CS61B Lecture #33

Today:

- Pseudo-random Numbers (Chapter 11)

- What use are random sequences?

- What *are* "random sequences"?

- Pseudo-random sequences.

- How to get one.

- Relevant Java library classes and methods.

- Random permutations.

Why Random Sequences?

- Choose statistical samples

- Simulations

- Random algorithms

- Cryptography:

  - Choosing random keys

  - Generating streams of random bits (e.g., SSL xor's your data with a regeneratable, pseudo-random bit stream that only you and the recipient can generate).

- And, of course, games

What Is a "Random Sequence"?

- How about: "a sequence where all numbers occur with equal fre-quency"?

  - Like 1, 2, 3, 4, . . . ?

- Well then, how about: "an unpredictable sequence where all numbers occur with equal frequency?"

  - Like 0, 0, 0, 1, 1, 2, 2, 2, 2, 2, 3, 4, 4, 0, 1, 1, 1,. . . ?

- Besides, what is wrong with 0, 0, 0, 0, . . . anyway? Can't that occur by random selection?

Pseudo-Random Sequences

- Even if definable, a "truly" random sequence is difficult for a computer (or human) to produce.

- For most purposes, need only a sequence that satisfies certain statistical properties, even if deterministic.

- Sometimes (e.g., cryptography) need sequence that is *hard* or *impractical* to predict.

- *Pseudo-random sequence:* deterministic sequence that passes some given set of statistical tests.

- For example, look at lengths of *runs:* increasing or decreasing contiguous subsequences.

- Unfortunately, statistical criteria to be used are quite involved. For details, see Knuth.

Generating Pseudo-Random Sequences

- Not as easy as you might think.

- Seemingly complex jumbling methods can give rise to bad sequences.

- *Linear congruential method* is a simple method used by Java:

$$X_0 = \text{arbitrary seed}$$
$$X_i = (aX_{i-1} + c) \bmod m, \quad i > 0$$

- Usually, m is large power of 2.

- For best results, want $a \equiv 5 \bmod 8$, and a, c, m with no common factors.

- This gives generator with a *period of m* (length of sequence before repetition), and reasonable *potency* (measures certain dependencies among adjacent X_i.)

- Also want bits of a to "have no obvious pattern" and pass certain other tests (see Knuth).

- Java uses $a = 25214903917$, $c = 11$, $m = 2^{48}$, to compute 48-bit pseudo-random numbers but I haven't checked to see how good this is.

What Can Go Wrong?

- Short periods, many impossible values: E.g., $a,\ c,\ m$ even.

- Obvious patterns. E.g., just using lower 3 bits of X_i in Java's 48-bit generator, to get integers in range 0 to 7. By properties of modular arithmetic,

$$\begin{aligned} X_i \bmod 8 &= (25214903917 X_{i-1} + 11 \bmod 2^{48}) \bmod 8 \\ &= (5(X_{i-1} \bmod 8) + 3) \bmod 8 \end{aligned}$$

so we have a period of 8 on this generator; sequences like

$$0, 1, 3, 7, 1, 2, 7, 1, 4, \ldots$$

are impossible. This is why Java doesn't give you the raw 48 bits.

- Bad potency leads to bad correlations.

  - E.g. Take $c = 0,\ a = 65539,\ m = 2^{31}$, and make 3D points: $(X_i/S, X_{i+1}/S, X_{i+2}/S)$, where S scales to a unit cube.
  - Points will be arranged in parallel planes with voids between.
  - So, "random points" won't ever get near many points in the cube.

Additive Generators

- Additive generator:

$$X_n = \begin{cases} arbitary\ value, & n < 55 \\ (X_{n-24} + X_{n-55}) \bmod 2^e, & n \geq 55 \end{cases}$$

- Other choices than 24 and 55 possible.

- This one has period of $2^f(2^{55} - 1)$, for some $f < e$.

- Simple implementation with circular buffer:

```
i = (i+1) % 55;
X[i] += X[(i+31) % 55];   // Why +31 (55-24) instead of -24?
return X[i];    /* modulo 2^32 */
```

- where X[0 .. 54] is initialized to some "random" initial seed values.

Hashing and PRNGs

- By hashing a sequence of numbers, can get a sequence of pseudo-random numbers.

- Using a *cryptographically secure hash function* (basically, one where it is really difficult to find collisions), one can get cryptographic random number generator (one whose sequence is difficult to predict, even knowing many items in it).

- This method, however, is not currently recommended.

Adjusting Range and Distribution

- Given raw sequence of numbers, X_i, from above methods in range (e.g.) 0 to 2^{48}, how to get uniform random integers in range 0 to $n-1$?

- If $n = 2^k$, is easy: use top k bits of next X_i (bottom k bits not as "random")

- For other n, be careful of slight biases at the ends. For example, if we compute $X_i/(2^{48}/n)$ using all integer division, and if $(2^{48}/n)$ doesn't come out even, then you can get n as a result (which you don't want).

- Easy enough to fix with floating point, but can also do with integers; one method (used by Java for type `int`):

```
/** Random integer in the range 0 .. n-1, n>0. */
int nextInt (int n) {
   long X = next random long (0 ≤ X < 2^48);
   if (n is 2^k for some k) return top k bits of X;
   int MAX = largest multiple of n that is < 2^48;
   while (Xᵢ >= MAX)  X = next random long (0 ≤ X < 2^48);
   return Xᵢ / (MAX/n);
}
```

Arbitrary Bounds

- How to get arbitrary range of integers (L to U)?

- To get random `float`, x in range $0 \le x < d$, compute

  ```
  return d*nextInt (1<<24) / (1<<24);
  ```

- Random `double` a bit more complicated: need two integers to get enough bits.

  ```
  long bigRand = ((long) nextInt(1<<26) << 27) + (long) nextInt(1<<27);
  return d * bigRand / (1L << 53);
  ```

Generalizing: Other Distributions

- Suppose we have some desired probability distribution function, and want to get random numbers that are distributed according to that distribution. How can we do this?

- Example: the normal distribution:

$$P(Y \leq X)$$
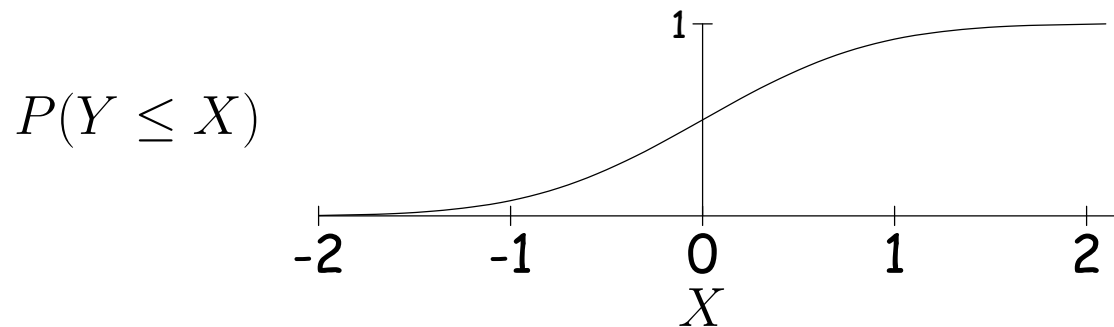
- Curve is the desired probability distribution $P(Y \leq X)$ is the probability that random variable Y is $\leq X$.

Other Distributions

Solution: Choose y uniformly between 0 and 1, and the corresponding x will be distributed according to P.
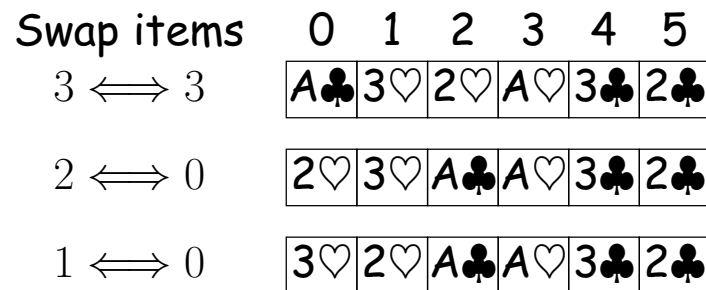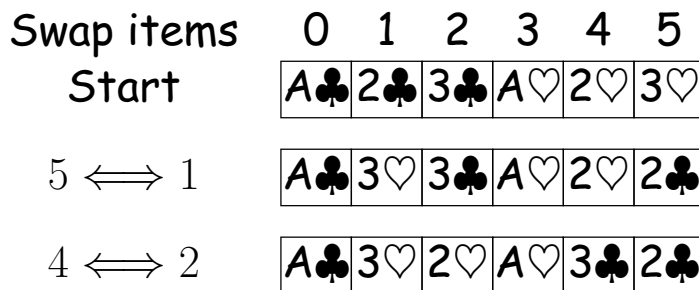

$P(X \leq Y)$
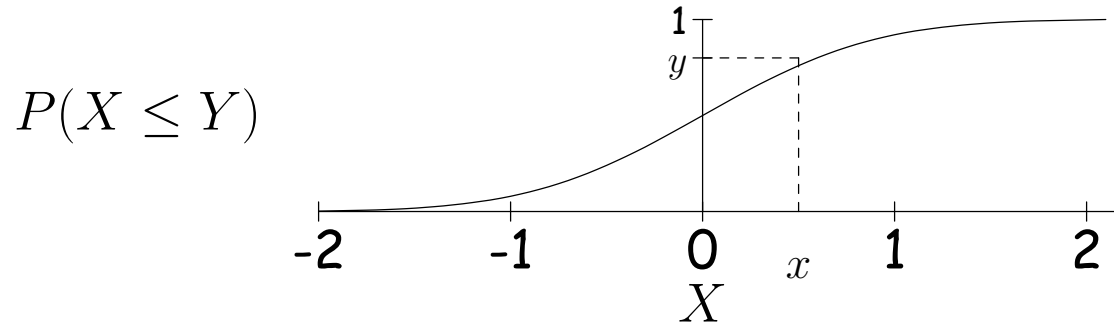
Java Classes

- `Math.random()`: random double in $[0..1)$.

- Class `java.util.Random`: a random number generator with constructors:

  Random() generator with "random" seed (based on time).

  Random(seed) generator with given starting value (reproducible).

- Methods

  next(k) k-bit random integer

  nextInt(n) `int` in range $[0..n)$.

  nextLong() random 64-bit integer.

  nextBoolean(), nextFloat(), nextDouble() Next random values of other primitive types.

  nextGaussian() normal distribution with mean 0 and standard deviation 1 ("bell curve").

- `Collections.shuffle($L, R$)` for list R and `Random` R permutes L randomly (using R).

Shuffling

- A *shuffle* is a random permutation of some sequence.

- Obvious dumb technique for sorting N-element list:

    - Generate N random numbers
    - Attach each to one of the list elements
    - Sort the list using random numbers as keys.

- Can do quite a bit better:

```
void shuffle (List L, Random R) {
   for (int i = L.size (); i > 0; i -= 1)
      swap element i-1 of L with element R.nextInt (i) of L;
}
```

- Example:

Swap items	0	1	2	3	4	5
Start	A♣	2♣	3♣	A♡	2♡	3♡
$5 \Longleftrightarrow 1$	A♣	3♡	3♣	A♡	2♡	2♣
$4 \Longleftrightarrow 2$	A♣	3♡	2♡	A♡	3♣	2♣

Swap items	0	1	2	3	4	5
$3 \Longleftrightarrow 3$	A♣	3♡	2♡	A♡	3♣	2♣
$2 \Longleftrightarrow 0$	2♡	3♡	A♣	A♡	3♣	2♣
$1 \Longleftrightarrow 0$	3♡	2♡	A♣	A♡	3♣	2♣

Random Selection

- Same technique would allow us to select N items from list:

```
/** Permute L and return sublist of K>=0 randomly
 *   chosen elements of L, using R as random source. */
List select (List L, int k, Random R) {
  for (int i = L.size (); i+k > L.size (); i -= 1)
    swap element i-1 of L with element
      R.nextInt (i) of L;
  return L.sublist (L.size ()-k, L.size ());
}
```

- Not terribly efficient for selecting random sequence of K distinct integers from $[0..N)$, with $K \ll N$.

Alternative Selection Algorithm (Floyd)

```
/** Random sequence of K distinct integers
 *  from 0..N-1, 0<=K<=N. */
IntList selectInts(int N, int K, Random R)
{
  IntList S = new IntList();

  for (int i = N-K; i < N; i += 1) {
    // All values in S are < i
    int s = R.randInt(i+1); // 0 <= s <= i < N
    if (s == S.get(j) for some j)
      // Insert value i (which can't be there
      // yet) after the s (i.e., at a random
      // place other than the front)
      S.add (j+1, i);
    else
      // Insert random value s at front
      S.add (0, s);
  }
  return S;
}
```

Example

i	s	S
5	4	$[4]$
6	2	$[2, 4]$
7	5	$[5, 2, 4]$
8	5	$[5, 8, 2, 4]$
9	4	$[5, 8, 2, 4, 9]$

selectRandomIntegers (10, 5, R)