1. How strong is the earth's gravity here at the surface? g_1 = ____ ______
   How far are we from the center of the earth? D_1 = _____ _____ (from p. ____ in the book)

2. Suppose the earth's gravity behaves like the sun's gravity, so that **g** is proportional to _______, as on page 112. If that is the case, then doubling our distance from the center should cause "g" to be multiplied by ____. Increasing "D" by a factor of 10 will cause "g" to ___crease by a factor of ___.

3. The moon is much farther from the earth's center than we are. Let "D_2" represent that distance. Using the information saved from p. 112 with #1 above, D_2/D_1 = (______)÷(_______) = _______.
   According to #2 we can calculate the ratio g_2/g_1 by inverting and _________ing that D ratio.
   (See 17d on RS II) - We get g_2 = ( )(g_1) = ______ m/s^2.

4. The "g_2" mentioned in #3 represents the strength of the _______'s gravity out where the ______ is located. Since the object mentioned in that last blank is falling freely, we expect its acceleration to be ________ m/s^2. (Use #3!) Did you round off properly in #1-3? ____
   a. Does that acceleration agree with the value that you saved from page 112? _____
   b. We can conclude that the hypothesis stated in #2 seems to be ________. (correct, wrong)
   c. How do you expect Jupiter's gravity to depend on distance from its center? __________
   * d. How could you find out if that guess is correct, without going to Jupiter? *Give detailed instructions.*

5. On pages 6, 32, 35, 39, RS III, and RS V you described how the gravitational force exerted on an object depends on the object's mass and the strength of the gravity. "Force = ____." In that equation the letter "__" represents the strength of the gravitational field. The SI unit for that field strength is the ___per___ or (equivalently) the ___per___. For example, in our lab the gravitational force on a 2-kg object would be (2.0 kg)(___ ___) = ___ ____.

6. In #2 on RS III you recorded Newton's "**interaction law**": "If object A pulls on B, then B pulls back on ___ with an ______ amount of force in the _________ direction." If we can double the gravitational attraction between two objects such as the earth and a banana by doubling the mass of *one* of the objects, (the banana) then symmetry demands that we can also double the force by doubling the *other* mass. If you see a flaw in that logic, please explain. If not, summarize your conclusions:
   a. Any two objects which have _______ must attract each other with a gravitational force.
   b. Let "__" represent the mass of the first object. How is the force of attraction related to that mass?
      F is ____________al to the mass. -Does 6b contradict #5? ____
   c. Let "__" represent the mass of the second object. How does the force of attraction depend on that mass? -Symmetry demands that **F must also be proportional to ____.**
   d. If the two objects are spherical and the *center-to-center* distance between them is "d", then the force is related to that distance as in #2: **F is proportional to ____.** *Insert a letter with an exponent.*

7. Combine the three relations reviewed in #6 into a single formula for gravitational attraction.
   Use the symbols defined in #6 and use "G" *(not "g")* to represent the proportionality constant:
   a. **F =** ________ (That **"Universal Law of Gravitation"** is recorded in #__ on RS ___.**)**
   b. Why is "G" called the **"Universal"** gravitation constant?
   c. Give examples of *other* universal constants, and some that are *not* universal.

* 8. Have we proved that *all* objects generate gravitational fields which diminish with distance as in #2? Please summarize the proof ***or*** describe the limitations of the evidence.

9. Suppose we reduced the earth's gravity to one billionth (10^{-9}) of its former strength:
   a. By what factor must you reduce the mass and volume of the earth in order to do that? ____
   * b. Roughly how far would an object fall in 10 sec? _____ ___ *Show how that distance was estimated.*
   c. The volume of a sphere is proportional to the radius with what exponent? ___
   * d. Use 17d on RS II with #1 and 9c above to *estimate* the radius of an asteroid with the same density as the earth but one billionth of the earth's mass. *Explain your estimate.* Use convenient and familiar units, and round off properly.
   e. Would that asteroid's gravity be easy to detect?

1. Newton was unable to obtain the data needed to calculate the proportionality constant in his gravitation law. But he *was* able to estimate the mass of the earth. We can *estimate* the value of "G" by using that mass as a "known" value in the gravitation law. The result is no more precise than the original mass estimate, but it *can* help us design an experiment for determining "G" more accurately:
   a. Estimate the earth's average density as a range, and explain how you know that your estimate is reasonable. Remember to round off properly, and don't forget to mention its units.
   b. Express the 4000-mile radius of the earth in SI units: ______ ___
   c. Convert that radius to the length units that were used in 1a. **R =** ______ ____
   Use scientific notation and remember that we are only making rough estimates!
   d. Conclusion: The earth's volume probably is between ________ and ________ ____.
   You can use the formula for the volume of a sphere if you know it, but it's not necessary because this volume estimate doesn't need to be any more precise than the _______ estimate above.
   e. Use 1a & 1d above to estimate the mass of the earth. Convert it to SI units, and save a copy for page 116: **The earth's mass is probably between ________ and _______ ____.**
   e. With how much gravitational force does the earth attract a kilogram of matter at sea level? ____ ____
   (See page 6, 32, 35, RS III, or 112.)
   f. Rearrange Newton's universal law of gravitation (on page 113) solving it for "G": G = _______
   g. Plug in the values estimated above to estimate the G value, using scientific notation and SI units.
   Remember to round off properly. Your result will be meaningless if you omit its units.

"G" is probably between __________ and __________ _____.

2. To *measure* the value of G we need to support a small object in such a way that it can move horizontally with absolutely no friction, but cannot move vertically at all. We also need some kind of spring-like mechanism to exert a horizontal restoring force on the object.
   a. What kind of motion will result if this object is displaced a short distance and then released? ____
   b. Suppose the object's mass is one kilogram and the period of its motion is ten seconds:
   Show how the stiffness ("k") of the "spring-like mechanism" can be calculated from that information. (See #6 on RS VIII.)
   c. How much force would be needed to hold the object just one centimeter from its equilibrium position? *Show how this result is obtained.*
   * d. If this force is to be exerted by the gravitational attraction of a second spherical object at a center-to-center distance of 0.10 meter, roughly how massive must the second sphere be? *Use the "G" range estimated in #1, above. Give your estimate as a range, using scientific notation.*
   * e. The density of lead is about 11.3 gram/cm^3. How big must the lead spheres be? *Explain.*
   * f. Will it be possible to place the two spheres 0.10 meters apart, as proposed? *Explain.*

3. In 1798 Henry Cavendish borrowed an idea from John Mitchell for a more clever "spring-like mechanism". He used a lead sphere mounted as in #2, but the oscillation period was 424 sec. instead of 10 sec. The sphere's diameter was 2 inches. *Show how each of the following are calculated:*
   a. How massive must it have been?
   b. A simple pendulum with that same period would have to be ____ meters long. (See #18 on RS II.)
   c. Calculate the spring constant, i.e. the slope of the restoring force vs displacement graph.
   d. Cavendish placed a 158-kilogram lead sphere at a center-to-center distance of 22.5 cm. from the first one, hoping to observe some displacement of the small sphere due to gravitational attraction. Use the "G" values estimated in #1 to estimate the expected force in *range* form.
   e. Use that result to predict how far Cavendish must have expected the small sphere to move when he placed the big one in position.
   f. Invent and describe a possible mechanism for this experiment. Then compare your ideas with Cavendish's. (His apparatus is described in most physics textbooks.) Remember to record the value of "G" that is given in the textbook.

P.S. It is interesting that Cavendish never used his results to determine the value of "G". Instead, he calculated the mass of the earth. People in 1798 did not have the benefit of modern terms like "proportionality constant", and the distinction between weight units and mass units was not made until 1873. It was only later that the term "Newtonian constant of gravitation" was coined. By 1896 textbook authors were changing the history of science by claiming that Cavendish had measured "G".
(B. E. Clotfelter tells the whole fascinating story in the AMERICAN JOURNAL OF PHYSICS, March, 1987.)