18.175: Lecture 9

Borel-Cantelli and strong law

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Outline

Laws of large numbers: Borel-Cantelli applications

Strong law of large numbers

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Strong law of large numbers

Borel-Cantelli lemmas

- **First Borel-Cantelli lemma:** If $\sum_{n=1}^{\infty} P(A_n) < \infty$ then $P(A_n \text{ i.o.}) = 0$.
- **Second Borel-Cantelli lemma:** If A_n are independent, then $\sum_{n=1}^{\infty} P(A_n) = \infty$ implies $P(A_n \text{ i.o.}) = 1$.

Convergence in probability subsequential a.s. convergence

- **Theorem:** $X_n \to X$ in probability if and only if for every subsequence of the X_n there is a further subsequence converging a.s. to X.
- **Main idea of proof:** Consider event E_n that X_n and X differ by ϵ. Do the E_n occur i.o.? Use Borel-Cantelli.

Pairwise independence example

- **Theorem:** Suppose $A_1, A_2, \dots$ are pairwise independent and $\sum P(A_n) = \infty$, and write $S_n = \sum_{i=1}^n 1_{A_i}$. Then the ratio S_n/ES_n tends a.s. to 1.
- **Main idea of proof:** First, pairwise independence implies that variances add. Conclude (by checking term by term) that $\mathrm{Var} S_n \le ES_n$. Then Chebyshev implies

$$P(|S_n - ES_n| > \delta ES_n) \le \mathrm{Var}(S_n)/(\delta ES_n)^2 \to 0,$$

  which gives us convergence in probability.
- Second, take a smart subsequence. Let $n_k = \inf\{n : ES_n \ge k^2\}$. Use Borel Cantelli to get a.s. convergence along this subsequence. Check that convergence along this subsequence deterministically implies the non-subsequential convergence.

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General strong law of large numbers

- **Theorem (strong law):** If $X_1, X_2, \dots$ are i.i.d. real-valued random variables with expectation m and $A_n := n^{-1} \sum_{i=1}^{n} X_i$ are the *empirical means* then $\lim_{n\to\infty} A_n = m$ almost surely.

Proof of strong law assuming $E[X^4] < \infty$

- Assume $K := E[X^4] < \infty$. Not necessary, but simplifies proof.
- Note: $\mathrm{Var}[X^2] = E[X^4] - E[X^2]^2 \geq 0$, so $E[X^2]^2 \leq K$.
- The strong law holds for i.i.d. copies of X if and only if it holds for i.i.d. copies of $X - \mu$ where μ is a constant.
- So we may as well assume $E[X] = 0$.
- Key to proof is to bound fourth moments of A_n.
- $E[A_n^4] = n^{-4}E[S_n^4] = n^{-4}E[(X_1 + X_2 + \ldots + X_n)^4]$.
- Expand $(X_1 + \ldots + X_n)^4$. Five kinds of terms: $X_iX_jX_kX_l$ and $X_iX_jX_k^2$ and $X_iX_j^3$ and $X_i^2X_j^2$ and X_i^4.
- The first three terms all have expectation zero. There are $\binom{n}{2}$ of the fourth type and n of the last type, each equal to at most K. So $E[A_n^4] \leq n^{-4}\Big(6\binom{n}{2} + n\Big)K$.
- Thus $E[\sum_{n=1}^\infty A_n^4] = \sum_{n=1}^\infty E[A_n^4] < \infty$. So $\sum_{n=1}^\infty A_n^4 < \infty$ (and hence $A_n \to 0$) with probability 1.

General proof of strong law

- Suppose X_k are i.i.d. with finite mean. Let $Y_k = X_k 1_{|X_k| \leq k}$. Write $T_n = Y_1 + \ldots + Y_n$. **Claim:** $X_k = Y_k$ all but finitely often a.s. so suffices to show $T_n/n \to \mu$. (Borel Cantelli, expectation of positive r.v. is area between cdf and line $y = 1$)
- **Claim:** $\sum_{k=1}^{\infty} \mathrm{Var}(Y_k)/k^2 \leq 4E|X_1| < \infty$. How to prove it?
- **Observe:** $\mathrm{Var}(Y_k) \leq E(Y_k^2) = \int_0^{\infty} 2yP(|Y_k| > y)dy \leq \int_0^k 2yP(|X_1| > y)dy$. Use Fubini (interchange sum/integral, since everything positive)

$$\sum_{k=1}^{\infty} E(Y_k^2)/k^2 \leq \sum_{k=1}^{\infty} k^{-2} \int_0^{\infty} 1_{(y<k)} 2yP(|X_1| > y)dy =$$

$$\int_0^{\infty} \left(\sum_{k=1}^{\infty} k^{-2} 1_{(y<k)}\right) 2yP(|X_1| > y)dy.$$

Since $E|X_1| = \int_0^{\infty} P(|X_1| > y)dy$, complete proof of claim by showing that if $y \geq 0$ then $2y \sum_{k>y} k^{-2} \leq 4$.

General proof of strong law

- **Claim:** $\sum_{k=1}^{\infty} \mathrm{Var}(Y_k)/k^2 \leq 4E|X_1| < \infty$. How to use it?
- Consider subsequence $k(n) = [\alpha^n]$ for arbitrary $\alpha > 1$. Using Chebyshev, if $\epsilon > 0$ then

$$\sum_{n=1}^{\infty} P\ \ |T_{k(n)} - ET_{k(n)}| > \epsilon k(n)) \leq \epsilon^{-1} \sum_{n=1}^{\infty} \mathrm{Var}(T_{k(n)})/k(n)^2$$

$$= \epsilon^{-2} \sum_{n=1}^{\infty} k(n)^{-2} \sum_{m=1}^{k(n)} \mathrm{Var}(Y_m) = \epsilon^{-2} \sum_{m=1}^{\infty} \mathrm{Var}(Y_m) \sum_{n:k(n)\geq m} k(n)^{-2}.$$

- **Sum series:**
$\sum_{n:\alpha^n \geq m} [\alpha^n]^{-2} \leq 4 \sum_{n:\alpha^n \geq m} \alpha^{-2n} \leq 4(1-\alpha^{-2})^{-1} m^{-2}$.
- **Combine computations (observe RHS below is finite):**

$$\sum_{n=1}^{\infty} P(|T_{k(n)} - ET_k(n)| > \epsilon k(n)) \leq 4(1-\alpha^{-2})^{-1} \epsilon^{-2} \sum_{m=1}^{\infty} E(Y_m^2) m^{-2}.$$

- Since ϵ is arbitrary, get $(T_{k(n)} - ET_{k(n)})/k(n) \to 0$ a.s.

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