18.175: Lecture 28

Even more on martingales

Scott Sheffield

MIT

Outline

Recollections

More martingale theorems

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More martingale theorems

Recall: conditional expectation

- Say we're given a probability space $(\Omega, \mathcal{F}_0, P)$ and a σ-field $\mathcal{F} \subset \mathcal{F}_0$ and a random variable X measurable w.r.t. $\mathcal{F}_0$, with $E|X| < \infty$. The **conditional expectation of X given $\mathcal{F}$** is a new random variable, which we can denote by $Y = E(X|\mathcal{F})$.
- We require that Y is $\mathcal{F}$ measurable and that for all A in $\mathcal{F}$, we have $\int_A X dP = \int_A Y dP$.
- Any Y satisfying these properties is called a **version** of $E(X|\mathcal{F})$.
- **Theorem:** Up to redefinition on a measure zero set, the random variable $E(X|\mathcal{F})$ exists and is unique.
- This follows from Radon-Nikodym theorem.
- **Theorem:** $E(X|\mathcal{F}_i)$ is a martingale if $\mathcal{F}_i$ is an increasing sequence of σ-algebras and $E(|X|) < \infty$.

Martingales

- Let $\mathcal{F}_n$ be increasing sequence of σ-fields (called a **filtration**).
- A sequence X_n is **adapted** to $\mathcal{F}_n$ if $X_n \in \mathcal{F}_n$ for all n. If X_n is an adapted sequence (with $E|X_n| < \infty$) then it is called a **martingale** if

$$E(X_{n+1}|\mathcal{F}_n) = X_n$$

  for all n. It's a **supermartingale** (resp., **submartingale**) if same thing holds with $=$ replaced by $\leq$ (resp., $\geq$).

Two big results

- **Optional stopping theorem:** Can't make money in expectation by timing sale of asset whose price is non-negative martingale.
- **Proof:** Just a special case of statement about $(H \cdot X)$ if stopping time is bounded.
- **Martingale convergence:** A non-negative martingale almost surely has a limit.
- **Idea of proof:** Count upcrossings (times martingale crosses a fixed interval) and devise gambling strategy that makes lots of money if the number of these is not a.s. finite. Basically, you buy every time price gets below the interval, sell each time it gets above.

Problems

- Assume Intrade prices are continuous martingales. (Forget about bid-ask spreads, possible longshot bias, this year's bizarre arbitrage opportunities, discontinuities brought about by sudden spurts of information, etc.)
- How many primary candidates does one expect to ever exceed 20 percent on Intrade primary nomination market? (Asked by Aldous.)
- Compute probability of having a martingale price reach a before b if martingale prices vary continuously.
- Polya's urn: r red and g green balls. Repeatedly sample randomly and add extra ball of sampled color. Ratio of red to green is martingale, hence a.s. converges to limit.

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L^p convergence theorem

- **Theorem:** If X_n is a martingale with $\sup E|X_n|^p < \infty$ where $p > 1$ then $X_n \to X$ a.s. and in L^p.
- **Proof idea:** Have $(EX_n^+)^p \le (E|X_n|)^p \le E|X_n|^p$ for martingale convergence theorem $X_n \to X$ a.s. Use L^p maximal inequality to get L^p convergence.

Orthogonality of martingale increments

- **Theorem:** Let X_n be a martingale with $EX_n^2 < \infty$ for all n. If $m \le n$ and $Y \in \mathcal{F}_m$ with $EY^2 < \infty$, then $E\big((X_n - X_m)Y\big) = 0$.
- **Proof idea:** $E\big((X_n - X_m)Y\big) = E\big[E\big((X_n - X_m)Y|\mathcal{F}_m\big)\big] = E\big[YE\big((X_n - X_m)|\mathcal{F}_m\big)\big] = 0$
- **Conditional variance theorem:** If X_n is a martingale with $EX_n^2 < \infty$ for all n then $E\big((X_n - X_m)^2|\mathcal{F}_m\big) = E(X_n^2|\mathcal{F}_m) - X_m^2$.

Square integrable martingales

- Suppose we have a martingale X_n with $EX_n^2 < \infty$ for all n.
- We know X_n^2 is a submartingale. By Doob's decomposition, an write $X_n^2 = M_n + A_n$ where M_n is a martingale, and

$$A_n = \sum_{m=1}^{n} E(X_m^2|\mathcal{F}_{m-1}) - X_{m-1}^2 = \sum_{m=1}^{n} E\big((X_m - X_{m-1})^2|\mathcal{F}_{m-1}\big).$$

- A_n in some sense measures total accumulated variance by time n.
- **Theorem:** $E(\sup_m |X_m|^2) \leq 4EA_\infty$
- **Proof idea:** L^2 maximal equality gives $E(\sup_{0\leq m\leq n} |X_m|^2) \leq 4EX_n^2 = 4EA_n$. Use monotone convergence.

Square integrable martingales

- Suppose we have a martingale X_n with $EX_n^2 < \infty$ for all n.
- **Theorem:** $\lim_{n\to\infty} X_n$ exists and is finite a.s. on $\{A_\infty < \infty\}$.
- **Proof idea:** Try fixing a and truncating at time $N = \inf\{n : A_{n+1} > a^2\}$, use L^2 convergence theorem.

Uniform integrability

- Say X_i, $i \in I$, are uniform integrable if
$$\lim_{M\to\infty}\left(\sup_{i\in I} E(|X_i|; |X_i| > M)\right) = 0.$$
- Example: Given $(\Omega, \mathcal{F}_0, P)$ and $X \in L^1$, then a uniformly integral family is given by $\{E(X|\mathcal{F})\}$ (where $\mathcal{F}$ ranges over all σ-algebras contained in $\mathcal{F}_0$).
- **Theorem:** If $X_n \to X$ in probability then the following are equivalent:
  - X_n are uniformly integrable
  - $X_n \to X$ in L^1
  - $E|X_n| \to E|X| < \infty$

Submartingale convergence

- Following are equivalent for a submartingale:
  - It's uniformly integrable.
  - It converges a.s. and in L^1.
  - It converges in L^1.

Backwards martingales

- Suppose $E(X_{n+1}|\mathcal{F}_n) = X$ with $n \leq 0$ (and $\mathcal{F}_n$ increasing as n increases).
- **Theorem:** $X_{-\infty} = \lim_{n \to -\infty} X_n$ exists a.s. and in L^1.
- **Proof idea:** Use upcrosing inequality to show expected number of upcrossings of any interval is finite. Since $X_n = E(X_0|\mathcal{F}_n)$ the X_n are uniformly integrable, and we can deduce convergence in L^1.

General optional stopping theorem

- Let X_n be a uniformly integrable submartingale.
- **Theorem:** For any stopping time N, $X_{N \wedge n}$ is uniformly integrable.
- **Theorem:** If $E|X_n| < \infty$ and $X_n 1_{(N>n)}$ is uniformly integrable, then $X_{N \wedge n}$ is uniformly integrable.
- **Theorem:** For any stopping time $N \leq \infty$, we have $EX_0 \leq EX_N \leq EX_\infty$ where $X_\infty = \lim X_n$.
- **Fairly general form of optional stopping theorem:** If $L \leq M$ are stopping times and $Y_{M \wedge n}$ is a uniformly integrable submartingale, then $EY_L \leq EY_M$ and $Y_L \leq E(Y_M | \mathcal{F}_L)$.

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