MATH180C: Introduction to Stochastic Processes II

Lecture A00: math-old.ucsd.edu/~ynemish/teaching/180cA
Lecture B00: math-old.ucsd.edu/~ynemish/teaching/180cB

Today: Limiting behavior

Next: Review

Week 4:

- homework 3 (due Saturday, April 23)
- Midterm 1: Friday, April 22

Forward and backward equations for B&D processes

Example Linear growth with immigration.

Recall $\lambda_k = \lambda \cdot k + a$ ← immigration
↑ linear birth rate

$\mu_k = \mu \cdot k$
↑ linear death rate

Compute $M(t) = \mathbb{E}(X_t \mid X_0 = i)$

$$\begin{cases} M'(t) = (\lambda-\mu) M(t) + a \\ M(0) = i \end{cases}$$

$$M(t) = i + at \quad \text{if } \lambda = \mu$$

$$M(t) = \frac{a}{\lambda-\mu}\left(e^{(\lambda-\mu)t} - 1\right) + i e^{(\lambda-\mu)t} \quad \text{if } \lambda \neq \mu$$

Long run behavior of discrete time MC. Summary

Let $(X_n)_{n\geq 0}$ be a disrete time MC on $\{0, \dots, N\}$ with stationary transition probability matrix $P = (P_{ij})_{i,j=0}^{N}$.

- P is called regular if there exists k such that $[P^k]_{ij} > 0$ for all i,j. [P is regular iff (X_n) is irreducible and aperiodic]

Thm. If P is regular, then there exist $\pi_0, \dots, \pi_N \in \mathbb{R}$ s.t.

1) $\pi_i > 0 \quad \forall i$
2) $\sum_{i=0}^{N} \pi_i = 1$
3) $\forall j \quad \lim_{n\to\infty} P_{ij}^{(n)} = \pi_j$

$(\pi_0, \dots, \pi_N)$ is called limiting (stationary) distribution of (X_n)

$(\pi_0, \dots, \pi_N)$ is uniquely defined by the system of equations

$$\begin{cases} \pi_j = \sum_{i=0}^{N} \pi_i P_{ij}, \\ \sum_{i=0}^{N} \pi_i = 1 \end{cases} \qquad (\pi_0, \pi_1, \dots, \pi_N) = (\pi_0, \dots, \pi_N) P$$

$$P = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$\pi = \left(\frac{1}{2}, \frac{1}{2}\right)$

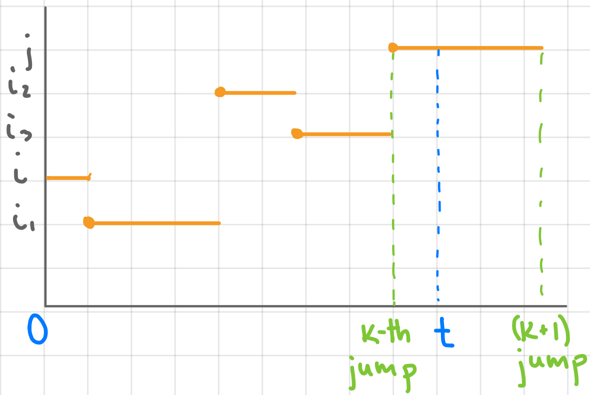
Long run behavior of continuous time MC.

Let $(X_t)_{t\geq 0}$ be a continuous time MC, $X_t \in \{0, \dots, N\}$ and let $(Y_n)_{n\geq 0}$ be the embedded jump chain.

<u>Def</u>. $(X_t)_{t\geq 0}$ is called irreducible if its jump chain $(Y_n)_{n\geq 0}$ is irreducible (consisting of one communicating class)

<u>Thm</u>. If $(X_t)_{t\geq 0}$ is irreducible, then

$$P_{ij}(t) > 0 \text{ for any } i,j \text{ and } t>0$$



Idea of the proof:

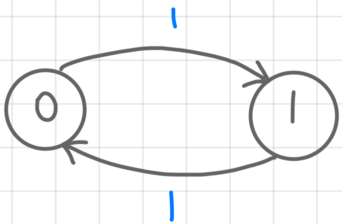
- Y_n is irreducible $\Rightarrow \exists\ i_1, \dots, i_{k-1}$ s.t. $P(Y_k = j, Y_{k-1} = i_{k-1}, \dots, Y_1 = i_1 \mid Y_0 = i) > 0$
- $P(k\text{-th jump} \leq t < (k+1)\text{-th jump}) > 0 \quad \forall t > 0$

Long run behavior of continuous time MC

Remarks: Continuous time MCs are "aperiodic"

All irreducible continuous time MCs are "regular"

Example.



(Y_n) has period 2

$$P(X_t=0 \mid X_0=0) \geq P(S_0>t) = e^{-t}$$

Thm. If $(X_t)_{t\geq 0}$ is irreducible, then there exists $\pi_0, \dots, \pi_N$

1) $\pi_i > 0$, $\sum_{i=0}^{N} \pi_i = 1$

2) $\lim_{t\to\infty} P_{ij}(t) = \pi_j$ for all i

$$\lim_{t\to\infty} P(t) = \begin{pmatrix} \pi_0 & \pi_1 & \cdots & \pi_N \\ \pi_0 & \pi_1 & & \pi_N \\ \vdots & \vdots & & \vdots \\ \pi_0 & \pi_1 & & \pi_N \end{pmatrix}$$

3) $\pi = (\pi_0, \dots, \pi_N)$ is uniquely determined by $\pi Q = 0$ and 1)

π is called limiting/stationary/equilibrium distribution of (X_t)

Long run behavior of continuous time MC

Remark about 3): $\pi Q = 0$ is equivalent to $\pi P(t) = \pi \quad \forall t$

($\Rightarrow$) If $\pi Q = 0$, then using Kolmogorov backward equation

$$(\pi P(t))' = \pi P'(t) \overset{K-B}{=} \pi Q P(t) = 0$$

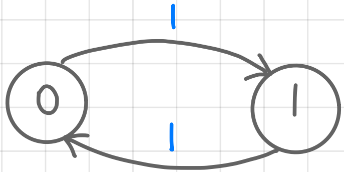
so $\pi P(t)$ is independent of t. Since $P(0) = I$, we get

$$\forall t \qquad \pi P(t) = \pi P(0) = \pi$$

($\Leftarrow$) If $\pi P(t) = \pi$, then $(\pi P(t))' = 0$. Using Kolmogorov forward equation

$$0 = (\pi P(t))' = \pi P'(t) \overset{K-F}{=} \pi P(t) Q = \pi Q$$

Example : Two-state MC



$$Q = \begin{pmatrix} -1 & 1 \\ 1 & -1 \end{pmatrix}$$

$$\pi Q = 0$$

$$\begin{cases} -\pi_0 + \pi_1 = 0 \\ \pi_0 - \pi_1 = 0 \\ \pi_0 + \pi_1 = 1 \end{cases}$$

$$\pi_0 = \pi_1$$

$$\pi_0 + \pi_0 = 1$$

$$\Rightarrow \pi_0 = \pi_1 = \frac{1}{2}$$

From Lecture 7 : if $Q = \begin{pmatrix} -\alpha & \alpha \\ \beta & -\beta \end{pmatrix}$, then

$$P(t) = I + \frac{1}{\alpha+\beta} Q - \frac{1}{\alpha+\beta} e^{-(\alpha+\beta)t} Q \to I + \frac{1}{\alpha+\beta} Q$$

. If $\alpha = \beta = 1$

$$\lim_{t \to \infty} P(t) = \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{pmatrix}$$

Note, that the jump process (Y_n) does not have limiting distribution! $\tilde{P}^{Y_n} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$

Long run behavior of discrete time MC. Summary (2)

Let $(X_n)_{n\geq 0}$ be a disrete time MC on $\{0, 1, \dots\}$ with stationary transition probability matrix $P = (P_{ij})_{i,j=0}^{\infty}$

Define $R_i = \min\{n : X_n = i\}$, $m_i = E(R_i \mid X_0 = i)$ mean duration between visits

<u>Thm.</u> If $(X_n)_{n\geq 0}$ is recurrent irreducible aperiodic, then

$$\lim_{n\to\infty} P_{ij}^{(n)} = \frac{1}{m_j} \quad \forall j$$

If $\lim_{n\to\infty} P_{ij}^{(n)} > 0$ for some (all) j, then MC is positive recurrent

$\lim_{n\to\infty} P_{ij}^{(n)} = 0$ for some (all) j, then MC is null recurrent.

If (X_n) is positive recurrent, $(\pi_j)_{j=0}^{\infty}$, $\pi_j = \lim_{n\to\infty} P_{ij}^{(N)}$ is called stationary distribution, uniquely determined by

$$\pi_j = \sum_{i=0}^{\infty} \pi_i P_{ij} \quad \forall j, \quad \sum_{i=0}^{\infty} \pi_i = 1, \quad \pi_i > 0$$

Long run behavior of continuous time MC (2)

Let $(X_t)_{t\geq 0}$ be a continuous time MC, $X_t \in \{0,1,\dots\}$ and let $(Y_n)_{n\geq 0}$ be the embedded jump chain.

Define $R_i = \min\{t > S_0 : X_t = i\}$,

$m_i = E(R_i \mid X_0 = i)$ — mean return time from i to i

If $m_i < \infty$, then i is positive recurrent (class property).

<u>Thm</u> 1) If $(X_t)_{t\geq 0}$ is irreducible, then

$$\lim_{t\to\infty} P_{ij}(t) = \frac{1}{q_j m_j} =: \pi_j \geq 0$$

2) $(X_t)_{t\geq 0}$ is positive recurrent iff there exists a (unique) solution $(\pi_j')_{j=0}^{\infty}$ to $\sum_{i=0}^{\infty} \pi_i' q_{ij} = 0$, $\sum_{i=0}^{\infty} \pi_i' = 1$, $\pi_i' > 0 \ \forall i$

in which case $\pi_j = \pi_j'$ and $(\pi_j)_{j=0}^{\infty}$ is called limiting/stationary distribution.

Remarks

1) Until now we discussed only the transition probabilities. But in order to describe completely MC (X_t) we need also the initial / starting distribution

$$\nu = (\nu_0, \nu_1, \dots), \quad \nu_i = P(X_0 = i)$$

$$(X_t) \longleftrightarrow (\nu, Q)$$

2) Distribution of X_{t_1} is given by $\nu P(t_1)$

$$P(X_{t_1} = i) = [\nu P(t_1)]_i = \sum_{k=0}^{\infty} P_{ki}(t_1)\nu_k$$

More generally

$$P(X_0 = i_0, X_{t_1} = i_1, \dots, X_{t_n} = i_n) = P_{i_{n-1}, i_n}(t_n - t_{n-1}) \cdots P_{i_0, i_1}(t_1) \cdot \nu_{i_0}$$

3) Stationary distribution remains unchaged in time

$$\pi P(t) = \pi \Rightarrow \text{ if } X_0 \sim \pi, \text{ then } X_t \sim \pi$$

Remarks

4) Similarly as in the discrete case, π_j gives the fraction of time spent in state j in long run

$$\lim_{T\to\infty} E\left(\frac{1}{T} \int_0^T \mathbb{1}_{\{X_t = j\}}\, dt \,\middle|\, X_0 = i \right) = \pi_j$$

(compare with $\lim_{m\to\infty} E\left[\frac{1}{m} \sum_{n=0}^{m-1} \mathbb{1}_{\{X_n = j\}} \,\middle|\, X_0 = i \right] = \pi_j$ for discrete time MC)

5) If we can find $(\pi_i)_{i=0}^{\infty}$ such that $\pi_i q_{ij} = \pi_j q_{ji}$ then $(\pi_i)_{i=0}^{\infty}$ satisfies $\pi Q = 0$

Indeed, $\sum_{j=0}^{\infty} \pi_i q_{ij} = \pi_i \sum_{j=0}^{\infty} q_{ij} = 0 = \sum_{j=0}^{\infty} \pi_j q_{ji} = (\pi Q)_i$

What you should know for midterm 1 (minimum):

- definition of continuous time MC, Markov property, transition probabilities, generator
- representations of MC: infinitesimal (generator), jump-and-hold, transition probabilities, rate diagram and relations between them (in particular Q and $P(t)$)
- computing absorption probabilities and mean time to absorption
- computing stationary distributions for finite and infinite state MCs and interpretation of $(\pi_i)_{i=0}^{\infty}$
- basic properties of birth and death processes