Mechatronics (ROB-GY 5103 Section A)

- **Today's lecture:**
  - PWM
  - Op-amps again
  - Sensors
- (See Topics #7 and #9 from Main Text for details)

Pulse-Width Modulation (PWM)

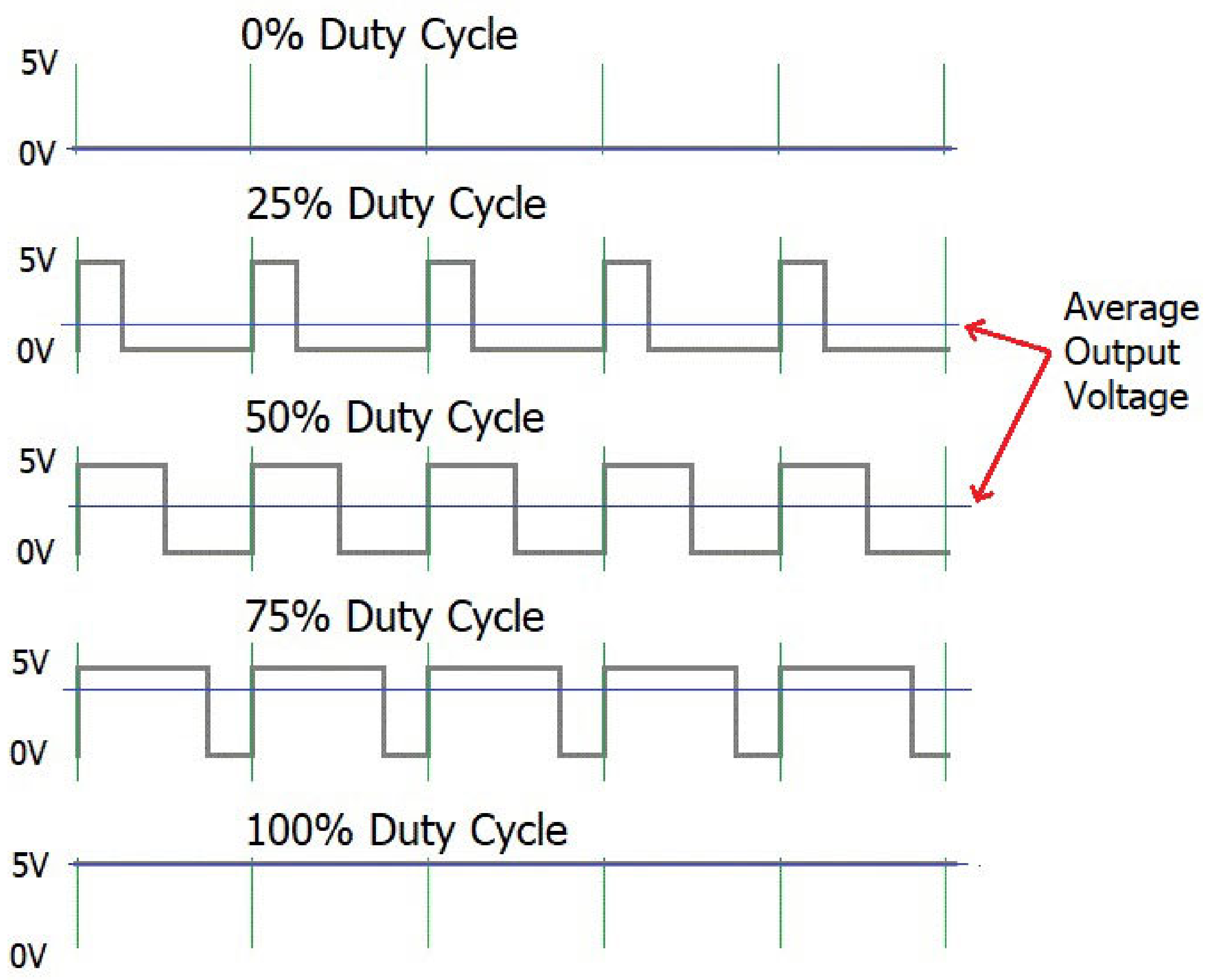
- **Objective:** Use a digital circuit to produce an analog output
- PWM is one technique to achieve an equivalent “analog” output with rapid switching, just by changing the pulse duration
    - Hence, pulse-width modulation

Pulse-Width Modulation (PWM)

- **Objective:** Use a digital circuit to produce an analog output
- PWM is one technique to achieve an equivalent “analog” output with rapid switching, just by changing the pulse duration
  - Hence, pulse-width modulation

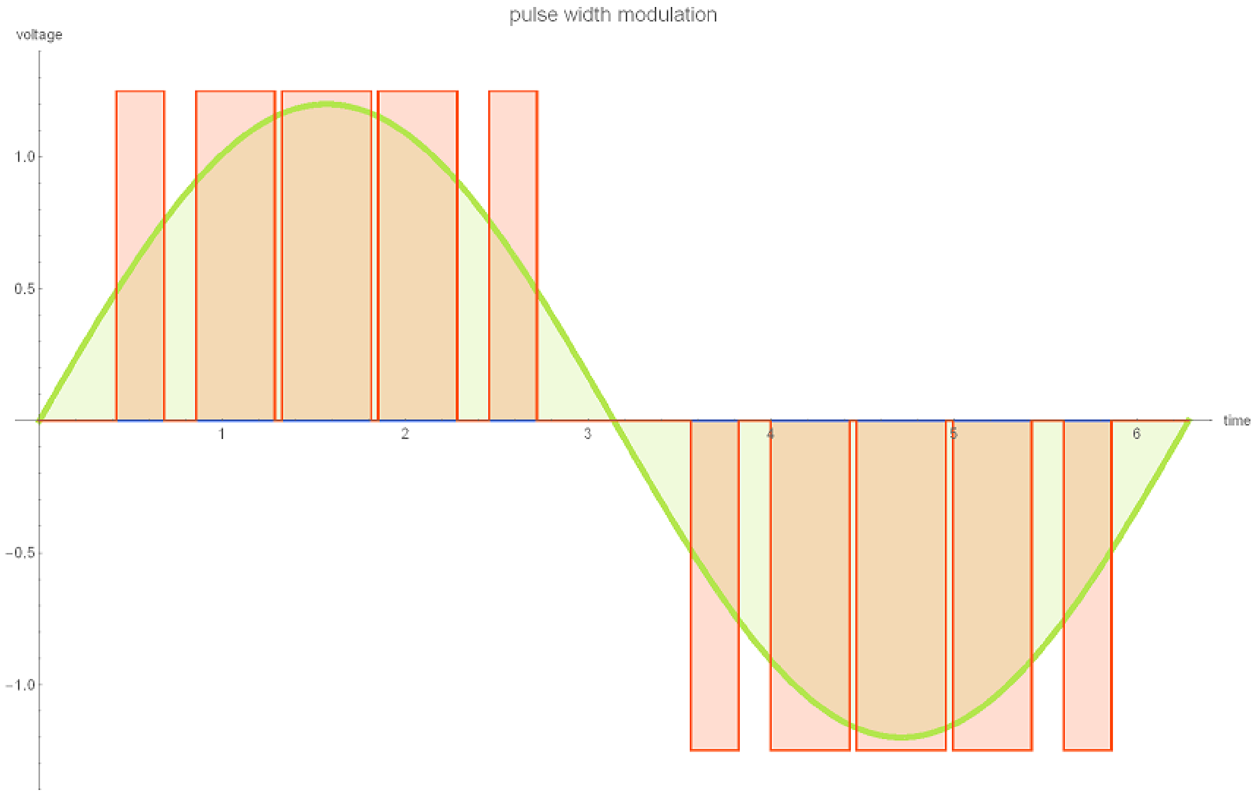
Pulse-Width Modulation (PWM)

- First, consider a fixed pulse frequency
    - 0% to 100% duty cycle maps to zero and maximum output



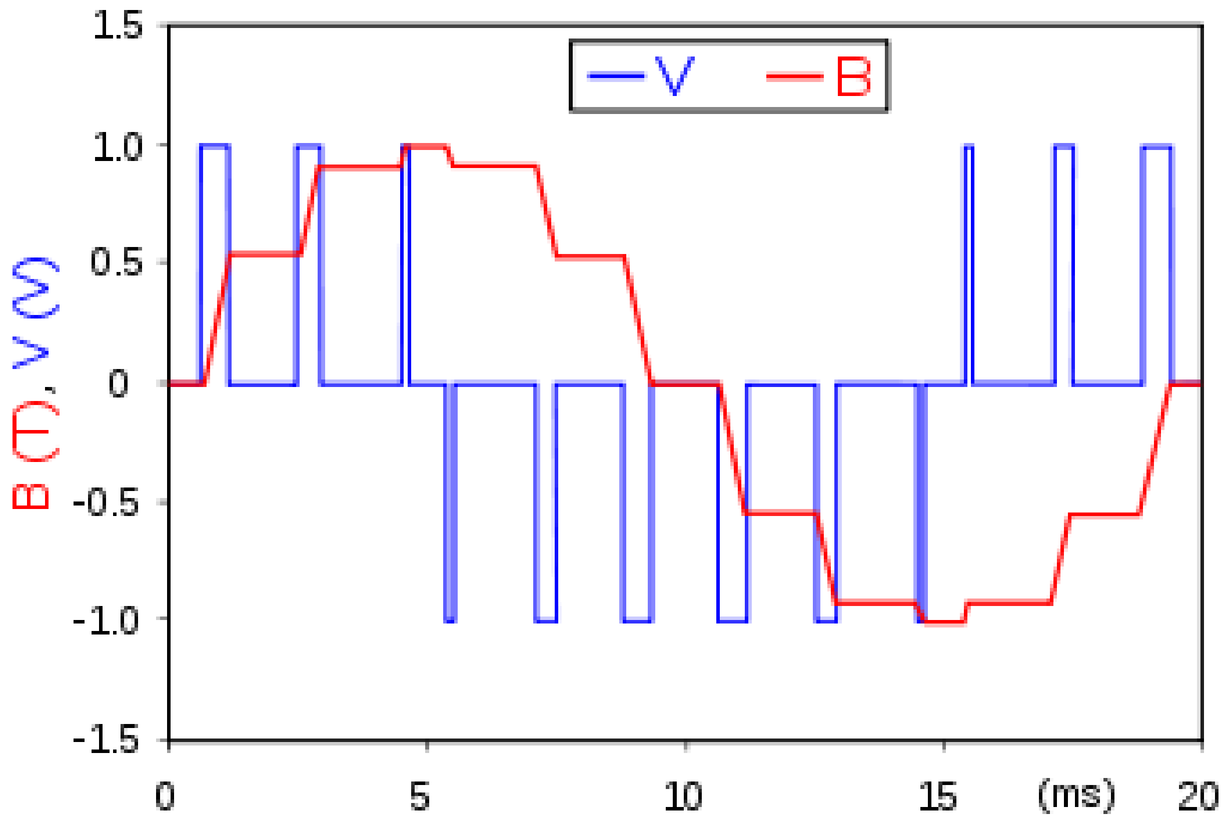
Pulse-Width Modulation (PWM)

- First, consider a fixed pulse frequency
  - 0% to 100% duty cycle maps to zero and maximum output
- If the duty cycle varies over time, an approximate “analog” output is generated



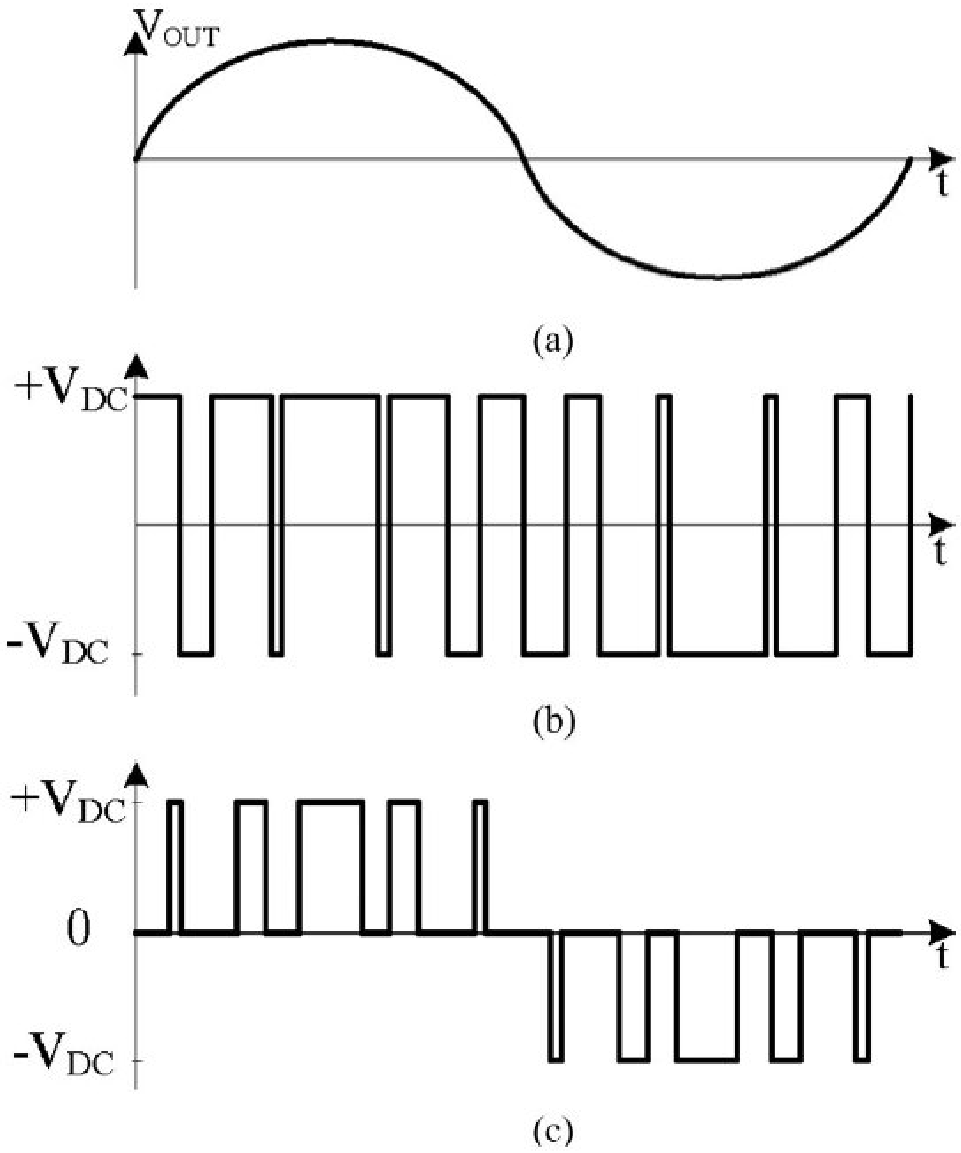
Pulse-Width Modulation (PWM)

- First, consider a fixed pulse frequency
  - 0% to 100% duty cycle maps to zero and maximum output
- If the duty cycle varies over time, an approximate “analog” output is generated
  - Frequency matters! Sufficiently high frequency is needed



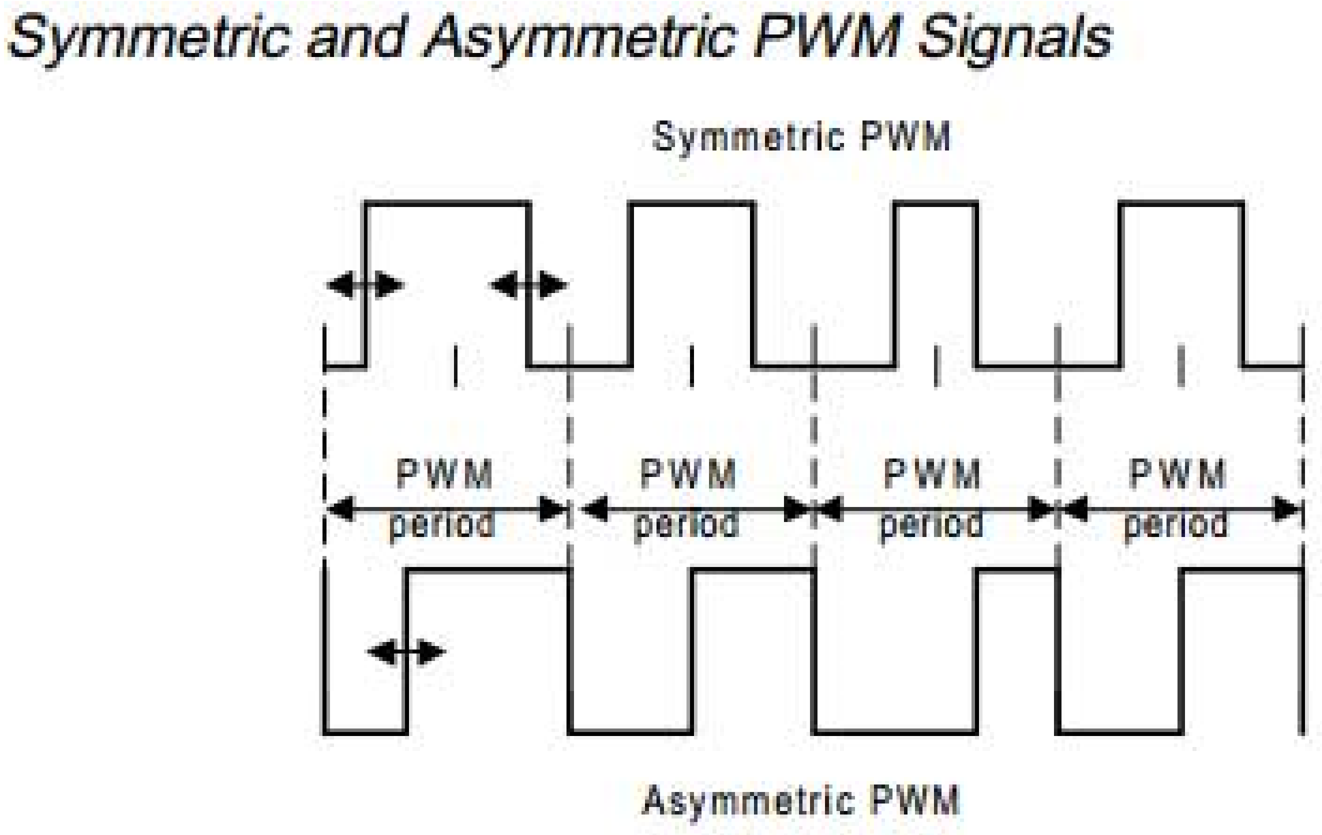
Pulse-Width Modulation (PWM)

- Unipolar vs Bipolar PWM



Pulse-Width Modulation (PWM)

- Edge-aligned vs Center-aligned

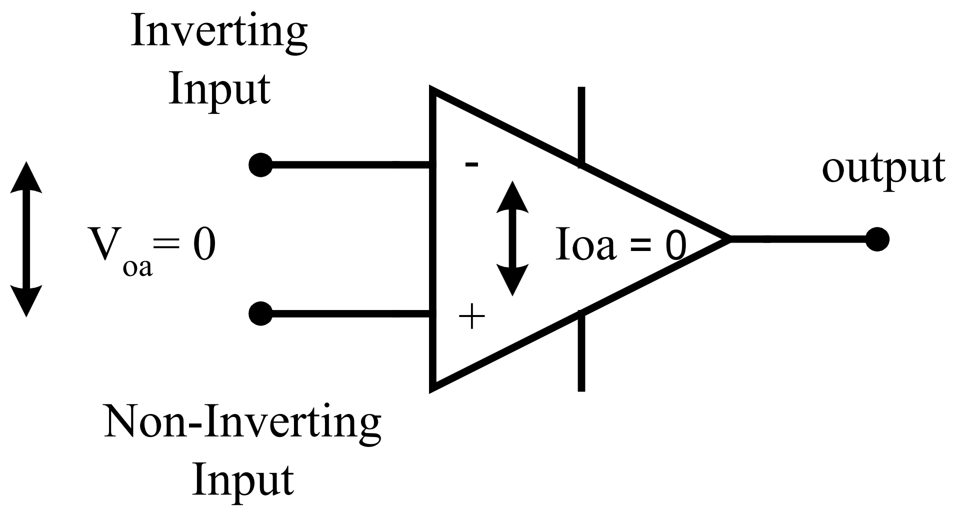


PWM is a powerful idea

- Can be used to dim LEDs
- Can be used to drive motors
    - Motors and H-bridge

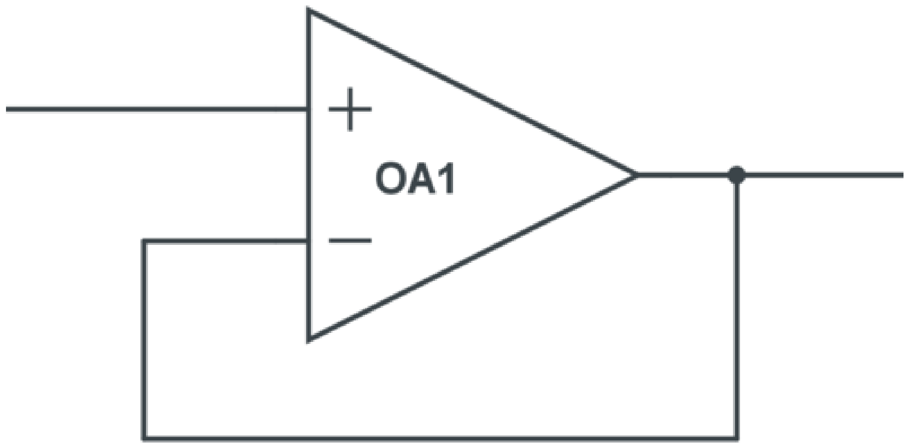
Operational Amplifier

- Active device composed of transistors
- Open-loop configuration:
  - Acts as comparator: voltage difference at inputs leads to high/low output
- Closed-loop configuration:
  - Interesting useful part



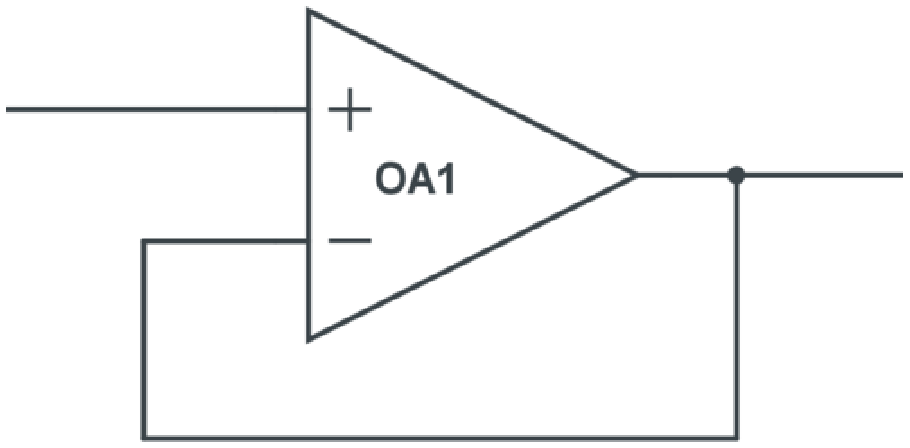
Op-Amp

- We usually think of amplification vs. stabilization as opposing tendencies



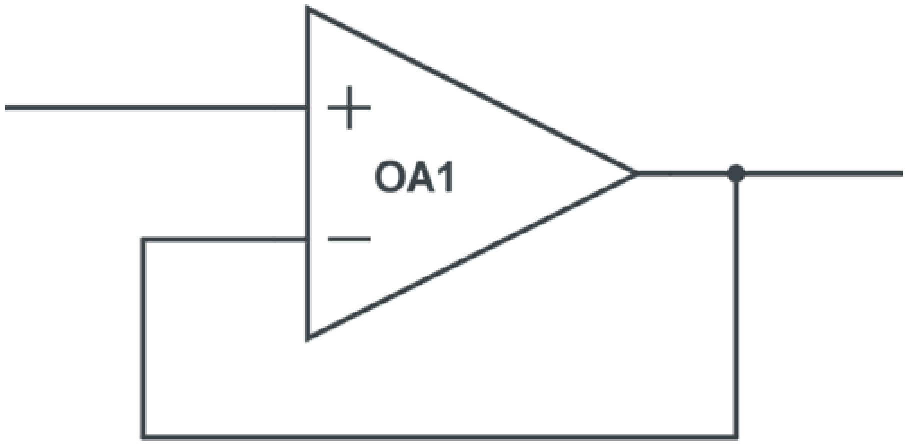
Op-Amp

- We usually think of amplification vs. stabilization as opposing tendencies
  - With feedback (closed-loop configuration), we see that amplification drives the two voltage inputs to be equal



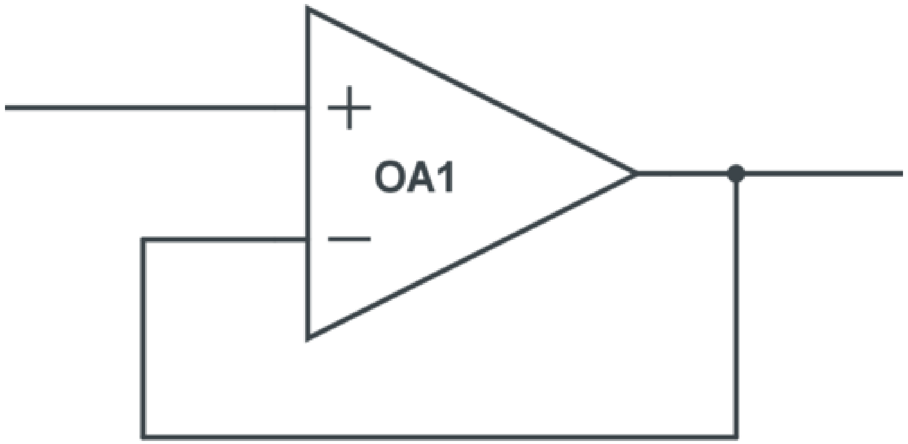
Op-Amp

- We usually think of amplification vs. stabilization as opposing tendencies
  - With feedback (closed-loop configuration), we see that amplification drives the two voltage inputs to be equal
  - Assume the + input is a fixed voltage. Then any tiny deviation at the – input is magnified at the output and fed back into the – input.



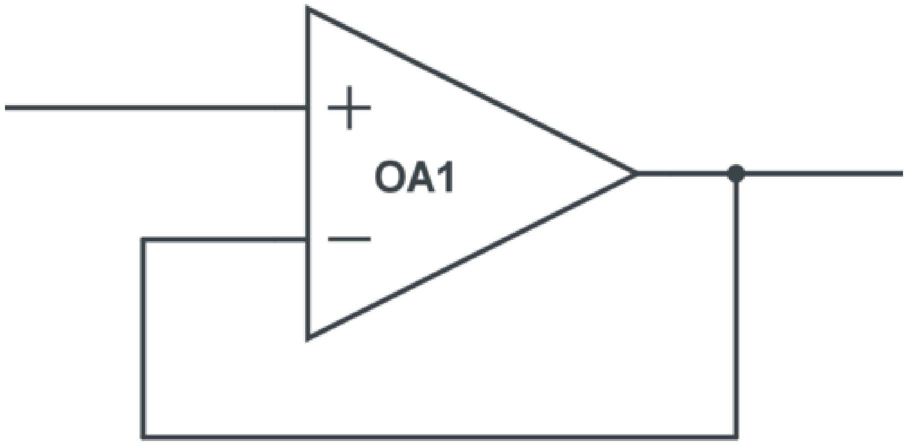
Op-Amp

- We usually think of amplification vs. stabilization as opposing tendencies
  - With feedback (closed-loop configuration), we see that amplification drives the two voltage inputs to be equal
  - Assume the + input is a fixed voltage. Then any tiny deviation at the – input is magnified at the output and fed back into the – input.
  - **This is self-correcting!**



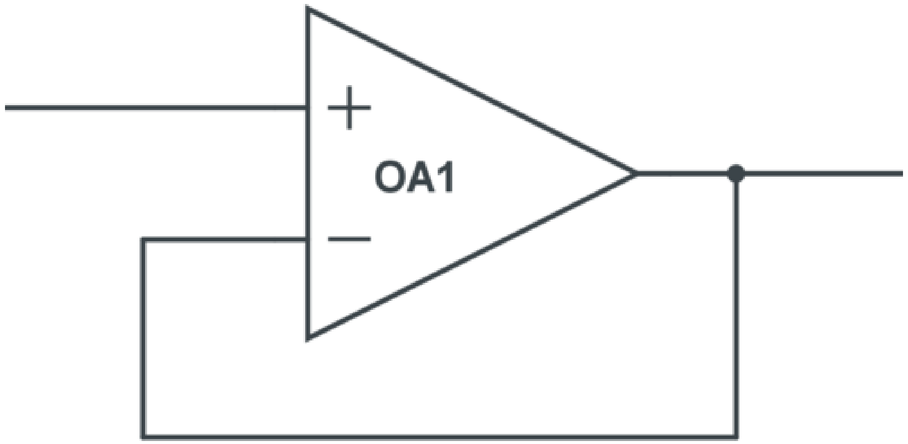
Op-Amp

- We usually think of amplification vs. stabilization as opposing tendencies
  - With feedback (closed-loop configuration), we see that amplification drives the two voltage inputs to be equal
  - Assume the + input is a fixed voltage. Then any tiny deviation at the – input is magnified at the output and fed back into the – input. **Self-correcting!**



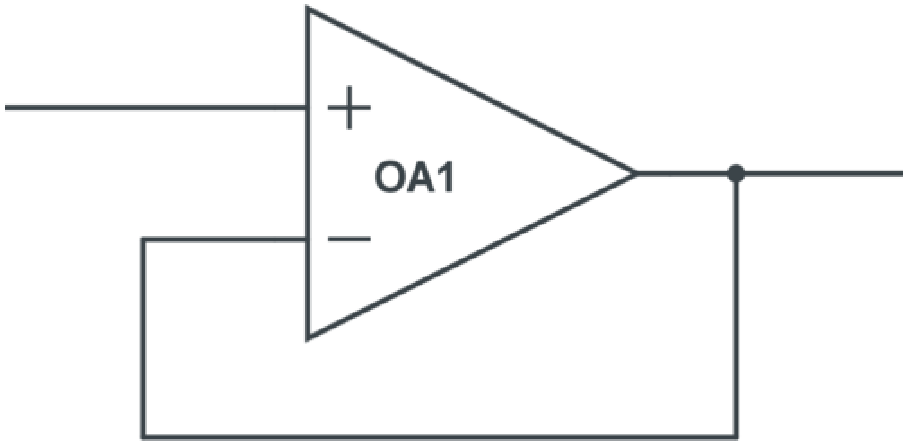
Op-Amp

- We usually think of amplification vs. stabilization as opposing tendencies
  - With feedback (closed-loop configuration), we see that amplification drives the two voltage inputs to be equal
  - Assume the + input is a fixed voltage. Then any tiny deviation at the – input is magnified at the output and fed back into the – input. **Self-correcting!**
  - **An ideal op-amp does all this with ZERO current at the + input.**



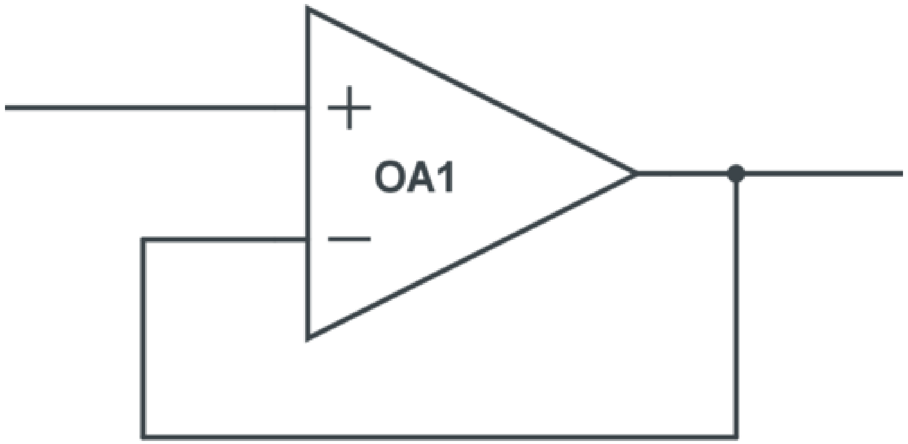
Op-Amp

- We usually think of amplification vs. stabilization as opposing tendencies
  - With feedback (closed-loop configuration), we see that amplification drives the two voltage inputs to be equal
  - Assume the + input is a fixed voltage. Then any tiny deviation at the – input is magnified at the output and fed back into the – input. **Self-correcting!**
  - **An ideal op-amp does all this with ZERO current at the + input.**



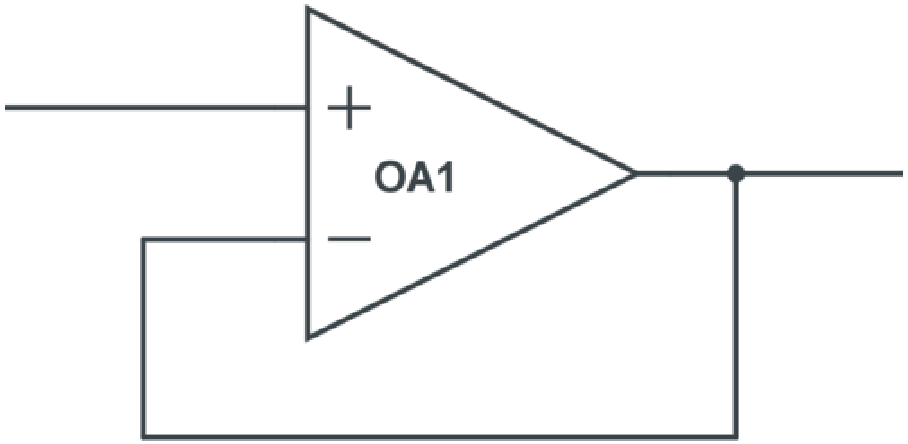
Op-Amp Application: Voltage Buffer

- Assume the + input is a **varying voltage signal**. The + input is equal to the – input and the output.



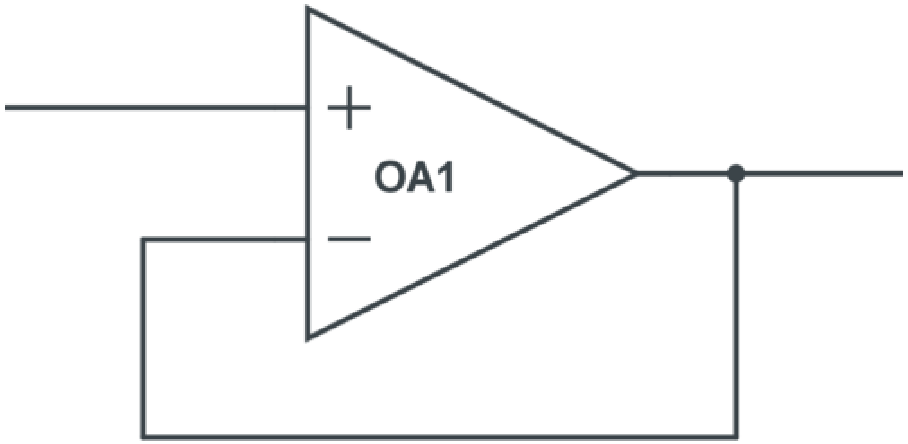
Op-Amp Application: Voltage Buffer

- Assume the + input is a **varying voltage signal**. The + input is equal to the – input and the output.
  - Input = output. Why do we even need this?



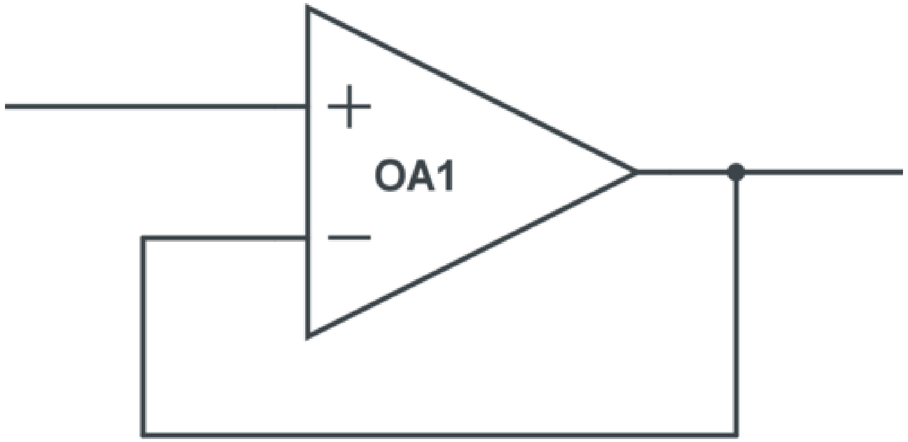
Op-Amp Application: Voltage Buffer

- Assume the + input is a **varying voltage signal**. The + input is equal to the – input and the output.
  - Input = output. Why do we even need this?
  - **An ideal op-amp does all this with ZERO current at the + input. High input impedance (resists current and change in input current)**

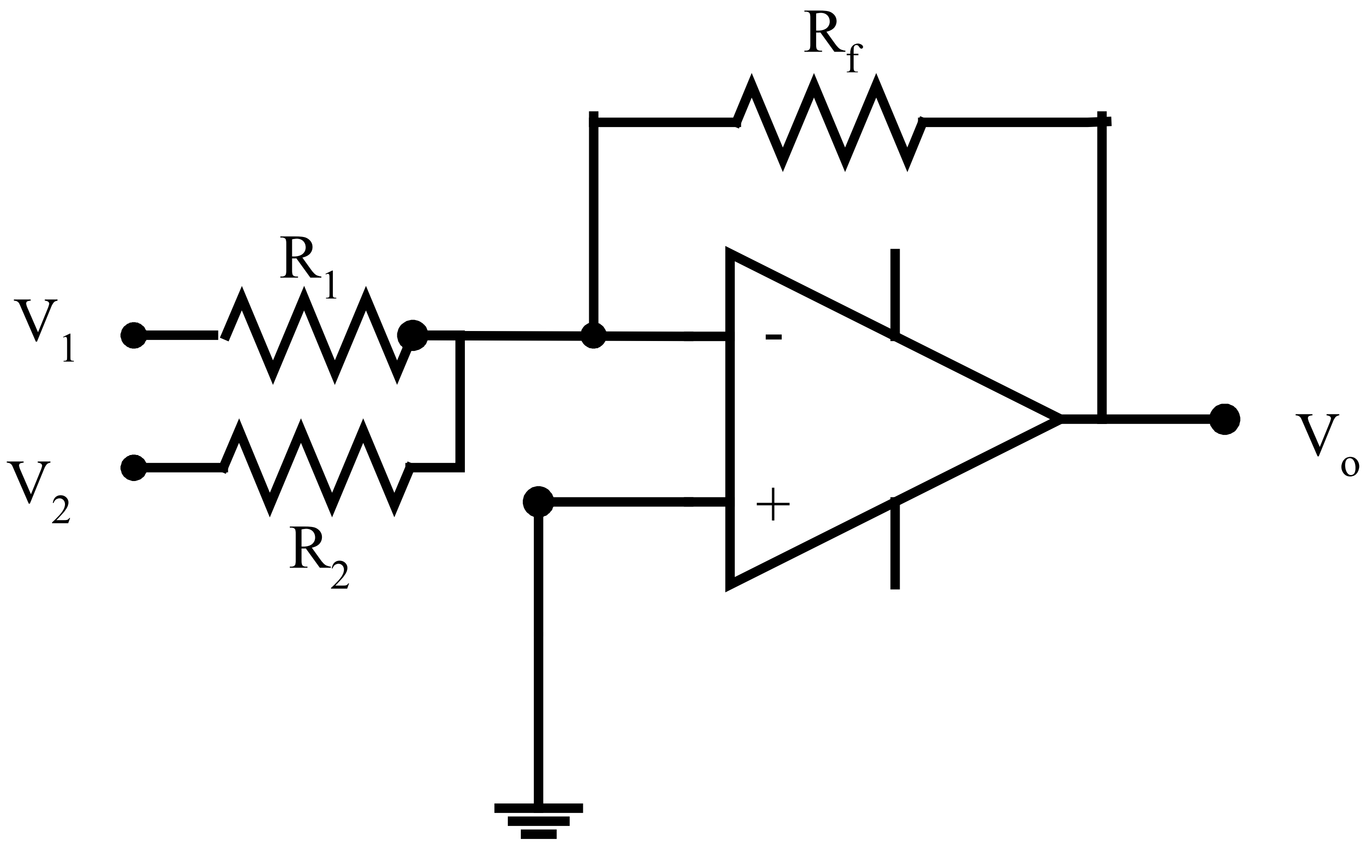


Op-Amp Application: Voltage Buffer

- Assume the + input is a **varying voltage signal**. The + input is equal to the – input and the output.
    - Input = output. Why do we even need this?
    - **An ideal op-amp does all this with ZERO current at the + input. High input impedance (resists current and change in input current)**
    - Buffers **isolate** and prevent **loading effects**: if the input voltage source has non-zero output impedance, the input voltage varies with current.

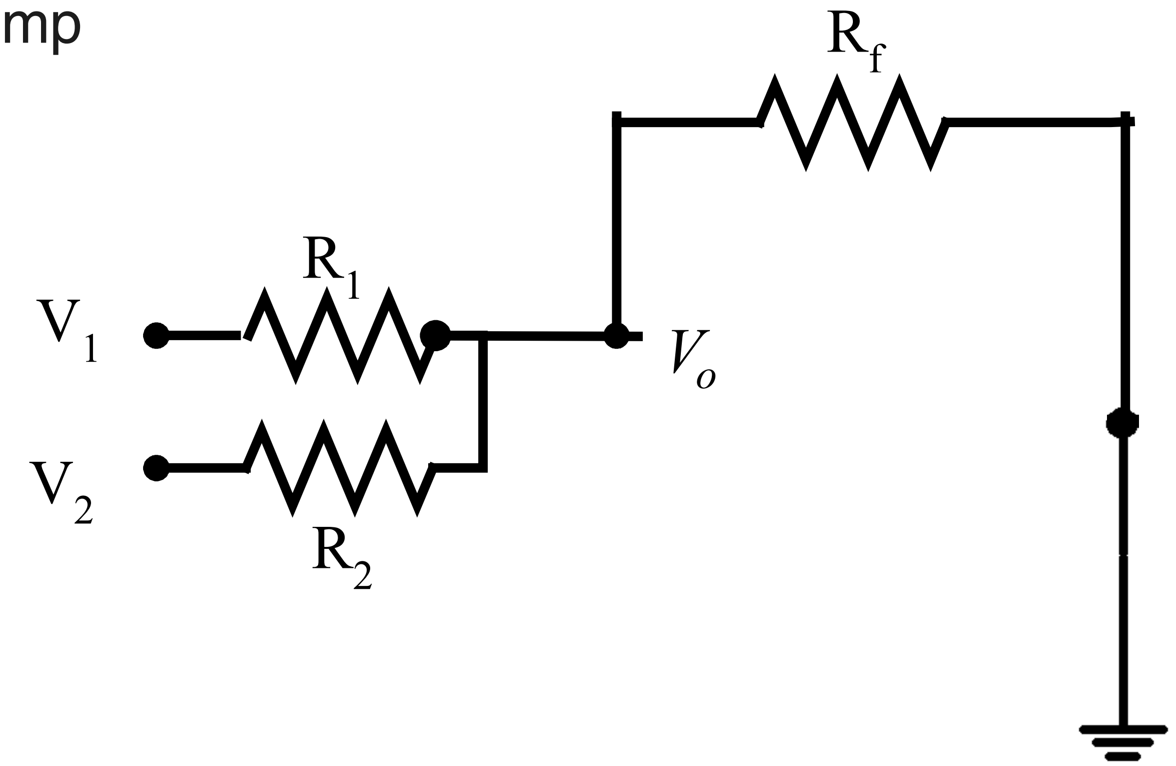


Active Summing Circuit: Summing Amplifier



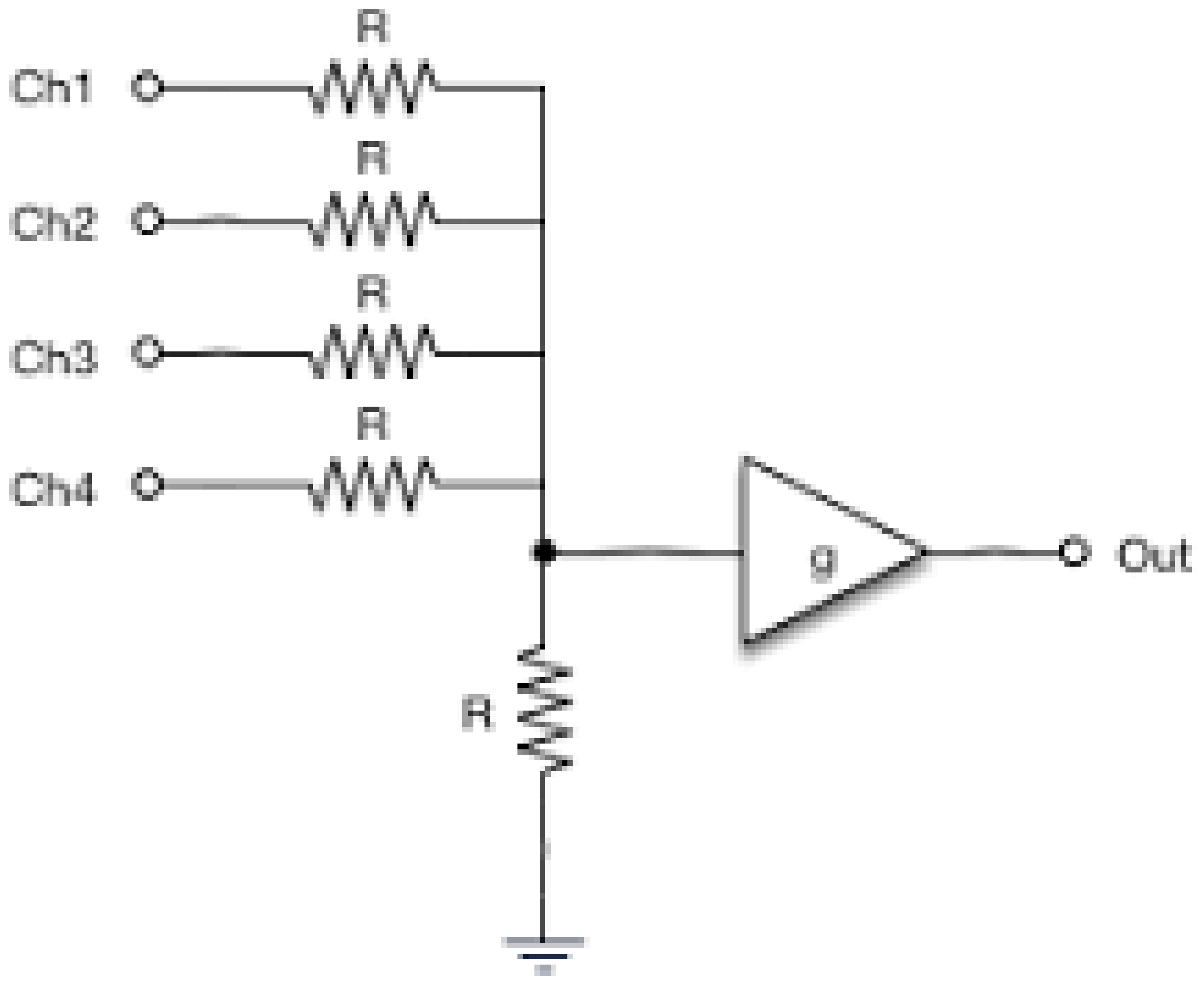
Passive Summing Circuit

- Without op-amp



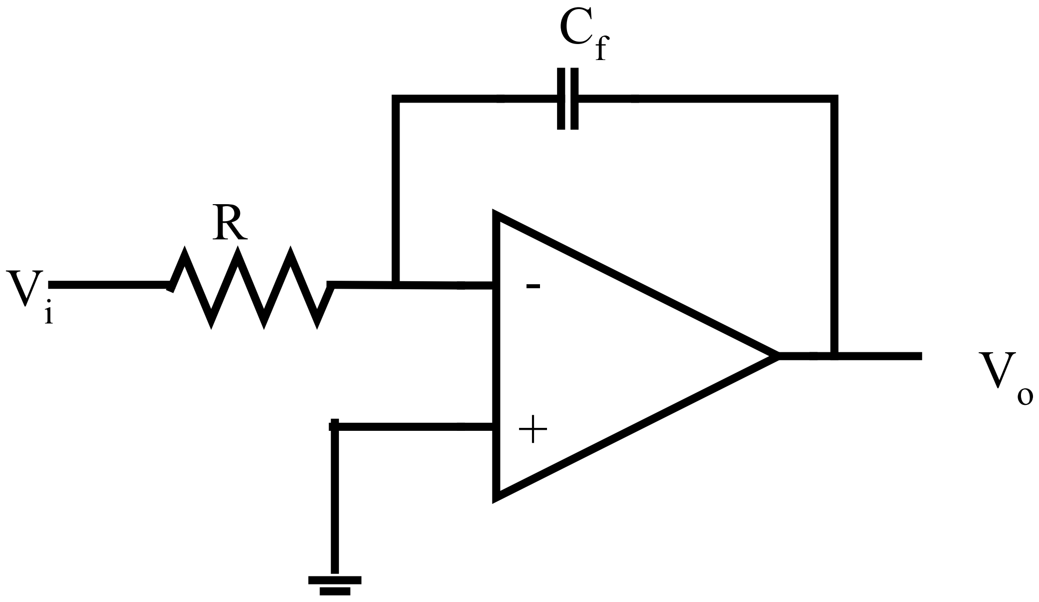
Passive Summing Circuit

- Without op-amp
  - **Signal loss**
  - **No amplification**
  - **Crosstalk**
  - **Loading effects**



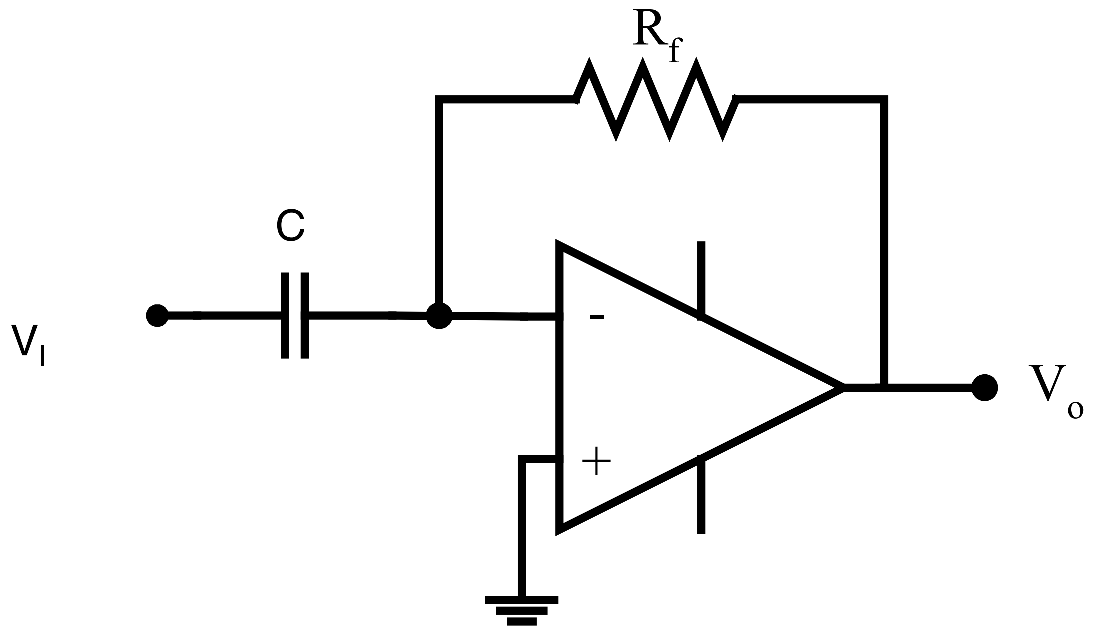
Op-Amp Application: Integrator Amplifier

- What is relationship between output and input voltage?



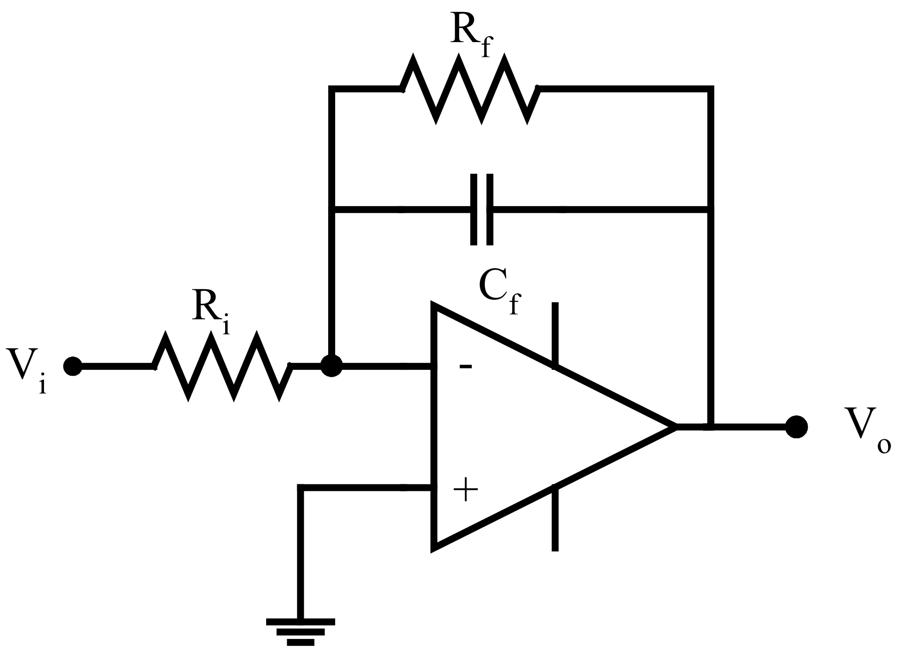
Op-Amp Application: Differentiator Amplifier

- What is relationship between output and input voltage?



Op-Amp Application:
Active First-Order Low-Pass Filter

- What is relationship between output and input voltage?



Situational Awareness

- To move about intelligently in its environment, a robot must have situational awareness
- Situational awareness necessitates knowing ranges and bearings of nearby objects

Situational Awareness

- **Tactile sensor:** Direct physical contact between an on-board sensor and an object indicates collision with the object (tactile feelers, tactile bumpers, micro-switches, etc.)

Situational Awareness

- **Tactile sensor:** Direct physical contact between an on-board sensor and an object indicates collision with the object (tactile feelers, tactile bumpers, micro-switches, etc.)
- **Proximity sensor:** a non-contact sensor provides advance warning on the presence of an object in close vicinity of the sensor (magnetic, inductive, capacitive, ultrasonic, optical, etc.)

Situational Awareness

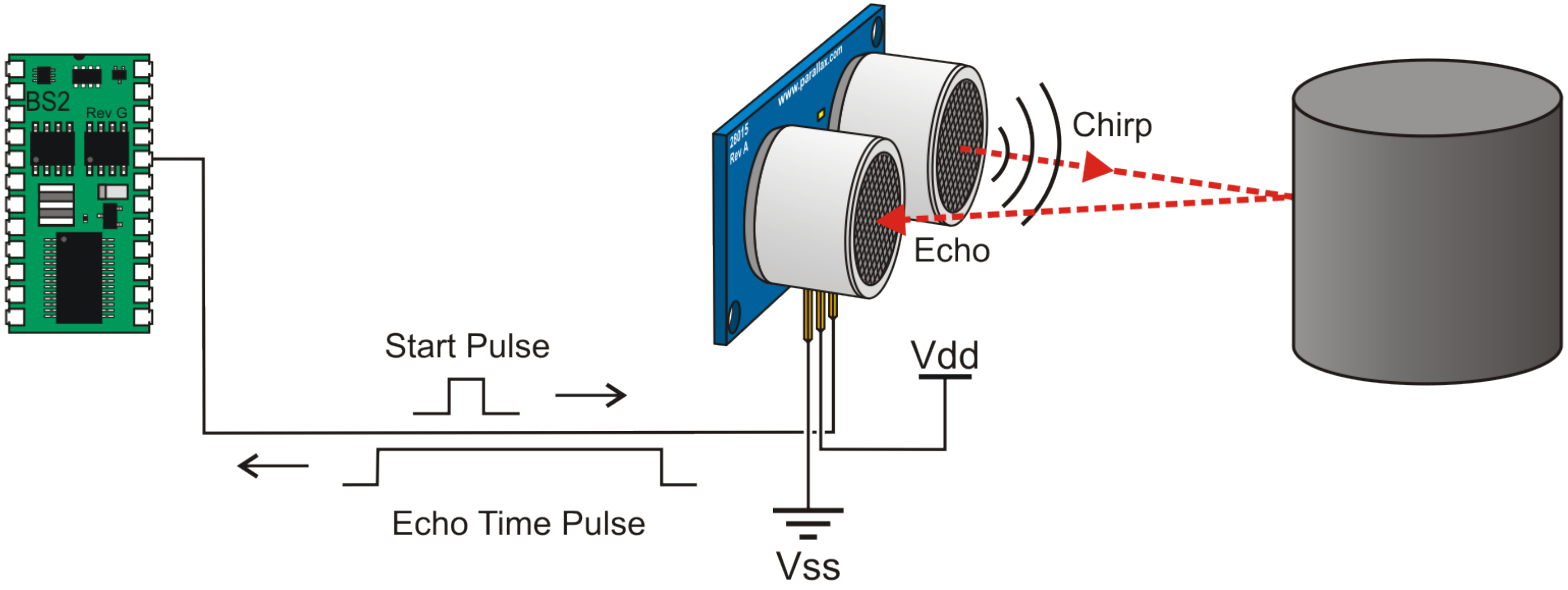
- **Tactile sensor:** Direct physical contact between an on-board sensor and an object indicates collision with the object (tactile feelers, tactile bumpers, micro-switches, etc.)
- **Proximity sensor:** a non-contact sensor provides advance warning on the presence of an object in close vicinity of the sensor (magnetic, inductive, capacitive, ultrasonic, optical, etc.)
- While tactile sensors indicate presence of object after physical contact with it, proximity sensors do not quantify the range to the object

Situational Awareness

- **Range sensor:** provides actual distance to a target of interest without physical contact (triangulation, time-of-flight, phase-shift measurement, frequency modulation, interferometry, return signal intensity); broadly classified as active and passive
  - Radar (radio direction and ranging): typically uses, time-of-flight, phase-shift measurements, or frequency modulation
  - Sonar (sound navigation and ranging): typically uses, time-of-flight since speed of sound is slow enough to be measured with inexpensive electronic
  - Lidar (light direction and ranging): laser-based schemes that typically use, time-of-flight or phase-shift measurements,

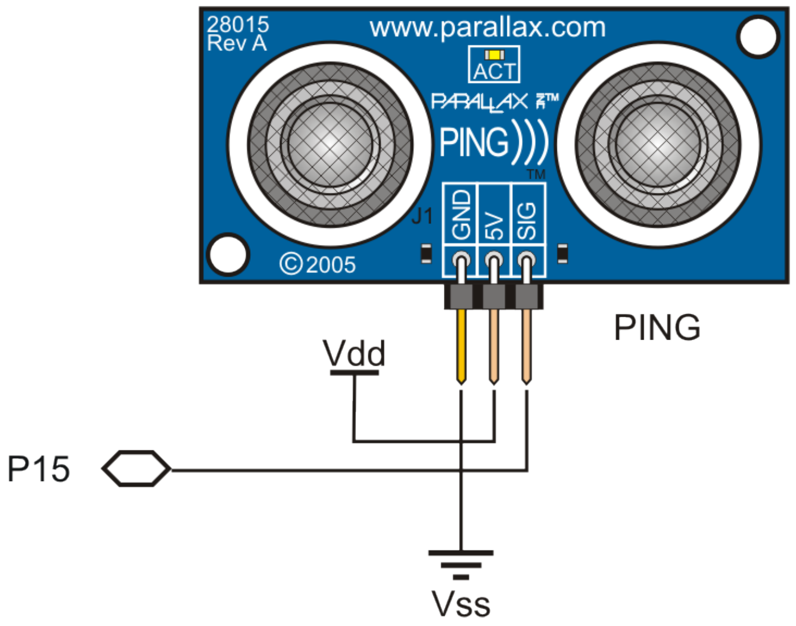
Ultrasonic Sensor—PING)))

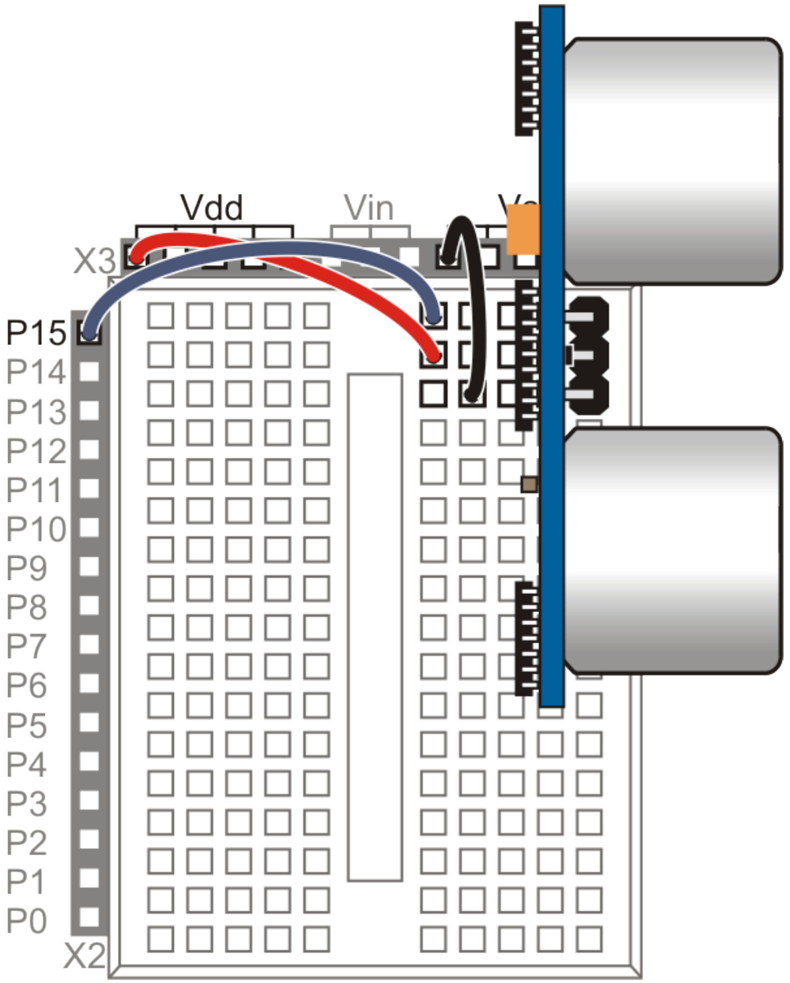
- Time-of-flight distance measurement (**range: 3.3 meters**)
- Sensor emits a 40KHz tone and measures time till it receives the echo signal
  - Round-trip time-of-flight yields distance measurement: D=0.5×C×T, D=distance (m), *C* = speed of sound in air @ 72 ºF (344.8 m/s), T=round trip time (s)



Interfacing PING))) to BS2

- Connect BS2's Vss, Vdd, and one I/O pin (say P15) to PING)))'s GND, 5V, and SIG pins, respectively





PING))): PBASIC Sample Code

- PULSOUT 15, 5: sends a 10µs pulse to P15
- PULSIN 15, 1, time: monitors for the return echo and stores it in the variable time (unit 2µs)

```
' {$STAMP BS2}

' {$PBASIC 2.5}

rawtime VAR Word

DO

PULSOUT 15, 5

PULSIN 15, 1, rawtime

DEBUG HOME, “rawtime = ", DEC5 rawtime

PAUSE 100

LOOP
```

Accelerometer

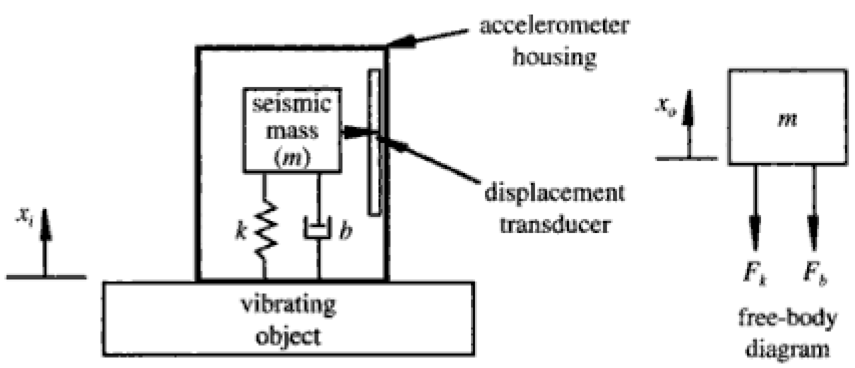
- Electromechanical device to measure acceleration forces
  - Static forces like gravity pulling at an object lying at a table
  - Dynamic forces caused by motion or vibration (D’Alembert’s Principle)

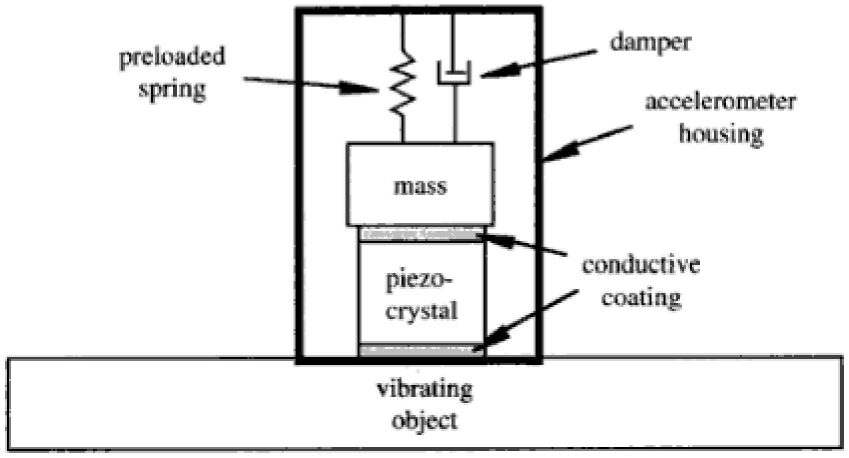
Accelerometer

- Electromechanical device to measure acceleration forces
  - Static forces like gravity pulling at an object lying at a table
  - Dynamic forces caused by motion or vibration (D'Alembert's Principle)

Accelerometer Types

- **Seismic mass accelerometer:** a seismic mass is connected to the object undergoing acceleration through a spring and a damper;
- **Piezoelectric accelerometers:** a microscopic crystal structure is mounted on a mass undergoing acceleration; the piezo crystal is stressed by acceleration forces thus producing a voltage





Accelerometer Types

- **Capacitive accelerometer:** consists of two microstructures (micromachined features) forming a capacitor; acceleration forces move one of the structure causing a capacitance changes.
- **Piezoresistive accelerometer:** consists of a beam or micromachined feature whose resistance changes with acceleration
- **Thermal accelerometer:** tracks location of a heated mass during acceleration by temperature sensing

Accelerometer Applications

- **Automotive:** monitor vehicle tilt, roll, skid, impact, vibration, etc., to deploy safety devices (stability control, anti-lock breaking system, airbags, etc.) and to ensure comfortable ride (active suspension)
- **Aerospace:** inertial navigation, smart munitions, unmanned vehicles
- **Industrial:** machinery health monitoring
- **Security:** motion and vibration detection
- **Robotics:** self-balancing

Accelerometer Applications

- **Sports/Gaming:** monitor athlete performance and injury, joystick, tilt
- **Personal electronics:** cell phones, digital devices

Helmet: Impact Detection

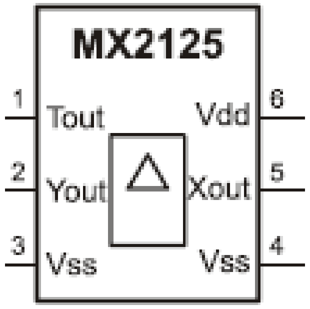
2 axis joystick

WII Nunchuk: 3 axis accelerometer

Segway

Memsic 2125 2-axis Accelerometer

- Measure acceleration, tilt angle, rotation angle
  - G-force measurements for X and Y axis reported in pulse-duration
- **Temperature measurement: analog output (Tout)**
- Low current operation: < 4 mA @ 5VDC
- Measures 0 to ±2 g on either axis
- Resolution: <1 mg
- Operating temperature: 0 °C to 70 °C

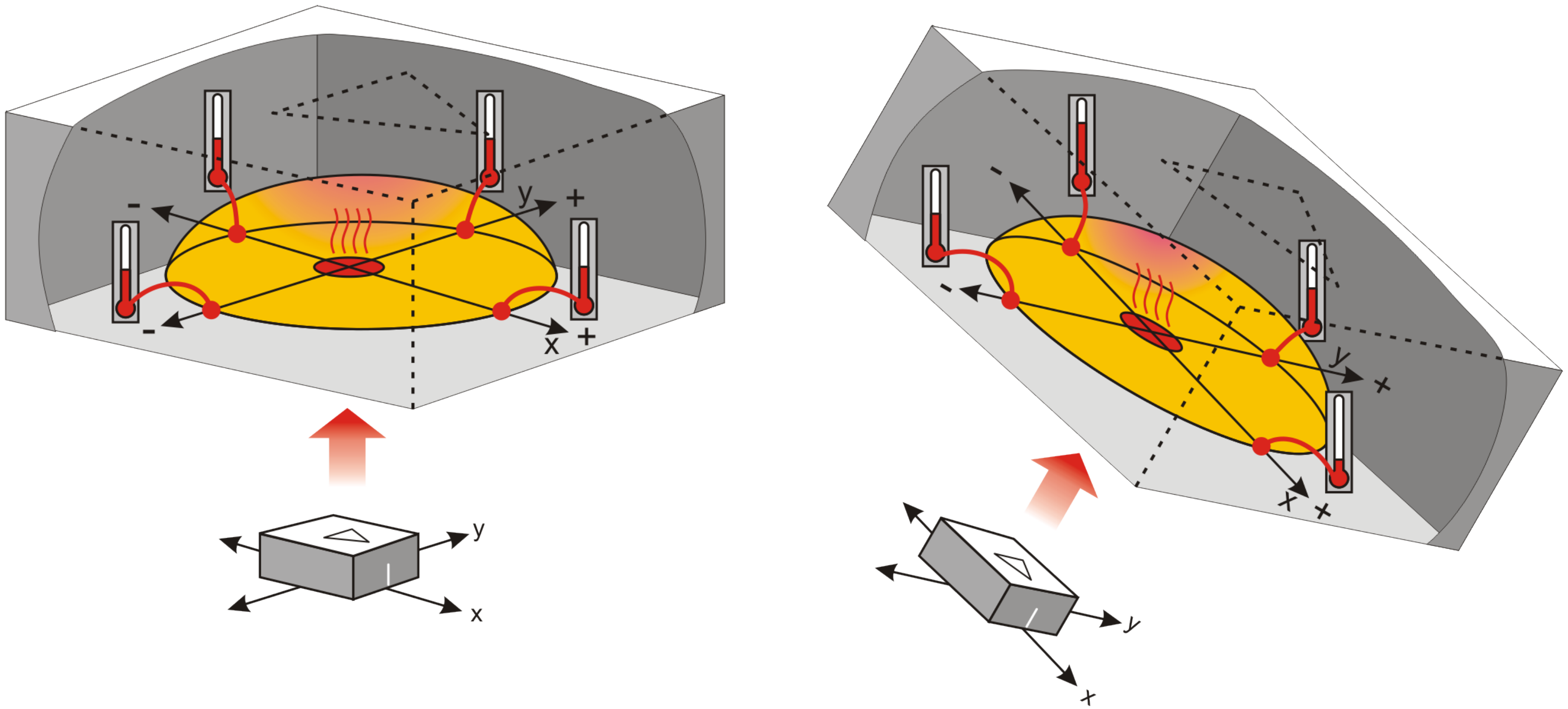


Accelerometer Module

MX2125 Chip

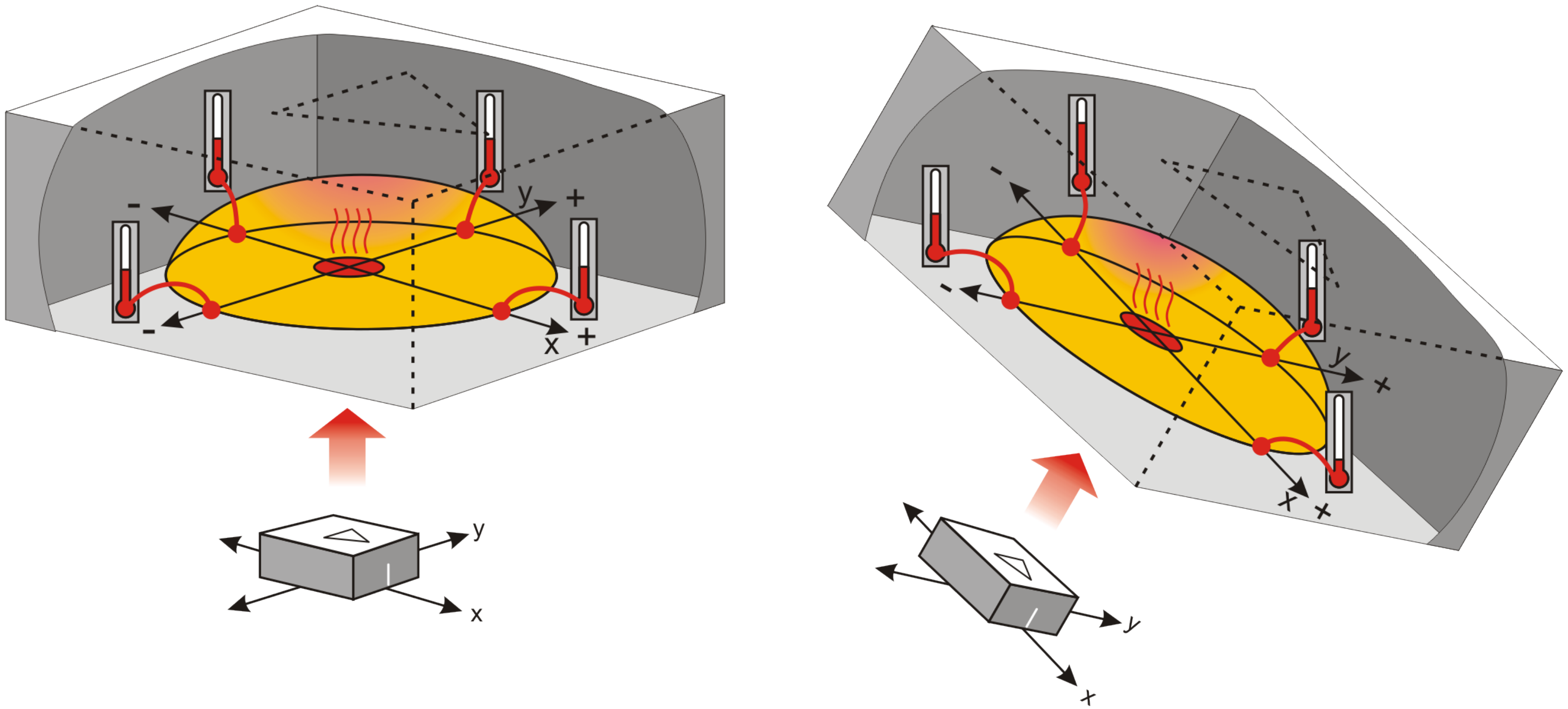
MX2125 Accelerometer: How it Works

- A micro-electromechanical system (MEMS) device consisting of
  - a chamber of gas with a heating element in the center
  - four temperature sensors around its edge



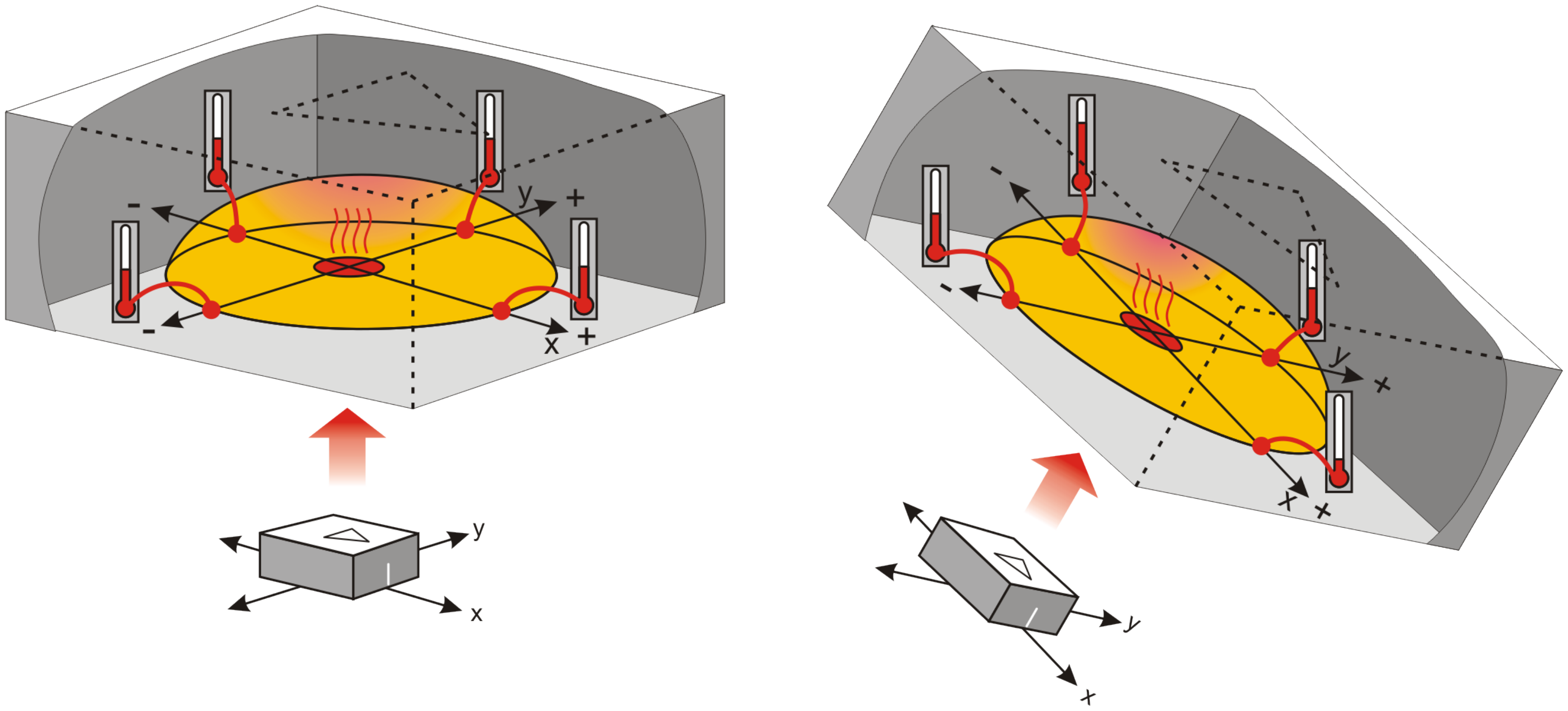
MX2125 Accelerometer: How it Works

- Hold accelerometer level→hot gas pocket rises to the top-center of the accelerometer's chamber→all sensors measure same temperature
- Tilt the accelerometer→hot gas pocket collects closer to one or two temperature sensors→sensors closer to gas pocket measure higher temperature



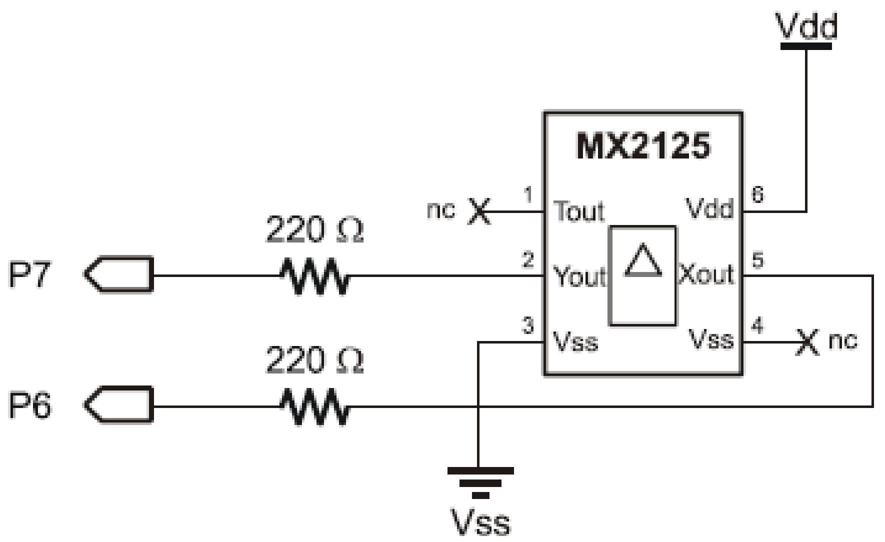
MX2125 Accelerometer: How it Works

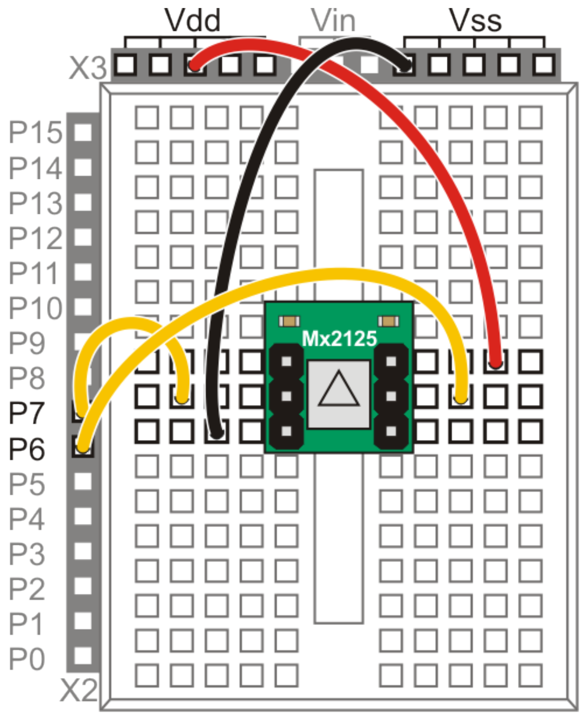
- MX2125 electronics compares temperature measurements and outputs pulses (pulse duration encodes sensor o/p)



Interfacing Accelerometer to BS2

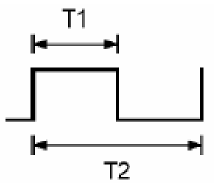
- Connect BS2's V_{ss} , V_{dd}, and two I/O pin (say P6 and P7) to MX2125's pins 3, 6, 5, and 2, respective





- X_{out} and Y_{out} pulse outputs are set to 50% duty cycle at 0g; the duty cycle changes in proportion to acceleration
- G Force can be computed from the duty cycle as shown below
- T_{out} provides analog output 1.25 volts @25.0°C, output change: 5 mV/°C

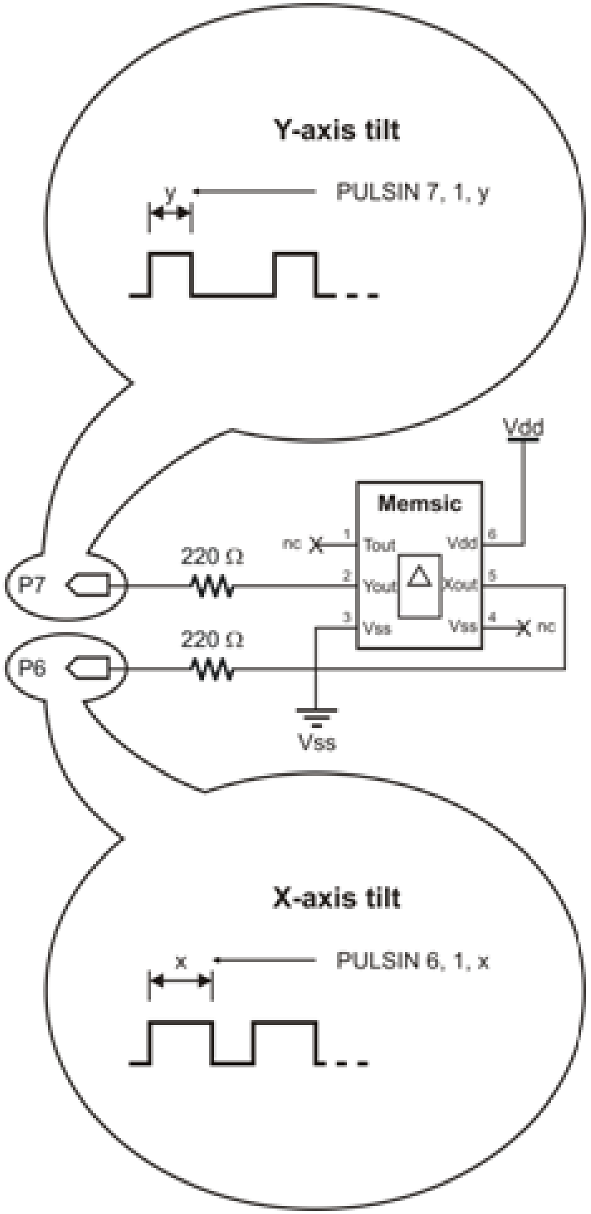
Memsic 2125 Pulse Output



$$A(g) = ((T1 / T2) - 0.5) / 12.5\%$$

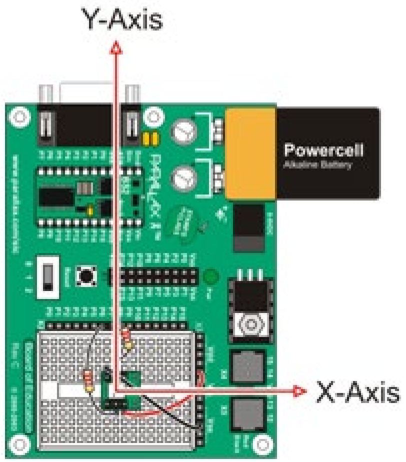
T2 duration is calibrated to 10 milliseconds at 25° C (room temperature)

Accelerometer Axis Pulse Measurements



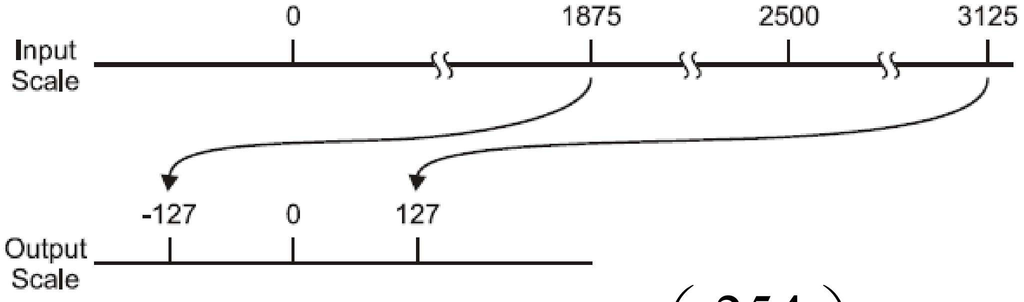

```
'{$STAMP BS2}
'{$PBASIC 2.5}
x VAR Word
y VAR Word
DEBUG CLS
DO
PULSIN 6, 1, x
PULSIN 7, 1, y
DEBUG HOME, DEC4 ? x, DEC4 ? y
PAUSE 100
LOOP
```

Pulsin o/p range: 1875 to 3125
When level: o/p=2500



Pulse Measurements: Offset and Scaling

- Let X_{raw}= Pulsin output
- $X_{raw} \in \{1875, 3125\}$ and when level X_{raw}=2500
- We wish X_{out}: $X_{raw} \rightarrow X_{out} \in \{-127, 127\}$, and X_{out}=0 when level



$$X_{\text{out}} = (X_{\text{raw}} - 2500) \times \left(\frac{254}{1250}\right)$$

$$= X_{\text{raw}} \times \left(\frac{254}{1250}\right) - 508$$

- Let Scale=INT((254/1250) ×65536)=13316
- Now compute X_{out} by using X_{raw}**13316-508

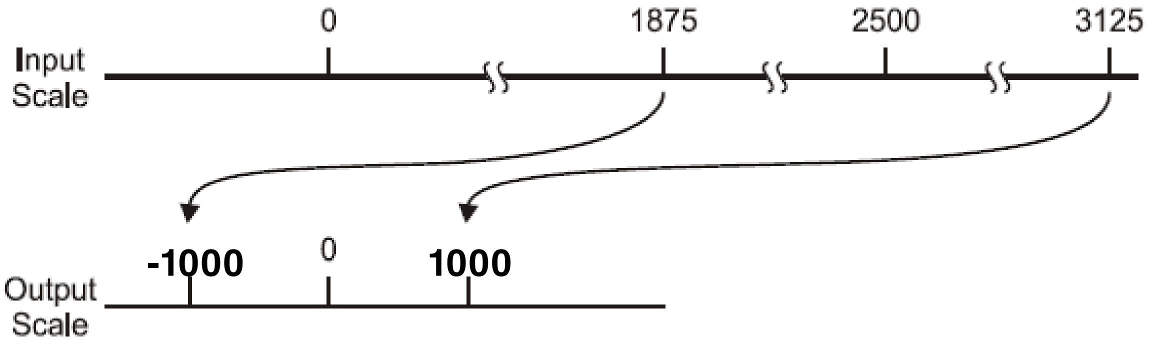
```
'{$STAMP BS2}
'{$PBASIC 2.5}
scalecon CON 13316
xraw VAR Word
yraw VAR Word
Xo VAR Word
Yo VAR Word
DEBUG CLS
DO
PULSIN 6, 1, xraw
PULSIN 7, 1, yraw
Xo=xraw**scalecon-508
Yo=yraw**scalecon-508
DEBUG HOME, SDEC Xo, SDEC Yo
PAUSE 100
LOOP
```

Clamp input range to {1875, 3125} using the following:

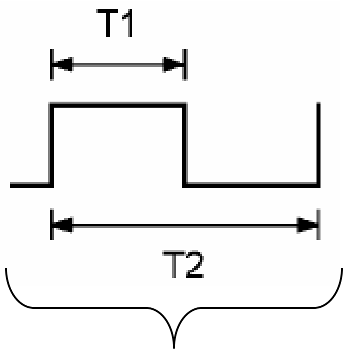
```
xout=(xraw Min 1875 Max 3125) **scalecon-508
yout=(yraw Min 1875 Max 3125) **scalecon-508
```

g-Force Measurements in mili-g—I

- Let T_{raw}= Pulsin output (2μs units)
- $T_{raw} \in \{1875, 3125\}$ and when level T_{raw}=2500
- T_{raw}=1875→-g (-1000 milli-g) and T_{raw}=3125→g (-1000 mili-g)
- So, we wish T_{out}: $T_{raw} \rightarrow T_{out} \in \{-1000, 1000\}$, and T_{out}=0 when level



Memsic 2125 Pulse Output



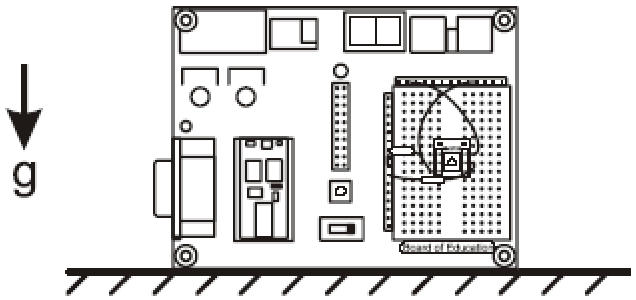
T_1: Pulsin output returns T_{raw}
T_2: 10milli-seconds @ 25ºC

- Moreover, recall g force is given by

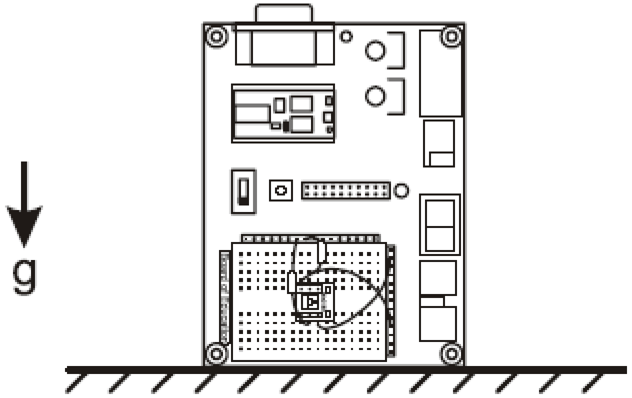
$$g_{\text{Force}} = \left(\frac{T_1}{T_2} - 0.5 \right) \times \left(\frac{1}{12.5\%} \right) \quad (\text{units}: \text{g})$$

g-Force Measurements in mili-g—II

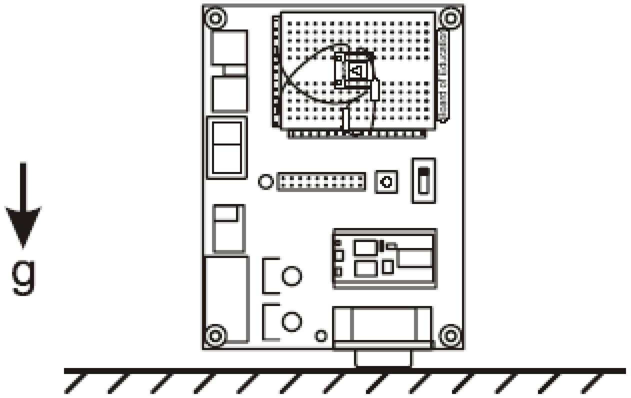
a. x=1000/1000, y=0/1000



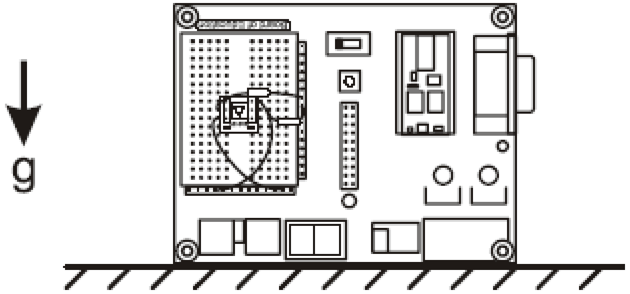
b. x=0/1000, y=1000/1000



d. x=0/1000, y=-1000/1000

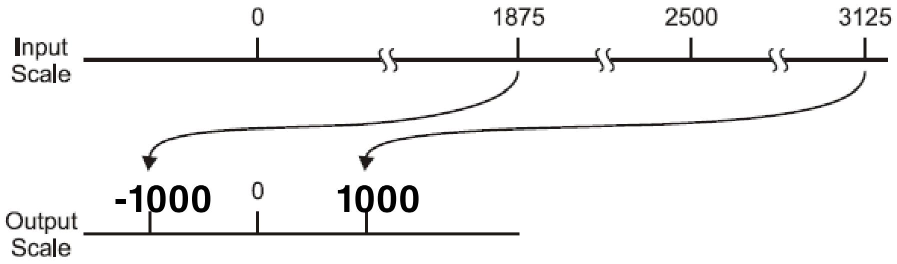


c. x=-1000/1000, y=0/1000



Sample Readings at Various Orientations (start at top left, rotate clockwise)

g-Force Measurements in mili-g—III



- **T_1: Pulsin output returns T_{raw} in 2µs units**
- **T_2: 10mili-seconds @ 25ºC**
- **Thus,**
  $T_1 = 2\times10^{-6}\times T_{raw}$ seconds$= 2\times10^{-3}\times T_{raw}$ mili-seconds

$$
\begin{aligned}
T_{\text{out}} &= (T_{\text{raw}} - 2500)\times\left(\frac{2000}{1250}\right)\\
&= \left(\frac{2\times T_{\text{raw}}}{10}\right)\times\left(\frac{1000}{125}\right) - 2500\times\left(\frac{2000}{1250}\right)\\
&= \left(\frac{2\times T_{\text{raw}}}{10}\right)\times 8 - 4000\\
&= \left(\left(\frac{2\times T_{\text{raw}}}{10}\right) - 500\right)\times 8
\end{aligned}
$$

$$
\begin{aligned}
g_{\text{Force}} &= \left(\frac{T_1}{T_2} - 0.5\right)\times\left(\frac{1}{12.5\%}\right),\ (\text{units}:\text{g})\\
&= \left(\frac{T_1}{T_2} - 0.5\right)\times\left(\frac{1}{12.5\%}\right)\times 10^3,\ (\text{units}:\text{milli-g})\\
&= \left(\frac{T_{\text{raw}}\times 2\times 10^{-3}}{10} - 0.5\right)\times\left(\frac{100}{12.5}\right)\times 10^3\\
&= \left(\frac{T_{\text{raw}}\times 2}{10} - 500\right)\times 8
\end{aligned}
$$

MX2125 Angle of Rotation in Vertical Plane—I

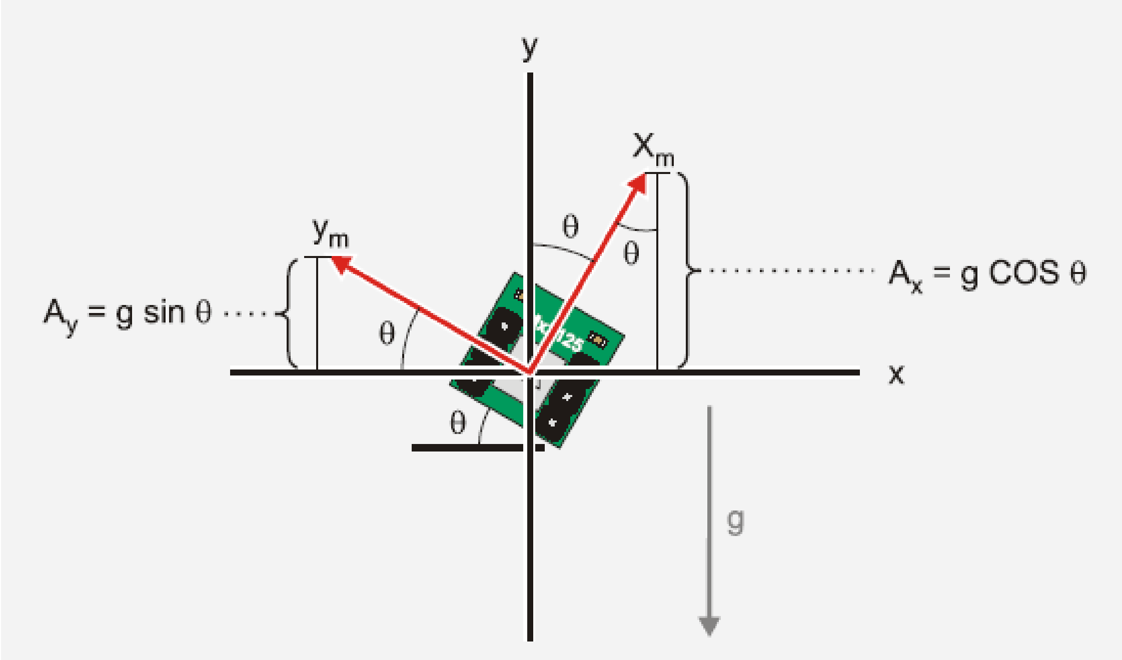
- MX2125's angle of rotation in the vertical plane:

$$\theta = \tan^{-1}\left(\frac{A_y}{A_x}\right), \text{ BS2 returns } A_x, A_y \in \{1875, 3125\}$$

- To compute $\tan^{-1}(Y/X)$ use PBASIC ATAN command: X ATN Y; ATN requires X, Y$\in${-127, 127} which is accomplished using

$$X = (A_x - 2500) \times \left(\frac{254}{1250}\right)$$
$$= A_x \times \left(\frac{254}{1250}\right) - 508$$

- **Let INT((254/1250) ×65536)=13316**
- **Now compute X by using Ax**13316-508**

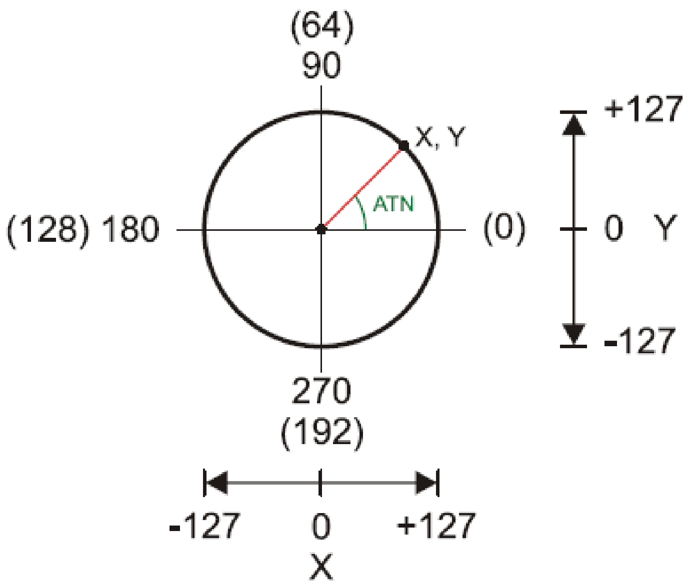


MX2125 Angle of Rotation in Vertical Plane—II

- ATN returns its output in binary radians (i.e., a circle is split up into 256 segments instead of 360 segments as in degrees)
- Convert ATN output from brad to degrees as follows:

$$\theta_{\mathrm{Deg}} = \theta_{\mathrm{BRad}} \times \left(\frac{360}{256}\right)$$

- **Let INT((360/256)×256)=360**
- **Now compute θ_{Deg} by using θ_{BRad}*/360**



Unit circle in degrees and binary radians

MX2125 Angle of Rotation in Vertical Plane: Sample Code

```
'{$STAMP BS2}
'{$PBASIC 2.5}
scale1 CON 13316
scale2 CON 360
Ax VAR Word
Ay VAR Word
angle VAR Word
DEBUG CLS
DO
PULSIN 6, 1, Ax
PULSIN 7, 1, Ay
Ax=(Ax MIN 1875 MAX 3125)**scale1-508
Ay=(Ay MIN 1875 MAX 3125)**scale1-508
angle=Ax ATN Ay
angle=angle*/scale2
DEBUG HOME, " Ax =", SDEC Ax, " Ay=", SDEC Ay, " angle=", SDEC3 angle, 176, "   "
PAUSE 300
LOOP
```

Hands-on Exercises: Digital Input

Smart Sensors and Applications The Ping))) Ultrasonic Distance Sensor Activities #1 – #4	Chapter 2