Lecture notes of Stochastic Process

lectured by prof. Hsueh-I Lu

pishen

AlgoLab, CSIE, NTU

March 25, 2012

Limiting Probabilities

Outline

1. Limiting probabilities
2. Stationary distribution
3. Long-run proportion
4. (Inverse of) Expected return time

Limiting Probabilities

Definition

Number π_j is the *limiting probability* of j if

$$\pi_j = \lim_{n \to \infty} P_{ij}^n$$

holds for all states $i \in S$ ($S \subseteq \mathbb{N}$ is the state space).

- π_j is independent of i.
- $\lim_{n \to \infty} P^n = \begin{pmatrix} \pi \\ \pi \\ \vdots \end{pmatrix}$, where $\pi = (\pi_1, \pi_2, \ldots)$

Stationary Probability Distribution

Definition

Non-negative row vector $\pi = (\pi_1, \pi_2, \ldots)$ is a *stationary probability distribution* of $\mathbb{X}$ if $\pi \times P = \pi$ holds and $\sum_{i \in S} \pi_i = 1$

- π is a normalized left eigenvector with eigenvalue $= 1$.
- If $X(0)$ has distribution π, then $X(t)$ has the same distribution π for all $t \geq 1$. π is also called as *steady-state distribution*.
- It doesn't mean that each $X(t)$ become independent. π only means the distribution of $X(t)$ when the previous random variable's value is unknown.

Theorem 1

Theorem

Let $\mathbb{X}$ be an irreducible, aperiodic, positive recurrent Markov chain, then

- *The limiting probability π_j of each state j exists.*
- *$\pi = (\pi_1, \pi_2, \ldots)$ is the unique stationary probability distribution.*

- The proof will be stated later.

Expected return time

Definition

The *expected return time* of state $i \in S$ is

$$\mu_i = \sum_{n \geq 1} n \cdot f_i^{(n)}$$

where

$$f_i^{(n)} = P(\min\{t : X(t) = i, t \geq 1\} = n | X(0) = i)$$

- $f_i = \sum_{n \geq 1} f_i^{(n)}$

Positive recurrent & null recurrent

Definition

State i is *positive recurrent* if $\mu_i < \infty$

Definition

State i is *null recurrent* if $\mu_i = \infty$

- Both are recurrent states, and are *class properties*, which means that if state i and j communicate, they will share this property.
- If $\mathbb{X}$ is finite, then each recurrent state of $\mathbb{X}$ is positive recurrent. Proof stated at page 45.

Example of null recurrent

Example

For a Markov chain with n states $(1, \ldots, n)$, if

$$P(X(t+1) = i+1 | X(t) = i) = 1 - 1/n$$

and

$$P(X(t+1) = 1 | X(t) = i) = 1/n$$

According to geometric distribution (taking $p = 1/n$), the expectation value of "steps taken for state 1 to come back" will be $1/p = n$, hence $\lim_{n \to \infty} n = \infty$.

Period of a chain

Definition

The *period* of state i is d if d is the largest integer such that

$$P_{ii}^n = 0$$

holds for all n which is not divisible by d.

Definition

If each state of $\mathbb{X}$ has period 1, then $\mathbb{X}$ is called *aperiodic*.

- If $P_{ii} > 0$ for all $i \in S$, then $\mathbb{X}$ is aperiodic.
- Period can be seen as the gcd of all n that have $P_{ii}^n > 0$, note that $P_{ii}^{\text{gcd}} > 0$ is not necessary.
- The period of drunken man problem is 2.

Lemma 1

Lemma

If state j is aperiodic and positive recurrent, then

$$\pi_j \equiv \lim_{n\to\infty} P_{ij}^n$$

exists and is positive for all states $i \in S$.

- This can be proved by the Blackwell theorem in Renewal theory.
- It doesn't promise that each π_j for different i will be the same. But they will be the same if we add the irreducible property.

Property of lim

- The position of lim cannot be switched arbitrarily in an equation.

Example

$$1 = \lim_{n\to\infty} \lim_{m\to\infty} \frac{m}{m+n} \neq \lim_{m\to\infty} \lim_{n\to\infty} \frac{m}{m+n} = 0$$

- lim would not influence the inequality.

Example

If $f(n) \geq g(n)$, then $\lim_{n\to\infty} f(n) \geq \lim_{n\to\infty} g(n)$

Property of lim (cont.)

- lim is linear operator under finite number of functions.

Example

For $m < \infty$,

$$\sum_{i=1}^{m} \lim_{n\to\infty} f_i(n) = \lim_{n\to\infty} \sum_{i=1}^{m} f_i(n)$$

- It may not work if we push m to ∞ first, since $\sum_{i=1}^{m} f_i(n)$ may influence the result. For example, if $1 \leq i \leq n$, $f_i(n) = 1/n$, then LHS will be 0, while RHS will be 1. But pushing m to ∞ after pushing n to ∞ first is OK.

Inequality 1

Inequality

$$\sum_{j \in S} \pi_j \leq 1$$

Proof.

$$\lim_{m\to\infty}\sum_{j=1}^{m}\pi_j = \lim_{m\to\infty}\sum_{j=1}^{m}\lim_{n\to\infty}P_{ij}^{n}$$
$$= \lim_{m\to\infty}\lim_{n\to\infty}\sum_{j=1}^{m}P_{ij}^{n}$$
$$\leq \lim_{m\to\infty}\lim_{n\to\infty}\sum_{j\in S}P_{ij}^{n} = 1$$

□

- The last equation works since $\sum_{j\in S}P_{ij}^{n} = 1$.

Inequality 2

Inequality

For state $j \in S$, we have

$$\pi_j \geq \sum_{i \in S} \pi_i P_{ij}$$

Proof.

For $m \geq 1$ and $n \geq 1$,

$$P_{ij}^{n+1} = \sum_{k \in S} P_{ik}^n P_{kj} \geq \sum_{k=1}^{m} P_{ik}^n P_{kj}$$

then

$$\begin{aligned}
\pi_j &= \lim_{n \to \infty} P_{ij}^{n+1} \\
&\geq \lim_{n \to \infty} \sum_{k=1}^{m} P_{ik}^n P_{kj} = \sum_{k=1}^{m} \lim_{n \to \infty} P_{ik}^n P_{kj} = \sum_{k=1}^{m} \pi_k P_{kj}
\end{aligned}$$

hence, we know

$$\lim_{m \to \infty} \sum_{k=1}^{m} \pi_k P_{kj} = \sum_{k \in S} \pi_k P_{kj} \leq \pi_j$$

□

Equality 1

Equality

$$\pi_j = \sum_{i \in S} \pi_i P_{ij}$$

Proof.

Assume that for some $j \in S$, $\pi_j > \sum_{i \in S} \pi_i P_{ij}$, then

$$\sum_{j \in S} \pi_j > \sum_{j \in S} \sum_{i \in S} \pi_i P_{ij}$$
$$= \sum_{i \in S} \pi_i \sum_{j \in S} P_{ij} = \sum_{i \in S} \pi_i$$

Since a value cannot be greater than itself, we got contradiction. $\square$

- $\sum$ should be represented by $\lim \sum$, the equation will still work.

Proof of theorem 1

- **Step 0**: existence of limiting probability.
- **Step 1**: existence of stationary probability distribution.
- **Step 2**: uniqueness.

0. Existence of limiting probability

Proof.

By lemma 1, we know that there exists a π_j for row i. Since the Markov chain is irreducible and all the states are positive recurrent, for any state i' other than i, we know that i' surely will visit i in finite steps. Therefore, the π_j value at row i' will equal to the π_j value at row i, which means that all the π_j for column j are the same, and is the limiting probability. □

TODO: refine, check email

1. Existence of stationary probability distribution

We want to prove that

Target

There's a vector $s = (s_1, s_2, \ldots)$ *such that*

1. $\sum_{i \in S} s_i = 1$
2. $s \times P = s$

Proof.

By lemma 1, we know that there exists a $\pi = (\pi_1, \pi_2, \ldots)$.
And by equality 1, we know that

$$(\pi_1, \pi_2, \ldots) \times P = (\pi_1, \pi_2, \ldots)$$

Hence π can satisfy the 2nd part of our target.
Then, we take $k = \sum_{i \in S} \pi_i$. By inequality 1, we know that $k < \infty$, and can get

$$(\frac{\pi_1}{k}, \frac{\pi_2}{k}, \ldots) \times P = (\frac{\pi_1}{k}, \frac{\pi_2}{k}, \ldots)$$

where $\sum_{i \in S} \frac{\pi_i}{k} = 1$ also satisfy the 1st part of our target.
Therefore, this vector can be s, which means that it exists. $\square$

2. Uniqueness

Target

If $s = (s_1, s_2, \ldots)$ is a stationary distribution of $\mathbb{X}$, then $s = \pi$.

- We'll prove this by inequality 3 & 4.

Inequality 3

Inequality

$$s_j \geq \pi_j, \forall j \in S$$

Proof.

Let the distribution of $X(0)$ be s, by the property of stationary distribution, we have

$$\begin{aligned}
s_j = P(X(n) = j) &= \sum_{i \in S} P(X(n) = j | X(0) = i) P(X(0) = i) \\
&= \sum_{i \in S} P_{ij}^n \cdot s_i \\
&\geq \sum_{i=1}^{m} P_{ij}^n \cdot s_i \\
\Rightarrow s_j &= \lim_{m \to \infty} \lim_{n \to \infty} s_j \\
&\geq \lim_{m \to \infty} \lim_{n \to \infty} \sum_{i=1}^{m} P_{ij}^n \cdot s_i = \lim_{m \to \infty} \sum_{i=1}^{m} \pi_j \cdot s_i = \pi_j
\end{aligned}$$

□

Inequality 4

Inequality

$$s_j \leq \pi_j, \forall j \in S$$

Proof.

Similar in the proof above, $\forall m, n \geq 1$, we have

$$
\begin{aligned}
s_j &= \sum_{i \in S} P_{ij}^n \cdot s_i \\
&\leq \sum_{i=1}^{m} P_{ij}^n \cdot s_i + \sum_{i=m+1}^{\infty} s_i \\
\Rightarrow s_j &= \lim_{m \to \infty} \lim_{n \to \infty} s_j \\
&\leq \lim_{m \to \infty} \lim_{n \to \infty} \left(\sum_{i=1}^{m} P_{ij}^n \cdot s_i + \sum_{i=m+1}^{\infty} s_i \right) \\
&= \pi_j
\end{aligned}
$$

□

An example Markov chain

Example

$$P = \begin{pmatrix} \alpha & 1-\alpha \\ \beta & 1-\beta \end{pmatrix}, 0 < \alpha, \beta < 1$$

$$\pi = \left(\frac{\beta}{1+\beta-\alpha}, \frac{1-\alpha}{1+\beta-\alpha}\right)$$

Real world example: Hardy-Weinberg Law

Example

There're two kinds of allele:

- dominant: **A**
- recessive: **a**

And three kinds of senotype with population proportion as follow:

- AA: p
- aa: q
- Aa: $r = 1 - (p + q)$

Example (cont.)

$$
P = \begin{array}{c} \\ AA \\ aa \\ Aa \end{array}
\begin{array}{c}
\begin{array}{ccc} AA & aa & Aa \end{array} \\
\begin{pmatrix}
p + \frac{r}{2} & 0 & q + \frac{r}{2} \\
0 & q + \frac{r}{2} & p + \frac{r}{2} \\
\frac{p}{2} + \frac{r}{4} & \frac{p}{2} + \frac{r}{4} & \frac{p+q+r}{2}
\end{pmatrix}
\end{array}
$$

we get $\pi = (p, q, r)$ when

- $p = \left(p + \frac{r}{2}\right)^2$
- $q = \left(q + \frac{r}{2}\right)^2$
- $r = 2\left(p + \frac{r}{2}\right)\left(q + \frac{r}{2}\right)$

Long-run proportion

Definition

We say that r_j is the *long-run proportion* of state $j \in S$ if

$$r_j = \lim_{n \to \infty} \frac{1}{n} \sum_{1 \le t \le n} P_{ij}^t$$

holds for each state $i \in S$.

- It represents the average appearance times of state j in the whole process.
- We will show that (in theorem 3) if $\mathbb{X}$ is irreducible, then the long-run proportion of all states exist.

Theorem 2

Theorem (type 1)

If r_j exists for each $j \in S$ and $\sum_{j \in S} r_j > 0$, then $r = (r_1, r_2, \ldots)$ is the unique stationary distribution of $\mathbb{X}$.

or

Theorem (type 2)

If r_j exists for each $j \in S$ and ***a stationary distribution exists****, then $r = (r_1, r_2, \ldots)$ is the unique stationary distribution of $\mathbb{X}$.*

Proof

Existence of stationary distribution in type 1:

Let

$$R = \begin{pmatrix} r \\ r \\ \vdots \end{pmatrix} = \lim_{n\to\infty} \frac{1}{n} \sum_{1\le t\le n} P^t$$

then

$$\begin{aligned} R \times P &= \lim_{n\to\infty} \frac{1}{n} \sum_{1\le t\le n} P^{t+1} \\ &= \lim_{n\to\infty} \frac{1}{n} \sum_{1\le t\le n} P^t + \lim_{n\to\infty} \frac{1}{n}(P^{n+1} - P) \\ &= R \end{aligned}$$

As stated later, $\sum_{j\in S} r_j \le 1$, hence by normalizing r, we prove that stationary distribution exist.

- $(\lim f(n)) \cdot g(n) = \lim f(n) \cdot g(n)$?

Proof (cont.)

Uniqueness:

Let π be an arbitrary stationary distribution, then

$$\begin{aligned} r &= \pi \times R \\ &= \pi \times \lim_{n\to\infty} \frac{1}{n} \sum_{1\le t\le n} P^t \\ &= \lim_{n\to\infty} \frac{1}{n} \sum_{1\le t\le n} \pi \times P^t \\ &= \lim_{n\to\infty} \frac{1}{n} \sum_{1\le t\le n} \pi \\ &= \pi \end{aligned}$$

Proof (cont.)

Prove that $\sum_{j \in S} r_j \leq 1$:

$$
\begin{aligned}
\sum_{j \in S} r_j &= \lim_{m \to \infty} \sum_{j=1}^{m} \lim_{n \to \infty} \frac{1}{n} \sum_{t=1}^{n} P_{ij}^{t} \\
&= \lim_{m \to \infty} \lim_{n \to \infty} \frac{1}{n} \sum_{t=1}^{n} \sum_{j=1}^{m} P_{ij}^{t} \\
&\leq \lim_{m \to \infty} \lim_{n \to \infty} \frac{1}{n} \sum_{t=1}^{n} \sum_{j \in S} P_{ij}^{t} \\
&= \lim_{m \to \infty} \lim_{n \to \infty} \frac{1}{n} \sum_{t=1}^{n} 1 = 1
\end{aligned}
$$

Example 1

On a highway, if we know the probability that

- A truck is followed by a truck: $1/4$
- A truck is followed by a car: $3/4$
- A car is followed by a truck: $1/5$
- A car is followed by a car: $4/5$

We can construct a matrix

$$\begin{array}{cc} & \begin{array}{cc} T & C \end{array} \\ \begin{array}{c} T \\ C \end{array} & \begin{pmatrix} 1/4 & 3/4 \\ 1/5 & 4/5 \end{pmatrix} \end{array}$$

and get the portion of trucks and cars on the whole highway as the eigenvector $(4/19, 15/19)$ (we will know that long-run proportion exists by Theorem 3).

Example 2

For a system which has several good and bad states, we have a matrix P:

$$\begin{array}{c|cccccc} & g_1 & g_2 & \cdots & b_1 & b_2 & \cdots \\ \hline \begin{matrix} g_1 \\ g_2 \\ \vdots \\ b_1 \\ b_2 \\ \vdots \end{matrix} & \multicolumn{6}{c}{\left(\begin{matrix} & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \end{matrix}\right)} \end{array}$$

Example 2 (cont.)

Q1: Breakdown rate (breakdown times / total time)
The long-run frequency of going to a bad state from a good state is

$$\sum_{i \in g} \sum_{j \in b} r_i P_{ij}$$

Example 2 (cont.)

Q2: The expected time μ_G (resp. μ_B) of staying in good (resp. bad) states once we reach a good (resp. bad) state?

Ans:

For each $t = 1, 2, \ldots$, let G_t (resp. B_t) be the length of the t-th good (resp. bad) phase of consecutive good (resp. bad) states. By the strong law of large numbers,

$$P\left(\lim_{t\to\infty} \frac{G_1 + B_1 + G_2 + B_2 + \cdots + G_t + B_t}{t} = \mu_G + \mu_B\right) = 1$$

Since the reciprocal of above is the breakdown rate, we get equation (1):

$$P\left(\sum_{i\in G}\sum_{j\in B} \pi_i P_{ij} = \frac{1}{\mu_G + \mu_B}\right) = 1$$

Example 2 (cont.)

Also, with probability 1, we get equation (2):

$$P\left(\sum_{i\in G} r_i = \lim_{t\to\infty} \frac{G_1 + G_2 + \cdots + G_t}{G_1 + B_1 + \cdots + G_t + B_t} = \frac{\mu_G}{\mu_G + \mu_B}\right) = 1$$

Then, by (2)/(1), we get that

$$P\left(\mu_G = \frac{\sum_{i\in G} r_i}{\sum_{i\in G}\sum_{j\in B} r_i P_{ij}}\right) = 1$$

- $\lim \frac{f(n)}{g(n)} = \frac{\lim f(n)}{\lim g(n)}$?

Theorem 3

Theorem

If $\mathbb{X}$ is irreducible, then the long-run proportion r_i exists with probability 1, moreover,

1. *If state i is positive recurrent (i.e. $0 < \mu_i < \infty$), then $P(r_i = \frac{1}{\mu_i}) = 1$.*
2. *If state i is null recurrent (i.e. $\mu_i = \infty$) or transient, then $P(r_i = 0) = 1$.*

Proof

Part 1:
Suppose $X(0) = i$, T_k is the number of steps required for the k-th i goes to $(k+1)$-st i, then by the strong law of large number,

$$P\left(\lim_{k\to\infty} \frac{T_1 + T_2 + \cdots + T_k}{k} = \mu_i\right) = 1$$
$$\Rightarrow P\left(r_i = \lim_{k\to\infty} \frac{k}{T_1 + T_2 + \cdots + T_k} = \frac{1}{\mu_i}\right) = 1$$

- $\lim(A/B) = \frac{1}{\lim(B/A)}$?

Proof (cont.)

Part 2:

1. If i is transient, i will only appear finite times in the long-run, hence

$$r_i = \frac{finite}{\infty} = 0$$

2. If i is null recurrent, μ_i is ∞, then

$$P\left(\lim_{k\to\infty} \frac{T_1 + T_2 + \cdots + T_k}{k} = \infty\right) = 1$$

$$P\left(r_i = \lim_{k\to\infty} \frac{k}{T_1 + T_2 + \cdots + T_k} = 0\right) = 1$$

(The first equation is not promised by the strong law of large number. But if it's not ∞, we can say that μ_i is not ∞, which is a contradiction.)

Example 1

Example (type 1)

If $\mathbb{X}$ is **irreducible** and finite, then $\mathbb{X}$ has no null recurrent states.

Example (type 2)

If $\mathbb{X}$ is finite, then $\mathbb{X}$ has no null recurrent states.

- Finite irreducible imply positive recurrent.

Proof

- **Type 1:**
  If there's a state which is null recurrent, by irreducible, all the states will be null recurrent. Then, all states have $P(r_i = 0) = 1$. By changing the proof in page 36 into finite states version, we know that $\sum r_i = 1$. So it's impossible for finite r_i, which are all close to 0, to sum up to 1.
- **Type 2:**
  If it's not irreducible, the finite set of communicated null recurrent states still form an irreducible and finite Markov chain, which can fit the requirement of type 1.

Example 2

Example

For an irreducible Markov chain $\mathbb{X}$ with infinite states, no state will be positive recurrent.

- Infinite irreducible imply no positive recurrent.

Proof

If all the states are positive recurrent, then by theorem 3, we know that all the $r_i > 0$ and is a finite value. We then set $r_{\min} = \epsilon \cdot \min(r_1, r_2, \ldots)$ $(0 < \epsilon < 1)$ such that $r_i > r_{\min} > 0, \forall i$. And get

$$\sum_{i \in S} r_i > \sum_{i \in S} r_{\min} = \infty > 1$$

which is contradiction to page 36.

Example 3: Grand Hotel

Example

There's a hotel, with N representing the number of newly occupied rooms each day (N is a poisson distribution with parameter λ). And the number of consecutive check-in days of each room is a geometric distribution with probability p (p is the probability of check-out). $X(t)$ is the number of occupied rooms in day t.

Q1: $P_{ij} = ?$

We set R_i as a binomial distribution with parameter $(i, 1-p)$, which represents the number of rooms which will remain occupied in the next day, then

$$\begin{aligned}
P_{ij} &= P(R_i + N = j) \\
&= \sum_{k \geq 0} P(R_i + N = j | R_i = k) P(R_i = k) \\
&= \sum_{k \geq 0} P(N = j - k) P(R_i = k) \\
&= \sum_{0 \leq k \leq \min(i,j)} \frac{e^{-\lambda} \cdot \lambda^{j-k}}{(j-k)!} \binom{i}{k} (1-p)^k p^{1-k}
\end{aligned}$$

Q2: $r_i =?$

We guess there's a stationary distribution which is a poisson distribution with parameter λ_0. Setting $X(0)$ with this distribution. And let R as the number of rooms in $X(0)$ which remain check-in in the next day (R is a poisson distribution with parameter $\lambda_0(1-p)$). $X(1)$ will have distribution $R+N$, which is a poisson distribution with parameter $\lambda_0(1-p)+\lambda$. Then since $X(0)$ is a stationary distribution, it will have the same distribution with $X(1)$, which means that $\lambda_0 = \lambda_0(1-p)+\lambda$, and we get $\lambda_0 = \lambda/p$.