1.4 Arrays
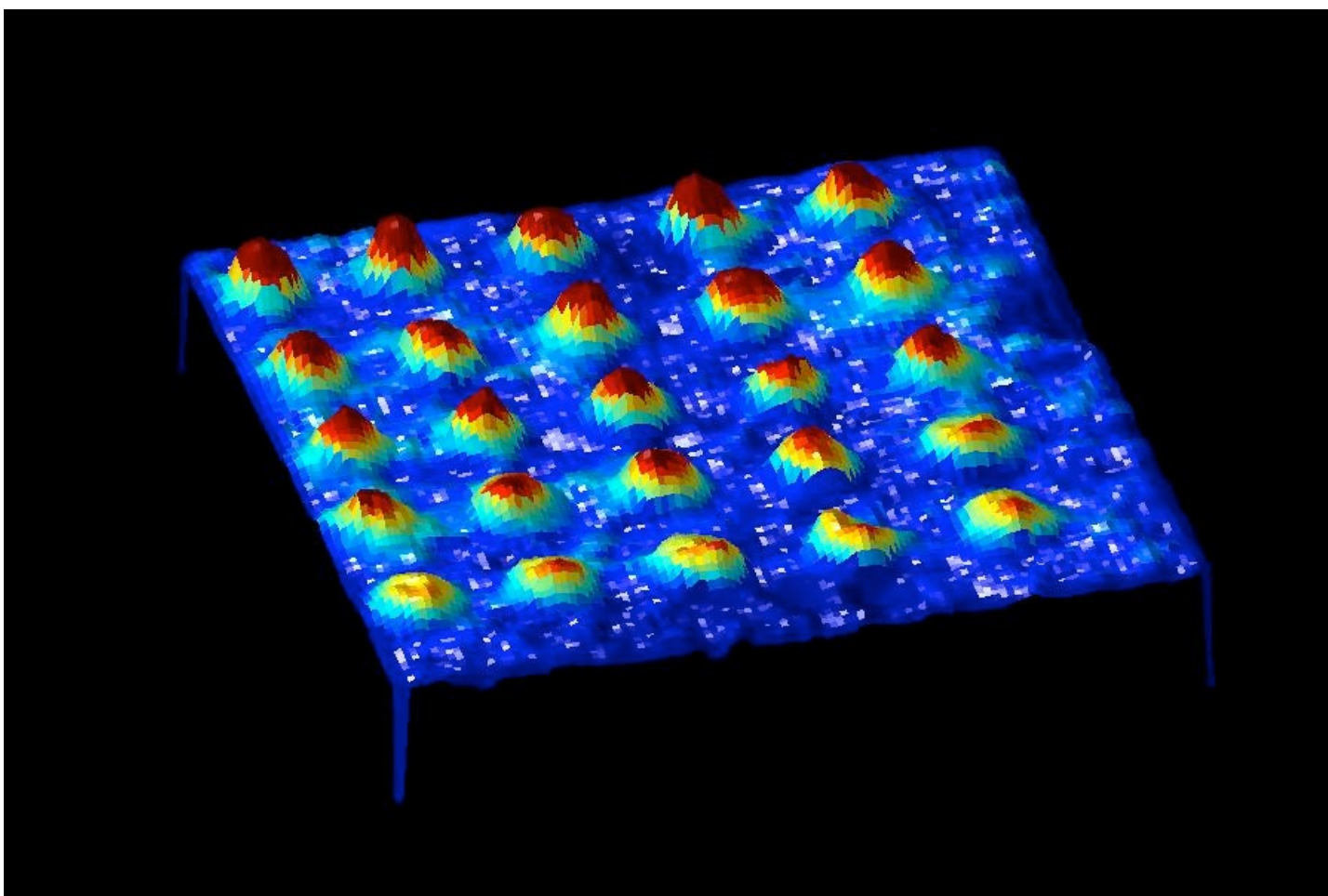
A Foundation for Programming

any program you might want to write

objects

functions and modules

graphics, sound, and image I/O
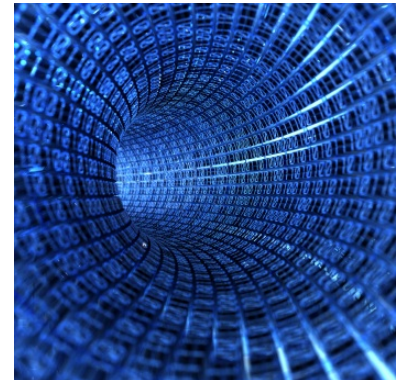
arrays

store and manipulate
huge quantities of data

conditionals and loops

Math | text I/O

primitive data types | assignment statements

Arrays

This lecture. Store and manipulate huge quantities of data.

Array. Indexed sequence of values of the same type.

Examples.
- 52 playing cards in a deck.
- 5 thousand undergrads at Princeton.
- 1 million characters in a book.
- 10 million audio samples in an MP3 file.
- 4 billion nucleotides in a DNA strand.
- 73 billion Google queries per year.
- 50 trillion cells in the human body.
- 6.02×10^{23} particles in a mole.

index	value
0	doug
1	dp6
2	dgabai
3	aboyko
4	borislav
5	jiaxis
6	nkang
7	xinyi
8	sy2
9	mojgan
10	kevinlee
11	maia
12	jlisrael
13	yannanw

Many Variables of the Same Type

Goal. 10 variables of the same type.

```
// Tedious and error-prone code.
double a0, a1, a2, a3, a4, a5, a6, a7, a8, a9;
a0 = 0.0;
a1 = 0.0;
a2 = 0.0;
a3 = 0.0;
a4 = 0.0;
a5 = 0.0;
a6 = 0.0;
a7 = 0.0;
a8 = 0.0;
a9 = 0.0;
...
a4 = 3.0;
...
a8 = 8.0;
...
double x = a4 + a8;
```

Many Variables of the Same Type

Goal. 10 variables of the same type (e.g.).

```
// Easy alternative.
double[] a = new double[10];
...
a[4] = 3.0;
...
a[8] = 8.0;
...
double x = a[4] + a[8];
```

declares, creates, and initializes
[stay tuned for details]

Many Variables of the Same Type

Goal. 1 million variables of the same type.

```java
// Scales to handle large arrays.
double[] a = new double[1000000];
...
a[234567] = 3.0;
...
a[876543] = 8.0;
...
double x = a[234567] + a[876543];
```

Arrays in Java

Java has special language support for arrays.

- To make an array: declare, create, and initialize it.

- To access element `i` of array named `a`, use `a[i]`.

- Array indices start at `0`.

```
int N = 1000;
double[] a;                      // declare the array
a = new double[N];               // create the array
for (int i = 0; i < N; i++)      // initialize the array
   a[i] = 0.0;                   // all to 0.0
```

Compact alternatives: Declare, create, and initialize in one statement.

- Default: all entries automatically set to 0.

```
double[] a = new double[1000];
```

- Initialize to literal values

compact version   equivalent code

```
double[] x = { 0.3, 0.6, 0.1 };
```

```
double[] x = new double[3];
x[0] = 0.3; x[1] = 0.6; x[2] = 0.1;
```

Sample Array Code: Vector Dot Product

Dot product. Given two vectors `x[]` and `y[]` of length `N`, their dot product is the sum of the products of their corresponding components.

```
double[] x = { 0.3, 0.6, 0.1 };
double[] y = { 0.5, 0.1, 0.4 };

double sum = 0.0;
for (int i = 0; i < N; i++)
   sum += x[i]*y[i];
```

i	x[i]	y[i]	x[i]*y[i]	sum
				0
0	.30	.50	.15	.15
1	.60	.10	.06	.21
2	.10	.40	.04	.25
				.25

Array Processing Examples

```java
double[] a = new double[N];
for (int i = 0; i < N; i++)
    a[i] = Math.random();
```

create an array with N random values

```java
double[] b = new double[N];
for (int i = 0; i < N; i++)
    b[i] = a[i];
```

copy to another array

```java
for (int i = 0; i < N; i++)
    System.out.println(a[i]);
```

print the array values, one per line

```java
double sum = 0.0;
for (int i = 0; i < N; i++)
    sum += a[i];
double average = sum / N;
```

compute the average of the array values

```java
double max = Double.NEGATIVE_INFINITY;
for (int i = 0; i < N; i++)
    if (a[i] > max) max = a[i];
```

find the maximum of the array values

```java
for (int i = 0; i < N/2; i++)
{
    double temp = b[i];
    b[i] = b[N-1-i];
    b[N-i-1] = temp;
}
```

reverse the elements within the array

Mumbo-Jumbo Demystification, Part 1

```java
public class Gambler {
   public static void main(String[] args) {
      int stake  = Integer.parseInt(args[0]);
      int goal   = Integer.parseInt(args[1]);
      int trials = Integer.parseInt(args[2]);
      . . .
      . . .
   }
}
```

Shuffling a Deck

Setting Array Values at Compile Time

Ex. Print a random card.

```
String[] rank =
{
   "2", "3", "4", "5", "6", "7", "8", "9",
   "10", "Jack", "Queen", "King", "Ace"
};


String[] suit =
{
   "clubs", "diamonds", "hearts", "spades"
};

int i = (int) (Math.random() * 13);   // between 0 and 12
int j = (int) (Math.random() * 4);    // between 0 and 3

System.out.println(rank[i] + " of " + suit[j]);
```

Setting Array Values at Compile Time

Want to initialize a whole deck? How about this:

```
String[] deck =
{
    "2 of clubs", "3 of clubs", "4 of clubs", "5 of clubs",
    "6 of clubs", "7 of clubs", "8 of clubs", "9 of clubs",
    "10 of clubs", "Jack of clubs", "Queen of clubs",
    "King of clubs", "Ace of clubs", "2 of diamonds",
    "3 of diamonds", "4 of diamonds", "5 of diamonds",
    "6 of diamonds", "7 of diamonds", "8 of diamonds",
    "9 of diamonds", "10 of diamonds", "Jack of diamonds",
    "Queen of diamonds", "King of diamonds", "Ace of diamonds",
    "2 of hearts", "3 of hearts", "4 of hearts", "5 of hearts",
    "6 of hearts", "7 of hearts", "8 of hearts", "9 of hearts",
    "10 of hearts", "Jack of hearts", "Queen of hurts",
    "King of hearts", "Ace of hearts", "2 of spades",
    "3 of spades", "4 of spades", "5 of spades",
    "6 of spades", "7 of spades", "8 of spades", "9 of spades",
    "10 of spades", "Jack of spades", "Queen of spades",
    "King of spades", "Ace of spades",
};
```

Setting Array Values at Run Time

This method saves ink:

```
String[] rank = { "2", "3" ..., "King", "Ace" };
String[] suit =
  { "clubs", "diamonds", "hearts", "spades" };

String[] deck = new String[52];
for (int i = 0; i < 13; i++)
   for (int j = 0; j < 4; j++)
      deck[4*i + j] = rank[i] + " of " + suit[j];

for (int i = 0; i < 52; i++)
   System.out.println(deck[i]);
```

typical array processing code changes values at runtime

Array Challenge 1

The following code sets array values to the 52 card values and prints them.
In which order are they printed?

```
String[] rank = { "2", "3" ..., "King", "Ace" };
String[] suit =
   { "clubs", "diamonds", "hearts", "spades" };

String[] deck = new String[52];
for (int i = 0; i < 13; i++)
   for (int j = 0; j < 4; j++)
      deck[4*i + j] = rank[i] + " of " + suit[j];

for (int i = 0; i < 52; i++)
   System.out.println(deck[i]);
```

typical array
processing code
changes values
at runtime

A. 2 of clubs
    2 of diamonds
    2 of hearts
    2 of spades
    3 of clubs
    ...

B. 2 of clubs
    3 of clubs
    4 of clubs
    5 of clubs
    6 of clubs
    ...

Array Challenge 2

Swap the `for` statements: `rank` index in inner loop, `suit` index in outer loop.

Now, in which order are they printed?

```
String[] rank = { "2", "3" ..., "King", "Ace" };
String[] suit =
   { "clubs", "diamonds", "hearts", "spades" };

String[] deck = new String[52];
for (int j = 0; j < 4; j++)
   for (int i = 0; i < 13; i++)
      deck[4*i + j] = rank[i] + " of " + suit[j];

for (int i = 0; i < 52; i++)
   System.out.println(deck[i]);
```

these lines swapped
from previous slide

A. 2 of clubs
    2 of diamonds
    2 of hearts
    2 of spades
    3 of clubs
    ...

B. 2 of clubs
    3 of clubs
    4 of clubs
    5 of clubs
    6 of clubs
    ...

Array Challenge 3

The following code sets array values to the 52 card values and prints them.
What change to the code will produce the "B" order ?

```
String[] rank = { "2", "3" ..., "King", "Ace" };
String[] suit =
   { "clubs", "diamonds", "hearts", "spades" };

String[] deck = new String[52];
for (int i = 0; i < 13; i++)
   for (int j = 0; j < 4; j++)
      deck[4*i + j] = rank[i] + " of " + suit[j];

for (int i = 0; i < 52; i++)
   System.out.println(deck[i]);
```

A. 2 of clubs
    2 of diamonds
    2 of hearts
    2 of spades
    3 of clubs
    ...

B. 2 of clubs
    3 of clubs
    4 of clubs
    5 of clubs
    6 of clubs
    ...

Shuffling

Goal. Given an array, rearrange its elements in random order.

Shuffling algorithm.

- In iteration `i`, pick random card from `deck[i]` through `deck[N-1]`, with each card equally likely.
- Exchange it with `deck[i]`.

```
int N = deck.length;
for (int i = 0; i < N; i++)
{
    int r = i + (int) (Math.random() * (N-i));
    String t = deck[r];
    deck[r] = deck[i];
    deck[i] = t;
}
```

swap idiom

between i and N-1

Shuffle an Array

Shuffle a deck of cards.

- In ith iteration, put a random element from remainder of deck at index i.
  - choose random integer r between i and N-1
  - swap values in positions r and i

Array index	0	1	2	3	4	5	6	7	8	9
Value	9♣	3♣	4♣	5♣	6♣	7♣	8♣	2♣	10♣	J♣

random integer = 7

Shuffle an Array

Shuffle a deck of cards.

- In i^{th} iteration, put a random element from remainder of deck at index i.
  - choose random integer r between i and N-1
  - swap values in positions r and i

Array index	0	1	2	3	4	5	6	7	8	9
Value	9♣	5♣	J♣	4♣	8♣	3♣	10♣	7♣	6♣	2♣

Shuffling a Deck of Cards

```java
public class Deck
{
   public static void main(String[] args)
   {
      String[] suit = { "Clubs", "Diamonds", "Hearts", "Spades" };
      String[] rank = { "2", "3", "4", "5", "6", "7", "8", "9",
                        "10", "Jack", "Queen", "King", "Ace"     };
      int SUITS = suit.length;
      int RANKS = rank.length;          ←——————— avoid "hardwired" constants like 52, 4, and 13.
      int N = SUITS * RANKS;


      String[] deck = new String[N];                                          build the deck
      for (int i = 0; i < RANKS; i++)
         for (int j = 0; j < SUITS; j++)
            deck[SUITS*i + j] = rank[i] + " of " + suit[j];


      for (int i = 0; i < N; i++)                                             shuffle
      {
         int r = i + (int) (Math.random() * (N-i));
         String t = deck[r];
         deck[r] = deck[i];
         deck[i] = t;
      }

      for (int i = 0; i < N; i++)                                             print shuffled deck
         System.out.println(deck[i]);
   }
}
```

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Shuffling a Deck of Cards

```
% java Deck
5 of Clubs
Jack of Hearts
9 of Spades
10 of Spades
9 of Clubs
7 of Spades
6 of Diamonds
7 of Hearts
7 of Clubs
4 of Spades
Queen of Diamonds
10 of Hearts
5 of Diamonds
Jack of Clubs
Ace of Hearts
...
5 of Spades
```

```
% java Deck
10 of Diamonds
King of Spades
2 of Spades
3 of Clubs
4 of Spades
Queen of Clubs
2 of Hearts
7 of Diamonds
6 of Spades
Queen of Spades
3 of Spades
Jack of Diamonds
6 of Diamonds
8 of Spades
9 of Diamonds
...
10 of Spades
```

Coupon Collector

Coupon Collector Problem

Coupon collector problem. Given N different card types, how many
do you have to collect before you have (at least) one of each type?
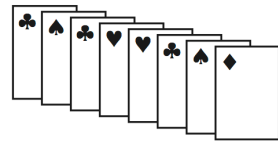
assuming each possibility is equally
likely for each card that you collect

Simulation algorithm. Repeatedly choose an integer i between 0 and $N-1$.
Stop when we have at least one card of every type.

Q. How to check if we've seen a card of type i?

A. Maintain a boolean array so that `found[i]` is `true` if we've already
collected a card of type i.

Coupon Collector: Java Implementation

```java
public class CouponCollector
{
   public static void main(String[] args)
   {
      int N = Integer.parseInt(args[0]);
      int cardcnt = 0;    // number of cards collected
      int valcnt = 0;     // number of distinct cards

      // Do simulation.
      boolean[] found = new boolean[N];
      while (valcnt < N)
      {
         int val = (int) (Math.random() * N);
         cardcnt++;
         if (!found[val])
         {
            valcnt++;
            found[val] = true;
         }
      }

      // all N distinct cards found
      System.out.println(cardcnt);
   }
}
```

type of next card
(between 0 and N-1)

Coupon Collector: Debugging

Debugging. Add code to print contents of all variables.

val	found						valcnt	cardcnt
	0	1	2	3	4	5		
	F	F	F	F	F	F	0	0
2	F	F	T	F	F	F	1	1
0	T	F	T	F	F	F	2	2
4	T	F	T	F	T	F	3	3
0	T	F	T	F	T	F	3	4
1	T	T	T	F	T	F	4	5
2	T	T	T	F	T	F	4	6
5	T	T	T	F	T	T	5	7
0	T	T	T	F	T	T	5	8
1	T	T	T	F	T	T	5	9
3	T	T	T	T	T	T	6	10

Challenge. Debugging with arrays requires tracing many variables.

Coupon Collector: Mathematical Context

Coupon collector problem. Given N different possible cards, how many do you have to collect before you have (at least) one of each type?

Fact. About N (1 + 1/2 + 1/3 + … + 1/N) ~ N ln N

see ORF 245 or COS 341

Ex. N = 30 baseball teams. Expect to wait ≈ 120 years before all teams win a World Series.

under idealized assumptions
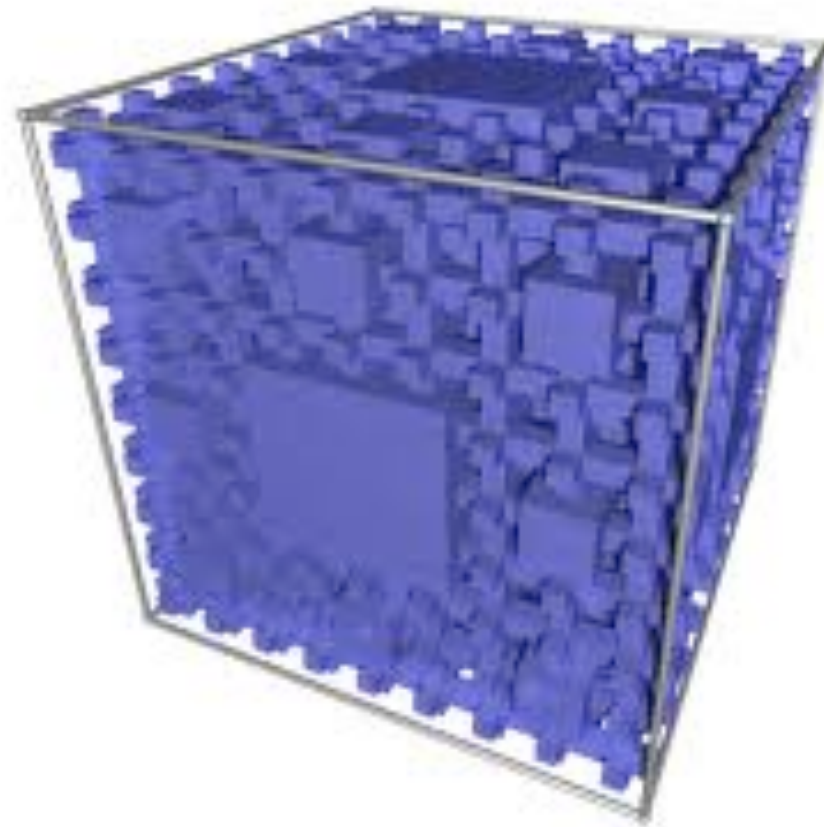
Coupon Collector: Scientific Context

Q. Given a sequence from nature, does it have same characteristics as a random sequence?

A. No easy answer - many tests have been developed.

Coupon collector test. Compare number of elements that need to be examined before all values are found against the corresponding answer for a random sequence.

Multidimensional Arrays

Two Dimensional Arrays

Two dimensional arrays.

- Table of data for each experiment and outcome.
- Table of grades for each student and assignments.
- Table of grayscale values for each pixel in a 2D image.

Mathematical abstraction. Matrix.

Java abstraction. 2D array.
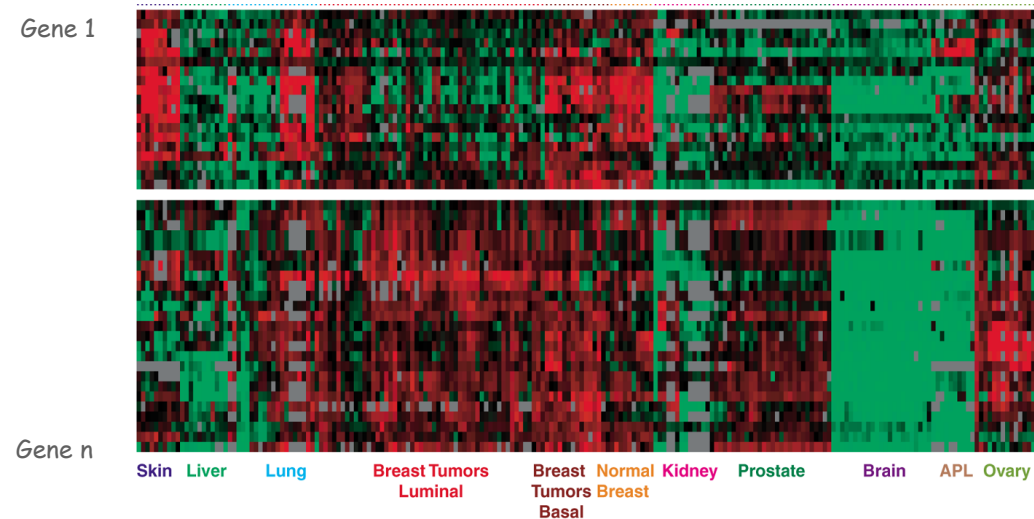
Reference: Botstein & Brown group

gene expressed
gene not expressed

Two Dimensional Arrays in Java

Declare, create, initialize. Like 1D, but add another pair of brackets.

```
int M = 10;
int N = 3;
double[][] a = new double[M][N];
```

Array access.

Use `a[i][j]` to access entry in row `i` and column `j`.

Both indices start at `0`.

Initialize.

This code is implicit (sets all entries to 0).

```
for (int i = 0; i < M; i++)
   for (int j = 0; j < N; j++)
      a[i][j] = 0.0;
```

a[][]

a[0][0]	a[0][1]	a[0][2]
a[1][0]	a[1][1]	a[1][2]
a[2][0]	a[2][1]	a[2][2]
a[3][0]	a[3][1]	a[3][2]
a[4][0]	a[4][1]	a[4][2]
a[5][0]	a[5][1]	a[5][2]
a[6][0]	a[6][1]	a[6][2]
a[7][0]	a[7][1]	a[7][2]
a[8][0]	a[8][1]	a[8][2]
a[9][0]	a[9][1]	a[9][2]

a[6] →

A 10-by-3 array

Warning. This implicit code might slow down your program for very big arrays.

Setting 2D Array Values at Compile Time

Initialize 2D array by listing values.

```
double[][] p =
{
    { .92, .02, .02, .02, .02 },
    { .02, .92, .32, .32, .32 },
    { .02, .02, .02, .92, .02 },
    { .92, .02, .02, .02, .02 },
    { .47, .02, .47, .02, .02 },
};
```

a[1][3]

```
          .92  .02  .02  .02  .02
row 1 →   .02  .92  .32  .32  .32
          .02  .02  .02  .92  .02
          .92  .02  .02  .02  .02
          .47  .02  .47  .02  .02
                         ↑
                      column 3
```
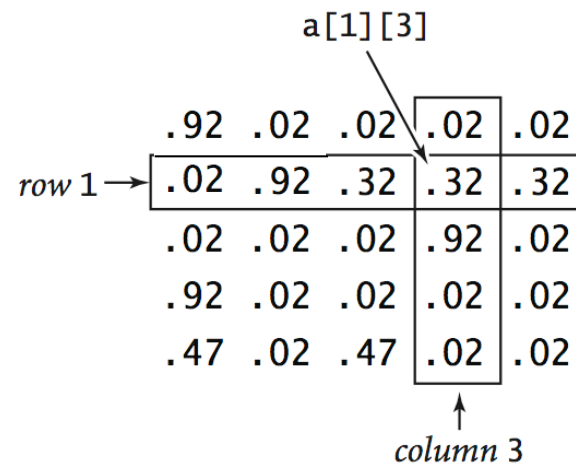
Matrix Addition

Matrix addition. Given two N-by-N matrices `a` and `b`, define `c`
to be the N-by-N matrix where `c[i][j]` is the sum `a[i][j] + b[i][j]`.

```
double[][] c = new double[N][N];
for (int i = 0; i < N; i++)
    for (int j = 0; j < N; j++)
        c[i][j] = a[i][j] + b[i][j];
```
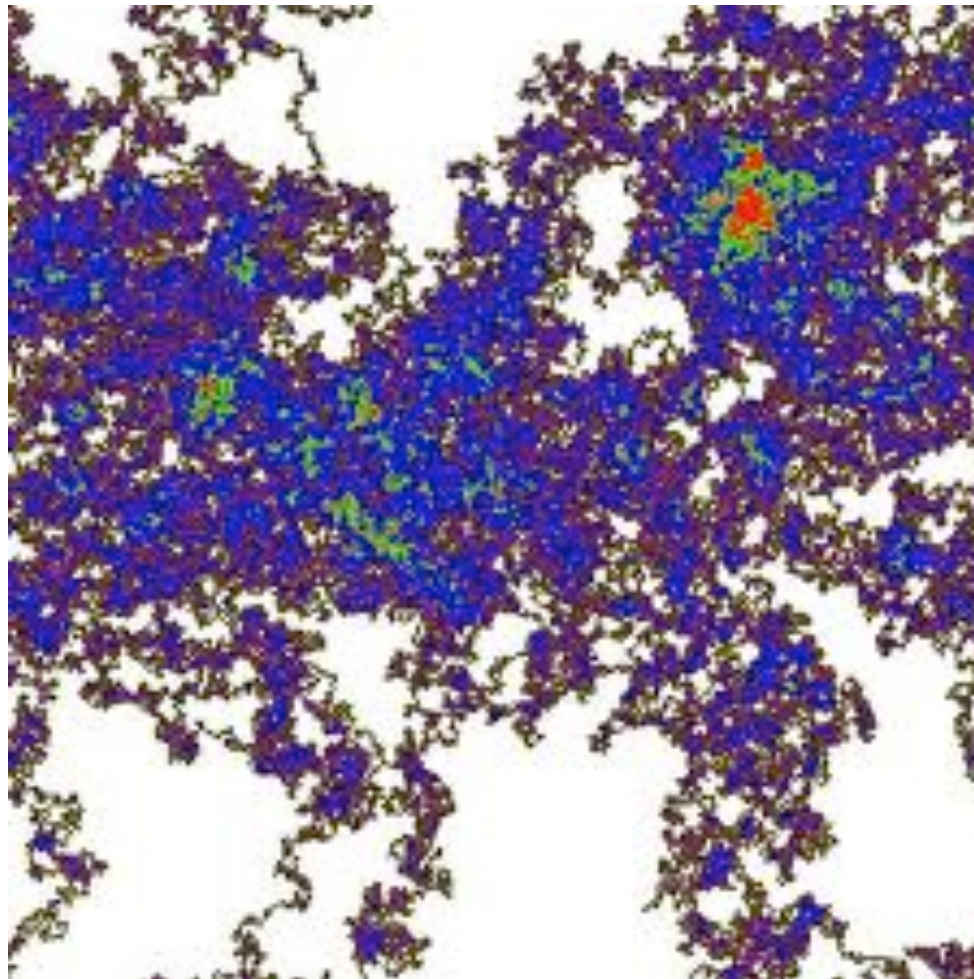
`a[][]`

```
.70  .20  .10        a[1][2]
.30  .60  .10
.50  .10  .40
```

`b[][]`

```
.80  .30  .50        b[1][2]
.10  .40  .10
.10  .30  .40
```

`c[][]`

```
1.5  .50  .60        c[1][2]
.40  1.0  .20
.60  .40  .80
```

Matrix Multiplication

Matrix multiplication. Given two N-by-N matrices `a` and `b`, define `c` to be the N-by-N matrix where `c[i][j]` is the dot product of the ith row of `a` and the jth row of `b`.

`a[][]`

```
.70  .20  .10
.30  .60  .10    ← row 1
.50  .10  .40
```

all values initialized to 0

```
double[][] c = new double[N][N];
for (int i = 0; i < N; i++)
    for (int j = 0; j < N; j++)
        for (int k = 0; k < N; k++)
            c[i][j] += a[i][k] * b[k][j];
```
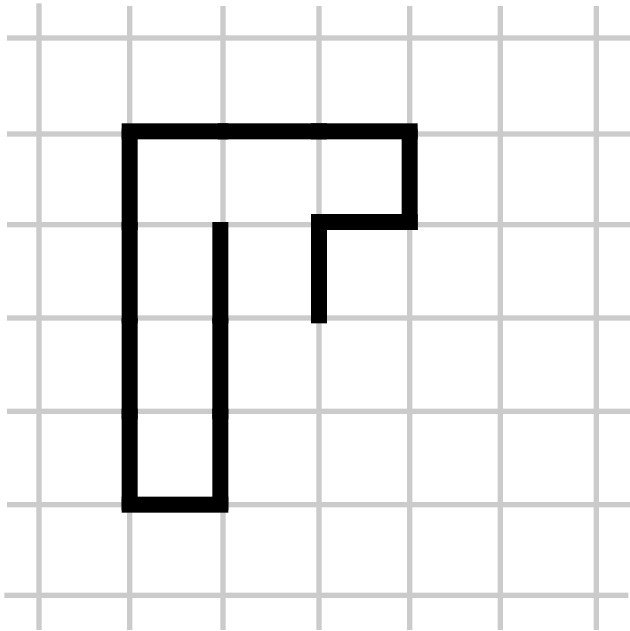
column 2

`b[][]`

```
.80  .30  .50
.10  .40  .10
.10  .30  .40
```

`c[1][2] = .3 *.5`

`c[][]`

```
.59  .32  .41
.31  .36  .25
.45  .31  .42
```

```
+.6 *.1
+.1 *.4
= .25
```

Array Challenge 4

How many multiplications to multiply two N-by-N matrices?

```
double[][] c = new double[N][N];
for (int i = 0; i < N; i++)
   for (int j = 0; j < N; j++)
      for (int k = 0; k < N; k++)
         c[i][j] += a[i][k] * b[k][j];
```
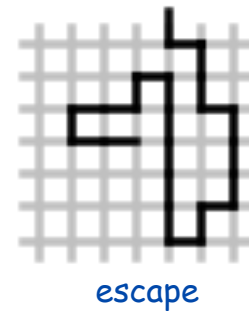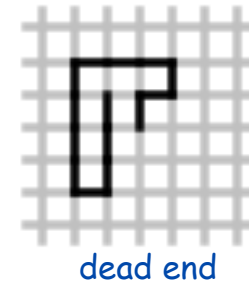
A. N

B. N^2

C. N^3

D. N^4

Application: 2D Random Walks

Self-Avoiding Walk

Model.

- N-by-N lattice.
- Start in the middle.
- Randomly move to a neighboring intersection, avoiding all previously visited intersections.
- Two possible outcomes: escape and dead end

dead end

escape

Applications. Polymers, statistical mechanics, etc.

Q. What fraction of time will you escape in an 5-by-5 lattice?
Q. In an N-by-N lattice?
Q. In an N-by-N-by-N lattice?

Self-Avoiding Walk: Implementation

```
public class SelfAvoidingWalk
{
   public static void main(String[] args)
   {
      int N = Integer.parseInt(args[0]);      // lattice size
      int T = Integer.parseInt(args[1]);      // number of trials
      int deadEnds = 0;                       // trials ending at dead end

      for ( each trial )
      {
         boolean[][] a = new boolean[N][N];  // intersections visited
         int x = N/2, y = N/2;               // current position

         while ( you're still inside the lattice )
         {

            if ( you're at a dead end )
            {   deadEnds++;   break; }


            a[x][y] = true;                   // mark as visited

            double r = Math.random();
            if       (r < 0.25) { if (!a[x+1][y]) x++; }
            else if (r < 0.50) { if (!a[x-1][y]) x--; }
            else if (r < 0.75) { if (!a[x][y+1]) y++; }
            else if (r < 1.00) { if (!a[x][y-1]) y--; }
         }
      }
      System.out.println(100*deadEnds/T + "% dead ends");
   }
}
```
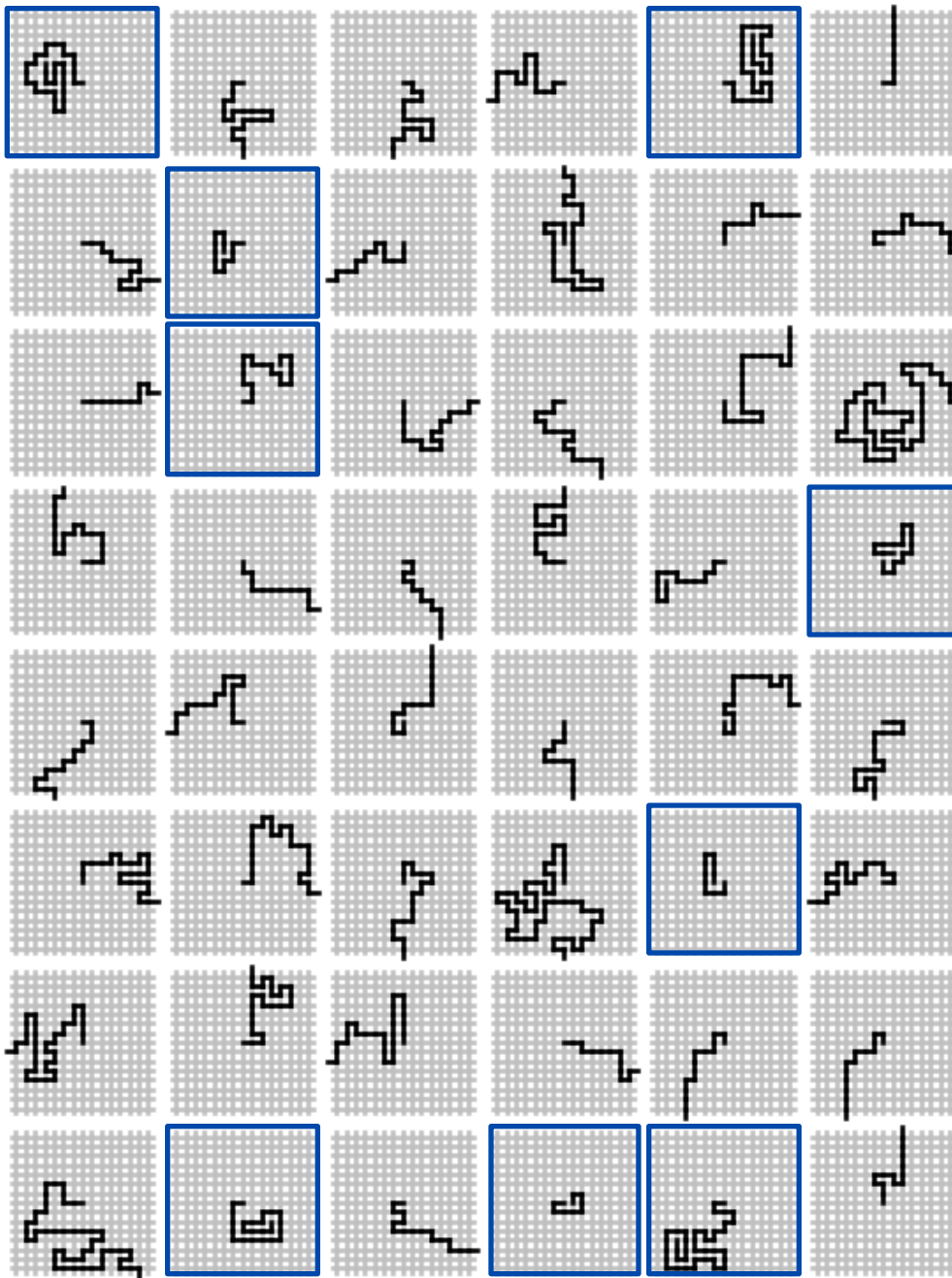
dead end

take a random
step to a new
intersection

Self-Avoiding Walk: Implementation

```java
public class SelfAvoidingWalk
{
   public static void main(String[] args)
   {
      int N = Integer.parseInt(args[0]);     // lattice size
      int T = Integer.parseInt(args[1]);     // number of trials
      int deadEnds = 0;                       // trials ending at dead end

      for (int t = 0; t < T; t++)
      {
         boolean[][] a = new boolean[N][N];  // intersections visited
         int x = N/2, y = N/2;                // current position

         while (x > 0 && x < N-1 && y > 0 && y < N-1)
         {

            if (a[x-1][y] && a[x+1][y] && a[x][y-1] && a[x][y+1])
            {  deadEnds++;  break; }

            a[x][y] = true;                    // mark as visited

            double r = Math.random();
            if       (r < 0.25) { if (!a[x+1][y]) x++; }
            else if (r < 0.50) { if (!a[x-1][y]) x--; }
            else if (r < 0.75) { if (!a[x][y+1]) y++; }
            else if (r < 1.00) { if (!a[x][y-1]) y--; }
         }
      }
      System.out.println(100*deadEnds/T + "% dead ends");
   }
}
```
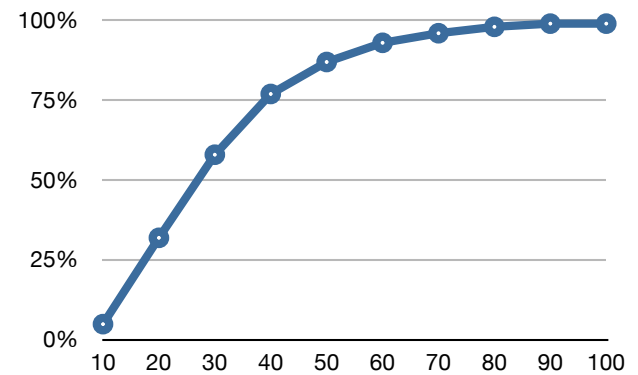
dead end

take a random
step to a new
intersection

Self-Avoiding Walks

Summary

Arrays.

- Organized way to store huge quantities of data.
- Almost as easy to use as primitive types.
- You can directly (and very quickly) access an element given its index.
- You can have as many dimensions as you like !

Caveats:

- Need to fix size of array ahead of time.
- Don't forget to allocate memory with new.
- Indices start at 0 not 1.
- Out-of-bounds to access a[-1] or a[N] of N element array.
    - in Java: ArrayIndexOutOfBoundsException
    - in C: "ghastly error"

Ahead. Reading in large quantities of data from a file into an array.