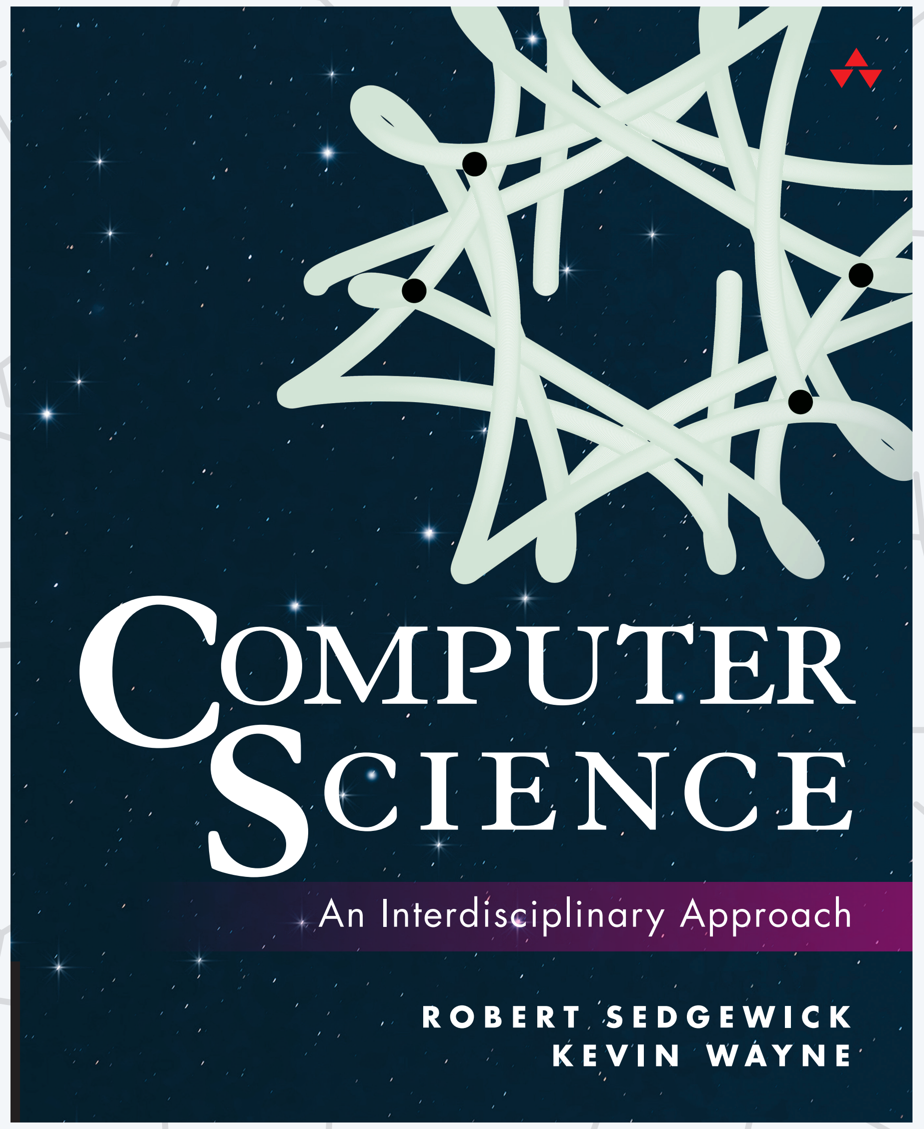

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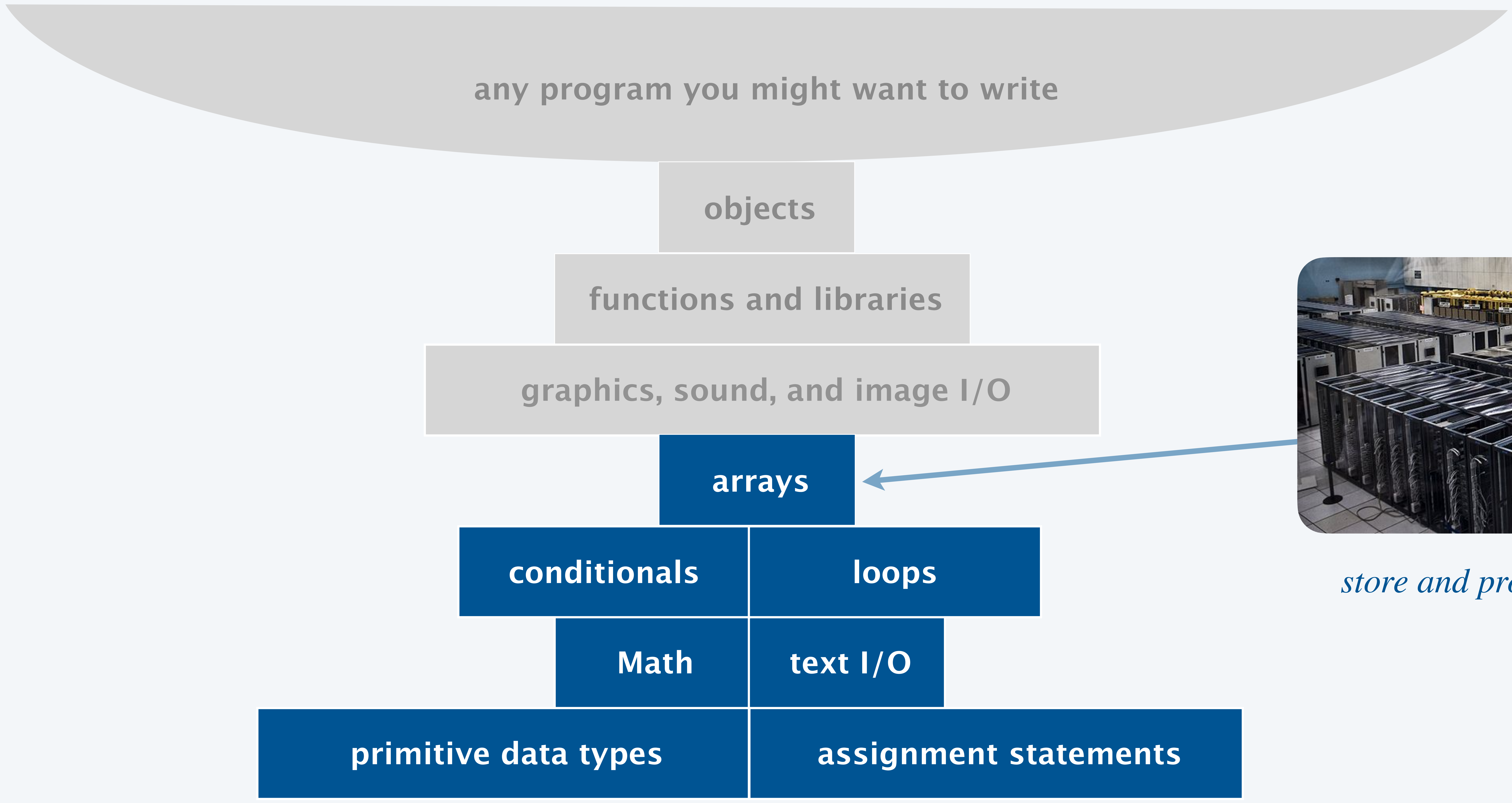
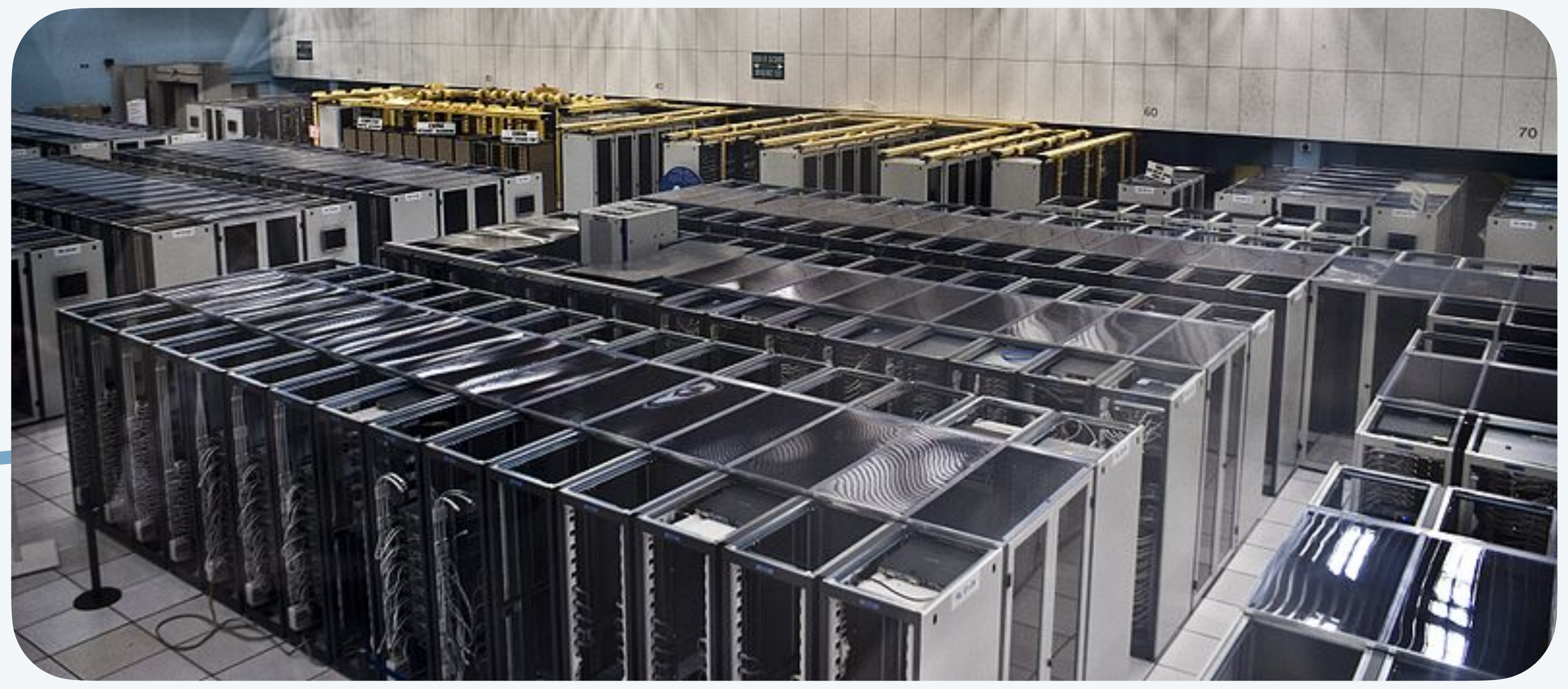
1.4 ARRAYS

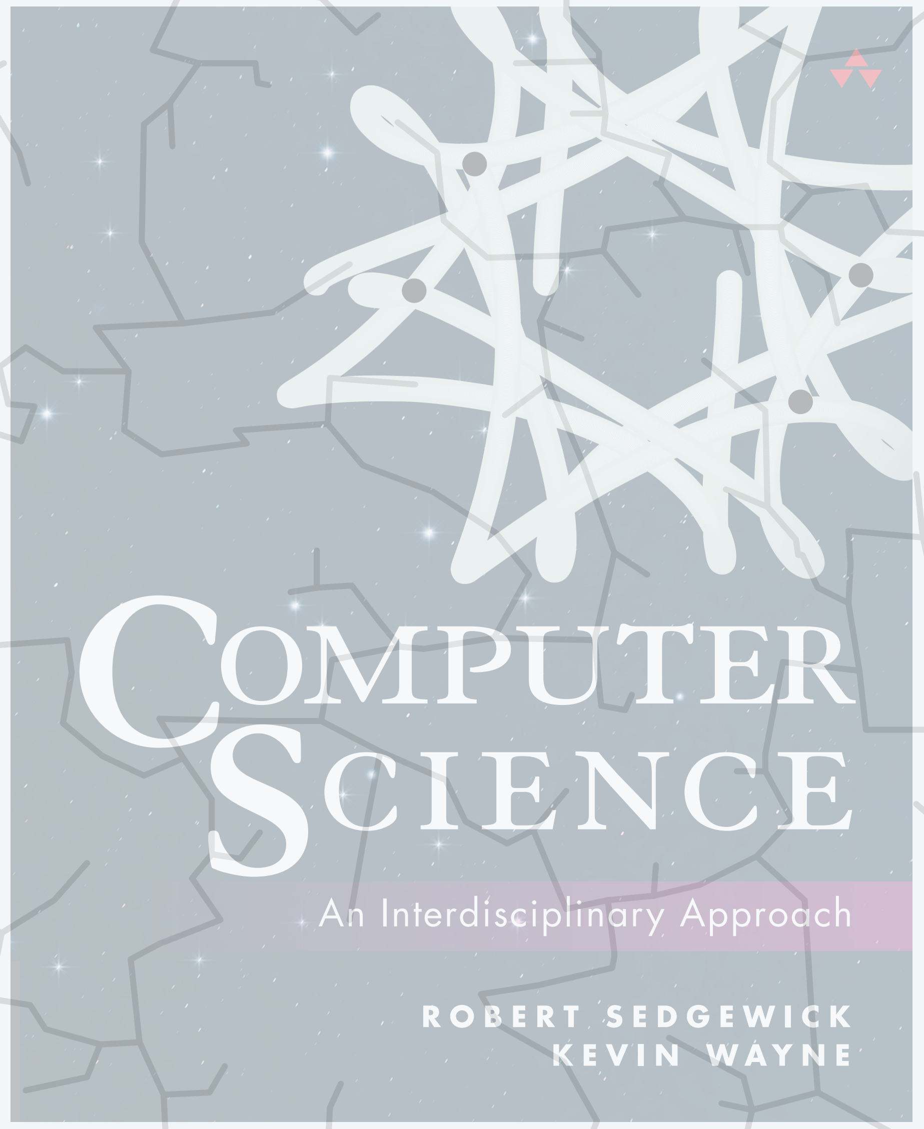
- *basic concepts*
- *shuffling*
- *digital audio*
- *memory representation*
- *two-dimensional arrays*

Basic building blocks for programming





store and process huge amounts of data



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1.4 Arrays

- *basic concepts*
- *shuffling*
- *digital audio*
- *memory representation*
- *two-dimensional arrays*

Your first data structure

An array is an *indexed sequence* of values of the same type.

Examples.

- 8 notes in a musical scale.
- 52 playing cards in a deck.
- 300 students in a COS class.
- 10 million audio samples in a song.
- 4 billion nucleotides in a DNA strand.
- 100 billion Google queries in a month.
- 1 trillion parameters in a large language model.
- …

index	value
0	2♥
1	6♠
2	A♦
3	A♥
⋮	⋮
49	3♣
50	K♣
51	4♠

Main purpose. Facilitate storage and manipulation of data.

Processing many values of the same type

10 values, without an array

```
double a0 = 0.0;
double a1 = 0.0;
double a2 = 0.0;
double a3 = 0.0;
double a4 = 0.0;
double a5 = 0.0;
double a6 = 0.0;
double a7 = 0.0;
double a8 = 0.0;
double a9 = 0.0;
...
a4 = 3.0;
...
a8 = 8.0;
...
double x = a4 + a8;
```

tedious and error-prone code

10 values, with an array

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

an easy alternative

1 million values, with an array

```
double[] a = new double[1000000];
...
a[234567] = 3.0;
...
a[876543] = 8.0;
...
double x = a[234567] + a[876543];
```

scales to handle huge amounts of data

Arrays in Java

Create an array. Specify its type and length.

Access an array element. Use name of array, square brackets, and index.

operation	typical code
declare an array	`double[] a;`
create an array of length n	`a = new double[n];`
declare, create, and initialize an array	`double[] b = new double[n];`
array initializer	`double[] c = { 0.3, 0.6, 0.1 };`
access an array element by index	`a[i] = b[i-1] + c[i+1];`
length of array	`a.length`

all elements initialized to default value (zero for numeric types, false for `boolean`*)*

index can be any expression of type `int`

Examples of programming with arrays

problem	code	
print array elements, one per line	`for (int i = 0; i < a.length; i++)` `   System.out.println(a[i]);`	*array indices go from* `0` *to* `a.length - 1`
sum of array elements	`double sum = 0.0;` `for (int i = 0; i < a.length; i++)` `   sum = sum + a[i];`	*array elements are variables (can be used in expressions)*
create a new array containing n random numbers	`double[] a = new double[n];` `for (int i = 0; i < n; i++)` `   a[i] = Math.random();`	*array elements are variables (can be used as LHS of assignment statement)*
command-line arguments	`int time = Integer.parseInt(args[0]);` `String folder = args[1] + "/";`	`args[]` *in* `main()` *is a* `String` *array*
months in the year	`String[] months = {` `   "Jan", "Feb", "Mar", "Apr", "May", "Jun",` `   "Jul", "Aug", "Sep", "Oct", "Nov", "Dec",` `}`	*store predefined constants*

Arrays: quiz 1

What are the contents of the array `a[]` after the loop terminates?

A. A B C D E

B. A B C B A

C. E D C B A

D. E D C D E

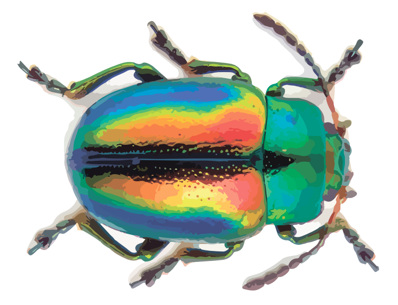
```
String[] a = { "A", "B", "C", "D", "E" };
int n = a.length;
for (int i = 0; i < n; i++) {
   String temp = a[i];
   a[i] = a[n-i-1];
   a[n-i-1] = temp;
}
```

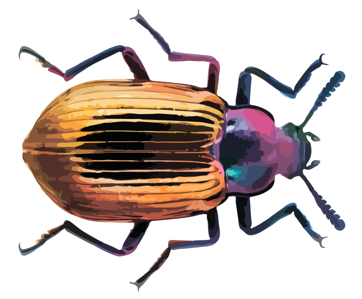
swap idiom

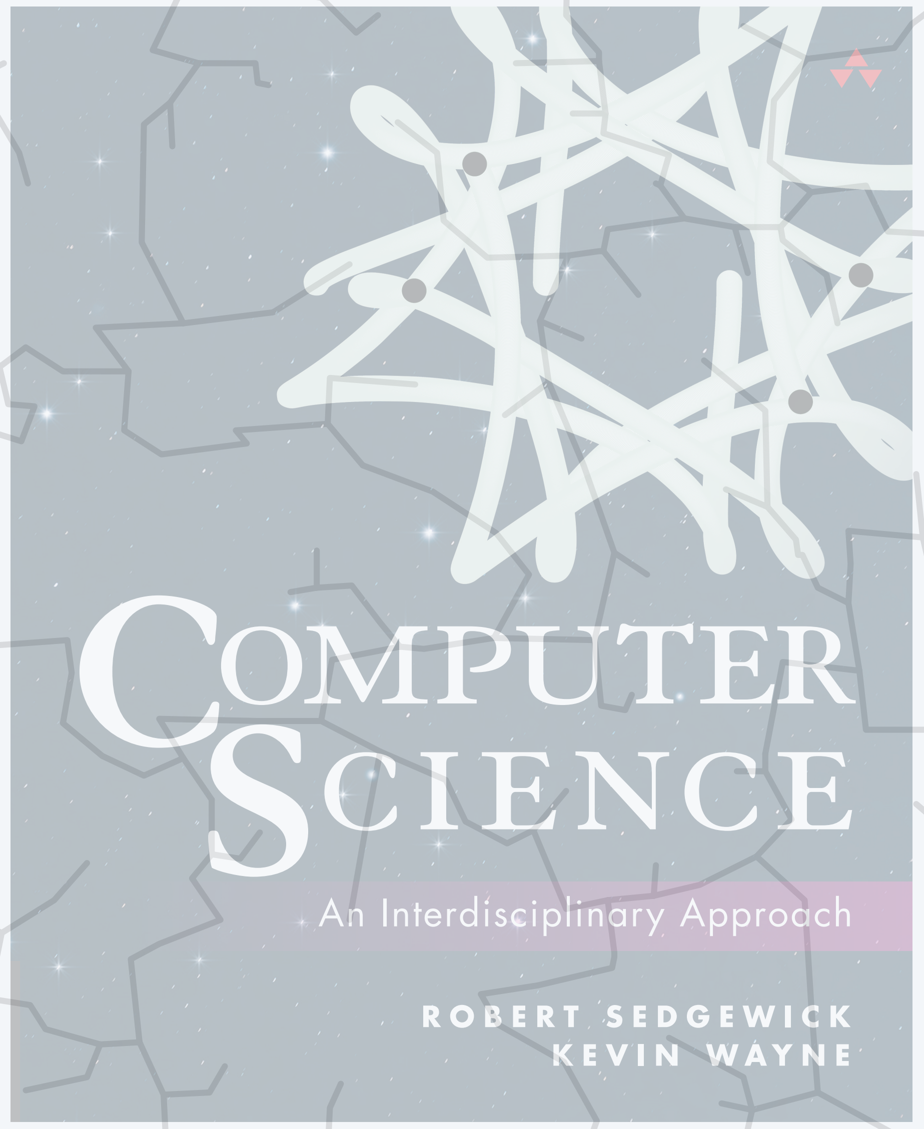
Programming with arrays: common bugs

bug	buggy code	error	error message

	`double[] a;`
	`for (int i = 0; i < 10; i++)`
	`    a[i] = Math.random();`
		uninitialized array (compile-time error)	`~/cos126/arrays> javac ArrayBug1.java`
			`ArrayBug1.java:5: error:`
			`variable a might not have`
			`been initialized`
			`     a[i] = Math.random();`
			`     ^`
			`1 error`

	`double[] a = new int[10];`
	`for (int i = 0; i < 10; i++)`
	`    a[i] = Math.random();`
		type mismatch error (compile-time error)	`~/cos126/arrays> javac ArrayBug2.java`
			`ArrayBug2.java:3: error:`
			`incompatible types: int[]`
			`cannot be converted to double[]`
			`    double[] a = new int[10];`
			`                 ^`
			`1 error`

	`double[] a = new double[10];`
	`for (int i = 1; i <= 10; i++)`
	`    a[i] = Math.random();`
		array index out of bounds (run-time error)	`~/cos126/arrays> javac ArrayBug3.java`
			`~/cos126/arrays> java ArrayBug3`
			`Exception in thread "main"`
			`java.lang.ArrayIndexOutOfBoundsException:`
			`Index 10 out of bounds for length 1`
			`    at ArrayBug3.java:5)`



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1.4 Arrays

- basic concepts
- shuffling
- digital audio
- memory representation
- two-dimensional arrays

Create a deck of cards

Define three arrays:

- Ranks. `String[] ranks = { "2", "3", "4", "5", "6", "7", "8", "9", "10", "J", "Q", "K", "A" };`
- Suits. `String[] suits = { "♣", "♦", "♥", "♠" };`
- Full deck. `String[] deck = new String[52];`

Use nested for loops to put all cards in the deck.

```
for (int j = 0; j < 4; j++)
   for (int i = 0; i < 13; i++)
      deck[i + 13*j] = ranks[i] + suits[j];
```

j

suits[]	0	1	2	3
	♣	♦	♥	♠

i

ranks[]	0	1	2	3	4	5	6	7	8	9	10	11	12
	2	3	4	5	6	7	8	9	10	J	Q	K	A

deck[]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	…
	2♣	3♣	4♣	5♣	6♣	7♣	8♣	9♣	10♣	J♣	Q♣	K♣	A♣	2♦	3♦	4♦	5♦	6♦	7♦	8♦	9♦	…

Create a deck of cards

```
public class Deck {
   public static void main(String[] args) {
      String[] ranks = { "2", "3", "4", "5", "6", "7", "8", "9", "10", "J", "Q", "K", "A" };
      String[] suits = { "♣", "♦", "♥", "♠" };

      String[] deck = new String[52];
      for (int j = 0; j < 4; j++)
         for (int i = 0; i < 13; i++)
            deck[i + 13*j] = ranks[i] + suits[j];

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

   }
}
```

```
~/cos126/arrays> java Deck
2♣ 3♣ 4♣ 5♣ 6♣ 7♣ 8♣ 9♣ 10♣ J♣ Q♣ K♣ A♣ 2♦ 3♦ 4♦ 5♦ … 2♠ 3♠ 4♠ 5♠ 6♠ 7♠ 8♠ 9♠ 10♠ J♠ Q♠ K♠ A♠
```

← *cards in order by suit*

Arrays: quiz 2

Which code fragment puts the cards in the array in order by rank?

```
~/cos126/arrays> java Deck
2♣ 2♦ 2♥ 2♠ 3♣ 3♦ 3♥ 3♠ 4♣ 4♦ 4♥ 4♠ 5♣ 5♦ 5♥ 5♠ … Q♣ Q♦ Q♥ Q♠ K♣ K♦ K♥ K♠ A♣ A♦ A♥
```

A.

```
for (int i = 0; i < 13; i++)
   for (int j = 0; j < 4; j++)
      deck[i + 13*j] = rank[i] + suit[j];
```

B.

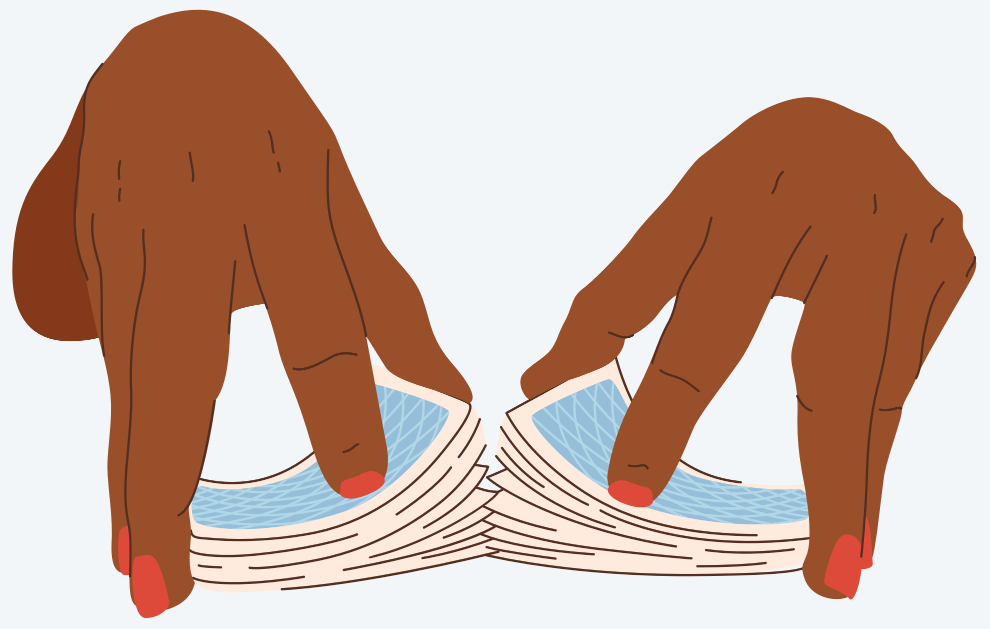
```
for (int i = 0; i < 13; i++)
   for (int j = 0; j < 4; j++)
      deck[4*i + j] = rank[i] + suit[j];
```

C. Both A and B.

D. Neither A nor B.

Shuffling

Goal. Rearrange deck of cards in uniformly random order.



Algorithm. For each index i from 0 to 51 :

- Pick a uniformly random index r between 0 and i.
- Exchange `deck[i]` and `deck[r]`.

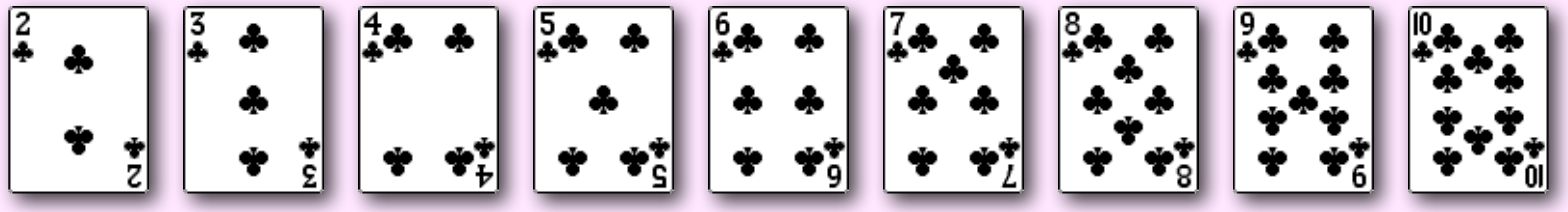
```
for (int i = 0; i < 52; i++) {
   int r = (int) (Math.random() * (i+1));
   String temp = deck[r];
   deck[r] = deck[i];
   deck[i] = temp;
}
```

between 0 and `i`
(equally likely)

Shuffling demo

Algorithm. For each index i from 0 to $n-1$:

- Pick a uniformly random index r between 0 and i.
- Exchange `a[i]` and `a[r]`.



Shuffling trace

```
for (int i = 0; i < 9; i++) {
   int r = (int) (Math.random() * (i+1));
   String temp = deck[r];
   deck[r] = deck[i];
   deck[i] = temp;
}
```

		deck[]								
i	r	0	1	2	3	4	5	6	7	8
		2♣	3♣	4♣	5♣	6♣	7♣	8♣	9♣	10♣
0	0	2♣	3♣	4♣	5♣	6♣	7♣	8♣	9♣	10♣
1	0	3♣	2♣	4♣	5♣	6♣	7♣	8♣	9♣	10♣
2	0	4♣	2♣	3♣	5♣	6♣	7♣	8♣	9♣	10♣
3	2	4♣	2♣	5♣	3♣	6♣	7♣	8♣	9♣	10♣
4	1	4♣	6♣	5♣	3♣	2♣	7♣	8♣	9♣	10♣
5	0	7♣	6♣	5♣	3♣	2♣	4♣	8♣	9♣	10♣
6	4	7♣	6♣	5♣	3♣	8♣	4♣	2♣	9♣	10♣
7	7	7♣	6♣	5♣	3♣	8♣	4♣	2♣	9♣	10♣
8	1	7♣	10♣	5♣	3♣	8♣	4♣	2♣	9♣	6♣
		7♣	10♣	5♣	3♣	8♣	4♣	2♣	9♣	6♣

trace of variables (at end of each iteration)

Shuffling a deck of cards: implementation

```
public class ShuffledDeck {
   public static void main(String[] args) {
      String[] ranks = { "2", "3", "4", "5", "6", "7", "8", "9", "10", "J", "Q", "K", "A" };
      String[] suits = { "♣", "♦", "♥", "♠" };
      int RANKS = ranks.length;
      int SUITS = suits.length;
      int n = RANKS * SUITS;

      String[] deck = new String[n];
      for (int j = 0; j < SUITS; j++)
         for (int i = 0; i < RANKS; i++)
            deck[i + RANKS*j] = ranks[i] + suits[j];

      for (int i = 0; i < n; i++) {
         int r = (int) (Math.random() * (i+1));
         String temp = deck[r];
         deck[r] = deck[i];
         deck[i] = temp;
      }

      for (int i = 0; i < n; i++)
         System.out.print(deck[i] + " ");

   }
}
```

avoid "magic constants" (such as 4, 13, and 52)

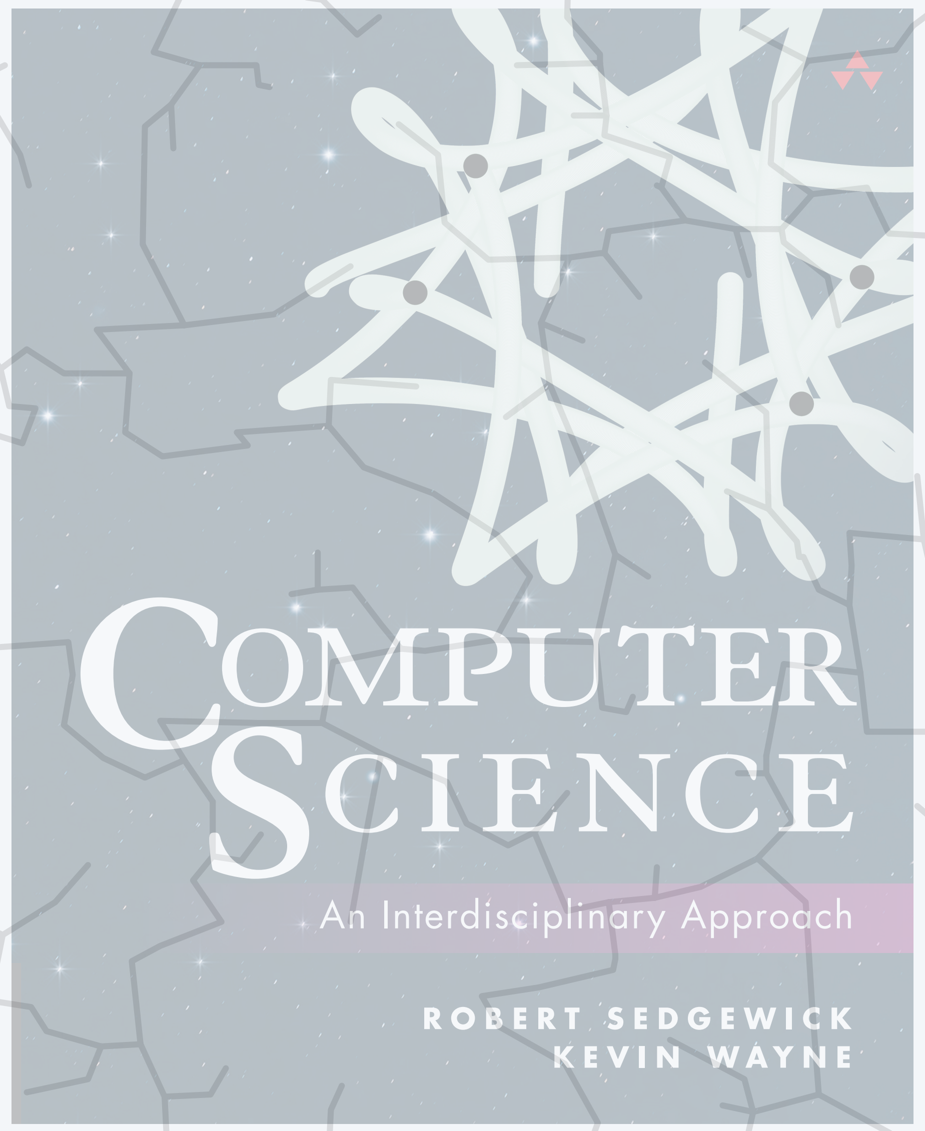
create deck

shuffle deck

print deck

```
~/cos126/arrays> java ShuffledDeck
8♠ A♦ A♥ 9♦ 6♥ 7♥ 9♠ Q♥ … K♣ 2♣ 6♦ 2♦ 5♥

~/cos126/arrays> java ShuffledDeck
K♦ J♥ 7♦ 9♦ Q♦ 5♥ 6♥ 9♥ … Q♥ K♠ 4♦ 6♠ 7♣
```



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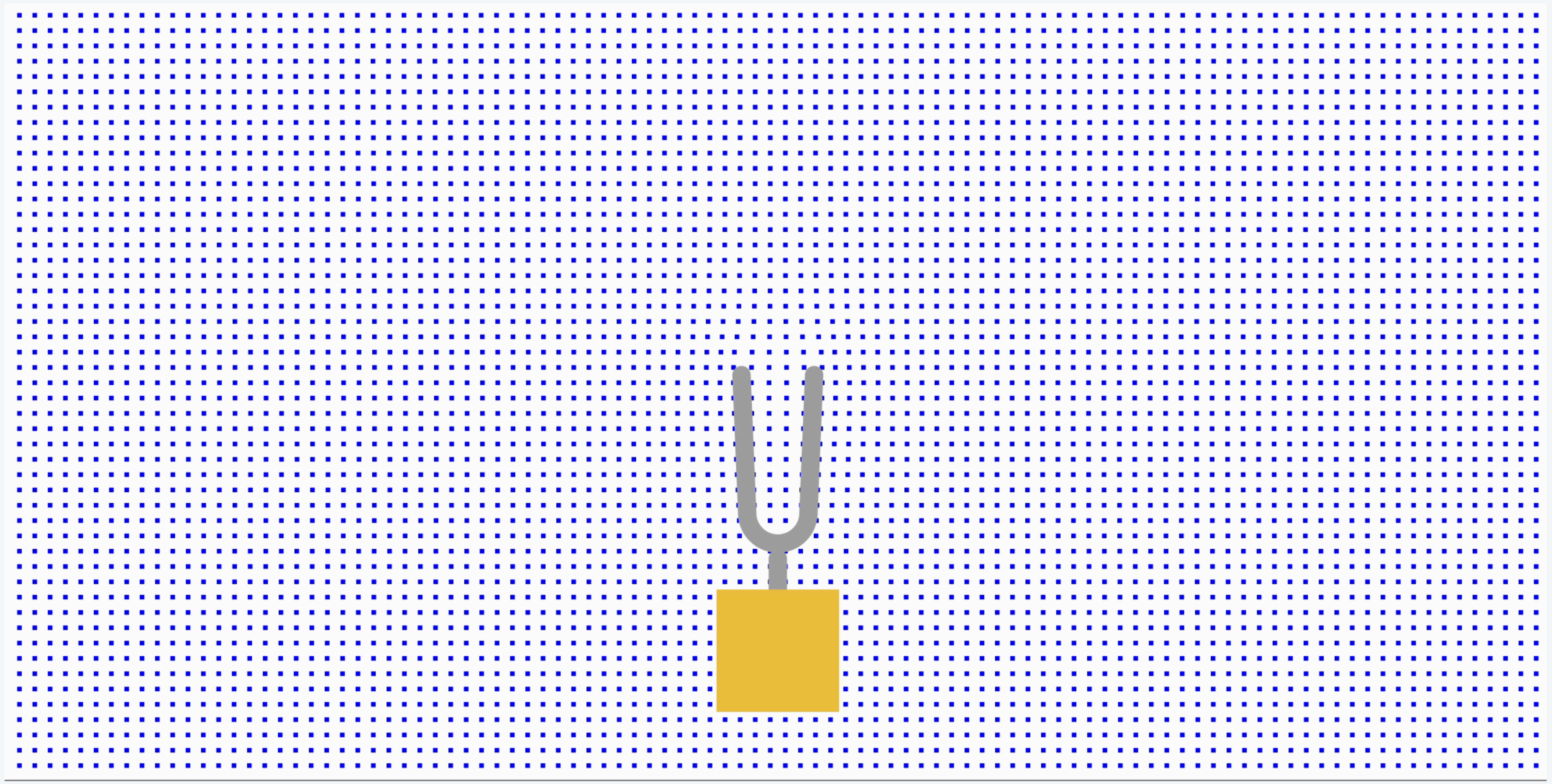
1.4 Arrays

- ▸ *basic concepts*
- ▸ *shuffling*
- ▸ *digital audio*
- ▸ *memory representation*
- ▸ *two-dimensional arrays*

Crash course in sound

Sound. The perceptible vibration of air by the ear.



https://javalab.org/en/tuning_fork_and_sound_wave_en

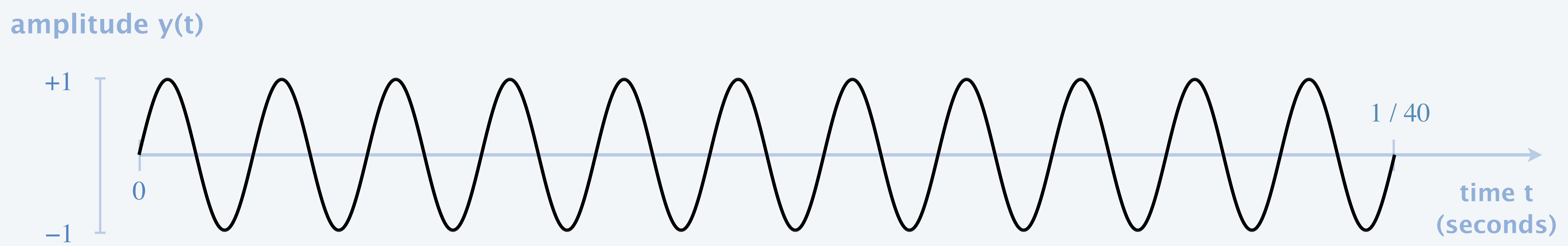
Crash course in digital audio

Audio. An analog or digital encoding of sound.

Audio formats. Vinyl, tape cassette, CD, WAV, MP3, AIFC, …

Audio signal. Real-valued (between -1 and $+1$) function of time. ⟵ *value (amplitude) relates to change in sound pressure*

- A loudspeaker converts an audio signal into sound.
- A microphone converts sound into an audio signal.



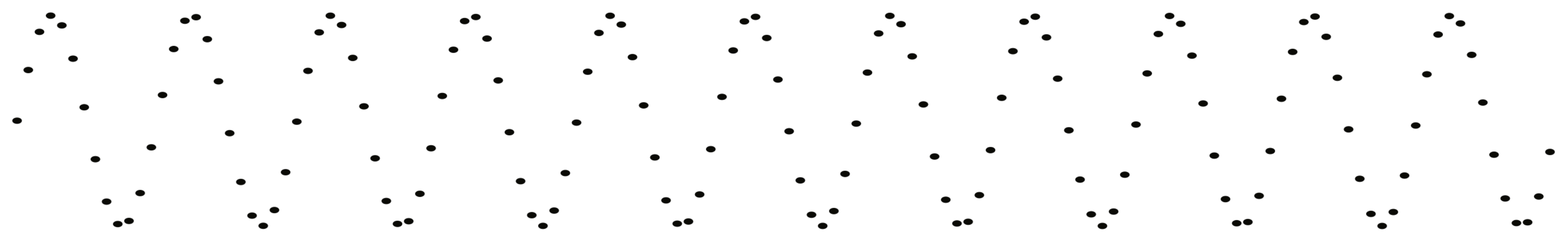
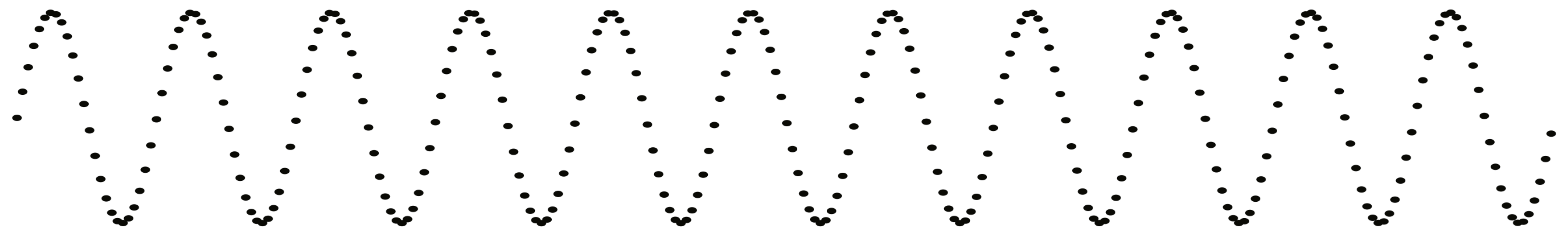
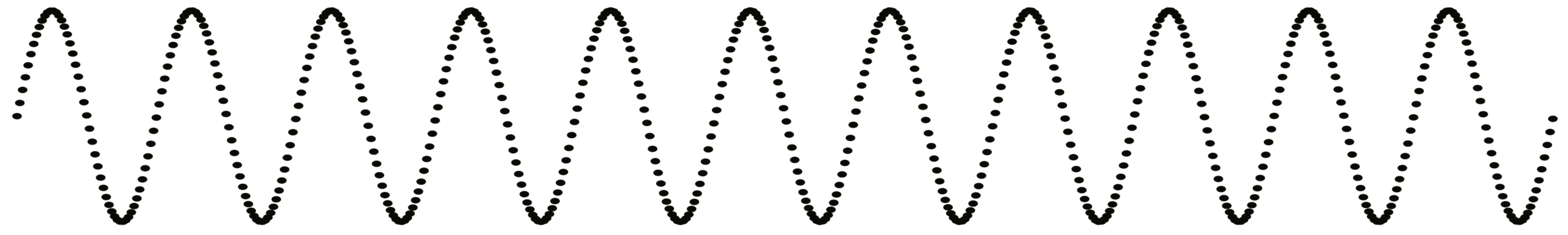
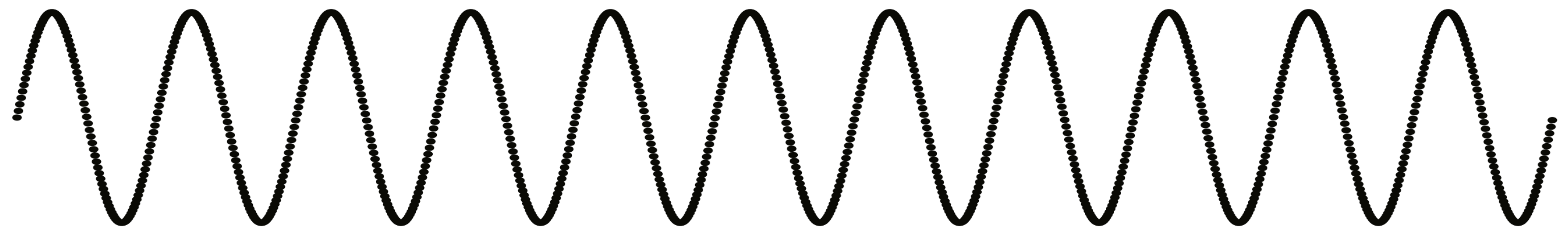
1/40 second of concert A
(sine wave with frequency 440 Hz)

Audio sampling

Goal. Convert a continuous-time signal into a discrete-time signal.

- A sample is a signal value at specific point in time.
- Take samples at evenly spaced points.

model sound with an array of real numbers between −1 and +1 (using 44,100 samples per second)

samples / second	samples	samples from a sine wave (440 Hz)
5,512	138	
11,025	276	
22,050	552	
44,100	1103	

a standard sampling rate

1/40 second of concert A

Standard audio library

StdAudio. Our library for playing, reading, and saving digital audio. ← *available with* `javac-introcs` *and* `java-introcs` *commands*

`public class StdAudio`

`static int`	`SAMPLE_RATE`	44,100 (*CD quality audio*) ← *1 hour of audio comprises about 159 million samples*
`static void`	`play(String filename)`	*play the audio file*
`static void`	`playInBackground(String filename)`	*play the audio file in the background*
`static void`	`play(double sample)`	*play the sample*
`static void`	`play(double[] samples)`	*play the samples*
`static double[]`	`read(String filename)`	*read the samples from an audio file* ← *supported file formats: WAV, AU, AIFF, MIDI*
`static void`	`save(String filename, double[] samples)`	*save the samples to an audio file*
`static void`	`drain()`	*play any samples left in buffer*
	⋮	⋮

Audio gain

Volume. Perceived loudness of a sound.

Audio gain. Multiply all samples by the same constant α.

- $|\alpha| > 1 \Rightarrow$ amplifies audio signal.
- $|\alpha| < 1 \Rightarrow$ attenuates audio signal.

```
public class Gain {
   public static void main(String[] args) {
      double[] samples = StdAudio.read(args[0]);
      double alpha = Double.parseDouble(args[1]);
      for (int i = 0; i < samples.length; i++) {
         samples[i] = samples[i] * alpha;
         if (samples[i] > +1.0) samples[i] = +1.0;
         if (samples[i] < -1.0) samples[i] = -1.0;
      }
      StdAudio.play(samples);
   }
}
```

"clipping"

```
~/cos126/arrays> java-introcs Gain Game.wav 1.0
[plays sound effect]

~/cos126/arrays> java-introcs Gain Game.wav 2.0
[plays louder version]

~/cos126/arrays> java-introcs Gain Game.wav 0.5
[plays quieter version]

~/cos126/arrays> java-introcs Gain Game.wav 0.0
[plays silence]

~/cos126/arrays> java-introcs Gain Game.wav -1.0
[plays inverted version]
```

Arrays: quiz 3

What sound will the following command produce?

A. Original audio.

B. Silence.

C. Static.

D. Ear-shattering noise.

E. None of the above.

```
~/cos126/arrays> java-introcs Gain HelloWorld.wav 9999.99
🔊 [plays sound with ???]
```

```
double[] samples = StdAudio.read("HelloWorld.wav");
for (int i = 0; i < samples.length; i++) {
   if      (samples[i] < 0.0) samples[i] = -1.0;
   else if (samples[i] > 0.0) samples[i] = +1.0;
}
StdAudio.play(samples);
```

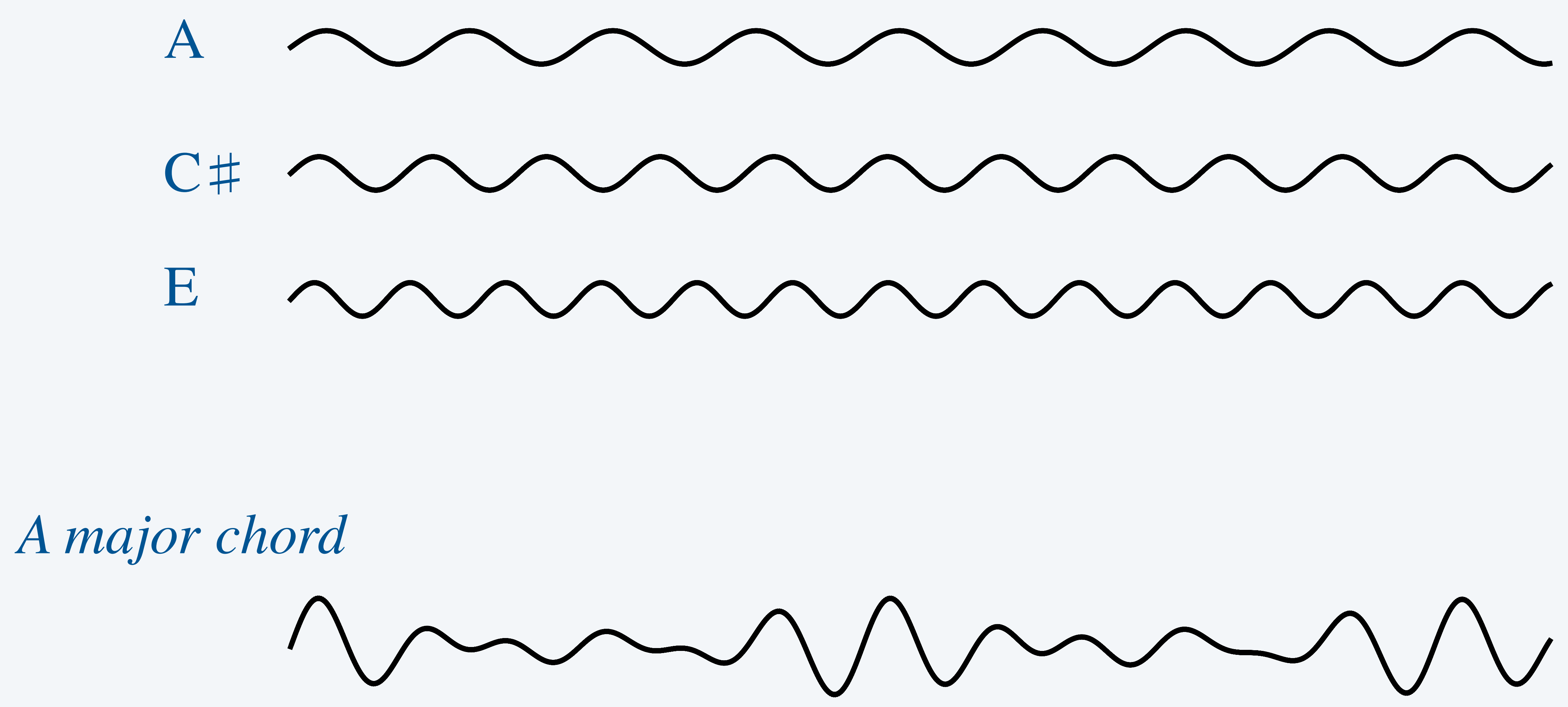
effectively equivalent to

Principle of superposition

Superposition. To combine two (or more) audio signals, add the corresponding samples.

sound waves are mechanical waves

Ex 1. Add audio signals of notes to produce a chord.

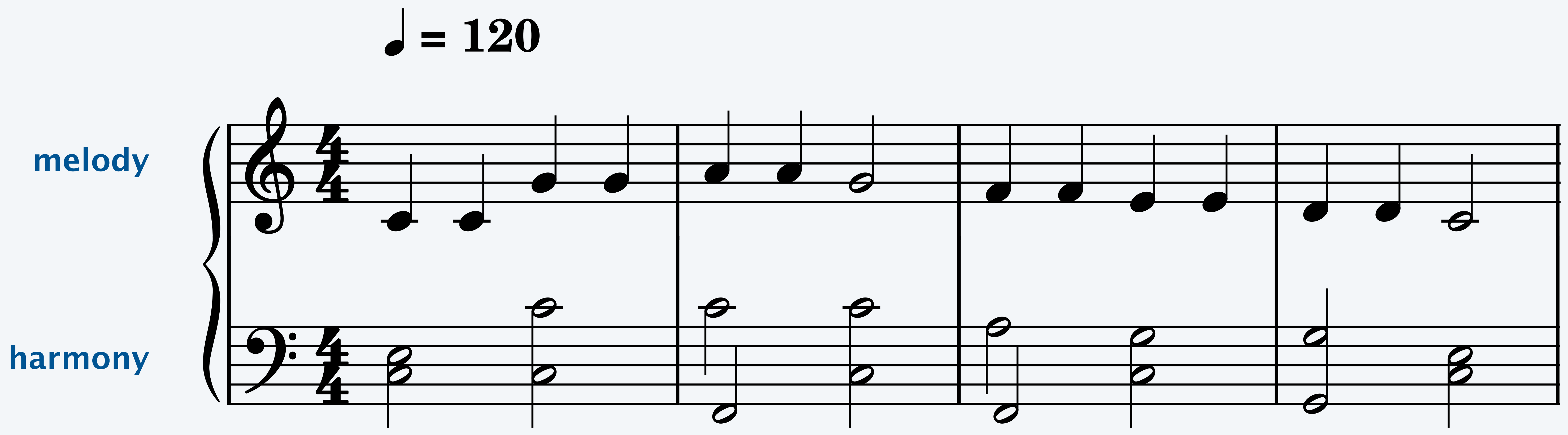


Principle of superposition

Superposition. To combine two (or more) audio signals, add the corresponding samples.

Ex 1. Add audio signals of notes to produce a chord.

Ex 2. Add audio signals of parts, instruments, and voices to produce a musical composition.



"Twinkle, Twinkle, Little Star"
(two parts)

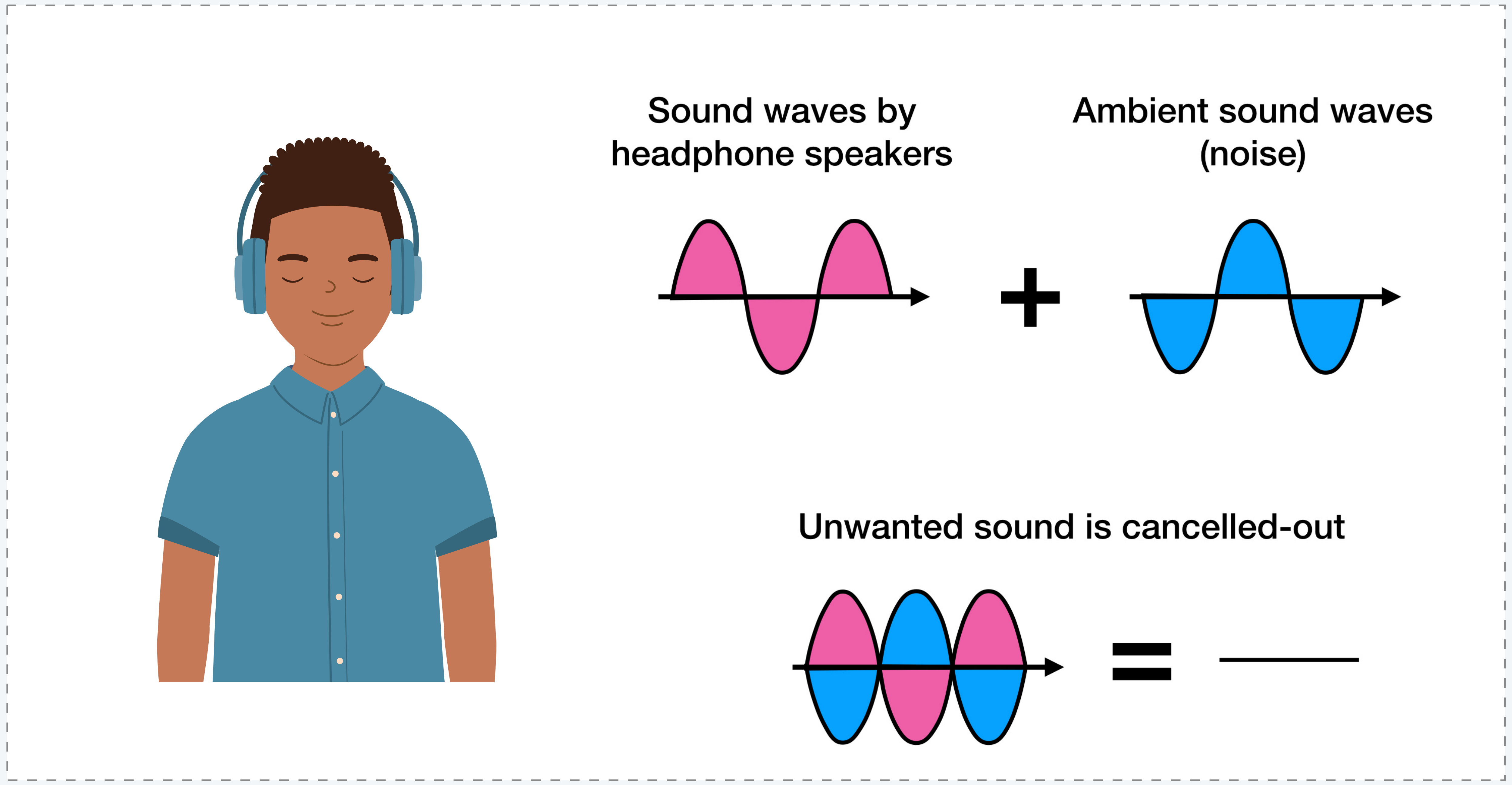
Principle of superposition

Superposition. To combine two (or more) audio signals, add the corresponding samples.

Ex 1. Add audio signals of notes to produce a chord.

Ex 2. Add audio signals of parts, instruments, and voices to produce a musical composition.

Ex 3. Noise-cancelling headphones.


Sound waves by headphone speakers
Ambient sound waves (noise)
+
Unwanted sound is cancelled-out
=

Superposition of audio files

```
public class Superpose {
   public static void main(String[] args) {
      double[] results = StdAudio.read(args[0]);
      for (int i = 1; i < args.length; i++) {
         double[] samples = StdAudio.read(args[i]);
         for (int j = 0; j < samples.length; j++) {
            results[j] = results[j] + samples[j];
         }
      }

      StdAudio.play(results);
   }
}
```

`args[]` *in* `main()` *is a* `String` *array*

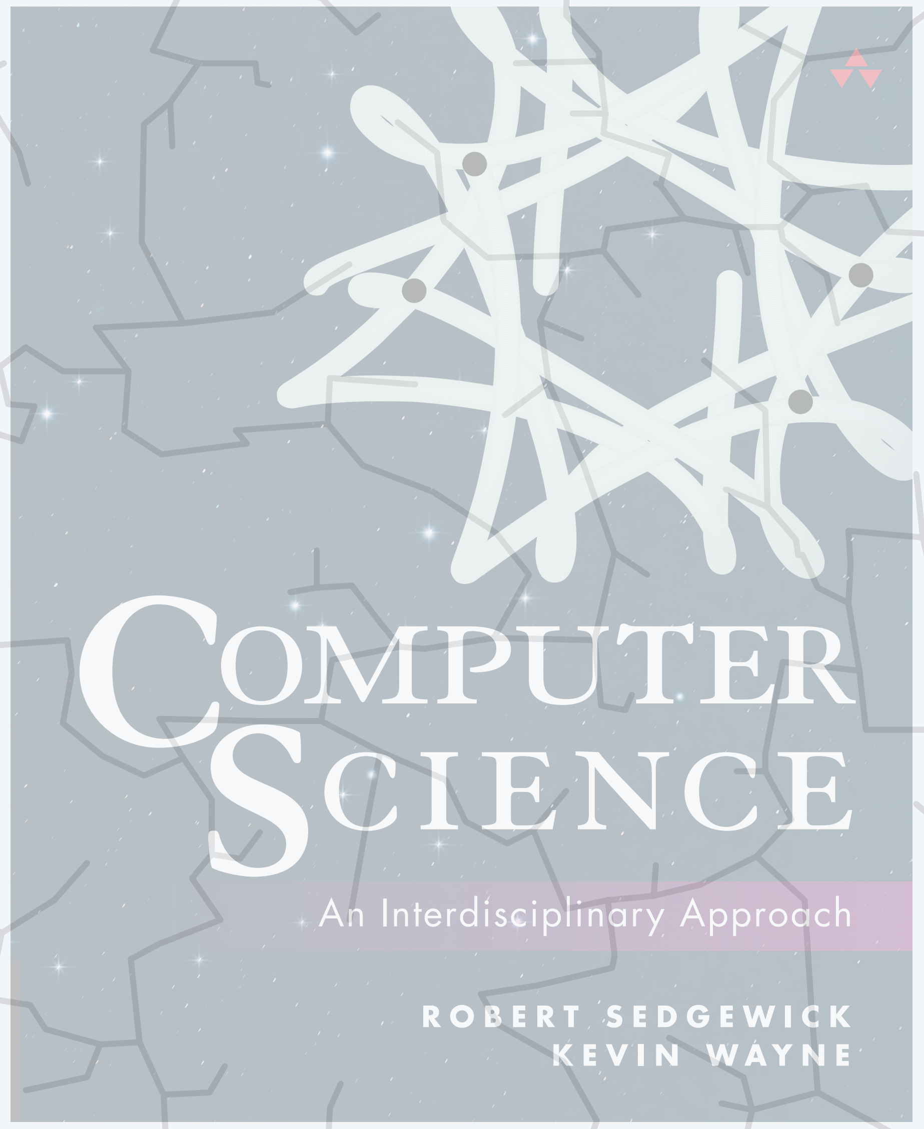
use a loop to add the corresponding samples (assumes all arrays of same length)

play the results

```
~/cos126/arrays> java-introcs Superpose PacManMelody.wav
 [plays Pac-Man startup melody]

~/cos126/arrays> java-introcs Superpose PacManHarmony.wav
 [plays Pac-Man startup harmony]

~/cos126/arrays> java-introcs Superpose PacManMelody.wav PacManHarmony.wav
 [plays Pac-Man startup melody and harmony]
```



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1.4 Arrays

- *basic concepts*
- *shuffling*
- *digital audio*
- *memory representation*
- *two-dimensional arrays*

Memory representation of an array

Java array. An array is an indexed sequence of values of the same type.

Computer memory. Your computer's memory is an indexed sequence of memory locations.

- Each *int*, *double*, or *boolean* occupies a fixed number of memory locations.
- Array elements are stored in contiguous memory locations.

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

Key properties.

- Given index `i`, accessing `a[i]` is extremely efficient.
- Once you create an array, you can never change its type or length.
- Arrays are reference types, not primitive types.

think of the variable `a[]` *as storing the memory address of its first element*

Assignment statements with arrays

Consequence 1. The assignment statement *b* = *a* makes *a* and *b* refer to the same array.

it does not create a new, independent, array

Ex.

```
double[] a = { 0.5, 0.25, -1.0, 0.125, 0.5 };
double[] b = new double[a.length];
b = a;
b[1] = 0.75;
```

a[]
0.5
0.75
-1.0
0.125
0.5
b[]
0.0
0.0
0.0
0.0
0.0
array is garbage collected when no longer accessible

Checking arrays for equality

Consequence 2. The expression *a* == *b* checks whether *a* and *b* refer to the same array.

not whether they store the same sequence of values

Ex.

```
double[] a = { 0.5, 0.25, -1.0, 0.125, 0.5 };
double[] b = { 0.5, 0.25, -1.0, 0.125, 0.5 };
System.out.println(a == b);    // false
```

a[]
0.5
0.25
-1.0
0.125
0.5
b[]
0.5
0.25
-1.0
0.125
0.5

Copying an array and checking for equality

Q. How to copy an array and check for equality?

A. Use loops.

```
double[] a = { 0.5, 0.25, -1.0, 0.125, 0.5 };
double[] b = new double[a.length];
for (int i = 0; i < a.length; i++)
    b[i] = a[i];
```

copying an array

```
boolean areEqual = true;
for (int i = 0; i < a.length; i++) {
   if (a[i] != b[i])
      areEqual = false;
}
```

checking two arrays (of same length) for equality

a[]
i
0.5
0.25
-1.0
0.125
0.5
b[]
i
0.5
0.25
-1.0
0.125
0.5

Arrays: quiz 4

What does the following code fragment print?

A. 0 1 2 0 1 2

B. 0 1 2 1 2 6

C. 1 2 6 0 1 2

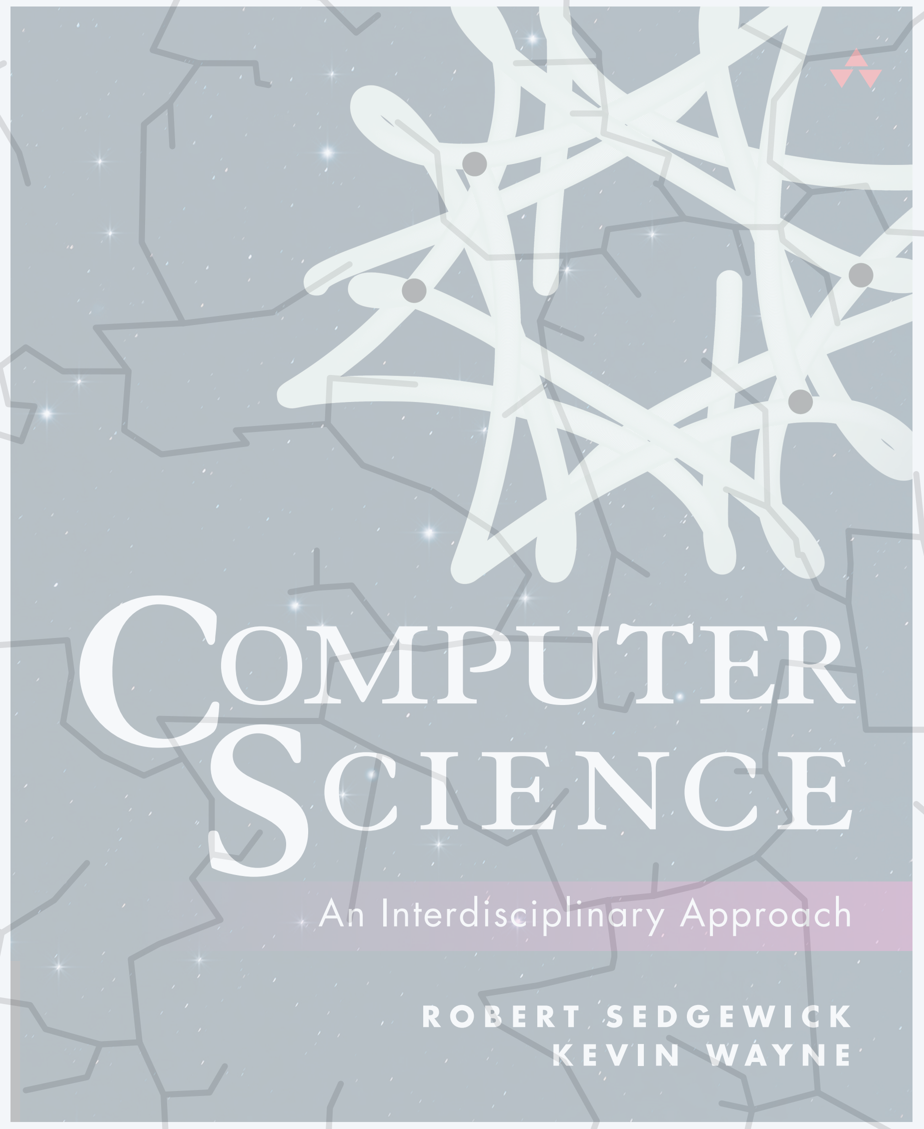
D. 1 2 6 1 2 6

```
int[] a = { 1, 2, 6 };
int[] b = new int[a.length];

b = a;
for (int i = 0; i < b.length; i++)
   b[i] = i;

for (int i = 0; i < a.length; i++)
   System.out.print(a[i] + " ");

for (int i = 0; i < b.length; i++)
   System.out.print(b[i] + " ");
```



https://introcs.cs.princeton.edu

1.4 ARRAYS

- basic concepts
- shuffling
- digital audio
- memory representation
- two-dimensional arrays

Two-dimensional arrays

A two-dimensional array is a *doubly-indexed* table of values of the same type.

Examples.

- Grades for students in an online class.
- Outcomes of a scientific experiment.
- Customer transactions in a bank.
- Entries in a feature matrix.
- Pixels in a digital image.
- Cells in a spreadsheet.
- …

grade

student ID

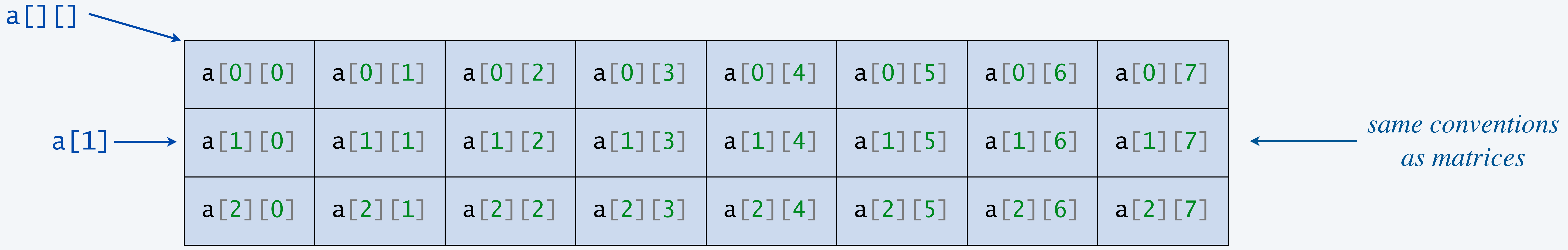
	0	1	2	3	4	5	⋯
0	A	A	C	B	A	C	
1	B	B+	B	B–	A	A–	
2	C	D	D	B	C	A	
3	A	A+	A	A–	A	A+	
4	C	C	B+	C	B	B–	
⋮							

Two-dimensional arrays in Java

operation	typical code
declare a two-dimensional array	`double[][] a;`
create an m-by-n array	`a = new double[m][n];`
declare, create, and initialize in one statement	`double[][] a = new double[m][n];`
refer to an array element by index	`a[i][j] = b[i][j] + c[j][k];`
number of rows	`a.length`
number of columns	`a[i].length`

all elements initialized to default value (zero for numeric types, false for `boolean`*)*

can be different for each row ("ragged" array)



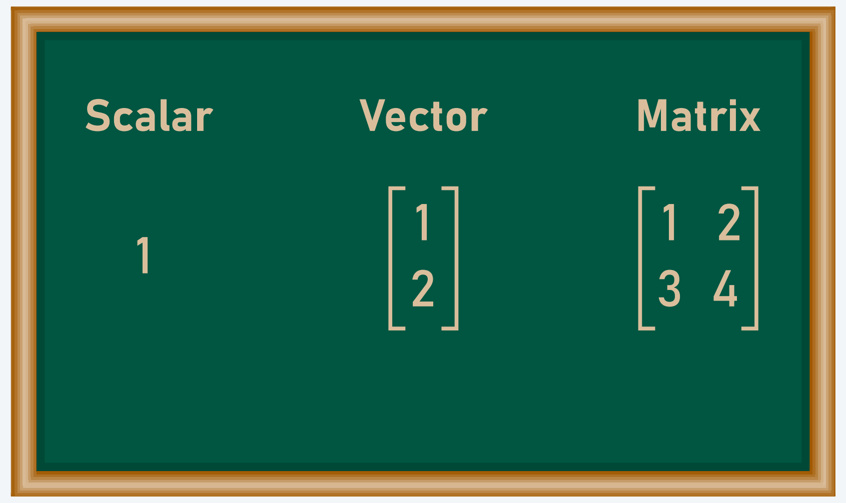
a[][]
a[1]
a[0][0] a[0][1] a[0][2] a[0][3] a[0][4] a[0][5] a[0][6] a[0][7]
a[1][0] a[1][1] a[1][2] a[1][3] a[1][4] a[1][5] a[1][6] a[1][7]
a[2][0] a[2][1] a[2][2] a[2][3] a[2][4] a[2][5] a[2][6] a[2][7]
same conventions as matrices

a 3-by-8 array

Vector and matrix calculations

Mathematical abstractions. Vectors and matrices.

Java implementation. 1D arrays and 2D arrays.


Scalar
Vector
Matrix
1
$\begin{bmatrix}1\\2\end{bmatrix}$
$\begin{bmatrix}1&2\\3&4\end{bmatrix}$

vector addition

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

matrix addition

```
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];
```

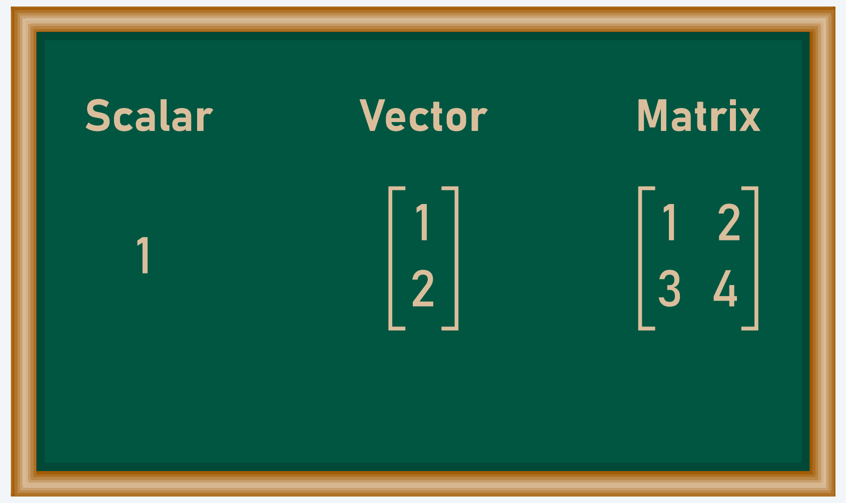
$$\underbrace{(0.8, 0.7, 0.5)}_{c} = \underbrace{(0.3, 0.6, 0.1)}_{a} + \underbrace{(0.5, 0.1, 0.4)}_{b}$$

$$\underbrace{\begin{bmatrix}1.5&0.5&0.6\\0.4&1.0&0.2\\0.6&0.4&0.8\end{bmatrix}}_{C} = \underbrace{\begin{bmatrix}0.7&0.2&0.1\\0.3&0.6&0.1\\0.5&0.1&0.4\end{bmatrix}}_{A} + \underbrace{\begin{bmatrix}0.8&0.3&0.5\\0.1&0.4&0.1\\0.1&0.3&0.4\end{bmatrix}}_{B}$$

Vector and matrix calculations

Mathematical abstractions. Vectors and matrices.

Java implementation. 1D arrays and 2D arrays.



vector dot product

```
double sum = 0.0;
for (int i = 0; i < n; i++)
   sum += a[i] * b[i];
```

$$0.25 = \underbrace{(0.3, 0.6, 0.1)}_{a} \cdot \underbrace{(0.5, 0.1, 0.4)}_{b}$$

i	a[i]	b[i]	a[i]*b[i]	sum
0	0.3	0.5	0.15	0.15
1	0.6	0.1	0.06	0.21
2	0.1	0.4	0.04	0.25

matrix multiplication

```
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];
```

$$\underbrace{\begin{bmatrix} 0.59 & 0.32 & 0.41 \\ 0.31 & 0.36 & \boxed{0.25} \\ 0.45 & 0.31 & 0.42 \end{bmatrix}}_{C} = \underbrace{\begin{bmatrix} 0.7 & 0.2 & 0.1 \\ \boxed{0.3 \quad 0.6 \quad 0.1} \\ 0.5 & 0.1 & 0.4 \end{bmatrix}}_{A} \times \underbrace{\begin{bmatrix} 0.8 & 0.3 & \boxed{0.5} \\ 0.1 & 0.4 & \boxed{0.1} \\ 0.1 & 0.3 & \boxed{0.4} \end{bmatrix}}_{B}$$

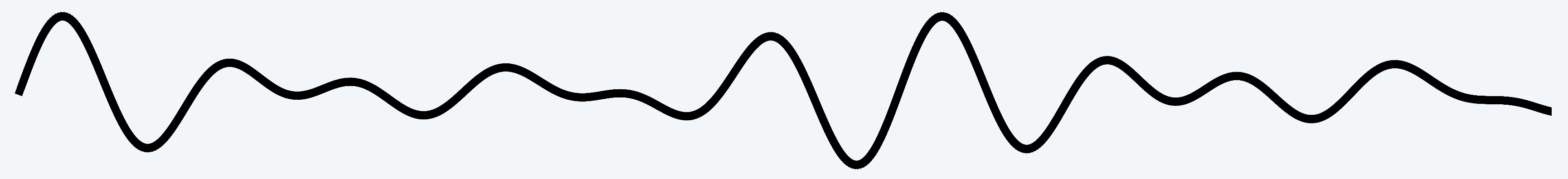
Summary

An array is an *indexed sequence* of values of the same type.

- Serves as a basic building block in programming.
- Enables efficient manipulation of large amounts of data.

Some examples. [in this course]

digital audio signal

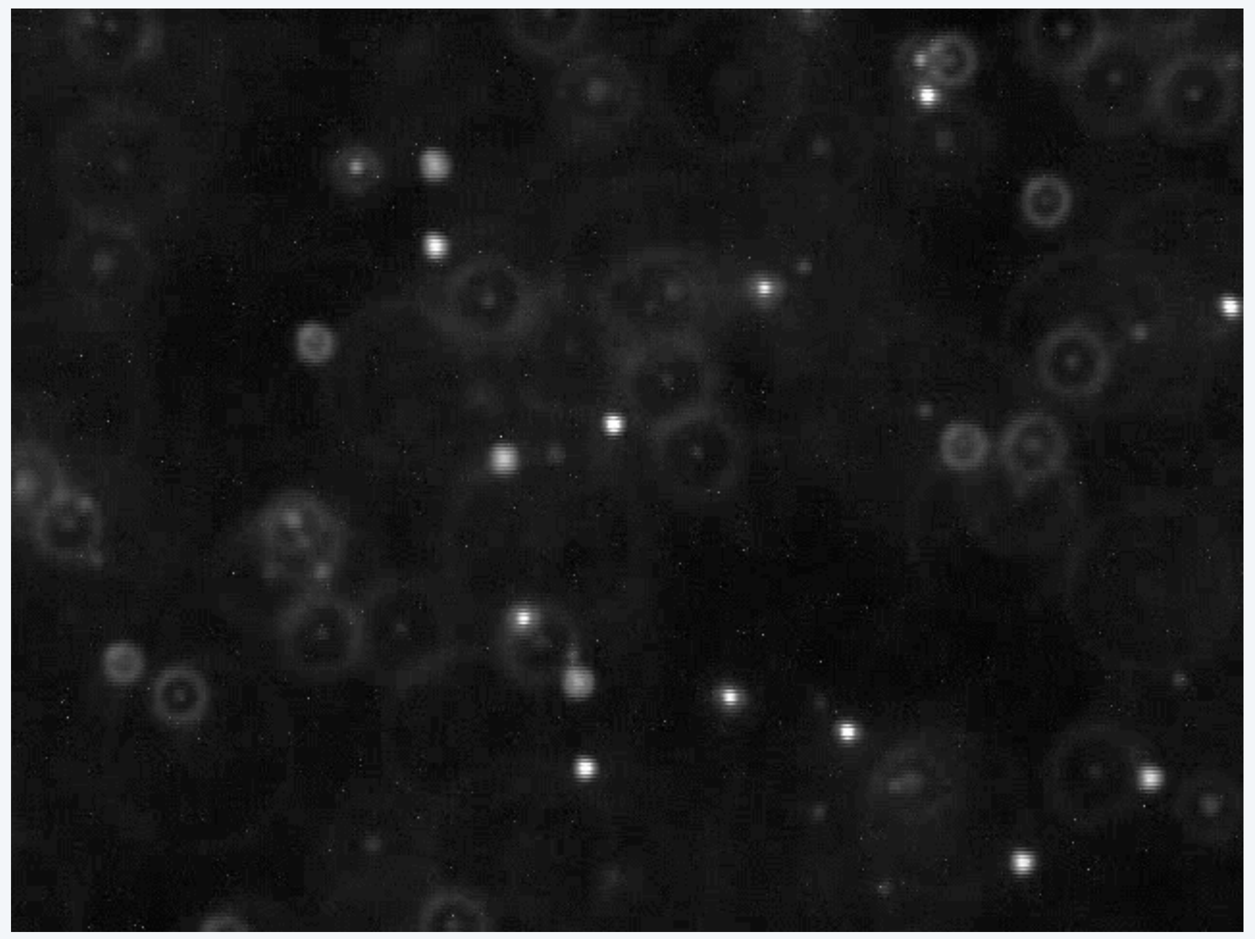


DNA string

T	A	G	A	T	G	T	G	C	T	A	G	C

digital image

digital video



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