Using High-Precision Specific Gravity Measurements to Study Minerals in Undergraduate Geoscience Courses

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ABSTRACT

This article describes ways to incorporate high-precision measurements of the specific gravities of minerals into undergraduate courses in mineralogy and physical geology. Most traditional undergraduate laboratory methods of measuring specific gravity are suitable only for unusually large samples, which severely limits their usefulness for student projects involving minerals in ordinary rocks of the sort usually encountered by working geologists. To overcome this limitation, a custom-built apparatus is described that, when combined with a precision analytical balance of the type commonly present in academic research laboratories, can be used to determine the specific gravities of samples as small as several milligrams. For a balance with precision to 0.01 mg, G can typically be measured with an accuracy of ±0.01 or better for specimens weighing several tens of milligrams and ±0.03 or better for specimens as small as 5-10 milligrams. The apparatus is easy to make and easy to use. It provides students with a simple and effective way to use quantitative methods to characterize and identify minerals in hand specimen, including small single crystals separated from common medium-grained rocks.

INTRODUCTION

Mineral characterization and identification in hand specimen have long been important parts of laboratory exercises in mineralogy and physical geology. Hands-on activities involving the careful examination and identification of minerals can help students develop observational, analytical, and critical skills as they familiarize themselves with common rock-forming and ore minerals (*e.g.* Moecher, 2004; Hollocher, 2008). Learning and experimenting with the relevant analytical methods simultaneously helps students hone their practical skills and critical thinking abilities (Wulff, 2004). Examples of specific classroom and laboratory exercises for undergraduates, culled from an NSF-sponsored workshop on "Teaching Mineralogy", are provided by Brady *et al.* (1997) and have been compiled on a website (Science Education Resource Center: Teaching Mineralogy, 2009).

In mineralogy and physical geology classes, hand specimen mineralogy typically comes very early in the term and helps to establish the tone of the course (*e.g.* Dyar *et al.*, 2004; Swope and Gieré, 2004; Wirth, 2007). Standard techniques of hand specimen characterization and identification are detailed in practically all mineralogy textbooks and are also described briefly in most introductory physical geology texts (*e.g.* Marshak, 2008; Tarbuck and Lutgens, 2008). Most of the techniques are essentially qualitative, dealing with properties such as form, habit, color, streak, luster, cleavage, fracture, and hardness. This early emphasis on qualitative methods is entirely reasonable but may contribute, unfortunately, to the widespread perception of geoscience as being "remedial science" rather than the highly quantitative field in which modern geoscientists actually work (Manduca *et al.*, 2008). In this context, measurement of specific gravities of minerals provides a special opportunity to emphasize quantitative approaches early in the curriculum. Specific gravity (G) is a quantifiable but intuitively simple property that can be used to characterize and identify minerals in introductory geology courses for non-science students as well as in mineralogy courses for geoscience majors. If sufficiently accurate and precise, specific gravity measurements can be used to estimate the chemical compositions of simple binary solid solution minerals such as olivines, orthopyroxenes, and plagioclase feldspars. This compositional information provides an opportunity to create a bridge between mineralogy and the fields of petrology and geochemistry. Such an emphasis on quantitative skills, and on the resulting links that can be established across the geosciences curriculum (*e.g.* Nelson and Corbett, 2000), contributes to the general goal of preparing students to deal thoughtfully with quantitative issues and problems in all fields of academics as well as in the world outside the classroom (Science Education Resource Center: Teaching Quantitative Skills in the Geosciences, 2008).

Various inexpensive instruments for measuring specific gravity, such as the pycnometer and Jolly balance, are described in introductory mineralogy textbooks (*e.g.* Nesse, 2000; Dyar and Gunter, 2008; Klein and Dutrow, 2008; Perkins, 2011). Though useful, these instruments lack the precision required for analysis of very small samples, such as the size fraction of pure mineral fragments (milligrams to tens of milligrams) that can be separated easily from medium-grained rock samples. Commercially available instruments designed specifically for this purpose, such as the Berman balance (Berman, 1939; Klein and Hurlbut, 1999), are expensive. The ability to measure very small samples, however, has considerable educational benefits: it can help students go beyond the examination of unusually large, well-formed crystals and work with the kinds of specimens that they are much more likely to encounter in the field. For example, vein-filling zeolites (G = 2.05–2.35) can be distinguished easily from feldspars (G = 2.60–2.76) without having to attempt hardness tests on tiny fragments. Massive or fibrous serpentine can be distinguished from other common dark silicates by its low density (G = 2.55–2.65). Some important non-silicate minerals have diagnostic specific gravities that can be extremely helpful for identification (*e.g.* sphalerite, G = 3.9–4.1; barite, G = 4.5; ilmenite, G = 4.70–4.79). In these and many other ways, the ability to

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analyze small crystals — of the size range commonly found in rocks — makes it easier for students to work with the types of specimens they are likely to encounter as geologists. This is useful for teaching and learning, as realistic and practical hands-on exercises capture the interest of students and help them learn how to think and work like scientists (Manduca, 2007; Perkins, 2007; Wirth, 2007).

In this paper I describe a simple custom-built apparatus that, when combined with a precision analytical balance of the type commonly present in academic research laboratories, can be used to determine the specific gravities of very small mineral samples. For a balance with precision to 0.01 mg, accuracy in measured G is typically ±0.01 or better for specimens weighing several tens of milligrams and ±0.03 or better for specimens as small as 5-10 milligrams. The apparatus can be made cheaply from materials that are easy to obtain and can be built in a few hours using only a few common tools. The expensive part of the setup is, of course, the precision analytical balance, so it's helpful to have one already in your laboratory or available nearby.

DESIGN AND OPERATION OF A HIGH-PRECISION SPECIFIC GRAVITY APPARATUS

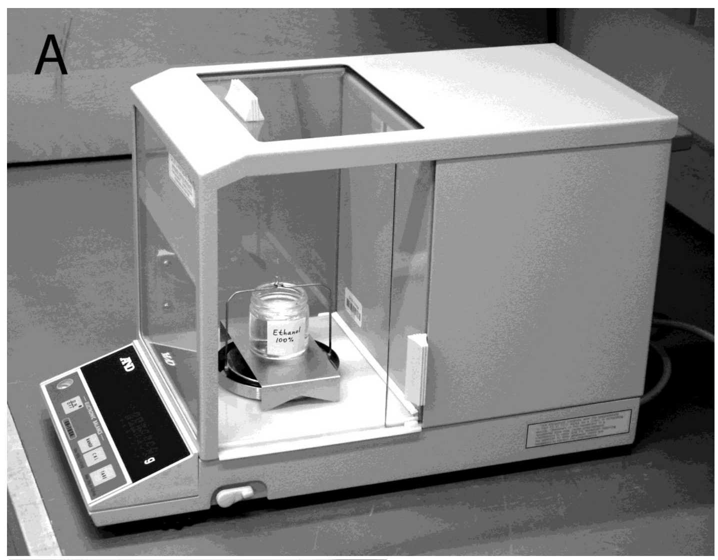
The apparatus, mounted in a precision analytical balance, is shown in Figure 1. It is a slightly modified version of a design for gemologists described by Hurlbut and Switzer (1979). The principle of operation is simple: due to the effects of buoyancy, a mineral immersed in liquid will weigh less than the same mineral in air, and the difference in weight can be used to determine the mineral's specific gravity (*i.e.* the hydrostatic method described in mineralogy textbooks, with various instrumental applications reviewed by Muller, 1977). In practice, a sample is weighed twice, once in air and once in liquid, and the difference in weights is used to calculate the specific gravity using the relationship:

$$G_{sample} = \left(\frac{weight\ in\ air}{weight\ in\ air - weight\ in\ liquid} \right) \times G_{liquid}$$

The apparatus in Figure 1 has two weighing pans, one in air and the other immersed in a bottle of liquid. Both pans are attached to a thin wire that hangs from a heavy wire loop attached to the balance's weighing platform. Note that the bottle of liquid does NOT rest on the balance's weighing platform, but is placed instead on a separate stand, so that the bottle and liquid are not being weighed. To measure the specific gravity, the sample is placed first on the upper weighing pan (dry) and the weight in air is recorded. The sample is then moved to the lower weighing pan (immersed in liquid) and the weight in liquid is recorded. The specific gravity of the sample can then be calculated, provided that the specific gravity of the liquid is known.

Choosing a suitable liquid - An appropriate choice of liquid is essential for accurate measurements. Experiments with small samples demonstrate that water is *not* suitable for this purpose because surface tension effects cause the measurements to be erratic. Ethanol, on the other hand, is a very good weighing medium that has much lower surface tension and produces highly reproducible results. Unlike some other organic liquids commonly employed for specific gravity determination (*e.g.* toluene), ethanol can be used safely on the bench top rather than in a fume hood, provided that appropriate lab safety practices are followed. Ethanol is not carcinogenic, and because the amount of liquid required is small, the amount of vapor produced during use of the apparatus does not create an inhalation hazard in a well-ventilated room. It should be noted, however, that in addition to its well-known toxicity when ingested (*e.g.* in alcoholic beverages), ethanol is highly flammable and the pure liquid is a severe irritant to the eyes. Appropriate safety glasses or goggles should be worn and the instructor should make sure that the apparatus is set up in an area safe from sparks and open flames. Students must also be instructed in safe handling methods in accordance with their school's laboratory safety programs.

All measurements reported in this paper were made using pure reagent-grade ethanol. Because the density of ethanol varies appreciably with temperature, it is essential to monitor the temperature carefully when making



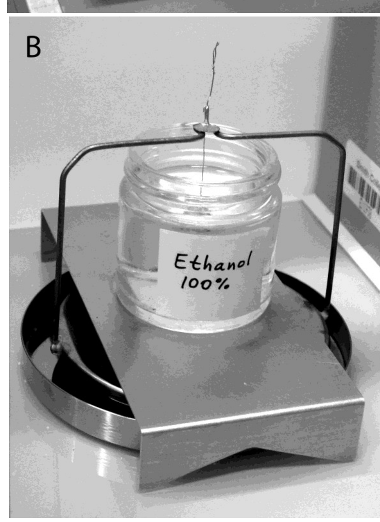


FIGURE 1. A) Specific gravity apparatus mounted in a precision analytical balance. B) Close-up, showing the bottle of ethanol resting on a sheet metal stand. A heavy wire loop is attached to the weighing platform. One small weighing pan rests directly on the loop, while the other is suspended in the alcohol by a thin wire joining the two pans.

measurements. The specific gravity of ethanol as a function of temperature is shown in Figure 2.

TYPICAL RESULTS

Results of measurements for samples of quartz, kyanite, galena and fluorite are given in Tables 1 and 2. The five quartz samples, with masses ranging from 5 mg to 198 mg, are fragments of a single pure transparent crystal. Each quartz fragment was weighed eight times and the results are depicted graphically in Figure 3. For all of the quartz fragments, measured G is very close to the value of 2.649 at 22°C determined by Smakula and Sils (1955). Errors for individual measurements range from about ±0.03 for the 5 mg sample to ±0.002 for the 198 mg sample, and are less than ±0.01 for samples weighing several tens of milligrams. When measurements are repeated and the results are averaged, the error is substantially diminished, especially for the smallest samples: the averages of eight weighings for the 5 mg and 8 mg samples are 2.66 and 2.65, respectively, while averages of eight weighings for each of the three larger samples are between 2.646 and 2.649. The average value of 2.649 for the 198 mg sample is identical to the value determined by Smakula and Sils (1955). Results for other minerals are also excellent: measurements for kyanite, fluorite and galena agree very well with values of G tabulated by Olhoeft and Johnson (1989), with discrepancies of 0.01 or less.

Sources of error – For samples of several tens of milligrams and smaller, the accuracy of the specific gravity determination is limited mainly by the precision of the balance. For larger samples the accuracy is limited mainly by uncertainty in the specific gravity of the ethanol. These errors are discussed in more detail below.

Consider first the limit of precision of the balance. The balance in our lab is an A&D Model ER-182A with a digital readout to 0.00001 g (0.01 mg). If the uncertainty of a single weight determination is taken to be ±0.01 mg, then the uncertainty in the difference between two weights (*i.e.* in air and in ethanol, the denominator in the equation for G) will be ±0.02 mg. For the quartz samples, the effect of this uncertainty on calculated values of G is represented by thin solid lines in Figure 3. For very small samples (<60 mg), uncertainty in the last decimal place during weighing can account for nearly all of the variation in measured G. This conclusion is strengthened by the observation that, in practice, the precision of each weighing is not quite as good as a single digit in the last decimal place (as shown by the results of repeated weighings in air, Table 1), so the true uncertainty is somewhat greater than that represented by the lines in Figure 3.

For larger samples, such as the 198 mg quartz fragment in this study, uncertainties in the last decimal place during weighing are much less important. Instead, the most significant source of error is probably uncertainty in the specific gravity of the ethanol, caused by errors in temperature measurement (G for ethanol varies by about 0.1% per °C at 22°C, causing a change of about 0.003 per °C in the apparent value of G for quartz) and by hydration of the ethanol by atmospheric water vapor. The latter effect is inferred from experiences in the classroom, where continued use of the same ethanol for several hours (or intermittent use over a few weeks) resulted in gradual decreases in calculated specific gravity for samples of all sizes (*e.g.* from G = 2.65 to G = 2.62–2.64 for quartz). This would be expected if the specific gravity of the ethanol increased slightly due to absorption of water vapor from the air, as the value used for G of the

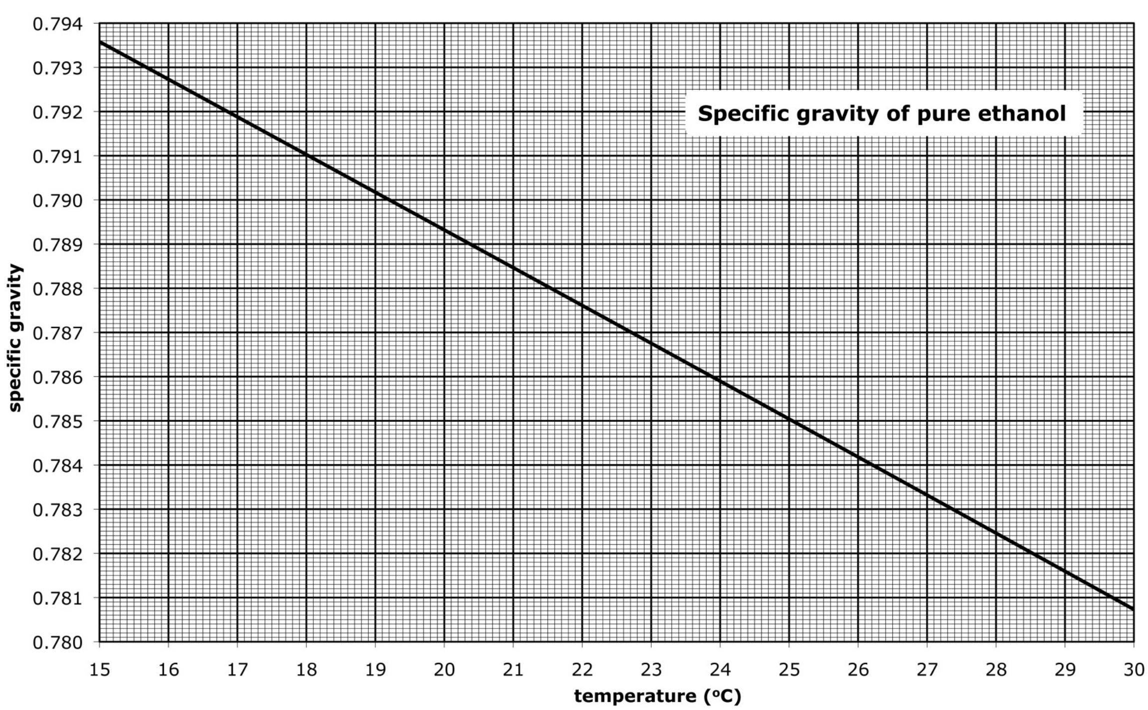


FIGURE 2. Specific gravity of pure ethanol as a function of temperature (data from Lide and Hayes, 2009, CRC Handbook of Chemistry and Physics, 90th Edition, page 15-41).

liquid in all calculations (based on the faulty assumption of pure ethanol) would then be too low.

Finally, it should be noted that the quantitative discussion above is based on measurements of quartz. For denser minerals, the effect of weighing errors on calculated values of G will be greater, as the buoyancy effect will be diminished and the difference in weights correspondingly lessened. For very dense minerals (*e.g.* galena) it is therefore advantageous to use slightly larger samples.

DESIGN AND FABRICATION OF THE APPARATUS

The individual parts of the apparatus are shown in Figure 4. Fabrication is easy and can be done by the instructor or by support staff in a school workshop. Required materials include nothing more complicated than a couple of pieces of sheet metal, some wire, and a few common tools such as pliers, metal snips, and a soldering iron (or epoxy glue). The required dimensions will naturally depend on the analytical balance being

TABLE 1. RESULTS OF MEASUREMENTS FOR FIVE FRAGMENTS OF A SINGLE QUARTZ CRYSTAL

Mineral	Sample	Weight in air (g)	Weight in ethanol (g)	Difference (g)	T (°C)	G ethanol	G mineral
quartz	A	0.00531	0.00375	0.00156	22.5	0.7872	2.68
quartz	A	0.00532	0.00375	0.00157	22.5	0.7872	2.67
quartz	A	0.00530	0.00372	0.00158	22.5	0.7872	2.64
quartz	A	0.00533	0.00377	0.00156	22.5	0.7872	2.69
quartz	A	0.00531	0.00374	0.00157	22.5	0.7872	2.66
quartz	A	0.00532	0.00373	0.00159	21.5	0.7881	2.64
quartz	A	0.00531	0.00373	0.00158	21.5	0.7881	2.65
quartz	A	0.00532	0.00374	0.00158	22.0	0.7876	2.65
Average	A	0.00532					2.66
quartz	B	0.00754	0.00529	0.00225	22.5	0.7872	2.64
quartz	B	0.00756	0.00531	0.00225	22.5	0.7872	2.65
quartz	B	0.00753	0.00531	0.00222	22.5	0.7872	2.67
quartz	B	0.00753	0.00530	0.00223	22.5	0.7872	2.66
quartz	B	0.00753	0.00529	0.00224	22.5	0.7872	2.65
quartz	B	0.00753	0.00527	0.00226	21.5	0.7881	2.63
quartz	B	0.00752	0.00528	0.00224	21.5	0.7881	2.65
quartz	B	0.00754	0.00529	0.00225	22.0	0.7876	2.64
Average	B	0.00754					2.65
quartz	C	0.04133	0.02907	0.01226	22.5	0.7872	2.654
quartz	C	0.04134	0.02904	0.01230	22.5	0.7872	2.646
quartz	C	0.04133	0.02906	0.01227	22.5	0.7872	2.652
quartz	C	0.04134	0.02905	0.01229	21.5	0.7881	2.651
quartz	C	0.04133	0.02903	0.01230	21.5	0.7881	2.648
quartz	C	0.04135	0.02904	0.01231	21.5	0.7881	2.647
quartz	C	0.04133	0.02900	0.01233	21.5	0.7881	2.642
quartz	C	0.04133	0.02901	0.01232	21.5	0.7881	2.644
Average	C	0.04134					2.648
quartz	D	0.05713	0.04015	0.01698	22.5	0.7872	2.649
quartz	D	0.05712	0.04011	0.01701	22.5	0.7872	2.643
quartz	D	0.05713	0.04015	0.01698	22.5	0.7872	2.649
quartz	D	0.05710	0.04010	0.01700	21.5	0.7881	2.647
quartz	D	0.05712	0.04012	0.01700	21.5	0.7881	2.648
quartz	D	0.05713	0.04014	0.01699	21.5	0.7881	2.650
quartz	D	0.05712	0.04011	0.01701	21.5	0.7881	2.646
quartz	D	0.05713	0.04016	0.01697	21.5	0.7881	2.653
Average	D	0.05712					2.648
quartz	E	0.19778	0.13906	0.05872	23.5	0.7863	2.649
quartz	E	0.19777	0.13899	0.05878	22.5	0.7872	2.649
quartz	E	0.19781	0.13897	0.05884	22.5	0.7872	2.647
quartz	E	0.19776	0.13898	0.05878	22.5	0.7872	2.649
quartz	E	0.19781	0.13898	0.05883	21.5	0.7881	2.650
quartz	E	0.19778	0.13896	0.05882	21.5	0.7881	2.650
quartz	E	0.19776	0.13894	0.05882	21.5	0.7881	2.650
quartz	E	0.19777	0.13893	0.05884	21.5	0.7881	2.649
Average	E	0.19776					2.649

TABLE 2. RESULTS OF MEASUREMENTS FOR SAMPLES OF OTHER MINERALS

Mineral	Sample	Weight in air (g)	Weight in ethanol (g)	Difference (g)	T (°C)	G ethanol	G mineral
kyanite	F	0.03692	0.02901	0.00791	22.5	0.7872	3.674
kyanite	G	0.04345	0.03411	0.00934	22.5	0.7872	3.662
galena	H	0.11827	0.10599	0.01228	22.5	0.7872	7.582
fluorite	I	0.10721	0.08065	0.02656	22.5	0.7872	3.178
fluorite	I	0.10712	0.08058	0.02654	21.5	0.7881	3.181
fluorite	I	0.10713	0.08055	0.02658	21.5	0.7881	3.176
fluorite	I	0.10712	0.08058	0.02654	22.0	0.7876	3.179
fluorite	I	0.10713	0.08058	0.02655	22.5	0.7872	3.176

adapted for use, so no precise specifications are given here. The exact shapes of the parts, and the specific materials used, are not particularly important, provided that they perform their desired functions adequately. A few considerations are described here.

Ethanol container - An ordinary glass bottle or beaker can be used to hold the ethanol. A small screw cap bottle is recommended, so that the ethanol can be stored between uses without having to pour it back into the reagent container. Capping the bottle tightly also helps minimize absorption of water vapor by the ethanol, which experience has shown can increase the specific gravity measurably in only a couple of hours. The mouth of the bottle should be wide enough to allow easy access with tweezers to the lower weighing pan (an opening of 3 cm, as pictured in Figure 4, is adequate). A transparent container works best, as this makes it easier to manipulate the sample during weighing in the liquid and to retrieve the sample if it is accidentally dropped to the bottom of the bottle.

Platform to hold the ethanol container - The platform is made from a single piece of sheet metal bent down at the ends to form a bench-like shape. The ends of the platform are deeply notched with metal snips to produce a stable 4-legged structure. The sheet metal should be heavy enough to provide a stable platform for the ethanol bottle, but light enough so that it can flex very slightly under the bottle's weight and thereby maintain firm 4-point contact with the balance (the platform in Figure 4 is 22 or 23-gauge aluminum, 0.024" thick).

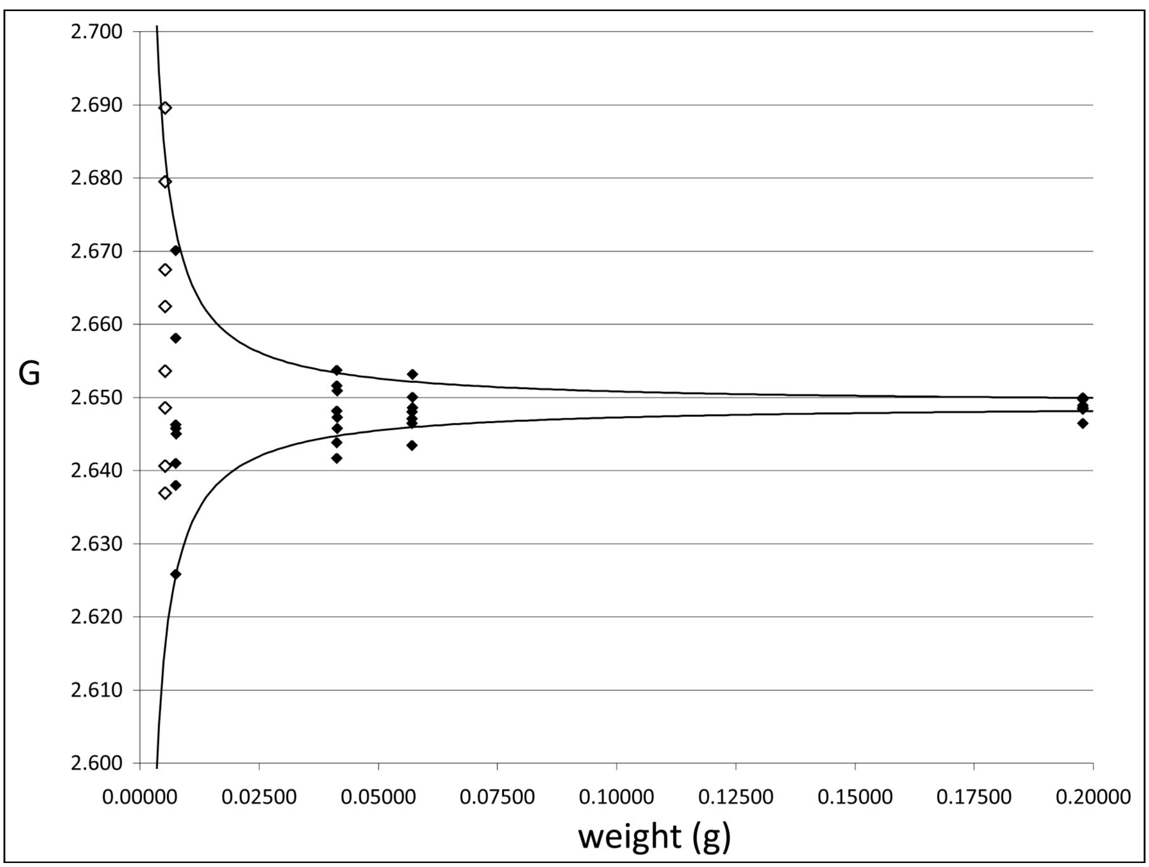


FIGURE 3. Results of specific gravity measurements for five fragments of a single crystal of pure transparent quartz, with eight separate measurements per fragment. For clarity, open symbols are used for the smallest fragment.

Balance pan and wire loop assembly - A loop of heavy wire is bent to the desired shape and soldered, welded, glued, or otherwise attached firmly to the edges of the balance pan (a spare balance pan can usually be purchased from the manufacturer). When shaping the loop, it is advantageous to make a small subsidiary loop at the top center on which to rest the upper weighing pan (Figures 1 and 4), so that the weighing pan assembly does not swing around during the delicate procedure of adding and removing samples. The wire loop should be rigid so that it doesn't flex during use (the wire loop in Figure 4 is 16-gauge steel, 0.062″ thick).

Double weighing pan assembly - The weighing pan assembly consists of two metal pans joined to a very thin wire (Figure 5). The pans are made of thin sheet metal and should be slightly cupped or have raised edges to keep samples from tumbling off. A method for fabricating the assembly is shown in Figure 6. The wire should be very thin in order to minimize potential errors caused by surface tension effects and minute changes in the level of immersion during weighing. The pans and wire in Figure 5 were made from bits of scrap platinum salvaged from an old crucible lid (0.010″ sheet) and thermocouple wire (0.009″), but less expensive metals can be used without compromising the function of the weighing apparatus. I made a less expensive weighing pan assembly from thin steel wire purchased at a hardware store and aluminum sheet metal snipped from a beer can, and achieved results as good as those obtained with the platinum pans. All else being equal, however, the platinum pans are easier to use because their greater density helps them to hang more stably. So, if you happen to have some spare platinum lying around, you may as well use it.

INSTRUCTIONAL ACTIVITIES USING SPECIFIC GRAVITY MEASUREMENTS

After seven years of teaching undergraduate mineralogy, I was frustrated by the difficulty of incorporating specific gravity determinations into laboratory studies of minerals in hand specimen. We had a Berman precision specific gravity balance in our teaching lab, but it had a very limited weight range (<25 mg), was difficult to use, and was easily (and frequently) damaged by rough handling. Students could use other instruments to measure the specific gravities of exceptionally large specimens from our collection, but they were unable to analyze small samples and were justifiably reluctant to do the time-consuming and painstaking work of extracting sufficiently large amounts of pure mineral material from ordinary rocks. As a result, my students rarely used specific gravity measurements to study minerals. This situation changed after we built the precision measuring apparatus and installed it in a balance from one of our research labs. Now, students in my course learn the technique in only a few minutes, can obtain accurate measurements quickly and easily, and can analyze even tiny fragments chipped from rock samples. Most of my students are glad to have the specific gravity balance available as a resource and they use it often. Some ways of incorporating specific gravity measurements into the undergraduate mineralogy curriculum are described below.

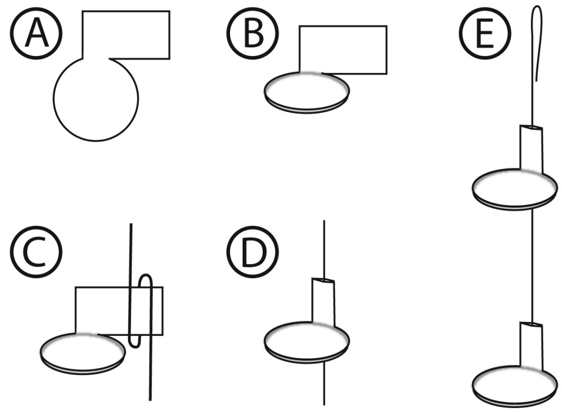


FIGURE 6. Fabrication of the double weighing pan. A) Cut out each pan from sheet metal, with a rectangular flange as shown. B) Bend the join between the pan and flange to a 90° angle. Press the round part over the end of a dowel, or similar tool, to create the shallow dish shape. C) Wrap a wire loop around the flange. D) Wrap the flange around the wire and crimp tightly. E) Repeat to make the lower pan. Trim the wire, leaving a loop at the top for a handle.

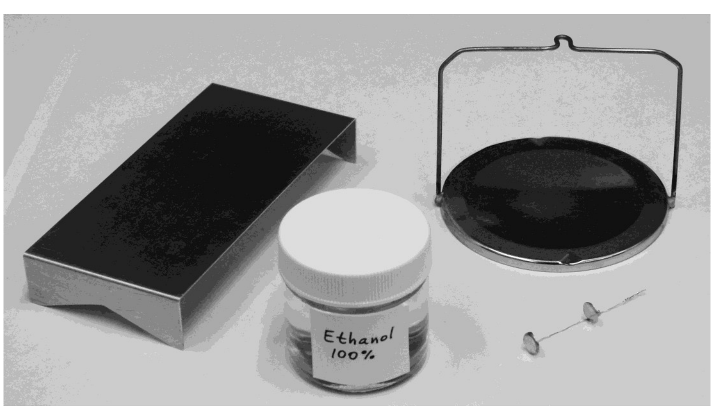


FIGURE 4. Individual parts of the apparatus pictured in Figure 1.

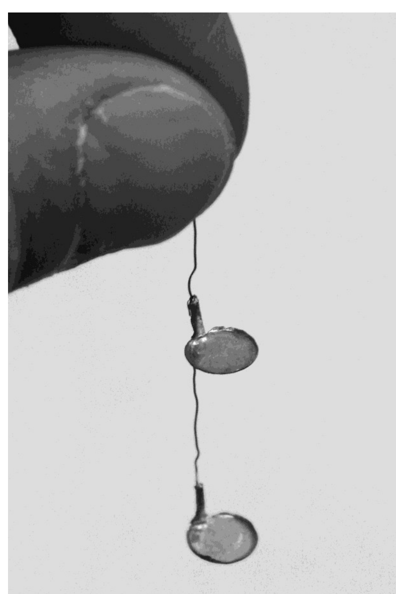


FIGURE 5. Close-up of the double weighing pan assembly.

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Mineral identification - My mineralogy course includes several mineral identification exercises in which students are asked to use all appropriate laboratory resources to identify a dozen or so unknown specimens, including grains in ordinary rock samples, using as much time as they wish over the course of a few weeks. They frequently use the specific gravity apparatus to help identify grains that are too small and too poorly formed to be identified confidently based on characteristics such as form, interfacial angles, twinning, cleavage, and so on (*i.e.* mineral specimens like those they would commonly find in outcrops). I also occasionally give students small fragments of uncommon minerals that they've never seen or heard about before (*e.g.* stibnite, G = 4.63); many of those who think to measure the specific gravity are visibly thrilled when they make their discovery and solve what had seemed an intractable problem.

Although most common minerals do not have unique or highly diagnostic specific gravities, students in my mineralogy lab often take advantage of the ease of measurement to use the specific gravity apparatus described here to test identifications based on other criteria ("I think these pale little prisms are sillimanite — is the specific gravity consistent with this hypothesis"?). Confirmation of a tentative identification is very satisfying for the students and provides a reward for industriousness and critical thinking. This was rarely possible when my students had to rely on the Jolly balance or other less precise methods, since these were not capable of making sufficiently accurate measurements on the tiny samples that could be extracted from most rock specimens.

The effectiveness of specific gravity measurement as a means of fostering student inquiry and learning is demonstrated by the extent to which my students utilize it as a tool in their mineral identification exams. Each of the last two times I taught undergraduate mineralogy (in 2007 and 2009), the final mineral identification exam included five hand specimens, one of which was a microcrystalline quartzite and another of which was a medium-grained

TABLE 3. SPECIFIC GRAVITY MEASUREMENTS FOR MINERAL IDENTIFICATION (ID) EXAMS

	Final mineral identification exam, Fall 2007					
	Large samples (grams)				Small samples (mg to mgx10)	
Student	microcline	wollastonite	quartz	prehnite	plagioclase	orthopyroxene
A	++	+0		++		
B		+0			++	++
C		++				
D	++	++	++	++	0+	
E	++	++	++	++		
F	++			++	++	+0
G	++	+0				
H		++				
I	++	++	++	++	++	
J	+0	00	0+			
	Final mineral identification exam, Fall 2009					
	Large samples (grams)				Small samples (mg to mgx10)	
Student	microcline	stibnite	quartz	prehnite	plagioclase	orthopyroxene
K	++	++	++	++	++	+0
L						
M		++		++	++	++
N	++	00	++		++	+0
O	++	++	++	++	++	++
P	++	++	++	++		+0
Q						
R	++	++	++	++		++
S	++	0+	0+	++	++	+0
T	++	++	++	++	++	++
U	++	++	++	++	++	++

++ = Specific gravity determined; accurate result (within 0.1); correct ID
+0 = Specific gravity determined; accurate result (within 0.1); incorrect ID
0+ = Specific gravity determined; inaccurate result; correct ID
00 = Specific gravity determined; inaccurate result; incorrect ID
Blank = Specific gravity not measured

norite composed of orthopyroxene and plagioclase feldspar (~ 2mm crystals). Students were not required to measure specific gravities but nearly all of them chose to do so for at least some of the specimens. As shown in Table 3, most students took the trouble to determine specific gravities for at least half of the unknowns, and most also went so far as to separate small grains of plagioclase and pyroxene from the norite and weigh them with the precision apparatus described in this paper. I often observed students using the precision apparatus to weigh small fragments of the larger specimens as well. The specific gravity measurements were almost always accurate (within 0.1 of the actual value) and they helped students make the correct identification more than 85% of the time (most misidentifications were made by students who mistook wollastonite for tremolite, or orthopyroxene for hornblende, which is not surprising given that the minerals in each of these pairs have similar habit, color, and hardness as well as specific gravity; Nesse, 2000).

The results reported in Table 3 demonstrate three important points: 1) given the opportunity, students will take the initiative and use specific gravity as an investigative tool; 2) students are consistently able to measure specific gravities with a high degree of accuracy, even for very small samples; 3) specific gravity measurements are helpful to students in making correct mineral identifications (as discussed later in more detail). Regarding this last point, it should be noted that students most often use specific gravity measurements to characterize relatively difficult samples that they don't feel confident identifying by other means, in light of which the high rate of success is especially significant.

Solid solution chemistry – Many common silicate rocks contain binary solid solution minerals whose chemical compositions can be estimated from specific gravity measurements. Such minerals include the olivines, orthopyroxenes, and plagioclase feldspars, all of which exhibit simple relationships between density and composition (*e.g.* Deer *et al.*, 1992; Nesse, 2000; Dutrow and Klein, 2008). These provide opportunities to perform simple hands-on laboratory investigations of crystal chemistry, and more importantly, to make the conceptual transition from mineralogy to petrology. For example, when my students separate small fragments of plagioclase feldspar from ordinary granites and gabbros, they can easily determine that the more felsic rocks contain the more sodic feldspars. When they separate small olivine crystals from porphyritic basalts, they find that the olivine is always richer in magnesium than in iron. These examples provide pathways to explore subjects such as fractional crystallization, binary phase diagrams, Bowen's Reaction Series, and so on. For example, I have used measured differences in plagioclase composition between granites and gabbros, together with examination of the plagioclase phase diagram, to engage students in a discussion of possible genetic relationships between mafic and felsic magmas. The ability to measure specific gravities of very small crystals makes it possible to do this with ordinary rocks.

Quantitative methods – Specific gravity measurements provide opportunities for students to apply quantitative methods to the study of hand specimens. Error analysis (as in this article) can be a useful exercise. Students in my mineralogy course, for example, conduct a semester-long project in which each student estimates the chemical composition of a single specimen of plagioclase, pyroxene, or olivine by several different methods (specific gravity, powder X-ray diffraction, optics, and SEM Energy-Dispersive Spectroscopy). For the final part of the project each student must compare her results obtained by different methods, explain why they aren't exactly the same, and discuss — quantitatively — the most likely sources of discrepancies and errors. This makes the point that every measurement has some degree of uncertainty, which often leads to fruitful discussions of precision, accuracy, systematic errors, and significant figures. Some students go a step further and examine the extent to which physical properties (such as specific gravity) can depend on factors other than major element chemical composition (*e.g.* structural state, minor element concentrations, etc.).

As another quantitative exercise, specific gravity measurements can be used to calculate unit cell volumes; *i.e.,* given the stoichiometry of the unit cell and the measured specific gravity, how many unit cells must there be in 1 cm^3? This problem requires students to understand the unit cell concept and to practice basic computational skills in mineral chemistry.

Class size and implementation – The activities described above require substantial amounts of hands-on lab work by individual students, each of whom must be instructed in the use of the instrument and must have adequate access to it during the semester. The larger the class size, the greater the investment of the instructor's time and the greater the need for accessible instrumentation. The activities described here have been used in classes of approximately ten to fifteen students, which is typical of our mineralogy enrollments at Smith College (an all-female undergraduate liberal arts institution). I normally teach students to use the apparatus during scheduled class time early in the semester, meeting with them in groups of two or three for hands-on instruction while the rest of the class is engaged in other activities. Allowing time for students to try it themselves, it takes me 20 minutes or so to demonstrate the use of the instrument to a small group. After that, most student work time takes place outside of scheduled class and lab hours. Each of my students uses the instrument frequently throughout the semester and I make sure that the lab is accessible for independent work during most hours of the day and evening.

Because the precision apparatus requires an expensive balance, and only a single student can use it at one time, scaling these activities to substantially larger class sizes would probably require some modifications. One possibility would be to shrink the scope of assignments and projects. For example, each student in a larger class might be required to use the balance to characterize and identify only a single mineral or a couple of minerals, or to distinguish between two similar-looking minerals with

TABLE 4. RESPONSES TO STUDENT SURVEY - USEFULNESS FOR MINERAL IDENTIFICATION

"Overall, which of the following best describes your opinion regarding the usefulness of the precision specific gravity apparatus for mineral identification in the mineral identification exams?"	
# of responses	
1	EXTREMELY USEFUL: It was helpful very often, and mineral ID would have been much more difficult or frustrating without it
4	VERY USEFUL: It was helpful often, and I was glad to have it available as a resource
1	SOMEWHAT USEFUL: It was helpful occasionally
0	NOT VERY USEFUL: It was helpful only rarely
0	NOT USEFUL AT ALL: It never helped me in any meaningful way
0	MORE TROUBLE THAN HELP: It caused frustration or wasted my time without providing any benefit

appreciably different specific gravities (*e.g.* aragonite and calcite). Some of the advantages of open-ended inquiry would be lost, but the emphasis on quantitative methods and investigative skills would be retained.

Another solution would be to use much larger samples (*e.g.* grams or more, available at low cost from mineral vendors). This would make it possible to use balances that are less precise and far less expensive, so that multiple instruments could be acquired. The ability to work easily with small mineral grains extracted from "ordinary" rock samples would be lost, but again, the emphasis on quantitative methods and investigative skills would be retained. Inexpensive balances could also be used to measure specific gravities of entire rock samples, providing students with the opportunity to collect data and apply them to geologic problems ranging from the isostatic behavior of oceanic and continental crust to the porosities of rocks in aquifer systems (Nelson and Corbett, 2000).

STUDENT FEEDBACK

After teaching mineralogy to a class of eleven undergraduates (all women) at Smith College in the fall of 2009, I distributed a questionnaire to the students at the beginning of the following semester, soliciting their comments and opinions regarding their use of the precision specific gravity balance for mineral identification exams. The survey was voluntary and anonymous, and six responses were received from the nine students still on campus. Results are summarized in Tables 4, 5 and 6.

Table 4 tallies responses to the multiple-choice question: "Overall, which of the following best describes your opinion regarding the usefulness of the precision specific gravity apparatus for mineral identification in the mineral ID exams?" All of the respondents felt that the precision apparatus was at least somewhat useful for mineral identification, and five out of six considered it "very useful" or "extremely useful" (the two students who didn't use the apparatus at all in the exam summarized in Table 3 presumably were not among the respondents, although it is impossible to be certain because the responses were anonymous).

Table 5 summarizes student responses to a question regarding the strategies they used for mineral identification. Specific gravities obtained with the precision apparatus were often used for "identifying mineral specimens that were unfamiliar or baffling" and for "testing (or confirming) tentative identifications made by other means". They were also used occasionally "as the main or primary means of mineral identification for a particular specimen".

The written comments reported in Table 6 show that respondents found the apparatus easy to use (with manipulation of small grains being the most common difficulty) and generally helpful for mineral identification (although one student reported occasional frustration arising from incorrect measurements). Most students were reasonably confident in their measurements, and became more confident with practice. Overall, the results indicate that students consider the precision specific gravity balance to be a valuable resource that is easy to use and quite useful for mineral identification.

TABLE 5. RESPONSES TO STUDENT SURVEY - PURPOSES FOR WHICH THE APPARATUS WAS USED IN MINERAL ID

"For which of the following purposes did you use the precision specific gravity apparatus when identifying minerals?"				
	# of responses			
	never	once	occasionally	often
Identifying mineral specimens that were unfamiliar or baffling	0	1	1	4
Testing (or confirming) tentative identifications made by other means	0	0	2	4
As the main or primary means of mineral identification for a particular specimen	2	0	4	0

TECHNICAL SUGGESTIONS AND COMMON PROBLEMS

A pair of fine-pointed tweezers is essential for manipulating samples. Suitable tweezers, if not available in your stockroom, can be obtained in the cosmetics sections of drugstores (the Cross company makes good ones). For many students, manipulating small samples and transferring them from one weighing pan to another is the most difficult and frustrating part of the procedure, so be prepared to offer advice and encouragement.

Another source of student frustration is the care that must be taken to obtain accurate weights to hundredths of a milligram. As regular users of precision analytical balances know well, many things can cause random or non-random fluctuations in apparent weights, including air movements in the room or weighing chamber, temperature and humidity changes in the weighing chamber caused by the user's hands, vibrations of the balance table, and so on. It is important for the instructor to be familiar with the things most likely to cause problems in a particular laboratory and to show students how to minimize these problems and obtain accurate

TABLE 6. RESPONSES TO STUDENT SURVEY - WRITTEN COMMENTS

QUESTION: How easy or difficult was it to use the apparatus? 1) "I think the scale is pretty easy to use." 2) "Not too difficult -– requires some steadiness of hand but otherwise easy." 3) "Fairly easy – major problem was … fishing for a dropped specimen. Sometimes hard to get an appropriately sized specimen." 4) "It was largely dependent on the situation and size of crystals being measured. Fluctuations did complicate matters sometimes." 5) "Manual manipulation of grains took a lot of practice." 6) "Fairly easy to use. Time consuming but simple once you learn the steps."
QUESTION: If you found it difficult at first, did it get easier with practice? 1) "I didn't think it was difficult to use, even in the beginning." 2) "A little bit easier." 3) "Yes – after a few times, easier to position and work with small specimens." 4) no response 5) "Yes." 6) "Calculations after measurements became easier."
QUESTION: How confident were you in the results of your measurements at the time you made them? Did you get more confident with practice? 1) "I was not confident at all in the beginning, but I definitely got more confident over time." 2) "I was fairly confident with my results initially and became a little more confident with practice. I could say that my confidence went from 85% to 90%." 3) "Somewhat. They were later confirmed to be reasonably accurate, though not good enough to be the sole or primary method of identification." 4) "I was mostly confident with my answers generally speaking." 5) "Depended on the mineral being examined (ones with more extreme specific gravities = more confident). Yes [I got more confident with practice]." 6) "More confident with practice. At times my measurements were incorrect and threw me off which was frustrating."
QUESTION: In retrospect, to what extent do you think your measurements were accurate enough to be potentially useful for mineral identification? 1) "The measurements were usually accurate enough to identify minerals without knowing too many other factors. Also, I used both the platinum [weighing basket] and the one made out of a can and did not see much of a difference." 2) "To a good extent. Usually I was able to tell the difference between two minerals if their specific gravity values were 0.15–0.20 apart." 3) "Good to confirm a mineral ID if there are two choices, with different G. Not accurate enough for primary ID" 4) "On the whole they were quite useful and I do go back to weighing specific gravity in other classes." 5) "Depended on range being examined. Best when comparing minerals with fairly different G (difference of at least 0.5 to make me confident)." 6) "At times my measurements were exactly what I was looking for which was useful for making decisions between two minerals with very different specific gravity."

results. As an example, the electronic readout on the balance in our laboratory always fluctuates slightly in the last decimal place regardless of how long the balance is allowed to equilibrate during weighing. So, in order to ensure consistency and minimize subjective bias, I encourage my students to always allow the balance to equilibrate for exactly the same amount of time — say, 40 seconds — before recording the weight.

A more insidious problem, discussed earlier, is that absorption of atmospheric water vapor by ethanol can cause measurable and systematic errors in the calculated values of G for mineral specimens. This problem is rectified easily by replacing the ethanol with fresh reagent. It is important to monitor the quality of the ethanol by regularly checking the specific gravity of a large mineral fragment of known specific gravity, such as pure quartz. If apparent specific gravities begin to decrease measurably over time, then the ethanol should be replaced.

Finally, when repeating a series of measurements, it is essential that the sample be allowed to dry completely before re-weighing in air. Be on the lookout for this.

CONCLUSION

The apparatus described in this paper provides an easy and inexpensive way for instructors to adapt a precision analytical balance for specific gravity measurements of small mineral samples. Once students become adept in manipulating tiny samples and using the balance properly, they become very fond of this simple method of mineral analysis and use it routinely and often for exercises in mineral characterization and identification.

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