Friction Experiment

by

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1. Introduction

Pushing a heavy box that is lying on the ground can be quite difficult for even a large muscular adult. However, if the same box is placed on a wheeled dolly instead, a small child may have little difficulty moving the box. How is this possible? Does the dolly somehow make the box any lighter? Friction is at the root of this issue. If you try to move the box while it is on the ground, you will encounter a significant amount of friction, which must be overcome. Placing the box on the dolly reduces the friction present in the system and makes it much easier to move the box. It may sound as though friction is something that makes life overly difficult and that you would be better off without it. The truth is very much the opposite, however. Cars use friction both to enable them to move and to brake while in motion. Have you ever tried to walk on ice? Even on ice there is a small amount of friction. Without friction, walking would be impossible. In this experiment we will classify the various forms of friction that are encountered in everyday life.

2. Background

2.1. Force

What is commonly referred to as friction is actually a frictional *force*. Therefore, to properly define friction, we must first introduce the concepts of force and *velocity*. Force and velocity are *vector* quantities; they have both a magnitude and direction. Velocity can be thought of as the speed in a specified direction, with which a given object is traveling. Force is the mechanism through which the object *accelerates*, or undergoes a change in its velocity. A body that is at rest is one in which the *resultant force*, the sum of all forces acting on the body, is zero. Such an object is said to be in *equilibrium*. Although many different forms of forces exist, there are two broad classifications that are commonly used to categorize forces. First, we distinguish between *conservative* and *dissipative* forces. Conservative forces act upon an object in a manner such that the total energy of the object is conserved. Dissipative forces are ones that reduce the total energy of the object upon which they act. Friction is a dissipative force. A different way to categorize forces is to distinguish between *contact* and *field* forces. Contact forces, as the name implies, rely upon physical contact to act on a body. Field forces require no physical contact to act on a body. Friction is a contact force. Gravitational and magnetic forces are common examples of field forces. See [8] for more details. We will now define and discuss a few types of forces that are of direct importance to our discussion on friction.

Gravitational force

Gravity is an attractive force that exists between two masses. The magnitude of the force depends on the proximity of the masses involved, as well as the magnitude of the masses. At large distances, and/or if the masses of interest are of small quantity, the effects of gravity can be ignored. That is why astronauts in outer space float freely, and astronauts on the moon bounce along as they do. We approximate the gravitational force that acts on an object on Earth as

$$F_g = mg$$

where m is the mass of the object and g is the *free-fall* acceleration. This value is only an approximation because the magnitude of g depends on the altitude of the object as well as the latitude of the location. However, because the spatial differences in acceleration due to gravity are so small, the approximation is well justified. The magnitude of the gravitational force exerted on an object is referred to as its *weight*. See [8] for more details.

Normal force

The normal force is a contact force that acts in the *normal* direction, i.e., perpendicular to, the contact surface between two objects. For an object subjected to no forces other than gravity, the magnitude of the normal force is equal to the component of the gravitational force that acts normal to the surface, but it acts in the opposite direction. See [2, 8] for more details. Figure 1 depicts a free-body diagram of a mass, m, lying on a horizontal surface, where the normal force, N, is equal in magnitude to the gravitational force mg.
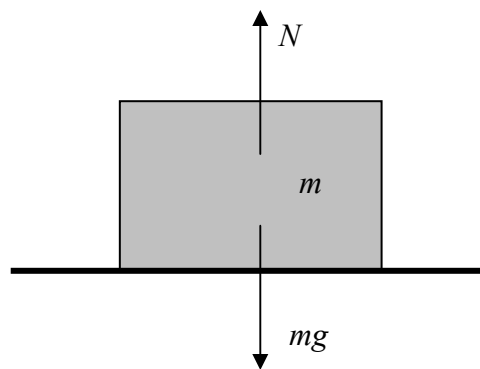

Figure 1: Free-body diagram of a mass lying on a horizontal surface

2.2. Friction

There are different forms of frictional forces that occur. When friction acts on an object that is at rest, we refer to the frictional force as *static* friction. An object that is in motion is subject to *kinetic*, or *dynamic*, friction. Friction is a *resistive* force, one that damps out motion in dynamic systems and prevents movement in static systems. Friction occurs because an object interacts with either the surface it lays upon, the medium it is contained in, or both. Only in a complete vacuum can a system be free of friction.

Static friction

When you want to push a heavy object, static friction is the force that you must overcome in order to get it moving. The magnitude of the static frictional force, f_s, satisfies

$$f_s \leq \mu_s N$$

where μ_s is the coefficient of static friction, a dimensionless constant that depends on the object and the surface it is laying upon. From this equation it is clear that the maximum force of static friction, $f_{s,\max}$, that can be exerted on an object by a surface is

$$f_{s,\max} = \mu_s N.$$

Once the applied force exceeds this threshold the object will begin to move. A common example of a static friction force is that of a stationary mass on an incline. Figure 2 depicts the free-body diagram of this case.
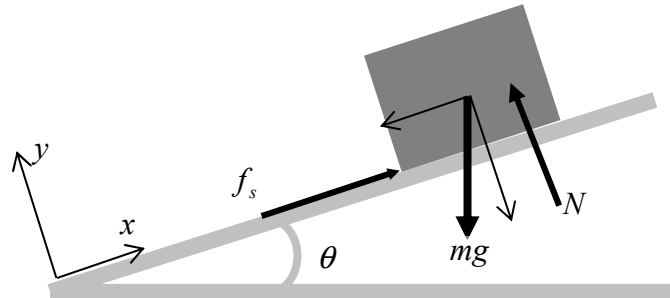

Figure 2: Free-body diagram of a mass on an incline

If the angle at which the mass begins to slide is known, we can determine μ_s by decomposing the forces into the Cartesian coordinates, $x, y,$ as given in Figure 2. Since we are interested in the instant at which movement begins, we are dealing with an object in equilibrium. Thus, the resultant force in both the x and y directions must be zero. Analysis of the forces in the x direction yields

$$f_s = mg \sin \theta. \tag{1}$$

Following a similar procedure for the y direction yields

$$N = mg \cos \theta. \tag{2}$$

However, we know that at the instant that the mass begins to move

$$f_s = f_{s,\max} = \mu_s N. \tag{3}$$

Thus, by substituting (2) into (3) and equating the result with (1) we can solve for μ_s as follows

$$f_s = \mu_s mg \cos \theta = mg \sin \theta$$
$$\Rightarrow \mu_s = \tan \theta.$$

Kinetic friction

Once the force applied on a mass exceeds $f_{s,\max}$ and the mass begins to move, a kinetic friction force, f_k, exists. Kinetic friction coefficients are generally less than static friction coefficients, which is the reason that it is much easier to keep a heavy object in motion than it is to start it in motion [4]. The magnitude of the kinetic frictional force is given as follows

$$f_k = \mu_k N$$

where μ_k is the coefficient of kinetic friction and is approximately constant. Figure 3 is a plot of frictional force versus applied force [1, 8]. The slight fluctuations in the kinetic region of the plot are due to the slight dependency of μ_k on the speed of the object [8].
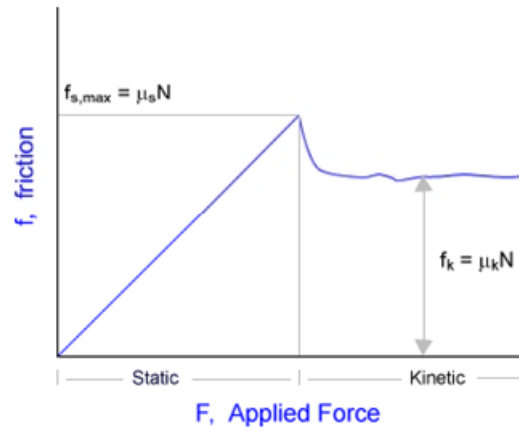

Figure 3: Plot of frictional force versus applied force

Table 1 lists the coefficients of static and kinetic friction for various object/surface combinations [5, 8]. The coefficient of static friction is less than that of kinetic friction for all cases in the table except Teflon on Teflon.

Table 1: Coefficients of static and kinetic friction

Materials	Coefficients of Static Friction (μ_s)	Coefficients of Kinetic Friction (μ_k)
Steel on Steel	0.74	0.57
Aluminum on Steel	0.61	0.47
Copper on Steel	0.53	0.36
Rubber on Concrete	1.0	0.8
Wood on Wood	0.25-0.5	0.2
Glass on Glass	0.94	0.4
Waxed wood on Wet snow	0.14	0.1
Waxed wood on Dry snow	-	0.04
Metal on Metal (lubricated)	0.15	0.06
Ice on Ice	0.1	0.03
Teflon on Teflon	0.04	0.04
Synovial joints in humans	0.01	0.003

Rolling friction

Rolling friction is a special case of kinetic friction. When we say that a wheel rolls without slipping, we are implying that the wheel is subjected to rolling friction. The motion of a wheel under rolling conditions is not affected by kinetic friction. There are no dissipative forces acting on the wheel subject to rolling friction, under ideal conditions, because the wheel does not slip at the point of contact. As a result, rolling friction does not impede on the motion of the wheel. However, once rolling ceases, kinetic friction is the only frictional force acting on the wheel.

In non-ideal conditions, rolling friction on a wheel does act as an energy dissipative force due to trace slippage caused by flexing of the wheel. Experimentally, the coefficient of rolling friction between the tire and the road is found to be 0.02-0.06, whereas the coefficient of static friction between the tire and the road is found to be 0.8. See [2] for more details.

3. Equipment list

Board of Education (BOE) with Basic Stamp 2 (BS2)

The combination of the BS2 embedded within the BOE will serve as the microcontroller that monitors the experiments that you are about to do. The BS2 is a 24 pin Dual Inline Package (DIP) integrated circuit (IC). It is based on Microchip Inc.'s PIC 16C57 microcontroller. The BS2 is powered by a 6-14V direct current (VDC) power supply. An onboard voltage regulator provides a steady 5VDC output to the BS2. The BS2 comes with ROM, 2KB Electronically Erasable Programmable ROM (EEPROM), and a small amount of RAM. The BS2 is programmed in PBasic language, the instruction set that is stored in the BS2 ROM. The user defined program is downloaded into the EEPROM from a PC to the BOE using a DB-9 serial cable. The excess EEPROM can be used for long term data storage. The BS2 has 16 general purpose digital input/output (I/O) pins that are user defined. The high position on a digital I/O pin refers to a 5VDC and a low position on a digital I/O pin refers to a 0VDC (ground potential). Each pin can source (supply) a maximum current of 20mA and sink (draw) a maximum current of 25mA. The 16 I/O pins on the BS2 at any given time can source/sink a maximum of 40mA/50mA. If using an external 5VDC voltage regulator, these limits apply to each group of 8 pins, P0-P7 and P8-P15. Exceeding these current source/sink limits or establishing a voltage on a pin greater than 5VDC will damage the BS2. See [6, 7] for more details.

A limitation that often arises when using the BS2 is the lack of support for floating point variables. Utilizing floating point operations like division in the absence of floating point variables may lead to mathematical errors due to truncation. The largest variable or constant that can be stored on the BS2 is of *word* size (16 bits), which has a numerical range of 0-65,535 in decimal notation.

A BOE and BS2 are depicted in Figure 4 [3]. The BS2 is placed, in the same orientation as shown, in the IC socket in the lower left corner of the BOE.
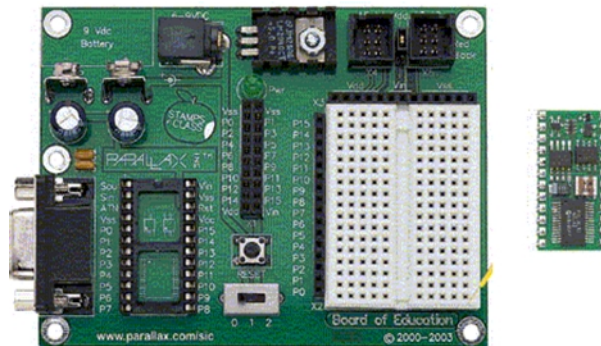

Figure 4: Parallax Board of Education with a Basic Stamp 2 at right

Static friction experiment test bed

The static friction coefficient test bed will be used to experimentally determine the coefficient of static friction between various surfaces. It consists of a horizontal base and a plate that can be rotated from a level plane that corresponds to $\theta = 0°$, and where the vertical position corresponds to $\theta = 90°$. The test bed relies upon $\mu_s = \tan\theta$, an equation that we have previously derived. The plate, which is

connected to the base through a hinge, is rotated by a DC motor. The DC motor is driven by a regulated 12 VDC external power supply. An H-Bridge is used to control the rotational direction of the DC motor. An InfraRed (IR) transmitter and receiver pair is used to detect movement of the mass. The pair has been mounted on the opposing sidewalls of the plate facing each other. The IR transmitter continuously sends an infrared pulse towards the receiver. When the mass starts to slide, it interrupts the infrared beam. To ensure accuracy, the experiment must be conducted so that the first instant of the mass's movement is detected. To achieve this accuracy, a stopper has been placed at the free end of the plate such that by placing the mass snug against it the IR beam will be tripped the instant the mass begins to slide. Once the IR receiver has been tripped, the BS2 shuts the motor down. The angle at which the mass begins to slide is measured by a rotary potentiometer connected to the hinge on which the plate turns. A constant 5VDC voltage is applied across the full resistance of the potentiometer. The wiper rotates along with the plate, and the voltage between the wiper and one end of the potentiometer is measured. Since the BS2 is a digital device and the quantity being measured is an analog voltage, an Analog to Digital Converter (ADC) IC is utilized. The quantization number, Q, of an ADC depends on the number of bits the ADC has and on the span (range of values) that is being digitized. Q for an n-bit ADC is given by

$$Q = \frac{V_{span}}{2^n}$$

where V_{span} is the voltage span to be digitized. This test bed uses an ADC0831 from National Semiconductor, an 8-bit, successive approximation converter that is easily interfaced with the BS2 using the PBasic *shiftin* command. See [6, 7] for more details. As an 8-bit device it can convert an analog signal into 256 discrete levels. To maximize the sensitivity of the ADC the offset and span voltages were provided to the ADC by adjusting two potentiometers to provide the proper voltages. A stopper has been installed at the foot of the plate to prevent the mass from falling down. Circuit schematics for the static friction coefficient can be found in Appendix A.

Figure 5 is an overhead view of the test bed. The DC motor can be seen in the lower left hand corner of the figure. The potentiometer can be seen in the upper left hand corner. The stopper that prevents the mass from falling of the plate can be seen on the left hand side of the figure. The electrical circuitry used by the test bed can be seen on the right hand side of the figure.
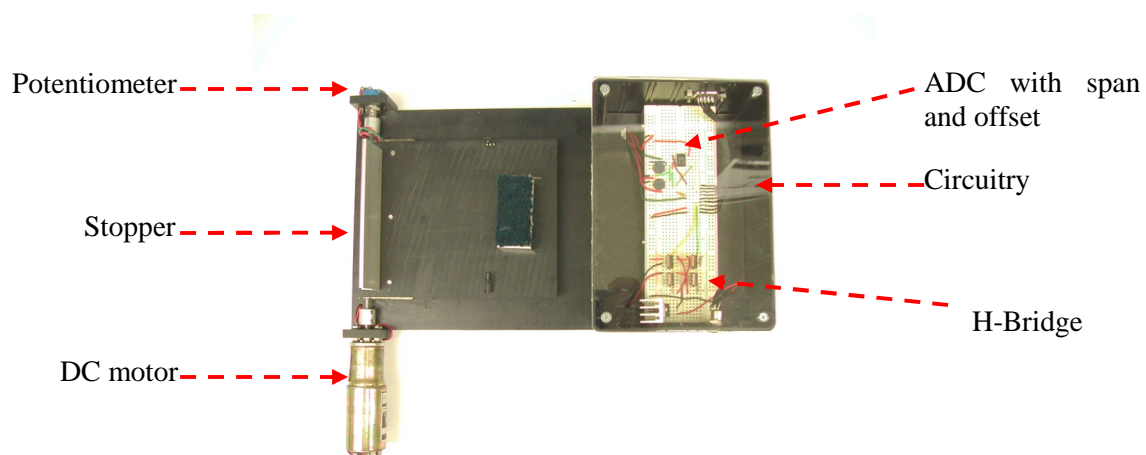

Figure 5: Overhead view of the static friction coefficient test bed

Figure 6 is a close up view of the test bed. In the upper left hand corner of the figure the IR receiver is visible. In the lower right hand corner of the figure the IR transmitter is visible. The stopper used to mark the starting position of the mass can be seen behind the mass.
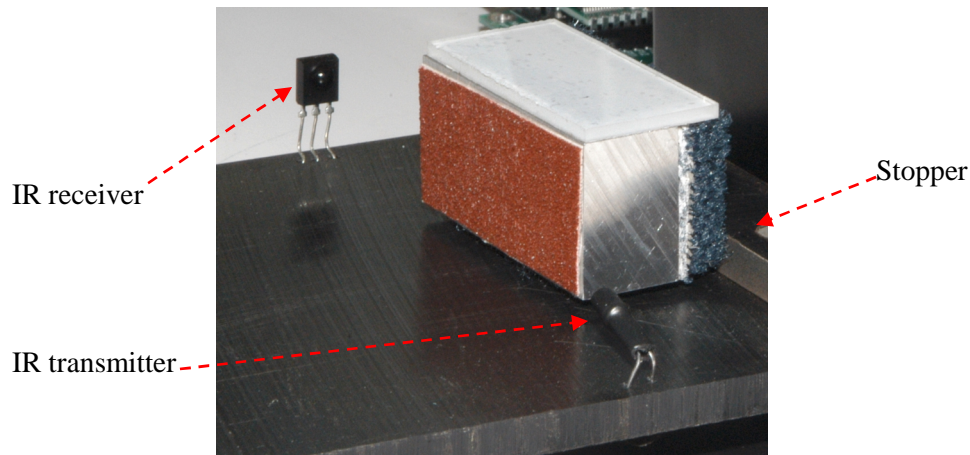

Figure 6: A view of the static friction coefficient experiment

4. Experimental procedure

4.1. Static friction experiment

Figure 7 is an illustrative diagram depicting the functionality of this experiment. A mass is placed on the plate, which is then rotated until the mass begins to slide down the inclination. An IR receiver detects the first instant of the mass's motion.
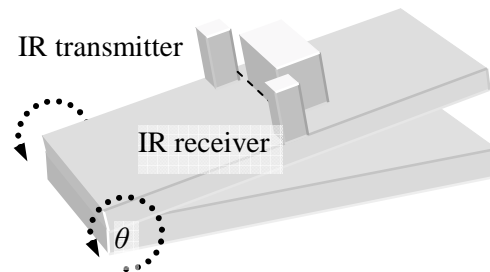

Figure 7: Static friction coefficient experiment

Goal:
1. Experimentally verify that the coefficient of static friction for various surfaces.

Static friction experiment procedure
1. Connect the BS2 to the test bed with the DB-9 adapter located on the test bed, and to a computer with another DB-9 serial cable.
2. Connect the BS2 to a 9VDC power source, either a power adapter or battery can be used.
3. Download the *StaticFriction.bs2* file to the BS2.
4. At the prompt place the mass on the test bed, lining it up properly.
5. The BS2 will then rotate the plate through an arc (0˚ to 90˚) until the IR detector is tripped.
6. The BS2 will calculate μ_s from the angle at which the IR detector was tripped.
7. To continue with this experiment follow the prompts regarding restarting the experiment.

Discussion

Which material has the highest coefficient of static friction? Does this agree with your intuition? What do you think determines the coefficient of static friction? Surface area? Contact area? See [2, 4, 8] for more details.

Once the mass begins to slide does it move smoothly, or does it undergo stop and go motion? What possible explanation for the motion can you think of?

5. Suggested Project

1) Kinetic and static friction coefficient detector: Devise a means of measuring the coefficient of kinetic friction. It may be possible to modify the static coefficient experiment to accomplish this project.

6. References

[1] Online: http://www.cord.edu/dept/physics/p128/lecture99_12.html, web site of the Physics Department at Concordia University containing physics lectures.

[2] Online: http://hyperphysics.phy-astr.gsu.edu/hbase/frict.html, educational web site for physics, math, chemistry, mechanics, and other natural sciences, by Carl R. Nave.

[3] Online: http://www.parallax.com, web site of Parallax, Inc. manufacturer and distributor of Basic Stamp microcontrollers containing technical specifications and user manuals.

[4] Online: http://www.physicseq.com/force/frictionhelp.html, web site of PhysicEq.com containing high school level physics tutorials, by Stephen Embree.

[5] Online: http://www.physlink.com/Reference/FrictionCoefficients.cfm, web site of Physlink.com containing coefficients of static and kinetic friction.

[6] Online: http://www.stampsinclass.com, web site of Stamps in Class containing educational resources for Basic Stamp microcontrollers.

[7] V. Kapila, *Course Notes for Mechatronics ME 3484*, Polytechnic University, Brooklyn, NY, (2003).

[8] R.A. Serway and R.J. Beichner, *Physics for Scientists and Engineers*. Saunders College Publishing, Orlando, FL, 5th Ed., (2000).
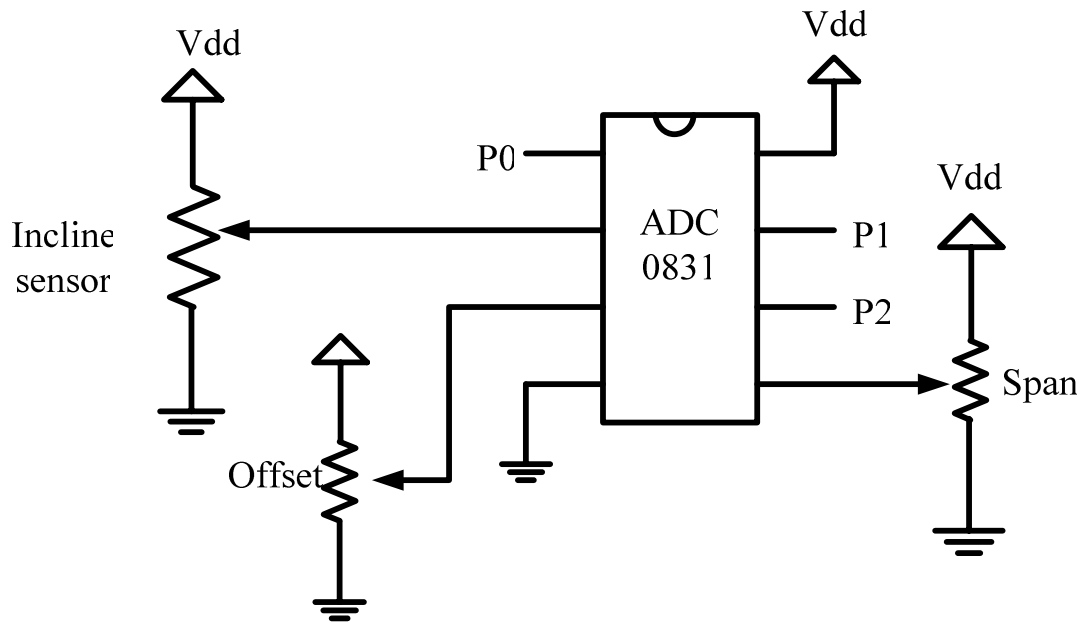
Appendix A: Circuit schematics

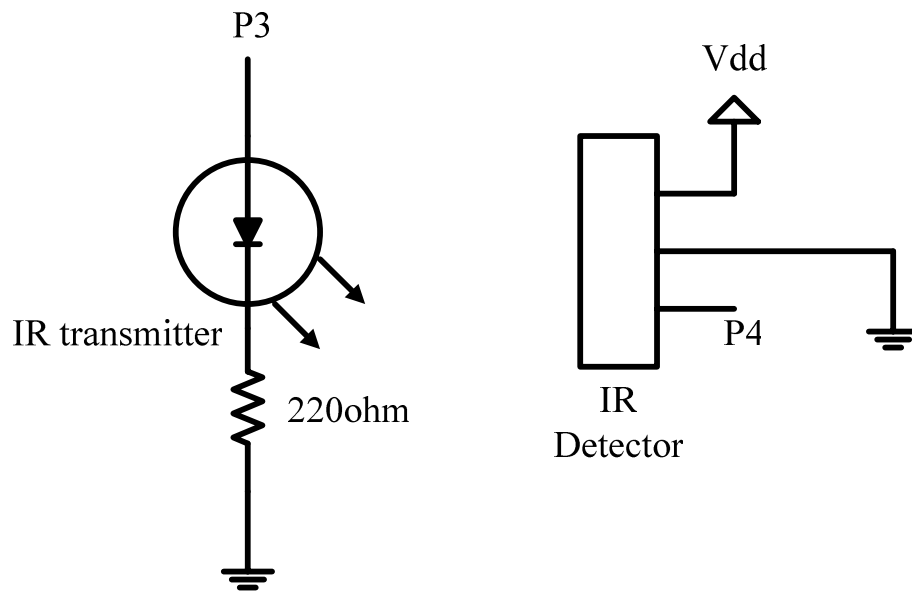Figure A1: Circuit schematic of the ADC used to digitize the angle of inclination

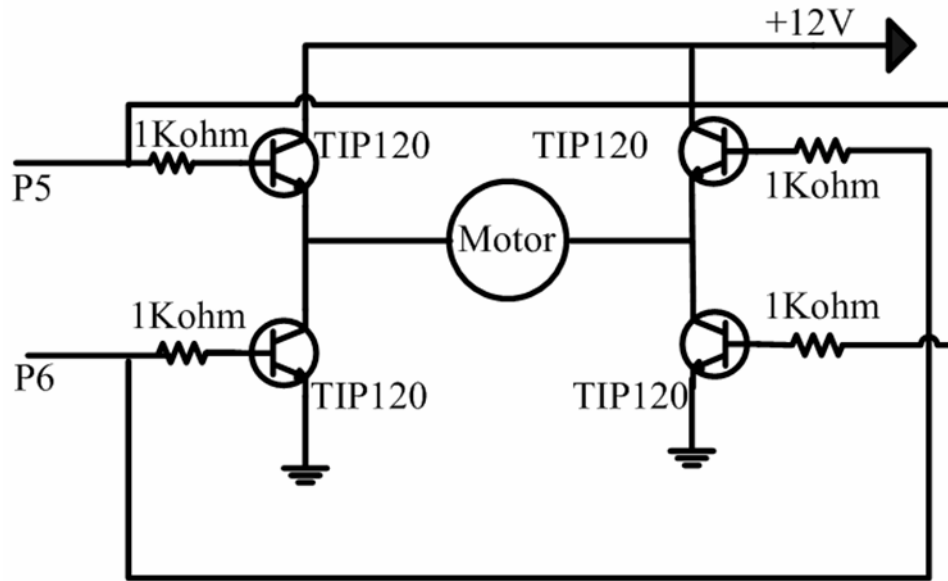Figure A2: Circuit schematic of the IR transmitter/receiver pair used to detect motion

Figure A3: Circuit schematic of an H-Bridge using BJT transistors