Gravity Methods (VI)
the terrain correction and the residual

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Geology 454
Group 1

1. A gravity station is located 400 meters above the surrounding area on top of, and at the center of, a butte (see below). The edge of the butte lies 600 meters from the station in all directions. Beyond the edge of the butte lies an expansive inland plain or plateau with elevation at sea level. The strata that form the butte have a relatively uniform density of 2.65 g/cm³. Definition: Butte – an isolated hill or small mountain with precipitously steep sides (see below).

![Diagram of Butte]

a) Calculate the Bouguer plate correction for this station. (Show starting equation and your calculations).

b) What is the terrain correction (in milligals)? Explain how you obtained it.
We didn’t get to the in-class tide and drift problem … take a minute

Geology 454
Group 2

At 8 am you start a gravity survey at Base Station 5 in your survey area. You set out to establish another base station (Base Station 6) about an hours drive from Base 5. At 8am the acceleration due to gravity at Base Station 5 is 5.3 milliGals relative to the main base station in your survey area. You make it to the new base station and take a measurement 53 minutes after making the Base 5 observation. Your reading at Base Station 6 is 4.3 milliGals. You return to Base 5 but stop for gas along the way. You finally re-measure the Base 5 acceleration at 10 am (120 minutes after your initial measurement). The reading at Base Station 5 dropped 2 milliGals during that 120 minute period. What is the acceleration at Base Station 6 relative to the main base?
Plot up your data to get a graphical sense then work through it.

tide and drift correction

Elapsed time (minutes)

g (mGals)
The terrain correction -

In dealing with the derivation of the Bouguer plate effect the trick to integration was in how one defined the volume element. This remains true in computing the acceleration of gravity produced by a ring. The approach to the terrain correction rests on the analytical expression derived for the acceleration due to gravity of the ring. This integration is broken down into sectors.

\[ g = \int G \frac{dm}{r^2} \]
Devil’s tower – what would its influence be?

\[ g = \int G \frac{dm}{r^2} \]
In practical application we want to approximate the distribution of topographic features with ring sectors because it’s easy to compute the effect of a mass that has the shape of the sector. In the formula above, we just compute the acceleration of a sector by dividing the acceleration of the ring by the number of sectors in the ring.

The tricky part is to get a reliable estimate of $z_n$.
In practice, the topography surrounding a particular observation point is divided into several rings (usually A through M). Each ring is divided into several sectors.

The F-ring, for example, extends from 1280 to 2936 feet and is divided into 8 sectors. The average elevation in each sector is estimated and it’s contribution to the acceleration at the observation point is computed.

Let’s spend a few moments working through a simple example to illustrate how the terrain correction is applied.
The effect of Devil’s Tower could be estimated by enclosing it in a sector

\[ g_{sector} = \frac{2\pi G \rho}{n} \left[ R_0 - R_i + \left( R_i^2 + z^2 \right)^{1/2} - \left( R_o^2 + z^2 \right)^{1/2} \right] \]
In areas where the terrain is too complex to estimate the average elevation visually, one can compile averages from the elevations observed at several points within a sector.

As you might expect - this was a laborious process.

The m-ring extends from 9.16 to 13.6 miles.
Hammer Table

$T$ has units of $1/100^{th}$ of a milliGal; $\rho$ is assumed to be 2.0 gm/cm$^3$

<table>
<thead>
<tr>
<th>Zone B, 4 compartments, radius 6.55-54.6 ft</th>
<th>Zone C, 6 compartments, radius 54.5-175 ft</th>
<th>Zone D, 6 compartments, radius 175-558 ft</th>
<th>Zone E, 8 compartments, radius 558-1280 ft</th>
<th>Zone F, 8 compartments, radius 1280-2936 ft</th>
<th>Zone G, 12 compartments, radius 2936-5018 ft</th>
</tr>
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<tbody>
<tr>
<td>$z$, ft</td>
<td>$h$, ft</td>
<td>$T$</td>
<td>$z$, ft</td>
<td>$h$, ft</td>
<td>$T$</td>
</tr>
<tr>
<td>0-1.1</td>
<td>0</td>
<td>0-4.3</td>
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<td>0-7.7</td>
<td>0</td>
</tr>
<tr>
<td>1.1-1.9</td>
<td>0.1</td>
<td>4.3-7.5</td>
<td>0.1</td>
<td>7.7-13.4</td>
<td>0.1</td>
</tr>
<tr>
<td>1.9-2.5</td>
<td>0.2</td>
<td>7.5-9.7</td>
<td>0.2</td>
<td>13.4-17.3</td>
<td>0.2</td>
</tr>
<tr>
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<td>0.3</td>
<td>9.7-11.5</td>
<td>0.3</td>
<td>17.3-20.5</td>
<td>0.3</td>
</tr>
<tr>
<td>2.9-3.4</td>
<td>0.4</td>
<td>11.5-13.1</td>
<td>0.4</td>
<td>20.5-23.2</td>
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<td>14.5-24</td>
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<td>43-56</td>
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<td>63-68</td>
<td>8</td>
<td>100-107</td>
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<td>24-27</td>
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<td>9</td>
<td>107-114</td>
<td>9</td>
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<tr>
<td>27-30</td>
<td>10</td>
<td>74-80</td>
<td>10</td>
<td>114-120</td>
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<tr>
<td>80-86</td>
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<td>120-127</td>
<td>11</td>
<td>266-280</td>
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<tr>
<td>86-91</td>
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<td>127-133</td>
<td>12</td>
<td>280-293</td>
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<td>91-97</td>
<td>13</td>
<td>133-140</td>
<td>13</td>
<td>293-306</td>
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<tr>
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<td>14</td>
<td>140-146</td>
<td>14</td>
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<td>14</td>
</tr>
<tr>
<td>104-110</td>
<td>15</td>
<td>146-152</td>
<td>15</td>
<td>318-331</td>
<td>15</td>
</tr>
</tbody>
</table>

* Each zone is a circular ring of given radius (in feet) divided into 4, 6, 8, 12, or 15 compartments of arbitrary azimuth. $h$ is the mean topographic elevation in feet (without regard to sign) in each compartment with respect to the elevation of the station. The tables give the correction $T$ for each compartment due to undulations of the terrain in units of $\downarrow$mgal for density 2.0 gm/cm$^3$. This correction, when applied to Bouguer anomaly values which have been calculated with the simple Bouguer correction, is always positive.

Taken from Dobrin, 1974
What’s the station elevation? **2840 feet**

What’s the average elevation in Sector 1? **2640 feet**

What’s the relative difference between the station elevation and the average elevation of sector 1? **200 feet**
As the legend in the Hammer table notes, the value for $T$ is in hundredths of a milligal and has been calculated assuming a replacement density of 2 gm/cm$^3$.

Thus the contribution to the topographic effect from the elevation differences in this sector is 0.03 milligals.

Note that the elevation difference is reported in a range, and the listed value is not exact for that specific difference - in this case 200 feet.

The value could be computed more precisely using the ring formula similar to that developed in Berger et al. but modified to compute the gravity associated with individual sectors. The Hammer table makes it easy, but approximate.

$$g_{sector} = \frac{2\pi G \rho}{n} \left[ R_0 - R_i + \left( R_i^2 + z^2 \right)^{1/2} - \left( R_o^2 + z^2 \right)^{1/2} \right]$$
For next time - determine the average elevation, relative elevation difference and T for all 8 sectors in the ring. Add these contributions to determine the total contribution of the F-ring to the terrain correction at this location.

Also determine the F-ring contribution if the replacement density of 2.67 gm/cm³ is used instead of 2 gm/cm³.

How?
This just requires multiplication of the results obtained assuming 2 gm/cm³ by the ratio 2.67/2 or 1.34.
In the Hammer terrain correction tables we can check his values using

\[ g_{\text{sector}} = \frac{0.04192}{n} \rho \left[ R_0 - R_i + \left( R_i^2 + z^2 \right)^{1/2} - \left( R_o^2 + z^2 \right)^{1/2} \right] \]

Remember, the formula in this form has a special constant that allows us to mix units and simplify calculations.

What is \( \rho \)? \( 2 \text{ gm/cm}^3 \) in the Hammer tables

The units of \( \rho \) in this formula are always in gm/cm\(^3\)

What is \( R_i \)? \( 390 \text{m} \)
What is \( R_o \)? \( 895 \text{m} \)
What is \( z \)? \( 61 \text{m} \)

Units of \( R \) and \( z \) in this formula are always in meters

\[ g_{\text{sector}} = \frac{0.04192}{8} \left[ 895 - 390 + \left( 390^2 + 61^2 \right)^{1/2} - \left( 895^2 + 61^2 \right)^{1/2} \right] \]

\[ g_{\text{sector}} = 0.0279 \text{mGals} \]
### Values from the Hammer table and from more precise computation

<table>
<thead>
<tr>
<th>Sector</th>
<th>Average Elevation</th>
<th>Relative Difference</th>
<th>T (100ths MG) From Hammer Table below</th>
<th>*Sector effect computed from Equation in Table 6.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2640</td>
<td>200</td>
<td>3 (i.e. 0.03mG)</td>
<td>0.0279</td>
</tr>
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</tr>
<tr>
<td>Total</td>
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</tr>
</tbody>
</table>

Values are given in feet and milliGals.
Now that we’ve described all the corrections and gained some experience and familiarity with their computation, let’s review the concept of the gravity anomaly.

In general an anomaly is considered to be the difference between what you actually have and what you thought you’d get. In gravity applications you make an observation of the acceleration due to gravity \( g_{\text{obs}} \) at some point and you also calculate or make a prediction about what the gravity should be at that point \( g_t \).

The prediction assumes you have a homogeneous earth - homogeneous in the sense that the earth can consist of concentric shells of differing density, but that within each shell there are no density contrasts. Similar assumptions are made in the computation of the plate and topographic effects. \( g_t \) then, in most cases, is an imperfect estimate of acceleration. Some anomaly exists.

\[
\text{g}_{\text{anom}} = g_{\text{obs}} - g_t
\]
There are several different types of anomalies, which depend on the degree to which the theoretical gravity has been estimated.

For example, in a relatively flat area, close to sea-level, we might only include the elevation effect in the computation of $g_t$. This would also be standard practice in ocean surveys. In general tide and drift effects are always included. In this case, the anomaly ($g_{anom}$) is referred to as the free-air anomaly (FAA).

$$\Delta g_{FAA} = g_{obs} - g_t$$

$$\Delta g_{FAA} = g_{obs} - \left( g_n (\theta) - \Delta g_{FA} \pm \Delta g_{Tide&Drift} \right)$$

$$\Delta g_{FAA} = g_{obs} - g_n (\theta) + \Delta g_{FA} \pm \Delta g_{Tide&Drift}$$
When only the elevation (or Free Air) and plate effects are included in the computation of theoretical gravity, the anomaly is referred to as the simple Bouguer anomaly or just the Bouguer anomaly. The combined corrections are often referred to as the elevation correction.

\[
\Delta g_{BA} = g_{obs} - g_t
\]

\[
\Delta g_{BA} = g_{obs} - \left( g_n(\theta) - \Delta g_{FA} + \Delta g_B \pm \Delta g_{Tide\&Drift} \right)
\]

\[
\Delta g_{BA} = g_{obs} - g_n(\theta) + \Delta g_{FA} - \Delta g_B \pm \Delta g_{Tide\&Drift}
\]
When all the terms, including the terrain effect are included in the computation of the gravity anomaly, the resultant anomaly is referred to as the **complete Bouguer anomaly** or the **terrain corrected Bouguer anomaly** ($\Delta g_{\text{TBA}}$).

\[
g_t = g_n(\theta) - \Delta g_{FA} + \Delta g_B - \Delta g_T \pm \Delta g_{\text{Tide\&Drift}}
\]

\[
\Delta g_{\text{TBA}} = g_{\text{obs}} - g_t
\]

\[
\Delta g_{\text{TBA}} = g_{\text{obs}} - g_n(\theta) + \Delta g_{FA} - \Delta g_B + \Delta g_T \pm \Delta g_{\text{Tide\&Drift}}
\]
In this form -

\[ \Delta g_{TBA} = g_{obs} - g_n(\theta) + \Delta g_{FA} - \Delta g_B + \Delta g_T \pm \Delta g_{Tide \& Drift} \]

Recall that in this form, the different terms in the theoretical gravity are referred to as corrections.

Thus -

+\( \Delta g_{FA} \) is referred to as the free-air correction

-\( \Delta g_B \) is referred to as the Bouguer plate correction

+\( \Delta g_T \) is referred to as the terrain correction, and

\( \pm \Delta g_{Tide \& Drift} \) is referred to as the tide and drift correction

Note the difference in the signs of corrections versus terms in the computation of the theoretical gravity.
There is one additional anomaly we need to add to our list. This anomaly is known as the residual anomaly. It could be the residual Bouguer anomaly, or the residual terrain corrected Bouguer anomaly, etc. In either case, we are interested in the residual. Recall from your reading of Stewart’s paper, that Stewart is dealing with the residual Bouguer anomaly.

What is it?

Most data contain long wavelength and short wavelength patterns or features such as those shown in the idealized data set shown below.
Long wavelength features are often referred to as the regional field. The regional variations are highlighted here in green.

The **residual** is the difference between the anomaly (whichever it is) and the regional field.
Just as a footnote, we shouldn’t lose sight of the fact that in all types of data there is a certain amount of noise. That noise could be in the form of measurement error and can vary from meter to meter or operator to operator. It could also result from errors in the terrain corrections (operator variability) and the accuracy of the tide and drift corrections.

When we filter out or remove the noise (below), we see the much cleaner residual next to it.

**Noisy Signal**

**Signal after noise attenuation filtering**
Stewart makes his estimates of valley depth from the residuals. You shouldn’t be concerned too much if you don’t understand the details of the method he used to separate out the residual, however, you should appreciate the concept of the residual in a general way - what has been achieved in it’s computation. There are *larger scale structural features* that lie beneath the drift valleys (see below) and variations of density within these deeper intervals superimpose *long wavelength* trends on the gravity variations across the area. These trends are not associated with the drift layer.

The potential influence of these deeper layers is hinted at in one of Stewart’s cross sections.

![Higher density dolomite layer thickens to the east.](image)
Breakdown more relevant to Stewart’s study

- **Bouguer Anomaly**
  - Anomaly (mGals)
  - Profile Distance (km)

- **Residual Anomaly**
  - Anomaly (mGals)
  - Profile Distance (km)

- **Regional Anomaly**
  - Regional Anomaly (mGals)
  - Profile Distance (km)

- **Shifted Residual**
  - Anomaly (mGals)
  - Profile Distance (mGals)
Map view

Bouguer anomaly

Regional anomaly

Residual anomaly

Fig. 3. Simple Bouguer gravity map, Outagamie County.

Fig. 4. Regional gravity map, Outagamie County.

Fig. 5. Residual gravity map, Outagamie County.
A closer look at Stewart’s maps

Bouguer anomaly map

Note that the Bouguer anomaly and the regional gravity generally drop in value to the west coincident with westward thinning of the Ordovician dolomite.
It’s critical in this case to remove that regional trend so that we need only be concerned with the bedrock & drift intervals.

If one were to attempt to model Stewart’s Bouguer anomalies without first separating out the residual, the interpreter would obtain results suggesting the existence of an extremely huge and deep glacial valley that dropped off to great depths to the west. However, this drop in the Bouguer anomaly is associated with the distribution of deeper, regional scale density contrasts, unrelated to the glacial processes. t=130g is developed to infer till thickness only from the residual anomaly.

Let’s spend a few minutes and discuss one method for determining the residual gravity anomaly. The method we will discuss is referred to as a graphical separation method.
Examine the map at right. Note the regional and residual (or local) variations in the gravity field through the area.

The graphical separation method involves drawing lines through the data that follow the regional trend.

The green lines at right extend through the residual feature and reveal what would be the gradual drop in the anomaly across the area if the local feature were not present.
What is producing this anomaly

The residual anomaly is identified by marking the intersections of the extended regional field with the actual anomaly and labeling them with the value of the actual anomaly relative to the extended regional field.

After labeling all intersections with the relative (or residual) values, you can contour these values to obtain a map of the residual feature.
Non-Uniqueness

Note that a particular anomaly, such as that shown below, could be attributed to a variety of different density distributions.

gravity anomaly

Note also, however, that there is a certain **maximum depth** beneath which this anomaly cannot have its origins.

Fig. 36. “Cone of Sources,” the sphere (1) is the deepest body which can approximately account for the gravity anomaly shown. Shallower and broader bodies, as 2 and 3, also could account for the anomaly. All would have the same total mass anomaly.

Nettleton, 1971
Recall the formula for the anomaly produced by a buried sphere?

\[ g_v = \frac{4}{3} \pi \rho G R^3 \left[ \frac{1}{z^2} \right] \left[ \frac{1}{\left( \frac{x^2}{z^2} + 1 \right)^{3/2}} \right] \]

This anomaly has a symmetrical bell-shape. It has a lateral extent that varies with z. Increase z and you increase the lateral extent of the anomaly.
Increased depth increases the lateral extent of the anomaly

\[ X_{1/2} = 0.766Z \]

We will find for example, that the distance from the peak out to a point (on either side) where the anomaly produced by a sphere drops to \( \frac{1}{2} \) its maximum value increases as 0.766 times the increase in depth to its center.
If there are no subsurface density contrasts - i.e. no geology, then the theoretical gravity equals the observed gravity and there is no anomaly.
But …

If there are density contrasts, i.e. if there are materials with densities different from the replacement density, then there will be an anomaly. That anomaly arises from density contrasts associated with the geology or site characteristics we are trying to detect.
Take a look at station 2

<table>
<thead>
<tr>
<th>Base Station</th>
<th>time</th>
<th>dial reading</th>
<th>Converted to milliGals</th>
<th>relative difference gsn#-gbase</th>
<th>Tide &amp; Drift</th>
<th>Drift corrected</th>
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<tbody>
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<td>Base Station</td>
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<td>-0.13296</td>
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</table>

What is the dial reading in milliGals?

What is the difference relative to the base – as measured at t=0?

Recall the tide and drift rate measured at the base station

\[
\frac{\Delta g}{\Delta t} = \frac{66.147 - 66.28}{110} = \frac{-0.133}{110} = -0.0012 \frac{mG}{\text{min}}
\]
Graphically, how does the actual difference (drift corrected) compare to the apparent (uncorrected) difference.

What was the base station drift at the time the station 2 measurement was made?

What is the drift corrected difference relative to the base?
1. Use the Hammer correction table below and determine the contribution to the total terrain correction for the F-ring on the attached topographic map. Compute the terrain correction using values of T listed in the Hammer table and also using the following equation modified from Kearey, Brooks, and Hill (Table 6.1).

\[
g = 0.04191 \frac{\rho}{n} \left[ r_o - r_i + (r_i^2 + z^2)^{1/2} - (r_o + z^2)^{1/2} \right]
\]

<table>
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<th>Relative Difference</th>
<th>T From Hammer Table below</th>
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<td>Total</td>
<td>feet</td>
<td>feet</td>
<td>In milliGals</td>
<td>In milliGals</td>
</tr>
</tbody>
</table>
What’s the station elevation?
What’s the average elevation in a given sector?
What’s the relative difference between the station elevation and the average elevation in that sector?
A couple problems similar to those in the text

6.5 What is the radius of the smallest equidimensional void (e.g. chamber in a cave) that can be detected by a gravity survey for which the Bouguer gravity values have an accuracy of 0.05 mGals? Assume the voids are formed in limestone (density 2.7 gm/cm³) and that void centers are never closer to the surface than 100m.

6.9 Determine the depth to the center of each of the three equidimensional bodies (∼spheres) producing the anomalies (A, B, and C) shown in the figure below.
Abstract: a brief description of what you did and the results you obtained (~200 words).

Background: Provide some background on the data we’re analyzing. All of this would come from Stewart’s paper. Explain his approach and answer question 1 below in this section to illustrate his approach.

Results: Describe how you tested the model proposed by Stewart along XX’. Include answers to questions 2 through 4 below in this discussion.

Conclusions: Summarize the highlights of results obtained in the forgoing modeling process.
1. The residual gravity plotted in Figure 5 of Stewart's paper (also see illustrations in this lab exercise) has both positive and negative values. Assume that an anomaly extends from +2 milligals to -2 milligals. Use the plate approximation (i.e. Stewart’s formula) and estimate the depth to bedrock? What do you need to do to get a useful result? Residuals of any kind usually fluctuate about zero mean value. What would you guess Stewart must have done to the residual values before he computed bedrock depth?
2. At the beginning of the lab you made a copy of GMSYS window showing some disagreement between the observations (dots) and calculations (solid line) across Stewart's model (section XX' Figure 7). As we did in class and in the lab manual, note a couple areas along the profile where this disagreement is most pronounced, label these areas in your figure for reference. In your lab report discussion offer an explanation for the cause(s) of these differences? Assume that the differences are of geological origin and not related to errors in the data.

In your write-up answer the following questions and refer to them by number for identification.
3. With a combination of inversion and manual adjustments of points defining the till/bedrock interface, you were able to eliminate the significant differences between observed and calculated gravity. Your model is incorrect though since the valleys do not extend to infinity in and out of the cross section. Use the 2 ¾ modeling option to reduce the extents of the valleys in and out of the section to ±800 feet. Make the changes to the Y+ and Y- blocks and then apply. Take a screen capture to illustrate the reduction in g associated with the glacial valleys. Make a screen capture of this display showing the new calculation line and the dashed gray values associated with the infinite valleys. Include this figure in your report and discuss your results.
In your write-up, answer the following questions and refer to them by number for identification.

4. Use Stewart's formula \( t = 130g \) and estimate the depth to bedrock at the \( x \) location of 7920 feet along the profile. Does it provide a reliable estimate of bedrock depth in this area? Explain in your discussion.

5. Lastly, describe the model you obtained and comment on how it varies from the starting model taken from Stewart.
Use the preceding questions to guide your discussion

These questions provide discussion points in your lab report. Use figures you've generated in GMSYS to illustrate your point. All figures should be numbered, labeled and captioned.
Items on the list ....

- **Gravity papers are in the mail room**
- Writing group – *Gravity paper summary 1 due this Thursday*
- Gravity paper summary(s) (both sections) due Thursday, Nov. 14th
- Gravity lab will be due on Thursday November 21st (writing section submission is self-reviewed showing track changes).
- Keep working up the gravity lab and bring questions to class
- Review the remainder of the chapter 6 (past page 378).
- Problems 6.1 and 6.2 are due today (5th).
- Problem 6.3 is due this Thursday, the 7th.
All those in the regular section submit paper copies of your paper summaries and lab reports.
Writing Section reminders
(electronic submissions only)

• Submit first paper summary this Thursday
• Review comments will be provided next Tuesday or sooner.
• Revised paper summary 1 and self-reviewed paper summary 2 are to be turned in next Thursday.
• The gravity lab is self reviewed and is due on Thursday, November 21st.

All those in the writing section submit their papers and lab electronically. Don’t forget to turn on track changes while doing your self-review. Only submit the self-reviewed file.