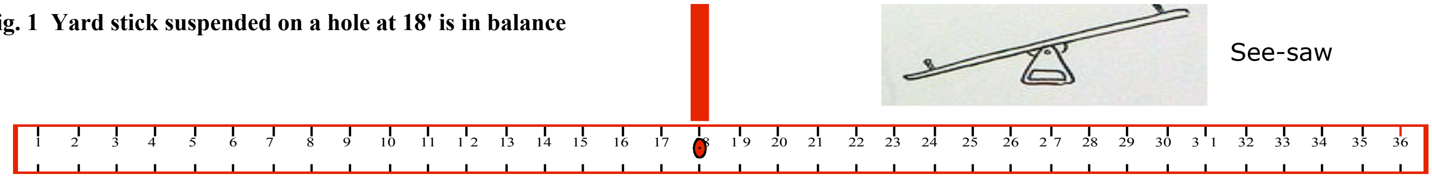
The Lever Principle in Aviation

by Sean G. Dwyer PhD

Understanding the Principle of the Lever is key to aircraft design and control. It is simple and most people get an intuitive understanding of it from playing with a see-saw or teeter-totter. The underlying math is also simple.

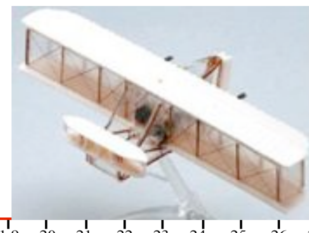
Fig. 1 Yard stick suspended on a hole at 18' is in balance



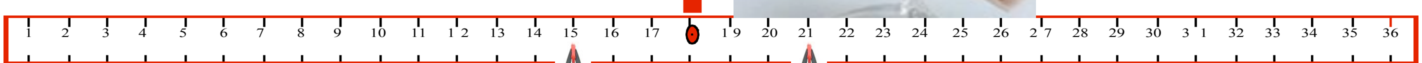
See-saw

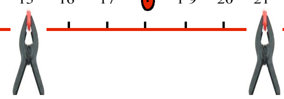
Fig. 2 Yard stick with clamps at 15" and 21" is also in balance

Similarly, the rudder of the Wright Flyer balanced the elevator. In fact, this is why they put the elevator in front in the first place. However, just as you can't push a string, there was a limit to how fast the Wright Flyer could go without breaking off the elevator. Making the elevator stronger would add weight, so later airplanes had elevators in the back until strong light materials became available.



Rutan Varieze





The elevator of the Varieze is the 'canard' in front of the cockpit and makes the aircraft essentially "stall proof".

Fig 3 Three Clamps at 15" Balance One at 27"

Moments on each side are balanced when measured from the fulcrum at 18".

Moment = Weight multiplied by the Arm

e.g. **3C x 3 = 1C x 9 = 9 clamp-inches**, where C = weight of a clamp

The heavier weight of an airplane's engine is balanced by the longer arm of the lighter tail, and that longer arm makes the aft control surfaces more effective per the Principle of the Lever.

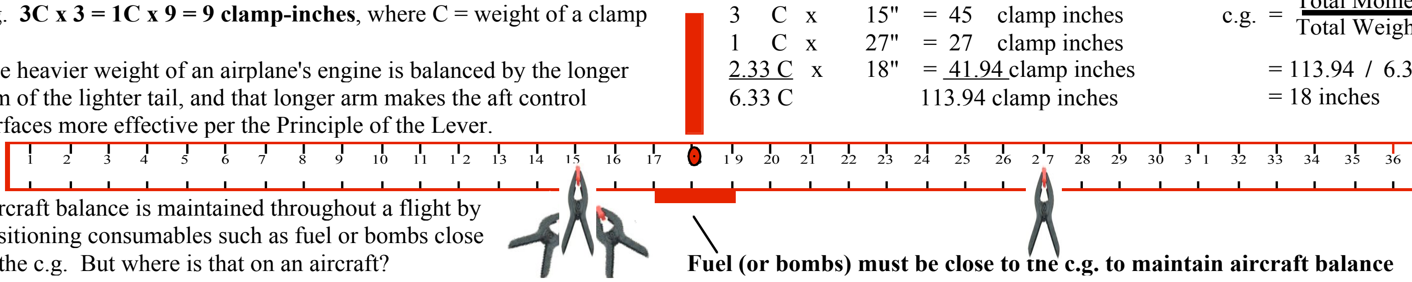
Moments can also be measured from 0" on the yard-stick, and this is how the c.g. of an aircraft is determined:

Note: A clamp weighs 15 g and the yard-stick weighs 35 g (or 2.33 clamps)

Weight	x	Arm =	Moment
3 C	x	15"	= 45 clamp inches
1 C	x	27"	= 27 clamp inches
2.33 C	x	18"	= 41.94 clamp inches
6.33 C			113.94 clamp inches

$$\text{c.g.} = \frac{\text{Total Moment}}{\text{Total Weight}}$$

= 113.94 / 6.33
= 18 inches



Aircraft balance is maintained throughout a flight by positioning consumables such as fuel or bombs close to the c.g. But where is that on an aircraft?

Fuel (or bombs) must be close to the c.g. to maintain aircraft balance

Unlike a static object, an aircraft in flight pivots around its 'aerodynamic center' rather than around its c.g., although the latter will be close. This is because air flowing over various surfaces during cruise flight imparts forces on those surfaces, like loads on a lever. In modern aircraft a downward force from the elevator compensates for the effect of the c.g. being forward of the aerodynamic center or neutral point. Slower speed would reduce this 'negative lift' from the tail, thereby causing the nose to drop (i.e. 'positive stability') and less tendency to stall or enter a flat spin after engine failure.

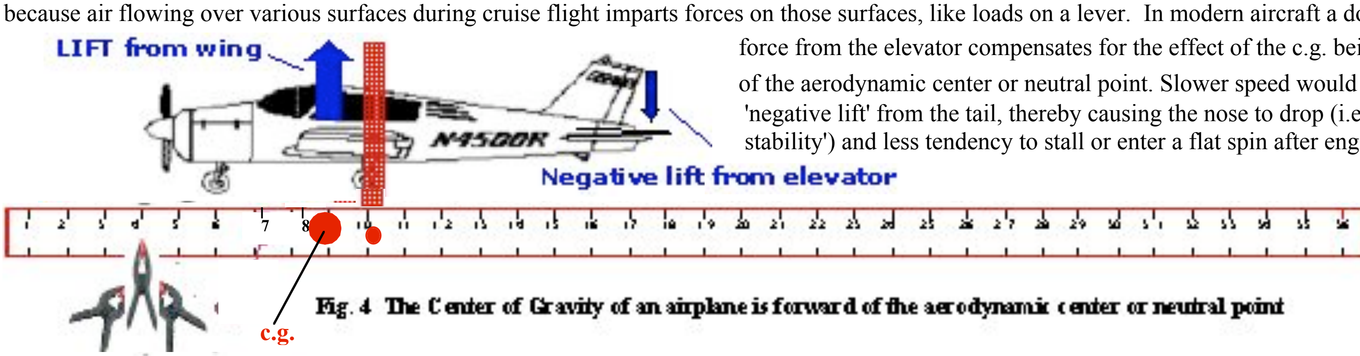


Fig. 4 The Center of Gravity of an airplane is forward of the aerodynamic center or neutral point

Homework Assignment: One clamp is missing from the bottom picture. Calculate where it should be to yield a c.g. of 8.68

Homework Assignment: Where to Put the Missing Clamp to Yield c.g. = 8.68?

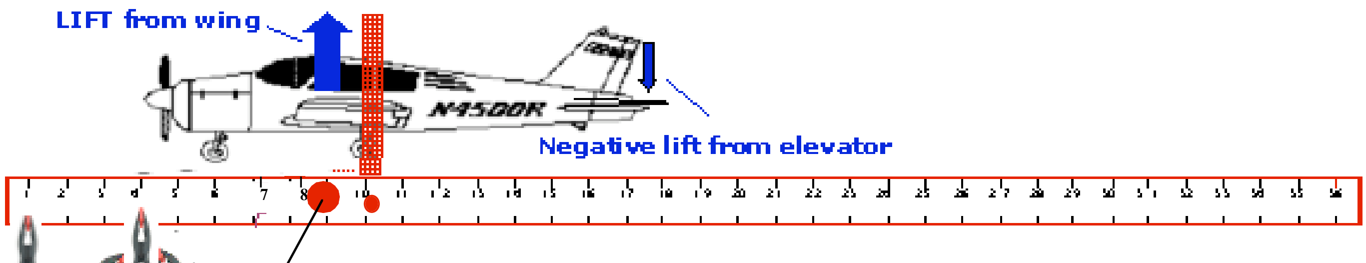


Fig. 4 The Center of Gravity of an airplane is forward of the aerodynamic center or neutral point

One clamp was missing in the final figure on the other side of this page. The homework assignment was to determine where it should be to yield a center of gravity (c.g.) equal to 8.68 inches from the left.
When measuring the Arm from the left, the mathematics are as follows:

	Weight	x	Arm	=	Moment	
(Ruler weighs 2.33 C Its c.g. is 18 inches)	2.33 C	x	18 inches	=	41.94 C.inches	
(The 3 clamps at 4 inches)	3 C	x	4 inches	=	12 C.inches	
(The previously missing clamp)	1 C	x	1 inches	=	1 C.inches	
(Total Weight)	6.33 C				54.94 C.inches	(Total Moment)

$$\text{Center of Gravity (c.g.)} = \frac{\text{Total Moment}}{\text{Total Weight}} = \frac{54.94 \text{ C.inches}}{6.33 \text{ C}} = 8.68 \text{ inches}$$

No Fair! You knew the answer. How was I supposed to calculate it?

Fair comment. Here is how you would calculate the missing clamp's Arm:

Assume that the missing clamp is at ***Y*** inches. Here is how you would determine ***Y*** knowing that c.g. = 8.68.

	Weight	x	Arm	=	Moment	
	2.33 C	x	18 inches	=	41.94 C.inches	
	3 C	x	4 inches	=	12 C.inches	
	1 C	x	***Y*** inches	=	***Y*** C.inches	
(Total Weight)	6.33 C				(53.94 + Y) C.inches	(Total Moment)

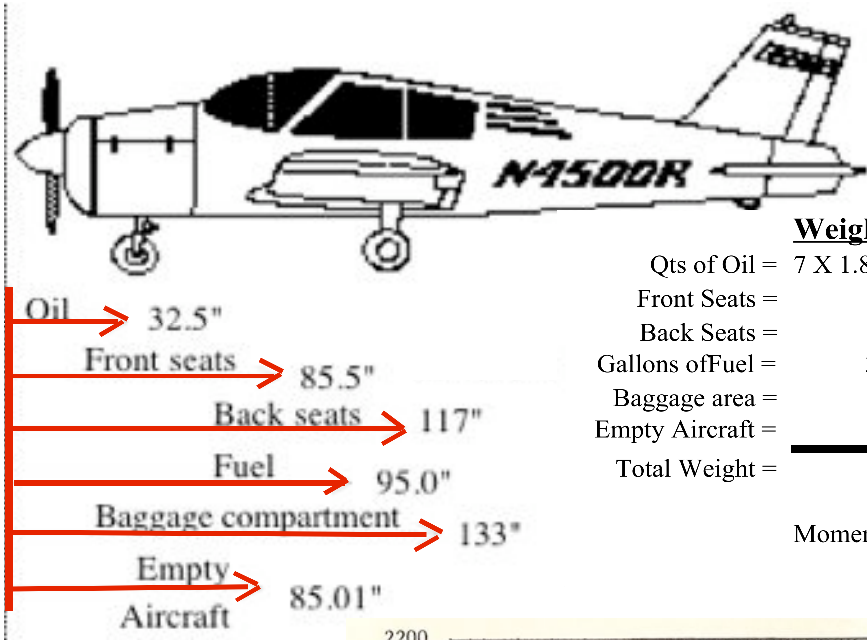
$$\text{Center of Gravity} = \frac{\text{Total Moment}}{\text{Total Weight}} = \frac{(53.94 + Y)\ \cancel{\text{C}}\text{.inches}}{6.33\ \cancel{\text{C}}} = 8.68 \text{ inches}$$

[Cs cancel out above & below line Multiply both sides by 6.33]

$$(53.94 + Y) \text{ inches} = 6.33 \times 8.68 \text{ inches} = 54.94 \text{ inches}$$

[Subtract 53.94 from both sides]

$$Y = 54.94 - 53.94 \text{ inches} = 1 \text{ inch}$$



Example

	Weight in Lbs	Arm	Moment
Qts of Oil =	7 X 1.875 = 13.125	32.5	426.56
Front Seats =	350	85.5	29,925.00
Back Seats =	150	117	17,550.00
Gallons ofFuel =	36 X 6 = 216	95	20,520.00
Baggage area =	24	133	3,000.00
Empty Aircraft =	1282.4	85.01	109,016.82
Total Weight =	2,035.53		180,438.38

Moment/weight = c.g. of aircraft = 88.64

Key Data Points:

Max Gross Weight = 2,150 lbs
Current Empty Wgt = 1,282.4
Available Load = 867.6 lbs

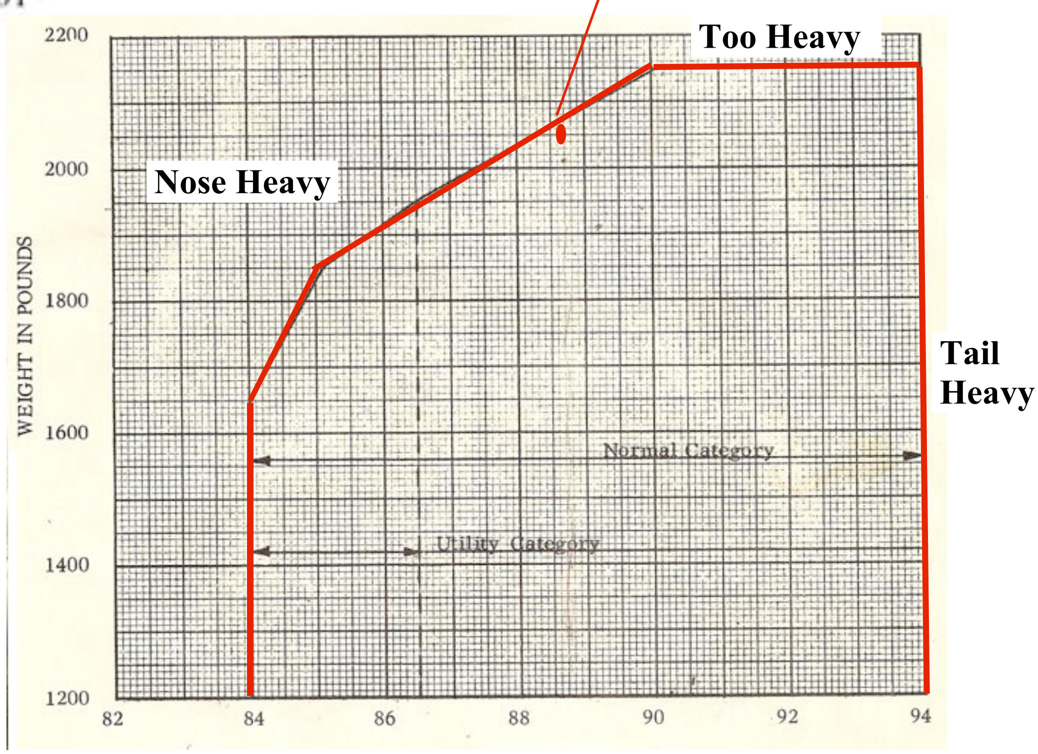
Maximum Fuel = 50 gallons (300 lbs)

Seats = Pilot + 3 passengers

Utility Category =1,950 lbs max & 86.5" Arm

Note that forward c.g. limit moves aft at higher gross weights

Note also that the allowed c.g. range is a mere 10 inches, and is less than that at higher weights



Inches Aft of Datum --->

Your Assignment:

		Weight in Lbs	x	Arm	=	Moment
Qts of Oil =	7 x 1.875 =	13.125		32.5		426.56
Front Seats =				85.5		
Back Seats =				117		
Gallons of Fuel =				95		
Baggage Area =				133		
Empty Aircraft =		1282.4		85.01		109,016.82
Total Weight =					Total Moment =	

Divide Total Moment by Total Weight to get c.g. c.g. =

Young Aviators Program: The Lever Principle in Aviation

(1) Objective:

Make high school or middle school students aware of the Principle of the Lever and and its application to aviation. A larger goal is to spark their interest in STEM (Science, Technology, Engineering, & Math) for their sakes and for America's future.

(2) Audience Assessment:

Teenagers who have been introduced to the Four Forces and aircraft control surfaces. Knowledge of science is undetermined. A wide span of ages makes it important to ensure that everybody is involved in discussions, so a seminar approach would be preferable to a classroom set up. Demonstrations & reference to applications of the lever that are familiar to them will be key.

(3) What is to be presented: (*Word pictures, sound bites, visuals)*

Welcome & Linkage: Invention of the wheel and development of the Principle of the Lever may be the two most important developments in the history of the world, and you are very familiar with both of them. If you understand how a see-saw works then you know how to balance an airplane. Later I'll show you the math so you can do it to the satisfaction of the FAA.

Introduction: The Lever Principle is used to control airplanes around all 3 axes. Ailerons control roll around the longitudinal axis from nose to tail. The rudder controls yaw around the vertical axis, which runs from top to bottom, and the elevator controls pitch around the lateral axis. Such control is done by sight & feel, so while pilots don't need math to use them, aircraft designers did. On the other hand, pilots need math for weight & balance calculations. In the Women's Trans-Continental Air Race I saw one woman climbing forward from the back seat while taxiing in. She had used the Lever Principle to make the plane fly faster.

Point #1: **3 Classes of Levers include a Fulcrum pivot point, a Load, and Effort. Aircraft use Class 1 levers primarily.**
* Class 1 is like a crow-bar with the **fulcrum between the Load and Effort**, or a see-saw where the Effort is like a 2nd Load.
* Class 2 is like a wheel barrow and has the **Load between the Fulcrum** (i.e. the wheel) **and Effort** (i.e. the handles)
* Class 3 is like a fishing rod and has the **Effort** (i.e. your hand) **between the Load** (i.e. the fish) **and Fulcrum** (base of the rod)

Point #2: **The Lever Principle's power lies in using the ARM to achieve balance between the MOMENTS of Load & Effort**
* The **Arm is the distance from the Fulcrum** to either the Load or the Effort. *(Aircraft empennage have a long arm, why?)*
* The **Moment is calculated by multiplying the Arm by either the Load or the Effort**. *(Think "momentum", not "minute")*
* **The longer the Arm** between Fulcrum and Effort, **the greater the Load** that can be moved *(i.e."mechanical advantage").*
* **The longer the handle, the more powerful the tool**. *(Demonstrate mechanical advantage of a hammer claw or a wrench)*
* Archimedes claimed he **could lift the world if he could find a long enough lever and a fulcrum** on which to put it.
* Demonstrate the math behind balancing 2 kids on one side of a see-saw with one kid on the other side.

Point #3: **The design of the Wright Flyer & later aircraft clearly reflect use of the Lever Principle**
* Paradigm paralysis (define!) put the propellers and rudder at the back, but why was the rudder so far out? *(Air Vs. water)*
* They balanced the rudder by putting the elevator in front. However, its fragility limited their speed *(You can't push a rope!)*
* Later aircraft combined the rudder & elevator in the empennage and achieved balance by putting the engine at the front.
* Eventually, new materials were light & strong enough to allow the elevator to be put in front in Rutan's CANARD designs.
* Bombs, fuel, and other expendables need to be close to the c.g. to avoid unbalancing the aircraft when used.
* Measure moments either from the pivot point, or from 0" on the yard stick if you enter the yard stick's own weight & moment.
* Twin engine planes have a problem around the vertical axis when an engine quits during take-off. *(Show Cessna Skymaster)*
* High wing Vs. low wing aircraft have interesting compromises around the longitudinal axis. *(Use couch Vs. barstool example)*
* Flying Wings like B-2 Stealth Bomber are marvels of balance, but all aircraft designs are compromises with advantages & costs.

Transition: "Positive Stability" enhances safety in aircraft, but has a cost in speed and aerobatic ability
* Remember how Goose was killed in TOP GUN when he and Maverick went into a flat spin? *(Demonstrate different spin types)*
* Aircraft in flight rotate around an "aerodynamic center" dictated by the flow of air over its surfaces rather than its c.g.
* Loss of both power and air flow over aircraft surfaces would let c.g. take over and cause the plane to nose up or down.
* Since 'nose down' facilitates a controlled glide and avoids a flat spin, my Cherokee's c.g. is forward of the aerodynamic center.
* This means the elevator must produce 'negative lift'. . . . which can be eliminated by having passengers sit in the back seat!

Close: Clearly, the Principle of the Lever plays a major role in aircraft design. By understanding it, you can select which aircraft best meets your purposes, or even make it fly faster. But pilots do need to know how to calculate aircraft weight & balance. This will be our next topic and the first question is "How do you measure the Arm if you don't know where the Fulcrum is?" Guess what, you already learned how to do that when we measured the moments on the yard stick from the 0" mark on the stick!

Young Aviators Program: Calculating Weight & Balance

(1) Objective:

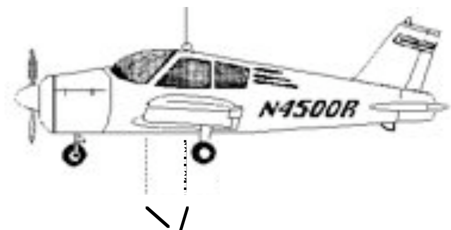
Show class how to calculate Weight & Balance for a Piper Cherokee

(2) Audience Assessment:

They have been introduced to control surfaces, 4 Forces, and the Lever Principle

(3) What is to be presented?

Welcome & Linkage: All the levers you have seen so far had a very obvious FULCRUM, so it was easy to determine the ARM of any load and calculate its MOMENT. But where is the fulcrum of an airplane? That varies with fuel and passenger loads. Also, why is it so important to calculate WEIGHT & BALANCE? It is life & death important and everybody screws it up once. I'll tell you my story.



Center of Gravity must be between these two lines

Introduction: The Pilot's Operating Handbook (POH) specifies a **MAXIMUM GROSS WEIGHT** and **SAFETY ENVELOPE** for for each plane. The forward & aft limits for c.g. are the 'balance' bit. If the c.g. is forward of the safety envelope then the plane may be so nose heavy that you can't get enough air over the elevator to raise the nose, a killer if you run out of runway during take-off. If the c.g. is too far aft, the tail heavy aircraft may stall, which can also be fatal. The solution is to calculate c.g. and compare it and the gross weight with the published limits before each flight. I'll show you how to do so for my Piper Cherokee.

Point #1: **The first thing you do is determine the gross weight and compare it with the max gross weight for N4500R**

* The POH lists the current empty weight of the aircraft and the maximum allowed gross weight (2,150 lbs).
* That is added to the weights of oil, fuel, front & bac k seat passengers, and the baggage compartment.
* If the total is less than max gross weight, you are in business. Otherwise, you have to leave something out.

Point #2: **Instead of a fulcrum, an arbitrary data point like the nose of the plane can be used to measure the ARM of a load**

* The POH lists the ARM and MOMENT of the empty aircraft. This moment is entered into the table.
* POH also shows the ARM, or distance from the nose, of each load, i.e. oil, fuel, pilot & passengers, baggage etc.
* MOMENTs of loads are determined by multiplying their ARMs by their WEIGHTS, and then added to the table.
* Quarts of oil and gallons of gasoline are converted to lbs by multiplying by 1.8 and by 6 respectively.
* The c.g., which is calculated by dividing the total moment by the total weight, is compared with the safety limits.
* If the aircraft is out of balance then something - or someone - has to be moved or left out.

Point #3: **The PIC is responsible for ensuring that the aircraft is within limits on every flight.**

* Every time equipment is added to the aircraft or removed a new weight & balance page is added to the POH
* Just because N4500R has 4 seats does not mean I can carry 4 people with full fuel.
* N4500R can hold 50 gallons, but would be forward of c.g. limit with two people of my weight in front and 36 gallons.
* Weight would not be a problem, but I would either have to ask the other person move his seat back or sit in back.
* I wrote a program to calculate Wgt & Bal when the right seat is all the way back at the 9th notch.
* Airlines, who assume an average weight of 170 lbs/person, can have a problem when all the passengers are big men.
* Higher temperature or airport elevation can degrade performance so much that load has to be reduced.

Transition: Understanding the Lever Principle provides a qualitative understanding of how aircraft are controlled. Calculating Weight & Balance adds a quantitative dimension. Every pilot screws it up at least once. The learning experience is memorable. It was a hot day and I was flying my 6 & 7 year old daughters to Tobacco City Airport near Madison. 50 gallons of fuel were no problem until the people I was meeting asked for a quick flight. 3 adults joined me in the plane, which had only burned about 4 gallons. We were overweight and forward of the c.g. limit. I had to slowly circle the field at a low altitude and land. Very hairy!

Close: Now the rubber hits the road. You each have an assignment to figure out if you can safely & legally fly N4500R with members of your family that you select. Fill in the numbers at the bottom of the sheet and don't forget to multiply gallons by 6 to get the weight of the fuel in lbs. Plot the total weight and c.g. on the graph as shown in the example. Some numbers are filled in because they don't change between flights, e.g. empty weight of the aircraft and oil weight. The right-seat-at-9th-notch program can be found at http://sites.google.com/site/seangdwyer/computer-corner

Conclusion: Aviation has many applications of science & engineering, and America needs more scientists & engineers. We are no longer in the Industrial Age where most people were hired from the neck down. In the Information Age, most are hired from the neck up, and our public schools do not compare well with those in Europe or Asia. China graduates 800,000 engineers every year and America produces only 80,000! This does not bode well. If you were turned on by anything you learned, then pass it on to your siblings & friends. Teaching is the best way to learn anything.