Markov Chains

Stochastic process: family $\{X_i; i \in I\}$ of rvs I the **index set**. Often $I \subset \mathbb{R}$, e.g. $[0, \infty)$, $[0, 1]$ $\mathbb{Z}$ or $\mathbb{N}$.

Continuous time: I is an interval

Discrete time: $I \subset \mathbb{Z}$.

Generally all X_n take values in **state space** S. In following S is a finite or countable set; each X_n is discrete.

Usually S is $\mathbb{Z}$, $\mathbb{N}$ or $\{0, \ldots, m\}$ for some finite m.

Markov Chain: stochastic process $X_n; n \in \mathbb{N}$. taking values in a finite or countable set S such that for every n and every event of the form

$$A = \{(X_0, \ldots, X_{n-1}) \in B \subset S^n\}$$

we have

$$P(X_{n+1} = j | X_n = i, A) = P(X_1 = j | X_0 = i) \tag{1}$$

Notation: $\mathbf{P}$ is the (possibly infinite) array with elements

$$P_{ij} = P(X_1 = j | X_0 = i)$$

indexed by $i, j \in S$.

$\mathbf{P}$ is the (one step) **transition matrix** of the Markov Chain.

WARNING: in (1) we require the condition to hold **only** when

$$P(X_n = i, A) > 0$$

Evidently the entries in $\mathbf{P}$ are non-negative and

$$\sum_j P_{ij} = 1$$

for all $i \in S$. Any such matrix is called **stochastic**.

We define powers of $\mathbf{P}$ by

$$(\mathbf{P}^n)_{ij} = \sum_k \left(\mathbf{P}^{n-1}\right)_{ik} P_{kj}$$

Notice that even if S is infinite these sums converge absolutely.

Chapman-Kolmogorov Equations

Condition on X_{l+n-1} to compute

$$P(X_{l+n} = j | X_l = i)$$

$$\begin{aligned}
P(X_{l+n} &= j | X_l = i) \\
&= \sum_k P(X_{l+n} = j, X_{l+n-1} = k | X_l = i) \\
&= \sum_k P(X_{l+n} = j | X_{l+n-1} = k, X_l = i) \\
&\qquad \times P(X_{l+n-1} = k | X_l = i) \\
&= \sum_k P(X_1 = j | X_0 = k) \\
&\qquad \times P(X_{l+n-1} = k | X_l = i) \\
&= \sum_k P(X_{l+n-1} = k | X_l = i) \mathbf{P}_{kj}
\end{aligned}$$

Now condition on X_{l+n-2} to get

$$P(X_{l+n} = j | X_l = i) = \sum_{k_1 k_2} \mathbf{P}_{k_1 k_2} \mathbf{P}_{k_2 j} P(X_{l+n-2} = k_1 | X_l = i)$$

Notice: sum over k_2 computes k_1, j entry in matrix $\mathbf{PP} = \mathbf{P}^2$.

$$P(X_{l+n} = j | X_l = i) = \sum_{k_1} (\mathbf{P}^2)_{k_1,j} P(X_{l+n-2} = k_1 | X_l = i)$$

We may now prove by induction on n that

$$P(X_{l+n} = j | X_l = i) = (\mathbf{P}^n)_{ij} \,.$$

This proves Chapman-Kolmogorov equations:

$$P(X_{l+m+n} = j | X_l = i) = \sum_k P(X_{l+m} = k | X_l = i) \times P(X_{l+m+n} = j | X_{l+m} = k)$$

These are simply a restatement of the identity

$$\mathbf{P}^{n+m} = \mathbf{P}^n \mathbf{P}^m \,.$$

Remark: It is important to notice that these probabilities depend on m and n but **not** on l. We say the chain has **stationary** transition probabilities. A more general definition of Markov chain than (1) is

$$P(X_{n+1} = j | X_n = i, A) \\ = P(X_{n+1} = j | X_n = i)\,.$$

Notice RHS now permitted to depend on n.

Define $\mathbf{P}^{n,m}$: matrix with i, jth entry

$$P(X_m = j | X_n = i)$$

for $m > n$. Then

$$\mathbf{P}^{r,s}\mathbf{P}^{s,t} = \mathbf{P}^{r,t}$$

Also called Chapman-Kolmogorov equations. This chain does not have stationary transitions.

Remark: The calculations above involve sums in which all terms are positive. They therefore apply even if the state space S is countably infinite.

Extensions of the Markov Property

Function $f(x_0, x_1, \ldots)$ defined on S^∞ = all infinite sequences of points in S.

Let B_n be the event

$$f(X_n, X_{n+1}, \ldots) \in C$$

for suitable C in range space of f. Then

$$P(B_n | X_n = x, A) = P(B_0 | X_0 = x) \qquad (2)$$

for any event A of the form

$$\{(X_0, \ldots, X_{n-1}) \in D\}$$

Also

$$P(AB_n | X_n = x) = P(A | X_n = x) P(B_n | X_n = x) \qquad (3)$$

"Given the present the past and future are conditionally independent."

Proof of (2):

Special case:

$$B_n = \{(X_n = x, X_{n+1} = x_1, \cdots, X_{n+m} = x_m\}$$

LHS of (2) evaluated by repeated conditioning (cf. Chapman-Kolmogorov):

$$\mathbf{P}_{x,x_1}\mathbf{P}_{x_1,x_2}\cdots\mathbf{P}_{x_{m-1},x_m}$$

Same for RHS.

Events defined from $X_n, \ldots, X_{n+m}$: sum over appropriate vectors $x, x_1, \ldots, x_m$.

General case: monotone class techniques.

To prove (3) write

$$\begin{aligned} P(AB_n|X_n = x) & \\ &= P(B_n|X_n = x, A)P(A|X_n = x) \\ &= P(B_n|X_n = x)P(A|X_n = x) \end{aligned}$$

using (2).

Classification of States

If an entry $\mathbf{P}_{ij}$ is 0 it is not possible to go from state i to state j in one step. It may be possible to make the transition in some larger number of steps, however. We say i **leads to** j (or j is accessible from i) if there is an integer $n \geq 0$ such that

$$P(X_n = j | X_0 = i) > 0 \, .$$

We use the notation $i \rightsquigarrow j$. Define $\mathbf{P}^0$ to be identity matrix $\mathbf{I}$. Then $i \rightsquigarrow j$ if there is an $n \geq 0$ for which $(\mathbf{P}^n)_{ij} > 0$.

States i and j **communicate** if $i \rightsquigarrow j$ and $j \rightsquigarrow i$.

Write $i {\leftrightarrow} j$ if i and j communicate.

Communication is an equivalence relation: reflexive, symmetric, transitive relation on states of S.

More precisely:

Reflexive: for all i we have $i \leftrightarrow i$.

Symmetric: if $i \leftrightarrow j$ then $j \leftrightarrow i$.

Transitive: if $i \leftrightarrow j$ and $j \leftrightarrow k$ then $i \leftrightarrow k$.

Proof:

Reflexive: follows from inclusion of $n = 0$ in definition of leads to.

Symmetry is obvious.

Transitivity: suffices to check that $i \rightsquigarrow j$ and $j \rightsquigarrow k$ imply that $i \rightsquigarrow k$. But if $(\mathbf{P}^m)_{ij} > 0$ and $(\mathbf{P}^n)_{jk} > 0$ then

$$\begin{aligned}(\mathbf{P}^{m+n})_{ik} &= \sum_l (\mathbf{P}^m)_{il}(\mathbf{P}^n)_{lk} \\ &\geq (\mathbf{P}^m)_{ij}(\mathbf{P}^n)_{jk} \\ &> 0\end{aligned}$$

Any equivalence relation on a set partitions the set into **equivalence classes**; two elements are in the same equivalence class if and only if they are equivalent.

Communication partitions S into equivalence classes called **communicating classes**.

Example:

$$\mathbf{P} = \begin{bmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & 0 & 0 & 0 & 0 \\ \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & 0 & 0 & 0 & 0 \\ \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & 0 & 0 & 0 & 0 \\ \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & 0 & 0 & 0 & 0 \\ \frac{1}{4} & \frac{1}{4} & 0 & 0 & \frac{1}{2} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

Find communicating classes: start with say state 1, see where it leads.

- $1 \rightsquigarrow 2$, $1 \rightsquigarrow 3$ and $1 \rightsquigarrow 4$ in row 1.

- Row 4: $4 \rightsquigarrow 1$. So: (transitivity) 1, 2, 3 and 4 all in the same communicating class.

- Claim: none of these leads to 5, 6, 7 or 8.

  Suppose $i \in \{1,2,3,4\}$ and $j \in \{5,6,7,8\}$. Then $(\mathbf{P}^n)_{ij}$ is sum of products of $\mathbf{P}_{kl}$. Cannot be positive unless there is a sequence $i_0 = i, i_1, \ldots, i_n = j$ with $\mathbf{P}_{i_{k-1},i_k} > 0$ for $k = 1, \ldots, n$.

  Consider first k for which $i_k \in \{5,6,7,8\}$ Then $i_{k-1} \in \{1,2,3,4\}$ and so $\mathbf{P}_{i_{k-1},i_k} = 0$.

So: $\{1, 2, 3, 4\}$ is a communicating class.

- $5 \rightsquigarrow 1$, $5 \rightsquigarrow 2$, $5 \rightsquigarrow 3$ and $5 \rightsquigarrow 4$.

- None of these lead to any of $\{5, 6, 7, 8\}$ so $\{5\}$ must be communicating class.

- Similarly $\{6\}$ and $\{7, 8\}$ are communicating classes.

Note: states 5 and 6 have special property. Each time you are in either state you run a risk of going to one of the states 1, 2, 3 or 4. Eventually you will make such a transition and then never return to state 5 or 6.

States 5 and 6 are **transient**.

To make this precise define hitting times:

$$T_k = \min\{n > 0 : X_n = k\}$$

We define

$$f_k = P(T_k < \infty | X_0 = k)$$

State k is **transient** if $f_k < 1$ and **recurrent** if $f_k = 1$.

Let N_k be number of times chain is ever in state k.

Claims:

1. If $f_k < 1$ then N_k has a Geometric distribution:
$$P(N_k = r | X_0 = k) = f_k^{r-1}(1 - f_k)$$
for $r = 1, 2, \ldots$.

2. If $f_k = 1$ then
$$P(N_k = \infty | X_0 = k) = 1$$

Proof using **Strong Markov Property**:

Stopping time for the Markov chain is a random variable T taking values in $\{0, 1, \cdots\} \cup \{\infty\}$ such that for each finite k there is a function f_k such that

$$1(T = k) = f_k(X_0, \ldots, X_k)$$

Notice that T_k in theorem is a stopping time.

Standard shorthand notation: by

$$P^x(A)$$

we mean

$$P(A|X_0 = x)\,.$$

Similarly we define

$$\mathsf{E}^x(Y) = \mathsf{E}(Y|X_0 = x)\,.$$

Goal: explain and prove

$$\mathsf{E}(f(X_T,\ldots)|X_T,\ldots,X_0) = \mathsf{E}^{X_T}(f(X_0,\ldots))$$

Simpler claim:

$$P(X_{T+1}=j|X_T=i) = \mathbf{P}_{ij} = P^i(X_1=j)\,.$$

Notation: $A_k = \{X_k = i, T = k\}$

Notice: $A_k = \{X_T = i, T = k\}$:

$$\begin{aligned}
P(X_{T+1}=j|X_T=i) &= \frac{P(X_{T+1}=j, X_T=i)}{P(X_T=i)} \\
&= \frac{\sum_k P(X_{T+1}=j, X_T=i, T=k)}{\sum_k P(X_T=i, T=k)} \\
&= \frac{\sum_k P(X_{k+1}=j, A_k)}{\sum_k P(A_k)} \\
&= \frac{\sum_k P(X_{k+1}=j|A_k)P(A_k)}{\sum_k P(A_k)} \\
&= \frac{\sum_k P(X_1=j|X_0=i)P(A_k)}{\sum_k P(A_k)} \\
&= \mathbf{P}_{i,j}
\end{aligned}$$

Notice use of fact that $T = k$ is event defined in terms of $X_0, \ldots, X_k$.

Technical problems with proof:

- It might be that $P(T = \infty) > 0$. What are X_T and X_{T+1} on the event $T = \infty$.

Answer: condition also on $T < \infty$.

- Prove formula only for stopping times where $\{T < \infty\} \cap \{X_T = i\}$ has positive probability.

We will now fix up these technical details.

Suppose $f(x_0, x_1, \ldots)$ is a (measurable) function on $S^{\mathbb{N}}$. Put

$$Y_n = f(X_n, X_{n+1}, \ldots) \, .$$

Assume $\mathsf{E}(\,|Y_0|\,|X_0 = x) < \infty$ for all x. Claim:

$$\mathsf{E}(Y_n | X_n, A) = \mathsf{E}^{X_n}(Y_0) \qquad (4)$$

whenever A is any event defined in terms of $X_0, \ldots, X_n$.

Proof:

1 Family of f for which claim holds includes all indicators; see extension of Markov Property in previous lecture.

2 family of f for which claim is true is vector space (so if f, g in family then so is $af + bg$ for any constants a and b.

- So family of f for which claim is true includes all simple functions.

- family of f for which claim true is closed under monotone increasing limits (of non-negative f_n) by the Monotone Convergence theorem.

- So claim true for every non-negative integrable f.

- Claim follows for integrable f by linearity.

Aside on "measurable": what sorts of events can be defined in terms of a family $\{Y_i : i \in I\}$?

Natural: any event of form $(Y_{i_1}, \ldots, Y_{i_k}) \in C$ is "defined in terms of the family" for any finite set $i_1, \ldots, i_k$ and any (Borel) set C in S^k.

For countable S: each singleton $(s_1, \ldots, s_k) \in S^k$ Borel. So every subset of S^k Borel.

Natural: if you can define each of a sequence of events A_n in terms of the Ys then the definition "there exists an n such that (definition of A_n)…" defines $\cup A_n$.

Natural: if A is definable in terms of the Ys then A^c can be defined from the Ys by just inserting the phrase "It is not true that" in front of the definition of A.

So family of events definable in terms of the family $\{Y_i : i \in I\}$ is a σ-field which includes every event of the form $(Y_{i_1}, \ldots, Y_{i_k}) \in C$. We call the smallest such σ-field, $\mathcal{F}(\{Y_i : i \in I\})$, the σ-field generated by the family $\{Y_i : i \in I\}$.

Using the Markov property:

Toss coin till I get a head. What is the expected number of tosses?

Define state to be 0 if toss is tail and 1 if toss is heads.

Define $X_0 = 0$.

Let $N = \min\{n > 0 : X_n = 1\}$. Want

$$\mathsf{E}(N) = \mathsf{E}^0(N)$$

Note: if $X_1 = 1$ then $N = 1$. If $X_1 = 0$ then $N = 1 + \min\{n > 0 : X_{n+1} = 1\}$.

In symbols:

$$N = \min\{n > 0 : X_n = 1\} = f(X_1, X_2, \cdots)$$

and

$$N = 1 + 1(X_1 = 0) f(X_2, X_3, \cdots)$$

Take expected values starting from 0:

$$\mathsf{E}^0(N) = 1 + \mathsf{E}^0\{1(X_1 = 0)f(X_2, X_3, \cdots)\}$$

Condition on X_1 and get

$$\mathsf{E}^0(N) = 1 + \mathsf{E}^0[\mathsf{E}\{1(X_1 = 0)f(X_2, \cdots)|X_1\}]$$

But

$$\begin{aligned}\mathsf{E}\{1(X_1 = 0)f(X_2, X_3, \cdots)|X_1\} \\ &= 1(X_1 = 0)\mathsf{E}^{X_1}\{f(X_1, X_2, \cdots)\} \\ &= 1(X_1 = 0)\mathsf{E}^0\{f(X_1, X_2, \cdots)\} \\ &= 1(X_1 = 0)\mathsf{E}^0(N)\end{aligned}$$

so that

$$\mathsf{E}^0(N) = 1 + p\mathsf{E}^0\{N\}$$

where p is the probability of tails. Solve for $\mathsf{E}(N)$ to get

$$\mathsf{E}(N) = \frac{1}{1-p}$$

This is the formula for expected value of the sort of geometric which starts at 1 and has p being the probability of failure.

Initial Distributions

Meaning of unconditional expected values?

Markov property specifies only cond'l probs; no way to deduce marginal distributions.

For every dstbn π on S and transition matrix $\mathbf{P}$ there is a a stochastic process $X_0, X_1, \ldots$ with

$$P(X_0 = k) = \pi_k$$

and which is a Markov Chain with transition matrix $\mathbf{P}$.

Note Strong Markov Property proof used only conditional expectations.

Notation: π a probability on S. E^π and P^π are expected values and probabilities for chain with initial distribution π.

Summary of easily verified facts:

- For any sequence of states $i_0, \ldots, i_k$

$$P(X_0 = i_0, \ldots, X_k = i_k) = \pi_{i_0} \mathbf{P}_{i_0 i_1} \cdots \mathbf{P}_{i_{k-1} i_k}$$

- For any event A:

$$\mathbf{P}^\pi(A) = \sum_k \pi_k \mathbf{P}^k(A)$$

- For any bounded rv $Y = f(X_0, \ldots)$

$$\mathsf{E}^\pi(Y) = \sum_k \pi_k \mathsf{E}^k(Y)$$

Recurrence and Transience

Now consider a transient state k, that is, a state for which

$$f_k = P^k(T_k < \infty) < 1$$

Note that $T_k = \min\{n > 0 : X_n = k\}$ is a stopping time. Let N_k be the number of visits to state k. That is

$$N_k = \sum_{n=0}^{\infty} 1(X_n = k)$$

Notice that if we define the function

$$f(x_0, x_1, \ldots) = \sum_{n=0}^{\infty} 1(x_n = k)$$

then

$$N_k = f(X_0, X_1, \ldots)$$

Notice, also, that on the event $T_k < \infty$

$$N_k = 1 + f(X_{T_k}, X_{T_k+1}, \ldots)$$

and on the event $T_k = \infty$ we have

$$N_k = 1$$

In short:

$$N_k = 1 + f(X_{T_k}, X_{T_k+1}, \ldots)1(T_k < \infty)$$

Hence

$$\begin{aligned}
&\mathbf{P}^k(N_k = r) \\
&\quad = \mathsf{E}^k \{P(N_k = r|\mathcal{F}_T)\} \\
&\quad = \mathsf{E}^k \Big[P\Big\{1 + f(X_{T_k}, X_{T_k+1}, \ldots) \\
&\qquad\qquad \times 1(T_k < \infty) = r|\mathcal{F}_T\}] \\
&\quad = \mathsf{E}^k [1(T_k < \infty) \\
&\qquad\qquad \times P^{X_{T_k}} \{f(X_0, X_1, \ldots) = r - 1\}\Big] \\
&\quad = \mathsf{E}^k \Big\{1(T_k < \infty)P^k(N_k = r - 1)\Big\} \\
&\quad = \mathsf{E}^k \{1(T_k < \infty)\} P^k(N_k = r - 1) \\
&\quad = f_k P^k(N_k = r - 1)
\end{aligned}$$

It is easily verified by induction, then, that

$$\mathbf{P}^k(N_k = r) = f_k^{r-1} P^k(N_k = 1)$$

But $N_k = 1$ if and only if $T_k = \infty$ so

$$\mathbf{P}^k(N_k = r) = f_k^{r-1}(1 - f_k)$$

so N_k has (chain starts from k) Geometric dist'n, mean $1/(1 - f_k)$. Argument also shows that if $f_k = 1$ then

$$P^k(N_k = 1) = P^k(N_k = 2) = \cdots$$

which can only happen if all these probabilities are 0. Thus if $f_k = 1$

$$P(N_k = \infty) = 1$$

Since

$$N_k = \sum_{n=0}^{\infty} 1(X_n = k)$$

$$\mathsf{E}^k(N_k) = \sum_{n=0}^{\infty} (\mathbf{P}^n)_{kk}$$

So: State k is transient if and only if

$$\sum_{n=0}^{\infty} (\mathbf{P}^n)_{kk} < \infty$$

and this sum is $1/(1 - f_k)$.

Proposition 1 *Recurrence (or transience) is a class property. That is, if i and j are in the same communicating class then i is recurrent (respectively transient) if and only if j is recurrent (respectively transient).*

Proof: Suppose i is recurrent and $i \leftrightarrow j$. There are integers m and n such that

$$(\mathbf{P}^m)_{ji} > 0 \quad \text{and} \quad (\mathbf{P}^n)_{ij} > 0$$

Then

$$\begin{aligned}
\sum_k (\mathbf{P}^k)_{jj} &\geq \sum_{k \geq 0} (\mathbf{P}^{m+k+n})_{jj} \\
&\geq \sum_{k \geq 0} (\mathbf{P}^m)_{ji} (\mathbf{P}^k)_{ii} (\mathbf{P}^n)_{ij} \\
&= (\mathbf{P}^m)_{ji} \left\{ \sum_{k \geq 0} (\mathbf{P}^k)_{ii} \right\} (\mathbf{P}^n)_{ij}
\end{aligned}$$

The middle term is infinite and the two outside terms positive so

$$\sum_k (\mathbf{P}^k)_{jj} = \infty$$

which shows j is recurrent.

A finite state space chain has at least one recurrent state:

If all states we transient we would have for each k $P(N_k < \infty) = 1$. This would mean $P(\forall k\, N_k < \infty) = 1$. But for any ω there must be at least one k for which $N_k = \infty$ (the total of a finite list of finite numbers is finite).

Infinite state space chain may have all states transient:

The chain X_n satisfying $X_{n+1} = X_n + 1$ on the integers has all states transient.

More interesting example:

• Toss a coin repeatedly.

• Let X_n be X_0 plus the number of heads minus the number of tails in the first n tosses.

• Let p denote the probability of heads on an individual trial.

$X_n - X_0$ is a sum of n iid random variables Y_i where $P(Y_i = 1) = p$ and $P(Y_i = -1) = 1 - p$.

SLLN shows X_n/n converges almost surely to $2p - 1$. If $p \neq 1/2$ this is not 0.

In order for X_n/n to have a positive limit we must have $X_n \to \infty$ almost surely so all states are visited only finitely many times. That is, all states are transient. Similarly for $p < 1/2$ $X_n \to -\infty$ almost surely and all states are transient.

Now look at $p = 1/2$. The law of large numbers argument no long shows anything. I will show that all states are recurrent.

Proof: We evaluate $\sum_n (\mathbf{P}^n)_{00}$ and show the sum is infinite. If n is odd then $(\mathbf{P}^n)_{00} = 0$ so we evaluate

$$\sum_m (\mathbf{P}^{2m})_{00}$$

Now

$$(\mathbf{P}^{2m})_{00} = \binom{2m}{m} 2^{-2m}$$

According to Stirling's approximation

$$\lim_{m\to\infty} \frac{m!}{m^{m+1/2}e^{-m}\sqrt{2\pi}} = 1$$

Hence

$$\lim_{m\to\infty} \sqrt{m}(\mathbf{P}^{2m})_{00} = \frac{1}{\sqrt{\pi}}$$

Since

$$\sum \frac{1}{\sqrt{m}} = \infty$$

we are done.

Mean return times

Compute expected times to return. For $x \in S$ let T_x denote the hitting time for x.

Suppose x recurrent in **irreducible** chain (only one communicating class).

Derive equations for expected values of different T_x.

Each T_x is a certain function f_x applied to $X_1, \ldots$. Setting $\mu_{ij} = \mathsf{E}^i(T_j)$ we find

$$\mu_{ij} = \sum_k \mathsf{E}^i(T_j 1(X_1 = k))$$

Note that if $X_1 = x$ then $T_x = 1$ so

$$\mathsf{E}^i(T_j 1(X_1 = j)) = \mathbf{P}_{ij}$$

For $k \neq j$, if $X_1 = k$ then

$$T_j = 1 + f_j(X_2, X_3, \ldots)$$

and, by conditioning on $X_1 = k$ we find

$$\mathsf{E}^i(T_j 1(X_1 = k)) = \mathbf{P}_{ik}\left\{1 + \mathsf{E}^k(T_j)\right\}$$

This gives

$$\mu_{ij} = 1 + \sum_{k \neq j} \mathbf{P}_{ik}\mu_{kj} \tag{5}$$

Technically, I should check that the expectations in (5) are finite. All the random variables involved are non-negative, however, and the equation actually makes sense even if some terms are infinite. (To prove this you actually study

$$T_{x,n} = \min(T_x, n)$$

deriving an identity for a fixed n, letting $n \to \infty$ and applying the monotone convergence theorem.)

Here is a simple example:

$$\mathbf{P} = \begin{bmatrix} 0 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & 0 & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & 0 \end{bmatrix}$$

The identity (5) becomes

$$\mu_{1,1} = 1 + \frac{1}{2}\mu_{2,1} + \frac{1}{2}\mu_{3,1}$$
$$\mu_{1,2} = 1 + \frac{1}{2}\mu_{3,2}$$
$$\mu_{1,3} = 1 + \frac{1}{2}\mu_{2,3}$$
$$\mu_{2,1} = 1 + \frac{1}{2}\mu_{3,1}$$
$$\mu_{2,2} = 1 + \frac{1}{2}\mu_{1,2} + \frac{1}{2}\mu_{3,2}$$
$$\mu_{2,3} = 1 + \frac{1}{2}\mu_{1,3}$$
$$\mu_{3,1} = 1 + \frac{1}{2}\mu_{2,1}$$
$$\mu_{3,2} = 1 + \frac{1}{2}\mu_{1,2}$$
$$\mu_{3,3} = 1 + \frac{1}{2}\mu_{1,3} + \frac{1}{2}\mu_{2,3}$$

Seventh and fourth show $\mu_{2,1} = \mu_{3,1}$. Similar calculations give $\mu_{ii} = 3$ and for $i \neq j$ $\mu_{i,j} = 2$.

Example: Coin tossing Markov Chain with $p = 1/2$ shows situation can be different when S is infinite. Equations above become:

$$m_{0,0} = 1 + \frac{1}{2}m_{1,0} + \frac{1}{2}m_{-1,0}$$
$$m_{1,0} = 1 + \frac{1}{2}m_{2,0}$$

and many more.

Some observations:

Have to go through 1 to get to 0 from 2 so

$$m_{2,0} = m_{2,1} + m_{1,0}$$

Symmetry (switching H and T):

$$m_{1,0} = m_{-1,0}$$

Transition probabilities are **homogeneous**:

$$m_{2,1} = m_{1,0}$$

Conclusion:

$$\begin{aligned} m_{0,0} &= 1 + m_{1,0} \\ &= 1 + 1 + \frac{1}{2} m_{2,0} \\ &= 2 + m_{1,0} \end{aligned}$$

Notice that there are **no** finite solutions!

Summary of the situation:

Every state is recurrent.

All the expected hitting times m_{ij} are infinite.

All entries $\mathbf{P}^n_{ij}$ converge to 0.

Jargon: The states in this chain are null recurrent.

Model: 2 state MC for weather: ‘Dry’ or ‘Wet’.

```
> p:= matrix(2,2,[[3/5,2/5],[1/5,4/5]]);
                      [3/5    2/5]
                 p := [          ]
                      [1/5    4/5]
> p2:=evalm(p*p):
> p4:=evalm(p2*p2):
> p8:=evalm(p4*p4):
> p16:=evalm(p8*p8):
```

This computes the powers (`evalm` understands matrix algebra).

Fact:

$$\lim_{n\to\infty} \mathbf{P}^n = \begin{bmatrix} \frac{1}{3} & \frac{2}{3} \\ \\ \frac{1}{3} & \frac{2}{3} \end{bmatrix}$$

```
> evalf(evalm(p));
              [.6000000000    .4000000000]
              [                          ]
              [.2000000000    .8000000000]
> evalf(evalm(p2));
              [.4400000000    .5600000000]
              [                          ]
              [.2800000000    .7200000000]
> evalf(evalm(p4));
              [.3504000000    .6496000000]
              [                          ]
              [.3248000000    .6752000000]
> evalf(evalm(p8));
              [.3337702400    .6662297600]
              [                          ]
              [.3331148800    .6668851200]
> evalf(evalm(p16));
              [.3333336197    .6666663803]
              [                          ]
              [.3333331902    .6666668098]
```

Where did 1/3 and 2/3 come from?

Suppose we toss a coin $P(H) = \alpha_D$ and start the chain with Dry if we get heads and Wet if we get tails.

Then

$$P(X_0 = x) = \begin{cases} \alpha_D & x = \text{Dry} \\ \alpha_W = 1 - \alpha_D & x = \text{Wet} \end{cases}$$

and

$$\begin{aligned} P(X_1 = x) &= \sum_y P(X_1 = x | X_0 = y) P(X_0 = y) \\ &= \sum_y \alpha_y P_{y,x} \end{aligned}$$

Notice last line is a matrix multiplication of row vector α by matrix $\mathbf{P}$. A special α: if we put $\alpha_D = 1/3$ and $\alpha_W = 2/3$ then

$$\begin{bmatrix} \frac{1}{3} & \frac{2}{3} \end{bmatrix} \begin{bmatrix} \frac{3}{5} & \frac{2}{5} \\ \\ \frac{1}{5} & \frac{4}{5} \end{bmatrix} = \begin{bmatrix} \frac{1}{3} & \frac{2}{3} \end{bmatrix}$$

So: if $P(X_0 = D) = 1/3$ then $P(X_1 = D) = 1/3$ and analogously for W. This means that X_0 and X_1 have the same distribution.

A probability vector α is called the initial distribution for the chain if

$$P(X_0 = i) = \alpha_i$$

A Markov Chain is **stationary** if

$$P(X_1 = i) = P(X_0 = i)$$

for all i

Finding stationary initial distributions. Consider $\mathbf{P}$ above. The equation

$$\alpha \mathbf{P} = \alpha$$

is really

$$\begin{aligned} \alpha_D &= 3\alpha_D/5 + \alpha_W/5 \\ \alpha_W &= 2\alpha_D/5 + 4\alpha_W/5 \end{aligned}$$

The first can be rearranged to

$$\alpha_W = 2\alpha_D.$$

So can the second. If α is probability vector then

$$\alpha_W + \alpha_D = 1$$

so we get

$$1 - \alpha_D = 2\alpha_D$$

leading to

$$\alpha_D = 1/3$$

Some more examples:

$$\mathbf{P} = \left[\begin{array}{cccc} 0 & 1/3 & 0 & 2/3 \\ 1/3 & 0 & 2/3 & 0 \\ 0 & 2/3 & 0 & 1/3 \\ 2/3 & 0 & 1/3 & 0 \end{array}\right]$$

Set $\alpha\mathbf{P} = \alpha$ and get

$$\begin{aligned} \alpha_1 &= \alpha_2/3 + 2\alpha_4/3 \\ \alpha_2 &= \alpha_1/3 + 2\alpha_3/3 \\ \alpha_3 &= 2\alpha_2/3 + \alpha_4/3 \\ \alpha_4 &= 2\alpha_1/3 + \alpha_3/3 \\ 1 &= \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 \end{aligned}$$

First plus third gives

$$\alpha_1 + \alpha_3 = \alpha_2 + \alpha_4$$

so both sums 1/2. Continue algebra to get

$$(1/4, 1/4, 1/4, 1/4)\,.$$

```
p:=matrix([[0,1/3,0,2/3],[1/3,0,2/3,0],
          [0,2/3,0,1/3],[2/3,0,1/3,0]]);

               [ 0     1/3     0     2/3]
               [                        ]
               [1/3     0     2/3     0 ]
          p := [                        ]
               [ 0     2/3     0     1/3]
               [                        ]
               [2/3     0     1/3     0 ]
> p2:=evalm(p*p);
             [5/9     0     4/9     0 ]
             [                        ]
             [ 0     5/9     0     4/9]
        p2:= [                        ]
             [4/9     0     5/9     0 ]
             [                        ]
             [ 0     4/9     0     5/9]
> p4:=evalm(p2*p2):
> p8:=evalm(p4*p4):
> p16:=evalm(p8*p8):
> p17:=evalm(p8*p8*p):
```

```
> evalf(evalm(p16));
    [.5000000116 , 0 , .4999999884 , 0]
    [                                  ]
    [0 , .5000000116 , 0 , .4999999884]
    [                                  ]
    [.4999999884 , 0 , .5000000116 , 0]
    [                                  ]
    [0 , .4999999884 , 0 , .5000000116]
> evalf(evalm(p17));
    [0 , .4999999961 , 0 , .5000000039]
    [                                  ]
    [.4999999961 , 0 , .5000000039 , 0]
    [                                  ]
    [0 , .5000000039 , 0 , .4999999961]
    [                                  ]
    [.5000000039 , 0 , .4999999961 , 0]
```

```
> evalf(evalm((p16+p17)/2));
  [.2500, .2500, .2500, .2500]
  [                          ]
  [.2500, .2500, .2500, .2500]
  [                          ]
  [.2500, .2500, .2500, .2500]
  [                          ]
  [.2500, .2500, .2500, .2500]
```

$\mathbf{P}^n$ doesn't converges but$(\mathbf{P}^n + \mathbf{P}^{n+1})/2$ does.
Next example:

$$\P = \begin{bmatrix} \frac{2}{5} & \frac{3}{5} & 0 & 0 \\ \frac{1}{5} & \frac{4}{5} & 0 & 0 \\ 0 & 0 & \frac{2}{5} & \frac{3}{5} \\ 0 & 0 & \frac{1}{5} & \frac{4}{5} \end{bmatrix}$$

Solve $\alpha \mathbf{P} = \alpha$:

$$\begin{aligned}
\alpha_1 &= \frac{2}{5}\alpha_1 + \frac{1}{5}\alpha_2 \\
\alpha_2 &= \frac{3}{5}\alpha_1 + \frac{4}{5}\alpha_2 \\
\alpha_3 &= \frac{2}{5}\alpha_3 + \frac{1}{5}\alpha_4 \\
\alpha_4 &= \frac{3}{5}\alpha_3 + \frac{4}{5}\alpha_4 \\
1 &= \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4
\end{aligned}$$

Second and fourth equations redundant. Get

$$\begin{aligned}
\alpha_2 &= 3\alpha_1 \\
3\alpha_3 &= \alpha_4 \\
1 &= 4\alpha_1 + 4\alpha_3
\end{aligned}$$

Pick α_1 in $[0, 1/4]$; put $\alpha_3 = 1/4 - \alpha_1$.

$$\alpha = (\alpha_1, 3\alpha_1, 1/4 - \alpha_1, 3(1/4 - \alpha_1))$$

solves $\alpha \mathbf{P} = \alpha$. So solution is not unique.

```
> p:=matrix([[2/5,3/5,0,0],[1/5,4/5,0,0],
            [0,0,2/5,3/5],[0,0,1/5,4/5]]);
                    [2/5    3/5     0       0 ]
                    [                         ]
                    [1/5    4/5     0       0 ]
               p := [                         ]
                    [ 0      0     2/5    3/5]
                    [                         ]
                    [ 0      0     1/5    4/5]
> p2:=evalm(p*p):
> p4:=evalm(p2*p2):
> p8:=evalm(p4*p4):
> evalf(evalm(p8*p8));
             [.2500000000 , .7500000000 , 0 , 0]
             [                                  ]
             [.2500000000 , .7500000000 , 0 , 0]
             [                                  ]
             [0 , 0 , .2500000000 , .7500000000]
             [                                  ]
             [0 , 0 , .2500000000 , .7500000000]
```

Notice that rows converge but to two different vectors:

$$\alpha^{(1)} = (1/4, 3/4, 0, 0)$$

and

$$\alpha^{(2)} = (0, 0, 1/4, 3/4)$$

Solutions of $\alpha\mathbf{P} = \alpha$ revisited? Check that

$$\alpha^{(1)}\mathbf{P} = \alpha^{(1)}$$

and

$$\alpha^{(2)}\mathbf{P} = \alpha^{(2)}$$

If $\alpha = \lambda\alpha^{(1)} + (1 - \lambda)\alpha^{(2)}$ $(0 \le \lambda \le 1)$ then

$$\alpha\mathbf{P} = \alpha$$

so again solution is not unique.

Last example:

```
> p:=matrix([[2/5,3/5,0],[1/5,4/5,0],
            [1/2,0,1/2]]);

                    [2/5    3/5     0 ]
                    [                 ]
               p := [1/5    4/5     0 ]
                    [                 ]
                    [1/2     0     1/2]
> p2:=evalm(p*p):
> p4:=evalm(p2*p2):
> p8:=evalm(p4*p4):
> evalf(evalm(p8*p8));
  [.2500000000 .7500000000        0        ]
  [                                        ]
  [.2500000000 .7500000000        0        ]
  [                                        ]
  [.2500152588 .7499694824 .00001525878906]
```

Interpretation of examples

- For some $\mathbf{P}$ all rows converge to some α. In this case this α is a stationary initial distribution.

- For some $\mathbf{P}$ the locations of zeros flip flop. $\mathbf{P}^n$ does not converge. Observation: average
$$\frac{\mathbf{P}+\mathbf{P}^2+\cdots+\mathbf{P}^n}{n}$$
does converge.

- For some $\mathbf{P}$ some rows converge to one α and some to another. In this case the solution of $\alpha\mathbf{P}=\alpha$ is not unique.

Basic distinguishing features: pattern of 0s in matrix $\mathbf{P}$.

The ergodic theorem

Consider a finite state space chain. If x is a vector then the ith entry in $\mathbf{P}x$ is

$$\sum_j \mathbf{P}_{ij} x_j$$

Rows of $\mathbf{P}$ probability vectors, so a weighted average of the entries in x.

If weights strictly between 0, 1 and largest and smallest entries in x not same then $\sum_j \mathbf{P}_{ij} x_j$ strictly between largest and smallest entries in x. In fact

$$\begin{aligned}\sum_j \mathbf{P}_{ij} x_j - \min(x_k) &= \sum_j \mathbf{P}_{ij}\{x_j - \min(x_k)\} \\ &\ge \min_j\{p_{ij}\}(\max\{x_k\} - \min\{x_k\})\end{aligned}$$

and

$$\begin{aligned}&\max\{x_j\} - \sum_j \mathbf{P}_{ij} x_j \\ &\qquad \ge \min_j\{p_{ij}\}(\max\{x_k\} - \min\{x_k\})\end{aligned}$$

Now multiply $\mathbf{P}^r$ by $\mathbf{P}^m$.

ijth entry in $\mathbf{P}^{r+m}$ is a weighted average of the jth column of $\mathbf{P}^m$.

So, if all the entries in row i of $\mathbf{P}^r$ are positive and the jth column of $\mathbf{P}^m$ is not constant, the ith entry in the jth column of $\mathbf{P}^{r+m}$ must be strictly between the minimum and maximum entries of the jth column of $\mathbf{P}^m$.

In fact, fix a j.

$\overline{x}_m =$ maximum entry in column j of $\mathbf{P}^m$

$\underline{x}_m$ the minimum entry.

Suppose all entries of $\mathbf{P}^r$ are positive.

Let $\delta > 0$ be the smallest entry in $\mathbf{P}^r$. Our argument above shows that

$$\overline{x}_{m+r} \leq \overline{x}_m - \delta(\overline{x}_m - \underline{x}_m)$$

and

$$\underline{x}_{m+r} \geq \underline{x}_m + \delta(\overline{x}_m - \underline{x}_m)$$

Putting these together gives

$$(\overline{x}_{m+r} - \underline{x}_{m+r}) \leq (1 - 2\delta)(\overline{x}_m - \underline{x}_m)$$

In summary the column maximum decreases, the column minimum increases and the gap between the two decreases exponentially along the sequence $m, m+r, m+2r, \ldots$.

This idea can be used to prove

Proposition 2 *Suppose X_n finite state space Markov Chain with stationary transition matrix $\mathbf{P}$. Assume that there is a power r such that all entries in $\mathbf{P}^r$ are positive. Then for $\mathbf{P}^k$ has all entries positive for all $k \geq r$ and $\mathbf{P}^n$ converges, as $n \to \infty$ to a matrix $\mathbf{P}^\infty$. Moreover,*

$$(\mathbf{P}^\infty)_{ij} = \pi_j$$

where π is the unique row vector satisfying

$$\pi = \pi \mathbf{P}$$

whose entries sum to 1.

Proof: First for $k > r$

$$(\mathbf{P}^k)_{ij} = \sum_\ell (\mathbf{P}^{k-r})_{i\ell} (\mathbf{P}^r)_{\ell j}$$

For each i there is an ℓ for which $(\mathbf{P}^{k-r})_{i\ell} > 0$ and since $(\mathbf{P}^r)_{\ell j} > 0$ we see $(\mathbf{P}^k)_{ij} > 0$.

The argument before the proposition shows that

$$\lim_{j\to\infty} \mathbf{P}^{m+jk}$$

exists for each m and $k \geq r$. This proves $\mathbf{P}^n$ has a limit which we call $\mathbf{P}^\infty$. Since $\mathbf{P}^{n-1}$ also converges to $\mathbf{P}^\infty$ we find

$$\mathbf{P}^\infty = \mathbf{P}^\infty \mathbf{P}$$

Hence each row of $\mathbf{P}^\infty$ is a solution of $x\mathbf{P} = x$. The argument before the statement of the proposition shows all rows of $\mathbf{P}^\infty$ are equal. Let π be this common row.

Now if α is any vector whose entries sum to 1 then $\alpha\mathbf{P}^n$ converges to

$$\alpha\mathbf{P}^\infty = \pi$$

If α is any solution of $x = x\mathbf{P}$ we have by induction $\alpha\mathbf{P}^n = \alpha$ so $\alpha\mathbf{P}^\infty = \alpha$ so $\alpha = \pi$. That is exactly one vector whose entries sum to 1 satisfies $x = x\mathbf{P}$. •

Note conditions:

There is an r for which all entries in $\mathbf{P}^r$ are positive.

The chain has a finite state space.

Consider finite state space case: $\mathbf{P}^n$ need not have limit. Example:

$$\mathbf{P} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

Note $\mathbf{P}^{2n}$ is the identity while $\mathbf{P}^{2n+1} = \mathbf{P}$. Note, too, that

$$\frac{\mathbf{P}^0 + \cdots + \mathbf{P}^n}{n+1} \to \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

Consider the equations $\pi = \pi\mathbf{P}$ with $\pi_1 + \pi_2 = 1$. We get

$$\pi_1 = \frac{1}{2}\pi_1 + \frac{1}{2}(1 - \pi_1) = \frac{1}{2}$$

so that the solution to $\pi = \pi\mathbf{P}$ is again unique.

Def'n: The period d of a state i is the greatest common divisor of

$$\{n : (\mathbf{P}^n)_{ii} > 0\}$$

Lemma 1 *If $i \leftrightarrow j$ then i and j have the same period.*

Def'n: A state is **aperiodic** if its period is 1.

Proof: I do the case $d = 1$. Fix i. Let

$$G = \{k : (\mathbf{P}^k)_{ii} > 0\}$$

If $k_1, k_2 \in G$ then $k_1 + k_2 \in G$.

This (and aperiodic) implies (number theory argument) that there is an r such that $k \geq r$ implies $k \in G$.

Now find m and n so that

$$(\mathbf{P}^m)_{ij} > 0 \text{ and } (\mathbf{P}^n)_{ji} > 0$$

For $k > r+m+n$ we see $(\mathbf{P}^k)_{jj} > 0$ so the gcd of the set of k such that $(\mathbf{P}^k)_{jj} > 0$ is 1. •

The case of period $d > 1$ can be dealt with by considering $\mathbf{P}^d$.

$$\mathbf{P} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

For this example $\{1,2,3\}$ is a class of period 3 states and $\{4,5\}$ a class of period 2 states.

$$\mathbf{P} = \begin{bmatrix} 0 & 1/2 & 1/2 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

has a single communicating class of period 2.

A chain is **aperiodic** if all its states are aperiodic.

Hitting Times

Start irreducible recurrent chain X_n in state i. Let T_j be first $n > 0$ such that $X_n = j$. Define

$$m_{ij} = \mathsf{E}(T_j | X_0 = i)$$

First step analysis:

$$\begin{aligned} m_{ij} &= 1 \cdot P(X_1 = j | X_0 = i) \\ &\qquad + \sum_{k \neq j} (1 + \mathsf{E}(T_j | X_0 = k)) P_{ik} \\ &= \sum_j P_{ij} + \sum_{k \neq j} P_{ik} m_{kj} \\ &= 1 + \sum_{k \neq j} P_{ik} m_{kj} \end{aligned}$$

Example

$$\mathbf{P} = \begin{bmatrix} \frac{3}{5} & \frac{2}{5} \\ \\ \frac{1}{5} & \frac{4}{5} \end{bmatrix}$$

The equations are

$$
\begin{aligned}
m_{11} &= 1 + \frac{2}{5} m_{21} \\
m_{12} &= 1 + \frac{3}{5} m_{12} \\
m_{21} &= 1 + \frac{4}{5} m_{21} \\
m_{22} &= 1 + \frac{1}{5} m_{12}
\end{aligned}
$$

The second and third equations give immediately

$$
\begin{aligned}
m_{12} &= \frac{5}{2} \\
m_{21} &= 5
\end{aligned}
$$

Then plug in to the others to get

$$
\begin{aligned}
m_{11} &= 3 \\
m_{22} &= \frac{3}{2}
\end{aligned}
$$

Notice stationary initial distribution is

$$
\left(\frac{1}{m_{11}}, \frac{1}{m_{22}}\right)
$$

Consider fraction of time spent in state j:

$$\frac{1(X_0 = j) + \cdots + 1(X_n = j)}{n+1}$$

Imagine chain starts in chain i; take expected value.

$$\frac{\sum_{r=1}^n \mathbf{P}_{ij}^r + 1(i = j)}{n+1}$$

If rows of $\mathbf{P}^r$ converge to π then fraction converges to π_j; i.e. limiting fraction of time in state j is π_j.

Heuristic: start chain in i. Expect to return to i every m_{ii} time units. So are in state i about once every m_{ii} time units; i.e. limiting fraction of time in state i is $1/m_{ii}$.

Conclusion: for an irreducible recurrent finite state space Markov chain

$$\pi_i = \frac{1}{m_{ii}}.$$

Real proof: Renewal theorem or variant.

Idea: $S_1 < S_2 < \cdots$ are times of visits to i. Segment i:

$$X_{S_{i-1}+1}, \ldots, X_{S_i}.$$

Segments are iid by Strong Markov.

Number of visits to i by time S_k is exactly k.

Total elapsed time is $S_k = T_1 + \cdots + T_k$ where T_i are iid.

Fraction of time in state i by time S_k is

$$\frac{k}{S_k} \to \frac{1}{m_{ii}}$$

by SLLN. So if fraction converges to π_i must have

$$\pi_i = \frac{1}{m_{ii}}.$$

Summary of Theoretical Results:

For an irreducible aperiodic positive recurrent Markov Chain:

1. $\mathbf{P}^n$ converges to a stochastic matrix $\mathbf{P}^\infty$.

2. Each row of $\mathbf{P}^\infty$ is π the unique stationary initial distribution.

3. The stationary initial distribution is given by

$$\pi_i = 1/m_i$$

   where m_i is the mean return time to state i from state i.

If the state space is finite an irreducible chain is positive recurrent.

Ergodic Theorem

Notice slight of hand: I showed

$$\frac{\mathsf{E}\left\{\sum_{i=0}^{n} 1(X_i = k)\right\}}{n} \to \pi_k$$

but claimed

$$\frac{\sum_{i=0}^{n} 1(X_i = k)}{n} \to \pi_k$$

almost surely which is also true. This is a step in the proof of the ergodic theorem. For an irreducible positive recurrent Markov chain and any f on S such that $\mathsf{E}^{\pi}(f(X_0)) < \infty$:

$$\frac{\sum_0^n f(X_i)}{n} \to \sum \pi_j f(j)$$

almost surely. The limit works in other senses, too. You also get

$$\frac{\sum_0^n f(X_i, \ldots, X_{i+k})}{n} \to \mathsf{E}^{\pi}\left\{f(X_0, \ldots, X_k)\right\}$$

E.g. fraction of transitions from i to j goes to

$$\pi_i \mathbf{P}_{ij}$$

For an irreducible positive recurrent chain of period d:

1. $\mathbf{P}^d$ has d communicating classes each of which forms an irreducible aperiodic positive recurrent chain.

2. $(\mathbf{P}^{n+1} + \cdots + \mathbf{P}^{n+d})/d$ has a limit $\mathbf{P}^\infty$.

3. Each row of $\mathbf{P}^\infty$ is π the unique stationary initial distribution.

4. Stationary initial distribution places probability $1/d$ on each of the communicating classes in 1.

For an irreducible null recurrent chain:

1. $\mathbf{P}^n$ converges to 0 (pointwise).

2. there is no stationary initial distribution.

For an irreducible transient chain:

1. $\mathbf{P}^n$ converges to 0 (pointwise).

2. there is no stationary initial distribution.

For a chain with more than 1 communicating class:

1. If $\mathcal{C}$ is a recurrent class the submatrix $\mathbf{P}_{\mathcal{C}}$ of $\mathbf{P}$ made by picking out rows i and columns j for which $i, j \in \mathcal{C}$ is a stochastic matrix. The corresponding entries in $\mathbf{P}^n$ are just $(\mathbf{P}_{\mathcal{C}})^n$ so you can apply the conclusions above.

2. For any transient or null recurrent class the corresponding columns in $\mathbf{P}^n$ converge to 0.

3. If there are multiple positive recurrent communicating classes then the stationary initial distribution is not unique.