Stochastic Processes

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Contents

1 Review of Martingales

- $(X_n)_{n\geq 0}$ is L^2-bounded martingale $\Rightarrow X_n$ converges in L^2.
- $(X_n)_{n\geq 0}$ is L^1-bounded martingale $\Rightarrow X_n$ converges a.s.
- (1) + (2): If $(X_n)_{n\geq 0}$ is L^p-bounded martingale for $p>1$, then X_n converges in $L^{p'}$ for $p' \in [1,p)$.
- Statement is false when $p=1$. Example: $\Omega=[0,1), \mathscr{F}_n=\sigma\{[\frac{i}{2^n},\frac{i+1}{2^n})\}_{i=0}^{2^n-1}, X_n(\omega):=\begin{cases} 2^n & \omega\in[0,\frac{1}{2^n}) \\ 0 & \text{otherwise}\end{cases}$.
- Let $p>1$ and $(X_n)_{n\geq 0}$ be L^p bounded martingale w.r.t. $\mathscr{F}_n$. Then $\exists X \in L^p(\Omega,\mathscr{F}_\infty,P)$ s.t. $X_n\to X$ in L^p and a.s. and $X_n=\mathbb{E}(X|\mathscr{F}_n)$.
- Let $(Z_n)_{n\geq 0}$ be a nonnegative sub-martingale and $Z_n^*=\sup_{0\leq k\leq n} Z_k$, then $\mathbb{P}(Z_n^*>\lambda)\leq \frac{1}{\lambda}\mathbb{E}(Z_n 1_{\{Z_n^*>\lambda\}})\leq \frac{1}{\lambda}\mathbb{E}Z_n$. Corollary: $\mathbb{P}(Z_n^*>\lambda)\leq \frac{1}{\lambda^p}\mathbb{E}(Z_n^p 1_{\{Z_n^*>\lambda\}})\leq \frac{1}{\lambda^p}\mathbb{E}(Z_n^p)$.
- Doob's maximal inequality: Let $p>1, \exists C=C_p$ s.t. $\forall$ martingale $(X_n)_{n\geq 0}$, we have $\mathbb{E}|X_n^*|^p\leq C_p\mathbb{E}|X_n|^p$ where $|X_n^*|=\sup_{0\leq k\leq n}\sup|X_k|$.
- If $(X_n)_{n\geq 0}$ is a martingale with $\sup_n \mathbb{E}(|X_n|\log(1+|X_n|))<+\infty$, then X_n converges in L^1.

  Proof $\mathbb{E}|X_n^*| = \int_0^{+\infty}\mathbb{P}(|X_n^*|>\lambda)\mathrm{d}\lambda \leq 1+\int_1^{+\infty}\frac{1}{\lambda}(\int_{|X_n^*>\lambda|}|X_n|\mathrm{d}\mathbb{P})\mathrm{d}\lambda = 1+\int |X_n|1_{X_n^*>1}(\int_1^{X_n^*}\frac{1}{\lambda}\mathrm{d}\lambda)\mathrm{d}\mathbb{P} \Rightarrow \mathbb{E}|X_n^*|\leq 1+\mathbb{E}(|X_n|\log(X_n^*\vee 1))\Rightarrow \mathbb{E}(X_n^*\vee 1)\leq 2+\mathbb{E}(|X_n|\log(X_n^*\vee 1))$. Since $x\log y\leq 10^{10}(2+x)\log(2+x)+\frac{y}{2}$ when x,y are large enough (insight: if $y>>x^2$ then $x\log y\leq \frac{y}{2}$; else $x\log y\leq 10^{10}(2+x)\log(2+x)$), $\mathbb{E}X_n^*\leq 10^{100}[1+\mathbb{E}(|X_n|+2)\log(|X_n|+2)]$. Then use dominated convergence theorem. □

- Two probability measures $\mathbb{P}$ and $\mathbb{Q}$ on $(\Omega,\mathscr{F})$, $\mathbb{Q}<<\mathbb{P}$ on $\mathscr{F}_n$ for every n and $M_n=\frac{\mathrm{d}\mathbb{Q}|_{\mathscr{F}_n}}{\mathrm{d}\mathbb{P}|_{\mathscr{F}_n}}$. $(M_n)_{n\geq 0}$ is a $\mathbb{P}$-martingale w.r.t. $(\mathscr{F}_n)_{n\geq 0}$. $\mathbb{Q}<<\mathbb{P}$ on $\mathscr{F}_\infty$ if and only if $M_n\to M$ in L^1. $\mathbb{Q}(A)=\int_A M\mathrm{d}\mathbb{P}+\mathbb{Q}(A\cap\{M=+\infty\})$.

  Proof Sufficiency. $\mathbb{Q}<<\mathbb{P}$ on $\mathscr{F}=\mathscr{F}_\infty$, thus let $Z=\frac{\mathrm{d}\mathbb{Q}|_{\mathscr{F}}}{\mathrm{d}\mathbb{P}|_{\mathscr{F}}}$, we need to show M_n converges to Z in L^1. $\forall A\in\mathscr{F}_n, \int_A M_n\mathrm{d}\mathbb{P}=\mathbb{Q}(A)=\int_A Z\mathrm{d}\mathbb{P}\Rightarrow M_n=\mathbb{E}(Z|\mathscr{F}_n)$. Thus M_n is uniformly integrable, thus converges in L^1.
  Necessity. Suppose $M_n\to M$ a.s. and in L^1 We need to show $M_n=\mathbb{E}(M|\mathscr{F}_n)$ and $M=\frac{\mathrm{d}\mathbb{Q}}{\mathrm{d}\mathbb{P}}$. It suffices to show $\mathbb{Q}(A)=\int_A M\mathrm{d}\mathbb{P}$ for all $A\in\cup_n\mathscr{F}_n$. Suppose $A\in\mathscr{F}_N$. Then $\mathbb{Q}(A)=\int_A M_N\mathrm{d}\mathbb{P}=\int_A M_{N+k}\mathrm{d}\mathbb{P}\to\int_A M\mathrm{d}\mathbb{P}$. By $\pi-\lambda$ theorem we can get the desired result.
  Special situation: Suppose $\mathbb{P}\perp\mathbb{Q}$ on $\mathscr{F}(\exists E$ s.t. $\mathbb{P}(E)=1,\mathbb{Q}(E^c)=1)$ and $\mathbb{P}<<\mathbb{Q}$ on $\mathscr{F}_n$. Then $\frac{1}{M_n}$ converges $\mathbb{Q}$-a.s. Let $\mathbb{R}=\frac{1}{2}(\mathbb{P}+\mathbb{Q})$, $\mathbb{P},\mathbb{Q}<<\mathbb{R}$ on $\mathscr{F}$, $\frac{\mathrm{d}\mathbb{P}|_{\mathscr{F}_n}}{\mathrm{d}\mathbb{R}|_{\mathscr{F}_n}}=\frac{2}{1+M_n}\to\frac{2M}{1+M}$ in $L^1(\mathbb{R})$, $\frac{\mathrm{d}\mathbb{Q}}{\mathrm{d}\mathbb{R}}=\frac{2M_n}{1+M_n}\to\frac{2}{1+M}$ in $L^1(\mathbb{R})$. Then $\mathbb{Q}(A)=\mathbb{Q}(A\cap E^c)=\int_{A\cap E^c}\frac{2M}{1+M}\mathrm{d}\mathbb{R}=\int_A\frac{2M}{1+M}1_{E^c}\mathrm{d}\mathbb{R}\overset{\mathbb{P}(E^c)=0}{=}2\mathbb{R}(A\cap E^c)=2\int_A 1_{E^c}\mathrm{d}\mathbb{R}\Rightarrow\frac{2M}{1+M}1_{E^c}=2\cdot 1_{E^c}\Rightarrow M=+\infty$ on $E^c\Rightarrow\mathbb{Q}(M=+\infty)=1$. Similarly $\mathbb{P}(M=0)=\mathbb{Q}(M=+\infty)=1$.
  General situation: $\mathbb{Q}=\mathbb{Q}_1+\mathbb{Q}_2,\mathbb{Q}_1<<\mathbb{P},\mathbb{Q}_2\perp\mathbb{P}$ on $\mathscr{F}$. Therefore we can decompose M_n as $M_n=Y_n+Z_n$ where $Y_n\to Y$ in $L^1(\mathbb{P})$ and $Z_n\to 0$ $\mathbb{P}$-a.s. $\mathbb{Q}_1(A)=\int_A Y\mathrm{d}\mathbb{P}=\int_A M\mathrm{d}\mathbb{P}$. $\mathbb{Q}_2(A)=\mathbb{Q}_2(A\cap\{Z=+\infty\})$. Since $Z=0$ $\mathbb{P}$-a.s., $M<+\infty$ $\mathbb{P}$-a.s. and $\mathbb{Q}_2(M=+\infty)=1$, we have $\mathbb{Q}_2(A)=\mathbb{Q}(A\cap\{Z=+\infty\})=\mathbb{Q}_2(A\cap\{M=+\infty\})=\mathbb{Q}(A\cap\{M=+\infty\})$. To sum up, $\mathbb{Q}(A)=\int_A M\mathrm{d}\mathbb{P}+\mathbb{Q}(A\cap\{M=+\infty\})$. □

- Statement is false if $M_n\not\to M$ in L^1. Example: $\Omega=\{\omega=(\omega_1,\cdots,\omega_n,\cdots)\in\{\pm 1\}^{\mathbb{N}}\}, X_n(\omega)=\omega_n$. X_n's are i.i.d. under $\mathbb{P}$ and $\mathbb{Q}$, but $\mathbb{P}(X_n=1)=\frac{1}{2},\mathbb{P}(X_n=-1)=\frac{1}{2},\mathbb{Q}(X_n=1)=\frac{1}{3},\mathbb{Q}(X_n=-1)=\frac{2}{3}$. $\mathscr{F}_n=\sigma(X_1,\cdots,X_n)$. $\mathbb{P}(\lim_{n\to\infty}\frac{1}{n}\sum_{k=1}^n X_k=0)=1,\mathbb{Q}(\lim_{n\to\infty}\frac{1}{n}\sum_{k=1}^n X_k=-\frac{1}{3})=1$.
- Monotone class theorem for functions: Suppose $\mathcal{A}$ us a π-system and $\mathcal{H}$ be a class of functions from Ω to $\mathbb{R}$ s.t. (1) $1_A\in\mathcal{H}$ for every $A\in\mathscr{A}$, (2) if $f,g\in\mathcal{H}$ then $af+bg\in\mathcal{H}$, (3) if $f_n\in\mathcal{H}$ and $f_n\uparrow f$ then $f\in\mathcal{H}$. Then all nonnegative $\sigma(\mathcal{A})$-measurable functions are in $\mathcal{H}$.
- Let $(Y_n)_{n\geq 0}$ be i.i.d., nonnegative r.v.'s with $\mathbb{E}Y_k=1$. Then $M_n=\prod_{k=1}^n Y_k$ converges in L^1 iff $Y_n\equiv 1$. Otherwise $M_n\to 0$ a.s.

  Proof Note that $\frac{1}{n}\log M_n=\frac{1}{n}\sum_{k=1}^n\log Y_k\to\mathbb{E}\log Y$ a.s. If $\mathbb{E}\log Y=0$ then by Jensen's inequality we have $Y_n\equiv 1$ which means M_n converges in L^1. If $\mathbb{E}\log Y<0$ then $M_n\to 0$ a.s. □

- Kakutani's theorem: $M_n = \prod_{k=1}^n Y_k$, $Y_k \geq 0$ are independent, $\mathbb{E}Y_k = 1$, $\lambda_k = \mathbb{E}\sqrt{Y_k}$. (1) If $\prod_k \lambda_k > 0$, then $M_n \to M$ in L^1; (2) If $\prod_k \lambda_k = 0$, then $M_n \to 0$ a.s.

  Proof Let $Z_n = \prod_{k=1}^n \frac{\sqrt{Y_k}}{\lambda_k}$. Then Z_n is a martingale and has an a.s. limit Z, and $M_n = (\prod_{k=1}^n \lambda_k)^2 Z_n^2$. If $\prod_k \lambda_k > 0$, then Z_n is L^2 bounded and then convergence in L^2, which implies $M_n \to M$ in L^1. If $\prod_k \lambda_k = 0$, it is obvious that $M_n \to 0$ a.s. □

- Martingale LLN: Let $(M_n)_{n\geq 0}$ be a martingale s.t. $\sum_{k=1}^{+\infty} \frac{\mathbb{E}(M_k - M_{k-1})^2}{k^2} < +\infty$. Then $\frac{M_n}{n} \to 0$ a.s.

  Proof Let $Y_n = \sum_{k=1}^n \frac{X_k}{k}$. Then $(Y_n)_{n\geq 0}$ is an L^2 bounded martingale, thus $Y_n \to Y$ a.s. Then use Kronecker's lemma. □

- Martingale CLT: Let $(M_n)_{n\geq 0}$ be a martingale with $M_0 = 0$ and $\sigma_n^2 = \sum_{k=1}^n \mathbb{E}X_k^2 = \mathbb{E}\langle M\rangle_n$. Assume that $\frac{1}{\sigma_n^2}\max_{1\leq k\leq n}(\mathbb{E}X_k^2) \to 0$, $\frac{1}{\sigma_n^2}\sum_{k=1}^n \mathbb{E}(X_k^2 1_{\{|X_k|>\epsilon\sigma_n\}}|\mathscr{F}_{k-1}) \xrightarrow{p} 0$ for all $\epsilon > 0$, $\frac{1}{\sigma_n^2}\langle M\rangle_n \xrightarrow{p} 1$. Then $\frac{M_n}{\sigma_n} \Rightarrow \mathcal{N}(0,1)$.

2 Markov Chains

- Let $(X_n)_{n\geq 0}$ be a homogeneous Markov chain on a discrete space S. $\mathbb{P}^x$: law of $(X_n)_{n\geq 0}$ conditioned on $X_0 = x$. $\mathbb{P}(X_{n+1} \in A|\mathscr{F}_n) = \mathbb{P}^{X_n}(X_1 \in A) = \mathbb{P}(X_1 \in A|X_0 = X_n)$. $\mathbb{E}^x$: expectation under $\mathbb{P}^x$. $\mathbb{P}^x(X_1 = y) = p(x,y)$.

- For every $f : S \to \mathbb{R}$ bounded, define $(\mathcal{P}f)(x) = \sum_{y\in S} p(x,y)f(y) = \mathbb{E}^x(f(X_1))$, $(\mathcal{L}f)(x) = \sum_{y\in S} p(x,y)f(y) - f(x)$. $\mathcal{L} = \mathcal{P} - \mathrm{id}$, the generator.

- Let $(X_n)_{n\geq 0}$ be a homogeneous Markov chain with generator $\mathcal{L}$. Then for every bounded $f : S \to \mathbb{R}$, $M_n = f(X_n) - f(X_0) - \sum_{k=0}^{n-1}(\mathcal{L}f)(X_k)$ is a martingale. Conversely, let $(X_n)_{n\geq 0}$ be a process and $\mathcal{L}$ be an operator on $\mathcal{B}(S)$ s.t. M_n^f is a martingale for every f, then $(X_n)_{n\geq 0}$ is a Markov chain with generator $\mathcal{L}$.

- Given operator $\mathcal{L}$ on $\mathcal{B}(S)$, we say $f : S \to \mathbb{R}$ is (1) harmonic for $\mathcal{L}$ if $\mathcal{L}f = 0$; (2) sub-harmonic for $\mathcal{L}$ if $\mathcal{L}f \geq 0$; (3) super-harmonic for $\mathcal{L}$ if $\mathcal{L}f \leq 0$.

- Let f be the generator of a Markov chain $(X_n)_{n\geq 0}$. Then f is (sub-/super-)harmonic $\Leftrightarrow$ $f(X_n)_{n\geq 0}$ is a (sub-/super-) martingale.

- f is (sub-/super-)harmonic on $D \subset S$ if $\mathcal{L}f \geq / \leq / = 0$ on D. Let $\tau = \inf\{k \geq 0 : X_k \in D^c\}$, then $(f(X_{n\wedge\tau}))_{n\geq 0}$ is a (sub-/super)martingale.

- Maximum principle: Let $(X_n)_{n\geq 0}$ be a Markov chain and $D \subset S$ s.t. the stopping time $\tau = \inf\{k \geq 0, X_k \in D^c\}$ is a.s. finite. If f is bounded and sub-harmonic on D, then $\sup_{x\in D} f(x) \leq \sup_{x\in D^c} f(x)$.

  Proof f is sub-harmonic implies $(f(X_{n\wedge\tau}))$ is a sub-martingale, hence for $x \in D$ we have $f(x) \leq \mathbb{E}^x(f(X_{n\wedge\tau})) \to \mathbb{E}^x(f(X_\tau)) \leq \sup_{x\in D^c} f(x)$. □

- $A \subset S, \tau_A = \sup\{k \geq 0 : X_k \in A\}$. (1) $u(x) = \mathbb{P}^x(\tau_A < +\infty) \Rightarrow \begin{cases} \mathcal{L}u = 0 & \text{on } A^c \\ u = 1 & \text{on } A \end{cases}$. (2) $u(x) = \mathbb{P}(\tau_A < \tau_B) \Rightarrow$ $\begin{cases} \mathcal{L}u = 0 & \text{on } (A\cup B)^c \\ u = 1 & \text{on } A \\ u = 0 & \text{on } B. \end{cases}$. (3) $u(x) = \mathbb{E}^x[\tau_A] \Rightarrow \begin{cases} \mathcal{L}u = -1 & \text{on } A^c \\ u = 0 & \text{on } A \end{cases}$.

- Any nonnegative solution v to $\begin{cases} \mathcal{L}v = 0 & \text{on } A^c \\ v = 1 & \text{on } A \end{cases}$ satisfies $v \geq u$. Furthermore, if $u \equiv 1$, then $\exists 1$ bounded solution to $\begin{cases} \mathcal{L}v = 0 & \text{on } A^c \\ v = f & \text{on } A \end{cases}$ with $v(x) = \mathbb{E}^x(f(X_{\tau_A}))$.

  Proof Let $v(x)$ be a non-negative solution, then $v(X_{n\wedge\tau_A})_{n\geq 0}$ is a martingale. $v(x) = \mathbb{E}^x v(X_{n\wedge\tau_A}) = \mathbb{E}^x v(X_{n\wedge\tau_A})1_{\tau_A<\infty} + \mathbb{E}^x v(X_{n\wedge\tau_A})1_{\tau_A=\infty} \geq \mathbb{E}v(X_{n\wedge\tau_A})1_{\tau_A<\infty}$. Let $n \to \infty$ and by Fatou's lemma, we have $v(x) \geq \mathbb{E}^x v(X_{\tau_A})1_{\tau_A<\infty} = \mathbb{P}^x(\tau_A < \infty) = u(x)$. If $u(x) \equiv 1$ and $v(x)$ is bounded, then by bounded convergence theorem, $v(x) = \mathbb{E}^x v(X_{n\wedge\tau_A}) \to \mathbb{E}^x v(X_{\tau_A}) = \mathbb{E}^x f(X_{\tau_A})$.□

- Doob's h-transform: Let h be nonnegative, harmonic with $h(x_0)=1$ for some $x_0 \in S$. Then $(h(X_n))_{n\ge 0}$ is a martingale with $\mathbb{E}^{\mathbb{P}^{x_0}}(h(X_n))=1$. Then $\exists 1$ measure $\mathbb{Q}^h$ on $\mathscr{F}_\infty$ s.t. $\frac{\mathrm{d}\mathbb{Q}^h}{\mathrm{d}\mathbb{P}^{x_0}|_{\mathscr{F}_n}}=h(X_n), \forall n\ge 0$. $\mathbb{Q}^h(X_0=x_0)=1$, $(X_n)_{n\ge 0}$ never visits the set $D=\{x: h(x)=0\}$. Under $\mathbb{Q}^h$, $(X_n)_{n\ge 0}$ is again a Markov chain on $S\backslash D$ with transition probability $q(x,y)=\frac{p(x,y)h(y)}{h(x)}$ (or equivalently, $(\mathcal{L}^h f)(x)=\frac{1}{h(x)}(\mathcal{L}(hf))(x)$).

Proof The first two props are trivial. $\mathbb{Q}(X_{n+1}=y|\mathscr{F}_n)=\frac{\mathbb{Q}(X_{n+1}=y,X_n=x_n,\cdots,X_0=x_0)}{\mathbb{Q}(X_n=x_n,\cdots,X_0=x_0)}=\frac{\int_{\{X_{n+1}=y,X_n=x_n,\cdots,X_0=x_0\}}h(X_{n+1})\mathrm{d}\mathbb{P}^{x_0}}{\int_{\{X_n=x_n,\cdots,X_0=x_0\}}h(X_n)\mathrm{d}\mathbb{P}^{x_0}}=\frac{h(y)\mathbb{P}^{x_0}(X_{n+1}=y,X_n=x_n,\cdots,X_0=x_0)}{h(x_n)\mathbb{P}^{x_0}(X_n=x_n,\cdots,X_0=x_0)}=\frac{h(y)p(x_n,y)}{h(x_n)}$. Next we show $M_n^f:=f(X_n)-f(X_0)-\sum_{k=0}^{n-1}(\mathcal{L}^h f)(X_k)$ is a $\mathbb{Q}$-martingale for any bounded f. Let $Z_n=\mathbb{E}^{\mathbb{Q}}f(X_{n+1})|\mathscr{F}_n$. $\forall A\in\mathscr{F}_n$, $\int_A Z_n h(X_n)\mathrm{d}\mathbb{P}^{x_0}=\int_A Z_n\mathrm{d}\mathbb{Q}=\int_A f(X_{n+1})\mathrm{d}\mathbb{Q}=\int_A f(X_{n+1})h(X_{n+1})\mathrm{d}\mathbb{P}^{x_0}=\mathbb{E}^{\mathbb{P}^{x_0}}[\mathbb{E}^{\mathbb{P}^{x_0}}(f(X_{n+1})h(X_{n+1})1_A|\mathscr{F}_n)]=\mathbb{E}^{\mathbb{P}^{x_0}}[1_A\mathbb{E}^{\mathbb{P}^{x_0}}(f(X_{n+1})h(X_{n+1})|\mathscr{F}_n)]=\int_A\mathcal{P}(hf)(X_n)\mathrm{d}\mathbb{P}^{x_0}$. Thus $Z_n=\frac{\mathcal{P}(hf)(X_n)}{h(X_n)}$ only depends on X_n, i.e. $(X_n)_{n\ge 0}$ is a MC on $\mathbb{Q}$ with generator $\mathcal{L}^h$. □

- An irreducible Markov chain $(X_n)_{n\ge 0}$ (1) is transient if $\exists x$ and $A\subset S$ s.t. $\mathbb{P}(\tau_A<\infty|X_0=x)<1$; (2) is recurrent if $\exists$ a finite set $A\subset S$ s.t. $\mathbb{P}(\tau_A<\infty)=1$ for all $x\in S$. (3) is positive recurrent if $\exists$ a finite set $A\subset S$ s.t. $\mathbb{E}(\tau_A)<\infty$ for all $x\in S$.

- Foster-Lyapunov criterion: An irreducible MC on a countable state space S (1) is transient iff $\exists v: S\to\mathbb{R}^+$ and $A\subset S$ non-empty s.t. $\mathcal{L}v\le 0$ on A^c and $v(x)<\inf_{y\in A}v(y)$ for some $x\in A^c$; (2) is recurrent iff $\exists v:S\to\mathbb{R}^+$ s.t. $\mathcal{L}v\le 0$ on A^c where A is a finite set and $\{x: v(x)\le N\}$ is finite for every N; (3) is positive recurrent iff $\exists v:S\to\mathbb{R}^+$, $A\subset S$ finite, $\exists\epsilon>0$ s.t. $\mathcal{L}v\le-\epsilon$ on A^c and $\sum_{y\in S}p(x,y)V(y)<+\infty$ for all $x\in A$.

Proof (1) $v(X_{n\wedge\tau_A})_{n\ge 0}$ is a super-martingale, hence $v(x)\ge\mathbb{E}v(X_{n\wedge\tau_A})\ge\mathbb{E}v(X_{n\wedge\tau_A})1_{\tau_A<\infty}$. Let $n\to\infty$ we know $v(x)\ge\mathbb{E}v(X_{\tau_A}1_{\tau_A<\infty})\ge(\inf_{y\in A}v(y))\mathbb{P}^x(\tau_A<\infty)\Rightarrow\mathbb{P}^x(\tau_A<\infty)<\frac{v(x)}{\inf_{y\in A}v(y)}<1$. (2) On $\{\tau_A=\infty\}$, $\limsup_{n\to\infty}v(X_{n\wedge\tau_A})=+\infty$ a.s. Since $(v(X_{n\wedge\tau_A}))_{n\ge 0}$ is a nonnegative super-martingale, hence converges a.s., therefore $\lim_{n\to\infty}v(X_{n\wedge\tau_A})=+\infty$ a.s. Note that $v(x)\ge\mathbb{E}v(X_{n\wedge\tau_A})1_{\tau_A=\infty}$. Since LHS is a finite number, we have $\mathbb{P}^x(\tau_A=\infty)=0$. (3) $\mathbb{E}v(X_{n\wedge\tau_A})|\mathscr{F}_{n-1}\le v(X_{(n-1)\wedge\tau_A})-\epsilon 1_{\tau_A\ge n}$. Taking expectation on the both sides, $\mathbb{E}v(X_{n\wedge\tau_A})\le\mathbb{E}v(X_{(n-1)\wedge\tau_A})-\epsilon\mathbb{E}^x 1_{\tau_A\ge n}\le\cdots\le v(x)-\epsilon\sum_{k=1}^n\mathbb{P}^x(\tau_A\ge k)\Rightarrow\mathbb{E}^x\tau_A=\sum_{k=1}^\infty\mathbb{P}^x(\tau_A\ge k)\le\frac{v(x)}{\epsilon}<\infty$.

Conversely, (1) Let $v(x)=\mathbb{P}^x(\tau_A<\infty)$. (2) Let $u(x)=\mathbb{P}^x(\tau_B<\tau_A)$. We have shown that if $x\in(A\cup B)^c$ then $\mathcal{L}u\le 0$. When $x\in B$, $(\mathcal{L}u)(x)=\sum_{y\in S}p(x,y)u(y)-1\le 0$. Take $B_N\downarrow\emptyset$ s.t. B_N^c is finite for every N. Via a diagonal argument $\Rightarrow\exists$ subsequence $\{N_k\}$ s.t. $v(x):=\sum_{k\ge 1}\mathbb{P}^x(\tau_{B_{N_k}}<\tau_A)<+\infty$ for every $x\in S$. (3) Let $v(x)=\mathbb{E}^x(\tau_A)$. □

- e.g. $h(x)=\frac{\mathbb{P}^x(\tau_A<\tau_B)}{\mathbb{P}^{x_0}(\tau_A<\tau_B)}$ is harmonic on $(A\cup B)^c$ with $h(x_0)=1(x_0\in(A\cup B)^c)$. Then $\forall x,y\in(A\cup B)^c, q(x,y)=\frac{h(y)p(x,y)}{h(x)}=\frac{\mathbb{P}^y(\tau_A<\tau_B)p(x,y)}{\mathbb{P}^x(\tau_A<\tau_B)}=\frac{\mathbb{P}^x(X_1=y,\tau_A<\tau_B)}{\mathbb{P}^x(\tau_A<\tau_B)}=\mathbb{P}^x(X_1=y|\tau_A<\tau_B)$.

- e.g. $\mathbb{P}$ is simple symmetric random walk on $\mathbb{Z}$ starting from $X_0=0$. Question: what is the law of $(X_n)_{n\ge 0}$ conditioned on $X_n\ge 0$ for all n? Let $\tau_k=\inf\{n\ge 0, X_n=k\}$. On $\{\tau_N<\tau_{-1}\}$, $\frac{h(y)}{h(x)}=\frac{\mathbb{P}^y(\tau_N<\tau_{-1})}{\mathbb{P}^x(\tau_N<\tau_{-1})}=\frac{y+1}{x+1}$. Thus $q_N(x,y)=\frac{1}{2}\frac{y+1}{x+1}, |x-y|=1, x\in\{0,\cdots,N-1\}\Rightarrow q(x,y)=\frac{1}{2}\frac{y+1}{x+1}, x\ge 0, |x-y|=1$.

3 Ergodic Theorem

- Basic setup: a measurable map $T:(\Omega,\mathscr{F})\to(\Omega,\mathscr{F})$. Examples: (1) circle rotations: $\Omega=\mathbb{R}/\mathbb{Z}, T: x\mapsto x+\alpha$; (2) doubling map: $\Omega=\mathbb{R}/\mathbb{Z}, x\mapsto 2x$; (3) shift map: $\Omega=S^{\mathbb{N}}, (T\omega)_n=\omega_{n+1}$.

- Let $T:(\Omega,\mathscr{F})\to(\Omega,\mathscr{F})$ measurable and $\mathbb{P}$ be a probability measure on $(\Omega,\mathscr{F})$. We say T is measure-preserving if $\mathbb{P}(T^{-1}(A))=\mathbb{P}(A)$ for every $A\in\mathscr{F}$ (or $\mathbb{P}\circ T^{-1}=\mathbb{P}$).

- Question: what if we define by $\mathbb{P}(T(A))=\mathbb{P}(A)$ for every $A\in\mathscr{F}$ instead? $\mathbb{P}\circ T=\mathbb{P}\Rightarrow\mathbb{P}\circ T^{-1}=\mathbb{P}$ while the converse proposition is false.

- $(X_n)_{n\ge 0}$ be i.i.d. $\sim\mu$. We can build $(\Omega,\mathscr{F},\mathbb{P})$ and $X_n:\Omega\to\mathbb{R}$ measurable s.t. $(X_n)_{n\ge 0}$ i.i.d. $\sim\mu$ under $\mathbb{P}$: (1) $\Omega=\mathbb{R}^{\mathbb{N}}=\{\omega:\omega=(\omega_0,\omega_1,\cdots)\}$; (2) $X_n(\omega)=\omega_n$; (3) $\mathscr{F}=\sigma(X_0,X_1,\cdots,X_n,\cdots)$; (4) $\mathbb{P}=\mu^{\otimes\mathbb{N}}$. It is easy to show that the shift map is measure-preserving: $\mathscr{F}$ is generated by sets of the form $A=\{\omega_{k_1}\in I_1,\cdots,\omega_{k_N}\in I_N\}$, $T^{-1}(A)=\{\omega:(T\omega)_{k_1}\in I_1,\cdots,(T\omega)_{k_N}\in I_N\}=\{\omega:\omega_{k_1+1}\in I_1,\cdots,\omega_{k_N+1}\in I_N\}$. Key: the only thing used is that $(X_{k_1},\cdots,X_{k_N})\overset{\text{law}}{=}(X_{k_1+1},\cdots,X_{k_N+1})$ for every N and every $k_1,\cdots,k_N$.

- A sequence of random variables is stationary if $(X_n)_{n\in J} \overset{\text{law}}{=} (X_{n+k})_{n\in J}$ for all k and finite set J.
- Let $T : (\Omega, \mathscr{F}, \mathbb{P}) \to (\Omega, \mathscr{F}, \mathbb{P})$ be measure-preserving and $X : \Omega \to \mathbb{R}$ be measurable. Then $X_n(\omega) := X(T^n\omega)$ defines a stationary sequence.

  Proof It suffices to show that for every N, every $I_1, \cdots, I_N \subset \mathbb{R}$ and every $k_1 < k_2 < \cdots < k_N$, we have $\mathbb{P}(X_{k_1} \in I_1, \cdots, X_{k_N} \in I_N) = \mathbb{P}(X_{k_1+1} \in I_1, \cdots, X_{k_N+1} \in I_N)$. $\mathbb{P}(\{\omega : X_{k_1}(\omega) \in I_1, \cdots, X_{k_N}(\omega) \in I_N\}) = \mathbb{P}(T^{-1}\{\omega : X_{k_1}(\omega) \in I_1, \cdots, X_{k_N}(\omega) \in I_N\}) = \mathbb{P}(\{\omega : X_{k_1}(T\omega) \in I_1, \cdots, X_{k_N}(T\omega) \in I_N\}) = \mathbb{P}(\{\omega : X_{k_1+1}(\omega) \in I_1, \cdots, X_{k_N+1}(\omega) \in I_N\})$. □

- Let $(\Omega, \mathscr{F}, \mathbb{P}, T)$ be a measure-preserving system. (1) A set $A \in \mathscr{F}$ is invariant if $\mathbb{P}(A \triangle T^{-1}(A)) = 0$. (2) A random variable $X : \Omega \to \mathbb{R}$ is invariant if $X = X \circ T$ $\mathbb{P}$-a.e.
- The collection of invariant sets $\mathcal{I} = \{A \in \mathscr{F} : A \text{ is invariant}\}$ is a σ-algebra and $X : \Omega \to \mathbb{R}$ is invariant iff it is $\mathcal{I}$-measurable.
- We say $T : (\Omega, \mathscr{F}, \mathbb{P}) \to (\Omega, \mathscr{F}, \mathbb{P})$ measurable-preserving is ergodic if $\mathbb{P}(A) = 0$ or 1 for all $A \in \mathcal{I}$.
- Let $T : (\Omega, \mathscr{F}, \mathbb{P}) \to (\Omega, \mathscr{F}, \mathbb{P})$ be measure preserving and $f \in L^p (p \geq 1)$. Then $\frac{1}{N}\sum_{k=0}^{N-1} f \circ T^K \to \mathbb{E}(f|\mathcal{I})$ a.s. and in L^p. In particular, $\mathbb{E}(f|\mathcal{I}) = \mathbb{E}f$ if T is ergodic.

  Proof We first show convergence in L^p.

  Lemma 1 If $(\Omega, \mathscr{F}, \mathbb{P}, T)$ is a measure-preserving system and $X \in L^1(\Omega, \mathscr{F}, \mathbb{P})$. Then $\int_\Omega X \mathrm{d}\mathbb{P} = \int_\Omega X \circ T \mathrm{d}\mathbb{P}$. In fact, $||X||_{L^p} = ||X \circ T||_{L^p}, p \in [1, +\infty]$.

  Proof Take $X = 1_A$. LHS $= \mathbb{P}(A) = \mathbb{P}(T^{-1}(A)) = \int_\Omega 1_A(T\omega)\mathrm{d}\mathbb{P}$. □

  Let $\mathcal{U}_T : L^p(\Omega, \mathscr{F}, \mathbb{P}) \to L^p(\Omega, \mathscr{F}, \mathbb{P})$ be defined by $(\mathcal{U}_T f)(\omega) := f(T\omega)$ (or $\mathcal{U}_T f = f \circ T$).

  For $p = 2$, $\mathcal{U}_T : L^2 \to L^2$ is an isometry in the sense that $\langle f, g\rangle = \langle \mathcal{U}_T f, \mathcal{U}_T g\rangle$. LHS $= \frac{1}{N}\sum_{k=0}^{N} \mathcal{U}_T^k f$, $f = \mathbb{E}(f|\mathcal{I}) + (f - \mathbb{E}(f|\mathcal{I})) \Rightarrow$ LHS $= \underbrace{\mathbb{E}(f|\mathcal{I})}_{\mathrm{Ker}(\mathcal{U}_T - \mathrm{Id}) \overset{?}{=} \mathrm{Ker}(\mathcal{U}_T^* - \mathrm{Id})} + \frac{1}{N}\sum_{k=0}^{N} \mathcal{U}_T^k (f - \mathbb{E}(f|\mathcal{I}))$. Since $\mathcal{H} = \mathrm{Ker}(A) \oplus \overline{\mathrm{Im}(A^*)}$, $\exists g \in \mathcal{H}$ s.t. $||f - \mathbb{E}(f|\mathcal{I}) - \underbrace{(\mathcal{U}_T^* - \mathrm{Id})g}_{\overset{?}{=}(\mathcal{U}_T - \mathrm{Id})g}|| < \epsilon$.

  Lemma 2 Let $A : \mathcal{H} \to \mathcal{H}$ be an isometry. If $Af = f$, then $A^* f = f$.

  Proof $\langle A^* f, g\rangle = \langle f, Ag\rangle = \langle Af, Ag\rangle = \langle f, g\rangle$. □

  Proposition 1 $\mathcal{H} = \mathrm{Ker}(A^*) \oplus \overline{\mathrm{Im}(A)}$.

  Proof We show that $\mathrm{Ker}(A^*) = (\mathrm{Im}(A))^\perp$. (i) $f \in \mathrm{Ker}(A^*) \Rightarrow A^* f = 0 \Rightarrow \langle f, Ag\rangle = \langle A^* f, g\rangle = 0$. (ii) $f \in (\mathrm{Im}(A))^\perp \Rightarrow \langle f, Ag\rangle = 0$ for all $g \in \mathcal{H} \Rightarrow \langle A * f, g\rangle = 0$ for all $g \in \mathcal{H} \Rightarrow A^* f = 0$. □

  $\mathcal{H} = L^2(\omega, \mathscr{F}, \mathbb{P}) = \mathrm{Ker}(\mathcal{U}_T^* - \mathrm{Id}) + \overline{\mathrm{Im}(\mathcal{U}_T - \mathrm{Id})} \Rightarrow \forall f \in \mathscr{H}, \forall \epsilon > 0, \exists g, h \in \mathscr{H}$ s.t. $||h||_{L^2} < \epsilon$ and $f = \mathbb{E}(f|\mathcal{I}) + (\mathcal{U}_T - \mathrm{Id})g + h \Rightarrow \frac{1}{N}\sum_{k=0}^{N-1} \mathcal{U}_T^k f = \mathbb{E}(f|\mathcal{I}) + \underbrace{\frac{1}{N}(\mathcal{U}_T^N g - g)}_{||\cdot||_{L^2} \leq \frac{2}{N}||g||_{L^2} \to 0} + \underbrace{\frac{1}{N}\sum_{k=0}^{N-1} \mathcal{U}_T^k h}_{||\cdot||_{L^2} < \epsilon} \Rightarrow \limsup_{N\to\infty} ||\frac{1}{N}\sum_{k=0}^{N-1} \mathcal{U}_T f - \mathbb{E}(f|\mathcal{I})||_{L^2} < \epsilon$.

  For $p \neq 2$, let $S_N f = \sum_{k=0}^{N-1} f \circ T^k$ and $A_N f = \frac{1}{N} S_N f$.

  (1) If $f \in L^\infty$, then $||A_N f||_{L^\infty} \leq ||f||_{L^\infty}, ||A_N f - \mathbb{E}(f|\mathcal{I})||_{L^2} \to 0 \Rightarrow A_N f \to \mathbb{E}(f|\mathcal{I})$ in L^p for every $p \in [1, +\infty)$ (for $p \geq 2$, $||A_N f - \mathbb{E}(f|\mathcal{I})||_{L^p}^p \leq ||f||_{L^\infty}^{p-2} ||A_N f - \mathbb{E}(f|\mathcal{I})||_{L^2}^2$; for $1 \leq p < 2$, $||A_N f - \mathbb{E}(f|\mathcal{I})||_{L^p}^p \leq ||A_N f - \mathbb{E}(f|\mathcal{I})||_{L^2}^p ||1||_{L^2}^{2-p}$).

  (2) If $f \in L^p (p \geq 1)$, then $\forall \epsilon > 0, \exists g \in L^\infty$ s.t $||f - g||_{L^p} < \epsilon$,

  $||A_N f - \mathbb{E}(f|\mathcal{I})||_{L^p} \leq \underbrace{||A_N(f - g)||_{L^p}}_{<\epsilon} + \underbrace{||A_N g - \mathbb{E}(g|\mathcal{I})||_{L^p}}_{\to 0 \text{ as } N \to +\infty} + \underbrace{||\mathbb{E}(g - f|\mathcal{I})||_{L^p}}_{<\epsilon} \Rightarrow \forall \epsilon > 0, \limsup_{N\to\infty} ||A_N f - \mathbb{E}(f|\mathcal{I})||_{L^p} < 2\epsilon$.

  We next show convergence a.s.

  Maximum ergodic theorem $f \in L^1(\Omega, \mathscr{F}, \mathbb{P}), S_n = \sum_{k=0}^{n-1} f \circ T^k, M_n = \max\{S_1, \cdots, S_n\}$. Then $\int_{\{M_n \geq 0\}} f(\omega)\mathbb{P}(\mathrm{d}\omega) \geq 0$.

  Proof $M_{n-1}(T\omega) = \max\{S_1(T\omega), \cdots, S_{n-1}(T\omega)\} = \max\{S_2(\omega), \cdots, S_n(\omega)\} - f(\omega) \Rightarrow \max\{0, M_{n-1}(T\omega)\} = M_n(\omega) - f(\omega) \Rightarrow f(\omega) = M_n(\omega) - \max\{0, M_{n-1}(T\omega)\}$. $\int_{\{M_n > 0\}} f\mathrm{d}\mathbb{P} = \int_{\{M_n > 0\}} M_n \mathrm{d}\mathbb{P} - \int_{\{M_n > 0\}} \max\{0, M_{n-1}(T\omega)\}\mathrm{d}\mathbb{P} = \int_{\{M_n > 0\}} M_n\mathrm{d}\mathbb{P} - \int_{\{M_n > 0\} \cap \{M_{n-1} \circ T > 0\}} M_{n-1} \circ T\mathrm{d}\mathbb{P} \Rightarrow \int_{\{M_n > 0\}} f\mathrm{d}\mathbb{P} \geq \int_{\{M_n \geq 0\}} M_n \mathrm{d}\mathbb{P} - \int_{\{\cdots\}} M_n \circ T\mathrm{d}\mathbb{P} = \int_{\{M_n \geq 0\}} M_n\mathrm{d}\mathbb{P} - \int_{T\{\cdots\}} M_n\mathrm{d}\mathbb{P} \geq 0$. □

  Corollary 1 $\mathbb{P}(\omega : \sup_{n\geq 1}(A_n f)(\omega) > \lambda) \leq \frac{\mathbb{E}|f|}{\lambda}$.

  Proof Let $E_N = \{\omega : \sup_{1\leq n\leq N}(A_n f)(\omega) > \lambda\} = \{\omega : \sup_{1\leq n\leq N}(A_n(f - \lambda))(\omega) > 0\} = \{\omega : \sup_{1\leq n\leq N}(S_n(f - \lambda))(\omega) > 0\}$. $E_N \uparrow E = \{\omega : \sup_{n\geq 1}(A_n f)(\omega) > \lambda\}$. $\int_{E_n}(f - \lambda)\mathrm{d}\mathbb{P} \geq 0 \Rightarrow \mathbb{P}(E_n) \leq \frac{\int_{E_n} f\mathrm{d}\mathbb{P}}{\lambda} \leq \frac{\mathbb{E}|f|}{\lambda} \Rightarrow \mathbb{P}(E) \leq \frac{\mathbb{E}|f|}{\lambda}$. □

Goal: $f \in L^1$ (for finite measure $\mathbb{P}$, $L^p \subset L^1$), need to show $\frac{1}{N}\sum_{k=0}^{N-1} f \circ T^k \to \mathbb{E}(f|\mathcal{I})$ a.s.

(1) If $f \in L^2$ is $\mathcal{I}$-measurable, then $A_N f = f = \mathbb{E}(f|\mathcal{I})$ a.s.

(2) If $f = (\mathcal{U}_T - \mathrm{Id})g$ for some $g \in L^\infty$, then $(A_N f)(\omega) = \frac{1}{N}(g(T^N\omega) - g(\omega)) \le \frac{2\|g\|_{L^\infty}}{N} \to 0$. Check $\mathbb{E}((\mathcal{U}_T - \mathrm{Id})g|\mathcal{I}) = 0 : \forall A \in \mathcal{I}, \int_A (g \circ T - g)\mathrm{d}\mathbb{P} = \int_{T^{-1}(A)} g \circ T \mathrm{d}\mathbb{P} - \int_A g\mathrm{d}\mathbb{P} = \int_A g\mathrm{d}\mathbb{P} - \int_A g\mathrm{d}\mathbb{P} = 0$.

(3) $\Lambda = \{f = \mathbb{E}(f_0|\mathcal{I}) + (\mathcal{U}_T - \mathrm{Id})g : f_0 \in L^2, g \in L^\infty\}$ is dense in L^1. If $f \in L^1$, then $\exists f_j \in \Lambda$ s.t. $f_j \to f$ in L^1. We need to show $\mathbb{P}(\limsup_{N\to\infty} |A_N f - \mathbb{E}(f|\mathcal{I})| > \epsilon) = 0$. $|A_N f - \mathbb{E}(f|\mathcal{I})| \le |A_N(f - f_j)| + \underbrace{|A_N f_j - \mathbb{E}(f_j|\mathcal{I})|}_{\to 0 \text{ a.s.}} + |\mathbb{E}(f_j - f|\mathcal{I})| \Rightarrow$ $\mathbb{P}(\limsup_{N\to\infty} |A_N f - \mathbb{E}(f|\mathcal{I})| > \epsilon) \le \mathbb{P}(\limsup_{N\to+\infty} |A_N(f - f_j)| > \frac{\epsilon}{2}) + \mathbb{P}(|\mathbb{E}(f_j - f|\mathcal{I})| > \frac{\epsilon}{2}) \le \frac{2\mathbb{E}|f_j - f|}{\epsilon} + \frac{2\mathbb{E}|f_j - f|}{\epsilon} \to 0$. $\square$

- Kingman's subadditive ergodic theorem: Let $(\Omega, \mathscr{F}, \mathbb{P}, T)$ be a measure-preserving space and $\{g_n\} \in L^1$ subadditive in the sense that $g_{n+m} \le g_n + g_m \circ T^n$ for every n, m. Then (1) $\lim_{n\to\infty} \frac{\mathbb{E}(g_n)}{n} \to \inf_{k\ge1} \frac{\mathbb{E}(g_k)}{k}$ (possibly $-\infty$); (2) $\frac{g_n}{n}$ convergence a.s. to F where F is $\mathcal{I}$-measurable and $\mathbb{E}F = \inf_{k\ge1}\frac{\mathbb{E}(g_k)}{k}$; (3) If $\mathbb{E}F > -\infty$, then the convergence is also in L^1.

Proof Recall an elementary version. If $\{a_n\} \in \mathbb{R}$ s.t. $a_{n+m} \le a_n + a_m, \forall n, m$, then $\frac{a_n}{n} \to \inf_{k\ge1} \frac{a_k}{k}$ as $n \to \infty$.

We assume $g_n \le 0$.

(1) $H(\omega) := \liminf_{n\to\infty} \frac{g_n(\omega)}{n}$. Claim $H = H \circ T$. $g_{n+1}(\omega) \le g_1(\omega) + g_n(T\omega) \Rightarrow H \le H \circ T$. T measure-preserving $\Rightarrow H \overset{\text{law}}{=} H \circ T$. Then we must have $H = H \circ T$ $\mathbb{P}$-a.s.

(2) Now need to show for every $\epsilon > 0$, we have $\limsup_{n\to\infty} \frac{g_n}{n} < H + \epsilon$ $\mathbb{P}$-a.s. Let $n_i = \sum_{j=1}^i k_j$ and $n_M = n$. Then $g_n(\omega) \le g_{k_1}(\omega) + g_{n-k_1}(T^{k_1}\omega) \le g_{k_1}(\omega) + g_{k_2}(T^{k_1}(\omega)) + g_{n-k_1-k_2}(T^{n_2}\omega) \le \cdots \Rightarrow g_n(\omega) \le \sum_{j=0}^{M-1} g_{k_{j+1}}(T^{n_j}\omega)$ (hope $g_{k_{j+1}}(T^{n_j}\omega) \le k_{j+1}(H(\omega) + \epsilon)$). Fix $k > 0$, define $A_k = \{\omega : \frac{g_l(\omega)}{l} < H(\omega) + \epsilon \text{ for some } 1 \le l \le k\}$, $B_k = \{\omega : \frac{g_l(\omega)}{l} \ge H(\omega) + \epsilon \text{ for every } 1 \le l \le k\}$. If $\exists 1 \le l \le k \wedge (n-1)$ s.t. $\frac{g_l(\omega)}{l} < H(\omega) + \epsilon$, then let $k_1 := \inf\{l : \frac{g_l(\omega)}{l} < H(\omega) + \epsilon\}$, otherwise let $k_1 = 1$. If $\exists 1 \le l \le k \wedge (n - n_p)$ s.t. $\frac{g_l(T^{n_p}\omega)}{l} < H(\omega) + \epsilon$, then $k_{p+1} := \inf\{l : \frac{g_l(T^{n_p}\omega)}{l} < H(\omega) + \epsilon\}$, otherwise let $k_{p+1} = 1$. Let $\Lambda(\omega) = \{0 \le j \le M(\omega) - 1 : g_{k_{j+1}}(T^{n_j}\omega) < k_{j+1}(\omega)(H(\omega) + \epsilon)\} \Rightarrow g_n(\omega) \le \sum_{j\in\Lambda(\omega)} g_{k_m}(T^{n_j}(\omega)) \le \sum_{j\in\Lambda(\omega)} k_{j+1}(H(\omega) + \epsilon) \Rightarrow g_n(\omega) < n\epsilon + H(\omega)\sum_{j\in\Lambda(\omega)} k_{j+1} \Rightarrow \limsup_{n\to\infty} \frac{g_n(\omega)}{n} < \epsilon + H(\omega)\liminf_{n\to\infty} \frac{\sum_{j\in\Lambda(\omega)} k_{j+1}}{n}$. $\sum_{j\in\Lambda} k_{j+1} \ge n - k - \sum_{j=0}^{M-1} 1_{B_k}(T^{n_j}\omega) \Rightarrow \frac{\sum_{j\in\Lambda} k_{j+1}}{n} \ge 1 - \frac{k}{n} - \frac{1}{n}\sum_{j=0}^{n-1} 1_{B_k}(T^j\omega) \Rightarrow \liminf_{n\to\infty} \frac{\sum_{j\in\Lambda} k_{j+1}}{n} \ge 1 - \mathbb{E}(1_{B_k}|\mathcal{I}) \Rightarrow \limsup_{n\to\infty} \frac{g_n(\omega)}{n} < \epsilon + H(\omega)(1 - \mathbb{E}(1_{B_k}|\mathcal{I}))$. Let $k \to \infty$, $B_k \downarrow \emptyset \Rightarrow \mathbb{E}(1_{B_k}|\mathcal{I}) \to 0$ a.s., thus RHS $\to \epsilon + H(\omega)$.

(3) Let $g_n^{(\lambda)} = \max\{-\lambda n, g_n\}$. Then $\{g_n^{(\lambda)}\}$ is subadditive and we have $\frac{g_n^{(\lambda)}}{n} \to F^{(\lambda)}$ a.s. and in L^1 (by uniform boundedness). $\mathbb{E}F^{(\lambda)} = \inf_{k\ge1} \frac{\mathbb{E}g_k^\lambda}{k}$ and $F^{(\lambda)} = \max\{F, -\lambda\}$. Then $\mathbb{E}F = \inf_{\lambda>0} \mathbb{E}F^\lambda = \inf_{\lambda>0}\inf_{k\ge1} \frac{\mathbb{E}g_k^{(\lambda)}}{k} = \inf_{k\ge1}\inf_{\lambda>0} \frac{\mathbb{E}g_k^{(\lambda)}}{k} = \inf_{k\ge1}\frac{\mathbb{E}g_k}{k}$.

For general subadditive $\{g_n\}$, define $\tilde{g}_n = g_n - \sum_{k=0}^{n-1} g_1 \circ T^k$ which is negative and subadditive, and $\frac{g_n}{n} = \frac{\tilde{g}_n}{n} + \frac{1}{n}\sum_{k=0}^{n-1} g_1 \circ T^k$. Convergence of the first term has been proved and convergence of the next term is by the standard ergodic theorem. $\square$

4 Brownian Motion

- A one-dimensional B.M. (on $[0, T]$) is a real-valued process $(B_t)_{t\in[0,T]}$ s.t. (1) For every $0 < t_1 < \cdots < t_n = T$, the r.v.'s $B_{t_1} - B_0, B_{t_2} - B_{t-1}, \cdots, B_{t_n} - B_{t_{n-1}}$ are independent $\mathcal{N}(0, t_i - t_{i-1})$; (2) With probability 1, the sample path $t \mapsto B_t$ is continuous.

- A real-valued stochastic process $(X_t)_{t\in I}$ is a map $X : I \times \Omega \to \mathbb{R}$ s.t. (i) For every $\omega \in \Omega$, $X(\omega)$ is a real-valued function on I; (ii) For every $t \in I$, X_t is a random variable.

- Construction of stochastic processes: $\mathscr{F}$ is the smallest σ-algebra s.t. $X_t : \Omega \to \mathbb{R}$ is measurable for every $t \in I$. Finite dimensional distributions (f.d.d.) are laws of $(X_{t_1}, \cdots, X_{t_n})$. Natural to take $\Omega = \mathbb{R}^I$. $\mathscr{F}$ is generated by cylinder sets $\{\omega : \omega|_J \in A, J \text{ finite}, A \subset \mathbb{R}^{|J|}\}$. For every finite index set $J = (t_1, \cdots, t_n) \in I^n$, need to specify the f.d.d. $Q_J := \mathrm{Law}(X_{t_1}, \cdots, X_{t_n})$. We are given $\{Q_J\}_{J \text{ finite}}$. We say the family of f.d.d. $\{Q_J\}_{J \text{ finite}}$ is consistent if for every $J' \subset J$, we have $Q_J \circ \pi_{J,J'}^{-1} = Q_{J'}$ where $\pi_{J,J'} : \mathbb{R}^J \to \mathbb{R}^{J'}$ is the canonical projection.

- Kolmogorov's extension theorem: If the family of f.d.d. is consistent, then $\exists 1$ probability measure $\mathbb{P}$ on $(\mathbb{R}^I, \mathscr{F})$ s.t. $\mathbb{P} \circ \pi_J^{-1} = Q_J$ for every J finite.

Proof Let $\mathcal{C} = \{\omega : \omega|_J \in A, J \text{ finite}, A \subset \mathbb{R}^{|J|}\}$. It suffices to construct $\mathbb{P}$ on $\mathcal{C}$ and prove uniqueness. (1) If $E \in \mathcal{C}$, then $E = \{\omega : \omega|_J \in A\}$ for some I and $A \subset \mathbb{R}^{|J|}$, and define $\mathbb{P}(E) = Q_J(A)$. Uniqueness follows immediately (if it is well defined).

Suppose $\exists J'$ and $A' \subset \mathbb{R}^{|J'|}$ s.t. $E = \{\omega : \omega|_J \in A\} = \{\omega : \omega_{J'} \in A'\}$. Let $J^* = J \cup J'$, then $\{\omega : \omega|_{J^*} \in A \times \mathbb{R}^{J^* \setminus J}\} = \{\omega : \omega|_J \in A\} = \{\omega : \omega|_{J'} \in A'\} = \{\omega : \omega|_{J^*} \in A' \times \mathbb{R}^{J^* \setminus J'}\}$. By consistency, $Q_J(A) = Q_{J^*}(A \times \mathbb{R}^{J^* \setminus J}) = Q_{J^*}(A' \times \mathbb{R}^{J^* \setminus J'}) = Q_{J'}(A')$. (2) We first show finite additivity. Let $E, E' \subset \mathcal{C}$ be disjoint. Then there exist J and $A, A' \subset \mathbb{R}^{|J|}$ disjoint s.t. $E = \{\omega : \omega|_J \in A\}$ and $E' = \{\omega : \omega|_J \in A'\}$. $\mathbb{P}(E \cup E') = Q_J(A \cup A') = Q_J(A) + Q_J(A') = \mathbb{P}(E) + \mathbb{P}(E')$. (3) For countable additivity, it suffices to show that if $E_n \downarrow \emptyset$, then $\mathbb{P}(E_n) \downarrow 0$. Need to show that if $\{E_n\}$ is a sequence of decreasing sets in $\mathcal{C}$ s.t. $\mathbb{P}(E_n) \downarrow \delta > 0$, then $\cap_{n \geq 1} E_n$ is non-empty. We can find $J_1 \subset \cdots \subset J_n \subset \cdots$ and sets $A_n \in J_n$ with $A_{n+1} \subset \pi^{-1}_{J_{n+1}, J_n}(A_n)$ s.t. $E_n = \{\omega : \omega|_{J_n} \in A_n\}$. For every n, $\exists$ compact $K_n \subset A_n$ s.t. $Q_{J_n}(K_n) > Q_{J_n}(A_n) - \frac{\delta}{2^{n+1}}$. Let $G_n = \pi^{-1}_{J_n}(K_n)$. Consider the set $\cap_{k=1}^N G_k$ in $\Omega = \mathbb{R}^I$. $\mathbb{P}(\cap_{k=1}^N G_k) \geq \mathbb{P}(\cap_{k=1}^N E_k) - \sum_{k=1}^N \mathbb{P}(E_k \backslash G_k) > \delta - \frac{\delta}{2} = \frac{\delta}{2} \Rightarrow$ For every N, $\exists \omega^{(N)} \in \cap_{k=1}^N G_k \Rightarrow \omega^{(N)}|_{J_m} \in K_m$ for every $m \leq N \Rightarrow \exists$ subsequence of $\{\omega^{(N)}|_{J_1}\}_N$ convergent in K_1 and denote the limit by $Z_1 \in K_1 \Rightarrow \exists$ further subsequence $\{\omega^{(N)}\}$ s.t. $\omega^{(N)}|_{J_2} \to Z_2 \in K_2$ and $Z_2|_{J_1} = Z_1 \Rightarrow \exists$ subsequence $\{\omega^{(m_l)}\}_{k \geq 1}$ s.t. $\omega^{(m_l)}_{J_n} \to Z_n \in K_n$ and $Z_n|_{J_{n-1}} = Z_{n-1} \Rightarrow \exists Z \in \mathbb{R}^{\mathbb{N}}$ s.t. $Z|_{J_n} = Z_n$. Let $\omega \in \mathbb{R}^I$ be the sample point s.t. $\omega|_{J_n} = Z_n \Rightarrow \omega \in \cap_{k \geq 1} G_k$. □

- We say two processes $(X_t)_{t \in I}$ and $(Y_t)_{t \in I}$ (1) have the same f.d.d. if $\mathrm{Law}_{\mathbb{P}}(X_{t_1}, \cdots, X_{t_n}) = \mathrm{Law}_{\mathbb{P}}(Y_{t_1}, \cdots, Y_{t_n})$ for every $t_1, \cdots, t_n \in I$; (2) are modifications of each other if for every $t \in I$ we have $\mathbb{P}(X_t = Y_t) = 1$; (3) are indistinguishable if $X(\omega) = Y(\omega)$ for $\mathbb{P}$ a.e. ω. In the following text we set $I = [0, 1]$.

- Kolmogorov's continuity criterion: Let $(X_t)_{t \in [0,1]}$ be a process s.t. $(\mathbb{E}|X_t - X_s|^p)^{\frac{1}{p}} \leq C|t - s|^\alpha$ where $\alpha p > 1$, C independent of s and t. Then for every $\beta < \alpha - \frac{1}{p}$, $\exists$ modification $\widetilde{X}$ of X s.t. $\mathbb{E}(\sup_{s \neq t} \frac{|\widetilde{X}_t - \widetilde{X}_s|}{|t-s|^\beta})^p < +\infty$.

  Proof Step 1: Choose a conutable dense subset $D \subset [0, 1]$ and show that $\mathbb{E}[\sup_{s,t \in D, s \neq t} \frac{|X_t - X_s|}{|t-s|^\beta}]^p < +\infty$.

  Step 2: $X|_D$ is β-Holder continuous $\Rightarrow$ can extend to $\widetilde{X}$ on $[0, 1]$ by $\widetilde{X}_t(\omega) = \begin{cases} X_t(\omega) & \text{if } t \in D \\ \lim_{n \to \infty} X_{t_n}(\omega) & \text{if } t_n \to t \end{cases}$ and $||\widetilde{X}||_\beta \leq ||X||_\beta$.

  Step 3: Show that $\widetilde{X}$ is a modification of X.

  Proof of Step 1: Let $D_n = \{\frac{j}{2^n}, j = 0, 1, \cdots, 2^n\}$ and $D = \cup_n D_n$. For $s, t \in D_N$, $\exists 1$ m s.t. $\frac{1}{2^{m+1}} < |t - s| \leq \frac{1}{2^m}$. For every n, let s_n, t_n be the points in D_n with smallest distance to s and t. Then (1) $|s_{n+1} - s_n| \leq \frac{1}{2^{n+1}}, |t_{n+1} - t_n| \leq \frac{1}{2^{n+1}}$; (2) $|s_m - t_m| \leq \frac{1}{2^m}$. Note that $X_t = X_{t_N} = \sum_{n=m}^{N-1}(X_{t_{n+1}} - X_{t_n}) + X_{t_m}, X_s = X_{s_N} = \sum_{n=m}^{N-1}(X_{s_{n+1}} - X_{s_n}) + X_{s_m} \Rightarrow |X_t - X_s| \leq |X_{t_m} - X_{s_m}| + \sum_{n \geq m}(|X_{t_{n+1}} - X_{t_n}| + |X_{s_{n+1}} - X_{s_n}|)$. Then we have

$$|X_{t_{n+1}} - X_{t_n}| \leq \sup_{0 \leq j \leq 2^{n+1}-1} |X_{\frac{j+1}{2^{n+1}}} - X_{\frac{j}{2^{n+1}}}| \text{ and } |X_{s_{n+1}} - X_{s_n}| \leq \sup_{0 \leq j \leq 2^{n+1}-1} |X_{\frac{j+1}{2^{n+1}}} - X_{\frac{j}{2^{n+1}}}|$$

$$\Rightarrow |X_t - X_s| \lesssim 2 \sum_{n \geq m} \sup_{0 \leq j \leq 2^n - 1} |X_{\frac{j+1}{2^n}} - X_{\frac{j}{2^n}}|$$

$$\Rightarrow \frac{|X_t - X_s|}{|t-s|^\beta} \lesssim 2^{m\beta} \sum_{n \geq m} \sup_{0 \leq j \leq 2^n - 1} |X_{\frac{j+1}{2^n}} - X_{\frac{j}{2^n}}| \leq \sum_{n \geq 0} 2^{n\beta} \sup_{0 \leq j \leq 2^n - 1} |X_{\frac{j+1}{2^n}} - X_{\frac{j}{2^n}}|$$

$$\Rightarrow \left|\left| \sup_{s,t \in D, s \neq t} \frac{|X_t - X_s|}{|t - s|^\beta} \right|\right|_p \lesssim \sum_{n \geq 0} 2^{n\beta} \left(\sum_{j=0}^{2^n - 1} \mathbb{E}|X_{\frac{j+1}{2^n}} - X_{\frac{j}{2^n}}|^p \right)^{\frac{1}{p}} \lesssim \sum_{n \geq 0} 2^{-(\alpha - \frac{1}{p} - \beta)n}$$

  The remaining details are left for exercise. □

- In case of B.M., the condition is satisfied for every $p \geq 1$ and $\alpha = \frac{1}{2}$.

- Almost none Brownian path is Hölder-$\frac{1}{2}$ continuous, i.e. $\mathbb{P}(\{\omega : \sup_{s,t \in [0,1]} \frac{||B_t(\omega) - B_s(\omega)||}{\sqrt{t-s}} < +\infty\}) = 0$.

  Proof $\sup_{s,t \in [0,1]} \frac{|B_t - B_s|}{\sqrt{t-s}} \geq \sup_n \sup_{0 \leq j \leq n-1} \sqrt{n}|B_{\frac{j+1}{n}} - B_{\frac{j}{n}}| \Rightarrow \mathbb{P}(\sup_{s,t \in [0,1]} \frac{|B_t - B_s|}{\sqrt{t-s}} \leq \lambda) \leq \mathbb{P}(\sup_{0 \leq j \leq n-1} |Z_j| \leq \lambda)$ for every n. Let $n \to \infty$ and then RHS $\to 0$. □

- For every t, almost none Brownian path is Hölder-$\frac{1}{2}$ continuous at t, i.e. $\mathbb{P}(\{\omega : \sup_{|h| \leq 1} \frac{|B_{t+h} - B_t|}{\sqrt{|h|}} < \infty\}) = 0$.

- Almost every Brownian path is Hölder-$\frac{1}{2}$ continuous at some t, i.e. $\mathbb{P}(\{\omega : \exists t \in [0, 1]$ s.t. $\sup_{|h| \leq 1} \frac{|B_{t+h} - B_t|}{\sqrt{|h|}} < \infty\}) = 1$.

- $\alpha > \frac{1}{2}$, almost none Brownian path is Hölder-α continuous at any t, i.e. $\mathbb{P}(\{\omega : \exists t \in [0, 1]$ s.t. $\sup_{|h| \leq 1} \frac{|B_{t+h} - B_t|}{h^\alpha} < \infty\}) = 0$.

- Let $\mathscr{F}_t = \sigma(B_s, 0 \leq s \leq t)$ and $W_t^{(s)} = B_{s+t} - B_s$. For every $s \geq 0$, define $\mathscr{F}_s^+ = \cap_{\epsilon > 0} \mathscr{F}_{s+\epsilon}$. Then $(\mathscr{F}_s^+)_{s \geq 0}$ is right-continuous in the sense that $\mathscr{F}_s^+ = \cap_{\epsilon > 0} F_{s+\epsilon}^+$.

- Markov property 1 of B.M.: $(W_t^{(s)})_{t\geq 0}$ is a B.M. inpendent of $\mathscr{F}_s$.

- Markov property 2 of B.M.: For every $s \geq 0$, $(W_t^s)_{t\geq 0}$ is a B.M. independent of $\mathscr{F}_s^+$.

  Proof We need to show that $\mathbb{E}(\Phi(W^{(s)})1_A) = \mathbb{E}(\Phi(B))\mathbb{P}(A)$ for every bounded measurable function $\Phi : C(\mathbb{R}^+, \mathbb{R}) \to \mathbb{R}$ and every $A \in \mathscr{F}_s^+$. By monotone class theorem, it suffices to prove it for $\Phi = 1_E$, where E ranges over all cylinder sets. Then it suffices to consisder Φ that depends on finitely many values $(W_{t_1}^{(s)}, \cdots, W_{t_n}^{(s)})$ and is bounded and continuous. Suppose $\Phi(g) = \Phi(g_{t_1}, \cdots, g_{t_n})$, and $\mathbb{E}(\Phi(W_{t_1}^{(s)}, \cdots, W_{t_n}^{(s)})1_A) = \mathbb{E}(\lim_{\epsilon\to 0} \Phi(W_{t_1}^{(s+\epsilon)}, \cdots, W_{t_n}^{(s+\epsilon)})1_A) = \lim_{\epsilon\to 0} \mathbb{E}(\Phi(W_{t_1}^{s+\epsilon}, \cdots, W_{t_n}^{(s+\epsilon)})1_A) = \lim_{\epsilon\to 0} \mathbb{E}(\Phi(W_{t_1}^{s+\epsilon}, \cdots, W_{t_n}^{(s+\epsilon)}))\mathbb{P}(A) = \mathbb{E}(\Phi(B_{t_1}, \cdots, B_{t_n}))\mathbb{P}(A)$. □

- Blumenthal's 0-1 law: If $A \in \mathscr{F}_0^+$, then $\mathbb{P}(A) = 0$ or 1.

  Proof If $A \in \mathscr{F}_0^+$, then $(B_t)_{t\geq 0} \perp\!\!\!\perp A$. On the other hand, $A \in \sigma(B_t, t \geq 0) \Rightarrow A$ is independent of A. □

- Let $\tau_1 = \inf\{t \geq 0 : B_t > 0\}$, then $\tau_1 = 0$ a.s.

  Proof $\{\tau_1 = 0\} = \cap_{n\geq 1}\{\sup_{s\in[0,\frac{1}{n}]} B_s > 0\} \in \mathscr{F}_0^+ \Rightarrow \mathbb{P}(\tau_1 = 0) = 0$ or 1. $\mathbb{P}(\tau_1 = 0) = \lim_{\epsilon\to 0} \mathbb{P}(\tau_1 \leq \epsilon) \geq \frac{1}{2}$. □

- Let $\tau_2 = \inf\{t > 0 : B_t = 0\}$. Then $\tau_2 = 0$ a.s.

  Proof The prior proposition + symmetry + continuity of B.M. □

- Strong Markov property: Let τ be a stopping time w.r.t. $(\mathscr{F}_t)_{t\geq 0}$. The process $(1_{\tau<+\infty} W_t^\tau)_{t\geq 0}$ is a B.M. independent of $\mathscr{F}_\tau$ under the measure $\mathbb{P}(\cdot|\tau < +\infty)$.

  Proof We only prove the case when $\mathbb{P}(\tau < +\infty) = 1$. It suffices to show $\mathbb{E}(\Phi(W_{t_1}^\tau, \cdots, W_{t_n}^{(\tau)})1_A) = \mathbb{E}(\Phi(B_{t_1}, \cdots, B_{t_n}))\mathbb{P}(A)$ for every continuous and bounded $\Phi : \mathbb{R}^n \to \mathbb{R}$ and $A \in \mathscr{F}_\tau$. Let $\tau_k(\omega) := \frac{j}{k}$ if $\tau(\omega) \in (\frac{j-1}{k}, \frac{j}{k}]$, $\tau_k \to \tau$ a.s. Bounded convergence $\Rightarrow \mathbb{E}(\Phi(W_{t_1}^{(\tau_k)}, \cdots, W_{t_n}^{(\tau_k)})1_A) \to \mathbb{E}(\Phi(W_{t_1}^{(\tau)}, \cdots, W_{t_n}^{(\tau)})1_A)$. Then

$$
\begin{aligned}
\mathbb{E}(\Phi(W_{t_1}^{(\tau)}, \cdots, W_{t_n}^{(\tau)})1_A) &= \lim_{k\to\infty} \mathbb{E}(\Phi(W_{t_1}^{(\tau_k)}, \cdots, W_{t_n}^{(\tau_k)})1_A) \\
&= \lim_{k\to\infty} \mathbb{E}(\sum_{j\geq 0} \Phi(W_{t_1}^{(\tau_k)}, \cdots, W_{t_n}^{(\tau_k)})1_{A\cap\{\frac{j-1}{k}<\tau\leq\frac{j}{k}\}}) \\
&= \lim_{k\to\infty} \mathbb{E}(\sum_{j\geq 0} \Phi(W_{t_1}^{(\frac{j}{k})}, \cdots, W_{t_n}^{(\frac{j}{k})})1_{A\cap\{\frac{j-1}{k}<\tau\leq\frac{j}{k}\}}) \\
&= \lim_{k\to\infty} \sum_{j\geq 0} \mathbb{E}(\Phi(B_{t_1}, \cdots, B_{t_n}))\mathbb{P}(A \cap \{\frac{j-1}{k} < \tau \leq \frac{j}{k}\}) \\
&= \mathbb{E}(\Phi(B_{t_1}, \cdots, B_{t_n}))\mathbb{P}(A)
\end{aligned}
$$
□

- Maximum principle: Let $M_t = \sup_{s\in[0,t]} B_s$. Then $\mathbb{P}(M_T \geq a) = 2\mathbb{P}(B_T \geq a)$ for $a > 0$.

  Proof Let $\tau_a = \inf\{t > 0 : B_t = a\}$. Then $\{M_T \geq a\} = \tau_a \leq T$. $\{W_t^{(\tau_a)}\}_{t\geq 0}$ is a B.M. independent of $\mathscr{F}_{\tau_a}$. $\mathbb{P}(M_T \geq a) = \mathbb{P}(M_T \geq a, B_T \geq a) + \mathbb{P}(M_T \geq a, B_T \leq a) = \mathbb{P}(B_T \geq a) + \mathbb{P}(M_T \geq a, B_T \leq a), \mathbb{P}(M_T \geq a, B_T \geq a) = \mathbb{P}(\tau_a \leq T, B_T - B_{\tau_a} \leq 0) = \mathbb{P}(\tau_a \leq T, B_T - B_{\tau_a} \geq 0) = \mathbb{P}(B_T \geq a)$. □

- Let $(\mathcal{X}, d)$ be a complete, separable metric space with Borel σ-algebra. Let $(\mathbb{P}_n)_{n\geq 0}$ and $\mathbb{Q}$ be probability measure on it. We say $\mathbb{P}_n$ convergences weakly to $\mathbb{Q}$ ($\mathbb{P}_n \Rightarrow \mathbb{Q}$) if for every bounded and continuous $f : \mathcal{X} \to \mathbb{R}$, we have $\int_{\mathcal{X}} f \mathrm{d}\mathbb{P}_n \to \int_{\mathcal{X}} f \mathrm{d}\mathbb{P}$.

- $\mathbb{P}_n \Rightarrow \mathbb{Q}$ (weakly on $C([0, 1], \mathbb{R})$) iff (1) $\mathbb{P}_n|J \Rightarrow \mathbb{Q}|_J$ for every finite $J \subset [0, 1]$; (2) $\{P_n\}_n$ is relatively compact, i.e., every subsequence has a further subsequence that is weakly convergent.

- Let $M = M(\mathcal{X})$ be the set of all probability measure on $(\mathcal{X}, d, \mathscr{B}(\mathcal{X}))$. We say $\Gamma \subset M$ is tight if for every $\epsilon > 0$, $\exists$ compact $K_\epsilon \subset \mathcal{X}$ s.t. $\sup_{\mu\in\Gamma} \mu(\mathcal{X}\backslash K_\epsilon) < \epsilon$.

- Prokhorov's theorem: Let $(\mathcal{X}, d)$ be a complete, separable metric space. Then, $\Gamma \subset M(\mathcal{X})$ is tight if and only if it is relatively compact.

- Arzela-Ascoli: A set $A \subset C([0, 1], \mathbb{R})$ is relatively compact iff (1) $\sup_{f\in A} |f(0)| < +\infty$; (2) $\sup_{f\in A} \mathrm{Osc}_f(\delta) \to 0$ as $\delta \to 0$ where $\mathrm{Osc}_f(\delta) = \sup_{|s-t|<\delta} |f(s) - f(t)|$.

- A set $\Gamma \subset M(C[0,1],\mathbb{R})$ is tight iff (i) $\lim_{\lambda\to\infty}\sup_{\mu\in\Gamma}\mu(\{\omega : |\omega(0)| \geq \lambda\}) = 0$; (ii) $\forall\epsilon > 0$, $\lim_{\delta\to 0}\sup_{\mu\in\Gamma}\mu(\{\omega : \mathrm{Osc}_\omega(\delta) > \epsilon\}) = 0$.

  Proof "$\Rightarrow$": Suppose $\Gamma \subset M$ is tight. Then $\forall\eta > 0$, $\exists$ compact $K \subset C([0,1],\mathbb{R})$ s.t. $\mu(K^c) < \eta$ for every $\mu \in \Gamma$. By Arzela-Ascoli, (a) $\sup_{\omega\in K}|\omega(0)| < +\infty$; (b) $\sup_{\omega\in K}\mathrm{Osc}_\omega(\delta) \to 0$ as $\delta \to 0$. (a) $\Rightarrow \{\omega : |\omega(0)| > \lambda\} \subset K^c$ for sufficient large λ. (b) $\Rightarrow \forall\epsilon > 0, \{\omega : \mathrm{Osc}_\omega(\delta) > \epsilon\} \subset K^c$ for sufficient small δ. $\Rightarrow \sup_{\mu\in\Gamma}\mu(\{\omega : |\omega(0)| > \lambda\}) < \eta, \sup_{\mu\in\Gamma}\mu(\{\omega : \mathrm{Osc}_\omega(\delta) > \epsilon\}) < \eta$.
  "$\Leftarrow$": Suppose $\Gamma \subset C([0,1],\mathbb{R})$ satisfies (i) and (ii). For every $\eta > 0$, we need find compact $K \subset C([0,1],\mathbb{R})$ s.t. $\sup_{\mu\in\Gamma}\mu(K^c) < \eta$. By (i), choose $\lambda > 0$ s.t. $\sup_{\mu\in\Gamma}\mu(\{\omega : |\omega(0)| > \lambda\}) < \frac{\eta}{2}$ and define $A_0 = \{\omega : |\omega(0)| \leq \lambda\}$. By (ii), $\forall k \geq 1$, $\exists\delta_k(\downarrow 0 \text{ as } k \to \infty)$ s.t. $\sup_{\mu\in\Gamma}\mu(\{\omega : \mathrm{Osc}_\omega(\delta_k) > \frac{1}{k}\}) \leq \frac{\eta}{2^{k+1}}$ and define $A_k = \{\omega : \mathrm{Osc}_\omega(\delta_k) \leq \frac{1}{k}\}$. $E := \cap_{k\geq 0}A_k$ is a compact subset of $C([0,1],\mathbb{R})$ and $\sup_{\mu\in\Gamma}\mu(E^c) \leq 1 - \eta$. □

- Donsker's invariance principle: $X_i, i = 1, 2, \cdots$ are i.i.d. r.v.'s with $\mathbb{E}X_i = 0$ and $\mathbb{E}X_i^2 = 1$. Define $W^{(n)}(t) := S_{\lfloor nt\rfloor} + \{nt\}(S_{\lfloor nt\rfloor+1} - S_{\lfloor nt\rfloor})$ and $\mathbb{P}_n := \mathbb{P}\circ(\frac{W_n}{\sqrt{n}})^{-1}$. Then $\mathbb{P}_n \Rightarrow$ B.M.

  Proof We need to show $\mathbb{P}_n(\{\omega : \mathrm{Osc}_\omega(\delta) > \epsilon\}) \to 0$ as $\delta \to 0$.

  Step 1. $\mathbb{P}_n(\{\omega : \mathrm{Osc}_\omega(\delta) > \epsilon\}) = \mathbb{P}(\mathrm{Osc}_{W^{(n)}}(\delta) > \epsilon\sqrt{n})$. It suffices to show $\forall\epsilon > 0$, $\limsup_{n\to\infty}\mathbb{P}(\mathrm{Osc}_{W^{(n)}}(\delta) > \epsilon\sqrt{n}) \to 0$ as $\delta \to 0$.

  Step 2. $\mathbb{P}(\mathrm{Osc}_{W^{(n)}}(\delta) > \epsilon\sqrt{n}) = \mathbb{P}(\sup_{|s-t|\leq\delta}|W^{(n)}(s) - W^{(n)}(t)| > \epsilon\sqrt{n}) = \mathbb{P}(\sup_{t\in[0,1-\delta]}\sup_{h\in[0,\delta]}|W^{(n)}(t+h) - W^{(n)}(t)| > \epsilon\sqrt{n}) \leq \mathbb{P}(\sup_k\sup_{h\in[0,2\delta]}|W^{(n)}(k\delta+h) - W^{(n)}(k\delta)| > \frac{\epsilon\sqrt{n}}{2}) \leq (\frac{1}{\delta}+1)\sup_{k\leq\frac{1}{\delta}+1}\mathbb{P}(\sup_{k\in[0,2\delta]}|W^{(n)}(k\delta+h) - W^{(n)}(k\delta)|) > \frac{\epsilon\sqrt{n}}{2}$.

  Step 3. We need to show $\forall\epsilon > 0$, $\frac{1}{\delta}\limsup_{n\to\infty}\sup_{t\in[0,1]}\mathbb{P}(\sup_{h\in[0,\delta]}|W^{(n)}(t+h)-W^{(n)}(t)| > \epsilon\sqrt{n}) \to 0$. $W^{(n)}(t+h)-W^{(n)}(t) = S_{\lfloor n(t+h)\rfloor} + \{n(t+h)\}X_{\lfloor n(t+h)\rfloor} - S_{\lfloor nt\rfloor} - \{nt\}X_{\lfloor nt\rfloor} \Rightarrow |W^{(n)}(t+h) - W^{(n)}(t)| \leq |S_{\lfloor n(t+h)\rfloor} - S_{\lfloor nt\rfloor}| + |X_{\lfloor n(t+h)\rfloor}| + |X_{\lfloor nt\rfloor}| \Rightarrow \mathbb{P}(\sup_{h\in[0,\delta]}|W^{(n)}(t+h) - W^{(n)}(t)| > \epsilon\sqrt{n}) \leq \mathbb{P}(\sup_{h\in[0,\delta]}|S_{\lfloor n(t+h)\rfloor} - S_{\lfloor nt\rfloor}| > \frac{\epsilon\sqrt{n}}{3}) + O_n(1)$. $\mathbb{P}(\sup_{0\leq k\leq n\delta}|S_{\lfloor nt\rfloor+k} - S_{\lfloor nt\rfloor}| > \frac{\epsilon\sqrt{n}}{3}) \lesssim \frac{\mathbb{E}(S_{\lfloor nt\rfloor+\lfloor n\delta\rfloor} - S_{\lfloor nt\rfloor})^2}{\epsilon^2 n} \sim \frac{\delta}{\epsilon^2}$, which means that the maximal inequality is not enough if we only have finite second moment.

  Step 4. We need to show $\frac{1}{\delta}\limsup_{n\to\infty}\mathbb{P}(\sup_{0\leq k\leq n\delta}|S_k| > \epsilon\sqrt{n}) = 0$. Let $\tau = \inf\{k \geq 1, |S_k| > \epsilon\sqrt{n}\}$. $\mathbb{P}(\max_{1\leq k\leq\lfloor n\delta\rfloor}|S_k| > \epsilon\sqrt{n}) = \mathbb{P}(\max_{1\leq k\leq\lfloor n\delta\rfloor}|S_k| > \epsilon\sqrt{n}, |S_{\lfloor n\delta\rfloor}| > \frac{\epsilon\sqrt{n}}{2}) + \mathbb{P}(\max_{1\leq k\leq\lfloor n\delta\rfloor}|S_k| > \epsilon\sqrt{n}, |S_{\lfloor n\delta\rfloor}| \leq \frac{\epsilon\sqrt{n}}{2})$. The first term $\leq \mathbb{P}(|S_{\lfloor n\delta\rfloor}| > \frac{\epsilon\sqrt{n}}{2}) \lesssim e^{-\frac{1}{\sqrt{\delta}}}$ (by CLT). The second term $= \sum_{k=1}^{\lfloor n\delta\rfloor}\mathbb{P}(|S_{\lfloor n\delta\rfloor}| \leq \frac{\epsilon\sqrt{n}}{2}|\tau = k)\mathbb{P}(\tau = k) \leq \sum_{k=1}^{\lfloor n\delta\rfloor}\mathbb{P}(|S_{\lfloor n\delta\rfloor-k}| > \frac{\epsilon\sqrt{n}}{2})\mathbb{P}(\tau = k) \leq \sum_{k=1}^{\lfloor n\delta\rfloor}\frac{4(\lfloor n\delta\rfloor-k)}{\epsilon^2 n}\mathbb{P}(\tau = k) \leq \frac{4\delta}{\epsilon^2}\mathbb{P}(\max_{1\leq k\leq\lfloor n\delta\rfloor}|S_k| > \epsilon\sqrt{n})$. If $\delta < \frac{\epsilon^2}{8} \Rightarrow \mathbb{P}(\max_{1\leq k\leq\lfloor n\delta\rfloor}|S_k| > \epsilon\sqrt{n}) \leq 2\mathbb{P}(|S_{\lfloor n\delta\rfloor}| > \frac{\epsilon\sqrt{n}}{2})$. □

- $(\mathcal{P}_t f)(x) = \mathbb{E}^x(f(X_t)), (\mathcal{L}f)(x) = \lim_{h\downarrow 0}\frac{(\mathcal{P}_h f)(x)-f(x)}{h}, \mathcal{P}_{t+s} = \mathcal{P}_t\circ\mathcal{P}_s, \mathcal{P}_t\circ\mathcal{L} = \mathcal{L}\circ\mathcal{P}_t$. For B.M., $p_t(y) = \frac{1}{\sqrt{2\pi t}}e^{-\frac{|y|^2}{2t}}$, therefore $(\mathcal{L}f)(x) = \lim_{t\downarrow 0}\frac{1}{t}(\mathbb{E}^x(f(B_t))-f(x)) = \lim_{t\downarrow 0}\frac{1}{t}\int_{\mathbb{R}}p_t(y)[f(x-y)-f(x)]\mathrm{d}y = \lim_{t\downarrow 0}\frac{1}{t}\int_{\mathbb{R}}p_t(y)(-f'(x)y + \frac{1}{2}f''(x)y^2 + O(|y|)^3) \sim \lim_{t\downarrow 0}(\frac{1}{t}\int_{\mathbb{R}}p_t(y)y^2\mathrm{d}y)\cdot\frac{1}{2}f''(x) = \frac{1}{2}f''(x) \Rightarrow \mathcal{L} = \frac{1}{2}\triangle$.

- Feynman-Kac formula: Suppose $v : \mathbb{R}^d \to \mathbb{R}$ is bounded and continuous and let $u(t,x) = \mathbb{E}^x[f(B_t)e^{\int_0^t v(B_s)ds}]$ where B is d-dim B.M. Then u satisfies the PDE $\begin{cases}\partial_t u = \frac{1}{2}\triangle u + vu \\ u(0,\cdot) = f(\cdot)\end{cases}$.

  Proof $e^{\int_0^t v(B_s)ds} = \sum_{n\geq 0}\frac{1}{n!}(\int_0^t v(B_s)ds)^n$

$$\begin{aligned}\frac{1}{n!}\int\cdots\int_{[0,1]^n}v(B_{s_1})\cdots v(B_{s_n})\mathrm{d}s_1\cdots\mathrm{d}s_n &= \int\cdots\int_{0<s_1<\cdots<s_n<t}v(B_{s_1})\cdots v(B_{s_n})\mathrm{d}s_1\cdots\mathrm{d}s_n \\ &= \int\cdots\int_{0<s_1<\cdots<s_n<t}v(B_{t-s_1})\cdots v(B_{t-s_n})\mathrm{d}s_1\cdots\mathrm{d}s_n\end{aligned}$$

  Denote the region $\Delta_n(t) = \{0 < s_1 < \cdots < s_n < t\}$, then $u(t,x) = \sum_{n\geq 0}\int\cdots\int_{\Delta_n(t)}\mathbb{E}^x(f(B_t)v(B_{t-s_1})\cdots v(B_{t-s_n}))\mathrm{d}s_1\cdots\mathrm{d}s_n := \sum_{n\geq 0}I_n(t,x)$. $I_0(t,x) = \mathbb{E}^x(f(B_t)) = (\mathcal{P}_t f)(x) \Rightarrow \begin{cases}\partial_t I_0 = \frac{1}{2}\triangle I_0 \\ I_0(0,\cdot) = f\end{cases}$.

$$I_1(t,x) = \int_0^t\mathbb{E}^x(f(B_t)v(B_{t-s}))\mathrm{d}s = \int_0^t\mathbb{E}^x(v(B_{t-s})\mathbb{E}^x(f(B_t)|\mathscr{F}_{t-s}))\mathrm{d}s = \int_0^t\mathbb{E}^x(v(B_{t-s})(\mathcal{P}_{\int}\{\})(B_{t-s}))\mathrm{d}s = \int_0^t(\mathcal{P}_{t-s}v\mathcal{P}_s f)(x)\mathrm{d}s$$
$$\Rightarrow \partial_t I_1 = v\mathcal{P}_t f + \frac{1}{2}\triangle I_1 = \frac{1}{2}\triangle I_1 + vI_0, I_1(0,\cdot) = 0.$$

$$\begin{aligned}I_n(t,x) &= \int\cdots\int_{0<s_1<\cdots<s_n<t}\mathbb{E}^x(f(B_t)v(B_{t-s_1})\cdots v(B_{t-s_n}))\mathrm{d}s_1\cdots\mathrm{d}s_n = \int_0^t\mathbb{E}^x(v(B_{t-s})\mathbb{E}^x(f(B_t)|\mathscr{F}_{t-s}))\mathrm{d}s \\ &= \int_0^t\left(\int\cdots\int_{\Delta_{n-1}(s_n)}(\mathcal{P}_{t-s_n}v\mathcal{P}_{s_n-s_{n-1}}v\cdots v\mathcal{P}_{s_2-s_1}v\mathcal{P}_{s_1}f)(x)\mathrm{d}s_1\cdots\mathrm{d}s_{n-1}\right)\mathrm{d}s_n \\ &\Rightarrow \partial_t I_n = vI_{n-1} + \frac{1}{2}\triangle I_n, I_n(0,\cdot) = 0.\end{aligned}$$
□

- Let $\xi_t = \frac{1}{t}\int_0^t 1_{\mathbb{R}^+}(B_s)\mathrm{d}s$, then $\mathbb{P}(\xi_t \le x) = \int_0^x \frac{1}{\pi\sqrt{y(1-y)}}\mathrm{d}y = \frac{2}{\pi}\arcsin(\sqrt{x})$.

  Proof $\xi_t = \frac{1}{t}\int_0^t 1_{\mathbb{R}^+}(B_s)\mathrm{d}s = \int_0^t 1_{\mathbb{R}^+}(B_{t\cdot\frac{s}{t}})\mathrm{d}\frac{s}{t} = \int_0^1 1_{\mathbb{R}^+}(\sqrt{t}\frac{B_{st}}{\sqrt{t}})\mathrm{d}s = \int_0^1 1_{\mathbb{R}^+}(\frac{B_{st}}{\sqrt{t}})\mathrm{d}s \overset{\text{Law}}{=} \int_0^1 1_{\mathbb{R}^+}(B_s)\mathrm{d}s := \xi$.

  Let $u(t,x) = \mathbb{E}^x(e^{-\sigma t\xi}) \Rightarrow \begin{cases}\partial_t u = \frac{1}{2}\partial_x^2 u - \sigma 1_{\mathbb{R}^+}u \\ u(0,\cdot) = 1\end{cases}$. Define $g(x) = \int_0^{+\infty} e^{-\lambda t}u(t,x)\mathrm{d}t \Rightarrow \frac{1}{2}g'' = (\lambda + \sigma 1_{\mathbb{R}^+})g - 1 \Rightarrow g''(x) = \begin{cases} 2(\lambda+\sigma)g(x) - 2, & x \ge 0 \\ 2\lambda g(x) - 2, & x \le 0\end{cases} \Rightarrow g(x) = \begin{cases} Be^{-\sqrt{2(\lambda+\sigma)}x} + \frac{1}{\lambda+\sigma}, & x \ge 0 \\ Ce^{\sqrt{2\lambda}x} + \frac{1}{\lambda}, & x \le 0\end{cases}$. $g(0)$ and $g'(0)$ well-defined $\Rightarrow B = \frac{\sqrt{\lambda+\sigma}-\sqrt{\lambda}}{\sqrt{\lambda}(\lambda+\sigma)}, C = -\frac{\sqrt{\lambda+\sigma}-\sqrt{\lambda}}{\lambda\sqrt{\lambda+\sigma}}$. $g(0) = \frac{1}{\sqrt{\lambda(\lambda+\sigma)}} = \mathbb{E}(\frac{1}{\lambda+\sigma\xi})$ for every $\lambda, \sigma > 0$ (take $\lambda = 1$) $\Rightarrow \mathbb{E}(\frac{1}{1+\sigma\xi}) = \frac{1}{\sqrt{1+\sigma}}$ for every $\sigma > 0$. Power expansion $\Rightarrow \sum_{n\ge 0}(-1)^n\mathbb{E}(\xi^n)\sigma^n = \sum_{n\ge 0}(-\sigma)^n\int_0^1 \frac{x^n}{\pi\sqrt{x(1-x)}}\mathrm{d}x$ □

- Law of iterated logarithm: $\limsup_{h\to 0}\frac{B_h}{\sqrt{2h\log\log(\frac{1}{h})}} = 1$ a.s., $\liminf_{h\to 0}\frac{B_h}{\sqrt{2h\log\log(\frac{1}{h})}} = -1$ a.s.

  Proof Since $W_t = tB_{1/t}$ is again a standard B.M., it is equivalent to prove $\limsup_{t\to\infty}\frac{B_t}{\sqrt{2t\log\log t}} = 1$ a.s.

  Step 1. Let $\Psi(t) = \sqrt{2t\log\log t}$ and $t_n = \gamma^n (\gamma > 1)$. We want to show $\limsup_{n\to\infty}\frac{B_{t_n}}{\Psi(t_n)} \le 1$ a.s.

  $\mathbb{P}(\frac{B_{t_n}}{\Psi(t_n)} > \alpha) = \mathbb{P}(\frac{B_{t_n}}{\sqrt{t_n}} > \sqrt{2}\alpha\sqrt{\log\log t_n}) \sim (C + o_n(1))\frac{1}{\sqrt{\log n}}(\frac{1}{n})^{\alpha^2} \Rightarrow \sum_n \mathbb{P}(\frac{B_{t_n}}{\Psi(t_n)} > \alpha) = \begin{cases} < +\infty, & \text{if } \alpha > 1 \\ = +\infty, & \text{if } \alpha \le 1\end{cases}$. Borel-Cantelli $\Rightarrow \mathbb{P}(\frac{B_{t_n}}{\Psi(t_n)} > 1 + \epsilon \text{ i.o.}) = 0$.

  For arbitrary t, assume $r^n < t < r^{n+1}$. Then $\frac{B_t}{\Psi(t)} = \frac{\Psi(r^n)}{\Psi(t)}\frac{B_{r^n}}{\Psi(r^n)} + \frac{\Psi(r^n)}{\Psi(t)}\frac{B_t - B_{r^n}}{\Psi(r^n)}$. The first term ≤ 1 a.s. Then need to show $\limsup_{n\to+\infty}\sup_{t\in[r^n,r^{n+1}]}\frac{B_t - B_{r^n}}{\Psi(r^n)} = \epsilon$ a.s. for every $\epsilon > 0$. $\mathbb{P}(\sup_{t\in[r^n,r^{n+1}]}\frac{B_t-B_{r^n}}{\Psi(r^n)} \ge \epsilon) = \mathbb{P}(\sup_{t\in[r^n,r^{n+1}]}(B_t - B_{r^n}) \ge \epsilon\Psi(r^n)) = 2\mathbb{P}(B_{r^{n+1}} - B_{r^n} \ge \epsilon\Psi(r^n)) = 2\mathbb{P}(\frac{B_{r^{n+1}} - B_{r^n}}{\sqrt{r^n(r-1)}} \ge \epsilon\frac{\Psi(r^n)}{\sqrt{r^n(r-1)}}) \sim (\log(r^n(r-1)))^{-\frac{\epsilon^2}{r-1}} \sim n^{-\frac{\epsilon^2}{r-1}}$. Take r close enough to 1 s.t. $\frac{\epsilon^2}{r-1} > 1$.

  Step 2. We want to show $\limsup_{t\to+\infty}\frac{B_t}{\Psi(t)} \ge 1$ a.s. Take $t_n = \gamma^n$. Need to show for every $\epsilon > 0$, $\exists r > 1$ s.t. $\limsup_{n\to+\infty}\frac{B_{r^n}}{\Psi(r^n)} > 1 - \epsilon$ a.s. $\mathbb{P}(\frac{B_{r^{n+1}} - B_{r^n}}{\Psi(r^n(r-1))}) = \mathbb{P}(\frac{B_{r^{n+1}} - B_{r^n}}{\sqrt{r^n(r-1)}} > \alpha\sqrt{2\log\log(r^n(r-1))}) \sim e^{-\alpha^2\log\log(r^n(r-1))}\frac{1}{\sqrt{\log\log(r^n(r-1))}} \sim \frac{1}{\sqrt{\log n}}n^{-\alpha^2} \Rightarrow \mathbb{P}(B_{r^{n+1}} - B_{r^n} > \Psi(r^n(r-1)) \text{ i.o.}) = 1$. $\frac{B_{r^{n+1}}}{\Psi(r^{n+1})} = \frac{\Psi(r^n)}{\Psi(r^{n+1})}\frac{B_{r^n}}{\Psi(r^n)} + \frac{\Psi(r^n(r-1))}{\Psi(r^{n+1})}\frac{B_{r^{n+1}} - B_{r^n}}{\Psi(r^n(r-1))} \Rightarrow \limsup_{n\to+\infty}\frac{B_{r^{n+1}}}{\Psi(r^{n+1})} \ge -\frac{1}{\sqrt{r}} + \sqrt{\frac{r-1}{r}}$ arbitrary close to 1 for sufficient large r. □

- Lévy's construction of B.M. (based on Gaussianity): Let $\{Z_t, t \text{ dyadic}\}$ be i.i.d. $\mathcal{N}(0,1)$ on a common probability space $(\Omega, \mathscr{F}, \mathbb{P})$. Let $B_0(t) = tZ_1, B_1(\frac{1}{2}) = \frac{1}{2}(B_0(0) + B_0(1)) + \frac{1}{2}Z_{\frac{1}{2}}, B_2(\frac{1}{4}) = \frac{1}{2}(B_1(0) + B_1(\frac{1}{2})) + \frac{1}{4}Z_{\frac{1}{4}}, B_2(\frac{3}{4}) = \frac{1}{2}(B_1(\frac{1}{2}) + B_1(1)) + \frac{1}{4}Z_{\frac{3}{4}}$. We will show that for every $p > 1$ and $\alpha < \frac{1}{2}$, $\{B_N\}$ is Cauchy on $L^p_w(C^\alpha[0,1],\mathbb{R})$.

  Proof We define the functions $\{h_n^{(k)}, n \ge 0, 0 \le k \le 2^{n-1}, \text{even}\}$. $h_0^{(0)} = 1$ on $[0,1]$, $h_n^{(k)} = 2^{\frac{n-1}{2}}(1_{[\frac{2k}{2^n},\frac{2k+1}{2^n})} - 1_{(\frac{2k+1}{2^n},\frac{2k+2}{2^n}]})$. The collection $\{h_n^{(k)}\}$ is an orthogonal basis of $L^2([0,1],\mathbb{R})$. Let $\{Z_n^{(k)}, k \le 2^n - 1, \text{even}, n \ge 0\}$ be i.i.d. $\mathcal{N}(0,1)$ and define $B_N(t) = \sum_{n=0}^N\sum_{k=0}^{2^n-1}Z_n^{(k)}\int_0^t h_n^{(k)}(r)\mathrm{d}r$. $\{B_N\}$ has the same law as the piecewise linear construction metioned above. We will show now for $p > 1, \alpha < \frac{1}{2}$, $\{B_N\}$ is Cauchy in $L^p_w(C^\alpha[0,1],\mathbb{R})$. In other words, we need to show $(\mathbb{E}||B_N - B_{N-1}||^p_{C^\alpha})^{\frac{1}{p}}$ decays fast enough as $N \to +\infty$ where $||B_N - B_{N-1}||_{C^\alpha} = \sup_{t\in[0,1]}|B_N(t) - B_{N-1}(t)| + \sup_{s,t\in[0,1]}\frac{|(B_N(t)-B_N(s)) - (B_{N-1}(t) - B_{N-1}(s))|}{|t-s|^\alpha}$. The first term is dominated by the second term. $|(B_N(t) - B_N(s)) - (B_{N-1}(t) - B_{N-1}(s))| = |\sum_{k=0}^{2^N-1}Z_N^{(k)}\int_s^t h_N^{(k)}(r)\mathrm{d}r| := (*)$. If $|t-s| \le \frac{1}{2^N}$, $(*) \lesssim 2^{\frac{N}{2}}|t-s|\sup_{0\le t\le 2^N-1}|Z_N^{(k)}|$ (at most one integral is nonzero); otherwise, $(*) \lesssim 2^{-\frac{N}{2}}\sup_{0\le t\le 2^N-1}|Z_n^{(k)}|$ (at most two integrals are nonzero). Thus $||B_N - B_{N-1}||_{C^\alpha} \lesssim \begin{cases} 2^{\frac{N}{2}}|t-s|^{1-\alpha}\sup_{0\le k\le 2^N-1}|Z_N^{(k)}| \lesssim 2^{-N(1-\alpha)}2^{\frac{N}{2}} = 2^{-(\frac{1}{2}-\alpha)N}, & |t-s| \le \frac{1}{2^N} \\ 2^{-\frac{N}{2}}|t-s|^{-\alpha}\sup_{0\le t\le 2^N-1}|Z_N^{(k)}| \lesssim 2^{-\frac{N}{2}}2^{\alpha N} \lesssim 2^{-(\frac{1}{2}-\alpha)N}, & \text{otherwise}\end{cases}$. □