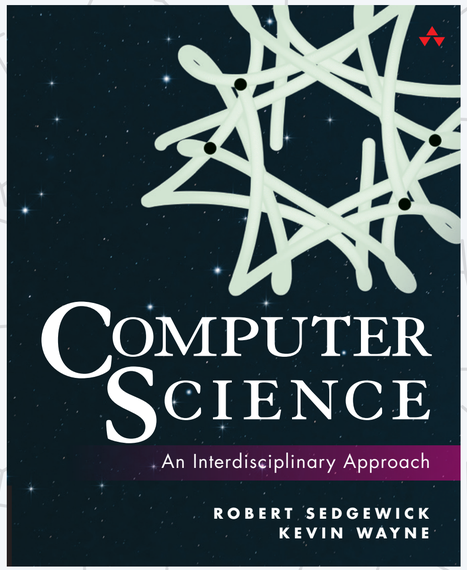
Robert Sedgewick | Kevin Wayne



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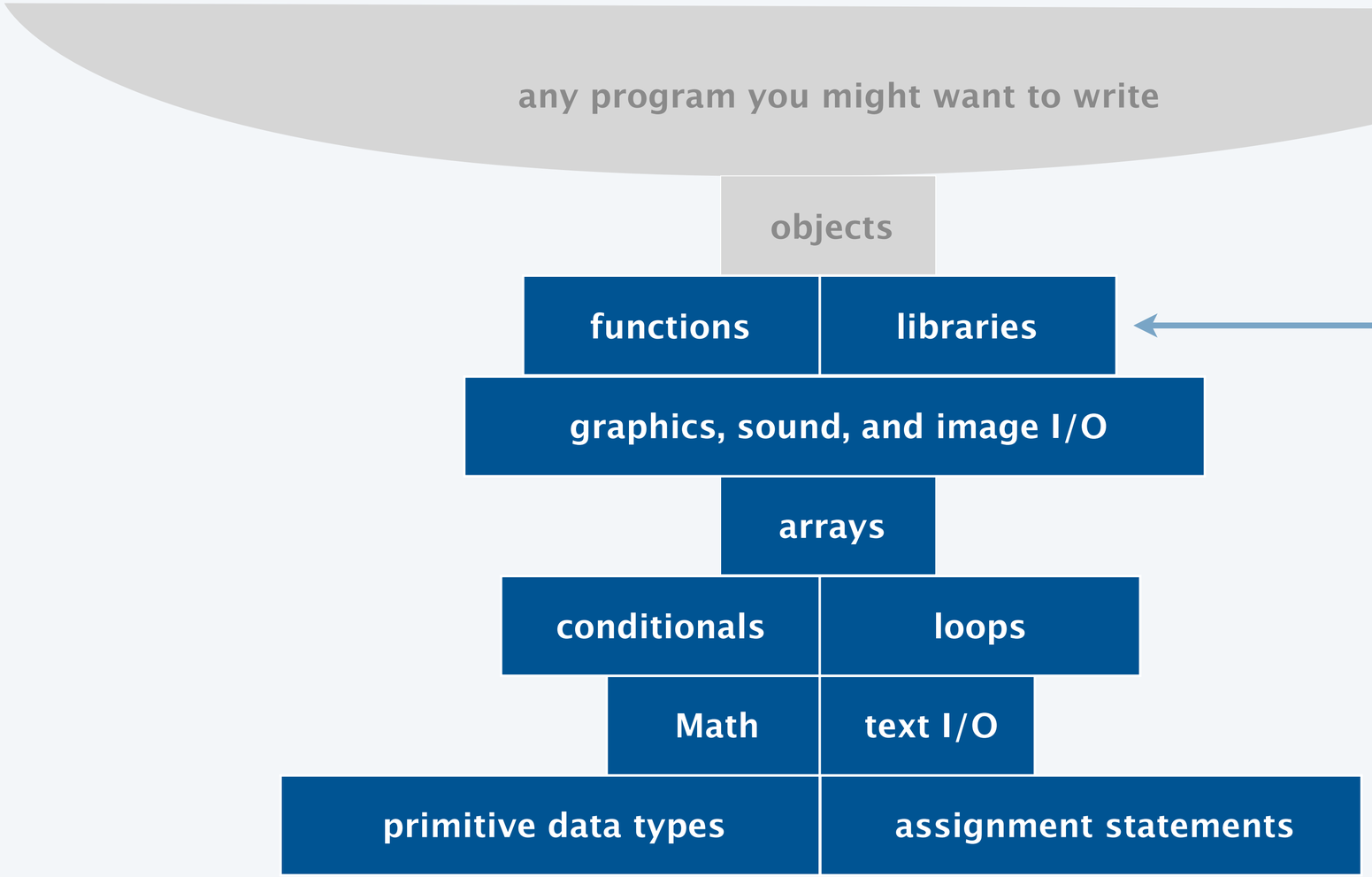
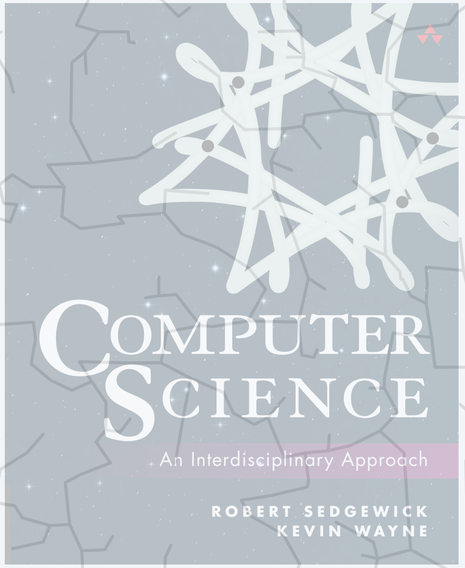
2.2 Libraries and Clients

- *random number library*
- *designing libraries*
- *sound synthesis*
- *synthesizer library*

Basic building blocks for programming



build reusable libraries



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2.2 Libraries and Clients

- *random number library*
- *designing libraries*
- *sound synthesis*
- *synthesizer library*

Standard random library

Goal. Design a library to generate pseudo-random numbers.

`public class StdRandom`

`static double uniformDouble()`	*real number between* 0 *and* 1
`static double uniformDouble(double lo, double hi)`	*real number between* `lo` *and* `hi`
`static boolean bernoulli(double p)`	`true` *with probability* `p`, `false` *otherwise*
`static int uniformInt(int n)`	*integer between* 0 *and* `n-1`
`static double gaussian()`	*normal with mean* 0 *and stddev* 1
`static double gaussian(double mu, double sigma)`	*normal with mean* `mu` *and stddev* `sigma`
`static void shuffle(String[] a)`	*shuffle the string array* `a[]`
`static int discrete(int[] freq)`	`i` *with probability proportion to* `freq[i]`
⋮	⋮

Standard random implementation: random numbers from various distributions

```
public class StdRandom {

   public static double uniformDouble() {
      return Math.random();
   }

   public static double uniformDouble(double lo, double hi) {
      return lo + (uniformDouble() * (hi - lo));
   }

   public static boolean bernoulli(double p) {
      return uniformDouble() < p;
   }

   public static int uniformInt(int n) {
      return (int) (uniformDouble() * n);
   }

   ⋮
}
```

calls a method (in a different class)

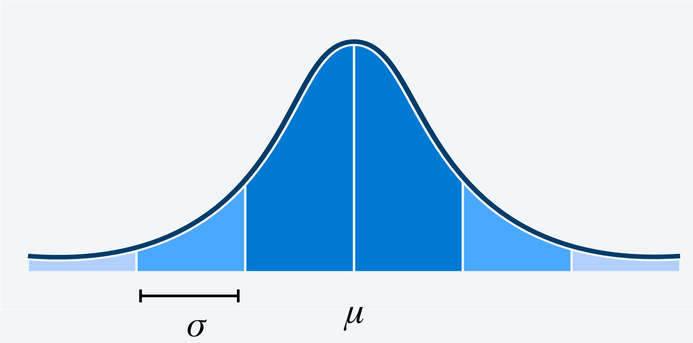
you could re-implement these methods in each program, but now you don't have to!

calls a method (in the same class)

Standard random implementation: random numbers from a Gaussian distribution

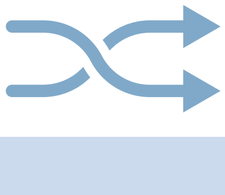
```
public class StdRandom {

   public static double gaussian() {
      double r, x, y;
      do {
         x = uniformDouble(-1.0, 1.0);
         y = uniformDouble(-1.0, 1.0);
         r = x*x + y*y;
      } while (r >= 1 || r == 0);
      return x * Math.sqrt(-2 * Math.log(r) / r);
   }

   public static double gaussian(double mu, double sigma) {
      return mu + gaussian() * sigma;
   }

   ⋮
}
```

can call a method without knowing how it is implemented



Standard random implementation: shuffling the elements in an array

```
public class StdRandom {

   private static void exch(String[] a, int i, int j) {
      String temp = a[i];
      a[i] = a[j];
      a[j] = temp;
   }

   public static void shuffle(String[] a) {
      for (int i = 0; i < a.length; i++) {
         int r = uniformInt(i+1);
         exch(a, i, r);
      }
   }

   ⋮
}
```

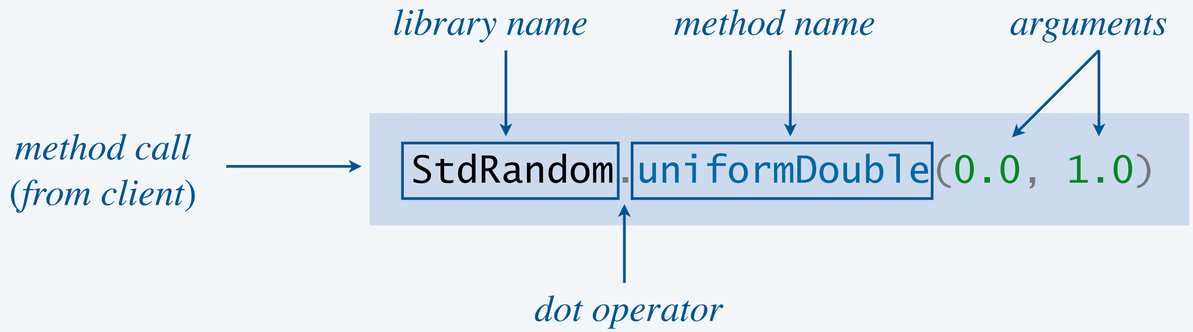


calls a `private` *method*
(in the same class)

`private` *helper method*
(cannot be called from outside this class)

Calling a library function

Calling from a client. Specify library name, dot operator, function name, and arguments.



Note. Must use fully qualified name if calling a function from another file.

Standard random clients

StdRandom client 1

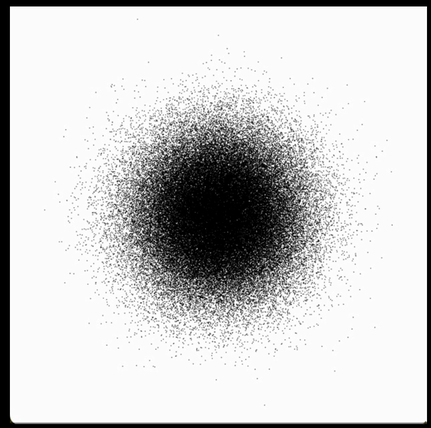
```
public class Shuffle {
   public static void main(String[] args) {
      StdRandom.shuffle(args);
      for (int i = 0; i < args.length; i++) {
         StdOut.print(args[i] + " ");
      }
      StdOut.println();
   }
}
```

```
~/cos126/libraries> java-introcs Shuffle A B C D E
E A D B C

~/cos126/libraries> java-introcs Shuffle A B C D E
C A E B D

~/cos126/libraries> java-introcs Shuffle 2C 2D 2H ... AS
4S 2D AC 9H QH 8C ... JS 4H 2S
```

StdRandom client 2

```
public class RandomPoints {
   public static void main(String[] args) {
      int n = Integer.parseInt(args[0]);
      for (int i = 0; i < n; i++) {
         double x = StdRandom.gaussian(0.5, 0.1);
         double y = StdRandom.gaussian(0.5, 0.1);
         StdDraw.point(x, y);
      }
   }
}
```

```
~/cos126/libraries> java-introcs RandomPoints 100000
```



Libraries and clients: quiz 1

What is the probability that the following code fragment prints "Paper" ?

A. 0

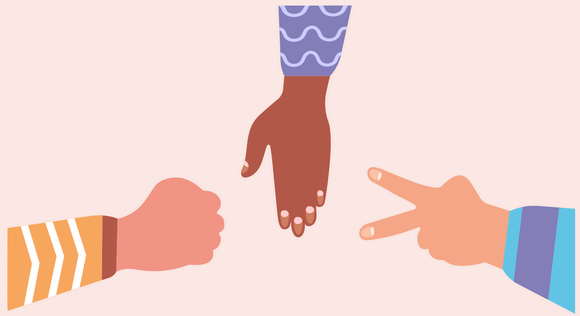
B. 2 / 9

C. 1 / 4

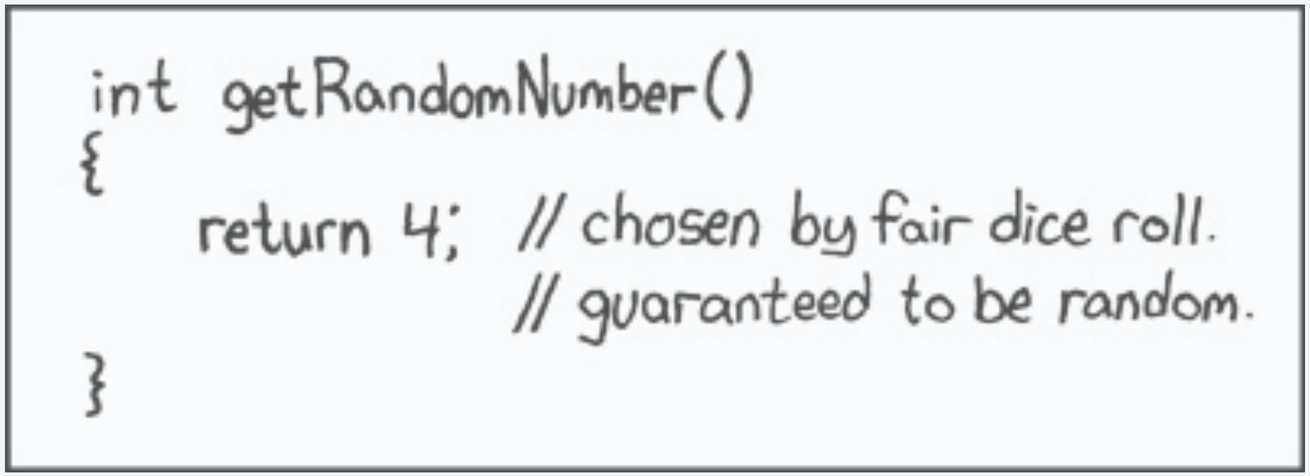
D. 1 / 3

E. 4 / 9

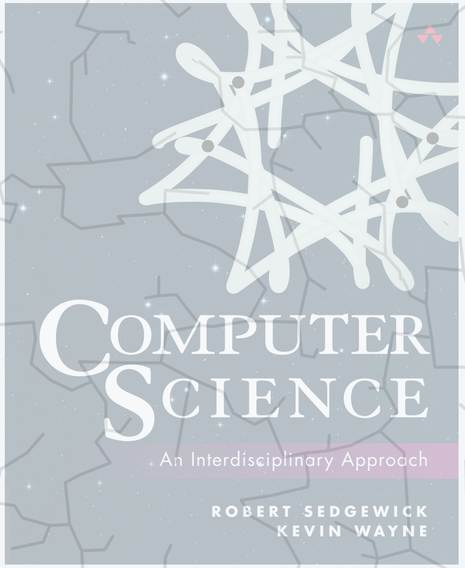
```
if (StdRandom.uniformInt(3) == 0) {
    System.out.println("Rock");
}
else if (StdRandom.uniformInt(3) == 1) {
    System.out.println("Paper");
}
else {
    System.out.println("Scissors");
}
```



Another bug...



https://xkcd.com/221/



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2.2 Libraries and Clients

- *random number library*
- *designing libraries*
- *sound synthesis*
- *synthesizer library*

Libraries

Def. A module is a set of functions stored in a single file.

Def. A library is a module whose primary purpose is for use by other programs.

← *definitions for this course*

library	description	example method call	source	logo
StdRandom	*generate random numbers*	`StdRandom.uniformInt(6)`	textbook	
StdDraw	*draw geometric shapes*	`StdDraw.circle(0.5, 0.5, 0.25)`		
Math	*compute mathematical functions*	`Math.sqrt(2.0)`	Java system	
java.util.Arrays	*manipulate arrays*	`Arrays.sort(a)`		
Gaussian	*compute Gaussian pdf and cdf*	`Gaussian.pdf(3.0)`	user-defined	
SayNumber	*speak numbers*	`SayNumber.sayInteger(126)`		
⋮	⋮		⋮	

API, client, and implementation

Application programming interface (API). Specifies method headers and behavior for a library.

Implementation. Program that implements the methods in an API.

Client. Program that uses a library through its API.

contract between client and implementation

client

```
StdRandom.uniformInt(6);

StdRandom.shuffle(args);
```

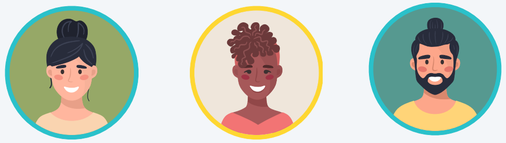
API

```
public class StdRandom
static int  uniformInt(int n)
static void shuffle(String[] a)
      ⋮
```

implementation

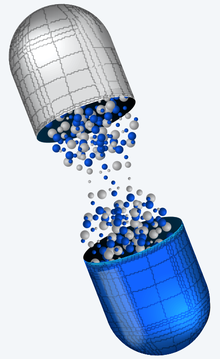
```
public class StdRandom {
   ...
   public static int uniformInt(int n) {
      ...
   }

   public static void shuffle(String[] a) {
      ...
   }
}
```



Encapsulation

Encapsulation. Separating clients from implementation details by hiding information.



Principle. A client does not need to know how a method is implemented in order to use it.

Benefits.

- Can develop client code and implementation code independently.
- Can change implementation details without breaking clients.

Private access modifier. Designates a method as not for use by a client.

- API does not list *private* methods.
- Compile-time error for client to call a *private* method.
- Advantage: implementation can add/remove *private* methods without impacting clients.

Accessing a library

Java classpath. Places where Java looks for user-defined libraries (and other resources).

- Simplest: put library `.class` file in same directory as client program.
- Best practice: bundle library `.class` files in a `.jar` file; add `.jar` file to Java classpath.

`stdlib.jar` *contains*:
`StdRandom.class`
`StdIn.class`
`StdOut.class`
`StdDraw.class`
`StdPicture.class`
`StdAudio.class`
⋮

```
~/cos126/libraries> javac Shuffle.java
Shuffle.java:3: error: cannot find symbol
      StdRandom.shuffle(args);

~/cos126/libraries> javac-introcs Shuffle.java

~/cos126/libraries> java-introcs Shuffle A B C D E
C A E B D
```

adds `stdlib.jar` *to Java classpath*

Unit testing

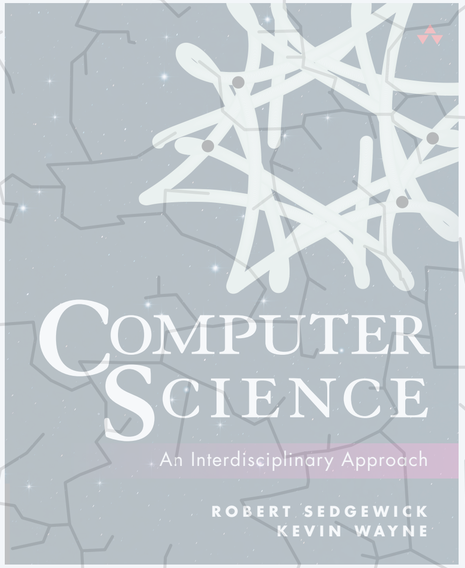
Best practice. Include a *main()* method in each class as a test client.

- Call each public method at least once.
- Use result to check behavior.
- Identify failed tests programmatically.

minimum requirements (in this course)

```
public class StdRandom {
   ⋮
   public static void main(String[] args) {
      int n = Integer.parseInt(args[0]);
      for (int i = 0; i < n; i++) {
         StdOut.printf("%8.5f ", uniformDouble(10.0, 99.0));
         StdOut.printf("%5b "  , bernoulli(0.5));
         StdOut.printf("%2d "  , uniformInt(100));
         StdOut.printf("%7.5f ", gaussian(9.0, 0.2));
         StdOut.println();
      }
      ⋮
   }
}
```

unit tests for `shuffle()` *and other methods*



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2.2 Libraries and Clients

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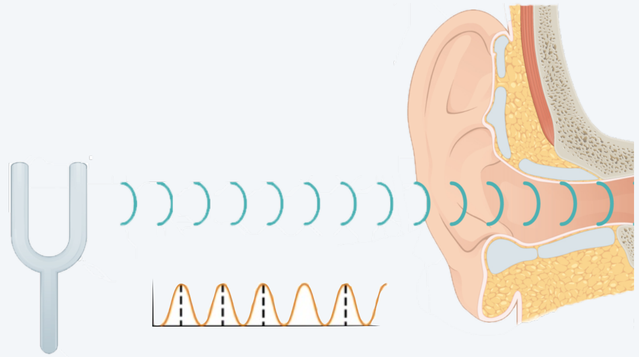
- *synthesizer library*

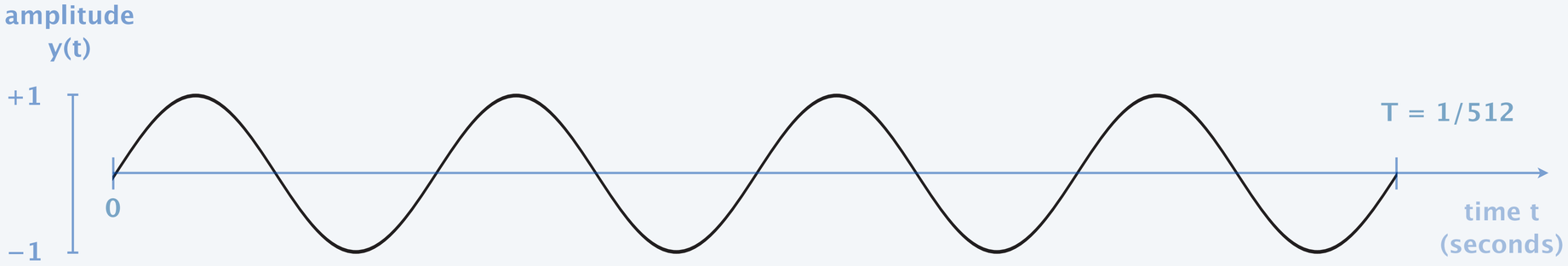
Review: digital audio

Sound is the perception the vibration of our eardrums.



Audio signal. Real-valued (between -1 and $+1$) function of time.

Pure tone. Sound wave defined by the sine function of given *frequency*, *amplitude* and *duration*.



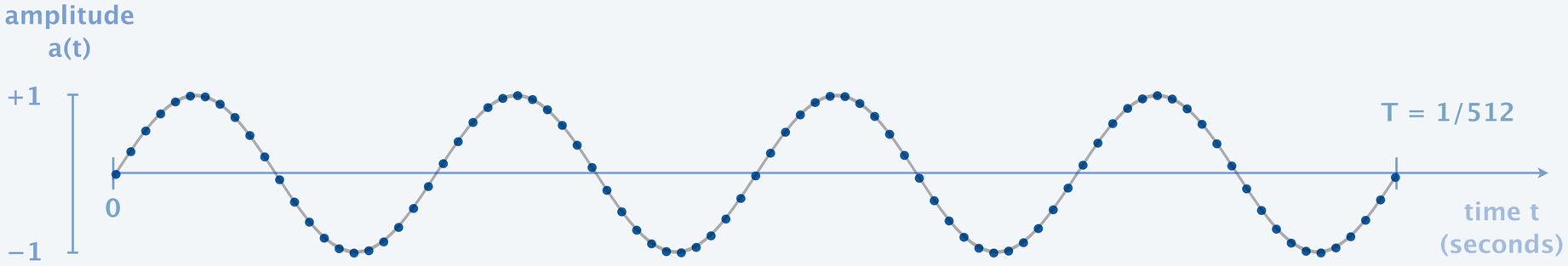
$$y(t) = \sin(2\pi \cdot 2048 \cdot t), \quad 0 \le t \le T$$

Review: 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)



$$y(t) = \sin(2\pi \cdot 2048 \cdot t), \quad 0 \le t \le T$$

$$a(t) = \sin(2\pi \cdot 2048 \cdot t), \quad t = \frac{0}{44100}, \frac{1}{44100}, \frac{2}{44100}, \ldots$$

Review: standard audio API

StdAudio. Our library for playing, reading, and saving digital audio.

`public class StdAudio`

`static int`	`SAMPLE_RATE`	44,100 (*CD quality audio*)
`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*
`static void`	`save(String filename, double[] samples)`	*save the samples to an audio file*
	⋮	⋮

Sine wave implementation

implementation

```
public class Synth {

   public static int numberOfSamples(double duration) {
      return (int) (StdAudio.SAMPLE_RATE * duration);
   }

   private static double sine(double freq, double t) {
      return Math.sin(2 * Math.PI * freq * t);
   }

   public static double[] sineWave(double freq, double amplitude, double duration) {
      int n = numberOfSamples(duration);
      double[] a = new double[n];
      for (int i = 0; i < n; i++) {
         double t = 1.0 * i / StdAudio.SAMPLE_RATE;
         a[i] = amplitude * sine(freq, t);
      }
      return a;
   }

}
```

utility method

for internal use only
(`private` helper methods)

sample at n equally spaced points

$$a(t) = A \sin\left(2\pi \cdot f \cdot t\right), \quad t = \frac{0}{44100}, \frac{1}{44100}, \frac{2}{44100}, \ldots$$

client

```
double[] a = Synth.sineWave(2048.0, 0.5, 3.0);
StdAudio.play(a);
```

Libraries and clients: quiz 2

What sound will the following code fragment produce?

```
double freq = 17400.0;
double amplitude = 0.5;
double duration = 10.0;
double[] a = Synth.sineWave(freq, amplitude, duration);
StdAudio.play(a);
```

A. Extremely high-pitched sound.

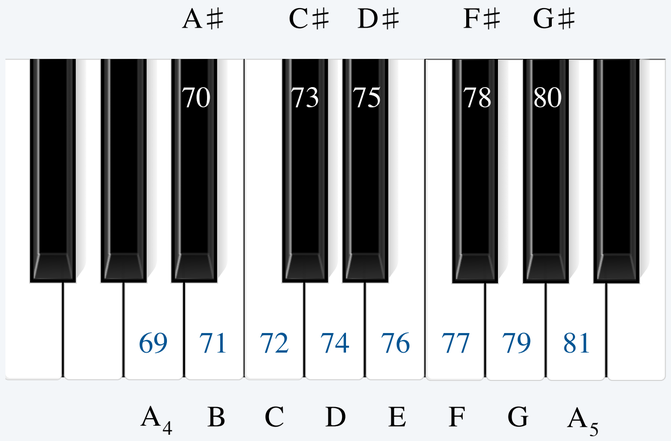
B. Inaudible.

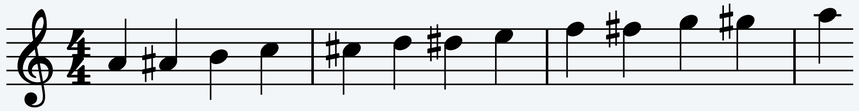
C. Ultrasonic weapon.

D. All of the above.

Crash course in Western music

- Concert A is 440 Hz.
- An octave is the interval between a note and one with twice its frequency.
- Octave is divided into 12 notes on a logarithmic scale. ⟵ *"twelve-tone equal temperament"*





note	MIDI (m)	frequency (Hz) $(440 \times 2^{(m-69)/12})$	sine wave
A_4	69	440	
A♯ / B♭	70	466.16	
B	71	493.88	
C	72	523.25	
C♯ / D♭	73	554.37	
D	74	587.33	
D♯ / E♭	75	622.25	
E	76	659.26	
F	77	698.46	
F♯ / G♭	78	739.99	
G	79	783.99	
G♯ / A♭	80	830.61	
A_5	81	880	

Libraries and clients: quiz 3

Which of the following converts from MIDI note number to frequency?

A.

```
private static double midiToFrequency(int midi) {
   return 440 * Math.pow(2, (midi - 69) / 12);
}
```

B.

```
private static double midiToFrequency(int midi) {
   return 440.0 * 2.0 ^ ((midi - 69.0) / 12.0);
}
```

$$frequency = 440 \times 2^{(midi - 69) / 12}$$

C. Both A and B.

D. Neither A nor B.

MIDI-number-to-frequency conversion

Goal. Add methods (and constants) to library that many clients might want to use.

Musical Instrument Digital Interface (MIDI). Digital music standard.

Class constant.

- Declare and initialize "variable" outside of any method, using *final* and *static* modifiers.
- Access modifier can be *public* or *private*.
- Java naming convention: use *SCREAMING_SNAKE_CASE*.

```
public class Synth {
   public static final double CONCERT_A = 440.0;

   private static double midiToFrequency(int midi) {
      return CONCERT_A * Math.pow(2, (midi - 69) / 12.0);
   }

   ...
}
```

class constant (`static` *variable*)

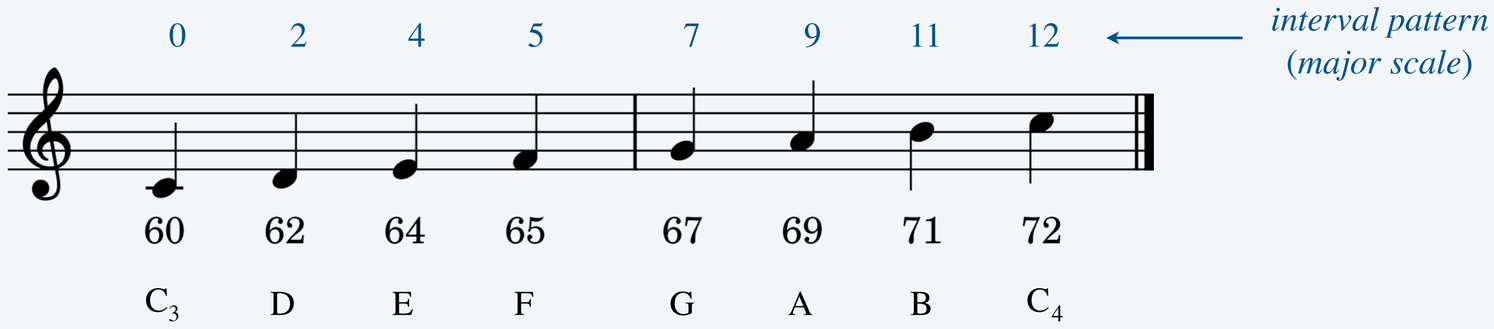
$$frequency = 440 \times 2^{(midi - 69) / 12}$$

implementation

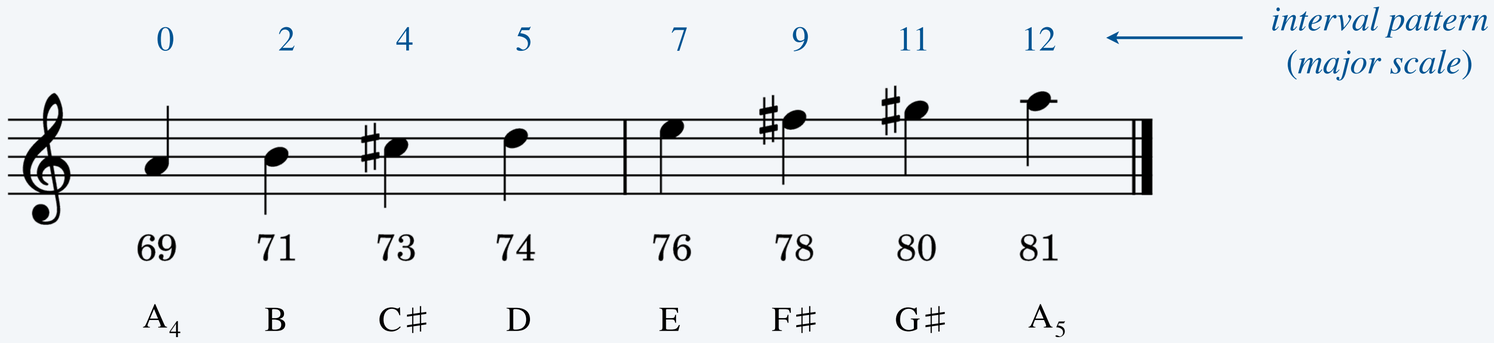
Musical scales

Major scale. Sequence of 8 notes in a specific interval pattern, starting with a root note and ending with the same note one octave higher.

Ex 1. C major scale.



Ex 2. A major scale.



Musical scales

Major scale. Sequence of 8 notes in a specific interval pattern, starting with a root note and ending with the same note one octave higher.

```
public class MajorScale {
   public static void main(String[] args) {
      int root = Integer.parseInt(args[0]);
      double duration = 0.5;
      double amplitude = 0.5;
      int[] pattern = { 0, 2, 4, 5, 7, 9, 11, 12 };
      for (int i = 0; i < pattern.length; i++) {
         int midi = root + pattern[i];
         double freq = Synth.midiToFrequency(midi);
         double[] a = Synth.sineWave(freq, amplitude, duration);
         StdAudio.play(a);
      }
   }
}
```

client

interval pattern (major scale)

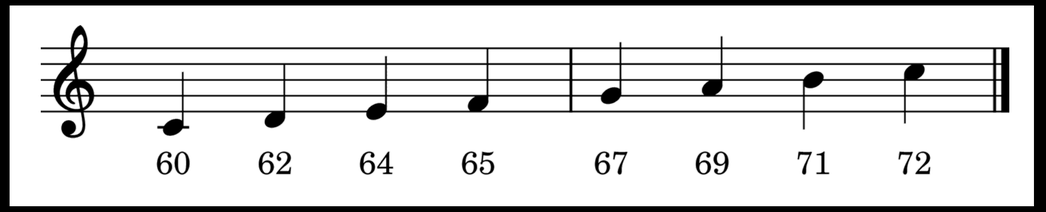
```
~/cos126/libraries> java-introcs MajorScale 60
[plays A major scale]

~/cos126/libraries> java-introcs MajorScale 69
[plays C major scale]
```

Play that tune

Goal. Read in a sequence of MIDI note numbers and durations from standard input, and play the synthesized results to standard audio.

```
~/cos126/libraries> more MajorScaleC.txt
60 0.5
62 0.5
64 0.5
65 0.5
67 0.5
69 0.5
71 0.5
72 0.5
```

duration (seconds)



MIDI note number

```
~/cos126/libraries> java-introcs PlayThatTune < MajorScaleC.txt
```

[plays C major scale]

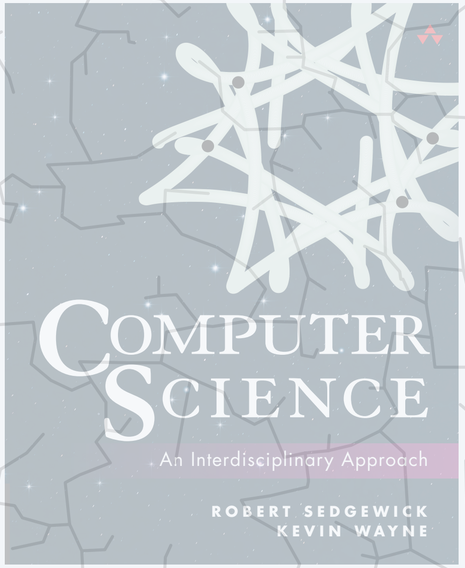
Play that tune

Goal. Read in a sequence of MIDI note numbers and durations from standard input, and play the synthesized results to standard audio.

client

```
public class PlayThatTune {
   public static void main(String[] args) {
      double amplitude = 0.5;
      while (!StdIn.isEmpty()) {
         int midi = StdIn.readInt();
         double duration = StdIn.readDouble();
         double freq = Synth.midiToFrequency(midi);
         double[] a = Synth.sineWave(freq, amplitude, duration);
         StdAudio.play(a);
      }
   }
}
```

```
~/cos126/libraries> java-introcs PlayThatTune < Arpeggio.txt
[plays arpeggio]

~/cos126/libraries> java-introcs PlayThatTune < LooneyTunes.txt
[plays Looney Tunes theme]

~/cos126/libraries> java-introcs PlayThatTune < FurElise.txt
[plays beginning of Fur Elise]
```



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2.2 Libraries and Clients

- *random number library*
- *designing libraries*
- *sound synthesis*
- *synthesizer library*

Digital synthesizers

Digital synth. Electronic musical instrument that generates audio signals digitally.

- Sound effects.
- Film and television soundtracks.
- Diverse genres of music (rock, jazz, pop, disco, hip-hop, electronic music, ...).
- ...

R2-D2
(Star Wars)

Axel F
(Harold Faltemeyer)

Synthesizer API

Synth. A library for synthesizing sound.

```
public class Synth
```

`static int CONCERT_A`	440.0 (*concert A pitch in Hz*)
`static int numberOfSamples(double duration)`	*number of audio samples*
`static double midiToFrequency(int midi)`	*frequency of MIDI note number*

utility methods

`static double sineWave(double freq, double amplitude, double duration)`	*sine wave*
`static double squareWave(double freq, double amplitude, double duration)`	*square wave*
`static double sawWave(double freq, double amplitude, double duration)`	*saw wave*
`static double supersawWave(double freq, double amplitude, double duration)`	*supersaw wave*
`static double whiteNoise( double amplitude, double duration)`	*white noise*

create sound waves

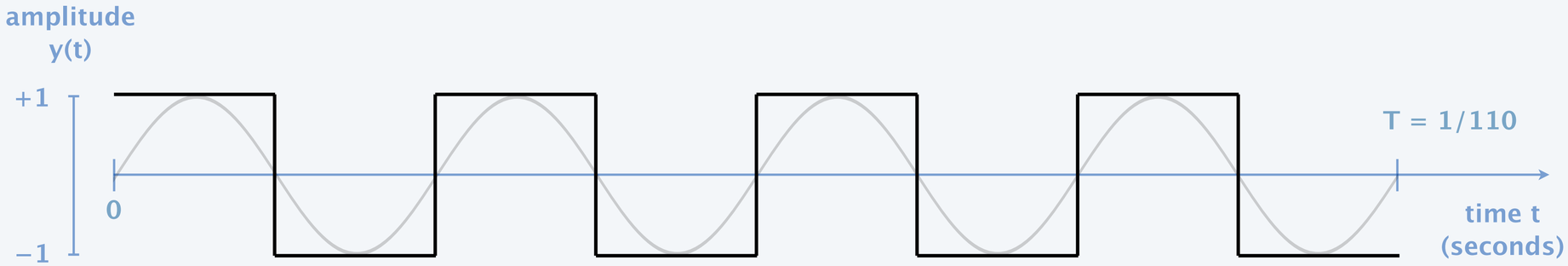
`static double[] superpose(double[] a, double[] b)`	*add the two waves*
`static double[] modulate(double[] a, double[] b)`	*multiply the two waves*
`static double[] fadeIn(double[] a, double lambda)`	*exponential fade in*
`static double[] fadeOut(double[] a, double lambda)`	*exponential fade out*

manipulate sound waves

⋮ ⋮

Square waves

Square wave. Alternates between +1 and −1 with frequency f, half the time at each value.



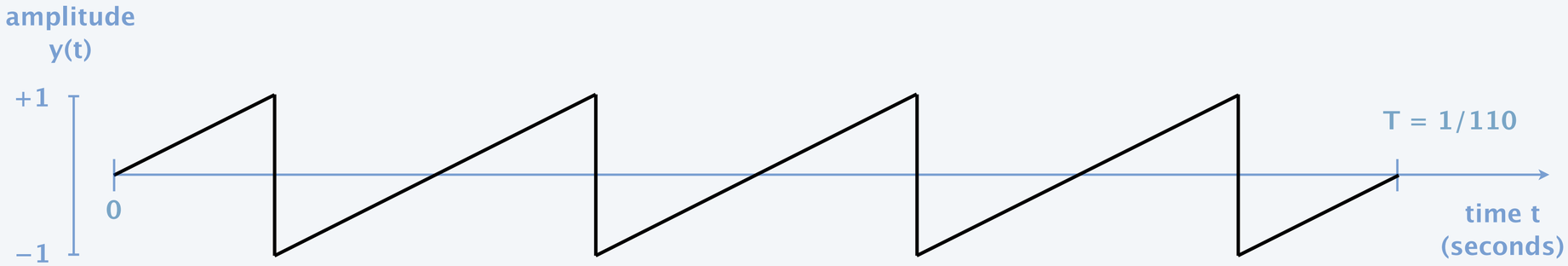
$$a(t) = sgn\left(\sin(2\pi \cdot 440 \cdot t)\right), \quad 0 \le t \le T \qquad sgn(x) = \begin{cases} -1 & \text{if } x < 0 \\ 0 & \text{if } x = 0 \\ +1 & \text{if } x > 0 \end{cases}$$

implementation

```
private static double square(double freq, double t) {
   return Math.signum(sine(freq, t));
}

public static double[] squareWave(double freq, double amplitude, double duration) {
   /* similar to sineWave() */
}
```

Sawtooth waves

Sawtooth wave. Rises from -1 to $+1$ linearly, then drops back to -1, and repeats with frequency f.



$$a(t) = 2\left(440\,t - \left\lfloor 440\,t + \tfrac{1}{2}\right\rfloor\right), \quad 0 \le t \le T$$

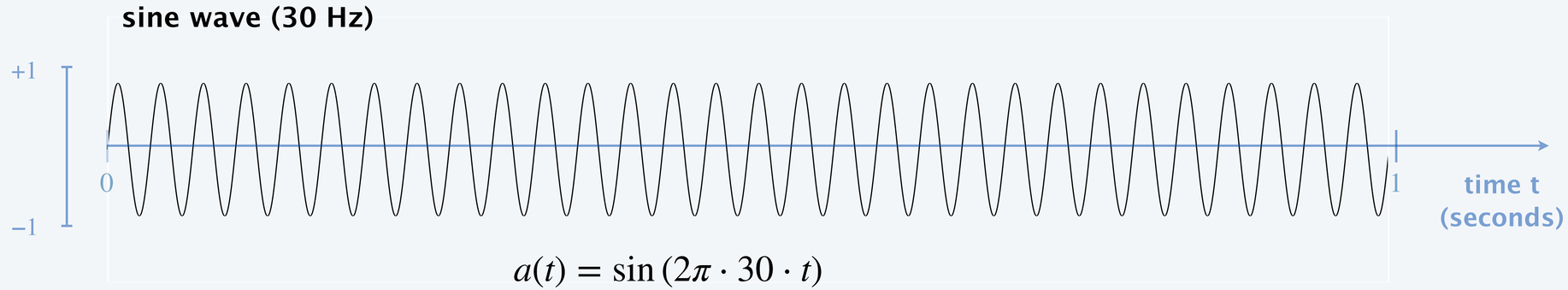
implementation

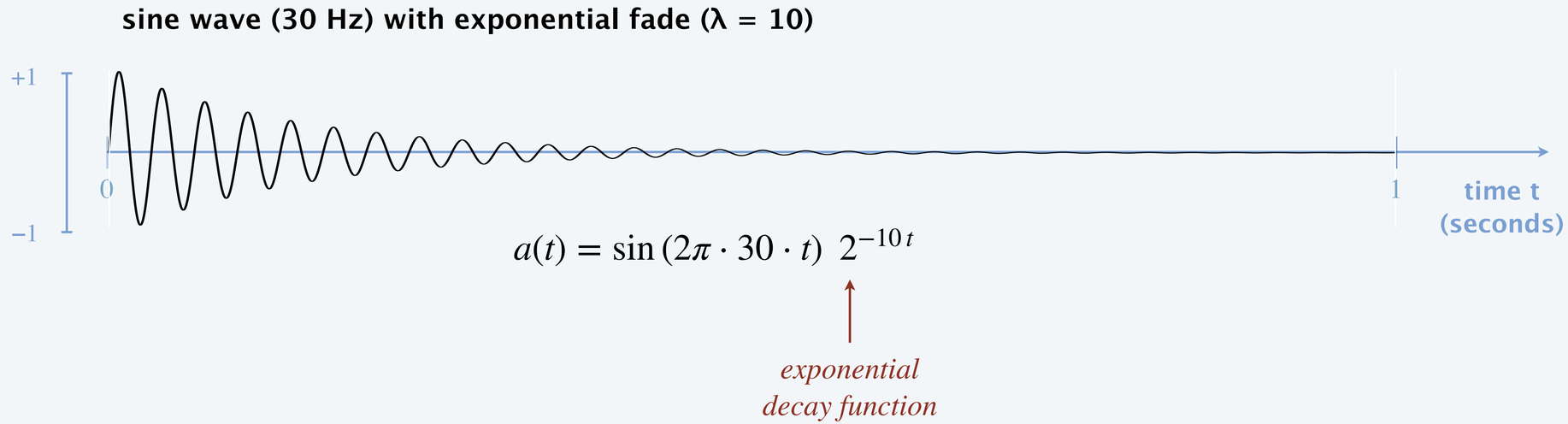
```
private static double saw(double freq, double t) {
   return 2 * (freq*t - Math.floor(freq*t + 0.5));
}

public static double[] sawWave(double freq, double amplitude, double duration) {
   /* similar to sineWave() */
}
```

Exponential fade

Sound envelope. Defines how a sound changes over time.

Exponential fade. A sound envelope whose amplitude decays according to exponential function.





Exponential fade

implementation

```
public class Synth {

   public static double[] fadeOut(double[] a, double lambda) {
      int n = a.length;
      double[] result = new double[n];
      for (int i = 0; i < n; i++) {
         double t = 1.0 * i / StdAudio.SAMPLE_RATE;
         result[i] = a[i] *  Math.pow(2.0, -lambda * t);
      }
      return result;
   }

}
```

client

```
while (true) {
   double[] a = Synth.sineWave(440.0, 0.5, 1.0);
   double[] b = Synth.fadeOut(a, 10.0);
   StdAudio.play(b);
}
```

client

```
while (true) {
   double[] a = Synth.squareWave(55.0, 0.25, 1.0);
   double[] b = Synth.fadeOut(a, 5.0);
   StdAudio.play(b);
}
```

Libraries and clients: quiz 4

What sound does *StdAudio.play*(*mystery*(5.0)) **produce?**

A. 5 seconds of concert A (440 Hz).

B. 5 seconds of a random frequency.

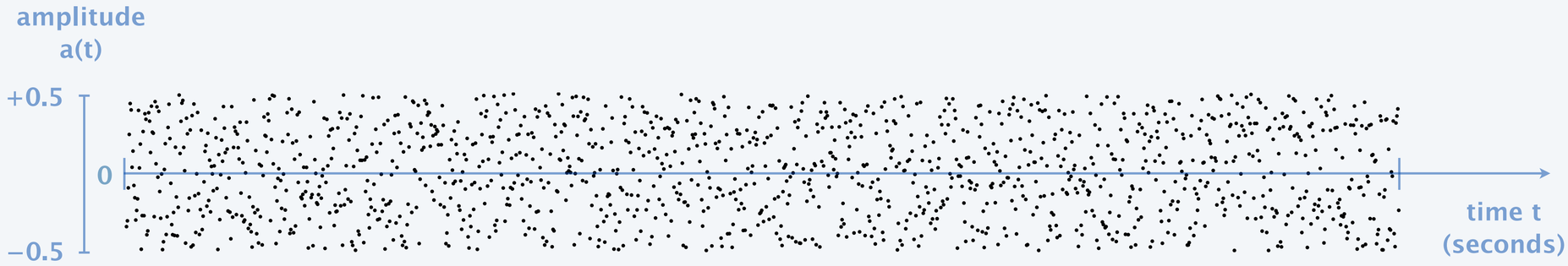
C. 5 seconds of silence.

D. 5 seconds of static.

```
public static double[] mystery(double duration) {
   int n = numberOfSamples(duration);
   double[] a = new double[n];
   for (int i = 0; i < n; i++) {
      a[i] = StdRandom.uniformDouble(-0.5, 0.5);
   }
   return a;
}
```

White noise

White noise. Samples are uniformly random values.



implementation

```
public static double[] whiteNoise(double amplitude, double duration) {
   int n = numberOfSamples(duration);
   double[] a = new double[n];
   for (int i = 0; i < n; i++) {
      a[i] = StdRandom.uniformDouble(-amplitude, +amplitude);
   }
   return a;
}
```

client

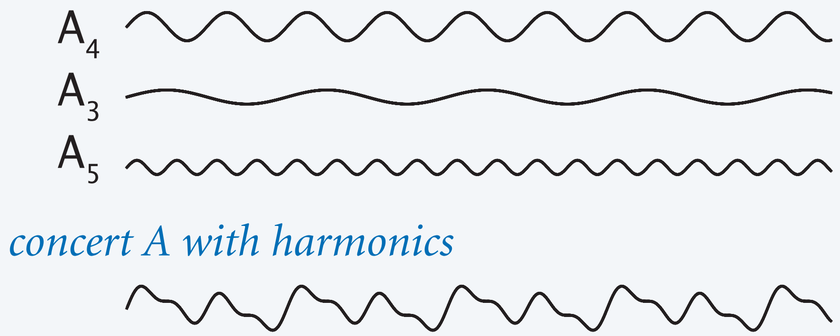
```
while (true) {
   double[] a = Synth.whiteNoise(0.5, 1.0);
   double[] b = Synth.fadeOut(a, 20.0);
   StdAudio.play(b);
}
```

Superposition

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

Ex 1. Harmonics.

```
double duration = 5.0;
double[] a4 = Synth.sineWave(440.0, 0.50, duration);
double[] a3 = Synth.sineWave(220.0, 0.25, duration);
double[] a5 = Synth.sineWave(880.0, 0.25, duration);
double[] harmonics = Synth.superpose(a4, a3, a5);
StdAudio.play(harmonics);
```



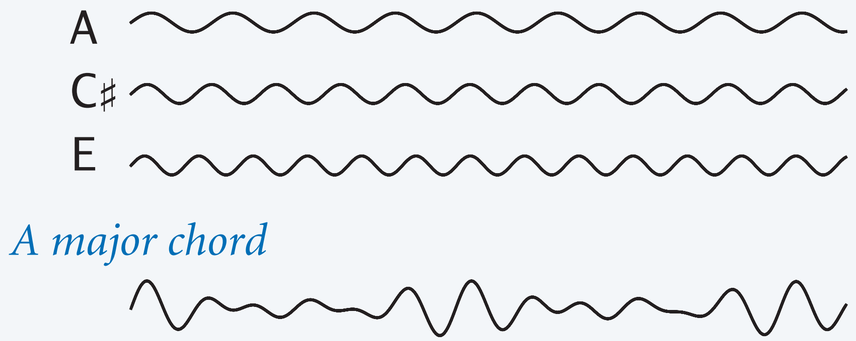
Superposition

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

Ex 1. Harmonics.

Ex 2. Chord.

```
double duration = 5.0;
double[] a4 = Synth.sineWave(440.00, 0.33, duration);
double[] c5 = Synth.sineWave(554.37, 0.33, duration);
double[] e5 = Synth.sineWave(659.26, 0.33, duration);
double[] chord = Synth.superpose(a4, c5, e5);
StdAudio.play(chord);
```



Superposition

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

Ex 1. Harmonics.

Ex 2. Chord.

Ex 3. Supersaw.

```
double freq = 220.0;
double amplitude = 0.05;
double duration = 10.0;
double[] a0 = Synth.sawWave(freq,         amplitude, duration);
double[] a1 = Synth.sawWave(freq - 0.191, amplitude, duration);
double[] a2 = Synth.sawWave(freq - 0.109, amplitude, duration);
double[] a3 = Synth.sawWave(freq - 0.037, amplitude, duration);
double[] a4 = Synth.sawWave(freq + 0.031, amplitude, duration);
double[] a5 = Synth.sawWave(freq + 0.107, amplitude, duration);
double[] a6 = Synth.sawWave(freq + 0.181, amplitude, duration);
double[] supersaw = Synth.superpose(a0, a1, a2, a3, a4, a5, a6);
StdAudio.play(supersaw);
```

"detuned" frequencies

Slay that tune

Goal. Play that tune, but with a supersaw.

client

```
public class SlayThatTune {
   public static void main(String[] args) {
      double amplitude = 0.5;
      while (!StdIn.isEmpty()) {
         int midi = StdIn.readInt();
         double duration = StdIn.readDouble();
         double freq = Synth.midiToFrequency(midi - 12);
         double[] a = Synth.supersawWave(freq, amplitude, duration);
         StdAudio.play(a);
      }
   }
}
```

transpose one octave lower

```
~/cos126/libraries> java-introcs SlayThatTune < Arpeggio.txt
[plays arpeggio]

~/cos126/libraries> java-introcs SlayThatTune < AxelF.txt
[plays beginning of Axel F]
```

Synth library

implementation

```
public class Synth {
   public static final double CONCERT_A = 440.0;

   public static int    numberOfSamples(double duration) { ... }
   public static double midiToFrequency(int midi)        { ... }

   private static double   sine(double freq, double t)  { ... }
   private static double square(double freq, double t)  { ... }
   private static double    saw(double freq, double t)  { ... }

   public static double[]     sineWave(double freq, double amplitude, double duration) { ... }
   public static double[]   squareWave(double freq, double amplitude, double duration) { ... }
   public static double[]      sawWave(double freq, double amplitude, double duration) { ... }
   public static double[] supersawWave(double freq, double amplitude, double duration) { ... }
   public static double[]   whiteNoise(             double amplitude, double duration) { ... }

   public static double[] superpose(double[] a, double[] b)          { ... }
   public static double[]  modulate(double[] a, double[] b)          { ... }
   public static double[]    fadeIn(double[] a, double lambda)       { ... }
   public static double[]   fadeOut(double[] a, double lambda)       { ... }

   public static void main(String[] args) { ... }

}
```

utility methods

private helper methods

create sound waves

manipulate sound waves

Summary

API. Defines method headers and behavior for a library.

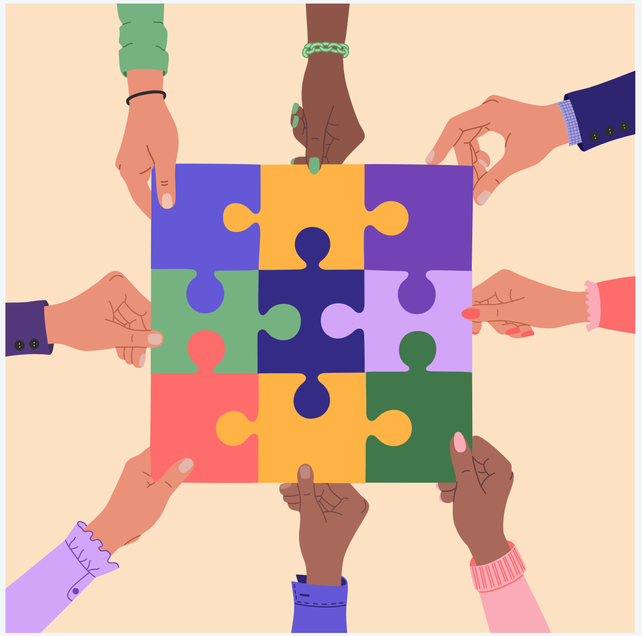
Client. Program that calls a library's methods.

Implementation. Program that implements the library's functionality.

Encapsulation. Separating clients from implementation details by hiding information.

Benefits.

- Reusable libraries.
- Independent development of small programs.
- Collaboration with a team of programmers.



Sound synthesis. You can write programs to synthesize sound.

Credits

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Family 1 *Watching TV*	Adobe Stock	education license
Family 2 *Watching TV*	Adobe Stock	education license
Family 3 *Watching TV*	Adobe Stock	education license

Credits

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