Data Types

The objects about which computer programs compute is data. We often think of integers as being the primary data on which computers operate. But at the lowest level all data is just binary bits.

But a program language organizes the bits into varieties called data types. With different data types the same bit pattern might represent a different object. A language can provide assistance in computing with these data types giving the illusion or the abstraction of computing with complex objects like real numbers, sound, video, graphs, etc.

Now we look at the data types supported by the Java programming language.
Overview

• Definition: objects are everything but primitives
• The eight primitive data type in Java
  • twos complement representation, IEEE754
• The wrapper classes: java.lang.Boolean, Character, Float, etc.
  • java.math.BigInteger, java.math.BigDecimal
• Strings: java.lang.String, and java.lang.StringBuilder, but do not use java.lang.StringBuffer.
• Arrays and its “wrapper” class java.util.Arrays
• Lists (abstractly and practically) is a later topic.
• Enums (particular kind of classes)
• Characters: Unicode
Know the Java API (i.e., memorize) for Integer, String, StringBuilder, and Arrays.
Java Primitive Data Types

The primitive data types (of which there are eight in Java) are those data types with simple structure and can be represented in the 32 or 64 bits of hardware, for example `int` and `long`. The operations on the primitive data types usually have hardware support. So computing with primitive data types is typically fast and convenient. These data types are used a lot in computing, though as computers get more powerful, programmers get more knowledgeable, and APIs get more expressive, it is more and more common for programs to use more complex data types.
Java Objects

The other families of data types in Java are called *objects*. (This is another use of the overworked word “object.” In Java jargon an object is a specific category of data types: namely all those that are not primitive.)

Arrays and strings are objects, not primitive types (but they have special support in the language syntax).

The programmer can even define new Java objects and this extremely important. This is the subject of a later lecture.
Java Primitive Data Types

- boolean
- char
- arithmetic
  - integral (twos-complement representation)
    - byte
    - short
    - int
    - long
  - floating-point (IEEE 754)
    - float
    - double
There are only two different boolean values: true and false. The boolean data type is essential for expressions to control conditional statements and loops.
The data type `char` represents characters of text like the letter 'A', 'B', etc. The repertoire of characters comes from the important and well-established Unicode standard. We discuss this interesting and Byzantine collection later in much detail.
Arithmetic Data Types
In an ideal world it ought not to matter how the data is represented. However, the usual mathematical laws do not apply to data represented by a computer. For example, none of the following hold for all values:

\[ |x| \geq 0 \]

\[ x(y + z) = xy + xz \]

\[ x + 1 > x \]

Worse is that fact that the laws often apply and so people educated in mathematics may delude themselves into thinking that they can program a computer. Society is beset by the consequences.
An educated person can look up, say, the equations for Hohmann transfer orbit on Wikipedia. But only a computer scientist can translate the concept into correctly working computer programs.

- \( v \) is the speed of an orbiting body
- \( \mu = GM \) is the standard gravitational parameter of the primary body
- \( r \) is the distance of the orbiting body from the primary focus
- \( a \) is the semi-major axis of the body's orbit

Therefore the \textit{delta-v} required for the Hohmann transfer can be computed as follows (this is only valid for instantaneous burns):

\[
\Delta v = \sqrt{\frac{\mu}{r_1}} \left( \sqrt{\frac{2r_2}{r_1 + r_2}} - 1 \right),
\]

\[
\Delta v' = \sqrt{\frac{\mu}{r_2}} \left( 1 - \sqrt{\frac{2r_1}{r_1 + r_2}} \right),
\]

where \( r_1 \) and \( r_2 \) are, respectively, the radii of the departure and arrival circular orbits; the smaller (greater) of \( r_1 \) and \( r_2 \) corresponds to the\textit{periapsis distance} (\textit{apoapsis distance}) of the Hohmann elliptical transfer orbit.

Whether moving into a higher or lower orbit, by \textit{Kepler's third law}, the time taken to transfer between the orbits is:

\[
t_H = \frac{1}{2} \sqrt{\frac{4\pi^2 a_H^3}{\mu}} = \pi \sqrt{\frac{(r_1 + r_2)^3}{8\mu}}.
\]
Failure to know the science of computing may led to disaster. Take the Ariane 5 disaster and many other failures, both big and small.

See the Ariane 5 explosion on YouTube.
Doing math is a lot like programming, but we are usually lost in the weeds and fail to see the goal at all. A computer does math rather poorly, and so the programmer must understand the limitations and avoid them, or provide better and better infrastructure.

In fact, looking at software development over time, much of programming can be viewed as taking a bad interface and improving it.
good interface

programmer

bad interface
By understanding data, particularly arithmetic data, it is possible to write correct programs in Java. But this is only possible because the Java programming language defines its data types. This means that a correctly written program will execute that same regardless of the Java implementation or the hardware on which it is run.

In some languages, notably C and C++, the properties of the data depend on the implementation or the hardware. Programs written in these languages are difficult to port.
Integral Data Types
Integral Data Types

How should an integer be represented?
Binary numbers as in discrete math class have two problems:

1. They assume an indefinite number of bits.
2. They do not have negative numbers.

Sign-magnitude seems simple enough. Why not?
Binary numbers as in discrete math class have two problems:

1. They assume an indefinite number of bits.
2. They do not have negative numbers.

Sign-magnitude seems simple enough. Why not?

Two bit patterns for zero.
Two’s complement (8 bits)

0 1 1 1 1 1 1 1 = 127
... 
0 0 0 0 0 0 1 0 = 2
0 0 0 0 0 0 0 1 = 1
0 0 0 0 0 0 0 0 = 0
1 1 1 1 1 1 1 1 = -1
1 1 1 1 1 1 1 0 = -2
... 
1 0 0 0 0 0 0 1 = -127
1 0 0 0 0 0 0 0 = -128
Two’s complement

\[-2^n - 2^n + 1\]

\[-2\] \(-1\) \(0\) \(1\) \(2\) \(2^n - 1\)
Two’s complement

\[-2^n - 2^n + 1 \quad -2 \quad -1 \quad 0 \quad 1 \quad 2 \quad 2^n - 1\]
Two's complement

\[-2^n - 2^n + 1\] \[
\begin{array}{cccccccc}
-2 & -1 & 0 & 1 & 2 & 2^n - 1 \\
\end{array}
\]
The byte data type is an 8-bit signed two’s complement integer. It has a minimum value of -128 and a maximum value of 127 (inclusive). The byte data type can be useful for saving memory in large arrays, where the memory savings actually matters. They can also be used in place of int where their limits help to clarify your code; the fact that a variable’s range is limited can serve as a form of documentation.
The short data type is a 16-bit signed two’s complement integer. It has a minimum value of \(-32,768\) and a maximum value of \(32,767\) (inclusive). As with byte, the same guidelines apply: you can use a short to save memory in large arrays, in situations where the memory savings actually matters.
**int**

The int data type is a 32-bit signed two’s complement integer. It has a minimum value of -2,147,483,648 and a maximum value of 2,147,483,647 (inclusive). For integral values, this data type is generally the default choice unless there is a reason to choose something else. This data type will most likely be large enough for the numbers your program will use, but if you need a wider range of values, use long instead.

approximately, ± a billion, all ± nine digit (decimal) numbers

The Library of Congress holds approximately 119 million items.
Approximately 402,000,000 native speakers of English.
Approximately 500,000,000 active Facebook users as of March 2010.
The Star Catalog lists 998,402,801 distinct astronomical objects.
The music video for South Korean singer Psy’s Gangnam Style has been viewed more than 2,147,483,647 times.
The long data type is a 64-bit signed two’s complement integer. It has a minimum value of -9,223,372,036,854,775,808 and a maximum value of 9,223,372,036,854,775,807 (inclusive). Use this data type when you need a range of values wider than those provided by int.

approximately, ± a quintillion, all ± 18 digit (decimal) numbers not quite enough to count all the insects on earth, or the possible states of the Rubik’s cube
Integer Literals

For int and long only.

0 2 0372 0xDada_Cafe 1996 0x00_FF___00_FF
0L 0777L 0x100000000L 2_147_483_648L 0xC0B0L
0b0110_1101_0000
0b0110_1101_0000L

0xffffffff
0b1111_1111_1111_1111_1111_1111_1111_1111 /* -1 */
0b1111_1111_1111_1111_1111_1111_1111_1111 /* -1 */
Floating-Point Types
The binary representation is:

\[1101.1011\]

This can be converted to decimal by adding the weighted values:

\[8 + 4 + 0 + 1 + 0.5 + 0 + 0.125 + 0.0625 = 13.6875\ (\text{Base } 10)\]
Why float the point?

A compromised between efficiency (the limited number of bits makes the operations easily implementable in hardware) and accuracy (not all real number can be represented).

This solution is not perfect and in some contexts one might represent the constructable reals with computer programs.
Scientific Notation

An practical way of presenting real numbers has been developed over a long period of time by scientists: scientific notation. In scientific notation all numbers are written in the form of

\[ a \times 10^b \]

(a times ten raised to the power of \(b\)), where the exponent \(b\) is an integer, and the coefficient \(a\) is a real number, called the significand or mantissa. This notation avoids lots of zeros which tend to make large and small numbers hard to read. A variant of this notation is often used by programming languages for the input and output of real numbers. Because of the typographical difficulty of superscripts these numbers are written with the letter 'e' or 'E' for “exponent.”
Floating point uses a fixed, total number of bits in the representation of real numbers. More bits in the exponent expand the range of numbers represented and the more bits in the mantissa extend the precision of the numbers represented.
<table>
<thead>
<tr>
<th>bits</th>
<th>exponent</th>
<th>mantissa</th>
<th>biase</th>
<th>range</th>
<th>places</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>8</td>
<td>23</td>
<td>127</td>
<td>$1.5 \cdot 10^{-45} \ldots 3.4 \cdot 10^{38}$</td>
<td>7–8</td>
</tr>
<tr>
<td>64</td>
<td>11</td>
<td>m5</td>
<td>1023</td>
<td>$5.0 \cdot 10^{-324} \ldots 1.7 \cdot 10^{308}$</td>
<td>15–16</td>
</tr>
</tbody>
</table>

$$1 = 1 \cdot 2^0 = 1 \cdot 2^{127-127} = 0x3F800000 = 00111111110 \ldots 0$$

$$1 = 1 \cdot 2^0 = 1 \cdot 2^{1023-1023} = 0xFF000000000000 = 0011111111110 \ldots 0$$
3DCCCCCD
0x1.99999ap-4

0.1 (decimal fraction approximation)

- sign bit = 0
- exponent (8 bits) = 01111011, 123; exp = -4
- mantissa (23 bits) = 10011001100110011001101
A sign bit, followed by $w$ exponent bits that describe the exponent offset by a bias $b = \ldots$, and $p - 1$ bits that describe the mantissa. $s \cdot m \cdot 2^e$ $s$ is 0 for positive or 1 for negative. For words of length 32 bits $m$ is a positive integer less than $2^{24}$, and $e$ is between -127 and 128, inclusive.

- zero 0 0 ±0
- infinity 2$b + 1$ 0 ±∞
- denormalized 0 $\neq$ 0 ±0.$f \times 2^{-b+1}$
- normalized $1 \leq e \leq 2b$ $\pm1.f \times 2^{e-b}$
- not a number $2b + 1 \neq 0$ NaN
The float data type is a single-precision 32-bit IEEE 754 floating point. Its range of values is beyond the scope of this discussion, but is specified in section 4.2.3 of the Java Language Specification. As with the recommendations for byte and short, use a float (instead of double) if you need to save memory in large arrays of floating point numbers. This data type should never be used for precise values, such as currency. For that, you will need to use the java.math.BigDecimal class instead.
The double data type is a double-precision 64-bit IEEE 754 floating point. Its range of values is beyond the scope of this discussion, but is specified in section 4.2.3 of the Java Language Specification. For real numbers, this data type is generally the default choice. As mentioned above, this data type should never be used for precise values, such as currency.
All the primitive, numeric data in Java are limited (obviously you can only represent $2^{32}$ or $2^{64}$ numbers). This is a lot of numbers, but we have the expectation that one does not run out of numbers and this causes trouble in some contexts.

Even worse, the mathematics of computer numbers, is not the same as “real” mathematical numbers and this causes a great deal of trouble.

To ameliorate these problems the Java libraries provide arbitrary-precision signed decimal numbers `java.lang.BigDecimal` arbitrary-precision integers `java.lang.BigInteger`. They are not primitive data types, but they have many of the same operations as the primitive data types.
Consider the difference between precise and imprecise quantities.

2. Can you measure velocity exactly? No.

But, can you measure money exactly? Yes.
Block, *Effective Java*, Item 48: Avoid float and double if exact answers are required

The float and double types are designed primarily for scientific and engineering calculations. They perform binary floating-point arithmetic, which was carefully designed to furnish accurate approximations quickly over a broad range of magnitudes. They do not, however, provide exact results and should not be used where exact results are required. The float and double types are particularly ill-suited for monetary calculations because it is impossible to represent 0.1 (or any other negative power of ten) as a float or double exactly.

Consider the following program.

```java
public final class Monetary {

    private static final String FMT = "Bought %d items @ $%.2f; funds remaining $%.2f%n";

    public static void main (final String[] args) {
        final double price = 0.10;
        double funds = 2.00;
        int items = 0;
        while (funds >= price) {
            funds -= price;
            items ++;
        }
        System.out.format (FMT, items, price, funds);
    }
}
```
The output is a surprising:

Bought 19 items @ $0.10; funds remaining $0.10

because the number 0.1 cannot be represented exactly in binary.

The problem can be avoided by using BigDecimal which does not represent numbers in binary digits.

(Of course, everything is binary in a computer; it is just that BigDecimal uses some bit patterns to represent decimal digits.)
import java.math.BigDecimal;

public final class Monetary2 {

    private static final String FMT = 
            "Bought %d items @ $%s; funds remaining $%s%n";

    public static void main (final String[] args) {
        final BigDecimal price = new BigDecimal (".10");
        BigDecimal funds = new BigDecimal ("2.00");
        int items = 0;
        while (funds.compareTo(price) >= 0) {
            funds = funds.subtract(price);
            items++;
        }
        System.out.format (FMT, items, price, funds);
    }
}

Bought 20 items @ $0.10; funds remaining $0.00
Binary Fractions

How is .1 represented on a computer?

Fractions are the sum of negative powers of two: \(0.1 = \frac{1}{16} + \frac{1}{32} + \frac{1}{256} \cdots\).

Binary powers (positive and negative) of two:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>8.0</td>
</tr>
<tr>
<td>2</td>
<td>4.0</td>
</tr>
<tr>
<td>1</td>
<td>2.0</td>
</tr>
<tr>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>-1</td>
<td>0.5</td>
</tr>
<tr>
<td>-2</td>
<td>0.25</td>
</tr>
<tr>
<td>-3</td>
<td>0.125</td>
</tr>
<tr>
<td>-4</td>
<td>0.0625</td>
</tr>
<tr>
<td>-5</td>
<td>0.03125</td>
</tr>
<tr>
<td>-6</td>
<td>0.015625</td>
</tr>
<tr>
<td>-7</td>
<td>0.0078125</td>
</tr>
</tbody>
</table>
An illustration of a simple algorithm to convert a tenth to a binary fraction.

0.1
0.1 × 2 = 0.2 < 1 0.0
0.2 × 2 = 0.4 < 1 0.00
0.4 × 2 = 0.8 < 1 0.000
0.8 × 2 = 1.6 ≥ 1 0.0001
0.6 × 2 = 1.2 ≥ 1 0.00011
0.2 × 2 = 0.4 < 1 0.000110
0.4 × 2 = 0.8 < 1 0.0001100
0.8 × 2 = 1.6 ≥ 1 0.00011001
0.6 × 2 = 1.2 ≥ 1 0.000110011
0.2 × 2 = 0.4 < 1 0.0001100110
0.1 (decimal) = 0.00011001100110011... (binary)

It may come as a surprise that terminating decimal fractions can have non-terminating expansions in binary. (But not the other way around.) Meaning that some (finite) decimal fractions cannot be represented precisely in a finite number of bits.
Binary Fractions

In Java, floating-point numbers can be read in and out (or, equivalently, converted to a string and back) without loss by avoiding base 10.

```
System.out.format("f = %f %a %s %08x %s%n", d, d,
                 Float.toString(d), Float.floatToIntBits(d), Float.toHexString(d));
```

f = 0.100000 0x1.99999ap-4 0.1 3dcccccd 0x1.99999ap-4

sign bit = 0
exponent (8 bits) = 01111011
mantissa (23 bits) = 10011001100110011001101
Hexadecimal Floating-Point Literals

[Do literals belong under the topic of expressions or here under data?]
More usefully, the maximum value of \((2 - 2^{-52}) \cdot 2^{1023}\) can be written as 0x1.fffffffffffffffffp1023 and the minimum value of \(2^{-1074}\) can be written as 0x1.0P-1074 or 0x0.0000000000001P-1022,
Hexadecimal Floating-Point Literals

Hexadecimal floating-point literals originated in C99 and were later included in a revision of the IEEE 754 floating-point standard. Sign, significand, and exponent fields defining a finite floating-point value; sign '0x' significand 'p' exponent. This syntax allows the literal

\[0x1.8p1\]

to be used to represent the value 3; \(1.8_{16} \times 2^1 = 1.5_{10} \times 2 = 3\). More usefully, the maximum value of can be written as \(0x1.fffffffffffffp1023\) and the minimum value of \(2^{-1074}\) can be written as \(0x1.0P-1074\) or \(0x0.0000000000001P-1022\), which maps easily to the various fields of the floating-point representation and is much more perspicacious than the raw-bit encoding.

In addition, "printf" facility including the %a format for hexadecimal floating-point.
Wrapper Classes

Corresponding to each primitive data type there is a Java class, known as its \textit{wrapper class}.
Instances of the class act as data just as the primitive data types do. So, an instance of \texttt{java.lang.Integer} is a lot like \texttt{int}. These wrapper class allows data of each primitive type to be used as an object. This redundancy is especially significant in the contest of generics which can only be used with objects (non-primitive data).
Java boxes and unboxes automatically.
Also, these class holds a few static methods that make the use of the primitive data type more convenient, for examples, methods to convert between strings and the data type.

```java
public static void main (final String[] args) {
    final int n = Integer.parseInt (args[0]);   /* primitive */
    final double x = Double.parseDouble (args[1]);  /* primitive */
    final boolean b = Boolean.parseBoolean (args[2]); /* primitive */
    final BigInteger big = new BigInteger (args[3]); /* object */

    // System property; note auto un-boxing
    final long g = Long.getLong ("sysPropKey", 234);
}
```
String Objects

String literals have special syntax:

" ... "

This raises the questions what can be a part of a string and how can a double quote be included in a string.

(Java raw strings were introduced in Java 13, so we ignore them.)

Do not confuse character escape sequences with Unicode escapes or with the language of printf.
### Character Escape

<table>
<thead>
<tr>
<th>Escape Sequence</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>\t</td>
<td>Insert a tab in the text at this point.</td>
</tr>
<tr>
<td>\b</td>
<td>Insert a backspace in the text at this point.</td>
</tr>
<tr>
<td>\n</td>
<td>Insert a newline in the text at this point.</td>
</tr>
<tr>
<td>\r</td>
<td>Insert a carriage return in the text at this point.</td>
</tr>
<tr>
<td>\f</td>
<td>Insert a formfeed in the text at this point.</td>
</tr>
<tr>
<td>'</td>
<td>Insert a single quote character in the text at this point.</td>
</tr>
<tr>
<td>&quot;</td>
<td>Insert a double quote character in the text at this point.</td>
</tr>
<tr>
<td>&quot;</td>
<td>Insert a backslash character in the text at this point.</td>
</tr>
</tbody>
</table>

And octal escapes. Don’t use them.
In many cases it is more efficient to use the class `java.lang.StringBuilder` than `java.lang.String`.

`java.lang.String` is a immutable class and `java.lang.StringBuilder` is a mutable class. Immutable classes will cause fewer programming errors, mutable are more efficient to use in some circumstances. This topic will be discussed later.
java.lang.String

An immutable sequence of characters.

- `int length()`  
  - string length
- `char charAt(int i)`  
  - ith character
- `String substring(int i, int j)`  
  - ith - j-1 characters
- `boolean equals(Object o)`  
  - test for same string
- `int compareTo(String s)`  
  - lexicographic ordering
java.lang.StringBuilder

A mutable sequence of characters.

- `int length()`  
  string length

- `char charAt(int i)`  
  ith character

- `void setCharAt(int i)`  
  set ith character

- `String substring(int i, int j)`  
  ith - j-1 characters

- `boolean equals(Object o)`  
  pointer equality

StringBuilder does not implement comparable.

http://www.javafaq.nu/java-article641.html

Know the Java API for String and StringBuilder!  
(StringBuffer class is obsolete.)
java.lang.StringBuilder

- A mutable sequence of characters.
- This class extends the Object class. The implication of class inheritance will be discussed later.
- Has numerous operations that change the string: append, insert, delete, replace, reverse, setCharAt, deleteCharAt
- BTW used to implement the '+’ operator
  ```java
  new StringBuilder().append("abc").append("xyz").toString()
  ```
- Pitfalls. equals() same as == and does not implement comparator
  ```java
  sb1.toString().equals(sb2.toString())
  sb1.toString().compareTo(sb2.toString())
  ```
Equality

While on the subject of equality ...

- for primitive data use ==
- for objects use (the instance method) equals()

Unfortunately for some objects equals() has not been implemented in the Java API. in the way one expects. So, we must:

- for arrays use Arrays.equals()
- for java.lang.StringBuilder use

\[
\text{sb1.toString().equals (sb2.toString())}
\]
Arrays

- Create, Triangle, Bool, Copy, Sort. Section 1.4, page 89.
- java.util.Arrays
Arrays

```java
final double[] a = new double[27];
for (int i=0; i<a.length; i++) {
    a[i] = Math.random();
}

for (int i=0; i<a.length; i++) {
    System.out.printf("%6.2f%n", a[i])
}
// Or, even easier ...
System.out.println(Arrays.toString(a));

double max = Double.NEGATIVE_INFINITY;
for (int i=0; i<a.length; i++) {
    if (a[i]>max) max=a[i];
}
// Or, even easier ...
for (double d: a) if (d>max) max=d;
```
Arrays

Something everybody should know:

```java
final int[] a = {4, 2, 8, 4, 7};
System.out.println(Arrays.toString(a));
```

Produces the output:

```
[4, 2, 8, 4, 7]
```
Arrays

```java
final int[] cost = new int[n];
Arrays.fill(cost, Integer.MAX_VALUE);
```
float[] a = {45.1, 32.9, 74.3};
int n = 5;
float[] b = Arrays.copyOf(a, n);
assert b.length==5;

float[] a = {45.1, 32.9, 74.3, 4.8};
int from = 1; // index, inclusive
int to = 3;  // index, exclusive
float[] b = Arrays.copyOfRange(a, from, to);
assert b.length==to-from;
[This does not really belong here.] Conditional expression:

```java
int max;
if (a>b) {
    max = a;
} else {
    max = b;
}
max = (a>b) ? a : b;
```

The “for each” loop is often used with arrays:

```java
double sum = 0.0;
final double[] ar = {2.3, 6.93, 0.011};
for (int i=0; i<a.length; i++) {
    sum += a[i];
}

for (double d: ar) {
    sum += d;
}
```
public final class Card {
    public enum Suit { CLUBS, DIAMONDS, HEARTS, SPADES }
    public enum Rank {
        DEUCE, THREE, FOUR, FIVE, SIX, SEVEN, EIGHT,
        NINE, TEN, JACK, QUEEN, KING, ACE
    }

    final Rank rank;
    final Suit suit;
}
enum Direction {
    RD(+2,-1), RU(+2,+1), LU(-2,+1), LD(-2,-1),
    UL(-1,+2), UR(+1,+2), DL(-1,-2), DR(+1,-2);

    private int dx, dy;
    Direction (int dx, int dy) {
        this.dx = dx; this.dy = dy;
    }

    public final Square move (Square p) {
        return new Square (p.x+dx,p.y+dy);
    }
}