Math 525: Lecture 19

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1 Strong Markov property

The memoryless/Markov property for a stationary Markov chain can be expressed as follows: "for each n, the process $X_n, X_{n+1}, \ldots$ is a Marko chain with the same transition probabilities as $X_0, X_1, \ldots$"

Question: is the same result true if we replace n by τ?

Let $(X_n)_{n\geq 0}$ be a Markov chain with transition matrix P and let $\mathcal{F}_n = \sigma(X_0, \ldots, X_n)$. The Markov property can be rephrased in terms of $\mathcal{F}_n$ as follows:

$$\mathbb{P}(X_{n+1} = j \mid X_n = i, \Lambda) = P_{ij} \qquad \text{for } \Lambda \in \mathcal{F}_n.$$

Equivalently,

$$\mathbb{P}(\Lambda, X_n = i, X_{n+1} = j) = \mathbb{P}(\Lambda, X_n = i)P_{ij} \qquad \text{for } \Lambda \in \mathcal{F}_n. \tag{1}$$

Proposition 1.1 (Strong Markov property)**.** *Let τ be a finite stopping time (i.e., $\tau < \infty$ a.s.). Given that $X_\tau = i$, the sequence $(X_{\tau+n})_{n\geq 0}$ is a Markov chain with transition matrix P.*

Proof. Let S be a finite stopping time and let $\Lambda \in \mathcal{F}_S$. Remember that

$$\mathcal{F}_S = \{\Lambda \in \mathcal{F} \colon \Lambda \cap \{S = n\} \in \mathcal{F}_n \text{ for all } n = 0, 1, 2 \ldots\}.$$

Then, for states i and j,

$$\mathbb{P}(\Lambda, X_S = i, X_{S+1} = j) = \sum_{k\geq 0} \mathbb{P}(\Lambda \cap \{S = k\}, X_k = i, X_{k+1} = j).$$

Since $\Lambda \in \mathcal{F}_S$, it follows that $\Lambda \cap \{S = k\} \in \mathcal{F}_S$ for each k. By (1),

$$\mathbb{P}(\Lambda, X_S = i, X_{S+1} = j) = P_{ij} \sum_{k\geq 0} \mathbb{P}(\Lambda \cap \{S = k\}, X_k = i) = P_{ij}\mathbb{P}(\Lambda, X_S = i).$$

Divide both sides by $\mathbb{P}(\Lambda, X_S = i)$ to get

$$\mathbb{P}(X_{S+1} = j \mid \Lambda, X_S = i) = \frac{\mathbb{P}(\Lambda, X_S = i, X_{S+1} = j)}{\mathbb{P}(\Lambda, X_S = i).} = P_{ij}. \tag{2}$$

Now, fix n. Take $S = \tau + n$. Since S is the sum of a stopping time and a constant, S is also a stopping time. Let $\Lambda = \{X_\tau = i_0, \ldots, X_{\tau+n} = i_n\}$. Therefore, by (2),

$$\mathbb{P}(X_{\tau+n+1} = i_{n+1} \mid X_{\tau+n} = i_n, \ldots, X_\tau = i_0) = P_{i_n i_{n+1}}.$$

That is, $(X_{\tau+n})_{n\geq 0}$ is a Markov chain with transition matrix P. □

An immediate corollary of the above is the following:

Corollary 1.2. *Let $X_0, X_1, \ldots$ be i.i.d. discrete random variables (so that $(X_n)_{n\geq 0}$ is a stationary Markov chain). Let τ be a finite stopping time. Then, $X_{\tau+1}$ has the same distribution as X_0.*

Before we prove this, let's try to understand the intuition.

Example 1.3. A gambler plays roulette and chooses a time to place a bet. Let X_n be the outcome of the n-th spin and τ be the stopping time at which the bet is placed. The above says that $X_{\tau+1}$ has the same distribution as X_0. In other words, assuming that the gambler eventually places a bet (i.e., $\tau < \infty$), they are no better off than they would have been had they placed the bet at time zero (i.e., $\tau = 0$).

Proof. $X_0, X_1, \ldots$ is a Markov chain with transition probabilities $P_{ij} = \mathbb{P}(X_{n+1} = x_j \mid X_n = x_i) \equiv p_j$. In other words, P_{ij} does not depend on i. By the strong Markov property, $X_\tau, X_{\tau+1}, \ldots$ is once again a Markov chain with the same transition probabilities. That is, if $\Lambda \in \mathcal{F}_\tau$,

$$\mathbb{P}(X_{\tau+1} = x_j \mid \Lambda, X_\tau = x_i) = P_{ij} = p_j = \mathbb{P}(X_0 = x_j).$$

□

Exercise 1.4. X_τ does not necessarily have the same distribution as X_0. Why?

2 Recurrence and transience

If we start a Markov chain at state i, will it ever return to i? How many times will it return to i? These are the questions we look to answer next.

Definition 2.1. For a discrete random variable Y, we define its expectation conditional on an event Λ with $\mathbb{P}(\Lambda) > 0$ by

$$\mathbb{E}[Y \mid \Lambda] = \frac{\mathbb{E}[Y \cdot I_\Lambda]}{\mathbb{P}(\Lambda)}.$$

Actually, the conditional expectation for a general random variable is *much* harder to define. We might come back to it later. To simplify notation, let

$$\mathbb{P}^i(\Lambda) = \mathbb{P}(\Lambda \mid X_0 = i)$$

be the probability of Λ conditional on the initial state of the Markov chain being i. Similarly, let

$$\mathbb{E}^i(Y) = \mathbb{E}[Y \mid X_0 = i].$$

Definition 2.2. The *first hitting time* of i is $T_i = \inf\{n \geq 1 \colon X_n = i\}$.

If $X_0 \neq i$, T_i is the <u>first time the chain reaches</u> i. If $X_0 = i$, T_i is the <u>first time the chain returns</u> to i. In the above, $\inf \emptyset = \infty$, so that $T_i = \infty$ corresponds to the chain never hitting/returning to i.

Exercise 2.3. T_i is a stopping time.

Exercise 2.4. Let $i \neq j$. Show that $i \to j$ if and only if $\mathbb{P}^i\{T_j < \infty\} > 0$.

Definition 2.5. A state i is *recurrent* if $\mathbb{P}^i\{T_i < \infty\} = 1$. It is *transient* otherwise.

We can extend the definition of T_i as follows: let $T_i^1 = T_i$ and

$$T_i^{n+1} = \inf\left\{k > T_i^n \colon X_k = i\right\}.$$

That is, T_i^n is the n-th time the Markov chain visits i.

Exercise 2.6. T_i^n is a stopping time for each $n \geq 1$.

Definition 2.7. The *total number of returns* to i is

$$N_i = \left|\{n \colon T_i^n < \infty\}\right| = \left|\{n \geq 1 \colon X_n = i\}\right|.$$

Proposition 2.8. *Let i be a given state and define $p = P^i\{T_i < \infty\}$. Then,*

$$\mathbb{P}^i\left\{N_i \geq n\right\} = p^n.$$

In particular, if $X_0 = i$ then

- *$N_i = \infty$ a.s. if i is recurrent and*
- *$\mathbb{E}^i[N_i] = \frac{p}{1-p}$ if i is transient.*

Proof. Let $p^{(n)} = \mathbb{P}^i\{N_i \geq n\}$. Note that

$$N_i \geq n \iff T_i^n < \infty.$$

Therefore, $p^{(1)} = p$ by definition. Now, suppose $p^{(k)} = p^k$ for $k = 1, 2, \ldots, n$. If $T_i^n < \infty$, then $X_{T_i^n} = i$. Therefore, by the strong Markov property, $(X_{T_i^n+n})_{n\geq 0}$ is a Markov chain with the same transition matrix as $(X_n)_{n\geq 0}$. Therefore,

$$\mathbb{P}^i(N_i \geq n+1) = \mathbb{P}^i(N_i \geq n)p.$$

Equivalently, $p^{(n+1)} = p^{(n)}p = p^n p = p^{n+1}$. This establishes that

$$p^{(n)} = p^n$$

for all $n \geq 1$. Now, note that

$$\mathbb{E}^i\left[N_i\right] = \sum_{k\geq 1} \mathbb{P}^i\left\{N_i \geq n\right\} = \sum_{k\geq 1} p^k = \left(\sum_{k\geq 0} p^k\right) - 1 = \frac{1}{1-p} - 1 = \frac{p}{1-p}.$$

□

Remark 2.9.

1. If the chain starts at a recurrent state, it returns to that state infinitely often.
2. The claim
$$\mathbb{E}^i\left[N_i\right] = \frac{p}{1-p}$$
is actually true even when i is recurrent under the interpretation $1/(1-p) = \infty$. Therefore,
$$\begin{aligned} i \text{ is transient} &\iff \mathbb{E}^i\left[N_i\right] < \infty \\ i \text{ is recurrent} &\iff \mathbb{E}^i\left[N_i\right] = \infty. \end{aligned}$$

We can express the above just using the transition matrix P.

Proposition 2.10. *A state i is recurrent if and only if $\sum_{n\geq 0}(P^n)_{ii} = \infty$.*

Proof. This is just a consequence of $(P^n)_{ii} = \mathbb{P}(X_n = i \mid X_0 = i)$. Since $N_i = \sum_{n\geq 1} I_{\{X_n=i\}}$, it follows that
$$\mathbb{E}^i\left[N_i\right] = \mathbb{E}^i\left[\sum_{n\geq 1} I_{\{X_n=i\}}\right] = \sum_{n\geq 1}\mathbb{E}^i\left[I_{\{X_n=i\}}\right] = \sum_{n\geq 1}(P^n)_{ii}.$$
□

Corollary 2.11. *A state i is transient if and only if $\sum_{n\geq 0}(P^n)_{ii} < \infty$.*

Corollary 2.12. *If $i \to j$ and i is recurrent, then $i \leftrightarrow j$, $\mathbb{P}^j\{T_i < \infty\} = 1$, and j is recurrent.*

Proof. Since $i \to j$, $\mathbb{P}^i\{T_j < \infty\} > 0$. Therefore, if $\mathbb{P}^j\{T_i < \infty\} < 1$, then we obtain a contradiction to $\mathbb{E}^i[N_i] = \infty$.

Therefore, we can find r and s such that $(P^r)_{ij} > 0$ and $(P^s)_{ji} > 0$ (since $i \leftrightarrow j$). Then, for any n,
$$(P^{s+n+r})_{jj} = \sum_{k,\ell}(P^s)_{jk}(P^n)_{k\ell}(P^r)_{\ell j} \geq (P^s)_{ji}(P^n)_{ii}(P^r)_{ij}.$$
Therefore,
$$\sum_n (P^n)_{jj} \geq \sum_n (P^{s+n+r})_{jj} = (P^s)_{ji}(P^r)_{ij}\sum_n (P^n)_{ii}$$
Now, since $(P^s)_{ji}(P^r)_{ij} > 0$, then j is recurrent since $\sum_n (P^n)_{ii} = \infty$. □