end{aligned}$$

It seems natural to conjecture that $w = V (= \sup_s V(s))$. We first prove

Lemma 3. For any strategy $s = (f_0, f_1, \dots)$ we have $V(s) \leq w$, i.e. $V \leq w$.

Proof.

$$V(s) = \sum_{t=0}^{\infty} \left[\prod_{n=0}^{t-1} P(f_n) \right] r(f_t) \leq \sum_{t=0}^{N-1} \left[\prod_{n=0}^{t-1} P(f_n) \right] r(f_t) + \sum_{t=N}^{\infty} \rho^t M \mu^{-1}.$$

Hence if $\frac{\rho^N M}{1-\rho} \leq \epsilon$, i.e. if N sufficiently large, we have

$$V(s) \leq U^N 0 + \epsilon \mu^{-1},$$

where 0 denotes the element of \mathbb{W} with all components 0 .

$U^N 0$ converges in norm and hence componentwise to w when $N \rightarrow \infty$. This implies

$$V(s) \leq w + \epsilon \mu^{-1}.$$

This inequality holds componentwise for any $\epsilon > 0$, hence $V(s) \leq w$. □

Theorem 1. For any $\epsilon > 0$ there is a policy f , such that the stationary strategy $f^{(\infty)} := (f, f, \dots)$ satisfies

$$\|V(f^{(\infty)}) - w\| \leq \epsilon ,$$

hence $V = w$.

Proof. Let $\delta := \frac{1}{2}(1 - \rho)\epsilon$. Select $v_0 \in W$, such that $v_0 < Uv_0$ (strictly smaller for each component, e.g. $v_0 = -c\mu^{-1}$ with $c < \frac{M}{1 - \rho}$). A policy f_n ($n = 1, 2, \dots$) is selected, such that

$$v_n := L_{f_n} v_{n-1} \geq \max\{v_{n-1}, Uv_{n-1} - \delta\mu^{-1}\} ,$$

where the maximum is taken componentwise. Such a policy f_n can always be found, as can be seen as follows. If $v_{n-1}(i) < (Uv_{n-1})(i)$ it is trivial by the definition of U . If $v_{n-1}(i) = (Uv_{n-1})(i)$ for certain $i \in S$, then $f_n(i) = f_{n-1}(i)$ satisfies, because - using induction - we have

$$v_{n-1} = L_{f_{n-1}} v_{n-2} \geq v_{n-2} ,$$

hence

$$(L_{f_{n-1}})^2 v_{n-2} \geq v_{n-1} , \text{ or } L_{f_{n-1}} v_{n-1} \geq v_{n-1} ,$$

as required.

We now proceed with the proof. The same reasoning gives

$$(L_{f_n})^k v_{n-1} \geq v_n ,$$

for any natural number k . Hence

$$V \geq V(f_n^{(\infty)}) \geq v_n .$$

It now suffices to prove that v_n approximates w in norm for sufficiently large n . We have

$$\begin{aligned} v_n = L_{f_n} v_{n-1} &\geq Uv_{n-1} - \delta\mu^{-1} \geq U[Uv_{n-2} - \delta\mu^{-1}] - \delta\mu^{-1} \geq \\ &\geq U^2 v_{n-2} - \delta\rho\mu^{-1} - \delta\mu^{-1} . \end{aligned}$$

Repetition of this argument yields

$$v_n \geq U^n v_0 - \delta(1 + \rho + \dots + \rho^{n-1})\mu^{-1} \geq U^n v_0 - \frac{\delta}{1 - \rho} \mu^{-1} .$$

Summarizing we have

$$U^n v_0 - \frac{\delta}{1-\rho} \mu^{-1} \leq v_n \leq V(f_n^{(\infty)}) \leq V \leq w .$$

Since $U^n v_0$ converges to w (in norm), we have for n sufficiently large

$$\|w - V(f_n^{(\infty)})\| \leq \frac{2\delta}{1-\rho} = \varepsilon . \quad \square$$

Now we have proved that the fixed point w of the operator U is equal to the optimal value vector V of the decision problem. Furthermore we have proved that for any $\varepsilon > 0$ a stationary strategy is ε -optimal (defined in terms of the norm). The question now arises whether one is able to find lower and upper bounds for $V(f_n^{(\infty)})$ and V at the n -th iteration step of the iteration process developed in the proof of theorem 1. Apparently, v_n is a lower bound. However, without much effort a better lower bound and upper bound can be constructed. The proofs follow the same line as van Nunen's proof [8] for the bounds of MacQueen [7] in the $\mu \equiv 1$, finite state, finite decision case. The same technique turned out to work for a variety of other successive approximation methods for the same case (van Nunen [8], van Nunen [9], Wessels and van Nunen [14]). Hinderer [4] used a similar approach for finite horizon problems.

Theorem 2. Suppose $\delta > 0$; $v, w \in \mathbb{V}$ such that $Uw - \delta\mu^{-1} \leq v$. Then

$$V \leq v + \frac{\delta + \rho\|v - w\|}{1-\rho} \mu^{-1} .$$

Proof. $Uv = U(w + v - w)$. Hence, since $Uw \leq v + \delta\mu^{-1}$

$$Uv \leq Uw + \rho\|v - w\|\mu^{-1} \leq v + \delta\mu^{-1} + \rho\|v - w\|\mu^{-1} .$$

This implies $Uv \leq v + \varepsilon\mu^{-1}$, with $\varepsilon := \delta + \rho\|v - w\|$. Hence

$$\begin{aligned} U^2 v &\leq U(v + \varepsilon\mu^{-1}) = U(w + v - w + \varepsilon\mu^{-1}) \\ &\leq Uw + \rho\|v - w\|\mu^{-1} + \varepsilon\rho\mu^{-1} \\ &\leq v + \delta\mu^{-1} + \rho\|v - w\|\mu^{-1} + \varepsilon\rho\mu^{-1} . \end{aligned}$$

Or

$$U^2 v \leq v + \varepsilon(1 + \rho)\mu^{-1} .$$

Generally

$$U^N v \leq v + \frac{\varepsilon}{1 - \rho} \mu^{-1} ,$$

which implies, since $\lim_{N \rightarrow \infty} U^N v = V$:

$$V \leq v + \frac{\varepsilon}{1 - \rho} \mu^{-1} .$$

□

Theorem 3. If $v, w \in \mathbb{V}$ satisfy $L_f w \geq v$, then

$$v + \frac{\rho_* \|v - w\|_*}{1 - \rho_*} \mu^{-1} \leq V(f^{(\infty)}) \leq v + \frac{\rho \|v - w\|}{1 - \rho} \mu^{-1} ,$$

where

$$\|v - w\|_* := \inf_i \mu(i)(v(i) - w(i)) ,$$

$$\rho_* := \inf_{i,k} \mu(i) \sum_j p_{ij}^k \mu^{-1}(j) .$$

The proof proceeds as the proof of theorem 2.

□

Remark. In theorem 3 the values of ρ and ρ_* may be replaced by

$$\rho(f) := \|P(f)\|$$

and

$$\rho_*(f) := \inf_i \mu(i) \sum_j p_{ij}^{f(i)} \mu^{-1}(j)$$

respectively. These replacements make the assertions sharper, however, they take more work.

We have now proved, that the following algorithm ends after a finite number of steps:

start: choose $\alpha > 0, \delta > 0, v_0 \in \mathbb{V}$ with $v_0 < Uv_0$ (< for all components) and $\frac{\delta}{1 - \rho} < \alpha$.

iteration part: find for $n = 1, 2, \dots$ a policy f_n , such that

$$v_n := L_{f_n} v_{n-1} \geq \max\{v_{n-1}, Uv_{n-1} - \delta\mu^{-1}\} ,$$

until

$$\frac{\delta + \rho \|v_n - v_{n-1}\|}{1 - \rho} - \frac{\rho_* \|v_n - v_{n-1}\|_*}{1 - \rho_*} < \alpha .$$

stop:

$$v_n + \frac{\rho_* \|v_n - v_{n-1}\|_*}{1 - \rho_*} \mu^{-1} \leq V(f_n^{(\infty)}) \leq V \leq v_n + \frac{\delta + \rho \|v_n - v_{n-1}\|}{1 - \rho} \mu^{-1} .$$

with a distance between lower and upper bound of less than α .

$$V(f_n^{(\infty)}) \leq v_n + \frac{\rho \|v_n - v_{n-1}\|}{1 - \rho} \mu^{-1} ,$$

hence the distance between upper and lower bounds for

$$V(f_n^{(\infty)}) \text{ is less than } \alpha - \frac{\delta}{1 - \rho} .$$

4. Extensions and remarks. An interesting extension of the theory presented here, these spaces and norms could be used to develop analogues to other successive approximation methods. For the supnorm case different successive approximation methods have been proposed (e.g. Reetz [10], Schellhaas [11], van Nunen [8]). These and several other ideas have been combined and extended by van Nunen [9], whereas a more general approach for generating successive approximation procedures for the supnorm case has been presented by Wessels [13] and Wessels and van Nunen [14]. In the papers [8] and [14], Howard's policy iteration method [5] appears as a specific successive approximation procedure. It seems possible to weaken the conditions under which these methods work.

An other interesting situation for extension in the sense of this paper may be found in a paper by Harrison [3]. Harrison considers a situation with unbounded reward functions where successive approximations converge in supremum norm if the starting vector is well chosen.

In the present paper the condition is:

A: a positive function μ exists, such that assumptions 1 and 2 are satisfied.

For the finite state case ($\$$ finite) condition A is equivalent to

B: r_i^k is bounded as a function of i, k , and there exist a positive number ϵ and a natural number N , such that

$$P(X_N \in \$ \mid X_0 = i, \text{ strategy } s) \leq 1 - \epsilon \quad \text{for all } s, i .$$

The proof of the equivalence is rather straightforward.

Actually, B implies A if \mathcal{S} is countably infinite, which is proved in the same way as in the finite case.

Such topics will be treated more extensively in a forthcoming paper by K.M. van Hee and the present author.

Condition A may be weakened by replacing assumption 2 by 2*.

Assumption 2*. For some $T \geq 1$, and all f_0, f_1, \dots, f_{T-1}

$$\| \prod_{t=0}^{T-1} P(f_t) \| \leq \rho < 1 .$$

It is not necessary to use a fixed δ in the algorithm: the δ -value, δ_n say, used in the n -th situation, may depend on n ; it is only required that $\delta_n \leq \delta^* < \alpha(1 - \rho)$, for n sufficiently large.

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