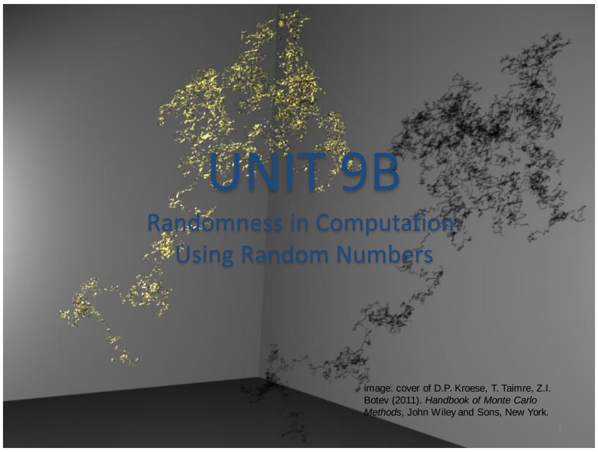

UNIT 9B

Randomness in Computation: Using Random Numbers

image: cover of D.P. Kroese, T. Taimre, Z.I. Botev (2011). *Handbook of Monte Carlo Methods*, John Wiley and Sons, New York.

Last Lecture: Pseudorandom Number Generation

- Linear Congruential Generators (LCGs)
  - We can generate a series of numbers, all different, that ***looks* random** even though it isn't
- If we choose appropriate constants for our LCG, then we can generate a very long sequence before numbers begin to repeat. The length of the sequence is its ***period***
- To generate random numbers in Python we can use randint(x,y), which generates a random integer between x and y.

2

Uses of Random Numbers

- Many!
  - Cryptography
  - Simulation
  - Gambling
  - Games

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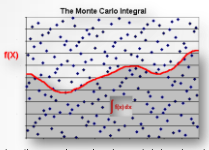
- This Lecture -
Monte Carlo methods

Idea: run many experiments with random inputs to approximate an answer to a question.

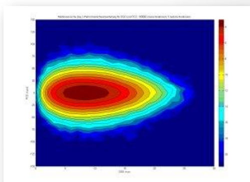
We might be unable to answer the question any other way, or an *analytical* (logical, mathematical, exact) solution might be too expensive.

4

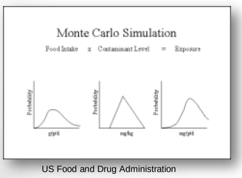
Some Applications



http://marcoagd.usuarios.rdc.puc-rio.br/quasi_mc.html



Dr.-Ing. Matthias Westhäuser. Statistical Analysis of Fiber Optical Systems using Multicanonical Monte Carlo Methods (http://www.hft.e-technik.tu-dortmund.de/forschung/projekt.php?id=18&lang=en)



US Food and Drug Administration

5

Monte Carlo Methods

- The hungry dice player
- The clueless student*
- The umbrella quandary*
- A survey of applications

* Source: *Digital Dice* by Paul J. Nahin

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What is a Monte Carlo Method?

- An algorithm that **uses** a source of (pseudo) **random numbers**
- **Repeats an "experiment"** many times and calculates a statistic, often an average
- **Estimates** a value (often a probability)
- … usually a value that is ***hard* or *impossible*** to calculate analytically

A simple Monte Carlo method

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(no computer needed!)

Simple example: dice statistics

- We can **analyze** throwing a pair of dice and get the following probabilities for the sum of the two dice:

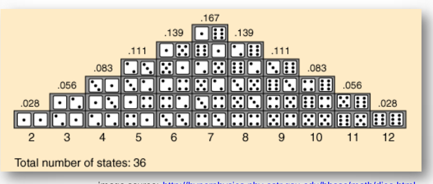
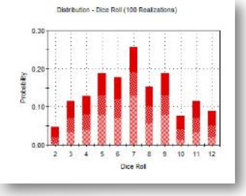


image source: http://hyperphysics.phy-astr.gsu.edu/hbase/math/dice.html
via http://www.goldsim.com/Web/Introduction/Probabilistic/MonteCarlo/

Simple example: dice statistics

- … **or** we can throw a pair of dice 100 times and record what happens, or 10000 times for a more accurate estimate.



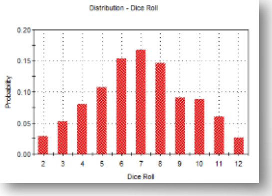


image source: http://www.goldsim.com/Web/Introduction/Probabilistic/MonteCarlo/

The Hungry Dice Player

estimating the expected value of a simple game

A game of dice

```
def dice_game() :
    strikes = 0
    winnings = 0
    while strikes < 3 :   # 3 strikes and you’re out
        # get 2 random numbers (1…6)
        die1 = roll()
        die2 = roll()
       # play: strike or win?
        if die1 == die2 :
            strikes = strikes + 1
        else :
            winnings = winnings + die1 + die2
    return winnings       # in centsz
```

The Hungry Dice Player

- In our simple game of dice:
  Can I expect to make enough money playing it to buy lunch?
- That is, what is the expected (average) value won in the game?
- We could figure it out by applying laws of probability
- …or use a Monte Carlo method

Monte Carlo method for the hungry dice player

```
def average_winnings(runs) :
    # runs is the number of experiments to run
    total = 0
    for n in range(runs) :
        total = total + dice_game()
    return total/runs
```

```
>>> [round(average_winnings(10),2) for i in range(5)]
[85.8, 94.8, 120.7, 123.3, 90.0]
>>> [round(average_winnings(100),2) for i in range(5)]
[105.97, 102.95, 107.74, 134.4, 114.54]
>>> [round(average_winnings(1000),2) for i in range(5)]
[106.84, 107.11, 105.59, 104.28, 106.41]
>>> [round(average_winnings(10000),2) for i in range(5)]
[104.94, 105.71, 105.81, 105.74, 104.62]
```


The Clueless Student

a famous matching problem

The Clueless Student

A clueless student faced a pop quiz:
a list of the 24 Presidents of the 19th century and another list of their terms in office, but scrambled.
The object was to match the President with the term.

If the student guesses a random one-to-one matching, how many matches will be right out of the 24, on average?

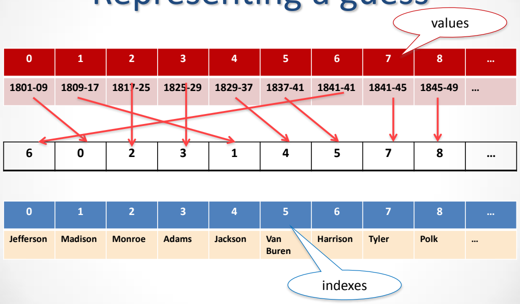
The quiz

1. Monroe	a. 1801-1809
2. Jackson	b. 1869-1877
3. Arthur	c. 1885-1889
4. Madison	d. 1850-1853
5. Cleveland	e. 1889-1893
6. Jefferson	f. 1845-1849
7. Lincoln	g. 1837-1841
8. Van Buren	h. 1853-1857
9. Adams	i. 1809-1817
etc.	etc.

Solving the problem

- The problem (1710, Pierre de Montmort) was important in development of probability theory
- The mathematical analysis is, um, interesting (see http://www.math.uah.edu/stat/urn/Matching.html)
- Let's just simulate the situation, randomly selecting guesses and checking to see how many correct match-ups they contain.

Representing a guess



Representing a guess

- **Representing a guess:** A guess is just a permutation (shuffling) of the numbers 0 … 23.

  E.g. [0, 1, 2, 3, 4, 5, …, 23] represents a completely correct guess
  [1, 0, 2, 3, 4, 5, …, 23] represents a guess that is correct except that it gets the first two presidents wrong.

- Let's define a ***match*** in a guess to be any number *k* that occurs in position *k*. (*E.g.,* 0 in position 0, 10 in position 10)

- With this representation, our question becomes:
  if I pick a random shuffling of the numbers 0…23, how many (on average) matches occur?

Randomly permuting a list

To get a random shuffling of the numbers 0 to 23 we use the `shuffle` function from module `random`:

```
>>> nums = list(range(10))
>>> nums
[0, 1, 2, 3, 4, 5, 6, 7, 8, 9]
```

```
>>> shuffle(nums)
>>> nums
[4, 5, 3, 2, 0, 9, 6, 1, 8, 7]
```

```
>>> shuffle(nums)
>>> nums
[3, 6, 1, 4, 5, 8, 2, 9, 0, 7]
```

Algorithm

We will solve a more general problem

- **Input:** *pairs* (number of things to be matched), *samples* (number of samples to test)
- **Output:** average number of correct matches per sample
- **Method:**
  1. Set *num_correct* = 0
  2. Do the following *samples* times:
     a. Set *matching* to a random permutation of the numbers 0…*pairs*-1
     b. For ***k*** in 0…*pairs*, if *matching*[***k***] = ***k*** add one to *num_correct*
  3. The result is *num_correct* / *samples*

Code for the clueless student

```
from random import shuffle
# pairs is the number of pairs to be guessed
# samples is the number of samples to take
def cl_student(pairs, samples) :
    num_correct = 0
    matching = list(range(pairs))
    for i in range(samples):          # experiment samples times
        shuffle(matching)             # generate a guess
        # if generated guess is a match, increment the num_correct
        for j in range(pairs):
            if matching[j] == j :
                num_correct = num_correct + 1
    # return the average value
    return num_correct / samples
```


Running the code

The mathematical analysis says the expected value is exactly 1 (**no matter how many matches are to be guessed**).

```
>>> cl_student(24, 10000)
0.9924
>>> cl_student(24, 10000)
1.0071
>>> cl_student(10, 10000)
1.0224
```

```
>>> cl_student(10, 10000)
0.9999
>>> cl_student(5, 10000)
1.0039
>>> cl_student(5, 10000)
0.9826
```

More samples – smaller error

```
>>> 1 - cl_student(5, 1000)
0.03600000000000003
>>> 1 - cl_student(5, 10000)
0.005900000000000016
>>> 1 - cl_student(5, 100000)
0.0014100000000000223
>>> 1 - cl_student(5, 1000000)
-0.0006679999999998909
```


The Umbrella Quandary

• • •

simulating a system

The Umbrella Quandary

- Mr. X walks between home and work every day
- He likes to keep an umbrella at each location
- But he always forgets to carry one if it's not raining

- If the probability of rain is *p*, how many trips can he expect to make before he gets caught in the rain?

  (Assuming that if it's not raining when he starts a trip, it doesn't rain during the trip.)

The trivial cases

- What if it always rains?
- What if it never rains (ok, that was too easy)
- So we only need to think about a probability of rain greater than zero and less than one

Solving the umbrella quandary

- Analysis of the problem can be done with Markov chains
- But we're just humble programmers,

  → we'll simulate and measure

Simulating an event with a given probability

- In contrast to the clueless student problem we're given a probability of an event
- We want to simulate that the event happens, with the given **probability *p*** (where *p* is a number between 0 and 1)
- **Technique:** get a random float between 0 and 1;
  if it's less than *p* simulate that the event happened

```
if random() < p :
     raining = True
```

Representing home, work, and umbrellas

- Use **0** for **home**,
  1 for **work** as **location**
- A list for the **number of umbrellas** at each location (2 locations)

- How should we initialize?

```
location = 0
umbrellas = [1, 1]
```

Remember that he likes to keep an umbrella at each location

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Figuring out when to stop

We want to count the number of trips before Mr. X gets wet, so we want to keep simulating trips until he does.

- To keep track:

```
wet = False
trips = 0
while (not wet):
     …
```

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Changing locations

Mr. X walks between home (0) and work (1)

- To keep track of where he is:

```
location = 0     #start at home
```

- To move to the other location:

```
location = 1 – location
```

- To find how many umbrellas at current location:

```
umbrellas[location]
```

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Putting it together

```
from random import random
def umbrella(p) :          # p is the probability of rain

    wet = False
    trips = 0
    location = 0
    umbrellas = [1, 1]      # index 0 stands for home, 1 stands for work

    while (not wet) :
        if random() < p :   # it's raining
            if umbrellas[location] == 0 :  # no umbrella at current loc.
                wet = True
            else:
                trips = trips + 1
                umbrellas[location] -= 1          # take an umbrella
                location = 1 - location           # switch locations
                umbrellas[location] += 1          # put umbrella
        else:    # it's not raining, leave umbrellas where they are
            trips = trips + 1
            location = 1 – location               # switch locations

    return trips
```


Running simulations

```
>>> umbrella(.5)
22
>>> umbrella(.5)
4
>>> umbrella(.5)
13
>>> umbrella(.5)
2
>>> umbrella(.5)
2
```

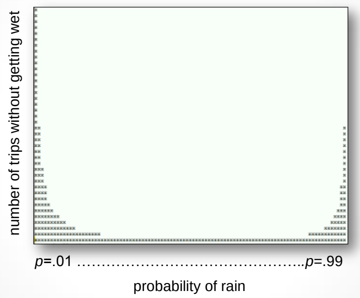

Great, but we want averages

- One experiment doesn't tell us much–we want to know, **on average**, if the probability of rain is *p*, how many trips can Mr. X make without getting wet?
- We add code to run `umbrella(p)` 10,000 times for different probabilities of rain, from *p* = .01 to .99 in increments of .01
- We accumulate the results in a list that will show us how the average number of trips is related to the probability of rain.

Running the experiments

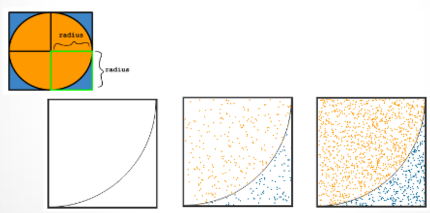
```
# 10,000 experiments for each probability from .01 to .99
# Accumulate averages in a list

def test() :
    results = [None]*99       # Initialize list
    p = .01                   # probability starts 0.1

    for i in range(99) :
        trips = 0

        # find average of 10000 experiments
        for k in range(10000) :
            trips = trips + umbrella(p)
        results[i] = trips/10000
        p = p + .01           # inc. for next probability

    return results
```


Crude plot of results



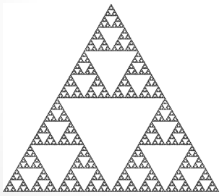
Other Samples and Uses

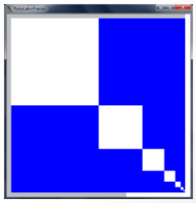
- Calculation of PI using the Monte Carlo Method (http://pumpkinprogrammer.com/2015/03/14/approximating-pi-monte-carlo-method/)



Fractals and Randomness

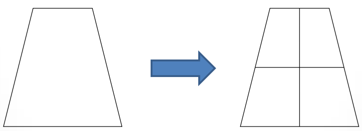
- Recall: A fractal is an image that is self-similar.
- Fractals are typically generated using recursion.





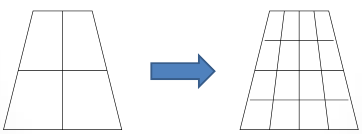
Simple Fractal

Connect midpoints of the quadrilateral



Simple Fractal

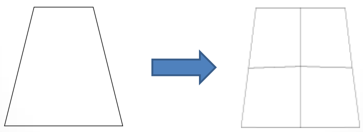
- Connect midpoints of each quadrilateral recursively



It makes a disco floor!

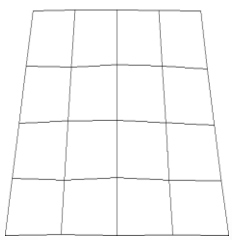
Fractal with Randomness

- Randomly move midpoints slightly and then connect.



Fractal with Randomness

- Randomly move midpoints slightly and then connect.



Fractal with Randomness

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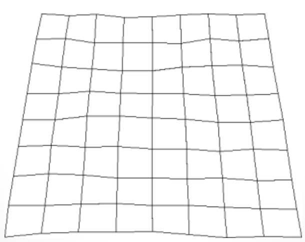

Fractal with Randomness

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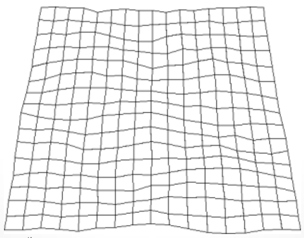
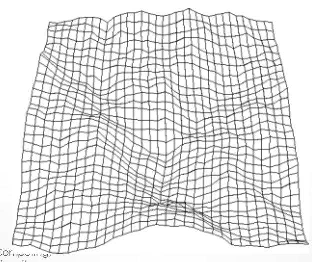


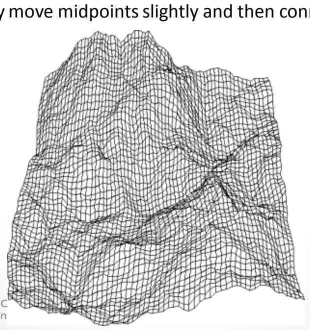
Fractal with Randomness

- Randomly move midpoints slightly and then connect.



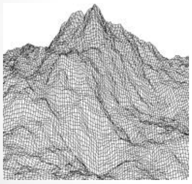
Fractal with Randomness

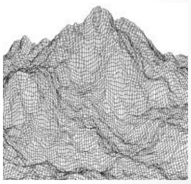
- Randomly move midpoints slightly and then connect.



Fractal with Randomness

- This technique can be used to create some realistic mountain ranges.





"Elevated"

- Was produced from somebody's 4 kilobyte computer program.

Applications

many, many, many

Finance

- Investment portfolio analysis
- Stock option analysis
- Personal financial planning

Engineering

- Reliability engineering
- Wireless network design
- Wind farm yield prediction
- Fluid dynamics
- Robotics

Mathematics and physics

- Multi-dimensional partial differentiation and integration
- Optimization
- Simulating quantum systems (pioneered by Fermi in 1930)

Many others

- Computational biology
- Physical chemistry
- Applied statistics where data distributions are difficult to analyze
- Game playing

Graphics: path tracing

image: http://www.graphics.cornell.edu/~eric/thesis/images.html

image: http://2.bp.blogspot.com/-cUQu1ym3krA/UPYw6qhsZPI/AAAAAAAADeU/YnqtyJjBJJc/s1600/cubecity9b.png

Summary

- Monte Carlo methods use random number generator to “run experiments” in software
- Operations we used:
  - get random integer in a given range
  - get a random permutation of a list
  - use random float between 0 and 1 to decide if an event with probability `p` happens

```
if random() < p : # event happened
```

Next time: Simulation

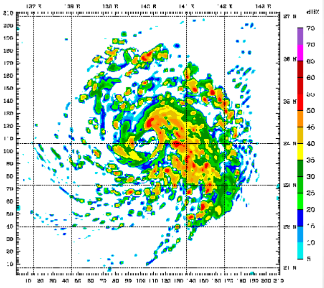


Image: Wikipedia

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