JOURNEY through the UNIVERSE

Voyage: A Journey through our Solar System

Grades 9-12

Lesson 1: A Scale Model Solar System

On a visit to the National Mall in Washington, DC, one can see monuments of a nation—Memorials to Lincoln, Jefferson, and WWII, the Vietnam Veterans Memorial Wall, and Washington Monument. Standing among them is *Voyage*—a one to 10-billion scale model of our Solar System—spanning 2,000 feet from the National Air and Space Museum to the Smithsonian Castle. *Voyage* provides visitors a powerful understanding of what we know about Earth's place in space and celebrates our ability to know it. It reveals the true nature of humanity's existence—six billion souls occupying a tiny, fragile, beautiful world in a vast space.

Voyage is an exhibition that speaks to all humanity. The National Center for Earth and Space Science Education is therefore making replicas of *Voyage* available for permanent installation in communities worldwide (http://voyagesolarsystem.org.)

This lesson is one of many grade K-12 lessons developed to bring the *Voyage* experience to classrooms across the nation through the Center's *Journey through the Universe* program. *Journey through the Universe* takes entire communities to the space frontier (http://journeythroughtheuniverse.org.)

The *Voyage* exhibition on the National Mall was developed by Challenger Center for Space Science Education, the Smithsonian Institution, and NASA.

Lesson 1: A Scale Model Solar System

Lesson at a Glance

Lesson Overview

Physical models are powerful tools of exploration. Even simple models can provide enormous understanding about the real objects they represent. In this lesson, students will investigate the properties of scale models of our Solar System. They will then try to design a conveniently-sized scale model of the Solar System to recognize that the model will likely need to be bigger than they thought.

Lesson Duration

One 50-minute class period

Core Education Standards

National Science Education Standards

Standard E1: Abilities of technological design

- Propose designs and choose between alternative solutions: Students should demonstrate thoughtful planning for a piece of technology or technique. Students should be introduced to the roles of models and simulations in these processes.
- Implement a proposed solution: A variety of skills can be needed in proposing a solution depending on the type of technology that is involved. The construction of artifacts can require the skills of cutting, shaping, treating, and joining common materials—such as wood, metal, plastics, and textiles. Solutions can also be implemented using computer software.
- Evaluate the solution and its consequences: Students should test any solution against the needs and criteria it was designed to meet. At this stage, new criteria not originally considered may be reviewed.

AAAS Benchmarks for Science Literacy
Benchmark 11B1:

- A mathematical model uses rules and relationships to describe and predict objects and events in the real world. A mathematical model may give insight about how something really works or may fit observations very well without any intuitive meaning.

Related Education Standards

AAAS Benchmarks for Science Literacy
Benchmark 9A1:

- Comparison of numbers of very different size can be made approximately by expressing them as nearest powers of 10.

Essential Questions

- How can a single scale model effectively demonstrate relative size and distance within the Solar System?
- Why is a single scale model better than multiple models and/or charts?

Concepts

Students will learn the following concepts:

- Models are powerful tools of exploration.
- In a scale model, all linear sizes and distances are reduced or enlarged by the same factor, but areas and volumes are not changed by the same factor.
- The sizes of the planets in the Solar System span a large range.
- It is difficult to construct a scale model in which the sizes of the planets and the distances between them are portrayed accurately at the same time.

Objectives

Students will be able to do the following:

- Create a scale model of the Solar System through scaling of the sizes and distances of Solar System objects.
- Determine whether a reasonable scale model can be drawn on a single sheet of paper.
- Define the characteristics of the Solar System that make construction of a good scale model so difficult.

Science Overview

Review of Scale Models

In a scale model, all linear sizes and distances are reduced or enlarged by the same factor, but areas and volumes are not changed by the same factor.

Models are powerful tools because they represent real objects scaled to humanly manageable sizes; a terrestrial globe is one example. Scale factors determine the relation between the model and the real object. The scale factor, s.f., can be defined as

$$\text{s.f.} = \frac{D_{Real}}{D_{Model}}$$

where D represents a measure (such as diameter or distance) with subscript *Real* for the real object and *Model* for the model. When both D_{Real} and D_{Model} have the same units, the scale factor, s.f., is dimensionless. In such a case, the scale factor is sometimes referred to as the constant of proportionality.

For example, a bow used at the Olympics is approximately 1.5 m long. A model toy bow is about 0.5 m long. The scale factor is

$$\text{s.f.} = \frac{D_{Real}}{D_{Model}} = \frac{1.5\text{ m}}{0.5\text{ m}} = 3$$

Thus, the real object is three times larger than the model, this means that 1 m on the model is really 3 m (i.e. 3 m on the real object).

In this example, only proportions were changed going from the real to the model bow. Other times, different units may be used on the model than on the real object. In such a case, the scale factor becomes

$$\text{s.f.} = \frac{D_{Real}\text{ (in real units)}}{D_{Model}\text{ (in model units)}}$$

For example, a street map may have a scale of 5 km/cm, which means that every centimeter on the map represents 5 km in the real world.

A scale, as opposed to a scale factor, is always dimensionless and refers to proportions only. It is written as

1 : scale

The relation between the scale factor, s.f., and the scale is

s.f. = *scale* × *(conversion factor from real units to model units)*

For example, a map of Lindbergh's flight from New York to Paris shows the distance he flew as 20 cm. The map is a model, however, and on the real Earth the distance he flew is 5,900 km. The scale factor is thus:

$$\text{s.f.} = \frac{5900\ \text{km}}{20\ \text{cm}} = 295\ \frac{\text{km}}{\text{cm}} = \mathit{scale} \times \left(\frac{1\ \text{km}}{100{,}000\ \text{cm}}\right)$$

where the real units are in km and the model units are in cm (and 1 km = 100,000 cm). Therefore the scale on the map was

1:29,500,000

so that 20 cm on the map corresponded to 590 million cm on Earth (or 5,900 km).

Solar System Object Sizes and Distances

Sizes and distances of Solar System objects are shown in Table 1 below. Distances are given in Astronomical Units (AU). One AU is the average distance from the Sun to the Earth—149.6 million km (or 93.0 million miles). Note the wide variation among the distances to the planets. Pluto, included here as an example of dwarf planets, is more than 100 times farther from the Sun than is Mercury. Pluto's distance from the Sun is more than 15,000 times the Earth-Moon distance. Therefore, it is not easy to make a small scale-model Solar System that shows the locations of the Sun and Pluto, as well as the Earth and Moon. Portraying the sizes of the Solar System bodies on the same scale as their distances is even more problematic. The Sun-Pluto distance is 2.5 million times the diameter of Pluto. It is therefore clear that showing the size of the objects as well as their distances cannot be done with a small model.

Table 1. Sizes and Distances in the Solar System

	Distance from Sun (AU)	Diameter (km)
Sun	0.0	1,400,000
Mercury	0.39	4,900
Venus	0.72	12,100
Earth	1.00	12,800
Mars	1.52	6,800
Jupiter	5.20	143,000
Saturn	9.58	121,000
Uranus	19.20	51,000
Neptune	30.05	50,000
Pluto (dwarf planet)	39.48	2,400

Conducting the Lesson

Warm-Up & Pre-Assessment

Teacher Materials

- Several models (e.g., model airplanes)
- Objects with simple geometric shapes (e.g., ball, dice, cone)
- Various Solar System posters (or the pictures from Student Worksheet 1)

Student Materials

- Calculator
- Pencil
- Paper
- Metric ruler with mm divisions
- Student Worksheet 1

Preparation & Procedures

1. Place some scale models (cars, airplanes, buildings, etc.) around the classroom.

2. If you can find some models that are not to scale, have them available as well.

3. Give each student a copy of Student Worksheet 1.

4. Ask students to brainstorm a list of characteristics of scale models. Write responses on the board, and then discuss, modify, and correct the list until it is satisfactory. (*Desired answer: dimensions, surface area, volume. All linear dimensions—length, width, height, diameter, etc.— are in the same proportion to the original*)

5. Ask students to identify any models that may be in the classroom. Challenge them to estimate the scale factors for those models.

6. Ask students to think of other examples of scale models. (*Desired answer: an architect may make a scale model of a building. If it is a 1:50 scale model, then the model's height, length, and width are all 1/50 of the size of the real building.*)

7. Referring to examples from Step 5, ask what quantities (related to distance, size, area, volume, etc.) are to scale. (*Desired answer: only distances and linear dimensions (e.g., width) will be to scale. Area will vary as the square of the linear dimension, and the volume will vary as the cube of the linear dimension. For example, if you have a sphere that is a 1:10 scale model of the real thing, its diameter is 1/10 the size of the original, its surface area is 1/100 that of the original, and its volume is 1/1000 that of the original.*)

8. Have students use their calculators to work other examples (using different scale factors).

9. Have students complete Student Worksheet 1.

Activity 1: Use a Scale Model to Compare Planet Sizes

Students examine a model of planets in the Solar System to investigate the nature of scale models. They determine what can be learned of the real objects with the help of scale models, and what may be the limitations of models. They use the model to compare the sizes of the planets.

Student Materials (per student)

- Calculator
- Pencil
- Paper
- Metric ruler with mm divisions
- Student Worksheet 2

Preparation & Procedures

1. Put the students in pairs.

2. Have students complete Questions 1-3 and the Data Table on Student Worksheet 2.

3. Discuss student answers and results.

4. Emphasize the fact that students were able to learn about circles and the planet sizes because the circles are scaled with respect to one another. A circle by itself cannot be compared.

Lesson Adaptation

Talented and Gifted: Imagine you had to design a spaceship. You know that a capsule 1.5 m x 1.5 m x 2 m has a volume big enough for one astronaut. What should the dimensions of your spaceship be for eight astronauts? (Desired answer: If each linear dimension is doubled, then the volume will increase by a factor of 8—which is what we want. Thus, the dimensions would have to be 3 m x 3 m x 4 m.)

Reflection & Discussion

Discuss student answers to Questions 4-7 on Student Worksheet 2.

Transfer of Knowledge

Have students apply their knowledge of scale models to a different world (in this case, Mars) by answering Questions 8 and 9 in Student Worksheet 2.

Assessment Criteria for Activity 1

Student performance can be evaluated according to the following criteria:

- Table in Worksheet 2 is filled out correctly.
- Students have a better feeling of the range of sizes among the planets.
- Answers to Questions 4-7 in Worksheet 2 show an understanding of the power of models.

Placing the Activity Within the Lesson

Discuss with the students how Activity 1 helps them to understand the power of scale models. Have students brainstorm ways they can create their own scale model.

Notes on Activity 1:

Activity 2: Draw a Scale Model Solar System

Students attempt to draw a scale model Solar System on one sheet of paper and discover that is impossible to draw the sizes of the planets on the scale that is necessary to portray the distances in the scale model correctly.

Student Materials (per student)

- Calculator
- Pencil
- Paper
- Metric ruler with mm divisions
- Student Worksheet 3

Preparation & Procedures

1. Have students complete Part I of Student Worksheet 3. Make sure the students understand how to calculate scale factors for the models. Emphasize that to create a true model, the size of the planets and the Sun must be represented correctly. This means to draw the diameters of planets and the Sun using the same scaling factor as the one used to determine their relative distances. They will find that the diameters are too small to be drawn at all!

2. Part II starts by assigning a size for the diameter of the model Sun. Explain that a 2.5 mm diameter Sun is chosen only so that we will be able to see the model Sun clearly, and then have students complete Part II of Student Worksheet 3.

3. Discuss Part II. Make sure that you discuss the fact that a model that shows the relative sizes of the Sun and planets in a useful manner, and that shows their relative distances, cannot fit on a single sheet of paper.

4. Reflect on what this implies for the distances between the planets compared to the size of the planets. Ask how a useful model of the Solar System should be designed. Note that the actual design of such a model is part of the next lesson in this module (*The Voyage Scale Model Solar System*).

Reflection & Discussion

Discuss with the students the answers to Questions 1-4 in Student Worksheet 3.

Transfer of Knowledge

There are many cases in which building a scale model can be challenging. Have students brainstorm other interesting models that could be built and the challenges associated with such models.

Assessment Criteria for Activity 2

Student performance can be evaluated according to the following criteria:

- Part I of Worksheet 3 is filled out correctly.
- Part II of Worksheet 3 is filled out correctly.
- Answers to Questions 1-3 in Student Worksheet 3 show a grasp of the challenges in designing a scale model of the Solar System.

Placing the Activity Within the Lesson

Discuss how Activity 2 helps students to understand that creating a scale model it is not always a simple matter. While a scale model is usually used to represent a very large (or small) object, the scale model may still have very large or small parts to it.

NOTES ON ACTIVITY 2:

Lesson Wrap-Up

Transfer of Knowledge for the Lesson

Have students examine whether they can portray a scale model of a water molecule accurately on a piece of paper. What are some problems they encounter? How are these problems similar and different from the problems of creating a scale model Solar System?

Assessment Criteria for the Lesson

Student performance can be evaluated according to the following criteria:

- All linear sizes in a scale model are to the same scale (but not areas or volumes).
- Even when they have a scale model, some sizes or distances might still be very large or very small.
- Much can be learned about an object or collection of objects by making use of a scale model.

Lesson Closure

Scale models are extremely powerful tools. They have applications in many different fields (chemists might have models of molecules, architects have models of buildings, etc.) Now that students have some idea of what it takes to make a scale model Solar System, they are prepared to go on to the next lesson and design a realistic scale model Solar System with almost the same scale as the *Voyage* scale model Solar System in Washington, DC.

Extensions for the Lesson

- Have students search in textbooks and on the Internet for different kinds of model Solar Systems and determine what is scaled correctly (distance or size).
- Is there a model Solar System that shows both distance and size accurately?

Curriculum Connections

Scale models are used in other disciplines such as geography (with maps, globes, etc., which are made to a certain scale), art/architecture (with scale model buildings or other scale representations), and even music (in which the word "scale" is used for a sequence of tones that have frequencies with certain ratios relative to one another).

Resources

Internet Resources & References

Student-Friendly Web Sites:

Astronomical Picture of the Day
    antwrp.gsfc.nasa.gov/apod/
NASA: Planetary Photojournal
    photojournal.jpl.nasa.gov
The Nine Planets
    www.nineplanets.org
Star Date
    stardate.org/resources/ssguide/

Teacher-Oriented Web Sites:

AAAS Benchmarks for Science Literacy
    www.project2061.org/tools/benchol/bolintro.htm
Exploring Planets in the Classroom
    www.spacegrant.hawaii.edu/class_acts/
NASA: Planetary Photojournal
    photojournal.jpl.nasa.gov
NASA: Planetary Sciences at the National Space Science Data Center
    nssdc.gsfc.nasa.gov/planetary/
NASA Quest
    quest.arc.nasa.gov/sso/teachers/
National Science Education Standards
    www.nap.edu/html/nses/
The Nine Planets
    www.nineplanets.org
Star Date
    stardate.org/resources/ssguide/
Voyage: A Journey through Our Solar System
    www.voyagesolarsystem.org
Journey through the Universe
    www.journeythroughtheuniverse.org
Discussion about Pluto's reclassification as a dwarf planet
    www.voyagesolarsystem.org/pluto/pluto_default.html

Teacher Answer Key

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Student Worksheet 1

Figure 1 comments: Neither the relative sizes nor distances are portrayed accurately.

Figure 2 comments: The relative sizes are portrayed accurately but the relative distances are not.

1. 25 cm
2. 1/16 of the original cube's surface area
3. 1/64 of the original cube's volume.

Student Worksheet 2

Data table

Note: The (crudely measured) values in this table may be different depending on how the diagram changed size during reproduction. Although the students' numbers for mm measurements may be different, the diameters, surface areas, and volumes in terms of Earth units should be almost the same.

	Earth	Pluto	Jupiter
Diameter (mm)	8	2	83
Diameter (in units of Earth diameters)	1.0	0.25	10.4
Surface Area (in mm^2)	201	13	2.2×10^4
Surface Area (in units of Earth surface areas)	1.0	0.065	109
Volume (in mm^3)	268	4	3.0×10^5
Volume (in units of Earth volumes)	1.0	0.015	1.1×10^3

The calculated values may vary slightly from actual values due to the precision of the rulers, student's skill in making measurements, etc.

1. No. Without knowing the scale factor, I don't know how big the object really is.
2. No. Surface area scales in proportion to the square of the radius (or diameter), while volume scales in proportion to the cube of the radius (or diameter).
3. We learned
   - how many real Earths fit across the real Jupiter and Pluto.
   - how the surface area of the real Pluto and real Jupiter compare to the surface area of Earth.
   - how many Earths fit inside the real Jupiter and the real Pluto.

4. They allow people to see relative sizes.
5. We can learn how big one object (or part of an object) is compared to another.
6. We cannot learn other characteristics (besides sizes and distances), such as the object's real color.
7. Both. Explanations will vary.
8. Radius = 2.2 mm
   Surface area = 61 mm^2 = 0.3 x Earth's surface area
9. They're very similar. Exploring the surface of Mars would be as big a task as exploring all the land on Earth.

Student Worksheet 3

Part I

1. Answers will vary. Assuming distance from Sun to Pluto is 10 in (254 mm) on the paper,
   s.f. = 39.24 AU / 254 mm = 0.15 (in AU/mm)
2. 0.15 AU/mm x 149.6 x 10^6 km/AU = 2.24 x 10^7 km/mm *s.f.* = 2.24 x 10^7 (in km/mm)
3. For the Sun, 1,400,000 km / 2.24 x 10^7 km/mm = 0.0625 mm
   $\text{Diameter}_{\text{Sun}}$ = 0.063 (mm)
   For the Earth, 12,800 km / 2.24 x 10^7 = 0.00057 mm (!)
   $\text{Diameter}_{\text{Earth}}$ = 0.00057 (mm)
4. They're so small! It will be impossible to accurately draw the size of the Earth, and even if it were accurately drawn, it would just look like a dot. Its size wouldn't be clearly visible.

Part II

1. 1,400,000 km / 2.5 mm = 5.6 x 10^5 km/mm.
2. 39.24 AU x 149.6 x 10^6 km/AU / 5.6 x 10^5 km/mm = 10,483 mm
3. 10,483 mm / 1000 mm/m = 10.5 m.
4. About 42 (10 in per sheet = 0.254 m per sheet; number of sheets = 10.5 m / 0.254 m/sheet)
5. Because the distances to the planets are so enormous compared to their sizes.

Questions

1. It would be useful only for seeing the relative distances.
2. It would be useful only for seeing the relative sizes.
3. You wouldn't be able to see how the sizes of the planets compared to the distances between the planets.
4. A model showing only correct distances to scale may cause one to think that the planets are much larger than they really are compared with the distances between the planets. A model showing only correct sizes of the planets to scale may cause one to think that the distances are much smaller than they really are.
5. Answers will vary.

Student Worksheet 1: A Scale Model Solar SYstem

Name ______________________________ Date __________

In what ways do these pictures accurately or not accurately represent relative sizes and distances in the Solar System?

Figure 1

Comments:

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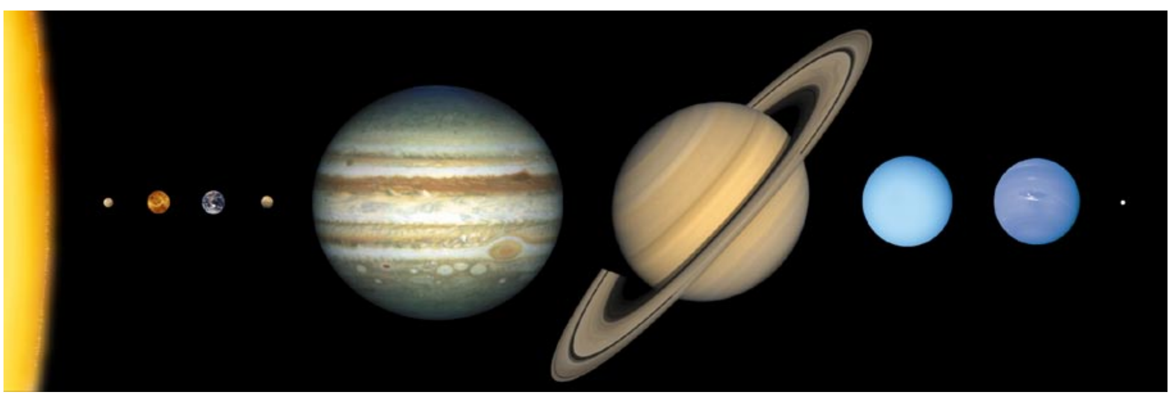
Figure 2



Comments:

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Questions

1. Given a cube with each side one meter long, what would be the length of the side of a 1/4 scale model?

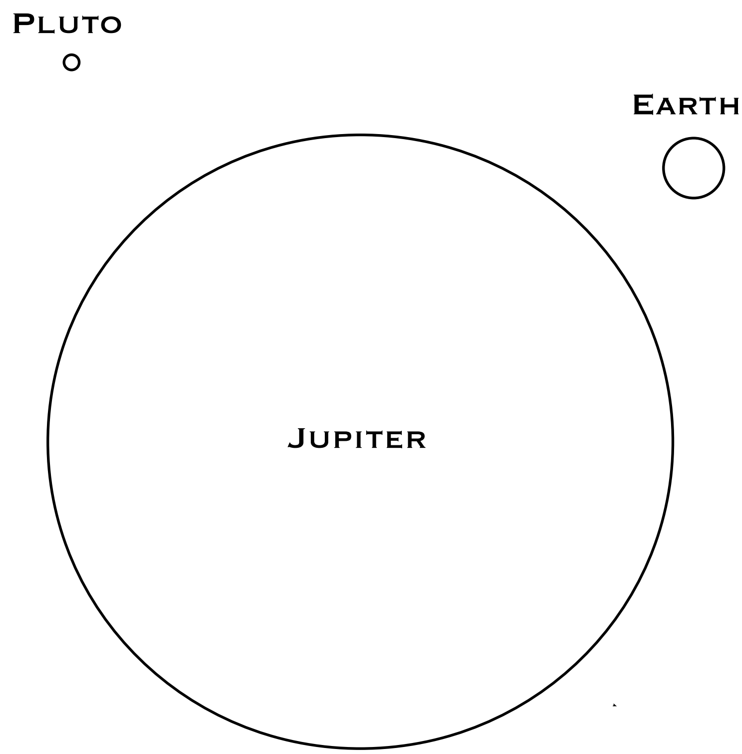
2. How does the surface area of this scale model cube compare to the original?

3. How does the volume of this scale model cube compare to the original?

Student Worksheet 2: Use a Scale Model to Compare Planet Sizes

Name ______________________________ Date __________

In the figure, three models of Solar System bodies are shown using one scale. Although these are but three circles, fill out the table below to get a sense of the amount of information contained in this model.



Basic Geometric Formulas

Volume of a sphere: $V = {}^{4}/_{3}\, \pi \times Radius^3$

Surface Area: $a_{circle} = \pi \times Radius^2$

$a_{sphere} = 4\pi \times Radius^2$

Data Table

	Earth	Pluto	Jupiter
Diameter (mm)			
Diameter (in units of Earth diameters)	1.0		
Surface Area (in mm^2)			
Surface Area (in units of Earth surface areas)	1.0		
Volume (in mm^3)			
Volume (in units of Earth volumes)	1.0		

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1. In the picture, does one circle on its own contain much information? Why?

2. Is the scale of the surface area and volume the same scale as the diameter? Why or why not?

3. What have we learned about the real planets based on the models?

4. Why is a scale model useful?

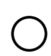
5. What can be learned from a scale model?

6. What information is missing from a scale model?

7. Can scale models be used for both very large objects and very small objects? Explain your answer.

8. Below is the size of Mars on the same scale as the diagram on the previous page. Calculate the surface area of Mars: first in mm^2, and then in units of Earth surface areas.

Mars



9. Over 70% of the Earth's surface is covered with water. How does the land area of Mars compare with the land area on Earth?

Student Worksheet 3: Draw a Scale Model Solar System

Name ________________________________ Date __________

Part I

Suppose you want to draw a scale model Solar System including the Sun and planets. Using a blank sheet of paper, mark a position for the Sun at one end of the paper and a position for the dwarf planet Pluto at the other end. Sizes and distances of the Sun and planets are provided in the table on the next page.

1. What scale factor (*s.f.*) is your model Solar System using?

   s.f. = ______________ (in AU/mm)

2. Given that Earth's distance from the Sun is 149.6 million km, change the units of the scale factor to km/mm.

   s.f. = ______________ (in km/mm)

3. Based on that scale, calculate the size of the model Sun and of Earth.

   $\text{Diameter}_{\text{Sun}}$ = __________(mm)

   $\text{Diameter}_{\text{Earth}}$ = __________(mm)

4. Do you see any problem with these sizes?

Part II

This time, we will start with a reasonable diameter for the Sun: say a circle 2.5 mm (1/10 inch) in diameter.

1. What is the scale factor?

   s.f. = ______________ km/mm

2. On this scale, how many millimeters is it from the Sun to Pluto? ______________ mm

3. How many meters is it from the Sun to Pluto? ____________ m

4. How many sheets of paper would you need to draw the distance from the Sun to Pluto on this scale?

5. Why is it so hard to fit the entire Solar System on a single sheet of paper and to be able to draw the diameter of the Sun and the planets?

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Sizes and Distances in the Solar System		
	Distance from Sun (AU)	Diameter (km)
Sun	0.0	1,400,000
Mercury	0.39	4,900
Venus	0.72	12,100
Earth	1.00	12,800
Mars	1.52	6,800
Jupiter	5.20	143,000
Saturn	9.58	121,000
Uranus	19.20	51,000
Neptune	30.05	50,000
Pluto (dwarf planet)	39.48	2,400
1 AU = 149.6 million km		

Questions

1. How would a model Solar System that shows the distances to scale, but not the sizes be useful?

2. How would a model Solar System that shows the relative sizes to scale, but not the distances be useful?

3. What information would you not get in either of the models in the two questions above?

4. How might such models lead to misconceptions?

5. Brainstorm with other students about other interesting models that could be built and the challenges associated with such models.