MATH180C: Introduction to Stochastic Processes II

Lecture A00: math.ucsd.edu/~ynemish/teaching/180cA
Lecture B00: math.ucsd.edu/~ynemish/teaching/180cB

Today: Brownian motion

Next: PK 8.1-8.2

Week 9:

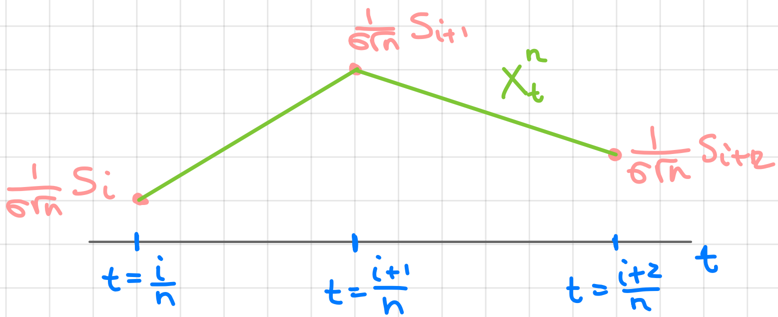
- homework 7 (due Friday, May 27)
- HW6 regrades are active on Gradescope until May 28, 11 PM
- Friday May 27 office hour: AP&M 7321

Construction of BM

BM can be constructed as a limit of properly rescaled random walks.

Let $\{\xi_k\}_{k=1}^{\infty}$ be a sequence of i.i.d. r.v.s, $E(\xi_i)=0$, $Var(\xi_i)=\sigma^2<\infty$. Denote $S_m=\sum_{k=1}^{m}\xi_k$ and define

$$X_t^n=\frac{1}{\sigma\sqrt{n}}\left(S_{[nt]}+(nt-[nt])\,\xi_{[nt]+1}\right)$$



Theorem (Donsker) $(X_t^n)_{t\geq 0}$ converges in distribution to the standard BM.

Applying Donsker's theorem

<u>Example</u> Let $(\xi_i)_{i=1}^{\infty}$ be i.i.d. r.v. $P(\xi_i = 1) = P(\xi_i = -1) = 0.5$

$$E(\xi_i) = 0, \quad Var(\xi_i) = 1.$$

Denote $(S_m)_{m \geq 0}$ is a Markov chain.

From the first step analysis of MC we know that for any $-a < 0 < b$

If X_t^n is the process interpolating S_m, then $\forall n$

$$P(X^n \text{ hits } -a \text{ before } b) =$$

$$\Rightarrow P(B \text{ hits } -a \text{ before } b) =$$

$\Rightarrow (\tilde{\xi}_i)_{i=1}^{\infty}$, $E(\tilde{\xi}_i) = 0$, $Var(\tilde{\xi}_i) = 1$, $P(\tilde{S} \text{ hits } -a \text{ before } b) \approx \frac{b}{a+b}$

BM as a martingale

Let $(X_t)_{t\geq 0}$ be a continuous time stochastic process. We say that $(X_t)_{t\geq 0}$ is a martingale if $E(|X_t|) < \infty$ $\forall t \geq 0$ and

Proposition Let $(B_t)_{t\geq 0}$ be a standard BM. Then

(i)

(ii)

"Proof": $E(B_t \mid \{B_u, 0 \leq u \leq s\}) =$

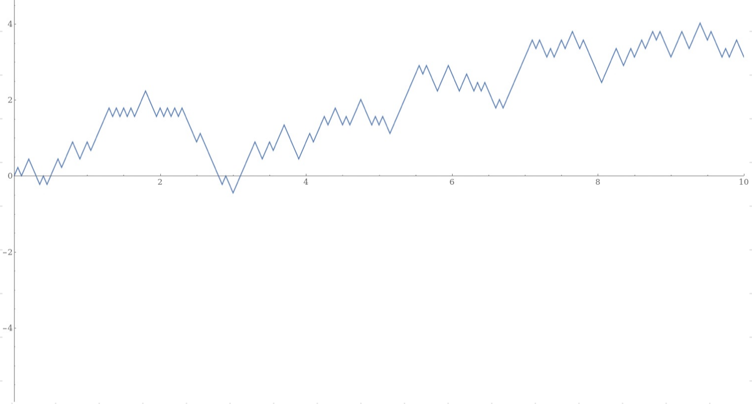
$E(B_t^2 - t \mid \{B_u, 0 \leq u \leq s\}) =$

$=$

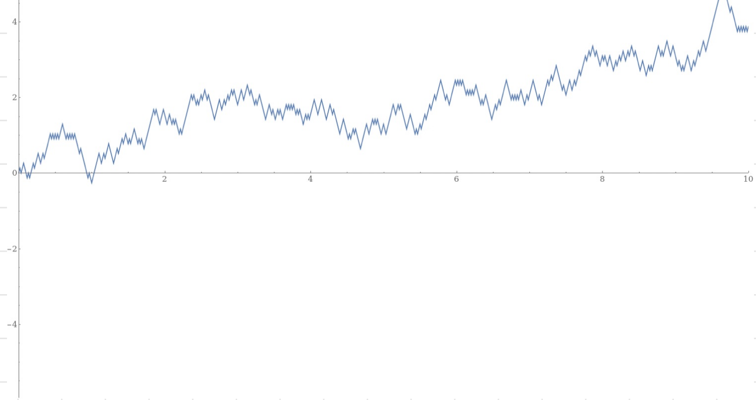
Thm (Lévy) Let $(X_t)_{t\geq 0}$ be a continuous martingale such that $(X_t^2 - t)_{t\geq 0}$ is a martingale.

Approximating a BM with random walks X_t^n

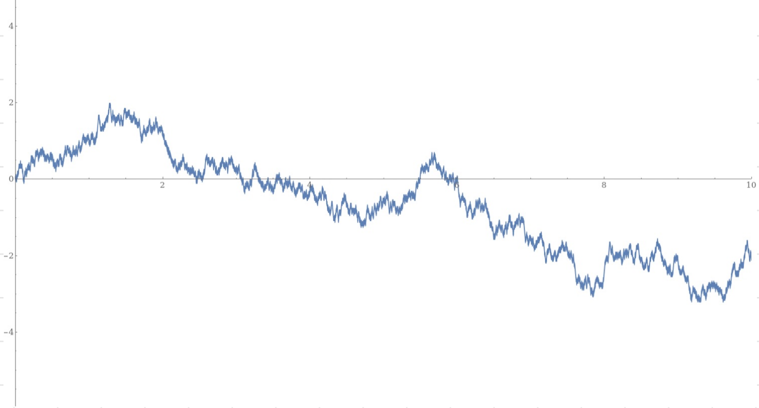
$n=20$



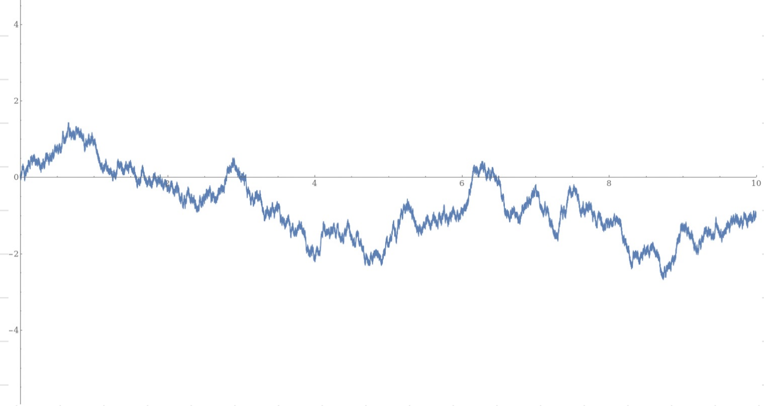
$n=100$



$n=500$



$n=1000$



Stopping times and the strong Markov property (lec. 3)

Def (Informal). Let $(X_t)_{t\geq 0}$ be a stochastic process and let $T \geq 0$ be a random variable. We call T a stopping time if the event

$$\{T \leq t\}$$

can be determined from the knowledge of the process up to time t (i.e., from $\{X_s : 0 \leq s \leq t\}$)

Examples: Let $(X_t)_{t\geq 0}$ be right-continuous

1. $\min\{t \geq 0 : X_t = x\}$ is a stopping time

2. $\sup\{t \geq 0 : X_t = x\}$ is not a stopping time

Stopping times and the strong Markov property (lec. 3)

Theorem (no proof)

Let $(X_t)_{t\geq 0}$ be a Markov process, let T be a stopping time of $(X_t)_{t\geq 0}$. Then, conditional on $T<\infty$ and $X_T = x$,

$$(X_{T+t})_{t\geq 0}$$

(i) is independent of $\{X_s,\ 0\leq s\leq T\}$

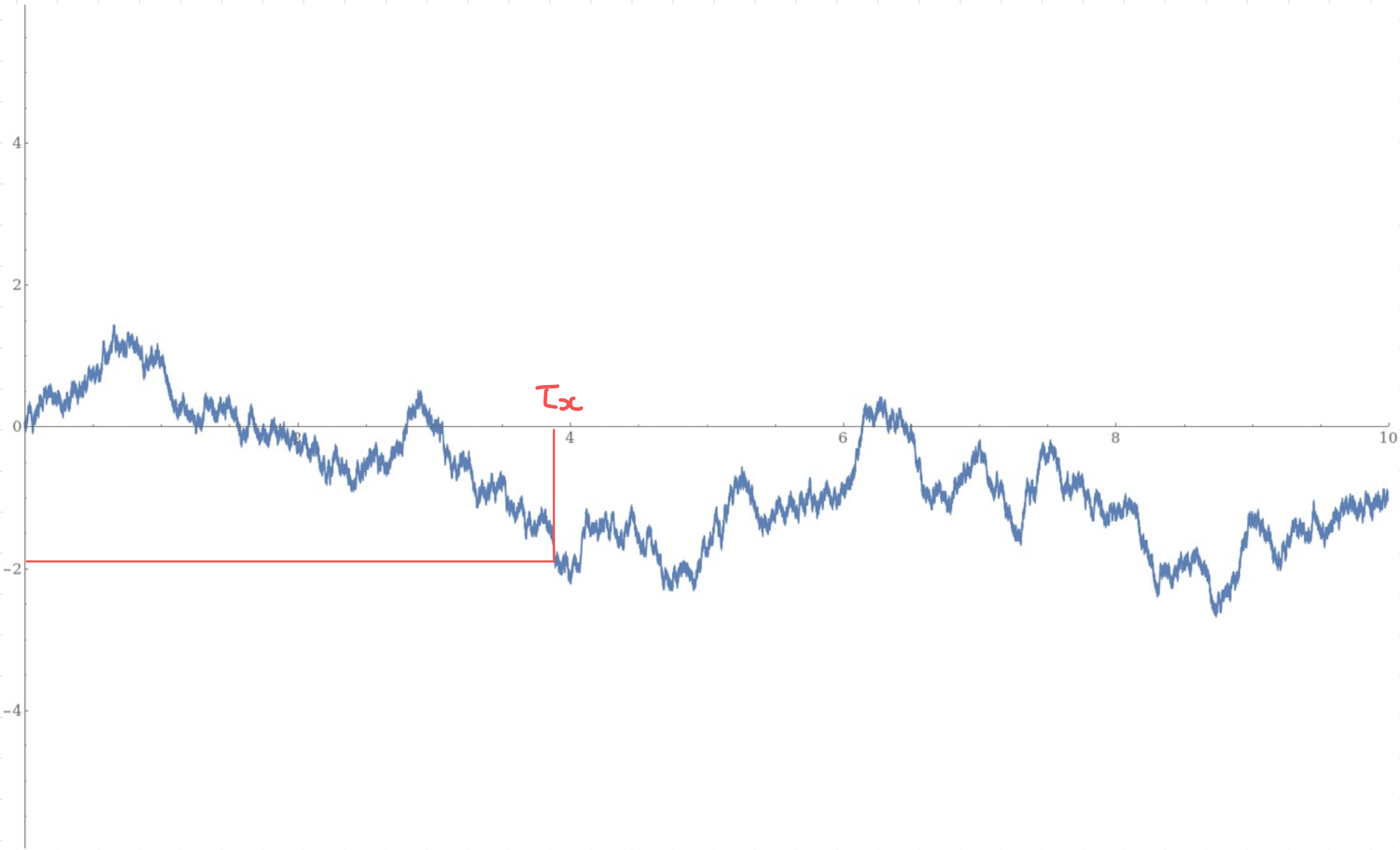
(ii) has the same distribution as $(X_t)_{t\geq 0}$ starting from x

Example $(B_t)_{t\geq 0}$ is Markov. For any $x\in\mathbb{R}$ define

$\tau_x = \min\{t : B_t = x\}$. Then

- $(B_{t+\tau_x} - B_{\tau_x})_{t\geq 0}$ is a BM starting from x
- $(B_{t+\tau_x} - B_{\tau_x})_{t\geq 0}$ is independent of $\{B_s,\ 0\leq s\leq \tau_x\}$

(independent of what B was doing before it hit x)



4
2
0
-2
-4
4
6
8
10
τ_x

Reflection principle

Thm. Let $(B_t)_{t\geq 0}$ be a standard BM. Then for any $t\geq 0$ and $x>0$

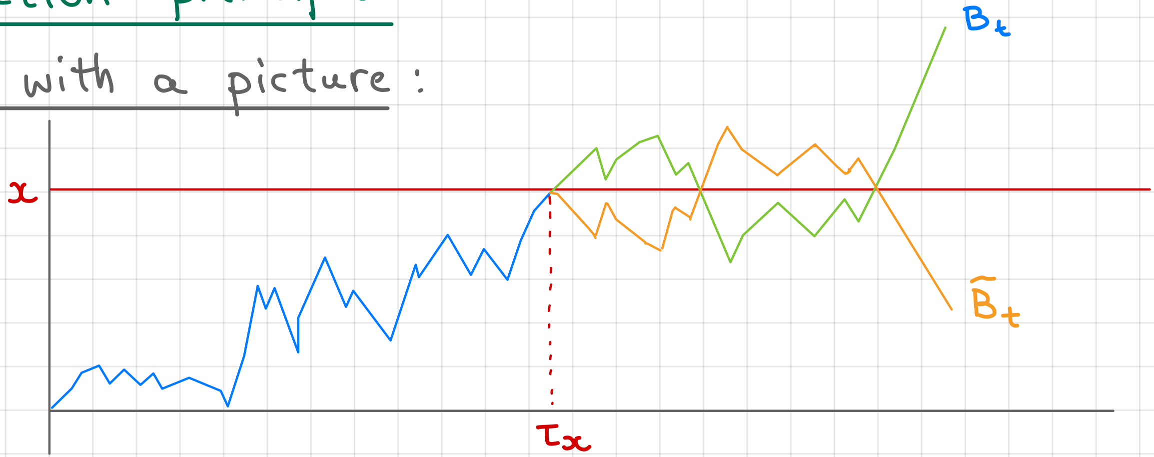
Proof. Let $\tau_x = \min\{t : B_t = x\}$. Note that τ_x is a stopping time and is uniquely determined by $\{B_u, 0\leq u\leq \tau_x\}$ From the definition of τ_x, . Then

$$P(\max_{0\leq u\leq t} B_u \geq x,\ B_t < x) =$$

Now $P(\max_{0\leq u\leq t} B_u \geq x) =$

Reflection principle

Proof with a picture:



If $(B_t)_{t\geq 0}$ is a BM, then $(\tilde{B}_t)_{t\geq 0}$ is a BM, where

$$\tilde{B}_t = \begin{cases} B_t , & t \leq \tau_x \\ B_{\tau_x} - (B_t - B_{\tau_x}) , & t > \tau_x \end{cases}$$

$\Rightarrow$ to each sample path with $\max\limits_{0\leq u\leq t} B_u > x$ and $B_t > x$ we associate a unique path with $\max\limits_{0\leq u\leq t} \tilde{B}_u > x$ and $\tilde{B}_t < x$, so

$$P(\max_{0\leq u\leq t} B_u \geq x, B_t < x) = P(B_t > x) \Rightarrow P(\max_{0\leq u\leq t} B_u \geq x) = 2P(B_t \geq x) \blacksquare$$

Application of the RP: distribution of the hitting time τ_x

By definition, $\tau_x \le t \iff \max_{0 \le u \le t} B_t \ge x$, so

$$P(\tau_x \le t) =$$

$$=$$

$$=$$

$\Rightarrow$ p.d.f. of τ_x $f_{\tau_x}(t) =$

<u>Thm</u>. $F_{\tau_x}(t) = \sqrt{\frac{2}{\pi}} \int_{x/\sqrt{t}}^{\infty} e^{-\frac{v^2}{2}} dv$,

$$f_{\tau_x}(t) = \frac{x}{\sqrt{2\pi}} t^{-3/2} e^{-\frac{x^2}{2t}}$$

Zeros of BM

Denote by $\theta(t,t+s)$ the probability that $B_u = 0$ on $(t,t+s)$

$$\theta(t,t+s) :=$$

Thm. For any $t,s>0$

$$\theta(t,t+s) =$$

Proof Compute $P(\,B_u = 0$ for some $u \in (t,t+s])$ by conditioning on the value of B_t.

$$\theta(t,t+s) =$$

(*)

Define $\tilde{B}_u = B_{t+u} - B_t$. Then

$$P(B_u = 0 \text{ on } (t,t+s] \mid B_t = x) =$$

(**)

Zeros of BM

Plugging (**) into (*) gives

$$\theta(t,t+s) = \int_{-\infty}^{+\infty} P(B_u = x \text{ for some } u \in (0,s]) \frac{1}{\sqrt{2\pi t}} e^{-\frac{x^2}{2t}} dx$$

$$= \int_{0}^{+\infty} P(B_u = x \text{ for some } u \in (0,s]) \frac{1}{\sqrt{2\pi t}} e^{-\frac{x^2}{2t}} dx$$

$$+ \int_{0}^{\infty} P(B_u = -x \text{ for some } u \in (0,s]) \frac{1}{\sqrt{2\pi t}} e^{-\frac{x^2}{2t}} dx$$

$$=$$

Finally, $P(B_u = x > 0 \text{ for some } u \in (0,s]) =$

$$(*) = \int_0^{\infty} \sqrt{\frac{2}{\pi t}} e^{-\frac{x^2}{2t}} \left(\int_0^s \frac{x}{\sqrt{2\pi}} y^{-3/2} e^{-\frac{x^2}{2y}} dy \right) dx =$$

Zeros of BM

$$\int_0^\infty x\, e^{-\frac{x^2}{2}\left(\frac{1}{t}+\frac{1}{y}\right)} dx =$$

$\Rightarrow (*) =$

Now use the change of variable $z = \sqrt{\frac{y}{t}}$, $dy = 2tdz$

$$(*) = \frac{\sqrt{t}}{\pi} \int_0^{\sqrt{s/t}} \frac{1}{t(1+z^2)\sqrt{t}\, z} \cdot 2t\,dz = \frac{2}{\pi} \int_0^{\sqrt{s/t}} \frac{1}{1+z^2}\, dz = \frac{2}{\pi} \arctan\left(\sqrt{\frac{s}{t}}\right)$$

$$= \frac{2}{\pi} \arccos\left(\sqrt{\frac{t}{s+t}}\right)$$

exercise

$\blacksquare$

<u>Remark</u> Let $T_0 := \inf\{t>0 : B_t = 0\}$. Then $P(T_0 = 0) = 1$

There is a sequense of zeros of $B_t(\omega)$ converging to 0.

To understand the structure of the set of zeros → Cantor set

Behavior of BM as $t \to \infty$

Thm. Let $(B_t)_{t \geq 0}$ be a (standard) BM. Then

$$P\left(\sup_{t \geq 0} B_t = +\infty , \inf_{t \geq 0} B_t = -\infty \right) = 1$$

(BM "oscilates with increasing amplitude")

Proof. Denote $Z = \sup_{t \geq 0} B_t$. Then for any $c > 0$

$$cZ =$$

By property (iii), cB_{t/c^2} is a standard BM, so cZ has the same distribution as $Z \Rightarrow P(Z=0) = p$, $P(Z=\infty) = 1-p$

$p = P(Z=0)$

$\Rightarrow P(Z=0) = 0$, $P(Z=\infty) = 1$. Similarly for $\inf_{t \geq 0} B_t$ ∎