205B Homework #1, due Tuesday January 31

Durrett Chapter 3 Exercises

2.2: Convergence of Maxima.
2.6 The Levy metric.
2.13 Converging together lemma.

1. Show that, given $X$, we can find random variables $X_n$ such that each $X_n$ takes only finitely many values but $X_n \xrightarrow{d} X$.

2. Suppose $X$ has a continuous density $f$. Let $\delta_n \downarrow 0$. Suppose $X_n$ takes only values which are integer multiples of $\delta_n$. And suppose that

$$k_n\delta_n \to x \text{ implies } \frac{\mathbb{P}(X_n = k_n\delta_n)}{\delta_n} \to f(x).$$

Show that $X_n \xrightarrow{d} X$.

3. For real $x > 0$ let $\text{dec}(x)$ be the decimal part of $x$, and let $\text{sig}(x)$ be the first significant digit of $x$. Thus

$$\text{dec}(83.472) = 0.472, \quad \text{sig}(83.472) = 8.$$  

Let $X_n > 1$ be r.v.’s such that $\text{dec}(\log_{10} X_n) \xrightarrow{d} U$, where $U$ is uniform on $(0, 1)$. Prove that $\text{sig}(X_n) \xrightarrow{d} D$ where $D$ has a certain distribution (which you should specify) on $\{1, 2, \ldots, 9\}$.  

Remark. Benford’s law asserts that, in real-world data where entries differ by several orders of magnitude, the observed distribution of first significant digit is approximately $D$. 
205B Homework #2, due Tuesday February 7

Durrett, Chapter 3, section 3, Exercises 1, 3, 5, 6, 7, 13, 15, 17, 18, 19, 22, 23.

[Note most of these have short proofs – nothing complicated is needed.]
Durrett, Chapter 3, section 4, Exercises 4, 6, 7, 9, 11.

4. Let \((X_j, j \geq 1)\) be independent and take values \([-2j^2, -j, 0, j, 2j^2]\) with

\[
\begin{align*}
P(X_j = -2j^2) &= P(X_j = 2j^2) = \frac{1}{12j^2} \\
P(X_j = -j) &= P(X_j = j) = \frac{1}{12}.
\end{align*}
\]

Show that the Lindeberg condition is not satisfied. Show that nonetheless there exist constants \(b_n\) (which you should specify) such that

\[
\frac{1}{b_n} \sum_{j=1}^{n} X_j \xrightarrow{d} \text{Normal}(0, 1).
\]
Durrett Chapter 3 Exercises 9.5, 3.27, 3.28.

5. Let $U$ and $V$ be independent, uniform $[0,1]$. Define $Y_n = nU - \lfloor nU \rfloor$. Show that

$$(U,Y_n) \xrightarrow{d} (U,V).$$

6. Let $Q = Q(x,A)$ be a kernel from $\mathbb{R}$ to $\mathbb{R}$. For each $1 \leq n \leq \infty$ let $(X_n,Y_n)$ be such that $Q$ is the conditional probability kernel for $Y_n$ given $X_n$. Suppose $X_n \xrightarrow{d} X_\infty$. Give an example to show that

$$(X_n,Y_n) \xrightarrow{d} (X_\infty,Y_\infty)$$

is not necessarily true. Show that either of the following two extra assumptions is sufficient to imply $(*).

(a) For each $1 \leq n \leq \infty$ there is a density $f_n$ for $X_n$, and $\int |f_n(x) - f_\infty(x)| dx \to 0$.

(b) $Q(x_m,\cdot) \to Q(x,\cdot)$ weakly whenever $x_m \to x$.

7. Give an example of a distribution $(Y_1,Y_2)$ such that $Y_1$ and $Y_2$ are Normal$(0,1)$ but the joint distribution is not bivariate Gaussian.

8. Let $(X_1,X_2)$ be bivariate Gaussian with $\mathbb{E}X_1^2 = \mathbb{E}X_2^2 = 1$ and $\mathbb{E}X_1 = \mathbb{E}X_2 = 0$ and $\mathbb{E}X_1X_2 = \rho$. Calculate $\mathbb{P}(X_1 > 0, X_2 > 0)$.

[Hint: for independent standard Normals $(Z_1,Z_2)$ the density is rotationally invariant]

9. For integers $x \geq 0, k \geq 1$ write $[x]_k = x(x-1)\cdots(x-k+1)$. Prove that, for positive integer-valued r.v.’s $X(n)$,

if $\mathbb{E}[X(n)]_k \to \lambda^k$ as $n \to \infty$, for each $k \geq 1$

then $X(n) \xrightarrow{d} \text{Poisson}(\lambda)$. 
10. Give an example to show that, if $X_n$ is a Markov chain and $f$ a function defined on its state space, then $f(X_n)$ need not be a Markov chain.

11. Show that for $K < \infty$ and $a > 0$ there is a constant $C(K, a) < \infty$ such that in every finite irreducible chain

$$\max_{i,j} \mathbb{E}_i T_j \leq C(K, a)$$

where $K =$ number of states and $a = \min\{p(i, j) : p(i, j) > 0\}$. 

Durrett Chapter 6 Exercises 4.2, 4.3, 5.4, 5.5, 5.8

12. Let $X_n$ be an irreducible chain with transition matrix $P$. Let $Y_n$ be the *jump chain* $Y_n = X(T_n)$ where $T_0 = 0$ and

$$T_{n+1} = \min\{m > T_n : X_m \neq X(T_n)\}.$$

(a) Show that $Y_n$ is Markov, and write its transition matrix $Q$ in terms of $P$.

(b) Show that $(Y_n)$ is recurrent iff $(X_n)$ is recurrent.

(c) Assuming recurrence, find the relation between the $P$-invariant measure and the $Q$-invariant measure.

(d) Deduce that, on an infinite state space, it is possible for $(Y_n)$ to be positive-recurrent while $(X_n)$ is not.

13. Let $X_n$ be an finite irreducible chain with transition matrix $P$. Fix a subset $A$ of $S$. Define a transition matrix $Q$ on $A$ by

$$q(i,j) = \frac{p(i,j)}{\sum_{k \in A} p(i,k)}.$$

Suppose $Q$ is irreducible. In the case where $P$ is *reversible*, find a simple explicit formula for the stationary distribution $\pi^*$ of $Q$ in terms of $P$ and its stationary distribution $\pi$. Give an example to show that the formula may not hold in the non-reversible case.
Durrett Chapter 6 Exercises 6.6, 6.7

14. Let \((X_n)\) be an irreducible Markov chain on \(S\) with transition matrix \((p(x,y))\). Let \(B\) be a finite subset of \(S\) such that the chain a.s. visits \(B\) infinitely often. Let \((Z_m)\) be the chain watched only on \(B\). Then \(Z\) is irreducible, and so has stationary distribution \(\hat{\pi}\), say. Define

\[
\mu(x,y) = \mathbb{E}_x \sum_{n=0}^{\infty} 1_{(X_n=y, T_B>n)}, \quad x \in B, \ y \in S.
\]

\[
\pi(y) = \sum_{x \in B} \hat{\pi}(x) \mu(x,y).
\]

Show that \(\pi\) is invariant, in the sense

\[
\pi(y) = \sum_{z \in S} \pi(z)p(z,y) \leq \infty, \ y \in S.
\]

15. A population consists of \(X_n\) individuals at times \(n = 0, 1, 2, \ldots\). Between time \(n\) and time \(n+1\) each of these individuals dies with probability \(p\) independently of the others; and the population at time \(n+1\) consists of the survivors together with an independent random (Poisson (\(\lambda\))) number of immigrants.

Let \(X_0\) have arbitrary distribution. What happens to the distribution of \(X_n\) as \(n \to \infty\)? [Hint: consider first the case where \(X_0\) has Poisson (\(\lambda_0\)) distribution]
16. Let $X_n$ be the Markov chain on states $0, 1, \ldots, K$ with transition matrix

$$ p(i, i + 1) = 2/3 \text{ and } p(i, i - 1) = 1/3; \ 1 \leq i \leq K - 1 $$

$$ p(0, 0) = p(K, K) = 1 $$

and initial state $i_0 \neq 0, K$. Let $X^*_n$ be the process $X_n$ conditioned on the event $\{X_m = K \text{ ultimately}\}$.

(a) Prove carefully that $X^*_n$ is Markov.
(b) Find its transition matrix.
(c) Find the distribution of $\min_{n \geq 0} X^*_n$.

17. Let $S$ be a finite set. Let $p(i, j)$ be an irreducible Markov transition matrix on $S$, with stationary distribution $\pi$. Consider a cat-and-mouse game, as follows. A state $i$ is chosen at random according to $\pi$; the cat and mouse are both placed at $i$, but before the cat can do anything the mouse jumps to another state chosen according to $p(i, \cdot)$. Thereafter, the mouse doesn’t move. The cat now searches for the mouse by moving at random according to the “time-reversed” Markov chain, i.e. the chain with transition matrix

$$ q(i, j) = \pi(j)p(j, i)/\pi(i). $$

Find a simple formula for the expected number of steps taken by the cat until it finds the mouse.

[more questions on next page]

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**205B homework #8; due Tuesday March 21**
18. Let \( P = p(i, j) \) be a Markov transition matrix on \( \{0, 1, 2, \ldots\} \). Give a simple necessary and sufficient condition, in terms of \( P \), for the following assertion to be true.

For any pair \( i_0 < j_0 \) it is possible to construct \( (X_n, Y_n; n \geq 0) \) such that

1. \( X \) is the \((i_0, P)\)-chain
2. \( Y \) is the \((j_0, P)\)-chain
3. \( X_n \leq Y_n \) for all \( n \).

19. Let \((X_n)\) be irreducible positive-recurrent with stationary distribution \( \pi \). Fix a subset \( B \) of \( S \). Let

\[
T_B = \min\{n \geq 1 : X_n \in B\}
\]

\[
A_{kn} = \{X_m \in B^c \text{ for all } k \leq m \leq n\}.
\]

(a) Show that for the stationary chain, \( \mathbb{P}(A_{kn}) \) depends only on \( n - k \), and deduce that for the stationary chain

\[
\mathbb{P}(X_0 \in B, T_B \geq n) = \mathbb{P}(T_B = n).
\]

(b) Use (a) to give a new proof that \( \mathbb{E}_i T_i = 1/\pi(i) \).

(c) Use (a) to prove

\[
\mathbb{E}_i (T_i^2) = \mathbb{E}_i T_i (2 \sum_j (\mathbb{E}_j T_i / \mathbb{E}_j T_j) - 1).
\]

20. Let \((X_n; n \geq 0)\) be a finite-state irreducible Markov chain. Write \( \pi \) for the stationary distribution and

\[
T_j = \min\{n \geq 0 : X_n = j\}
\]

for the first hitting time.

(a) Prove that \( \sum_j \pi_j \mathbb{E}_i T_j \) does not depend on \( i \).

(b) Give an example to show that \( \sum_i \pi_i \mathbb{E}_i T_j \) may depend on \( j \).
21. Let \((X_n)\) be an irreducible Markov chain on states \(I = \{0, 1, 2, \ldots\}\). Let \(g : I \to \mathbb{R}\) be such that
(a) \(\mathbb{E}_i g(X_1) \geq g(i)\) for all \(i\), with strict inequality for some \(i\).
(b) \(\sup_i \mathbb{E}_i |g(X_1) - g(i)| < \infty\).
Prove that \((X_n)\) is not positive-recurrent. Give an example to show it may be null-recurrent.

22. Let \((X_n : n \geq 0)\) be a non-homogeneous Markov chain on states \(\{1, 2, \ldots, K\}\). Let \(\mathcal{T}\) be its tail \(\sigma\)-field. Prove that there exists a partition \((B_1, \ldots, B_m)\), \(m \leq K\) of \(\Omega\) such that \(\mathcal{T} = \sigma(B_1, \ldots, B_m)\) up to null sets.
[Hint. Consider \(\mathbb{E}(Z|X_n)\) for tail-measurable \(Z\).]

23. Let \((X_n, n \geq 0)\) be a finite-state irreducible Markov chain with transition matrix \(P\). Let \(f\) be a non-constant real-valued function and \(0 < \lambda < 1\) be such that \(\sum_j p_{ij} f(j) = \lambda f(i) \ \forall i\).
   (i) Show that \(\lambda^{-n} f(X_n)\) is a martingale.
   (ii) Let \(\tau_b\) be the first hitting time on a state \(b\). Show that
   \[
   \sup \{\theta : \mathbb{E}(\theta^{\tau_b} | X_0 = i) < \infty \ \forall i\} \leq 1/\lambda.
   \]

[more questions on next page]
24. Let $p(i,j)$ be a Markov transition matrix on $\{0,1,\ldots,K\}$ such that 0 and $K$ are absorbing, $\{1,2,\ldots,K-1\}$ forms a strongly connected component and 

$$\sum_j j p(i,j) = i \text{ for each } 0 \leq i \leq K.$$ 

Fix $B \geq 2$. Define a Markov process $(X_n; n \geq 0)$ on state-space $\{1,2,\ldots,K\}^B$ as follows. A state $(x(1),\ldots,x(B))$ represents the positions of $B$ particles, particle $b$ being in position $x(b)$. Initially all particles are at position $i_0$, for some $1 \leq i_0 \leq K - 1$. A step of the process $X$ is as follows. Pick one of the particles uniformly at random, and let it perform a move according to $p(\cdot,\cdot)$. If the move takes the particle to a position which is not 0, that concludes the step of $X$. Otherwise the particle tries to move to 0, in which case it is immediately replaced at the position of another particle, picked uniformly at random from the other $B-1$ particles. Call this latter move a 0-jump.

Ultimately the process will reach the absorbing state with all particles in position $K$. Let $N$ be the random total number of 0-jumps made. Prove

$$\mathbb{E}\left(\left(\frac{B-1}{B}\right)^N\right) = \frac{i_0}{K}.$$ 

What can you deduce about $\mathbb{E}N$ ?

[Hint: Let $A_n$ be the average position of the $B$ particles after $n$ steps. Find a martingale related to $A_n$.]
205B Homework #10; due Tuesday April 11

Durrett Chapter 7 Exercises 1.6, 3.1, 3.3, 3.4
Durrett Chapter 7 Exercises 4.1, 5.1, 5.2, 5.4.
205B Homework #12; due Tuesday April 25

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