NBody Simulation

Please report any errors with autograding or submission using this autograder thread on Piazza.

Important note: any image or sound files you add to your NBody folder will NOT be saved to your git repository. We've set up a file called .gitignore that will restricts you to only adding .java and .txt files. This is to keep your repos small so that the autograder moves quickly. We ask that you do not use the force command to upload other types of files, especially if they are large.

Introduction

The goal of this project is to give you a crash course in Java. Since CS61B is not intended to be a course about Java, we will be moving quickly, learning fundamental aspects of the Java language in just four weeks.

Before starting this project, we are assuming that you either have prior Java experience, or have watched lecture 2 and (ideally) have also completed HW0. If you have not watched lecture 2, do so now. The code that I built during that lecture can be found at this link. You do not need to fully understand the contents of lecture 2 to begin this assignment. Indeed, the main purpose of this project is to help you build some comfort with the material in that lecture.

Unlike later projects, this assignment has a great deal of scaffolding. Future assignments will require significantly more independence. For this project, you may work in pairs. To work in a pair, you must read the collaboration guide and fill out the partner request form linked in the partnership guide. You do not need to wait for our approval to begin as long as you meet the requirements for partnerships. If you work with someone who is more experienced, you are likely to miss lots of important subtleties, which will be painful later when you start working on your own (i.e. the entire second half of the course).

Your goal for this project is to write a program simulating the motion of `N` objects in a plane, accounting for the gravitational forces mutually affecting each object as demonstrated by Sir Isaac Newton's Law of Universal Gravitation.

Ultimately, you will be creating a program `NBody.java` that draws an animation of bodies floating around in space tugging on each other with the power of gravity.

If you run into problems, be sure to check out the FAQ section before posting to Piazza. We'll keep this section updated as questions arise during the assignment. Always try googling before asking questions on Piazza. Knowing how to find what you want on Google is a valuable skill. However, know when to give up! If you start getting frustrated with your search attempts, then turn to Piazza.

Getting the Skeleton Files

Before proceeding, make sure you have completed lab1, and if you are working on your own computer, that you have completed lab1setup to set up your computer.

To do this, head to the folder containing your copy of your repository. For example, if your login is 'agz', then head to the 'agz' folder (or any subdirectory). If you're working with a partner, you are allowed to clone each other's repository (temporary access will be granted based on your response to the partnership registration form). You can share files between each other however you find best. We'll discuss normal git-based file sharing practices when we get to project 2.

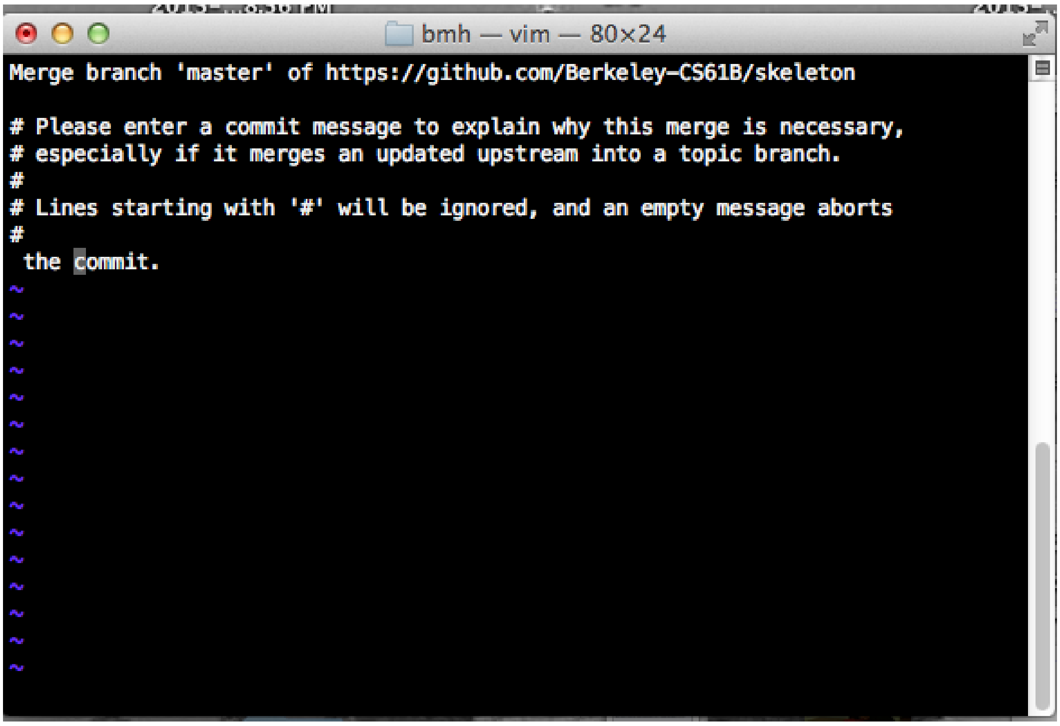
Now we'll make sure you have the latest copy of the skeleton files with by using `git pull skeleton master`. If the folder you're pulling into already has an older copy of the skeleton repo (from lab 1, for example), this will cause a so-called `merge` (see git guide for more details if you want). A text editor will automatically open asking you to provide a message on why you are merging.

Depending on the settings on the computer you're using, you will possibly find yourself in one of three *command line* text editors:

- nano
- vim
- emacs

Unfortunately, git will likely default to one of these text editors, meaning that the simple act of providing a merge message may cause you considerable consternation. Don't worry, this is normal! One of the goals of 61B is to teach you to handle these sorts of humps. Indeed, one of the reasons we're making you use a powerful real-world version control system like git this semester is to have you hit these common hurdles now in a friendly pedagogical environment instead of the terrifying real world. However, this also means we’re going to suffer sometimes, particularly at this early point in the semester. **Don’t panic!**

For reference, this is what vim looks like:



See this link if you are stuck in vim. If you are in emacs, type something and then press ctrl-x then ctrl-s to save, then ctrl-x then ctrl-c to exit.

Once you’ve successfully merged, you should see a proj0 directory appear with files that match the skeleton repository (to be released soon!).

Note that if you did not already have a copy of the skeleton repo in your current folder, you will not be asked for a merge message.

If you somehow end up having a merge conflict, consult the git weird technical failures guide.

If you get some sort of error, STOP and either figure it out by carefully reading the git guide or seek help at OH or Piazza. You’ll potentially save yourself a lot of trouble vs. guess-and-check with git commands. If you find yourself trying to use commands you Google like `force push`, don’t.

The Planet Class and Its Constructor

You’ll start by creating a Planet class. In your favorite text editor, create a file called `Planet.java`. If you haven’t picked a text editor, we recommend

Sublime Text. Remember that your .java files should have the same name as the class it contains.

Begin by creating a basic version of the Planet class with the following 6 instance variables:

- `double xxPos`: Its current x position
- `double yyPos`: Its current y position
- `double xxVel`: Its current velocity in the x direction
- `double yyVel`: Its current velocity in the y direction
- `double mass`: Its mass
- `String imgFileName`: The name of the file that corresponds to the image that depicts the planet (for example, `jupiter.gif`)

Your instance variables must be named exactly as above, and they must be explicitly set to public via the `public` keyword. The reason we call them by double letters, e.g. `xxPos` rather than `xPos` is to reduce the chance of typos. In past semesters, students have accidentally pressed x when they meant y, and this has caused significant debugging hassle. After adding the 6 instance variables above, add in two Planet constructors that can initialize an instance of the Planet class. The signature of the first constructor should be:

```
public Planet(double xP, double yP, double xV,
              double yV, double m, String img)
```

Note: We have given parameter names which are different than the corresponding instance variable name. If you insist on making the parameter names the same as the instance variable names for aesthetic reasons, make sure to use the "this" keyword appropriately (mentioned only briefly in lecture).

The second constructor should take in a Planet object and initialize an identical Planet object (i.e. a copy). The signature of the second constructor should be:

```
public Planet(Planet p)
```

Your Planet class should NOT have a main method, because we'll never run the Planet class directly (i.e. we will never do `java Planet`). Also, all methods should be non-static.

All of the numbers for this project will be doubles. We'll go over what exactly a double is later in the course, but for now, think of it is a real number, e.g.

`double x = 3.5`. In addition, all instance variables and methods will be declared using the public keyword.

Once you have filled in the constructors, you can test it out by compiling your `Planet.java` file and the `TestPlanetConstructor.java` file we have provided.

You can compile with the command:

```
javac Planet.java TestPlanetConstructor.java
```

You can run our provided test with the command

```
java TestPlanetConstructor
```

If you pass this test, you're ready to move on to the next step. **Do not proceed until you have passed this test.**

Understanding the Physics

Let's take a step back now and look at the physics behind our simulations. Our `Planet` objects will obey the laws of Newtonian physics. In particular, they will be subject to:

- Pairwise Force: *Newton's law of universal gravitation* asserts that the strength of the gravitational force between two particles is given by the product of their masses divided by the square of the distance between them, scaled by the gravitational constant $G = 6.67 \cdot 10^{-11} \frac{\mathrm{Nm}^2}{\mathrm{kg}^2}$. The gravitational force exerted on a particle is along the straight line between them (we are ignoring here strange effects like the curvature of space). Since we are using Cartesian coordinates to represent the position of a particle, it is convenient to break up the force into its x- and y-components (F_x, F_y). The relevant equations are shown below. We have not derived these equations, and you should just trust us.
    - $F = \frac{G \cdot m_1 \cdot m_2}{r^2}$
    - $r^2 = dx^2 + dy^2$
    - $F_x = \frac{F \cdot dx}{r}$
    - $F_y = \frac{F \cdot dy}{r}$

Look at the image below and make sure you understand what each variable represents!

Note that force is a vector (i.e., it has direction). In particular, be aware that dx and dy are signed (positive or negative).

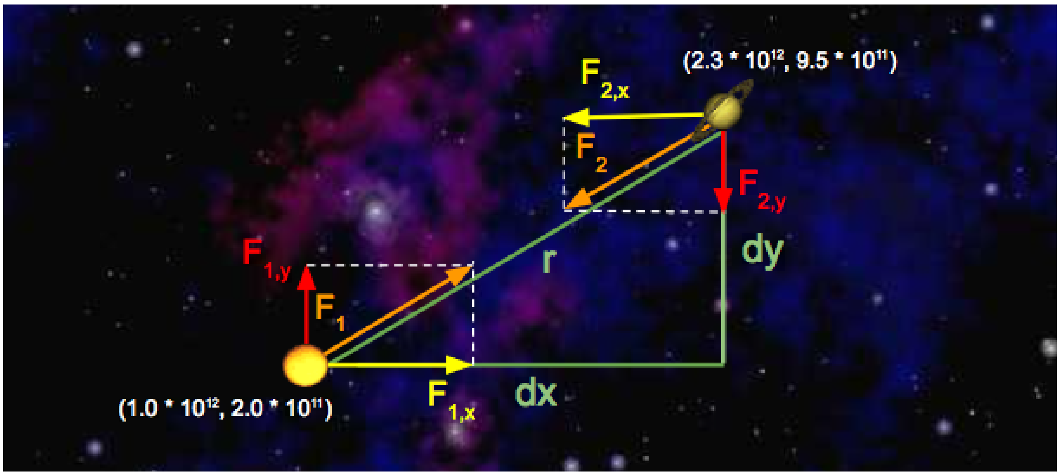
- Net Force: The *principle of superposition* says that the net force acting on a particle in the x- or y-direction is the sum of the pairwise forces acting on the particle in that direction.

In addition, all planets have:

- Acceleration: Newton's *second law of motion* says that the accelerations in the x- and y-directions are given by:
  - $a_x = \dfrac{F_x}{m}$
  - $a_y = \dfrac{F_y}{m}$

Check your understanding!

Consider a small example consisting of two celestial objects: Saturn and the Sun. Suppose the Sun is at coordinates $(1.0 \cdot 10^{12}, 2.0 \cdot 10^{11})$ and Saturn is at coordinates $(2.3 \cdot 10^{12}, 9.5 \cdot 10^{11})$. Assume that the Sun's mass is $2.0 \cdot 10^{30}$ kg and Saturn's mass is $6.0 \cdot 10^{26}$ kg. Here's a diagram of this simple solar system:



Let's run through some sample calculations. First let's compute F_1, the force that Saturn exerts on the Sun. We'll begin by calculating r, which we've already expressed above in terms of dx and dy. Since we're calculating the force exerted by Saturn, dx is Saturn's x-position minus Sun's x-position, which is 1.3×10^{12} m. Similarly, dy is $7.5 \cdot 10^{11}$ m.

So, $r^2 = dx^2 + dy^2 = (1.3 \cdot 10^{12})^2 + (7.5 \cdot 10^{11})^2$. Solving for r gives us $1.5 \cdot 10^{12}$ m. Now that we have r, computation of F is straightforward:

$$F = \frac{G \cdot (2.0 \cdot 10^{30}\ \text{kg}) \cdot (6.0 \cdot 10^{26} \text{kg})}{(1.5 \cdot 10^{12}\ \text{m})^2} = 3.6 \cdot 10^{22}\ \text{N}$$

Note that the magnitudes of the forces that Saturn and the Sun exert on one another are equal; that is, $|F| = |F_1| = |F_2|$. Now that we've computed the pairwise force on the Sun, let's compute the x- and y-components of this force, denoted with $F_{1,x}$ and $F_{1,y}$, respectively. Recall that dx is $1.3 \cdot 10^{12}$ meters and dy is $7.5 \cdot 10^{11}$ meters. So,

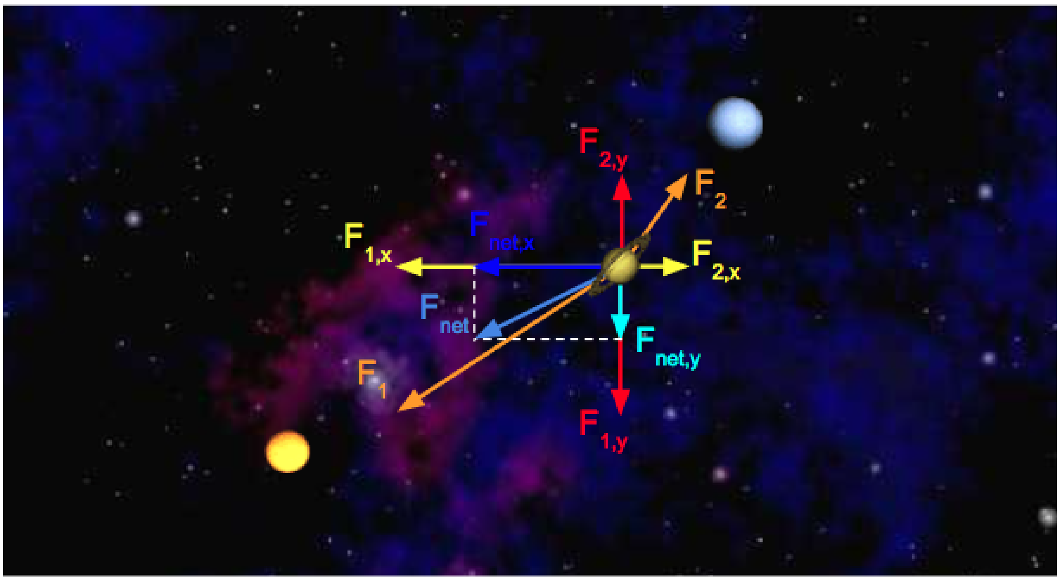
- $F_{1,x} = \dfrac{F_1 \cdot (1.3 \cdot 10^{12}\ \text{m})}{1.5 \cdot 10^{12}\ \text{m}} = 3.1 \cdot 10^{22}\ \text{N}$
- $F_{1,y} = \dfrac{F_1 \cdot (7.5 \cdot 10^{11}\ \text{m})}{1.5 \cdot 10^{12}\ \text{m}} = 1.8 \cdot 10^{22}\ \text{N}$

Note that the sign of dx and dy is important! Here, dx and dy were both positive, resulting in positive values for $F_{1,x}$ and $F_{1,y}$. This makes sense if you look at the diagram: Saturn will exert a force that pulls the Sun to the right (positive $F_{1,x}$) and up (positive $F_{1,y}$).

Next, let's compute the x and y-components of the force that the Sun exerts on Saturn. The values of dx and dy are negated here, because we're now measuring the displacement of the Sun relative to Saturn. Again, you can verify that the signs should be negative by looking at the diagram: the Sun will pull Saturn to the left (negative dx) and down (negative dy).

- $F_{2,x} = \dfrac{F_2 \cdot (-1.3 \cdot 10^{12}\ \text{m})}{1.5 \cdot 10^{12}\ \text{m}} = -3.1 \cdot 10^{22}\ \text{N}$
- $F_{2,y} = \dfrac{F_2 \cdot (-7.5 \cdot 10^{11}\ \text{m})}{1.5 \cdot 10^{12}\ \text{m}} = -1.8 \cdot 10^{22}\ \text{N}$

Let's add Neptune to the mix and calculate the net force on Saturn. Here's a diagram illustrating the forces being exerted on Saturn in this new system:



We can calculate the x-component of the net force on Saturn by summing the x-components of all pairwise forces. Likewise, $F_{\mathrm{net},y}$ can be calculated by summing the y-components of all pairwise forces. Assume the forces exerted on Saturn by the Sun are the same as above, and that $F_{2,x} = 1.1 \cdot 10^{22}$ N and $F_{2,y} = 9.0 \cdot 10^{21}$N.

- $F_{\mathrm{net},x} = F_{1,x} + F_{2,x} = -3.1 \cdot 10^{22} \mathrm{~N} + 1.1 \cdot 10^{22} \mathrm{~N} = -2.0 \cdot 10^{22} \mathrm{~N}$
- $F_{\mathrm{net},y} = F_{1,y} + F_{2,y} = -1.8 \cdot 10^{22} \mathrm{~N} + 9.0 \cdot 10^{21} \mathrm{~N} = -9.0 \cdot 10^{21}\mathrm{N}$

Double check your understanding!

Suppose there are three bodies in space as follows:

- Samh: $x = 1, y = 0, \mathrm{mass} = 10$
- Aegir: $x = 3, y = 3, \mathrm{mass} = 5$
- Rocinante: $x = 5, y = -3, \mathrm{mass} = 50$

Calculate $F_{\mathrm{net},x}$ and $F_{\mathrm{net},y}$ exerted on Samh. To check your answer, click here for $F_{\mathrm{net},x}$ and here for $F_{\mathrm{net},y}$.

Writing the Planet Class

In our program, we'll have instances of Planet class do the job of calculating all the numbers we learned about in the previous example. We'll write helper methods, one by one, until our Planet class is complete.

calcDistance

Start by adding a method called `calcDistance` that calculates the distance between two Planets. This method will take in a single Planet and should return a double equal to the distance between the supplied planet and the planet that is doing the calculation, e.g.

```
samh.calcDistance(rocinante);
```

It is up to you this time to figure out the signature of the method. Once you have completed this method, go ahead and recompile and run the next unit test to see if your code is correct.

Compile and run with:

```
javac Planet.java TestCalcDistance.java
java TestCalcDistance
```

Hint: In Java, there is no built in operator that does squaring or exponentiation. We recommend simply multiplying a symbol by itself instead of using `Math.pow`, which will result in slower code.

calcForceExertedBy

The next method that you will implement is `calcForceExertedBy`. The `calcForceExertedBy` method takes in a planet, and returns a double describing the force exerted on this planet by the given planet. You should be calling the `calcDistance` method in this method. For example `samh.calcForceExertedBy(rocinante)` for the numbers in "Double Check Your Understanding" return $1.334 \cdot 10^{-9}$.

Once you've finished `calcForceExertedBy`, re-compile and run the next unit test.

```
javac Planet.java TestCalcForceExertedBy.java
java TestCalcForceExertedBy
```

Hint: It is good practice to declare any constants as a 'static final' variable in your class, and to use that variable anytime you wish to use the constant.

Hint 2: Java supports scientific notation. For example, I can write `double someNumber = 1.03e-7;`.

calcForceExertedByX and calcForceExertedByY

The next two methods that you should write are `calcForceExertedByX` and `calcForceExertedByY`. Unlike the `calcForceExertedBy` method, which returns the total force, these two methods describe the force exerted in the X and Y directions, respectively. *Remember to check your signs!* Once you've finished, you can recompile and run the next unit test. For example `samh.calcForceExertedByX(rocinante)` in "Double Check Your Understanding" should return $1.0672 \cdot 10^{-9}$.

NOTE: Do not use Math.abs to fix sign issues with these methods. This will cause issues later when drawing planets.

```
javac Planet.java TestCalcForceExertedByXY.java
java TestCalcForceExertedByXY
```

calcNetForceExertedByX and calcNetForceExertedByY

Write methods `calcNetForceExertedByX` and `calcNetForceExertedByY` that each take in an array of Planets and calculate the net X and net Y force exerted by all planets in that array upon the current Planet. For example, consider the code snippet below:

```
Planet[] allPlanets = {samh, rocinante, aegir};
samh.calcNetForceExertedByX(allPlanets);
samh.calcNetForceExertedByY(allPlanets);
```

The two calls here would return the values given in "Double Check Your Understanding."

As you implement these methods, remember that Planets cannot exert gravitational forces on themselves! Can you think of why that is the case (hint: the universe will possibly collapse in on itself, destroying everything including you)? To avoid this problem, ignore any planet in the array that is equal to the current planet. To compare two planets, use the .equals method: `samh.equals(samh)` (which would return true).

When you are done go ahead and run:

```
javac Planet.java TestCalcNetForceExertedByXY.java
java TestCalcNetForceExertedByXY
```

If you're tired of the verbosity of for loops, you might consider reading about less verbose looping constructs (for and the 'enhanced for') given on page 114-116 of HFJ, or online at this link. HW0 also goes into detail about enhanced for loops. This is not necessary to complete the project.

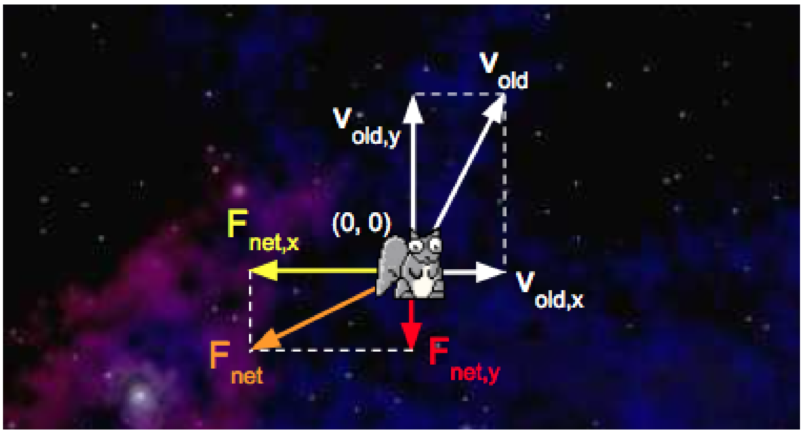
update

Next, you'll add a method that determines how much the forces exerted on the planet will cause that planet to accelerate, and the resulting change in the planet's velocity and position in a small period of time dt. For example, `samh.update(0.005, 10, 3)` would adjust the velocity and position if an x-force of 10 Newtons and a y-force of 3 Newtons were applied for 0.005 seconds.

You must compute the movement of the Planet using the following steps:

1. Calculate the acceleration using the provided x- and y-forces.
2. Calculate the new velocity by using the acceleration and current velocity. Recall that acceleration describes the change in velocity per unit time, so the new velocity is $(v_x + dt \cdot a_x, v_y + dt \cdot a_y)$.
3. Calculate the new position by using the velocity computed in step 2 and the current position. The new position is $(p_x + dt \cdot v_x, p_y + dt \cdot v_y)$.

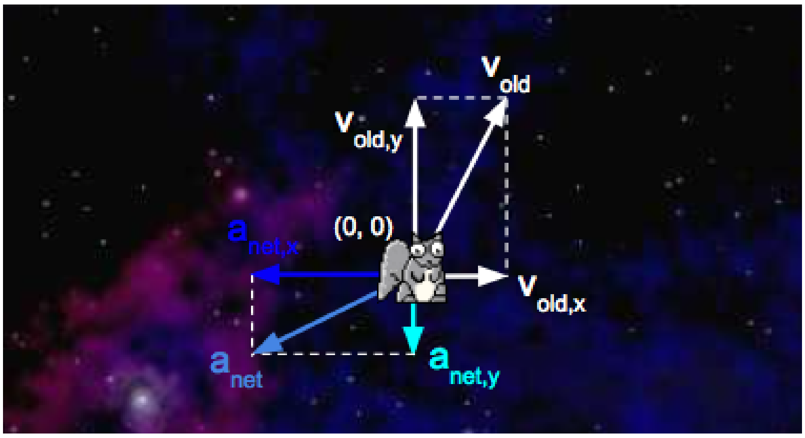
Let's try an example! Consider a squirrel initially at position $(0, 0)$ with a v_x of $3\frac{\mathrm{m}}{\mathrm{s}}$ and a v_y of $5\frac{\mathrm{m}}{\mathrm{s}}$. $F_{\text{net},x}$ is $-5\ \mathrm{N}$ and $F_{\text{net},y}$ is $-2\ \mathrm{N}$. Here's a diagram of this system:



We'd like to update with a time step of $1\ \mathrm{second}$. First, we'll calculate the squirrel's net acceleration:

- $a_{\text{net},x} = \frac{F_{\text{net},x}}{m} = \frac{-5\ \mathrm{N}}{1\ \mathrm{kg}} = -5\frac{\mathrm{m}}{\mathrm{s}^2}$
- $a_{\text{net},y} = \frac{F_{\text{net},y}}{m} = \frac{-2\ \mathrm{N}}{1\ \mathrm{kg}} = -2\frac{\mathrm{m}}{\mathrm{s}^2}$

With the addition of the acceleration vectors we just calculated, our system now looks like this:



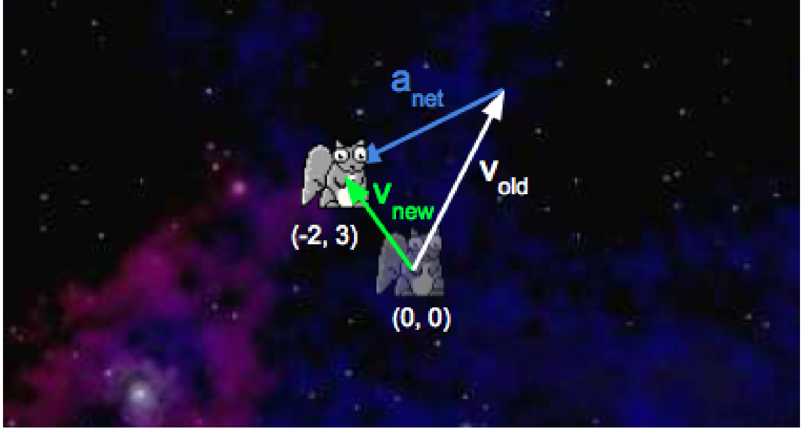
Second, we'll calculate the squirrel's new velocity:

- $v_{\text{new},x} = v_{\text{old},x} + dt \cdot a_{\text{net},x} = 3\frac{\mathrm{m}}{\mathrm{s}} + 1\ \mathrm{s} \cdot -5\frac{\mathrm{m}}{\mathrm{s}^2} = -2\frac{\mathrm{m}}{\mathrm{s}}$
- $v_{\text{new},y} = v_{\text{old},y} + dt \cdot a_{\text{net},y} = 5\frac{\mathrm{m}}{\mathrm{s}} + 1\ \mathrm{s} \cdot -2\frac{\mathrm{m}}{\mathrm{s}^2} = 3\frac{\mathrm{m}}{\mathrm{s}}$

Third, we'll calculate the new position of the squirrel:

- $p_{\text{new},x} = p_{\text{old},x} + dt \cdot v_{\text{new},x} = 0\ \mathrm{m} + 1\ \mathrm{s} \cdot -2\frac{\mathrm{m}}{\mathrm{s}} = -2\ \mathrm{m}$
- $p_{\text{new},y} = p_{\text{old},y} + dt \cdot v_{\text{new},y} = 0\ \mathrm{m} + 1\ \mathrm{s} \cdot 3\frac{\mathrm{m}}{\mathrm{s}} = 3\ \mathrm{m}$

Here's a diagram of the updated system:



For math/physics experts: You may be tempted to write a more accurate simulation where the force gradually increases over the specified time window. Don't! Your simulation must follow exactly the rules above.

Write a method `update(dt, fX, fY)` that uses the steps above to update the planet's position and velocity instance variables (this method does not need to return anything).

Once you're done, recompile and test your method with:

```
javac Planet.java TestUpdate.java
java TestUpdate
```

Once you've done this, you've finished implementing the physics. Hoorah! You're halfway there.

(Optional) Testing Your Planet

As the semester progresses, we'll be giving you fewer and fewer tests, and it will be your responsibility to write your own tests. Writing tests is a good way to improve your workflow and be more efficient.

Go ahead and try writing your own test for the Planet class. Make a `TestPlanet.java` file and write a test that creates two planets and prints out the pairwise force between them. This is optional and we will not be grading this part of the assignment.

Getting Started with the Simulator (NBody.java)

NBody is a class that will actually run your simulation. This class will have NO constructor. The goal of this class is to simulate a universe specified in one of the data files. For example, if we look inside data/planets.txt (using the command line `more` command), we see the following:

```
$ more planets.txt
5
2.50e+11
1.4960e+11  0.0000e+00  0.0000e+00  2.9800e+04  5.9740e+24    ear
2.2790e+11  0.0000e+00  0.0000e+00  2.4100e+04  6.4190e+23     ma
5.7900e+10  0.0000e+00  0.0000e+00  4.7900e+04  3.3020e+23  mercu
0.0000e+00  0.0000e+00  0.0000e+00  0.0000e+00  1.9890e+30      s
1.0820e+11  0.0000e+00  0.0000e+00  3.5000e+04  4.8690e+24    ven
```

The input format is a text file that contains the information for a particular universe (in SI units). The first value is an integer `N` which represents the number of planets. The second value is a real number `R` which represents the radius of the universe, used to determine the scaling of the drawing window. Finally, there are `N` rows, and each row contains 6 values. The first two values are the x- and y-coordinates of the initial position; the next pair of values are the x- and y-components of the initial velocity; the fifth value is the mass; the last value is a String that is the name of an image file used to display the planets. Image files can be found in the `images` directory. The file above contains data for our own solar system (up to Mars).

ReadRadius

Your first method is readRadius. Given a file name, it should return a double corresponding to the radius of the universe in that file, e.g. `readRadius("./data/planets.txt")` should return 2.50e+11.

To help you understand the `In` class, we've provided a few examples for you. The first one is called `BasicInDemo.java`, which you can find in the `examples` folder that came with the skeleton. Take a look at the code, and take a look at the input file `BasicInDemo_input_file.txt`. This program should output: `The file contained 5, 9.0, ketchup, brass, and 5.0`.

There's a slightly more complicated example called `InDemo.java`, which you can also find in the examples folder. While this demo does not perfectly match what you'll be doing in this project, every method that you need is somewhere in this file. You're also welcome to search the web for other examples (though it might be tricky to find since the class name `In` is such a common English word).

NOTE: Do not use System.exit(0) in your code, despite the example using it. This will break the autograder, and you will not obtain a score.

Alternately, you can consult the full documentation for the In class, though you might find it a bit intimidating.

We encourage you (and your partner, if applicable) to do your best to figure out this part of the assignment on your own. In the long run, you'll need to gain the skills to independently figure out this sort of thing. However, if you start getting frustrated, don't hesitate to ask for help!

You can test this method using the supplied TestReadRadius.

```
javac NBody.java TestReadRadius.java
java TestReadRadius
```

ReadPlanets

Your next method is readPlanets. Given a file name, it should return an array of Planets corresponding to the planets in the file, e.g. `readPlanets("./data/planets.txt")` should return an array of five planets. You will find the `readInt()`, `readDouble()`, and `readString()` methods in the In class to be useful.

You can test this method using the supplied TestReadPlanets.

```
javac Planet.java NBody.java TestReadPlanets.java
java TestReadPlanets
```

Drawing the Initial Universe State (main)

Next, build the functionality to draw the universe in its starting position. You'll do this in four steps. Because all code for this part of the assignment is in main, this part of the assignment will NOT have automated tests to check each little piece.

Collecting All Needed Input

Create a `main` method in the NBody class. Write code so that your NBody class performs the following steps:

- Store the 0th and 1st command line arguments as doubles named `T` and `dt`. Hint: the arguments come in as Strings. You will have to Google around in order to learn how to convert the Strings to doubles!
- Store the 2nd command line argument as a String named `filename`.

- Read in the planets and the universe radius from the file described by `filename` using your methods from earlier in this assignment.

Drawing the Background

After your main method has read everything from the files, it's time to get drawing. First, set the scale so that it matches the radius of the universe. Then draw the image `starfield.jpg` as the background. To do these, you'll need to figure out how to use the StdDraw library.

See `StdDrawDemo.java` in the examples folder for a demonstration of StdDraw. This example, like `InDemo.java`, does not perfectly match what you're doing.

In addition, make sure to check out the StdDraw section of this mini-tutorial, and if you're feeling bold, the full StdDraw documentation. This will probably take some trial and error. This may seem slightly frustrating, but it's good practice!

Hint: You may notice that putting `starfield.jpg` as a parameter into `StdDraw.picture()` results in a blank screen. This is because our `starfield.jpg` is inside the `images` folder. Thus, you will need to use the full path, i.e. `images/starfield.jpg` in order to get your image. This applies to any other images you may use in the future.

Drawing One Planet

Next, we'll want a planet to be able to draw itself at its appropriate position. To do this, take a brief detour back to the Planet.java file. Add one last method to the Planet class, `draw`, that uses the StdDraw API mentioned above to draw the Planet's image at the Planet's position. The `draw` method should return nothing and take in no parameters.

Drawing All of the Planets

Return to the main method in NBody.java and use the `draw` method you just wrote to draw each one of the planets in the planets array you created. Be sure to do this after drawing the `starfield.jpg` file so that the planets don't get covered up by the background.

Test that your main method works by compiling:

```
javac NBody.java
```

And running the following command:

```
java NBody 157788000.0 25000.0 data/planets.txt
```

You should see the sun and four planets sitting motionless. You are almost done.

Creating an Animation

Everything you've done so far is leading up to this moment. With only a bit more code, we'll get something very cool.

To create our simulation, we will discretize time (please do not mention this to Stephen Hawking). The idea is that at every discrete interval, we will be doing our calculations and once we have done our calculations for that time step, we will then update the values of our Planets and then redraw the universe.

Finish your main method by adding the following:

- Enable double buffering by calling `enableDoubleBuffering()`. This is a graphics technique to prevent flickering in the animation. This should be just a single method call, so you shouldn't do anything complicated here. You can see an example in `StdDrawDemo.java`. Here's the offical documentation that explains it in a few sentences. You don't have to understand this for CS61B. Just know that if you don't call this function, any attempt at smooth animation will look bad and flickery (remove it and see what happens!).
    - When double buffering is enabled by calling `enableDoubleBuffering()`, all drawing takes place on the offscreen canvas. The offscreen canvas is not displayed. Only when you call `show()` does your drawing get copied from the offscreen canvas to the onscreen canvas, where it is displayed in the standard drawing window. You can think of double buffering as collecting all of the lines, points, shapes, and text that you tell it to draw, and then drawing them all simultaneously, upon request.
- Create a time variable and set it to 0. Set up a loop to loop until this time variable is `T`.
- For each time through the loop, do the following:
- Create an `xForces` array and `yForces` array.
- Calculate the net x and y forces for each planet, storing these in the `xForces` and `yForces` arrays respectively.

- Call update on each of the planets. This will update each planet's position, velocity, and acceleration.
- Draw the background image.
- Draw all of the planets.
- Show the offscreen buffer (see the `show` method of StdDraw).
- Pause the animation for 10 milliseconds (see the `pause` method of StdDraw). You may need to tweak this on your computer.
- Increase your time variable by `dt`.

Important: For each time through the main loop, do not make any calls to `update` until all forces have been calculated and safely stored in `xForces` and `yForces`. For example, don't call `planets[0].update()` until after the entire `xForces` and `yForces` arrays are done! The difference is subtle, but the autograder will be upset if you call `planets[0].update` before you calculate `xForces[1]` and `yForces[1]`.

Compile and test your program:

```
javac NBody.java
java NBody 157788000.0 25000.0 data/planets.txt
```

Make sure to also try out some of the other simulations, which can all be found in the `data` directory. Some of them are very cool.

Printing the Universe

When the simulation is over, i.e. when you've reached time `T`, you should print out the final state of the universe in the same format as the input, e.g.:

```
5
2.50e11
1.4925e+11 -1.0467e+10  2.0872e+03  2.9723e+04  5.9740e+24    eart
-1.1055e+11 -1.9868e+11  2.1060e+04 -1.1827e+04  6.4190e+23     mar
-1.1708e+10 -5.7384e+10  4.6276e+04 -9.9541e+03  3.3020e+23 mercur
2.1709e+05  3.0029e+07  4.5087e-02  5.1823e-02  1.9890e+30       su
6.9283e+10  8.2658e+10 -2.6894e+04  2.2585e+04  4.8690e+24    venu
```

You are welcome to try to figure this out on your own, but if you'd prefer not to, the solution is right below:

```
StdOut.printf("%d\n", planets.length);
StdOut.printf("%.2e\n", radius);
for (int i = 0; i < planets.length; i++) {
```

```
        StdOut.printf("%11.4e %11.4e %11.4e %11.4e %11.4e %12s\n",
                      planets[i].xxPos, planets[i].yyPos, planets[i].x
                      planets[i].yyVel, planets[i].mass, planets[i].im
  }
```

This isn’t all that exciting (which is why we’ve provided a solution), but we’ll need this method to work correctly to autograde your assignment.

Submission

Submit to Gradescope via Github. If you pass all the tests, you get all the points. Hoorah! You may submit as many times as you’d like. If you have multiple submissions, select the one you wish for us to grade by pressing activate. If you are working with a partner, be sure to add them on Gradescope—after you make your submission, click “Add Group Member” (above your score).

Important note: any image or sound files you add to your NBody folder will NOT be saved to your git repository. We've set up a file called .gitignore that will restricts you to only adding .java and .txt files. This is to keep your repos small so that the autograder moves quickly. We ask that you do not use the force command to upload other types of files, especially if they are large.

Trying Out Other Universes

There are many more universes provided in the skeleton other than `planets.txt`. You can find them in the `data` folder, e.g. `java NBody 20000000 20000 ./data/suninterference.txt`. Try them out and see if you can find any favorites.

For those of you who want to create and share universes, we’ve created a marketplace for sharing student and staff created content associated with homeworks and projects that have easily sharable contents like `NBody`. This tool Bazaar (LINK COMING SOON) hosts universe files that you can download and check out for yourself. You can also upload your own universe file to the site and vote on which ones you like best. If you’re interested in learning more about this tool and how to use it, check out this guide here (LINK ALSO COMING SOON).

Simulating a universe from the web is as simple as giving a URL instead of a filename, for example: `java NBody 100000000 65000 http://TBA.com/fourellipses.txt`.

Extra for Experts

Adding Audio

For a finishing touch, play the theme to *2001: A Space Odyssey* using `StdAudio` and the file `2001.mid`. Feel free to add your own audio files and create your own soundtracks! You may find the StdAudio section of this mini-tutorial helpful. There is no extra credit for adding sound. For some reason in more recent versions of Java, `StdAudio` has occasionally failed to work. We'll try to help, but we've had a few cases where we were unable to get the sound file to play.

Going Above and Beyond (Gold Points)

For those of you who finish early and want to try something wild, crazy, and new, create new files `NBodyExtreme.java` and `PlanetExtreme.java`. You may also add additional classes as needed. Please include "Extreme" at the end of the filenames for clarity.

In the Extreme version of your NBody simulator, you should do something fundamentally new. There are a number of other interesting possibilities:

- Support elastic (or inelastic) collisions.
- Add the ability to programmatically generate planet images (rather than relying on input image files).
- Add the ability to control a spacecraft that is subject to the gravitational forces of the objects in the solar system.

No tips are provided here in the spec. If you want to know how to do any of the things listed above (or something else of your own imagining), try using search engines to learn how to do the thing you want to do.

For 12 gold points, create a public youtube video that demonstrates the behavior `NBodyExtreme` and explains the changes you made. This video should be between 3 and 15 minutes long, and must include examples of the code running. Ideally, you'll have a narrative voiceover, though it's OK if you just want to use text captions instead. As with the assignment itself, we do not provide any specific guidance on HOW to make your video, and again encourage you to use search engines to learn how. Gold Points are all about staking off on your own and doing something independently. For reference, I've found that OBSStudio is pretty good for recording videos, and it's what I use for the lecture recordings.

There are no specific requirements for these points. If you've built something big enough that you feel happy publicly sharing and explaining what you've made, that's good enough for us. Make sure your `NBodyExtreme` and `PlanetExtreme` are pushed to GitHub. When you've posted your video, fill out this form.

Even though your youtube video will be public, you should not post your code publicly. In addition, **you should not display your code in the video**.

Frequently Asked Questions

I'm passing all the local tests, but failing even easy tests like testReadRadius in the autograder.

Make sure you're actually using the string argument that testReadRadius takes as input. Your code should work for ANY valid data file, not just planets.txt.

The test demands 133.5, and I'm giving 133.49, but it still fails!

Sorry, our sanity check tests have flaws. But you should ensure that your value for `G` is 6.67 * 10^{-11} N-m^2 / kg^2 exactly, and not anything else (don't make it more accurate).

When I run the simulation, my planets start rotating, but then quickly accelerate and disappear off of the bottom left of the screen.

- Look at the way you're calculating the force exerted on a particular planet in one time step. Make sure that the force doesn't include forces that were exerted in past time steps.
- Make sure you did not use `Math.abs(...)` when calculating `calcForceExertedByX(...)` and `calcForceExertedByY(...)`. Also ensure that you are using a `double` to keep track of summed forces (not `int`)!

Why'd you name the class Planet? The sun isn't a Planet.

You got us. We could have used Body, but we didn't. Maybe next time?

What is a constructor? How do I write one?

A constructor is a block of code that runs when a class is instantiated with the `new` keyword. Constructors serve the purpose of initializing a new object's fields. Consider an example below:

```
public class Dog {
    String _name;
    String _breed;
    int _age;

    public Dog(String name, String breed, int age) {
        _name = name;
        _breed = breed;
        _age = age;
    }
}
```

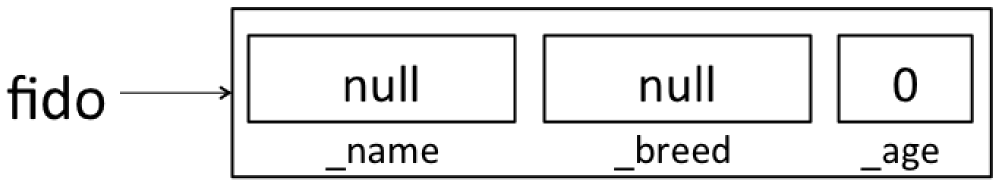
The `Dog` class has three non-static fields. Each instance of the `Dog` class can have a name, a breed, and an age. Our simple constructor, which takes three arguments, initializes these fields for all new `Dog` objects.

I’m having trouble with the second Planet constructor, the one that takes in another Planet as its only argument.

Let’s walk through an example of how a constructor works. Suppose you use the `Dog` constructor above to create a new `Dog`:

```
Dog fido = new Dog("Fido", "Poodle", 1);
```

When this line of code gets executed, the JVM first creates a new `Dog` object that’s empty. In essence, the JVM is creating a “box” for the `Dog`, and that box is big enough to hold a box for each of the `Dog`’s declared instance variables. This all happens before the constructor is executed. At this point, here’s how you can think about what our new fluffy friend `fido` looks like (note that this is a simplification! We’ll learn about a more correct view of this when we learn about Objects and pointers later this semester):



Java will put some default values in each instance variable. We’ll learn more about where these defaults come from (and what `null` means) later this semester. For now, just remember that there’s space for all of the instance variables, but those instance variables haven’t been assigned meaningful values yet. If you ever want to see this in action, you can add some print statements to your constructor:

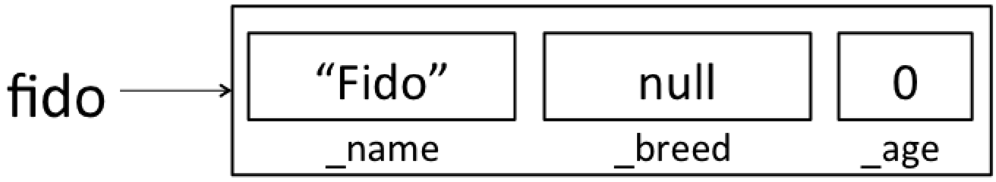
```
public Dog(String name, String breed, int age) {
    System.out.println("_name: " + _name + ", _breed: " + _breed
```

```
        _name = name;
        _breed = breed;
        _age = age;
    }
```

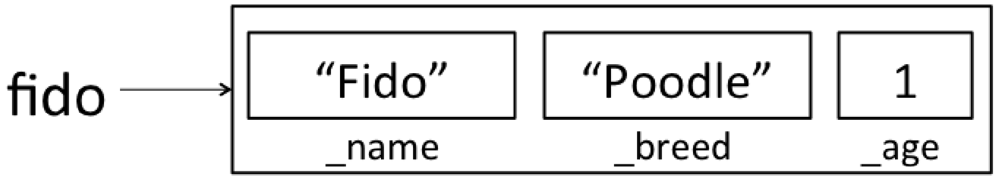
If this constructor had been used to create `fido` above, it would have printed:

```
_name: null, _breed: null, _age: 0
```

OK, back to making `fido`. Now that the JVM has made some "boxes" for `fido`, it calls the `Dog` constructor function that we wrote. At this point, the constructor executes just like any other function would. In the first line of the constructor, `_name` is assigned the value `name`, so that `fido` looks like:



When the constructor completes, `fido` looks like:



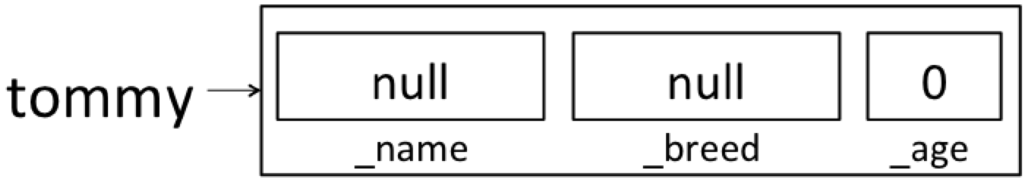
Now, suppose you want to create a new `Dog` constructor that handles cross-breeding. You want the new constructor to accept a name, an age, and two breeds, and create a new `Dog` that is a mixture of the two breeds. Your first guess for how to make this constructor might look something like this:

```
public Dog(String name, String breed1, String breed2, int age) {
    Dog dog = new Dog(name, breed1 + breed2, age);
}
```

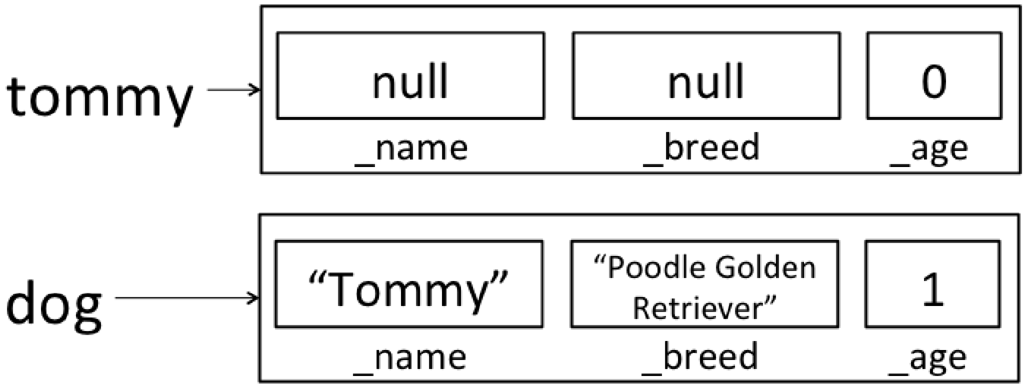
However, if you try to create a new `Dog` using this constructor:

```
Dog tommy = new Dog("Tommy", "Poodle", "Golden Retriever", 1);
```

This won't do what you want! As above, the first thing that happens is that the JVM creates empty "boxes" for each of `tommy`'s instance variables:



But then when the 4-argument constructor got called, it created a second `Dog` and assigned it to the variable `dog`. It didn't change any of `tommy`'s instance variables. Here's how the world looks after the line in our new constructor finishes:

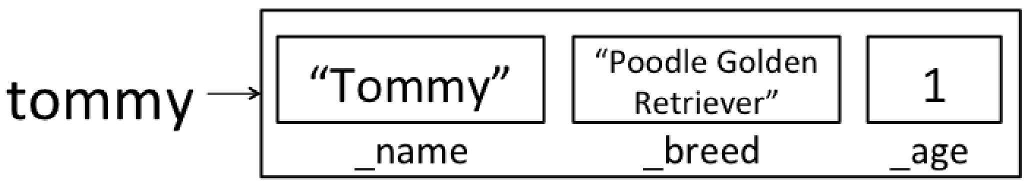


`dog` isn't visible outside of the constructor method, so when the constructor completes, `dog` will be destroyed by the garbage collector (more on this later!) and all we'll have is the still un-initialized `tommy` variable.

Here's a cross-breed constructor that works in the way we'd like:

```
public Dog(String name, String breed1, String breed2, int age) {
    this(name, breed1 + breed2, age);
}
```

Here, we're calling the old 3-argument constructor on `this`; rather than creating a new `Dog`, we're using the 3-argument constructor to fill in all of the instance variables on this dog. After calling this new constructor to create `tommy`, `tommy` will correctly be initialized to:



We could have also written a new constructor that assigned each instance variable directly, rather than calling the existing constructor:

```
public Dog(String name, String breed1, String breed2, int age) {
    _name = name;
    _breed = breed1 + breed2;


    _age = age;
```

```
}
```

Acknowledgements

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