

# Sampling with Markov chain Monte Carlo



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# Today we are going to learn...

- 1 Markov Chains
- 2 Metropolis Algorithm
- 3 Metropolis-Hastings
- 4 Multiple variables

# Markov Chains

- The goal of today's lecture is to learn about the **Metropolis Hastings algorithm**
- The Metropolis Hastings algorithm allows us to simulate from any distribution as long as we have the kernel of the density of the distribution.
- To understand the Metropolis Hastings algorithm, we must learn a little bit about **Markov chains**

# Basic Probability Rules

- **Law of conditional probability**

$$\Pr(A = a, B = b) = \Pr(A = a|B = b)\Pr(B = b) \quad (1)$$

- More general conditional probability

$$\Pr(A = a, B = b|C = c) = \Pr(A = a|B = b, C = c) \times \Pr(B = b|C = c) \quad (2)$$

# Basic Probability Rules

- **Marginalizing** (for a discrete variable)

$$\Pr(A = a) = \sum_b \Pr(A = a, B = b) \quad (3)$$

- More general

$$\Pr(A = a|C = c) = \sum_b \Pr(A = a, B = b|C = c) \quad (4)$$

# Independence

- Two variables are **independent** if

$$\Pr(A = a, B = b) = \Pr(A = a)\Pr(B = b) \quad \forall a, b \quad (5)$$

- Dividing both sides by  $\Pr(B=b)$  gives

$$\Pr(A = a|B = b) = \Pr(A = a) \quad \forall a, b \quad (6)$$

# Conditional Independence

- Two variables  $A$  and  $B$  are **Conditionally Independent** if

$$\Pr(A = a, B = b|C = c) = \Pr(A = a|C = c) \times \Pr(B = b|C = c) \quad \forall a, b, c \quad (7)$$

- Dividing both sides by  $\Pr(B = b|C = c)$  gives

$$\Pr(A = a|B = b, C = c) = \Pr(A = a|C = c) \quad \forall a, b, c \quad (8)$$

## A simple game

- Player A and Player B play a game. The probability that Player A wins each game is 0.6 and the probability that Player B wins each game is 0.4.
- They play the game  $N$  times.
- Each game is **independent**.
- Let
  - $X_i = 0$  if Player A wins game  $i$
  - $X_i = 1$  if Player B wins game  $i$
- Also assume there is an initial Game called Game 0 ( $X_0$ )



## Some simple questions

- What is the probability that Player A wins Game 1 ( $(X_1 = 0)$ ) if
  - If  $X_0 = 0$  (Player A wins Game 0)
  - If  $X_0 = 1$  (Player B wins Game 0)
- What is the probability that Player A wins Game 2 ( $(X_2 = 0)$ ) if
  - If  $X_0 = 0$  (Player A wins Game 0)
  - If  $X_0 = 1$  (Player B wins Game 0)
- Since each game is independent all answers are 0.6.

## A different game: A Markov chain

- Now assume that both players have a better chance of winning Game  $i + 1$  if they already won Game  $i$ .

$$\Pr(X_{i+1} = 0 | X_i = 0) = 0.8 \quad (9)$$

$$\Pr(X_{i+1} = 1 | X_i = 1) = 0.7 \quad (10)$$

- Assume nothing other than game  $i$  has a direct effect on Game  $i + 1$ .
- This is called the **Markov Property**. Mathematically

$$\Pr(X_{i+1} | X_i, X_{i-1}, \dots, X_1, X_0) = \Pr(X_{i+1} | X_i) \quad (11)$$

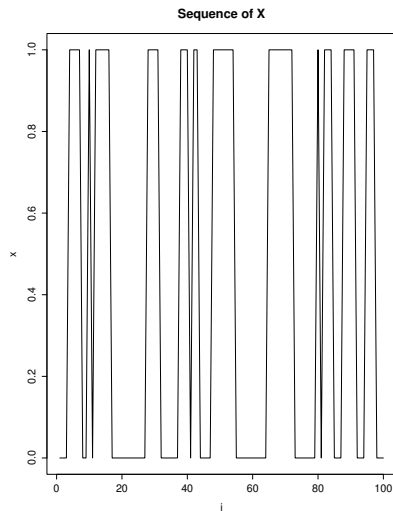
# Markov Property

- Another way to define the Markov property is to notice that  $X_{i+1}$  and  $X_{i-1}, \dots, X_0$  are **independent** conditional on  $X_i$
- This may be a model for the stock market, all the valuable information about tomorrow's stock price is contained in today's price.
- This is related to the **Efficient Market Hypothesis**, a popular theory in finance.
- Now back to the simple game.

## Simulating from a Markov chain

- Now let's simulate a sequence  $X_1, X_2, \dots, X_{100}$  from the Markov chain.
- Initialize at  $x_0 = 0$ . Then inside a loop
- Code the following using *if*.
  - if  $X_i = 0$  then  $X_{i+1} = \begin{cases} 0 & \text{with probability 0.8} \\ 1 & \text{with probability 0.2} \end{cases}$
  - if  $X_i = 1$  then  $X_{i+1} = \begin{cases} 0 & \text{with probability 0.3} \\ 1 & \text{with probability 0.7} \end{cases}$
- Try it

# Markov chain



## Simple questions again

- What is the probability that Player A wins the first game (i.e. ( $X_1 = 0$ )) if
  - If  $X_0 = 0$  (Player A wins initial game)
  - If  $X_0 = 1$  (Player B wins initial game)
- The answers are 0.8 and 0.3.
- What is the probability that Player A wins the second game ( $X_2 = 0$ ) if
  - If  $X_0 = 0$  (Player A wins initial game)
  - If  $X_0 = 1$  (Player B wins initial game)

## Solution

- Let  $X_0 = 0$ . Then  $\Pr(X_2 = 0|X_0 = 0)$

$$\begin{aligned} &= \sum_{x_1=0,1} \Pr(X_2 = 0, X_1 = x_1|X_0 = 0) \\ &= \sum_{x_1=0,1} \Pr(X_2 = 0|X_1 = x_1, X_0 = 0)\Pr(X_1 = x_1|X_0 = 0) \\ &= \sum_{x_1=0,1} \Pr(X_2 = 0|X_1 = x_1)\Pr(X_1 = x_1|X_0 = 0) \\ &= 0.8 \times 0.8 + 0.3 \times 0.2 \\ &= 0.7 \end{aligned}$$

- What if  $X_0 = 1$ ?

# Recursion

- Notice that the distribution of  $X_i$  depends on  $X_0$
- The sequence is no longer independent.
- How could you compute  $\Pr(X_n = 0 | X_0 = 0)$  when  $n = 3$ , when  $n = 5$ , when  $n = 100$ ?
- This is hard, but the Markov Property does make things simpler
- We can use a recursion to compute the probability that Player A wins any game.



# Recursion

Note that  $\Pr(X_i = 0 | X_0 = 0)$

$$\begin{aligned} &= \sum_{x_{i-1}} \Pr(X_i = 0, X_{i-1} = x_{i-1} | X_0 = 0) \\ &= \sum_{x_{i-1}} \Pr(X_i = 0 | X_{i-1} = x_{i-1}, X_0 = 0) \Pr(X_{i-1} = x_{i-1} | X_0 = 0) \\ &= \sum_{x_{i-1}} \Pr(X_i = 0 | X_{i-1} = x_{i-1}) \Pr(X_{i-1} = x_{i-1} | X_0 = 0) \end{aligned}$$

We already applied this formula when  $i = 2$ . We can continue for  $i = 3, 4, 5, \dots, n$

# Recursion

$$\Pr(X_i = 0|X_0 = 0) = \sum_{x_{i-1}} \Pr(X_i = 0|X_{i-1} = x_{i-1})\Pr(X_{i-1} = x_{i-1}|X_0 = 0)$$

- Start with  $\Pr(X_1 = 0|X_0 = 0)$
- Get  $\Pr(X_1 = 1|X_0 = 0)$
- Use these in formula with  $i = 2$
- Get  $\Pr(X_2 = 0|X_0 = 0)$
- Get  $\Pr(X_2 = 1|X_0 = 0)$
- Use these in formula with  $i = 3$
- Get  $\Pr(X_3 = 0|X_0 = 0)$
- $\vdots \quad \vdots \quad \vdots \quad \vdots$

# Matrix Form

It is much easier to do this calculation in matrix form (especially when  $X$  is not binary). Let  $P$  be the transition matrix

	$X_i = 0$	$X_i = 1$
$X_{i-1} = 0$	$\Pr(X_i = 0 X_{i-1} = 0)$	$\Pr(X_i = 1 X_{i-1} = 0)$
$X_{i-1} = 1$	$\Pr(X_i = 0 X_{i-1} = 1)$	$\Pr(X_i = 1 X_{i-1} = 1)$

# Matrix Form

In our example:

	$X_i = 0$	$X_i = 1$
$X_{i-1} = 0$	0.8	0.2
$X_{i-1} = 1$	0.3	0.7

$$P = \begin{pmatrix} 0.8 & 0.2 \\ 0.3 & 0.7 \end{pmatrix} \quad (12)$$

## Matrix Form

Let  $\pi_i$  be a  $1 \times 2$  row vector which denotes the probabilities of each player winning Game  $i$  conditional on the initial Game

$$\pi_i = (\Pr(X_i = 0|X_0), \Pr(X_i = 1|X_0)) \quad (13)$$

In our example if  $X_0 = 0$

$$\pi_1 = (0.8, 0.2) \quad (14)$$

In our example if  $X_0 = 1$

$$\pi_1 = (0.3, 0.7) \quad (15)$$

## Recursion in Matrix form

- The recursion formula is

$$\pi_i = \pi_{i-1}P \quad (16)$$

Therefore

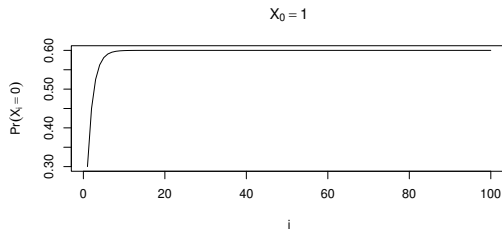
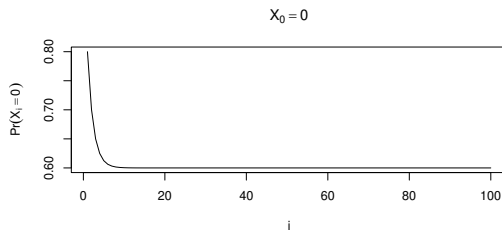
$$\pi_n = \pi_1 P \times P \times \dots \times P \quad (17)$$

- Now code this up in R.
- What is  $\Pr(X_n = 0 | X_0 = 0)$  when
  - $n = 3$
  - $n = 5$
  - $n = 100$ ?
- Do the same when  $X_0 = 1$

# Convergence?

- For  $n = 3$  and  $n = 5$ , the starting point made a big difference.
- For  $n = 100$  it did not make a big difference.
- Could this Markov chain be converging to something?
- Now write code to keep the values of  $\pi_i$  for  $i = 1, 2, \dots, 100$ .
- Then plot the values of  $\pi_{i1}$  against  $i$

# Convergence





## More Questions

- What is  $\Pr(X_{100} = 0 | X_0 = 0)$ ?
- What is  $\Pr(X_{100} = 0 | X_0 = 1)$ ?
- What is  $\Pr(X_{1000} = 0 | X_0 = 0)$ ?
- What is  $\Pr(X_{1000} = 0 | X_0 = 1)$ ?
- The answer to all of these is 0.6.
- The  $X$  do not converge. They keep changing from 0 to 1. The Markov chain however converges to a **stationary distribution**.

## Simulation with a Markov chain

- Go back to your code for generating a Markov chain and generate a chain with  $n = 110000$
- Exclude the first 10000 values of  $X_i$  and keep the remaining 100000 values.
- How many  $X_i = 0$ ? How many  $X_i = 1$
- We have discovered a new way to simulate from a distribution with  $\Pr(X_i = 0) = 0.6$  and  $\Pr(X_i = 1) = 0.4$

# Markov Chains

- Sometimes two different Markov chains converge to the same stationary distribution. See what happens when

$$P = \begin{pmatrix} 0.9 & 0.1 \\ 0.15 & 0.85 \end{pmatrix} \quad (18)$$

- Sometimes Markov chains do not converge to a stationary distribution at all.
- Some Markov chains can get stuck in an **absorbing state**. For example what would the simple example look like if  $\Pr(X_{i+1} = 0 | X_i = 0) = 1$ ?
- Markov chains can be defined on continuous support as well,  $X_i$  can be continuous.

## Some important points

- This is a very complicated way to generate from a simple distribution.
- For the binary example the direct method would be better.
- However for other examples, either the direct method or accept/reject algorithm do not work.
- In these cases we can construct a Markov chain that has a stationary distribution that is our **target distribution**.
- All we need is the kernel of the density function, and an algorithm called the **Metropolis Algorithm**

## Normalizing Constant and Kernel

What are the normalizing constant and kernel of the Beta density?

$$\text{Beta}(x; a, b) = \frac{\Gamma(a+b)}{(\Gamma(a)\Gamma(b))} x^{a-1} (1-x)^{b-1} \quad (19)$$

# The Metropolis algorithm

- The Metropolis algorithm was developed in a 1953 paper by Metropolis, Rosenbluth, Rosenbluth, Teller and Teller.
- The aim is to simulate  $x \sim p(x)$  where  $p(x)$  is called the **target density**.
- We will need a **proposal density**  $q(x^{[\text{old}]} \rightarrow x^{[\text{new}]})$
- For example one choice of  $q$  is

$$x^{[\text{new}]} \sim N(x^{[\text{old}]}, 1) \quad (20)$$

- This is called a **Random Walk proposal**

# Symmetric proposal

- An important property of  $q$  in the Metropolis algorithm is symmetry of the proposal

$$q(x^{[\text{old}]} \rightarrow x^{[\text{new}]}) = q(x^{[\text{new}]} \rightarrow x^{[\text{old}]}) \quad (21)$$

- Later we will not need this assumption
- Can you confirm this is true for  $x^{[\text{new}]} \sim N(x^{[\text{old}]}, 1)$ ?
- Can you simulate from this random walk (use  $x_0 = 0$  as a starting value)?

# Proof of symmetry of random walk

The proposal

$$q(x^{[\text{old}]} \rightarrow x^{[\text{new}]}) = (2\pi)^{-1/2} \exp \left\{ -\frac{1}{2} \left( x^{[\text{new}]} - x^{[\text{old}]} \right)^2 \right\} \quad (22)$$

$$= (2\pi)^{-1/2} \exp \left\{ -\frac{1}{2} \left[ -1 \left( x^{[\text{new}]} - x^{[\text{old}]} \right) \right]^2 \right\} \quad (23)$$

$$= (2\pi)^{-1/2} \exp \left\{ -\frac{1}{2} \left( x^{[\text{old}]} - x^{[\text{new}]} \right)^2 \right\} \quad (24)$$

$$= q(x^{[\text{new}]} \rightarrow x^{[\text{old}]}) \quad (25)$$



## Accept and reject

- By itself the random walk will not converge to anything.
- To make sure this Markov chain converges to our target, we need to include the following.
- At step  $i + 1$  set  $x^{[old]} = x^{[i]}$ .
- Generate  $x^{[new]} \sim N(x^{[old]}, 1)$  and compute

$$\alpha = \min \left( 1, \frac{p(x^{[new]})}{p(x^{[old]})} \right) \quad (26)$$

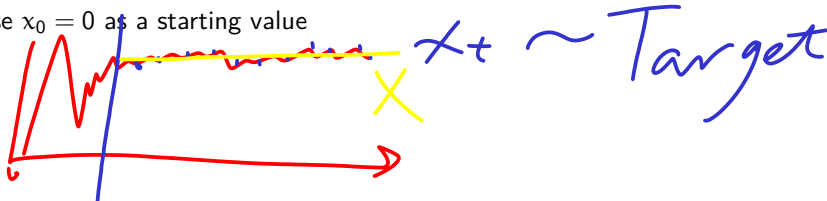
- Then
  - Set  $x^{[i+1]}$  to  $x^{[new]}$  with probability  $\alpha$  (accept)
  - Set  $x^{[i+1]}$  to  $x^{[old]}$  with probability  $1 - \alpha$  (reject)

## Code it up

- Use the Metropolis algorithm with a random walk proposal to simulate a sample from the standard t distribution with 5 df.
- The target density is

$$p(x) = \left[1 + \frac{x^2}{5}\right]^{-3} \quad \text{Kernel} \quad (27)$$

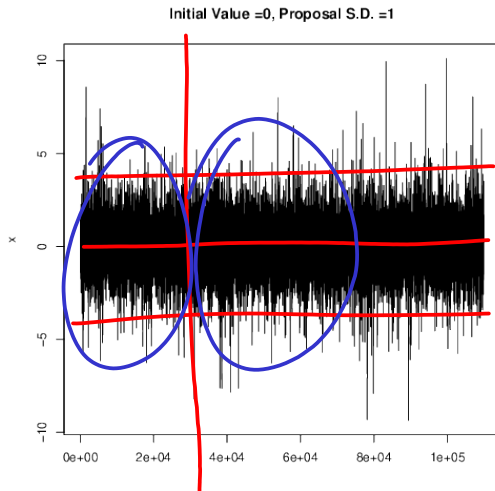
- Simulate a Markov chain with 110000 iterates using the random walk as a proposal.
- The first 10000 iterates are the **burn-in** and will be left out because the Markov chain may not have converged yet.
- Use  $x_0 = 0$  as a starting value



## Some diagnostics - Convergence

- There are a few diagnostics we can use to investigate the behaviour of the chain
- One is a trace plot (including burn in), which is simply a line plot of the iterates.
- Plot this for your Markov chain
- Another diagnostic is the **Geweke diagnostic** which can be found in the R package coda.
- The Geweke diagnostic tests the equality of the means of two different parts of the chain (excluding burn-in). The test statistic has a standard normal distribution.
- Rejecting this test is evidence that the chain has not converged

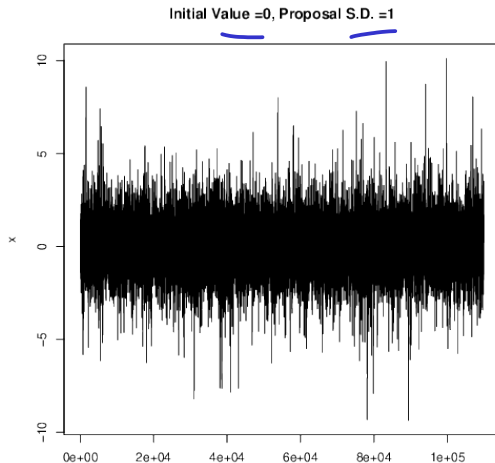
# Trace Plot



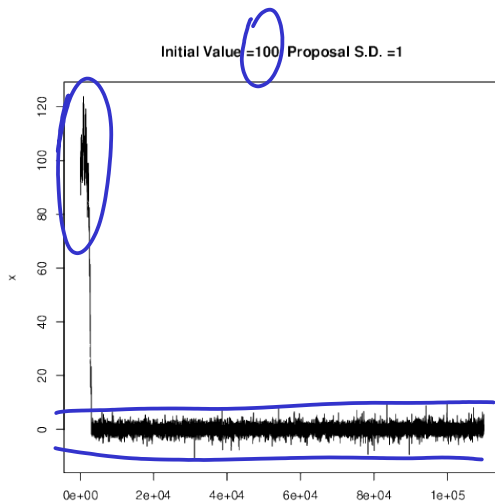
# The effect of starting value

- Now rerun the code with a starting value of  $X_0 = 100$
- Does the chain still converge?
- Does it converge quicker or slower?

# Trace Plot



# Trace Plot

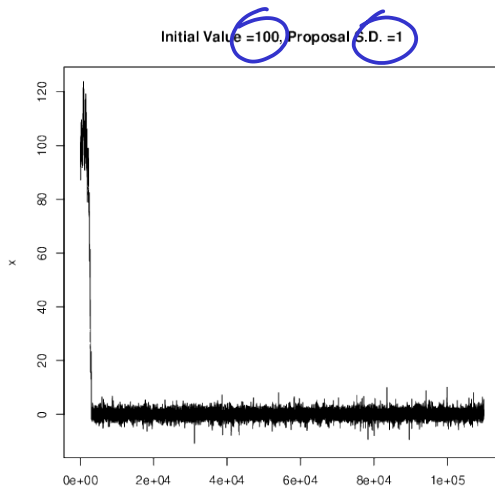


## The effect of proposal variance

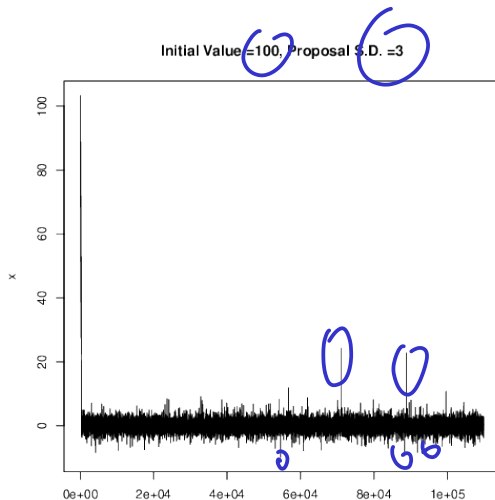
- Keep the starting value of  $X_0 = 100$
- No change the standard deviation of the proposal to 3.
- Does the chain still converge?
- Does it converge quicker or slower?



# Trace Plot



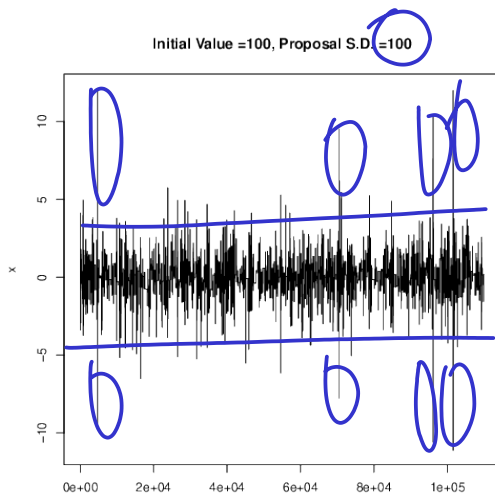
# Trace Plot



## Huge proposal variance

- Maybe you think the best strategy is to choose a huge standard deviation.
- Try to use a proposal standard deviation of 100. Plot a trace plot of the chain.
- The plot is rejecting many iterates. This must be inefficient
- Change your code to compute the percentage of times a new iterate is accepted (excluding burn in).
- Use  $x_0 =$  as an initial value. What is the acceptance rate when the proposal standard deviation is 1? What is the acceptance rate when the proposal standard deviation is 100?

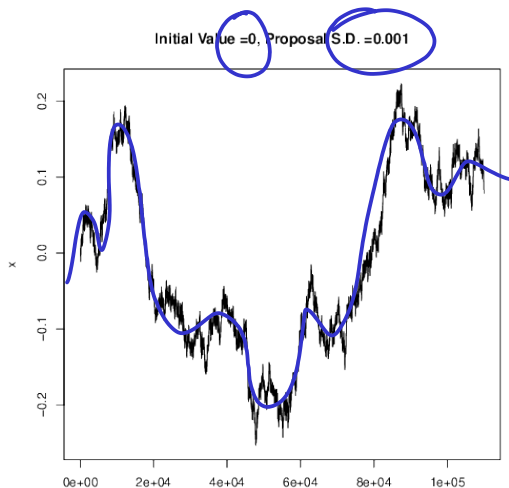
# Trace Plot



# Acceptance Rate

- If the proposal variance is too high
  - Values will be proposed that are too far into the tails of the stationary distribution
  - The Metropolis algorithm will mostly reject these values.
  - The sample will still come from the correct target distribution but this is a very inefficient way to sample.
- What happens if a very small proposal variance is used.
- Try a proposal variance of 0.001. What is the acceptance rate?

# Trace Plot



# Acceptance Rate

- The acceptance rate is almost 1.
- However is this a good proposal?
- The jumps made by this proposal are too small, and do not sample enough iterates from the tails of the distribution.
- If it runs long enough the Markov chain will provide a sample from the target distribution. However, it is very inefficient.

# Random Walk proposal

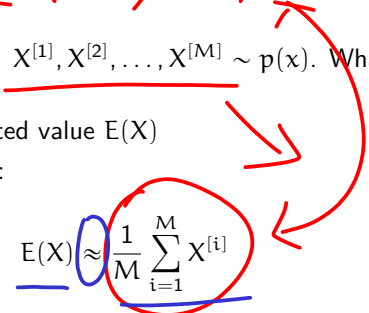


- For a random walk proposal it is not good to have an acceptance rate that is too high or too low.
- What exactly is *too high* and *too low*?
- It depends on many things including the target and proposal.
- A rough rule is to aim for an acceptance rate between 20% and 70%
- If your acceptance rate is outside this range the proposal variance can be doubled or halved
- There are better (but more complicated) ways to do this.

ACF



## Monte Carlo Error

$$f(x) \quad E(x) = \mu$$


- Now that there is a sample.  $X^{[1]}, X^{[2]}, \dots, X^{[M]} \sim p(x)$ . What can it be used for?
- We can estimate the expected value  $E(X)$
- This can be done by taking:

$$E(X) \approx \frac{1}{M} \sum_{i=1}^M X^{[i]}$$

- Note we use  $\approx$  instead of  $=$ . There is some error since we are estimating  $E(X)$  based on a sample.
- Luckily we can make this smaller by generating a bigger sample.
- We call this Monte Carlo error.

# Measuring Monte Carlo Error

- One way to measure Monte Carlo Error is the variance of the sample mean.

$$\begin{aligned}\text{Var}\left(\frac{1}{M} \sum_{i=1}^M X^{[i]}\right) &= \frac{1}{M^2} \text{Var}\left(\sum_{i=1}^M X^{[i]}\right) \\ &= \frac{1}{M^2} \sum_{i=1}^M \text{Var}(X^{[i]}) \\ &= \frac{\text{Var}(X)}{M}\end{aligned}$$

- A sample from a Markov chain is correlated

$M \rightarrow \infty$

# Measuring Monte Carlo Error

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# Measuring Monte Carlo Error

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$$\begin{aligned}\text{Var}\left(\frac{1}{M} \sum_{i=1}^M X^{[i]}\right) &= \frac{1}{M^2} \text{Var}\left(\sum_{i=1}^M X^{[i]}\right) \\&= \frac{1}{M^2} \sum_{i=1}^M \text{Var}(X^{[i]}) + \frac{2}{M^2} \sum_{i=1}^M \sum_{j>i}^M \text{cov}(X^{[i]}, X^{[j]}) \\&= \frac{\text{Var}(X)}{M} + \frac{2}{M^2} \sum_{i=1}^M \sum_{j>i}^M \text{cov}(X^{[i]}, X^{[j]}) \neq 0\end{aligned}$$

- A sample from a Markov chain is **correlated**

$\rightsquigarrow \infty$

# Monte Carlo efficiency

- It is better to have lower correlation in the Markov chain.
- The efficiency of the chain can be measured using the **effective sample size**.
- The effective sample size can be computed using the function *effectiveSize* in the R Package coda.
- Obtain an effective sample size for your sample (excluding burn in) where
  - Proposal S.D. = 1
  - Proposal S.D. = 5
- My answers were about 6000 and 18000 and yours should be close to that

# Interpret Effective Sample Size

- What does it mean to say a Monte Carlo with a sample size of 100000 has an effective sample size (ESS) of just 6000?
- The sampling error of a correlated sample of 100000 is equal to the sampling error of an *independent sample* of 6000.
- Mathematically

$$\text{Var}\left(\frac{1}{M} \sum_{i=1}^M X^{[i]}\right) = \frac{\text{Var}(X)}{M} + \frac{2}{M^2} \sum_{i=1}^M \sum_{j>i}^M \text{cov}(X^{[i]}, X^{[j]}) = \frac{\text{Var}(X)}{M_{\text{eff}}}$$

- It is a useful diagnostic for comparing two different proposal variances. A higher ESS implies a more efficient scheme.

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# Non-Symmetric proposal

- In 1970, Hastings proposed an extension to the Metropolis Hastings algorithm.
- This allows for the case when

$$q(x^{[old]} \rightarrow x^{[new]}) \neq q(x^{[new]} \rightarrow x^{[old]}) \quad (28)$$

- The only thing that changes is the acceptance probability

$$\alpha = \min \left( 1, \frac{p(x^{[new]}) q(x^{[new]} \rightarrow x^{[old]})}{p(x^{[old]}) q(x^{[old]} \rightarrow x^{[new]})} \right) \quad (29)$$

- This is called the **Metropolis-Hastings algorithm**

$$\alpha_{n+1} > \alpha_n$$

## An interesting proposal

$\alpha_n =$

- Suppose we use the proposal:

$$x^{\text{new}} \sim N(0, \sqrt{(5/3)})$$

(30)

- What is  $q(x^{\text{old}} \rightarrow x^{\text{new}})$ ?
- It is  $q(x^{\text{new}})$  where  $q(\cdot)$  is the density of a  $N(0, \sqrt{(5/3)})$ .
- Is this symmetric?
- No, since generally  $q(x^{\text{new}}) \neq q(x^{\text{old}})$



# Metropolis Hastings

- Code this where  $p(\cdot)$  is the standard t density with 5 d.f, and  $q(\cdot)$  is normal with mean 0 and standard deviation  $\sqrt{5/3}$ .

- Inside a loop

- Generate  $x^{[new]} \sim N(0, \sqrt{(5/3)})$
- Set  $x^{old} = x^{[i]}$  and compute

$$\alpha = \min \left( 1, \frac{p(x^{[new]})q(x^{[old]})}{p(x^{[old]})q(x^{[new]})} \right)$$

(31)

- Set  $x^{[i+1]}$  to  $x^{[new]}$  with probability  $\alpha$  (accept)
  - Set  $x^{[i+1]}$  to  $x^{[old]}$  with probability  $1 - \alpha$  (reject)
- Try it

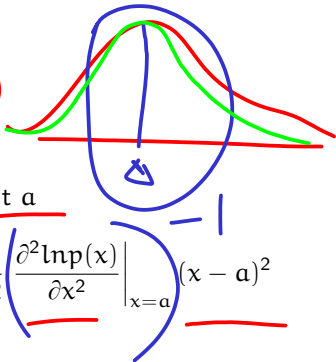
$M: X \sim N$   
 $\sim N(\mu, \sigma^2)$

# Comparison

- The Effective Sample Size of this proposal is about 43000 much higher than the best random walk proposal.
- Why does it work so well?
- The standard t distribution with 5 df has a mean of 0 and a standard deviation of  $\sqrt{(5/3)}$
- So the  $N(0, \sqrt{(5/3)})$  is a good approximation to the standard student t with 5 df.

## Laplace Approximation

$\ln P(x)$



Using a Taylor expansion of  $\ln p(x)$  around the point  $a$

$$\ln p(x) \approx \ln p(a) + \left. \frac{\partial \ln p(x)}{\partial x} \right|_{x=a} (x-a) + \frac{1}{2} \left( \left. \frac{\partial^2 \ln p(x)}{\partial x^2} \right|_{x=a} \right) (x-a)^2$$

Let  $a$  be the point that maximises  $\ln p(x)$  and let

$$b = - \left( \left. \frac{\partial^2 \ln p(x)}{\partial x^2} \right|_{x=a} \right)^{-1} \quad (32)$$

$P \times P$

The approximation is

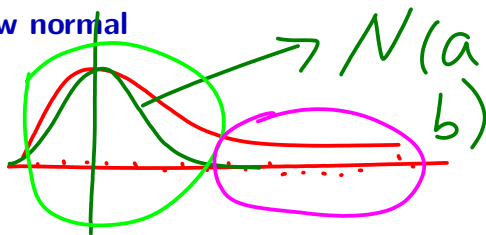
$$\ln p(x) \approx \ln p(a) - \frac{1}{2b}(x - a)^2$$

Taking exponential of both sides

$$p(x) \approx k \times \exp \left[ -\frac{(x - a)^2}{2b} \right]$$

Any distribution can be approximated by a normal distribution with mean  $a$  and variance  $b$  where  $a$  and  $b$  values can be found numerically if needed.

## Exercise: Generating from skew normal



- The density of the skew normal is

$$p(x) = 2\phi(x)\Phi(\delta x) \quad (33)$$

where  $\phi(x)$  is the density of the standard normal  $\Phi(x)$  is the distribution of the standard normal.

- Using a combination of *optim*, *dnorm* and *pnorm* find the Laplace approximation of the skew normal when  $\delta = 3$
- Use it to generate a sample from the skew normal distribution using the Metropolis Hastings algorithm.

① MH only  
② MH + LAP

# Indirect method v Metropolis Hastings

- Some similarities are:
  - Both require a proposal
  - Both are more efficient when the proposal is a good approximation to the target.
  - Both involve some form of accepting/rejecting
- Some differences are:
  - Indirect method produces an independent sample, MH samples are correlated.
  - Indirect method requires  $p(x)/q(x)$  to be finite for all  $x$ .
  - MH works better when  $x$  is a (high-dimensional vector).
- Why?

$X \sim p(x)$

## Multiple variables

$$p(x_1, x_2, \dots, x_p)$$

- Suppose we now want to sample from a bivariate distribution  $p(x, z)$
- The ideas involved in this section work for more than two variables.
- It is possible to do a 2-dimensional random walk proposal. However as the number of variables goes up the acceptance rate becomes lower.
- Also the Laplace approximation does not work as well in high dimensions.
- Indirect methods of simulation suffer from the same problem.
- We need a way to break the problem down.

$$x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_p \end{bmatrix}$$

$$\frac{p(\beta, \sigma)}{R, R^+}$$

## Method of composition

$$P(\beta, \sigma) = P(\beta | \sigma) \overset{(2)}{\times} P(\sigma) \overset{(1)}$$

- Markov chain methods, allow us to break multivariate distributions down.
- If it is easy to generate from  $p(x)$  then the best way is **Method of composition**. Generate
  - $x^{[i]} \sim p(x)$
  - $z^{[i]} \sim p(z|x = x^{[i]})$
- Sometimes  $p(x)$  is difficult to get

$$\begin{matrix} \sigma^{(1)}, & \beta^{(1)} \\ \sigma^{(2)}, & \beta^{(2)} \\ \vdots & \vdots \\ \sigma^{(n)}, & \beta^{(n)} \end{matrix}$$



## Gibbs Sampler

$$p(\beta, \gamma, \sigma, \dots, z)$$

- If it is easy to simulate from the conditional distribution  $f(x|z)$  then that can be used as a proposal
- What is the acceptance ratio?

$$p(z)$$

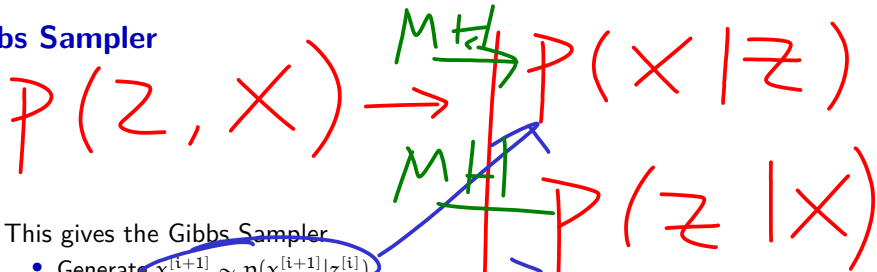
$$\alpha = \left( 1, \frac{p(x^{\text{new}}, z)p(x^{\text{old}}|z)}{p(x^{\text{old}}, z)p(x^{\text{new}}|z)} \right)$$

$$p(\sigma|z) = \left( 1, \frac{p(x^{\text{new}}|z)p(z)p(x^{\text{old}}|z)}{p(x^{\text{old}}|z)p(z)p(x^{\text{new}}|z)} \right)$$

$$= 1$$

$$p(\gamma) \dots$$

## Gibbs Sampler



• This gives the Gibbs Sampler

- Generate  $x^{[i+1]} \sim p(x^{[i+1]}|z^{[i]})$
  - Generate  $z^{[i+1]} \sim p(z^{[i+1]}|x^{[i+1]})$
  - Repeat
- $x$  and  $z$  can be swapped around.
- It works for more than two variables.
- Always make sure the conditioning variables are at the current state.

MH-within  
Gibbs

$$P(x_1, \dots, x_n)$$

$$\rightarrow P(x_i | x_1, x_{i-1}, x_{i+1}, \dots, x_n)$$

# Metropolis within Gibbs

- Even if the individual conditional distributions are not easy to simulate from, Metropolis Hastings can be used *within* each Gibbs step.
- This works very well because it breaks down a multivariate problem into smaller univariate problems.
- We will practice some of these algorithms in the context of *Bayesian Inference*

## Summary

①  $LP$ .  $z \phi(x) \propto \psi(x)$

$$\sigma = 3$$

$MH$ ,  $MH + LP$

- You should be familiar with a *Markov chain*
- You should understand this can have a *stationary distribution*
- You should have a basic understanding of the Metropolis Hastings and the special cases
  - Random Walk Metropolis
  - Laplace approximation
  - Gibbs Sampler

②  $CRAN$ ,  $z \propto$ ,  $M+1$ , ⑥

③  $P(x_1, x_2) = 0.4 N(x_1, 0, 1)$   
Gibbs  $+ 0.6 T(x_2, 2, 4)$