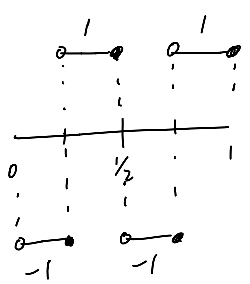
Lecture 7: Maximal inequality & the law of the iterated log

Throughout this lecture $(\Omega, \mathcal{F}, P)$ will denote the uniform prob measure on $\Omega = (0,1]$ generated by the binary digit coinflips from lecture 1.

Recall

$$S_n(w) := \sum_{k=1}^{n} R_k(w)$$



We will show two "maximal inequalities" which are useful for studying random series, martingales the law of the iterated log etc...

Thm 1.

If $a \geq 0$ then

$$P\left(\max_{k \leq n} S_k \geq a\right) \leq 2P(S_n \geq a).$$

Thm 2 (Kolmogorov's inequality).

If $a \geq 0$ then

$$P\left(\max_{k \leq n} |S_k| \geq a\right) \leq \frac{1}{a^2} \sum_{k=1}^{n} E(R_k^2).$$

Remark 1:

After the proof notice Thm 1 & 2 both hold when R_k is replaced with $\frac{R_k}{k}$ & S_n is replaced with $S_n' := \sum_{k=1}^{n} \frac{R_k}{k}$

Remark 2:

Thm 2 will generalize to the case $S_n := \sum_{k=1}^{n} Y_k$ for indep Y_k s.t. $E(Y_k) = 0$.

Also generalizes to martingale sequences $S_1, S_2, \ldots$

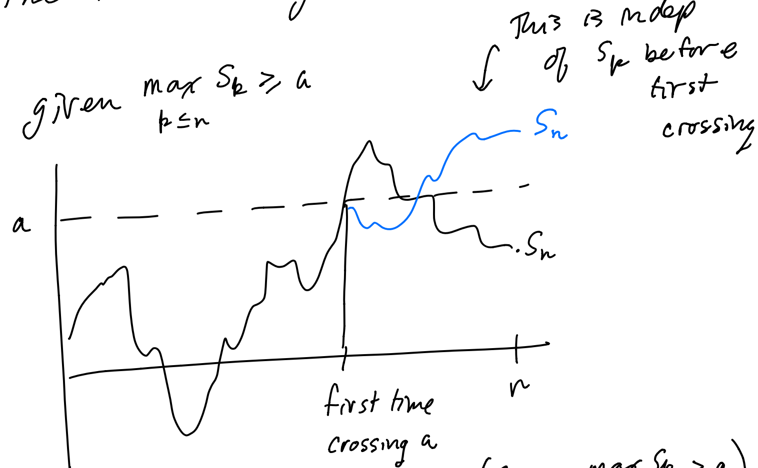
Remark 3:

Thm 1 will generalize when S_n is a "symmetric random walk"

$S_n := \sum_{k=1}^{n} Y_k$ where Y_k's are indep & Y_k has the same distribution as $-Y_k$.

Also generalizes to Brownian motion.

The heuristic argument is as follows:



$$\frac{1}{2} = P\left(S_n \geq a \,\middle|\, \max_{k \leq n} S_k \geq a\right) = \frac{P(S_n \geq a, \max_{k \leq n} S_k \geq a)}{P(\max_{k \leq n} S_k \geq a)}$$

$$\therefore\ P\left(\max_{k \leq n} S_k \geq a\right) = 2P\left(S_n \geq a, \max_{k \leq n} S_k \geq a\right) \leq 2P(S_n \geq a).$$

③

Proof of Thm 1:

trick #1 partition via $S_n \geq a$ vrs $S_n < a$

$$P(\max_{k\le n} S_k \geq a) = P(\max_{k\le n} S_k \geq a,\ S_n < a) + P(\underbrace{\max_{k\le n} S_k \geq a}_{\text{This set}} \supset \underbrace{S_n \geq a}_{\text{This set}})$$

$$= P(\max_{k\le n} S_k \geq a,\ S_n < a) + P(S_n \geq a)$$

So we just need to show

idea ... try to flip this to $a < S_n$

(*) $$P(\max_{k\le n} S_k \geq a,\ S_n < a) \leq P(S_n \geq a).$$

Trick #2, partition $\{\max_{k\le n} S_k \geq a\}$ by the first time $S_k \geq a$:

$$\{\max_{k\le n} S_k \geq a\} = \bigcup_{k=1}^{n} \underbrace{\{S_1 < a, \ldots, S_{k-1} < a, S_k \geq a\}}_{=: F_k \text{ are disjoint.}}$$

$$\therefore P(\max_{k\le n} S_k \geq a, S_n < a)$$

$$= \sum_{k=1}^{n-1} P(F_k \cap \{S_n < a\}), \quad F_n \cap \{S_n < a\} = \emptyset$$

$$\leq \sum_{k=1}^{n-1} P(F_k \cap \{S_n - S_k < 0\})$$

since $S_k \geq a$ on F_k
$\therefore S_n < a \leq S_k$
$\therefore S_n - S_k < 0$

$$= \sum_{k=1}^{n-1} P(\underbrace{F_k}_{\in \sigma\langle H_1, \ldots, H_k\rangle}) P(\underbrace{S_n - S_k < 0}_{\in \sigma\langle H_{k+1}, \ldots, H_n\rangle})$$

are indep

$$= \sum_{k=1}^{n-1} P(F_k) P(S_k - S_n < 0)$$

since probabilities for $S_1, S_2, \ldots$ are the same for $-S_1, -S_2, \ldots$

$$= \sum_{k=1}^{n-1} P(F_k \cap \{S_k - S_n < 0\})$$

again by indep.

④

$$= \sum_{k=1}^{n-1} P(F_k \cap \{S_k < S_n\})$$

$$\leq \sum_{k=1}^{n-1} P(F_k \cap \{a < S_n\})$$

since $a \leq S_k < S_n$ ← on F_k

$$\leq \sum_{k=1}^{n} P(F_k \cap \{a < S_n\})$$

$$= P\left(\left(\bigcup_{k=1}^{n} F_k\right) \cap \{a < S_n\}\right)$$

$$= P(\underbrace{\max_{k\le n} S_k \geq a}_{\text{this}} \supset \underbrace{a < S_n}_{\text{this}})$$

$$= P(a < S_n) \leq P(a \leq S_n)$$

$\therefore$ (*) holds as was to be shown. QED

Proof of Kolmogorov's inequality:

Use same trick #2

$$\{\max_{k\le n} |S_k| \geq a\} = \bigcup_{k=1}^{n} \underbrace{\{|S_1| < a, \ldots, |S_{k-1}| < a, |S_k| \geq a\}}_{=: F_k \text{, disjoint}}$$

Note: if $A_i \in \sigma\langle H_1, \ldots, H_k\rangle$ & $B_j \in \sigma\langle H_{k+1}, \ldots, H_n\rangle$ s.t.

$$\left.\begin{aligned} Y(w) &:= \sum a_i I_{A_i}(w) \\ X(w) &:= \sum b_j I_{B_j}(w) \end{aligned}\right\} \text{Finite sums with } a_i, b_j \in \mathbb{R}$$

Then $E(Y) := \int_0^1 Y(w)\,dw$ is well defined as a Riemann integral.

Similarly for $E(X)$.

Moreover

$$E(XY) = \sum_{ij} a_i b_j \underbrace{\int_0^1 I_{A_i}(w) I_{B_j}(w)\,dw}_{P(A_i \cap B_j)}$$

$$= \sum_{ij} a_i b_j P(A_i)P(B_j) \quad \text{by indep.}$$

$$\vdots$$

$$= E(X)E(Y).$$

Now

$$\sum_{p=1}^{n} E(R_p^2) = E(S_n^2) \quad \text{since } R_p\text{'s are orthonormal.}$$

$$\geq \sum_{p=1}^{n} E(I_{F_p} S_n^2)$$

since $\sum_{p}^{n} I_{F_p} = I_{\{\max_{p \le n} |S_p| \geq a\}}$

expand $(S_n \pm S_p)^2 I_{F_p}$

$$\geq \sum_{p=1}^{n} E(I_{F_p} S_p^2)$$

& drop $E(S_n - S_p)^2 I_{F_p}$

$$+ 2\sum_{p=1}^{n} E(S_p I_{F_p} (S_n - S_p))$$

where

$$E(\underbrace{S_p I_{F_p}}_{\substack{\text{constant over}\\ \sigma\langle H_1,\dots,H_p\rangle \text{ sets}}} \underbrace{(S_n - S_p)}_{\substack{\text{constant over } \sigma\langle H_{p+1},\dots,H_n\rangle\\ \text{sets}}}) = E(S_p I_{F_p}) \underbrace{E(S_n - S_p)}_{=0}$$

$$\therefore \sum_{p=1}^{n} E(R_p^2) \geq \sum_{p=1}^{n} E(I_{F_p} S_p^2)$$

on F_p, $|S_p| \geq a$

$$\geq a^2 \sum_{p=1}^{n} E(I_{F_p})$$

$$= a^2 P(\max_{p \le n} |S_p| \geq a)$$

QED

Application: Series with random signs

$\sum_n \frac{1}{n} = \infty$ } No cancelation at all

$\sum_n R_n \frac{1}{n} = ?$
$\sum_n R_n \frac{1}{\sqrt{n}} = ?$ } cancelation is given by random coin flips

$\sum_n (-1)^n \frac{1}{\sqrt{n}} < \infty$ } cancelation is finely tuned

For now we will only analyze the second. The third is answered by the Rademacher–Paley–Zygmund Thm.

Let $\tilde{S}_N = \sum_{n=1}^{N} R_n \cdot \frac{1}{n}$.

Notice that the proof of Kolmogorov's inequality goes through for

$$P\left(\max_{n: N \le n \le M} |\tilde{S}_n - \tilde{S}_N| > a\right) \le \frac{1}{a^2} \sum_{n=N+1}^{M} E\left(R_n^2 \frac{1}{n^2}\right)$$

$$= \frac{1}{a^2} \sum_{n=N+1}^{M} \frac{1}{n^2}$$

Note $\max_{n: N \le n \le M} |\tilde{S}_n - \tilde{S}_N| \uparrow$ as $M \to \infty$.

$$\therefore \left\{\max_{n: N \le n \le M} |\tilde{S}_n - \tilde{S}_N| > a\right\} \uparrow \left\{\sup_{n: N \le n} |\tilde{S}_n - \tilde{S}_N| > a\right\}$$

as $M \to \infty$

$$\therefore P\left(\sup_{n: N \le n} |\tilde{S}_n - \tilde{S}_N| > a\right) \le \frac{1}{a^2} \sum_{n=N+1}^{\infty} \frac{1}{n^2}$$

by continuity from below

$$\therefore P\left(\sup_{n,m: N \le n,m} |\tilde{S}_n - \tilde{S}_m| > 2a\right)$$

$\pm \tilde{S}_N$

$$\le P\left(2 \sup_{n: N \le n} |\tilde{S}_n - \tilde{S}_N| > 2a\right)$$

$$\le \frac{1}{a^2} \sum_{n=N+1}^{\infty} \frac{1}{n^2} \longrightarrow 0 \text{ as } N \to \infty$$

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$\therefore \quad \forall a > 0$

$$\lim_{N\to\infty} P\Big(\sup_{N\le n,m} |\tilde{S}_n - \tilde{S}_m| > 2a\Big) = 0$$

$$\|$$

$$P\Big(\lim_{N\to\infty}\downarrow \Big\{\sup_{N\le n,m} |\tilde{S}_n - \tilde{S}_m| > 2a\Big\}\Big)$$

$\therefore$

$$P\Big(\bigcup_{a\in\mathbb{Q}^+} \bigcap_{N=1}^{\infty} \Big\{\sup_{N\le n,m} |\tilde{S}_n - \tilde{S}_m| > 2a\Big\}\Big) = 0$$

$$\therefore P\Big(\underbrace{\bigcap_{a\in\mathbb{Q}^+} \bigcup_{N=1}^{\infty} \Big\{\sup_{N\le n,m} |\tilde{S}_n - \tilde{S}_m| \le 2a\Big\}}\Big) = 1$$

$\Rightarrow \tilde{S}_n$ is a Cauchy sequence

$\Rightarrow \lim_n \tilde{S}_n(w)$ exists & is finite

Notice: we didn't need a summable decay rate in the upper bound $P(X_N > a) \le b(a, N)$ to conclude $P(X_N \to 0) = 1$ where $X_N := \sup_{N\le n,m} |\tilde{S}_n - \tilde{S}_m|$ since $X_N \downarrow$ monotonically.

QED

Remark: This was a lot of work for one series... However the proofs are exactly similar for general Random sums $\sum_{k=1}^{\infty} Y_k$ where the Y_k's are indep, $E(Y_k) = 0$.

See durett p. 79.

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The law of the iterated logarithm

Reminder: P is the uniform measure on $[0,1]$ & $S_n(w) := \sum_{k=1}^{n} R_k(w)$.

Modivation:

WLLN: $\lim_n P\left(\left|\frac{S_n}{n}\right| > \varepsilon\right) \to 0$ as $n \to \infty$

SLLN: $P\left(\lim_n \frac{S_n}{n} = 0\right) = 1$.

So the WLLN describes the ensemble

$$\left\{\frac{S_n(w)}{n} : w \in \Omega\right\}$$

for a fixed $n \in \mathbb{N}$.

The SLLN describes the ensemble

$$\left\{\frac{S_n(w)}{n} : n \in \mathbb{N}\right\}$$

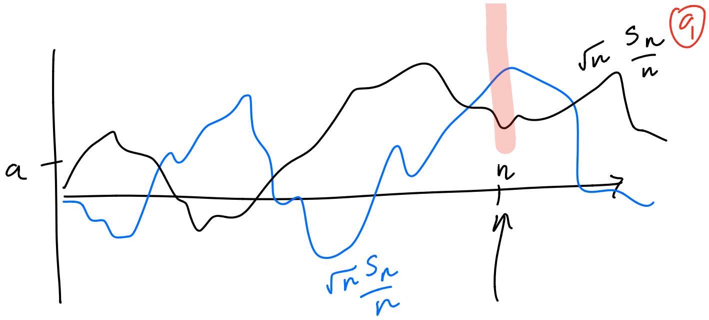
for a fixed $w \in \Omega$.

However both results say $\frac{S_n(w)}{n}$ is "near" 0. To get an idea of rates consider scaling $a_n \frac{S_n(w)}{n}$ for some $a_n \uparrow \infty$ to lift $\frac{S_n(w)}{n}$ away from 0.

Later we will show the CLT (central limit thm) which says

CLT:

$$\lim_{n\to\infty} P\left(\sqrt{n}\,\frac{S_n}{n} \ge a\right) = \frac{1}{\sqrt{2\pi}} \int_a^{\infty} e^{-t^2/2}\, dt$$



The CLT describes the probability a random from $\left\{\sqrt{n}\frac{S_n(w)}{n} : w \in \Omega\right\}$ is greater than a For a fixed but large n.

Unfortunately these rates are not right for $\left\{\sqrt{n}\frac{S_n}{n}(w) : n \in \mathbb{N}\right\}$ since the sup of $\}$ is ∞ for nearly all w.

The LIL (law of the iterated log) gives the right "almost sure rates".

$$\sup\left\{\frac{\sqrt{n}}{\sqrt{\log\log n}}\frac{S_n}{n}(w) : n \in \mathbb{N}\right\} = \sqrt{2}$$

$$\inf\left\{\frac{\sqrt{n}}{\sqrt{\log\log n}}\frac{S_n}{n}(w) : n \in \mathbb{N}\right\} = -\sqrt{2}$$

for nearly all $w \in \Omega$ (i.e. with prob 1).

Intuitively the $\sqrt{\log\log n}$ term controls the rare gaussian excursions $\sqrt{n}\frac{S_n}{n}$ takes under the CLT.

Another way to write this is

(i) $P\left(\limsup_{n\to\infty} \frac{S_n}{\sqrt{2n\log\log n}} = 1\right) = 1$

(ii) $P\left(\liminf_{n\to\infty} \frac{S_n}{\sqrt{2n\log\log n}} = -1\right) = 1$

Notice that (i) is equivalently written: $\forall \varepsilon > 0$

$$P\left(\frac{S_n}{\sqrt{2n\log\log n}} > 1-\varepsilon \text{ i.o.n}\right) = 1$$

$$\& \quad P\left(\frac{S_n}{\sqrt{2n\log\log n}} < 1+\varepsilon \text{ a.a.n}\right) = 1$$

(& similarly for (ii)) which follows since

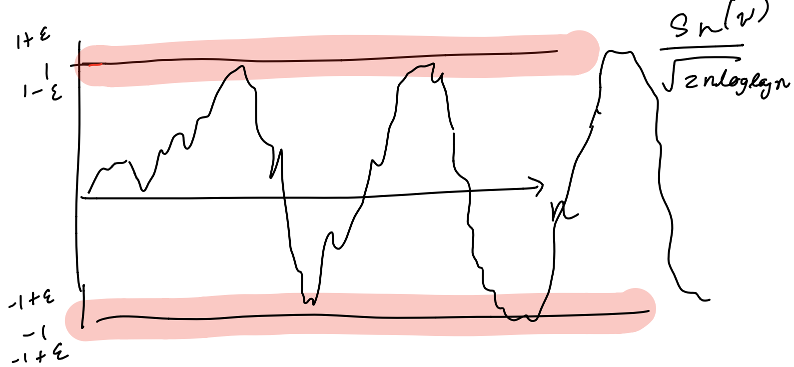
$$\left\{\limsup_{n\to\infty} \frac{S_n}{\sqrt{2n\log\log n}} = 1\right\}$$

implies $\limsup > 1-\varepsilon$

$$= \bigcap_{\varepsilon \in (0,1)\cap\mathbb{Q}^+} \left\{\frac{S_n}{\sqrt{2n\log\log n}} > 1-\varepsilon \text{ i.o.n} \text{ and } \frac{S_n}{\sqrt{2n\log\log n}} < 1+\varepsilon \text{ a.a.n}\right\}$$

implies $\limsup < 1+\varepsilon$

This gives a nice picture: for almost all w



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The LIL is a very detailed/fine analysis ... but it's a bit tedious.

I like covering it, however, since it gives a very advanced usage of both the First & second Borel-Cantelli lemmas.

The FBCL is used to show

$$P\left(\frac{S_n}{\sqrt{2n\log\log n}} \geq 1+\varepsilon \text{ i.o.n}\right)=0$$

but it can't be applied directly since $\sum_{n=1}^{\infty} P\left(\frac{S_n}{\sqrt{2n\log\log n}} \geq 1+\varepsilon\right)=\infty$.

The trick is to study sub-sequences n_k.

The SBCL is used to show

$$P\left(\frac{S_n}{\sqrt{2n\log\log n}} > 1-\varepsilon \text{ i.o.n}\right)=1$$

but, again, can't be applied directly since the events

$\left\{\frac{S_n}{\sqrt{2n\log\log n}} > 1+\varepsilon\right\}$ are not independent. The trick is to again look at subsequences & find

$$I_k \cap A_k \subset \left\{\frac{S_{n_k}}{\sqrt{2n_k\log\log n_k}} > 1+\varepsilon\right\}$$

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where the SBCL can be applied to I_k & $P(A_k \text{ a.a.k})=1$

so $P(I_k \cap A_k \text{ i.o.k})=1$.

Instead of writing the proof on the blackboard lets move to the projector