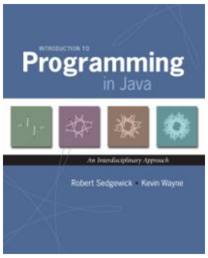
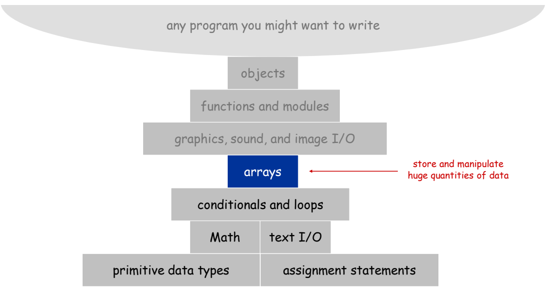
1.4 Arrays



A Foundation for Programming



store and manipulate huge quantities of data

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
- 10 thousand undergrads at Penn
- 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	bjbrown
1	hawka
2	apathare
3	anann
4	catheriz
5	ericslee
6	fannliu
7	lilleyia

Many Variables of the Same Type

Goal 10 variables of the same type

```
// tedious and error-prone
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

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

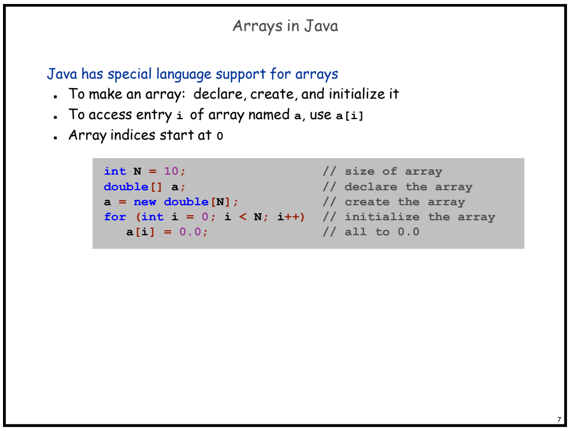
declares, creates, and initializes
[stay tuned for details]

Many Variables of the Same Type

Goal 1 million variables of the same type

```
// scales to handle large arrays
double[] a = new double[1000000];
…
a[123456] = 3.0;
…
a[987654] = 8.0;
…
double x = a[123456] + a[987654];
```

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

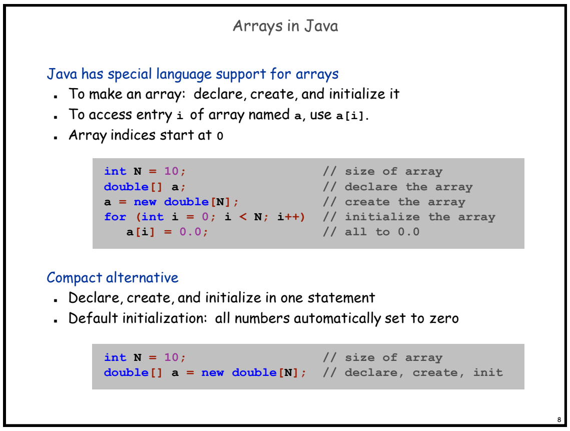


Arrays in Java

Java has special language support for arrays

- To make an array: declare, create, and initialize it
- To access entry `i` of array named `a`, use `a[i]`
- Array indices start at `0`

```
int N = 10;                      // size of array
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
```



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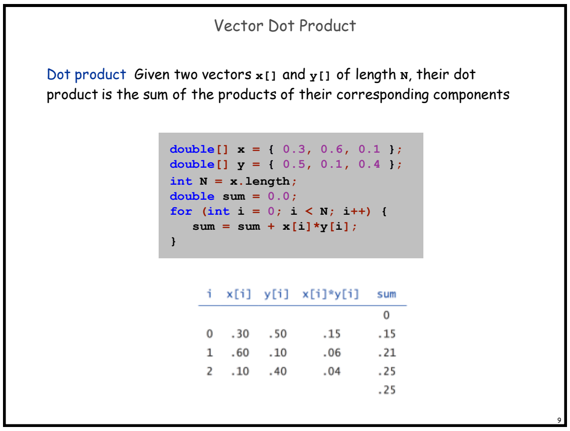
```
int N = 10;                      // size of array
double[] a;                      // declare the array
a = new double[N];               // create the array
for (int i = 0; i < N; i++)      // initialize the array
   a[i] = 0.0;                   // all to 0.0
```

Compact alternative

- Declare, create, and initialize in one statement
- Default initialization: all numbers automatically set to zero

```
int N = 10;                      // size of array
double[] a = new double[N];      // declare, create, init
```

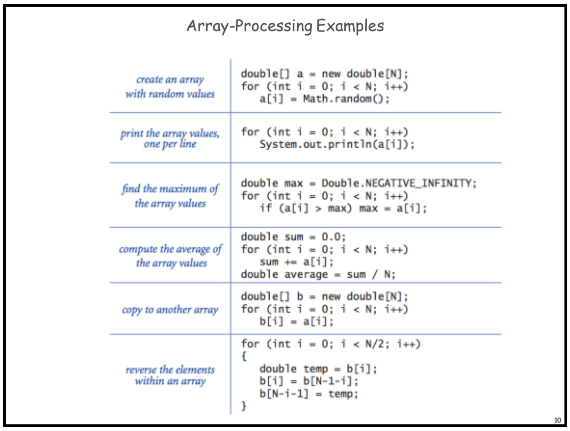


Vector Dot Product

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 };
int N = x.length;
double sum = 0.0;
for (int i = 0; i < N; i++) {
   sum = 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

create an array with random values

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

print the array values, one per line

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

find the maximum of the array values

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

compute the average of the array values

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

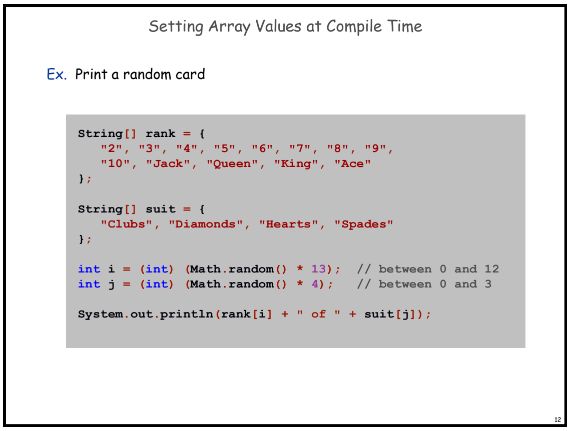
copy to another array

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

reverse the elements within an array

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

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 Run Time

Ex. Create a deck of playing cards and print them out

```
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

Q. In what order does it output them?

A.

```
two of clubs
two of diamonds
two of hearts
two of spades
three of clubs
...
```

B.

```
two of clubs
three of clubs
four of clubs
five of clubs
six 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

▶

Shuffling a Deck of Cards: Putting Everything Together

```
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;
      int N = SUITS * RANKS;

      String[] deck = new String[N];
      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++) {
         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++)
         System.out.println(deck[i]);
   }
}
```

avoid "hardwired" constants

build the deck

shuffle

print shuffled deck

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
```

War Story (PlanetPoker.com)

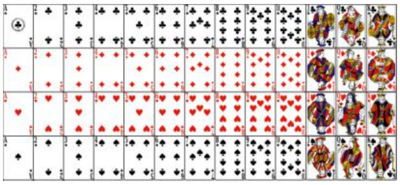
Texas hold 'em poker. Software must shuffle electronic deck of cards

mamajoe: Hey guys, Big R is in!

How we learned to cheat at online poker: a study in software security

http://itmanagement.earthweb.com/entdev/article.php/616221

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

```
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

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

under idealized assumptions

Coupon Collector: Scientific Context

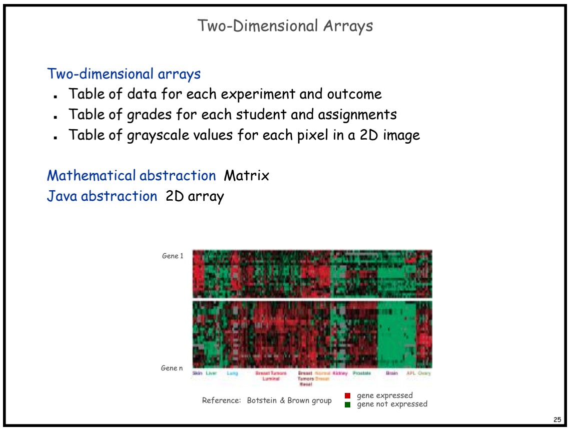
Q. Given a sequence from nature, does it have same characteristics as a random sequence?

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

TOUR OF ACCOUNTING
OVER HERE WE HAVE OUR RANDOM NUMBER GENERATOR.
NINE NINE NINE NINE NINE NINE
ARE YOU SURE THAT'S RANDOM?
THAT'S THE PROBLEM WITH RANDOMNESS: YOU CAN NEVER BE SURE.

Multidimensional Arrays



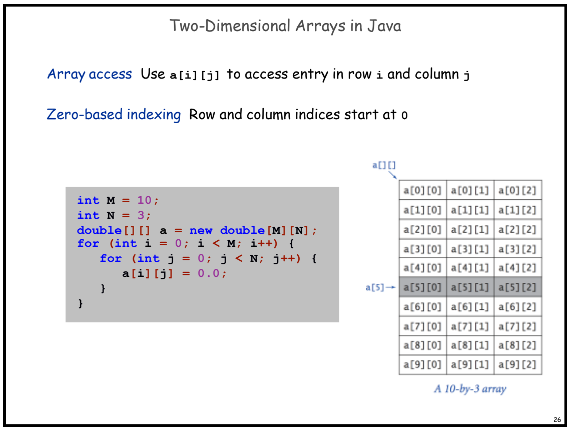
Two-Dimensional Arrays

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

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

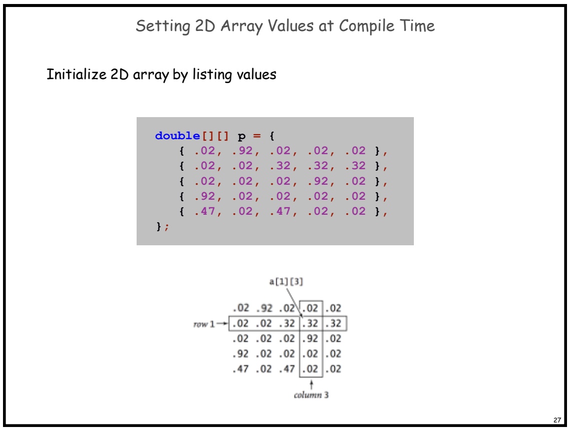
Zero-based indexing Row and column indices start at `0`

```
int M = 10;
int N = 3;
double[][] a = new double[M][N];
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] →	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 10-by-3 array



Setting 2D Array Values at Compile Time

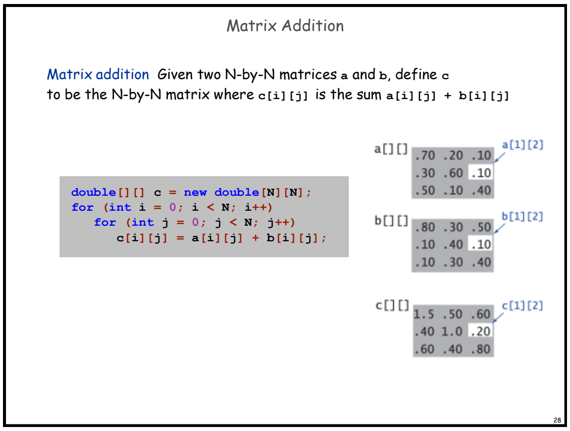
Initialize 2D array by listing values

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

a[1][3]

	.02	.92	.02	.02	.02
row 1 →	.02	.02	.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[][] (a[1][2])

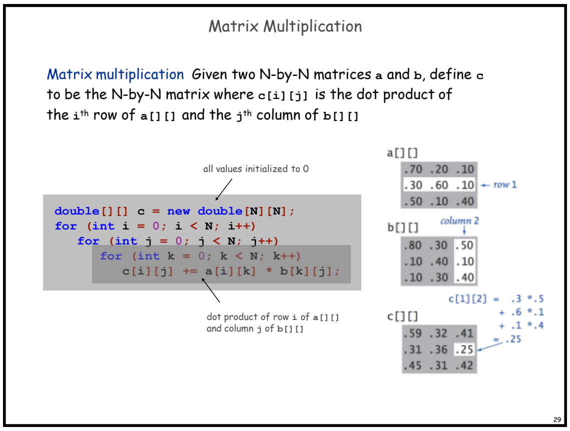
.70	.20	.10
.30	.60	.10
.50	.10	.40

b[][] (b[1][2])

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

c[][] (c[1][2])

1.5	.50	.60
.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 `i`th row of `a[][]` and the `j`th column of `b[][]`

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];
```

dot product of row `i` of `a[][]` and column `j` of `b[][]`

a[][]

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

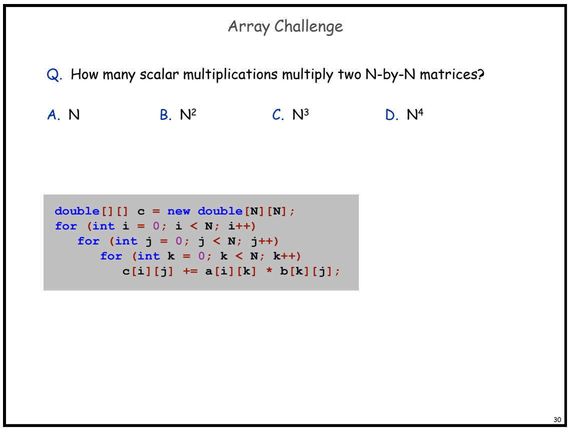
b[][] (column 2)

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

```
c[1][2] =   .3 *.5
          + .6 *.1
          + .1 *.4
          = .25
```

c[][]

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



Array Challenge

Q. How many scalar multiplications multiply two N-by-N matrices?

A. N B. N^2 C. N^3 D. N^4

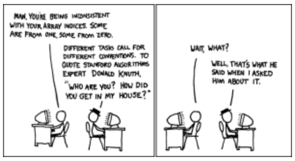
```
double[][] c = new double[N][N];
for (int i = 0; i < N; i++)
   for (int j = 0; j < N; j++)
      for (int k = 0; k < N; k++)
         c[i][j] += a[i][k] * b[k][j];
```

Summary

Arrays

- Organized way to store huge quantities of data
- Almost as easy to use as primitive types
- Can directly access an element given its index

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


MAN, YOU'RE BEING INCONSISTENT WITH YOUR ARRAY INDICES. SOME ARE FROM ONE, SOME FROM ZERO.
DIFFERENT TASKS CALL FOR DIFFERENT CONVENTIONS. TO QUOTE STANFORD ALGORITHMS EXPERT DONALD KNUTH, "WHO ARE YOU? HOW DID YOU GET IN MY HOUSE?"
WAIT, WHAT?
WELL, THAT'S WHAT HE SAID WHEN I ASKED HIM ABOUT IT.

http://imgs.xkcd.com/comics/donald_knuth.png