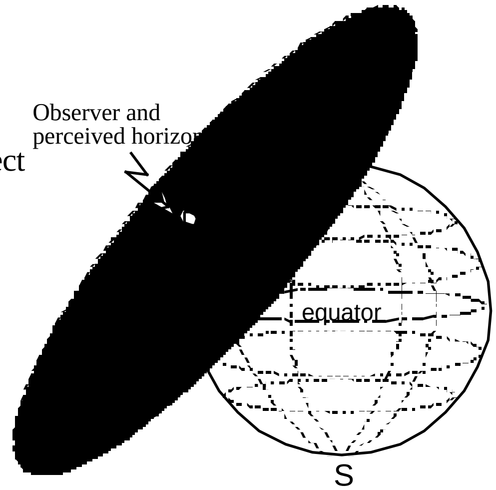
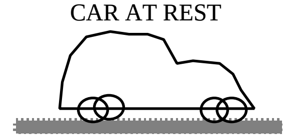
TAKE-HOME EXP. # 5B   Standing Still: A Special Case of Equilibrium, Newton's Laws and "Balanced "Forces



Many objects in the world stand still, at rest with respect to a frame of reference attached to the Earth's surface, like the horizon frame pictured to the right. Relative to this frame, although skyscrapers may sway in a wind and roll with earthquakes, most buildings, bridges, trees, parked cars, and our sitting selves are usually at rest. It's easy to see: look around you right now. The buildings, parked cars and sidewalks are not changing their motion. They are not accelerating.

Consider a parked car. **Newton's 1st law** says that an object will stay at rest unless a "resultant" force acts it on. A resultant force is produced by the vector addition of all the forces acting on the object.



The sum of the forces on a car at must be zero in any direction.

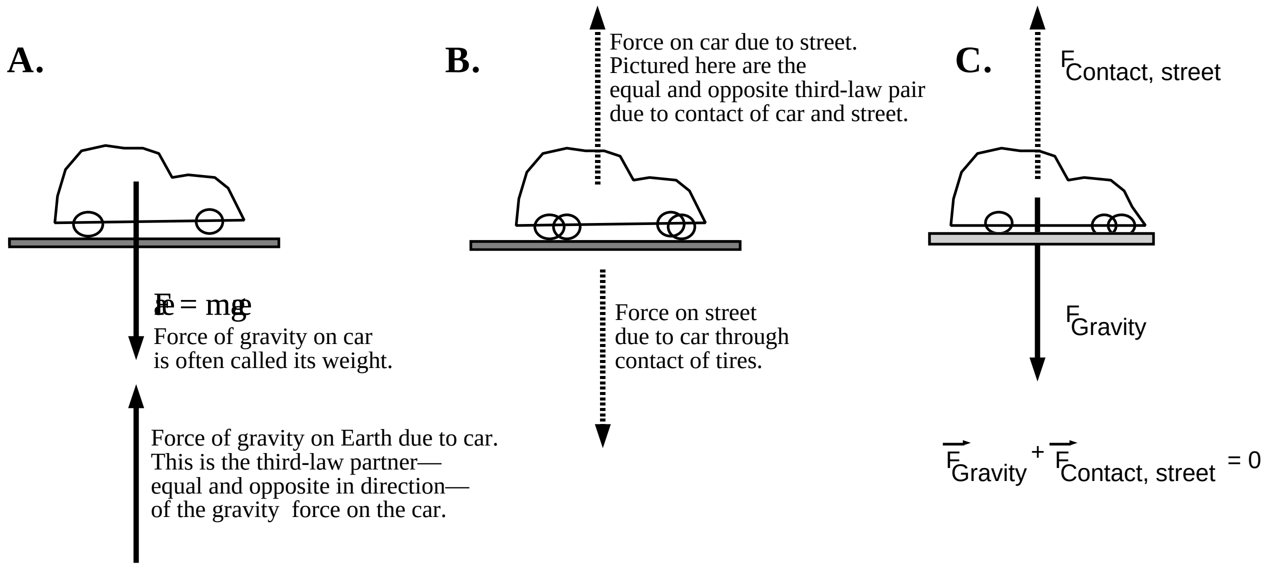
Newton's 2nd law says an object will accelerate —change its motion—if the sum of all the forces acting on it is some value other than zero. However, on each building, parked car, and sidewalk, the summed forces must be zero, since we can see that none of them are accelerating.

We can find all the forces acting on an object by reasoning with **Newton's 3rd law**, which states that all forces occur in equal-magnitude pairs.

If all the forces acting on an object sum to zero, the object is said to be in "equilibrium". For a parked car, the vertical forces on the object are in equilibrium. This equilibrium—the forces in the vertical direction sum to zero—means that the car does not accelerate vertically.

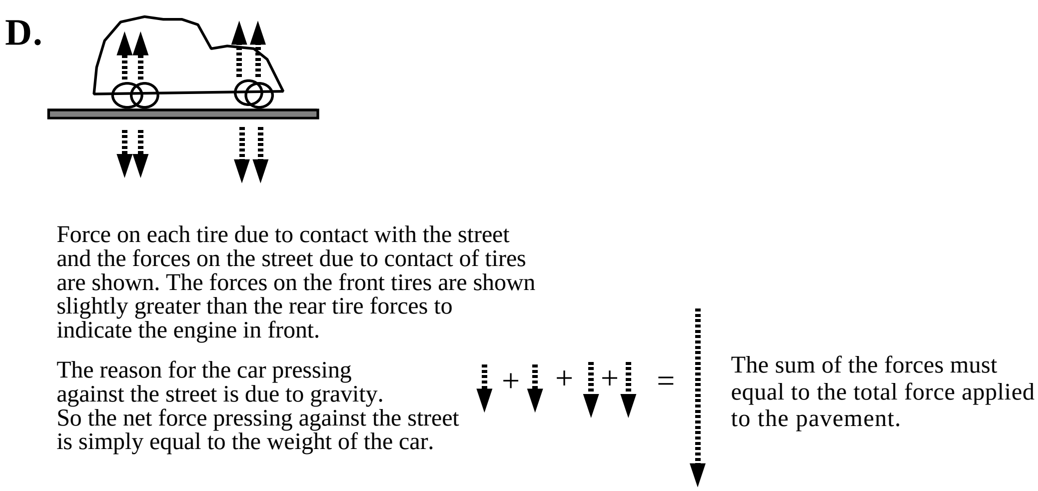
You can use this idea to weigh your car.

Observing a Car at Rest. Imagine a car of mass, m, at rest in a parking lot or in a driveway. The surface is horizontal and flat. The Earth and car interact gravitationally. Drawing **A**, shown below, pictures the pair of forces created by gravity. The Earth pulls on the car with a force of magnitude F = mg. Newton's third law calls attention to its partner, the force on the Earth due to the car.

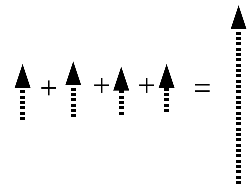


Drawing **B** shows a different pair of third-law forces, the ones due to short-range contact of the tires to the pavement (where the rubber meets the road). Note the important difference in the two drawings. The forces in drawing **A** are due to a long-range force. The pair of forces in drawing **B** are due to short-range contact forces. Drawing **C** summarizes the two vertical forces acting on the car.

Since four tires are in contact with the pavement, we can redraw the **B** diagram to show the forces on each tire, as seen in drawing **D** below.



How do we know that the total force acting upward on the car through the tires is exactly equal in magnitude to the weight of the car? BECAUSE THE CAR IS NOT CHANGING ITS VERTICAL MOTION. Said another way, we infer that the upward and downward forces on the car are equal because the car is not accelerating vertically. We observe this experimental fact, and from it, we conclude that the forces in the vertical direction must sum to zero. The downward weight of the car is "balanced" exactly by an upward force exerted by the pavement.



The upward force on the car is equal to the car's weight.

Equipment needed: You can measure the weight of your car with a tire pressure gauge, two sheets of paper, a ruler that measures in *inches*, and some reasonable assumptions. We will use "inches" as a distance unit because most local tire gauges will read the tire-pressure in $\frac{\text{lbs}}{\text{in}^2}$, read as "pounds per square inch". "One pound" is the traditional American force unit; in terms of international units, 1 lb = 4.45 newtons.

The Experiment:

The four tires must support the entire weight of the car. If you know the weight of the car on each tire, add those four forces to give you the weight of the car. Therefore the experimental question reduces to the following: how can we find the weight supported by each tire?

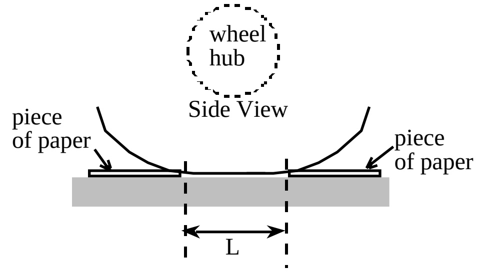
SAFETY FIRST: DO THIS EXPERIMENT IN A PARKING LOT OR DRIVEWAY. DO <u>NOT</u> PERFORM THIS EXPERIMENT IN THE STREET.

Measuring the pressure in the tires. The pressure in your tires can be measured or set by you if your gas station has an air hose with an air gauge on it. Your tires have a recommended fill pressure, usually around 28 to 30 $\frac{\text{lbs}}{\text{in}^2}$. You can also use a simple tire-pressure gauge, or perhaps ask the attendant if one is available. The simplest procedure might be to fill all the tires to the same recommended pressure value.

Pressure is defined as $P = \frac{\text{force}}{\text{area}}$. In our case of tire pressure, it tells you how much force (pounds) is pressing outward on each square inch on the inside of the tire. Estimate a reasonable uncertainty in your measurement, so the reported value will have the form $P \pm \Delta P$.

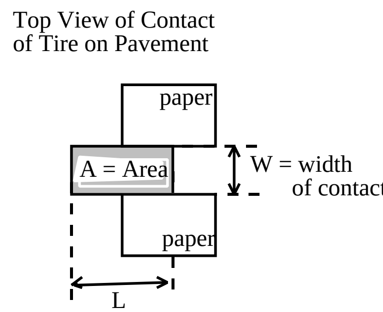
A reasonable assumption to simplify our model of weighing: We will assume the car is symmetrical from side to side. Then we need only measure one front tire and one back tire, and assume the other front and back tires have the same weight on them.

Slide one piece of paper up against the front edge and the other against the back edge of the front tire. Keep the edges of the paper parallel to each other. Measure the distance L between the parallel pieces of paper as shown in the drawing to the right. Use inches as a unit, since the tire gauge will likely read in those units. Pull the papers out, and then carefully repeat the measurement. Then do it once more, for a total of three measurements.



L = length of contact,
between tire and pavement

Then place the two papers inside and outside the tire, as shown to the right, and measure the width of contact, W. Pull the papers out. Then repeat this measurement twice more.



Average the three measurements of the length and width and determine the likely uncertainties as you do in the regular laboratory. (See Guideline#5 in the manual.)

Then, using the average values, multiply L times W to give you the area, A, of contact. Using the uncertainties of L and W, determine the uncertainty on the area. (See Guideline#4 in the manual.) You will then have a number for the area of contact, $A \pm \Delta A$ in square inches. This area is the "footprint" of your tire.

Comparison. The gross vehicle weight (GVW) of your car when empty of everything can often be on the end of the driver's side door under the locking mechanism. If not there, it is often on a sticker just opposite, mounted on the doorpost that the locking mechanism engages. Note that the GWV does not include anything you put in your trunk or vehicle. If those are in the car when you do this experiment, try to estimate their weight, as indicated in the Data Table.

Have fun, but be careful. Do not work where there is any traffic.

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NAME ______________________________ ID# ________________ PARTNER _______________________

Name, Model of Car: _________________________ Year: ________ Manuf. empty car wt., GVW: __________ lbs

Data Sheet: Measure or set all four tire pressures. IF ALL THE TIRE PRESSURES ARE THE SAME WITHIN UNCERTAINIES, then you can measure either the driver or passenger front-rear set, and then double the supported weight values. Or you can do all four tires, which is necessary if they have very different pressures.

1 Tire Position	**2** Pressure (lbs/in^2) $P \pm \Delta P$	**3** Length (inches) $L \pm \Delta L$	**4** Width, W (inches) $W \pm \Delta W$	**5** Area, A = LxW (in^2) $A \pm \Delta A$	**6** Supported weight, PxA $F \pm \Delta F$ (lbs)
Front, Driver	±	±	±	±	±
Rear, Driver	±	±	±	±	±
Front,Passenger	±	±	±	±	±
Rear, Passenger	±	±	±	±	±

Your estimate of car weight based on values in column 6: __________________ ± ______________ lbs

Absolute difference between the manufacturer's GVW and your estimate: _________________ lbs

1. This absolute difference, if relatively small, could be due to stuff added to the car and trunk and to the gas tank. Gasoline weighs about 8 lbs per gallon. State whether you think the absolute difference makes sense, and explain why in terms of what you had (or did not have) in your car.

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2. Does the vertical equilibrium (vertical forces sum to zero) also hold when you are driving your car down the street? Explain your answer.

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APPENDIX: Example Calculation.

Dr. George Kuck suggested this experiment, and he provided an example of the calculation for his own car.

From Guideline #4 in your laboratory manual: When numbers with uncertainties are added or subtracted, the uncertainty in the result is approximately the sum of the uncertainties on the input values. When numbers with uncertainties are multiplied or divided, the fractional or percentage uncertainty applied to the result is the sum of the fractional or percentage uncertainties of the input values.

Because you have calculators, this is lots easier than it looks. Carefully go through the procedure and record your values clearly at each step.

Tire pressure: $\mathbf{P} \pm \Delta\mathbf{P}$ = (29 ± 1) lb/in^2 or 29 lb/in^2 ± 3.4%

[Obtained by $\dfrac{\text{uncertainty in the value}}{\text{value}} \times 100\% = \dfrac{1}{29} \times 100\% = 3.4\%$]

$\mathbf{L} \pm \Delta\mathbf{L}$ = (7.0 ± 0.1) in or 7.0 in ± 1.4%

[Obtained by $\dfrac{\text{uncertainty in the value}}{\text{value}} \times 100\% = \dfrac{0.1}{7.0} \times 100\% = 1.4\%$]

$\mathbf{W} \pm \Delta\mathbf{W}$ = (5.8 ± 0.1) in or 5.8 in ± 1.7%

A = 7.0 x 5.8 = 40.6 in^2

To get $\Delta\mathbf{A}$: 1.4% + 1.7% = 3.1% = 0.031 Then multiply 0.031 x [value of A] =0.031 x 40.6 ≈1.3 in^2

Therefore, $\mathbf{A} \pm \Delta\mathbf{A}$ = (40.6 ± 1.3) in^2

F = P x A = 29 lbs x 40.6 $\dfrac{\text{lbs}}{\text{in}^2}$ = 1177 lbs ≈1180 lbs

To get $\Delta\mathbf{F}$: 3.4% + 3.1% = 6.5% =0.065 Then multiply 0.065 x [value of F] = 0.065 x 1180 = 77 lbs ≈ 80 lbs

Therefore, $\mathbf{F} \pm \Delta\mathbf{F}$ = (1180 ± 80) lb the force exerted by one tire on the contact region.

If we assume all four tires exert the same force on their contact regions,

then the total force is 4 x 1180 = 4720 lbs.

The uncertainty in the total force is simply the sum of the input uncertainties,

namely, 80 + 80 + 80 + 80 = 320 lbs.

Therefore $\mathbf{F}_{total} \pm \Delta\mathbf{F}_{total}$ **= (4720 ± 320) lbs,** the measured weight of the car.

[We have neglected the formal use of significant figures and the effect round-off in some of these calculations.]

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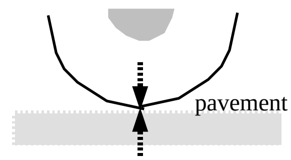
EXTRA CREDIT: WRITE UP THIS PROBLEM ON A SHEET OF PAPER.

3. Here's a problem that can baffle even physics and engineering majors, even though you can do it with some qualitative reasoning. Read the reasoning through carefully.

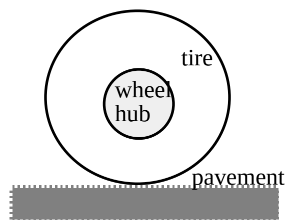
We know a car is held up in the air by four inflated tires, because if we let the air out, the metal wheel hubs will rest on the ground. Because we can see the latter situation, it is also clear that the sides of the rubber tires are very flexible, not at all rigid enough to hold the car up. *So how—precisely—is the car held up above the ground? "Precisely" means that you need to explain: what force, applied where, actually does the job of holding the car body up against the pull of the force of gravity?*

REASONING to get started:

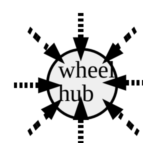
a) Many people will say it's obvious, that the pavement holds up the car. But this is *not* directly the case. The pavement presses upward on the rubber in contact and the pressure inside exerts an equal force on the same rubber. Our observation that the rubber in contact is not accelerating tells us this information directly. There is no "extra force" left over to counteract the pull of gravity on the wheel hub.



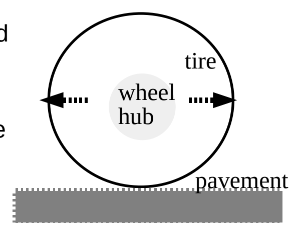
b) Could the force from the pavement be transmitted up to the hub through the sidewalls of the tire and through the air in the tire? No. Both the sidewalls and the air are very flexible materials, and could not possibly support any weight. Said another way, the sidewalls and air are completely unlike a rigid block of wood, which could indeed do the job of transmitting the force from the pavement to the hub.



c) How about the air pressure that provides a force pushing upward against the hub? That looks promising until one realizes that because of the circular symmetry of the hub, the same value of air pressure provides a force on the top of the hub of exactly the same magnitude. The air pressure completely surrounds the hub, so that any force acting on a particular area of the hub has an exactly compensating force on the other side. Nowhere is there any "excess" force to hold the car up.



d) What about the air pressure outward against the tread of the tire in the forward direction? As seen in the drawing to the right, the forward force that attempts to push the tire to the right is exactly compensated by the backward force attempting to move the tire to the left. (Atmospheric air pressure makes some contribution, but the resultant forces on each side are equal. How do we know? The tire is not accelerating forward or backward, which it would do if one of those forces was larger than the other.



e) We know the answer has something to do with the air pressure, so where else inside the tire should we look? The gravity force, $F_{Gravity}$, can be pictured as acting on the center of the hub. Since $F_{Gravity}$ acts vertically downward, I suggest looking at *all* the forces along the vertical dotted line in the drawing to the right. One further fact you need: the sidewalls of the tire, although flexible, are very strong when pulled and stretch very little.