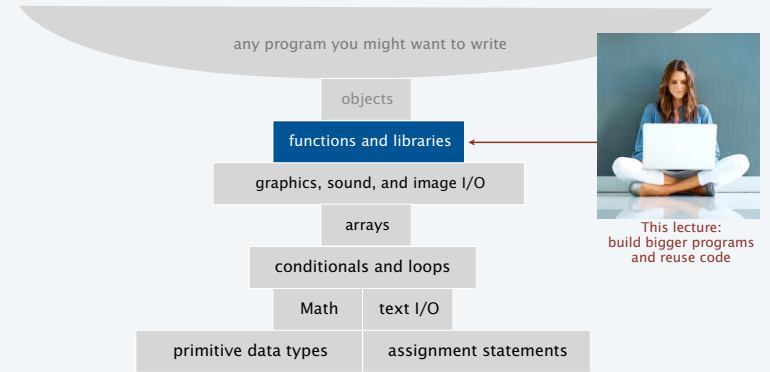


## 6. Functions and Libraries

### Context: basic building blocks for programming



### Functions, libraries, and modules

#### Modular programming

- Organize programs as independent **modules** that do a job together.
- Why? Easier to **reuse code** and build bigger programs.



#### Facts of life

- Support of modular programming has been a holy grail for decades.
- Ideas can conflict and get highly technical in the real world.

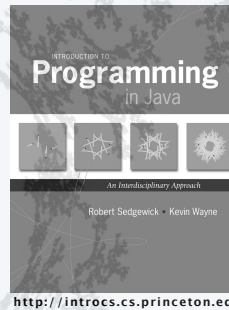
Def. A **library** is a set of functions.

↑  
for purposes of this lecture

Def. A **module** is a .java file.

↑  
for purposes of this course

For now. Libraries and modules are the *same thing*: .java files containing sets of functions.



## 6. Functions and Libraries

- **Basic concepts**
- Case study: Digital audio
- Application: Gaussian distribution
- Modular programming and libraries

## Functions (static methods)

### Java function ("aka *static method*")

- Takes zero or more input arguments.
- Returns zero or one output value.
- May cause side effects (e.g., output to standard draw).

Java functions are *more general* than mathematical functions

### Applications

- Scientists use mathematical functions to calculate formulas.
- Programmers use functions to build modular programs.
- *You* use functions for both.

### Examples seen so far

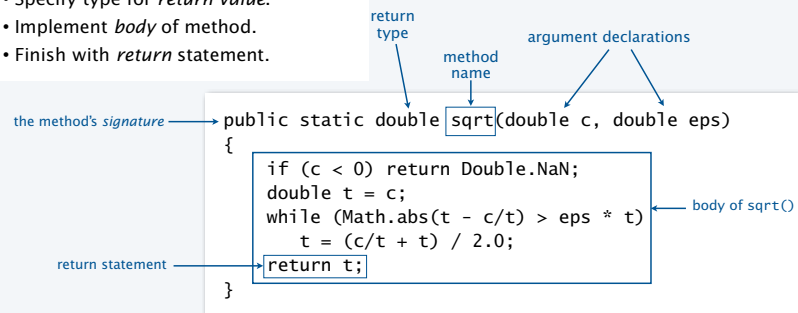
- Built-in functions: `Math.random()`, `Math.abs()`, `Integer.parseInt()`.
- Our I/O libraries: `StdIn.readInt()`, `StdDraw.line()`, `StdAudio.play()`.
- User-defined functions: `main()`.

5

## Anatomy of a Java static method

### To implement a function (static method)

- Create a *name*.
- Declare type and name of *argument(s)*.
- Specify type for *return value*.
- Implement *body* of method.
- Finish with *return* statement.



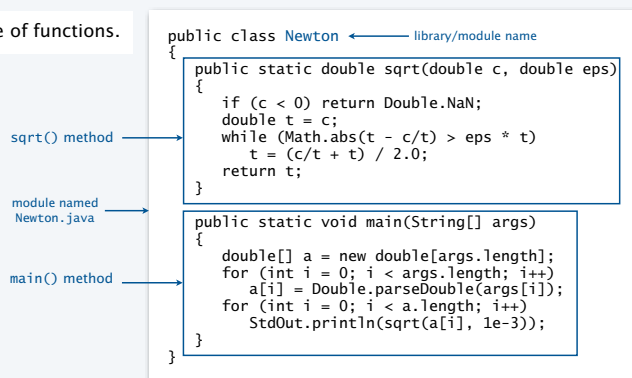
6

## Anatomy of a Java library

A **library** is a sequence of functions.

Note: We are using our own implementation of `sqrt()` here to illustrate the basics with a familiar function.

You can use `Math.sqrt()`.

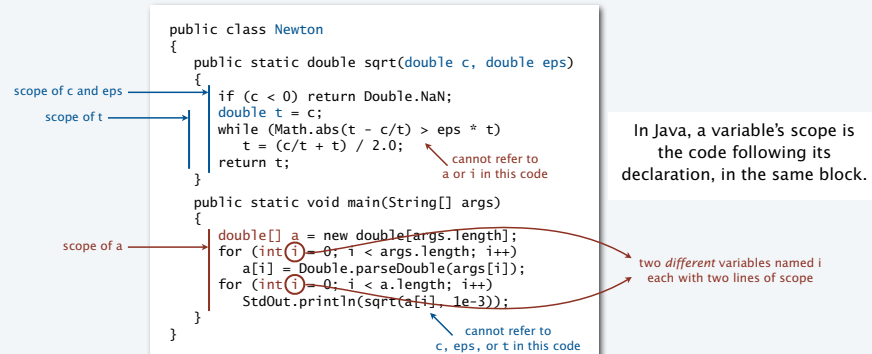


**Key point.** Functions provide a *new way* to control the flow of execution.

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## Scope

Def. The **scope** of a variable is the code that can refer to it by name.



In Java, a variable's scope is the code following its declaration, in the same block.

**Best practice.** Declare variables so as to *limit* their scope.

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## Flow of control

```

public class Newton
{
    public static double sqrt(double c, double eps)
    {
        if (c < 0) return Double.NaN;
        double t = c;
        while (Math.abs(t - c/t) > eps * t)
            t = (c/t + t) / 2.0;
        return t;
    }
    public static void main(String[] args)
    {
        double[] a = new double[args.length];
        for (int i = 0; i < args.length; i++)
            a[i] = Double.parseDouble(args[i]);
        for (int i = 0; i < a.length; i++)
        {
            double x = sqrt(a[i], 1e-3);
            StdOut.println(x);
        }
    }
}

```

### Summary of flow control for a call

- Control transfers to the function code.
- Argument variables are declared and initialized with the given values.
- Function code is executed.
- Control transfers back to the calling code (with return value assigned in place of the function name in the calling code)..

"pass by value"  
(other methods used in other systems)

Note. OS calls main() on java command

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## Function call flow of control trace

```

public class Newton
{
    public static double sqrt(double c, double eps)
    {
        if (c < 0) return Double.NaN;
        double t = c;
        while (Math.abs(t - c/t) > eps * t)
            t = (c/t + t) / 2.0;
        return t;
    }
    public static void main(String[] args)
    {
        double[] a = new double[args.length];
        for (int i = 0; i < args.length; i++)
            a[i] = Double.parseDouble(args[i]);
        for (int i = 0; i < a.length; i++)
        {
            double x = sqrt(a[i], 1e-3);
            StdOut.println(x);
        }
    }
}

```

c	t
3.0	3.0
	2.0
	1.75
	1.732

i	a[i]	x
0	1.0	1.000
1	2.0	1.414
2	3.0	1.732
3		

```

% java Newton 1 2 3
1.000
1.414
1.732

```

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## TEQ 1a on functions

Q. What happens when you compile and run the following code?

```

public class TEQ6_1a
{
    public static int cube(int i)
    {
        int j = i * i * i;
        return j;
    }
    public static void main(String[] args)
    {
        int N = Integer.parseInt(args[0]);
        for (int i = 1; i <= N; i++)
            StdOut.println(i + " " + cube(i));
    }
}

```

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## TEQ 1b on functions

Q. What happens when you compile and run the following code?

```

public class TEQ6_1b
{
    public static int cube(int i)
    {
        int i = i * i * i;
        return i;
    }
    public static void main(String[] args)
    {
        int N = Integer.parseInt(args[0]);
        for (int i = 1; i <= N; i++)
            StdOut.println(i + " " + cube(i));
    }
}

```

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## TEQ 1c on functions

Q. What happens when you compile and run the following code?

```
public class TEQ6_1c
{
    public static int cube(int i)
    {
        i = i * i * i;
    }
    public static void main(String[] args)
    {
        int N = Integer.parseInt(args[0]);
        for (int i = 1; i <= N; i++)
            StdOut.println(i + " " + cube(i));
    }
}
```

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## TEQ 1d on functions

Q. What happens when you compile and run the following code?

```
public class TEQ6_1d
{
    public static int cube(int i)
    {
        i = i * i * i;
        return i;
    }
    public static void main(String[] args)
    {
        int N = Integer.parseInt(args[0]);
        for (int i = 1; i <= N; i++)
            StdOut.println(i + " " + cube(i));
    }
}
```

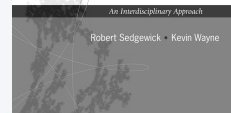
14

## TEQ 1e on functions

Q. What happens when you compile and run the following code?

```
public class TEQ6_1e
{
    public static int cube(int i)
    {
        return i * i * i;
    }
    public static void main(String[] args)
    {
        int N = Integer.parseInt(args[0]);
        for (int i = 1; i <= N; i++)
            StdOut.println(i + " " + cube(i));
    }
}
```

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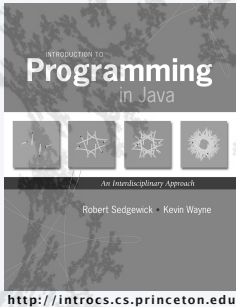


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## 6. Functions and Libraries

- **Basic concepts**
- Case study: Digital audio
- Application: Gaussian distribution
- Modular programming and libraries





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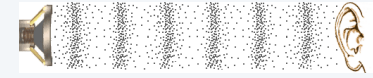
## 6. Functions and Libraries

- Basic concepts
- Case study: Digital audio
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- Modular programming

## Crash course in sound

Sound is the perception of the vibration of molecules in our eardrums.

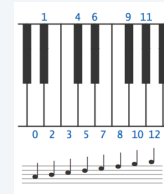
A musical tone is a steady periodic sound.



A pure tone is a sinusoidal waveform.

### Western musical scale

- Concert A is 440 Hz.
- 12 notes, logarithmic scale.



pitch	$i$	frequency ( $440 \cdot 2^{i/12}$ )	sinusoidal waveform
A	0	440.00	
A# / Bb	1	466.16	
B	2	493.88	
C	3	523.25	
C# / Db	4	554.37	
D	5	587.33	
D# / Eb	6	622.25	
E	7	659.26	
F	8	698.46	
F# / Gb	9	739.99	
G	10	783.99	
G# / Ab	11	830.61	
A	12	880.00	

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## Digital audio

To represent a wave, *sample* at regular intervals and save the values in an array. ← same as when plotting a function (previous lecture)

	samples/sec	samples	sampled waveform
1/40 second of concert A	5,512	137	
	11,025	275	
	22,050	551	
CD standard	44,100	1102	

Bottom line. You can write programs to manipulate sound (arrays of double values).

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## StdAudio library

Developed for this course, also broadly useful

- Play a sound wave (array of double values) on your computer's audio output.
- Convert to and from standard .wav file format.

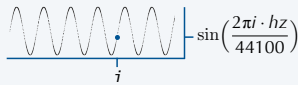
API	Method	Description
	<code>public class StdAudio</code>	
	<code>void play(String file)</code>	play the given .wav file
	<code>void play(double[] a)</code>	play the given sound wave
	<code>void play(double x)</code>	play the sample for 1/44100 second
	<code>void save(String file, double[] a)</code>	save to a .wav file
	<code>double[] read(String file)</code>	read from a .wav file

Enables you to hear the results of your programs that manipulate sound.

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## "Hello, World" for StdAudio

```
public class PlayThatNote
{
    public static double[] tone(double hz, double duration)
    {
        int N = (int) (44100 * duration);
        double[] a = new double[N+1];
        for (int i = 0; i <= N; i++)
            a[i] = Math.sin(2 * Math.PI * i * hz / 44100);
        return a;
    }
    public static void main(String[] args)
    {
        double hz = Double.parseDouble(args[0]);
        double duration = Double.parseDouble(args[1]);
        double[] a = tone(hz, duration);
        StdAudio.play(a);
    }
}
```



```
% java PlayThatNote 440 3
```

```
% java PlayThatNote 880 3
```

```
% java PlayThatNote 220 3
```

```
% java PlayThatNote 494 3
```

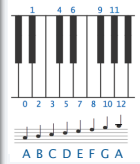
21

## Play that tune

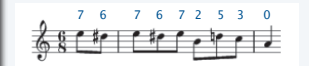
Read a list of tones and durations from standard input to **play a tune**.

```
public class PlayThatTune
{
    public static void main(String[] args)
    {
        double tempo = Double.parseDouble(args[0]);
        while (!StdIn.isEmpty())
        {
            int pitch = StdIn.readInt();
            double duration = StdIn.readDouble() * tempo;
            double hz = 440 * Math.pow(2, pitch / 12.0);
            double[] a = PlayThatNote.tone(hz, duration);
            StdAudio.play(a);
        }
        StdAudio.close();
    }
}
```

```
% more < elise.txt
7 .125
6 .125
7 .125
6 .125
7 .125
2 .125
5 .125
3 .125
0 .25
...
```



```
% java PlayThatTune 2 < elise.txt
```



```
% java PlayThatTune 1 < elise.txt
```

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## TEQ 2 on functions

Q. What sound does the following program produce?

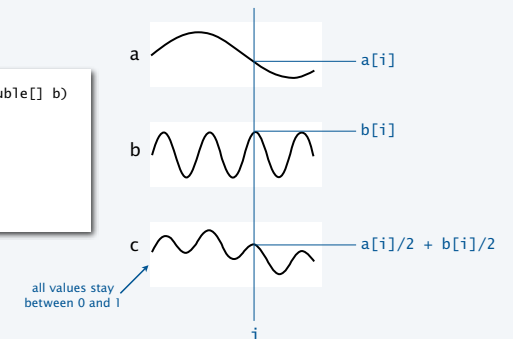
```
public class TEQ6_2
{
    public static void main(String[] args)
    {
        int N = (int) (44100 * 11);
        double[] a = new double[N+1];
        for (int i = 0; i <= N; i++)
            a[i] = Math.random();
        StdAudio.play(a);
    }
}
```

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## Play that chord

Produce chords by **adding** waveforms (normalized).

```
public static double[] sum(double[] a, double[] b)
{
    double[] c = new double[a.length];
    for (int i = 0; i < a.length; i++)
        c[i] = a[i]/2.0 + b[i]/2.0;
    return c;
}
```



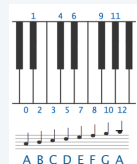
24

## Play that chord implementation

```
public class PlayThatChord
{
    public static double[] sum(double[] a, double[] b)
    { // See previous slide. }

    public static double[] chord(int pitch1, int pitch2, double d)
    {
        double hz1 = 440.0 * Math.pow(2, pitch1 / 12.0);
        double hz2 = 440.0 * Math.pow(2, pitch2 / 12.0);
        return sum(PlayThatNote.tone(hz1, d), PlayThatNote.tone(hz2, d));
    }

    public static void main(String[] args)
    {
        int pitch1 = Integer.parseInt(args[0]);
        int pitch2 = Integer.parseInt(args[1]);
        double duration = Double.parseDouble(args[2]);
        double[] a = chord(pitch1, pitch2, duration);
        StdAudio.play(a);
    }
}
```



```
% java PlayThatChord 0 3 5
```

```
% java PlayThatChord 0 12 5
```

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## Play that tune (deluxe version)

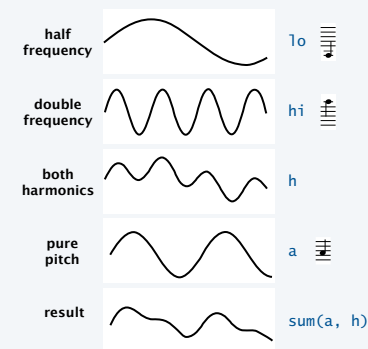
Add harmonics to PlayThatTune to produce a more realistic sound.

Function to add harmonics to a tone

```
public static double[] note(int pitch, double duration)
{
    double hz = 440.0 * Math.pow(2, pitch / 12.0);
    double[] a = tone(1.0 * hz, duration);
    double[] hi = tone(2.0 * hz, duration);
    double[] lo = tone(0.5 * hz, duration);
    double[] h = sum(hi, lo);
    return sum(a, h);
}
```

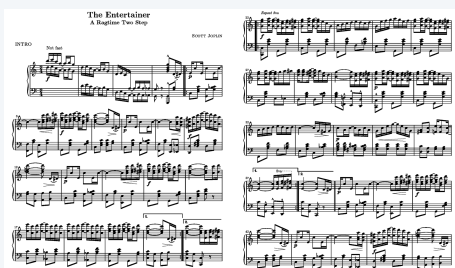
```
% java PlayThatTune 1.5 < elise.txt
```

Program 2.1.4 in text (with tempo added)



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## Digital audio (summary)



```
% java PlayThatTune 1.5 < entertainer.txt
```

**Bottom line.** You can write programs to manipulate sound.  
This lecture: Case study of the utility of functions.  
Upcoming assignment: Fun with musical tones.

```
public class PlayThatTune
{
    public static double[] sum(double[] a, double[] b,
        double amt, double det)
    {
        double[] c = new double[a.length];
        for (int i = 0; i < a.length; i++)
            c[i] = a[i]*amt + b[i]*det;
        return c;
    }

    public static double[] tone(double hz, double t)
    {
        int nps = 44100;
        int ns = (int)(nps * t);
        double[] a = new double[ns];
        for (int i = 0; i < ns; i++)
            a[i] = Math.sin(2 * Math.PI * i * hz / nps);
        return a;
    }

    public static double[] note(int pitch, double t)
    {
        double hz = 440.0 * Math.pow(2, pitch / 12.0);
        double[] a = tone(hz, t);
        double[] hi = tone(2*hz, t);
        double[] lo = tone(hz/2, t);
        double[] h = sum(hi, lo, .5, .5);
        return sum(a, h, .5, .5);
    }

    public static void main(String[] args)
    {
        while (!StdIn.isEmpty())
        {
            int pitch = StdIn.readInt();
            double duration = StdIn.parseDouble();
            double[] a = note(pitch, duration);
            StdAudio.play(a);
        }
    }
}
```

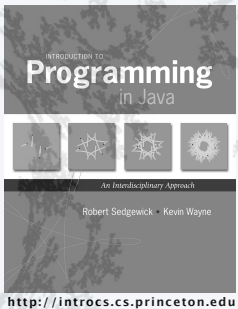
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## 6. Functions and Libraries

- Basic concepts
- **Case study: Digital audio**
- Application: Gaussian distribution
- Modular programming

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## 6. Functions and Libraries

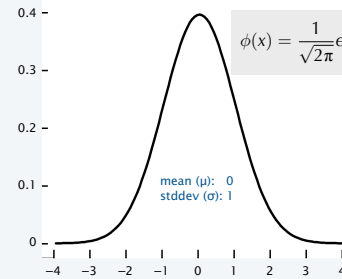
- Basic concepts
- Case study: Digital audio
- **Application: Gaussian distribution**
- Modular programming

## Gaussian distribution

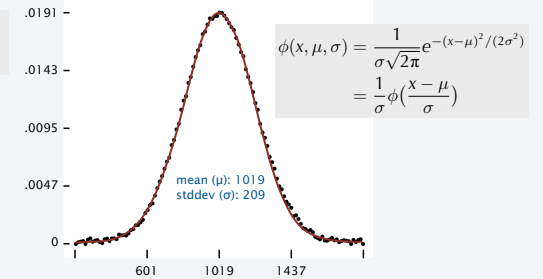
### Gaussian distribution.

- A mathematical model used successfully for centuries.
- "Bell curve" fits experimental observations in many contexts.

### Gaussian distribution function



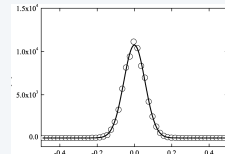
### Example: SAT scores in 20xx (verbal + math)



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## Gaussian distribution in the wild

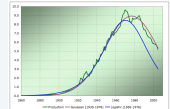
Polystyrene particles in glycerol



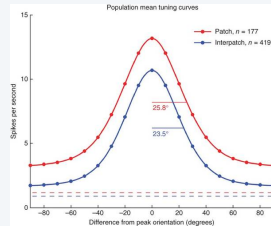
German money



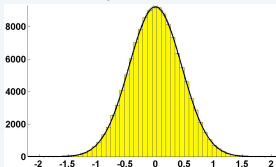
Predicted US oil production



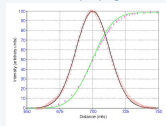
Cytochrome oxidase patches in macaque primary visual cortex



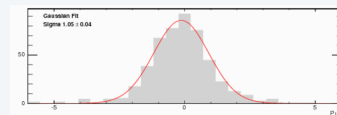
Calibration of optical tweezers



Laser beam propagation



Polarized W bosons from top-quark decay



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## Defining a library of functions

Q. Is the Gaussian function implemented in Java's Math library?

A. No.

Q. Why not?

A. Maybe because it is so easy for you to do it yourself.

```

public class Gaussian
{
    public static double phi(double x)
    { return Math.exp(-x*x / 2) / Math.sqrt(2 * Math.PI); }

    public static double phi(double x, double mu, double sigma)
    { return phi((x - mu) / sigma) / sigma; }

    // Stay tuned for more functions.
}
    
```

Annotations in the code:

- call a function in another module (pointing to Math.exp and Math.sqrt)
- module named Gaussian.java (pointing to the class name)
- functions with different signatures are different (even if names match) (pointing to the two phi methods)

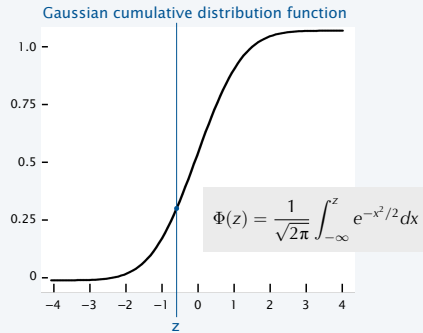
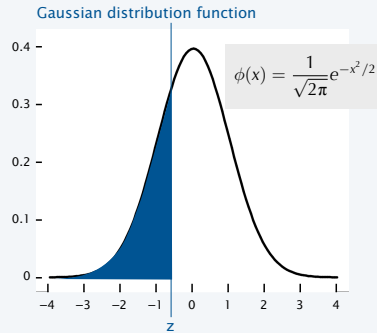
Functions and libraries provide an easy way for any user to *extend* the Java system.

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## Gaussian cumulative distribution function

- Q. What percentage of the total is less than or equal to  $z$ ?  
 Q. (equivalent). What is the area under the curve to the left of  $z$ ?  
 A. Gaussian *cumulative distribution function*.

$$\Phi(x, \mu, \sigma) = \Phi\left(\frac{x - \mu}{\sigma}\right)$$

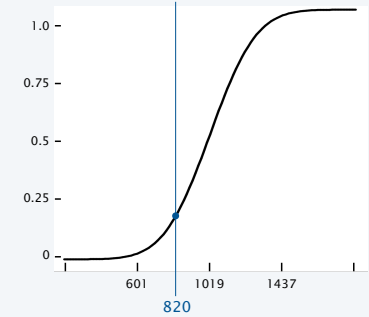
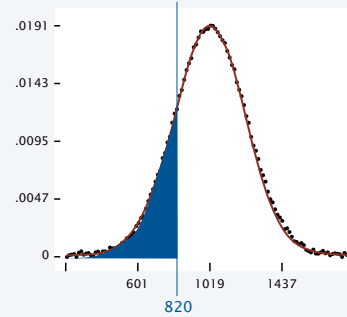


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## Typical application: SAT scores

- Q. In 20xx NCAA required at least 820 for Division I athletes. What fraction of test takers did not qualify??

- A. About 17%, since  $\Phi(820, 1019, 209) = 0.17050966869132111\dots$



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## Gaussian CDF implementation

- Q. No closed form for Gaussian CDF. How to implement?

- A. Use Taylor series.  $\Phi(z) \equiv \int_{-\infty}^z \phi(x) dx = \frac{1}{2} + \phi(z) \left( z + \frac{z^3}{3} + \frac{z^5}{3 \cdot 5} + \frac{z^7}{3 \cdot 5 \cdot 7} + \dots \right)$

```
public static double Phi(double z)
{
    if (z < -8.0) return 0.0;
    if (z > 8.0) return 1.0;
    double sum = 0.0, term = z;
    for (int i = 3; sum + term != sum; i += 2)
    {
        sum = sum + term;
        term = term * z * z / i;
    }
    return 0.5 + sum * phi(z); ← accurate to 15 places
}

public static double Phi(double z, double mu, double sigma)
{ return Phi((z - mu) / sigma); }
```

Bottom line. 1,000 years of mathematical formulas at your fingertips.

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## Summary: a library for Gaussian distribution functions

### Best practice

- Test all code at least once in main().
- Also have it do something useful.

- Q. What fraction of SAT test takers did not qualify for NCAA participation in 20xx?

```
% java Gaussian 820 1019 209
0.17050966869132111
```

### Fun fact

We use `Phi()` to evaluate randomness in submitted programs.

### Bottom line

YOU can build a layer of abstraction to use in any future program.

```
public class Gaussian
{
    public static double phi(double x)
    { return Math.exp(-x*x / 2) / Math.sqrt(2 * Math.PI); }
    public static double phi(double x, double mu, double sigma)
    { return phi((x - mu) / sigma) / sigma; }
    public static double Phi(double z)
    {
        if (z < -8.0) return 0.0;
        if (z > 8.0) return 1.0;
        double sum = 0.0, term = z;
        for (int i = 3; sum + term != sum; i += 2)
        {
            sum = sum + term;
            term = term * z * z / i;
        }
        return 0.5 + sum * phi(z);
    }
    public static double Phi(double z, double mu, double sigma)
    { return Phi((z - mu) / sigma); }
    public static void main(String[] args)
    {
        int z = Integer.parseInt(args[0]);
        int mu = Integer.parseInt(args[1]);
        int sigma = Integer.parseInt(args[2]);
        Stdout.println(Phi(z, mu, sigma));
    }
}
```

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## Using a library

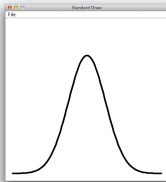
### To use these methods in another program

- Put a copy of `Gaussian.java` in your working directory.
- Call `Gaussian.phi()` or `Gaussian.Phi()` from any other module in that directory.

Learn to use your OS "classpath" mechanism if you find yourself with too many copies.

Example. Draw a plot of  $\phi(x, 0, 1)$  in  $(-4, 4)$

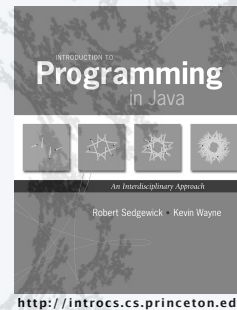
```
% java GaussianPlot 200
```



Libraries of functions provide an easy way for *any* user (you) to extend the Java system.

```
public class GaussianPlot
{
    public static void main(String[] args)
    {
        int N = Integer.parseInt(args[0]);
        StdDraw.setXscale(-4.0, +4.0);
        StdDraw.setYscale(0, .5);
        StdDraw.setPenRadius(0.01);
        double[] x = new double[N+1];
        double[] y = new double[N+1];
        for (int i = 0; i <= N; i++)
        {
            x[i] = -4.0 + 8.0 * i / N;
            y[i] = Gaussian.phi(x[i], 0, 1);
        }
        for (int i = 0; i < N; i++)
            StdDraw.line(x[i], y[i], x[i+1], y[i+1]);
    }
}
```

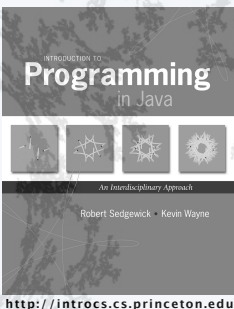
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## 6. Functions and Libraries

- Basic concepts
- Case study: Digital audio
- **Application: Gaussian distribution**
- Modular programming

<http://introcs.cs.princeton.edu>



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## Fundamental abstractions for modular programming



### Client

Module that calls a library's methods.

### Applications programming interface (API)

Defines signatures, describes methods.

### Implementation

Module containing library's Java code.

### Client

```
public class GaussianPlot
{
    ...
    y[i] = Gaussian.phi(x[i], 0, 1);
    ...
}
```

### API

```
public class Gaussian
{
    double phi(double x) Gaussian distribution
    double Phi(double x) Gaussian CDF
}
```

### Implementation

```
public class Gaussian
{
    public static double phi(double x)
    { return Math.exp(-x*x / 2)
      / Math.sqrt(2 * Math.PI); }
    ...
}
```

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## StdRandom library

Developed for this course, but broadly useful

- Implement methods for generating random numbers of various types.
- Available for download at booksite (and included in introcs software).



API	Method	Description
	<code>int uniform(int N)</code>	integer between 0 and N-1
	<code>double uniform(double lo, double hi)</code>	real between lo and hi
	<code>boolean bernoulli(double p)</code>	true with probability p
	<code>double gaussian()</code>	normal with mean 0, std. dev. 1
	<code>double gaussian(double m, double s)</code>	normal with mean m, std. dev. s
	<code>int discrete(double[] a)</code>	i with probability a[i]
	<code>void shuffle(double[] a)</code>	randomly shuffle the array a[]

```
int getRandomNumber()
{
    return 4; // chosen by fair dice roll.
             // guaranteed to be random.
}
```

First step in developing a library: Articulate the API!

## StdRandom details

### Implementation

```
public class StdRandom
{
    public static double uniform(double a, double b)
    { return a + Math.random() * (b-a); }

    public static int uniform(int N)
    { return (int) (Math.random() * N); }

    public static boolean bernoulli(double p)
    { return Math.random() < p; }

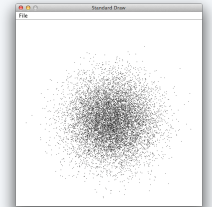
    public static double gaussian()
    /* see Exercise 1.2.27 */

    public static double gaussian(double m, double s)
    { return mean + (stddev * gaussian()); }
    ...
}
```

You could implement many of these methods, but now you don't have to!

### Typical client

```
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, 0.2);
            double y = StdRandom.gaussian(0.5, 0.2);
            StdDraw.point(x, y);
        }
    }
}
```



% java RandomPoints 10000

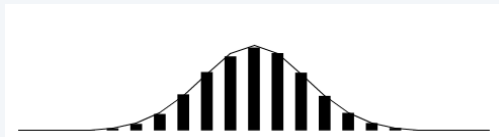
## Example of modular programming: StdStats, StdRandom, and Gaussian client

### Experiment

- Flip  $N$  coins.
- How many heads?
- Prediction: Expect  $N/2$ .

### Prediction (more detailed)

- Run experiment  $T$  times.
- How many heads?



Goal. Write a program to validate predictions.

## Example of modular programming: Bernoulli trials

```
public class Bernoulli
{
    public static int binomial(int N)
    // See previous slide.

    public static void main(String[] args)
    {
        int N = Integer.parseInt(args[0]);
        int T = Integer.parseInt(args[1]);

        int[] freq = new int[N+1];
        for (int i = 0; i < T; i++)
            freq[binomial(N)]++;

        double[] normalized = new double[N+1];
        for (int i = 0; i <= N; i++)
            normalized[i] = (double) freq[i] / T;
        StdStats.plotBars(normalized);

        double mean = N / 2.0;
        double stddev = Math.sqrt(N) / 2.0;
        double[] phi = new double[N+1];
        for (int i = 0; i <= N; i++)
            phi[i] = Gaussian.phi(i, mean, stddev);
        StdStats.plotLines(phi);
    }
}
```

### Bernoulli simulation

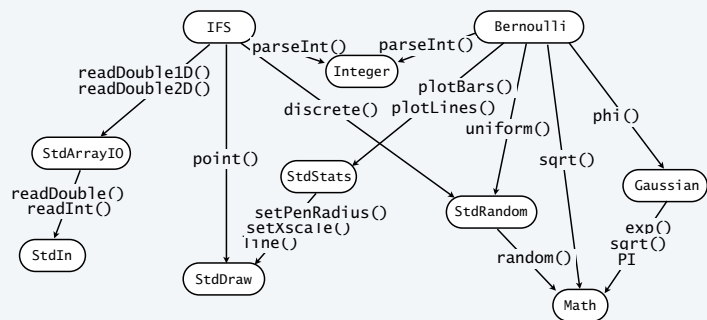
- Get command-line parms ( $T$  experiments of  $N$  flips).
- Compute frequency of occurrence of each count of heads.
- Normalize to between 0 and 1; plot histogram.
- Plot theoretical curve.

% java Bernoulli 20 10000



## Modular programming

enables development of complicated programs via simple independent modules.



Advantages. Code is easier to understand, debug, maintain, improve, and reuse.

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## Why modular programming?

### Modular programming enables

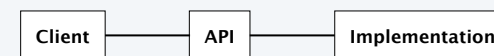
- Independent development of small programs.
- Every programmer to develop and share layers of abstraction.
- Self-documenting code.

### Fundamental characteristics

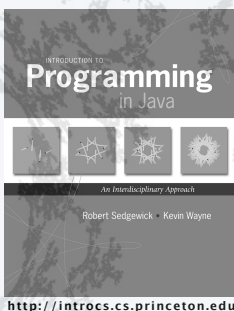
- Separation of client from implementation benefits all *future* clients.
- Contract between implementation and clients (API) benefits all *past* clients.

### Challenges

- How to break task into independent modules?
- How to specify API?



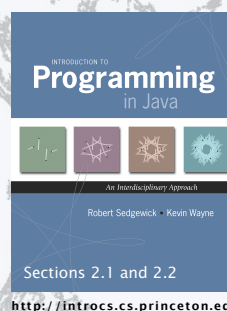
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