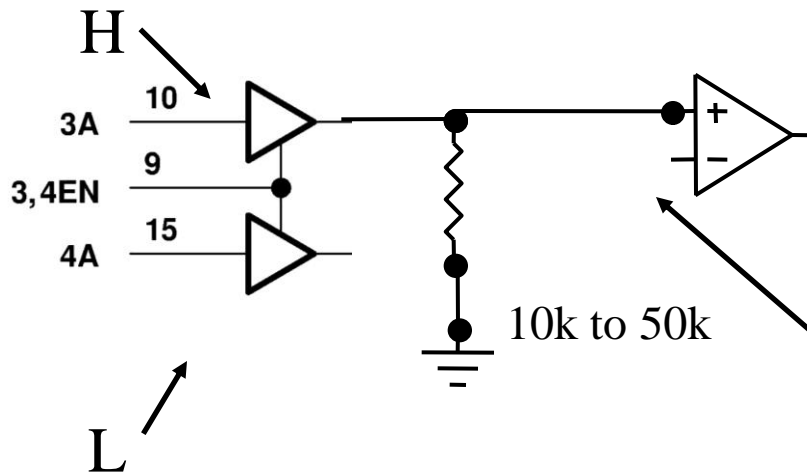


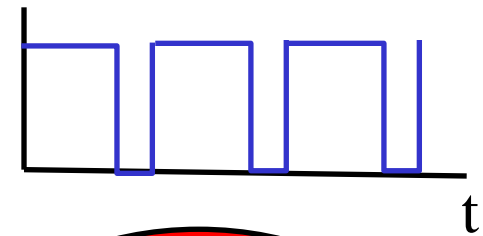
Lab 3 re-cap

Need to connect TINAH motor outputs to H-bridge inputs:

Build an interface circuit for doing this

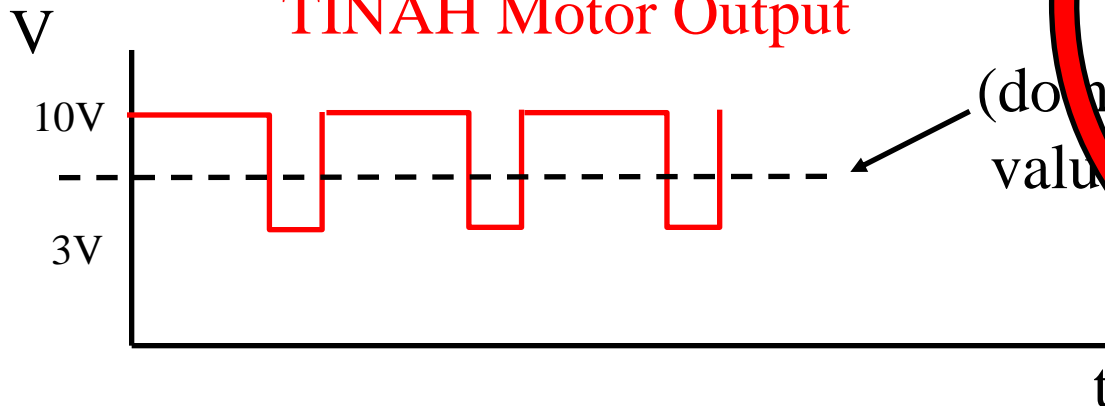


To H-Bridge input



Comparator level – USE 3V FROM TINAH Board???

TINAH Motor Output



(do not use voltage divider, since value decreases with decreasing battery voltage)

Design Review

Process

Design Reviews - Overview

Each group has 2 in-person discussions + 1 written plan:

1. **Pre-Review** (15-20 min) early June (Week 4, Week 5)
2. **Elective Design Discussion** (~10min) mid-June Week 6
3. **Design Document** – Wed June 20th

All can be found in greater detail on course website under

“ENPH 253 → Labs and Lectures → Design Review”

1. Informal Pre-Review

- ~15 min long, done during Week 4 / Week 5 labs
- Talk directly to TA/Instructor about your general robot plans.
- TA/Instructors will check that all groups have passed

Expected:

- Verbal overview of robot function
- Sketches of primary mechanical mechanisms

Outcome:

- With the help of TAs/instructors, identify the major problem areas in your initial idea, which can be addressed in the Design Document

2. Elective Group Presentation

- An elective group discussion for groups to present their ideas to all instructors and classmates.
- All groups are invited to attend.
- 5-7min “presentation”, ~5min immediate feedback
- Done at 5pm during 2nd week of Lab 5

Expected:

- Initial plans for all areas (mechanical design, electronics, software, build/testing plan)
- You should emphasize the application of engineering theory versus “tinkering”. Show calculations and estimates wherever applicable.

3. Design Document

- ~10-20 pages of notes, drawings, diagrams
- no paragraph-form prose, focus on tables, drawings, sketches, and lists.

- Examples of will be available in Hebb 42.
- **The most successful design documents are the ones which provide documentation that is actually useful during the build phase.** (avoid filler material, excessive descriptions...)
- Do not spend excess amounts of time formatting text and getting documentation down – instead, focus on producing content and plans which are used to plan, fabricate and test your robot.

3. Design Document – Areas to Include

- Overview of basic strategy.
- Chassis
- Drive System
- Grippers / arms / mechanical systems
- Sensor systems
- Circuit Schematics and Wiring Connections
- Software algorithm
- Team Responsibilities, Major Milestones, and Timeline

Key areas to address

- **Calculations** - What is the speed of each mechanism? What is its estimated time to travel the course? How many objects do you expect to handle in 2 minutes?
- **Estimates** – Estimate any quantities that you can't measure easily. This can include estimating various masses, required forces.
- **Testing procedure** - Once part of your robot is constructed, how do you verify whether it works adequately or not? Can you identify options during the design stage?

Come to the review prepared to answer detailed questions to defend any part of your design.

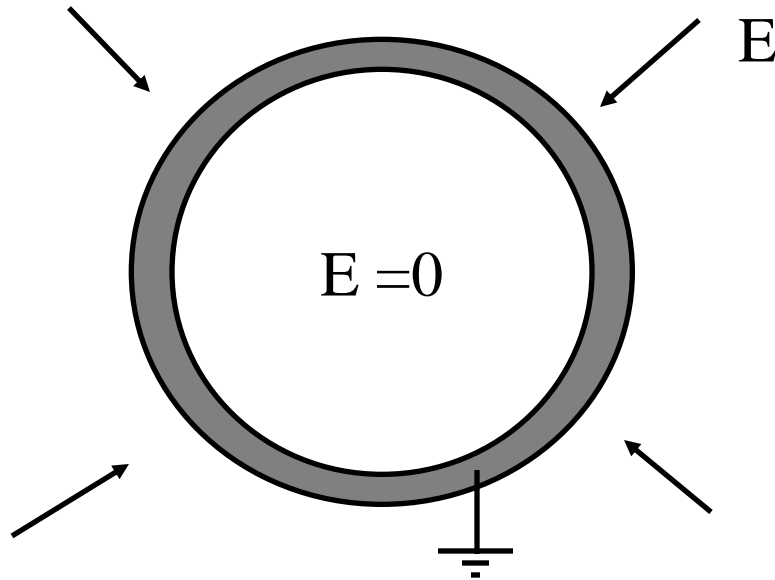
THE MORE DETAIL YOU SHOW US, THE MORE WE CAN HELP YOU!

Noise and **Shielding**

Shielding and grounding

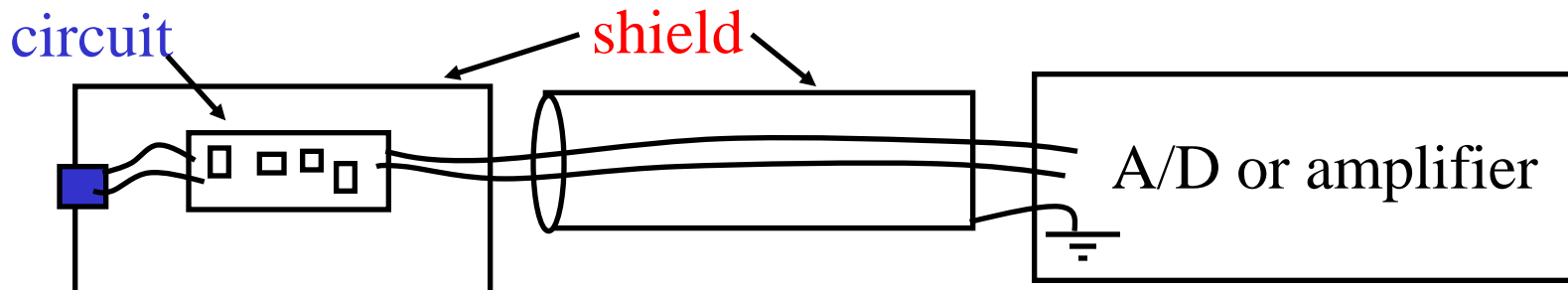
How to keep your low-level signals from being contaminated by noise:

Gauss' law:



$E=0$ everywhere inside a **grounded** conducting shell (with no charge inside the shell).

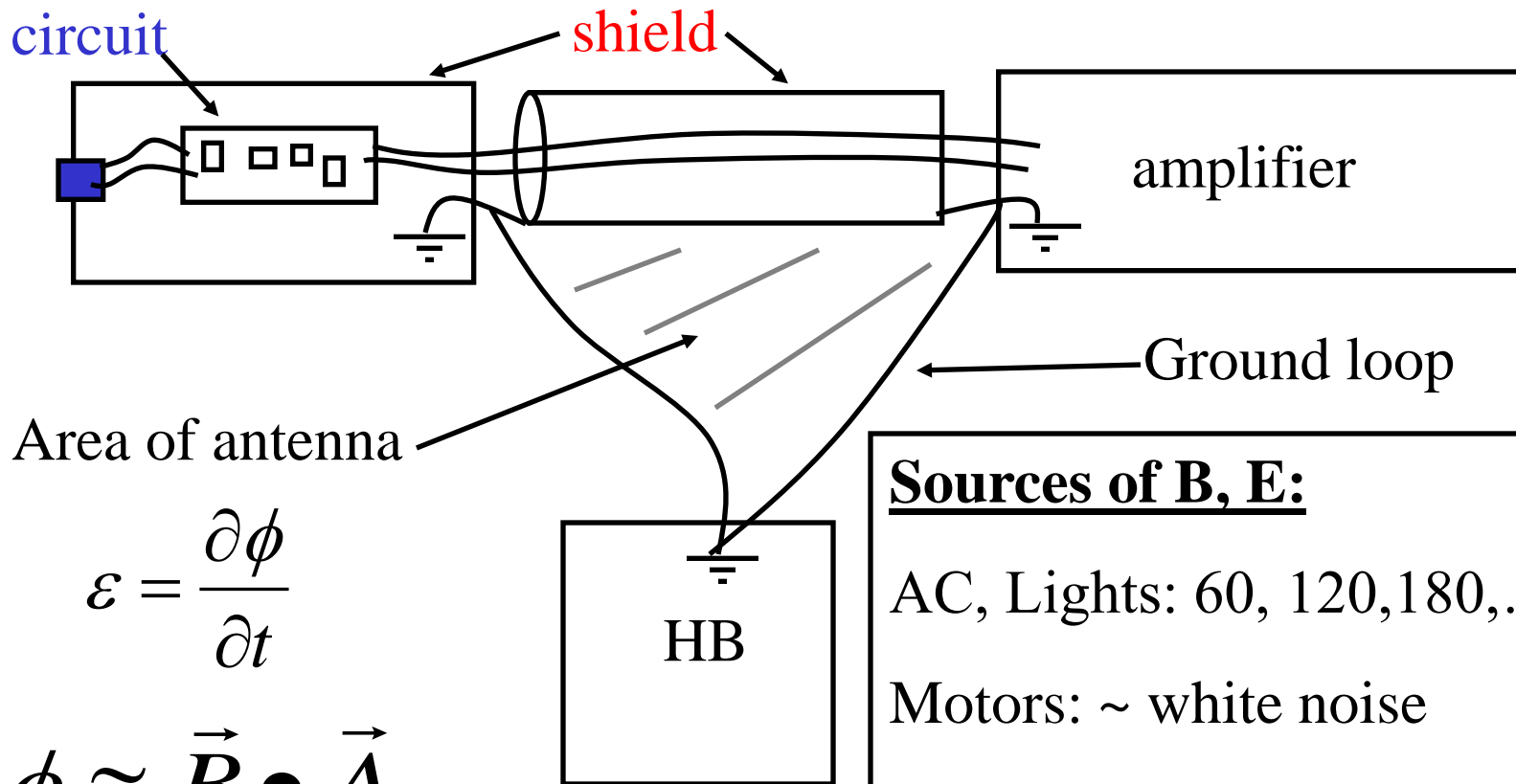
We take advantage of this to shield circuits and wires carrying sensitive signals:



Shielding and grounding

Ground loops:

Improper grounding can lead to noise of its own:



Area of antenna

$$\varepsilon = \frac{\partial \phi}{\partial t}$$

$$\phi \cong \vec{B} \bullet \vec{A}$$

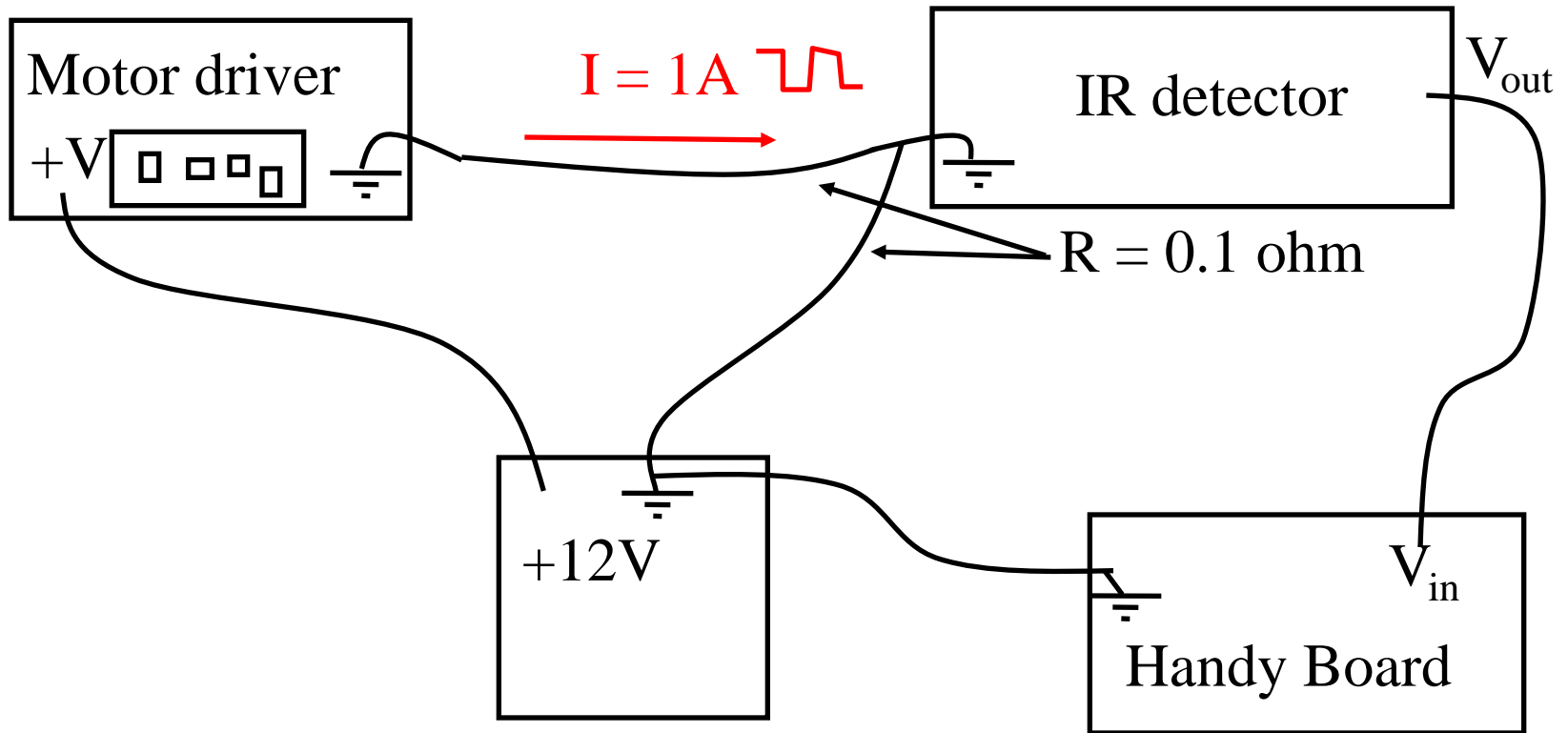
Sources of B, E:

AC, Lights: 60, 120, 180, ... Hz

Motors: ~ white noise

PWM to motors: PWM freq.
+harmonics

Shielding and grounding

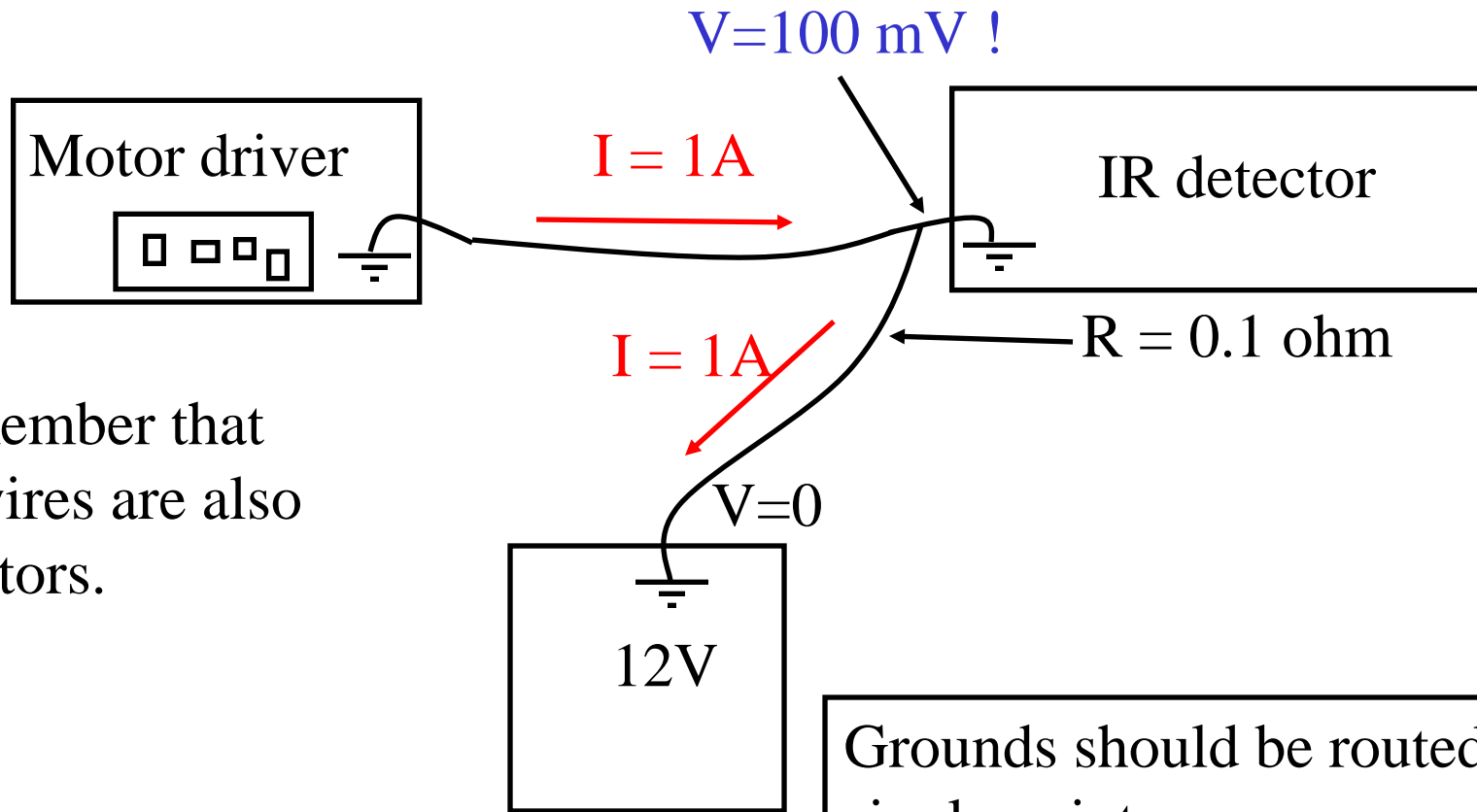


What is the minimum noise amplitude on V_{in} ?

Shielding and grounding

More bad grounding:

Improper grounding can lead to noise of its own:



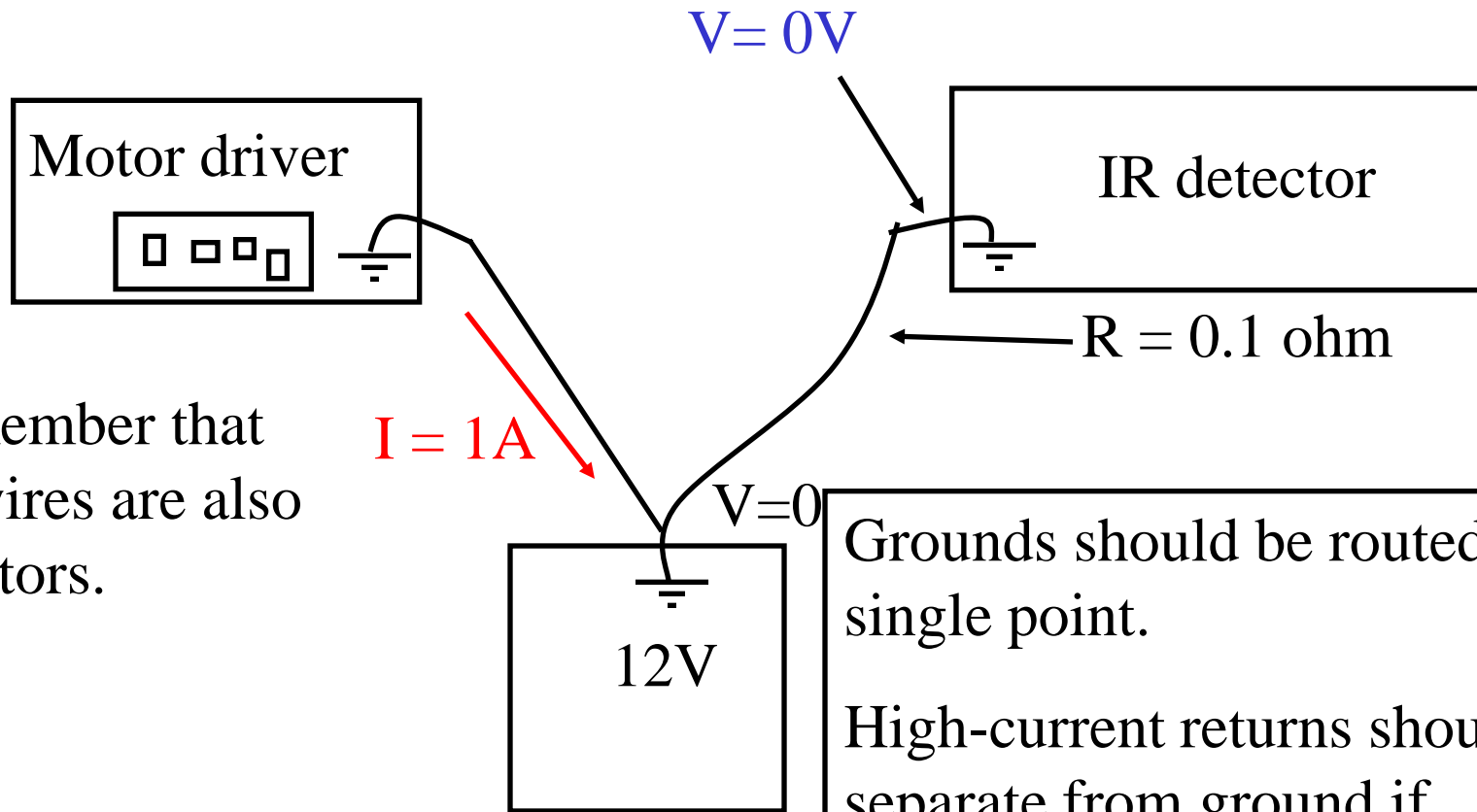
Remember that
all wires are also
resistors.

Grounds should be routed to a
single point.

Shielding and grounding

Proper grounding:

Improper grounding can lead to noise of its own:



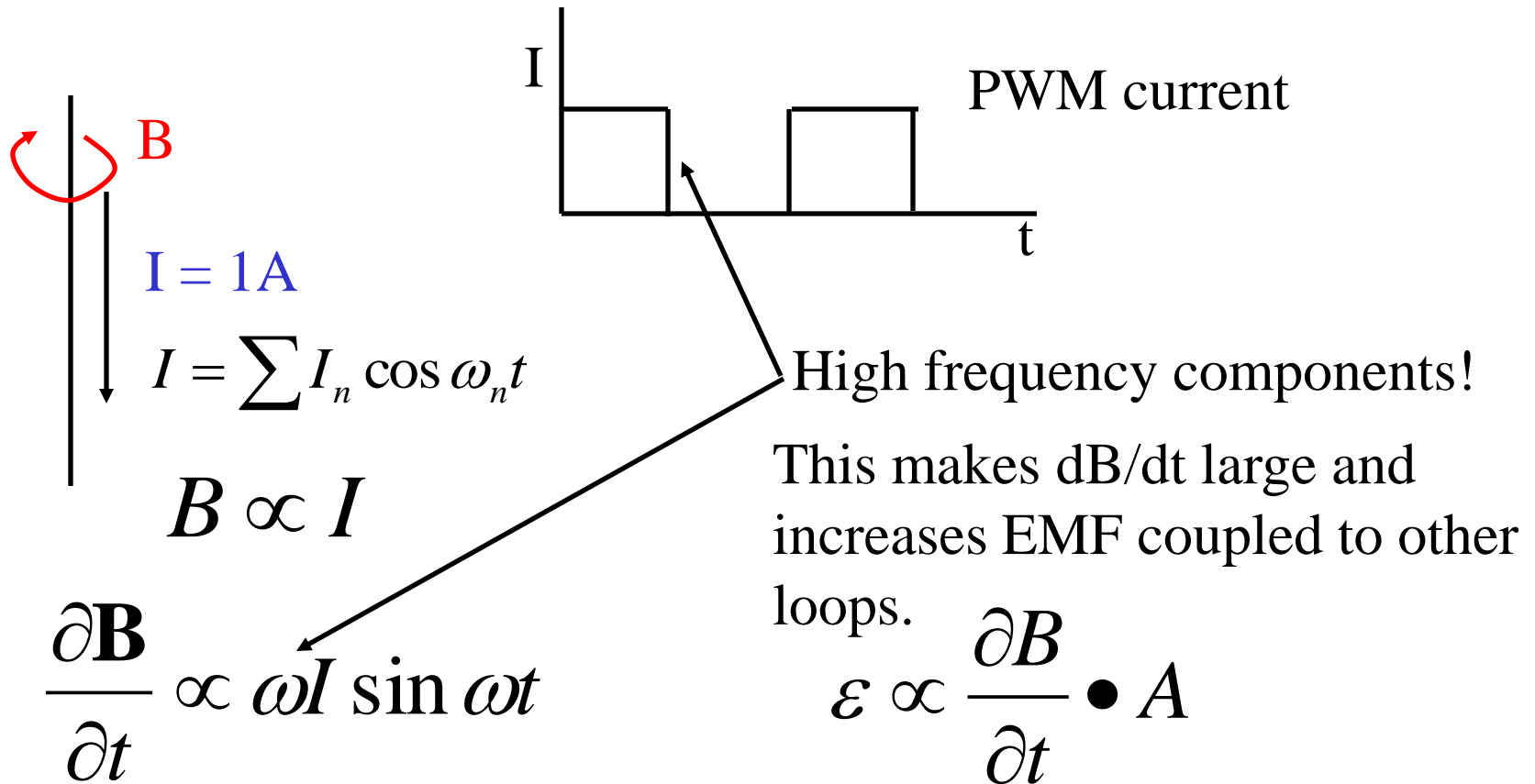
Remember that all wires are also resistors.

Grounds should be routed to a single point.
High-current returns should be separate from ground if possible.

Shielding and grounding

Minimizing noise sources:

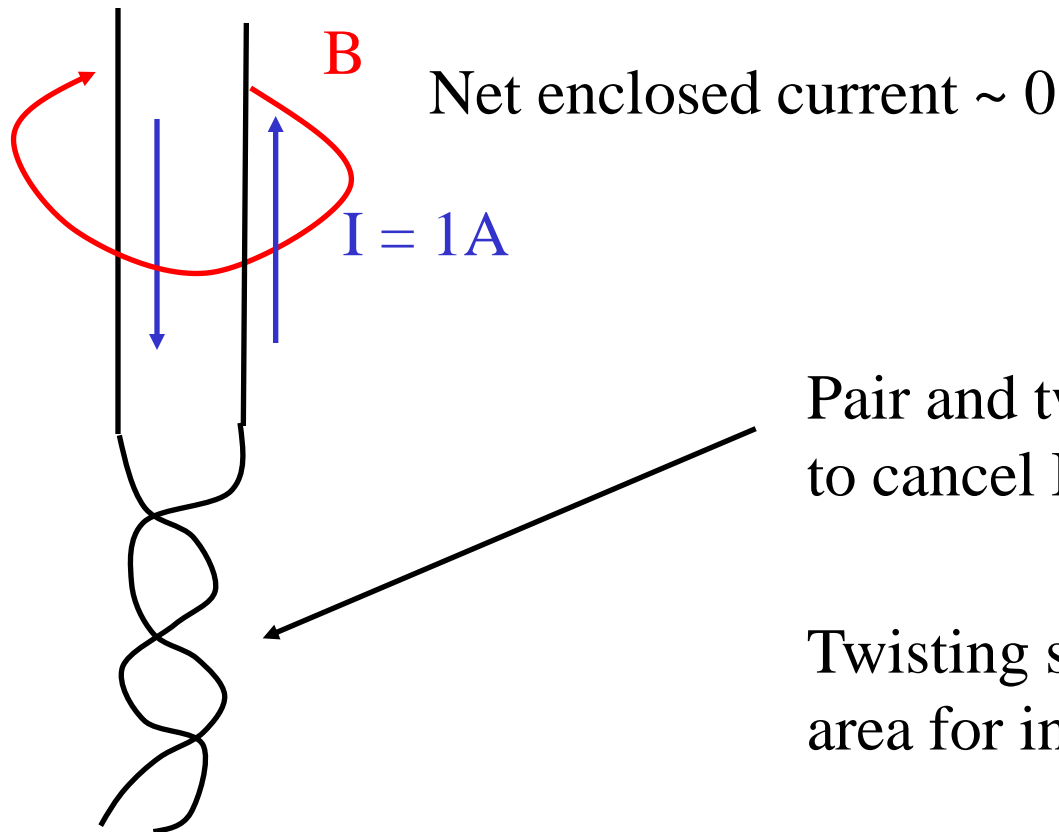
High-current, high frequency signals are the worst offenders: The wires running to your motors are a great example of this.



Shielding and grounding

Minimizing noise sources:

High-current, high frequency signals are the worst offenders: The wires running to your motors are a great example of this.



Net enclosed current ~ 0

$I = 1A$

Pair and twist current carrying wires to cancel B !

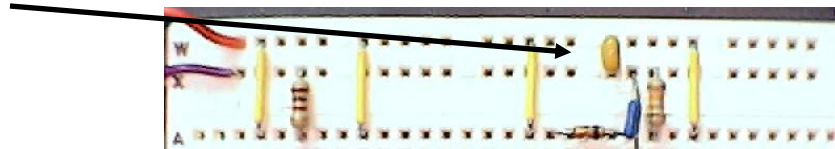
Twisting signal wires also reduces area for inductive coupling.

Power conditioning

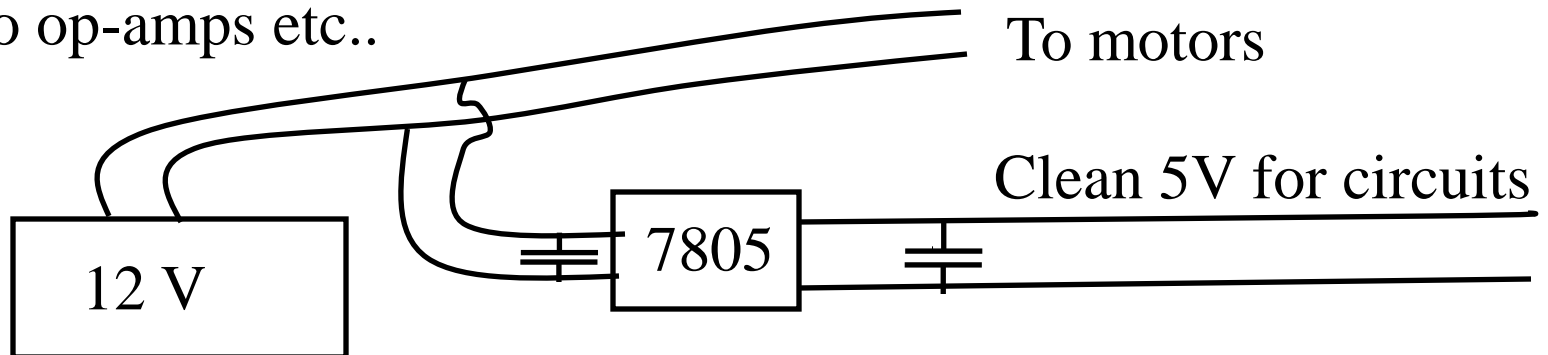
Keep your power lines clean of high frequency oscillations:

High-current, high frequency loads in your circuit can propagate voltage fluctuations in your power lines.

- Put a 10 or 100 pF capacitor from power to ground every 1” of circuit board for digital circuits. Possibly less frequently for lower speed analog circuits



- Use a separate power source for your high current, fluctuating loads, or filter and regulate power from such a source before using it as power to op-amps etc..



Lecture 5 – Introduction to control

Feedback control is a way of automatically adjusting a variable to a desired value despite possible external influence or variations.

Eg: Heating your house.

No feedback (open loop):

Actual temperature varies depending on whether windows are open, how cold it is outside etc,...

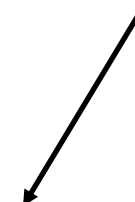
Outside temperature

House temperature responds to heat

Desired temperature T

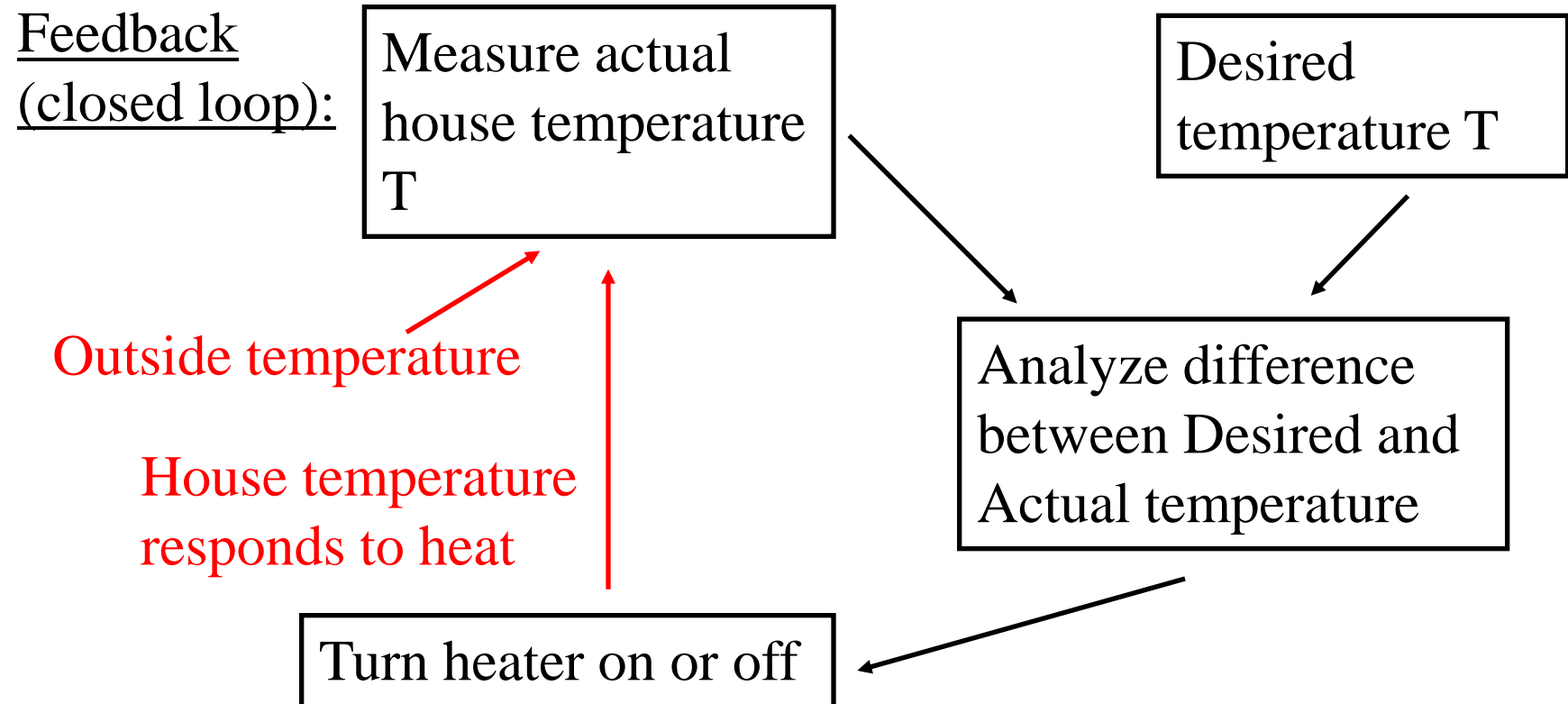
Determine typical heater power required

Turn heater on or off



Control: Introduction

Feedback control is a way of automatically adjusting a variable to a desired value despite possible external influence or variations.

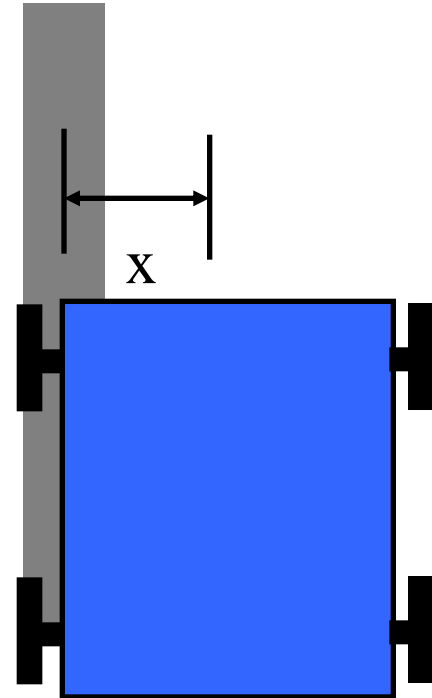


Control: Introduction

ON/OFF control:

X = distance between center of robot and center of tape

```
while(1)
{
  if (x=0) go_straight();
  if (x>0) turn_left();
  if (x<0) turn_right();
}
```



This tends to lead to oscillations around the center of the tape.

Control: Introduction

Proportional control:

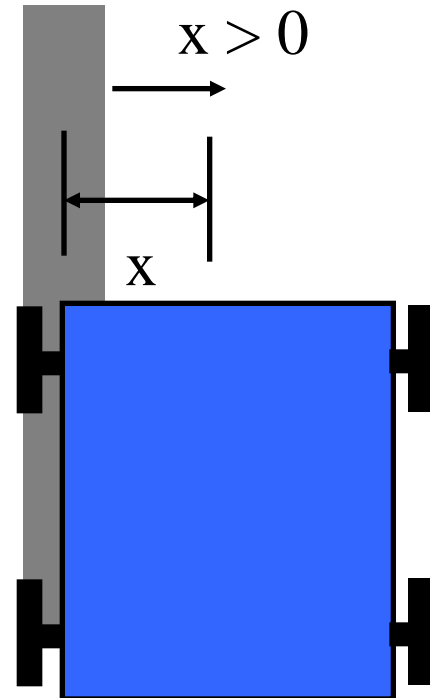
X = distance between center of robot and center of tape

steer(int dir); - a hypothetical function that steers robot left ($dir < 0$) or right ($dir > 0$) in a radius of $600''/dir$.

```
while(1)
{
    steer(K*X);
}
```

K is the proportional gain of this feedback loop and **MUST** be negative.

This is much better and more accurate than ON/OFF control, though it will also oscillate for large values of K .

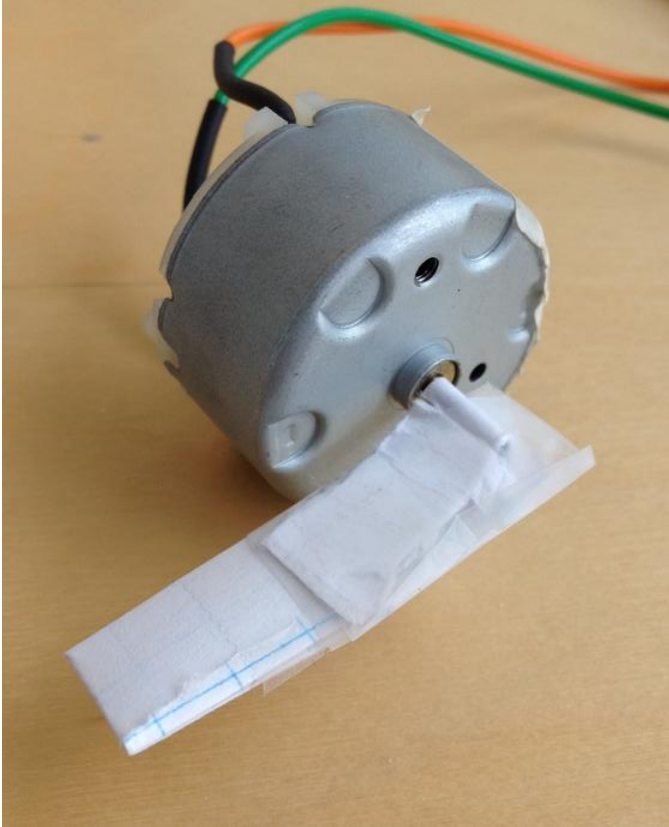


Feedback Control

Build a circuit that:

- Steadies a piece of paper attached to a motor by optical feedback, such that when the motor is translated, the end of the paper remains stationary.
- ❖ Note: Use the QRD1114 to detect the paper position.
- ❖ Feed this through an op-amp with controllable gain, and use the op-amp to drive a motor that turns the paper.
- ❖ Experiment with different gain values.

Feedback Control

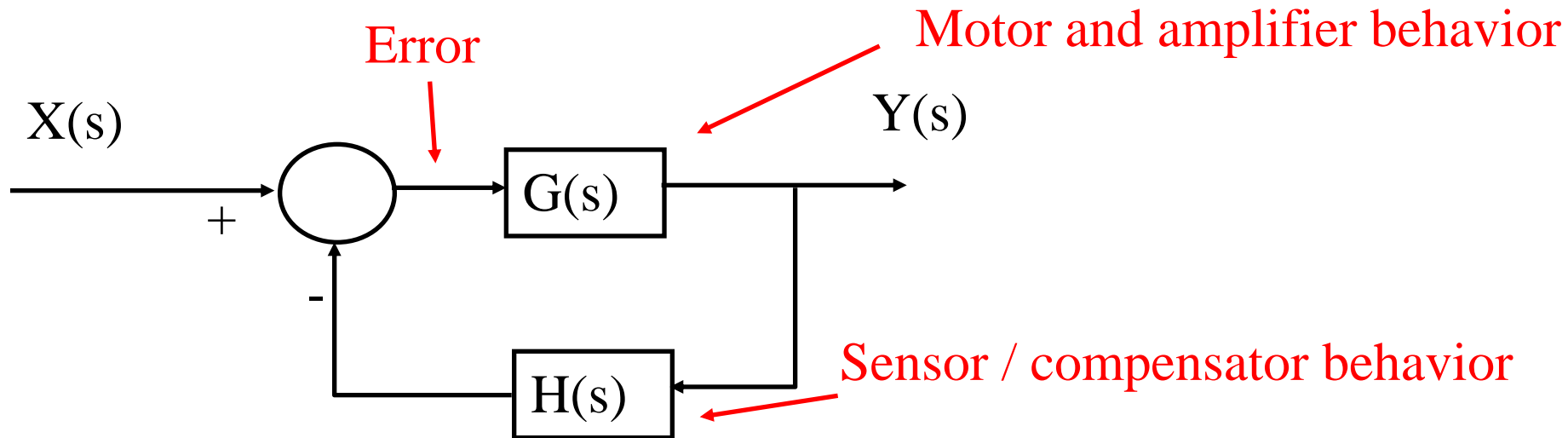


- Build a QRD circuit and use voltmeter to check that output varies by a few volts when paper comes near QRD
- Buffer its output with a TL082
- Build a variable gain inverting amp with a TL082 and a pot. Use a fixed positive voltage reference that lies in the range of the QRD values.
- Hook it all up...

Feedback loops

Y = variable you'd like to control (eg: shaft angle of a servo motor)

X = your desired value of Y (eg: 10 degrees)



$$Y = G(X - HY)$$

$$Y(1 + GH) = GX$$

$$Y/X = G/(1 + GH)$$

$$\frac{Y}{X} = \frac{G}{1 + GH}$$

G = forward transfer function, GH = loop transfer function

Feedback loops: stability

$$\frac{Y}{X} = \frac{G}{1 + GH}$$

This loop will be unstable if $GH = -1$

$\rightarrow |GH|=1, \text{ phase}(GH) = \pm 180 \text{ deg.}$

$G(s)H(s) = -1$ implies $\frac{Y}{X} = \infty$ for some value of s

i.e. there will exist a frequency for which the loop will provide infinite amplification

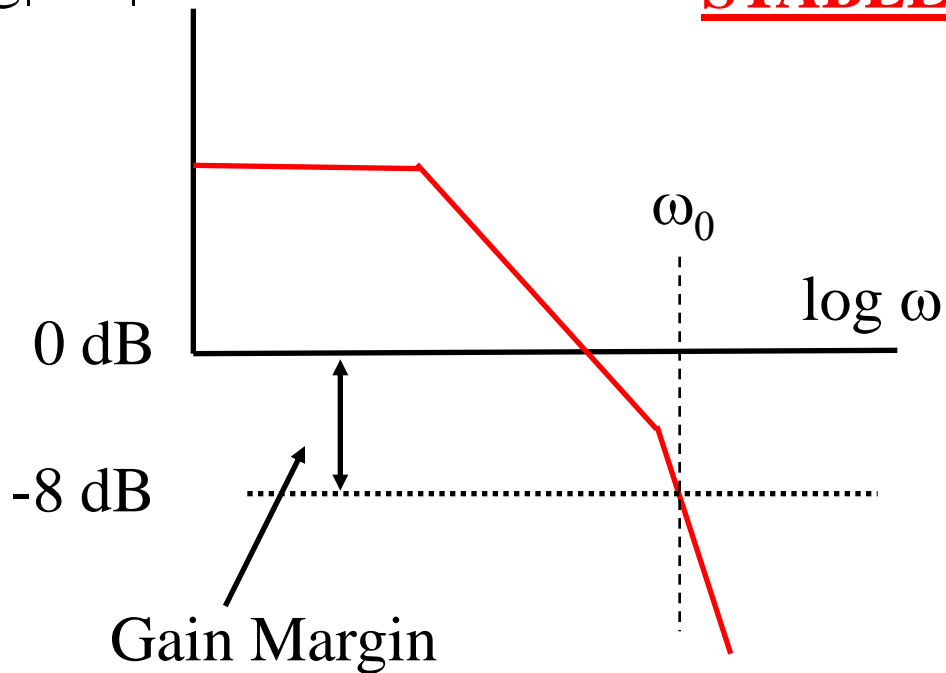
Loop Stability

$$\frac{Y}{X} = \frac{G}{1+GH}$$

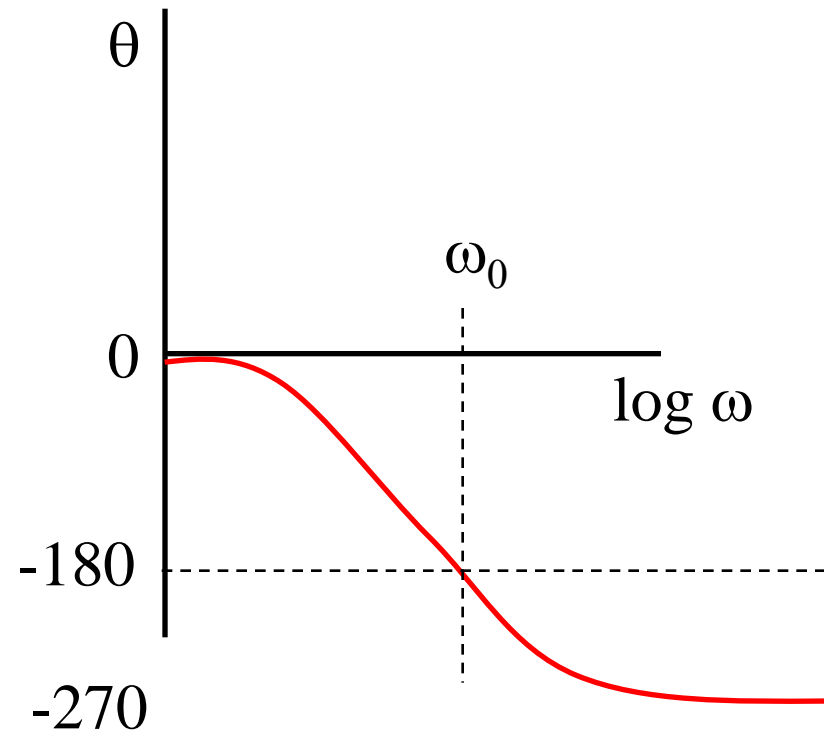
Partial stability criterion:

$|GH| < 1$ where the phase of GH is ± 180 deg.

$10\log|GH|$



STABLE

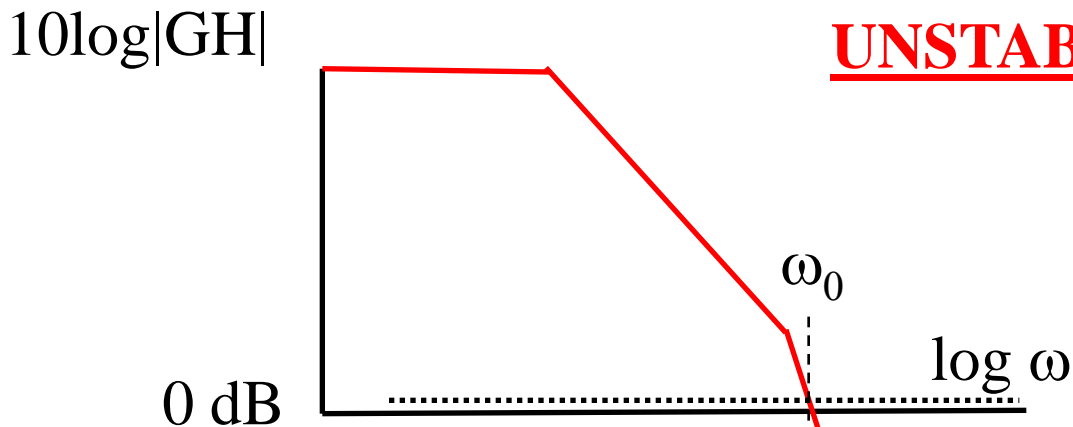


Loop Stability

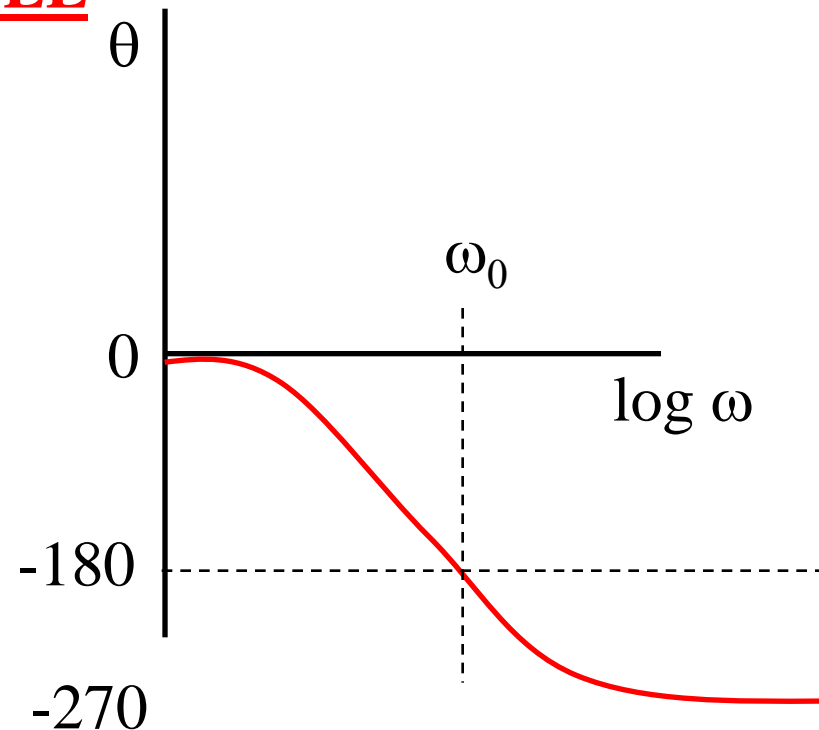
$$\frac{Y}{X} = \frac{KG}{1 + KGH}$$

Partial stability criterion:

$|GH| < 1$ where the phase of GH is ± 180 deg.



Increasing loop gain eventually makes all systems unstable

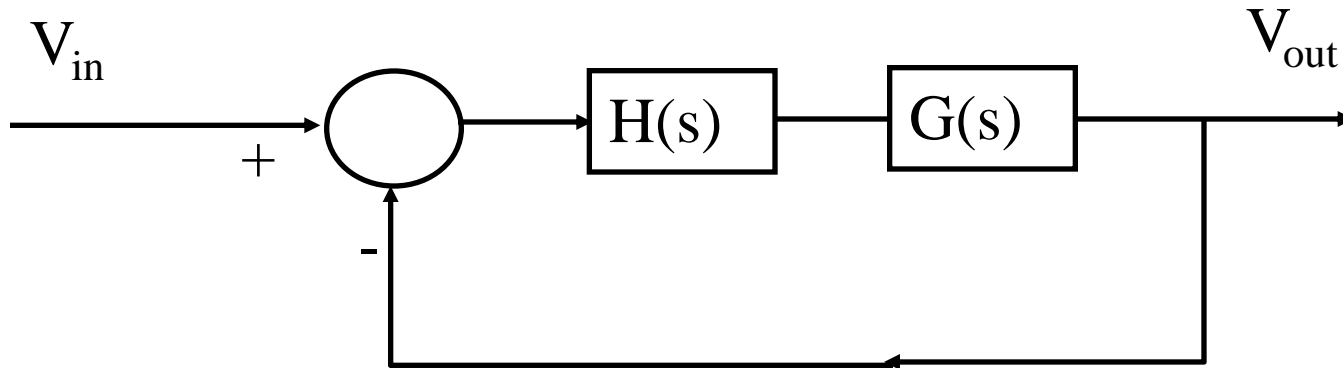


Stability Summary

$$\frac{Y}{X} = \frac{KG}{1 + KGH}$$

- Having one or fewer poles in the plant function KGH ensures that the loop is never unstable.
- The more poles exist in KGH , the harder it will be to control.
- Problems will start to occur when controlling at frequencies above the pole frequencies.
- Increasing loop gain eventually makes all systems unstable due to unexpected high frequency poles.

Compensation



- A feedback system is usually divided into two transfer functions:
 - The “plant” function ($G(s)$) which usually you cannot alter (motor characteristics etc.)
 - A compensator circuit $H(s)$ that you can design to optimize the feedback loop
- A common type of “all-purpose” compensation is PID:
 - Proportional (K_p)
 - Integral (K_i/s)
 - Derivative (sK_d)

Transfer functions revisited (Laplace transform notation: $s \sim j\omega$)

$V(s)$ is the Laplace transform of $v(t)$.

$$V(s) = \int_{0^-}^{\infty} v(t) e^{-st} dt$$

Some rules:

1) Proportionality:

$$v_{\text{out}}(t) = K * v_{\text{in}}(t)$$

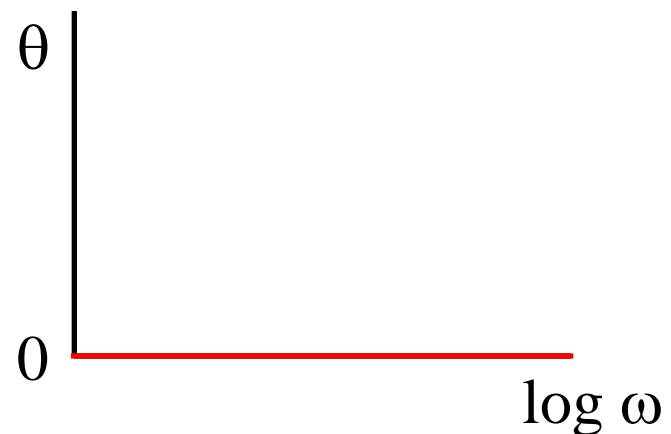
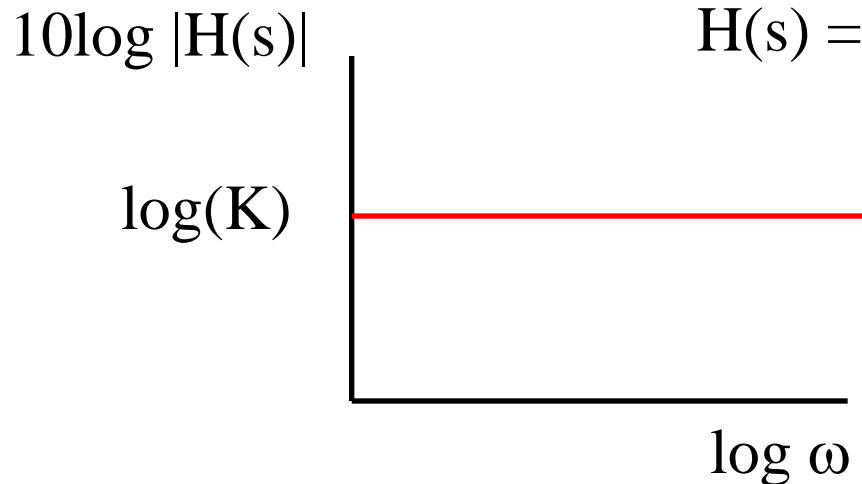
Time domain

$$V_{\text{out}}(s) = K * V_{\text{in}}(s)$$

Frequency domain

$$H(s) = V_{\text{out}}(s) / V_{\text{in}}(s)$$

$$H(s) = K$$



2) Integration:

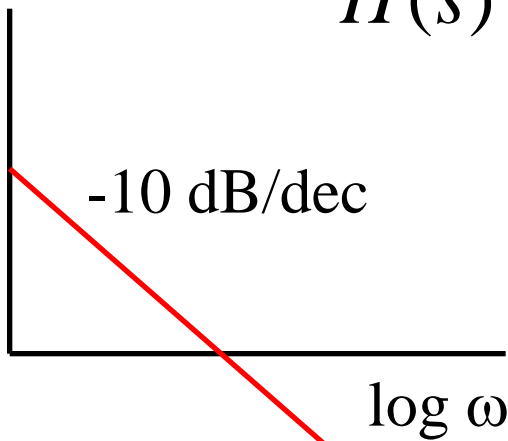
$$v_{out}(t) = K \int v_{in}(t) dt$$

Time domain

$$V_{out}(s) = \frac{KV_{in}(s)}{s}$$

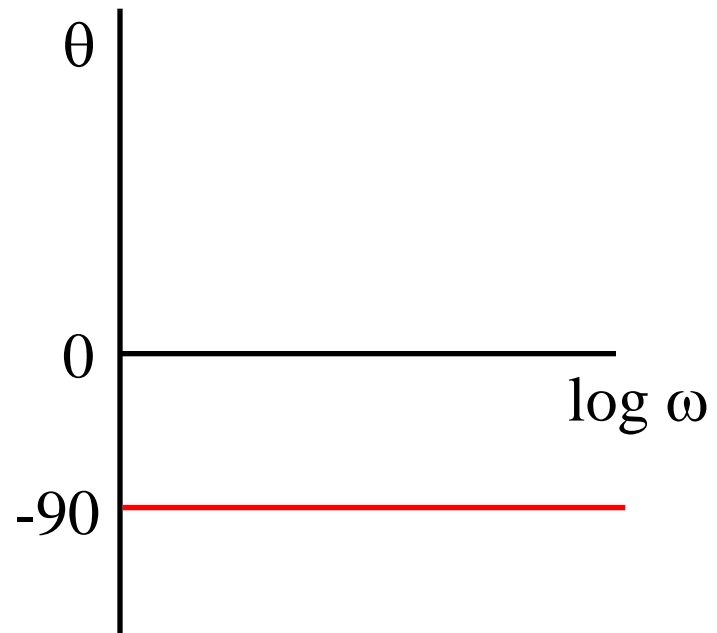
Frequency domain

$10\log|H(s)|$



$$H(s) = \frac{K}{s}$$

θ

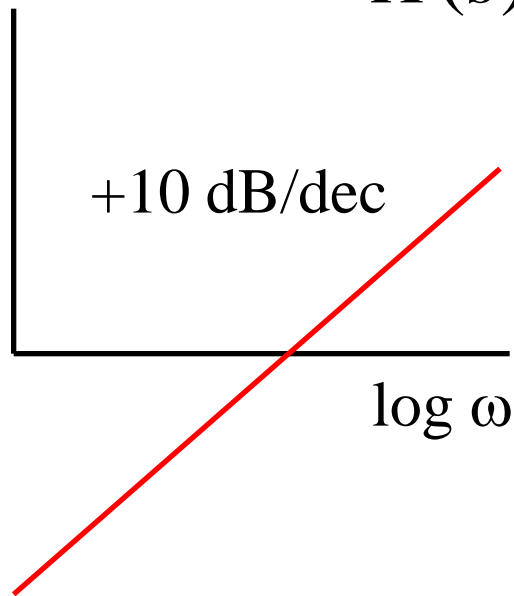


3) Differentiation:

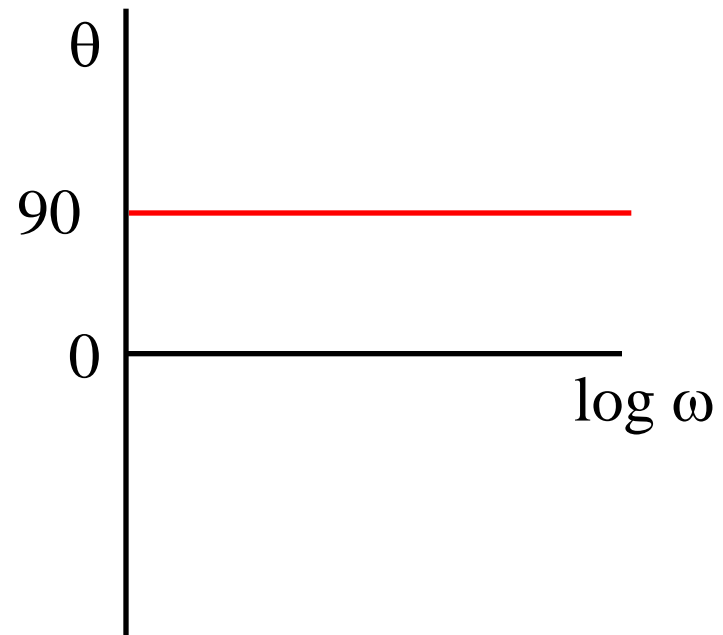
$$v_{out}(t) = K \frac{dv_{in}(t)}{dt}$$

$$V_{out}(s) = KsV_{in}(s)$$

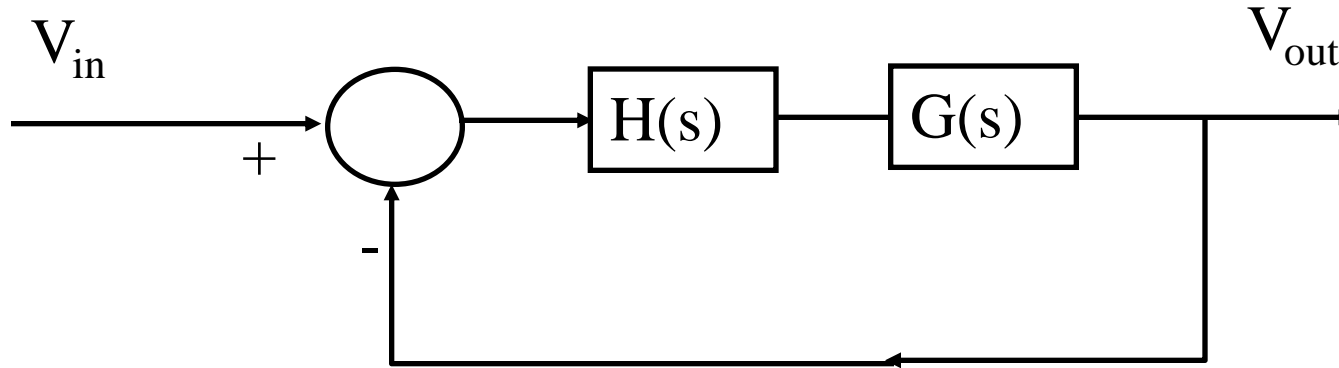
$10\log|H(s)|$



$$H(s) = Ks$$



PID Compensation



Typical PID transfer function:

$$H(s) = K_{tot}(K_p + K_i/s + sK_d)$$

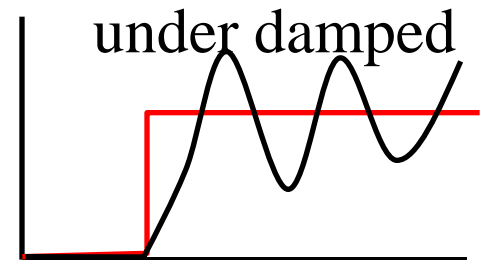
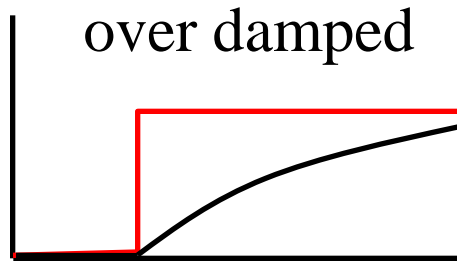
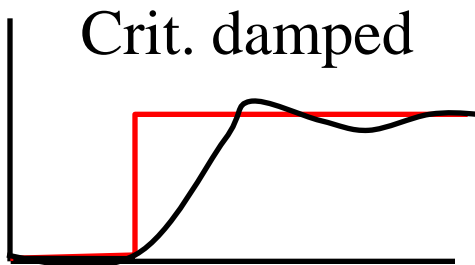
The various gains (K_{tot}, K_p, K_i, K_d) are adjusted to control how much of each type of compensation is applied for a specific plant function $G(s)$.

This adjustment is referred to as “tuning” and is often done iteratively (a slightly improved form of trial and error) when the plant function G is not well known.

Tuning PID

Often PID tuning is done by nearly trial and error. Here is a common Procedure which works for many (**but not all**) plant functions.

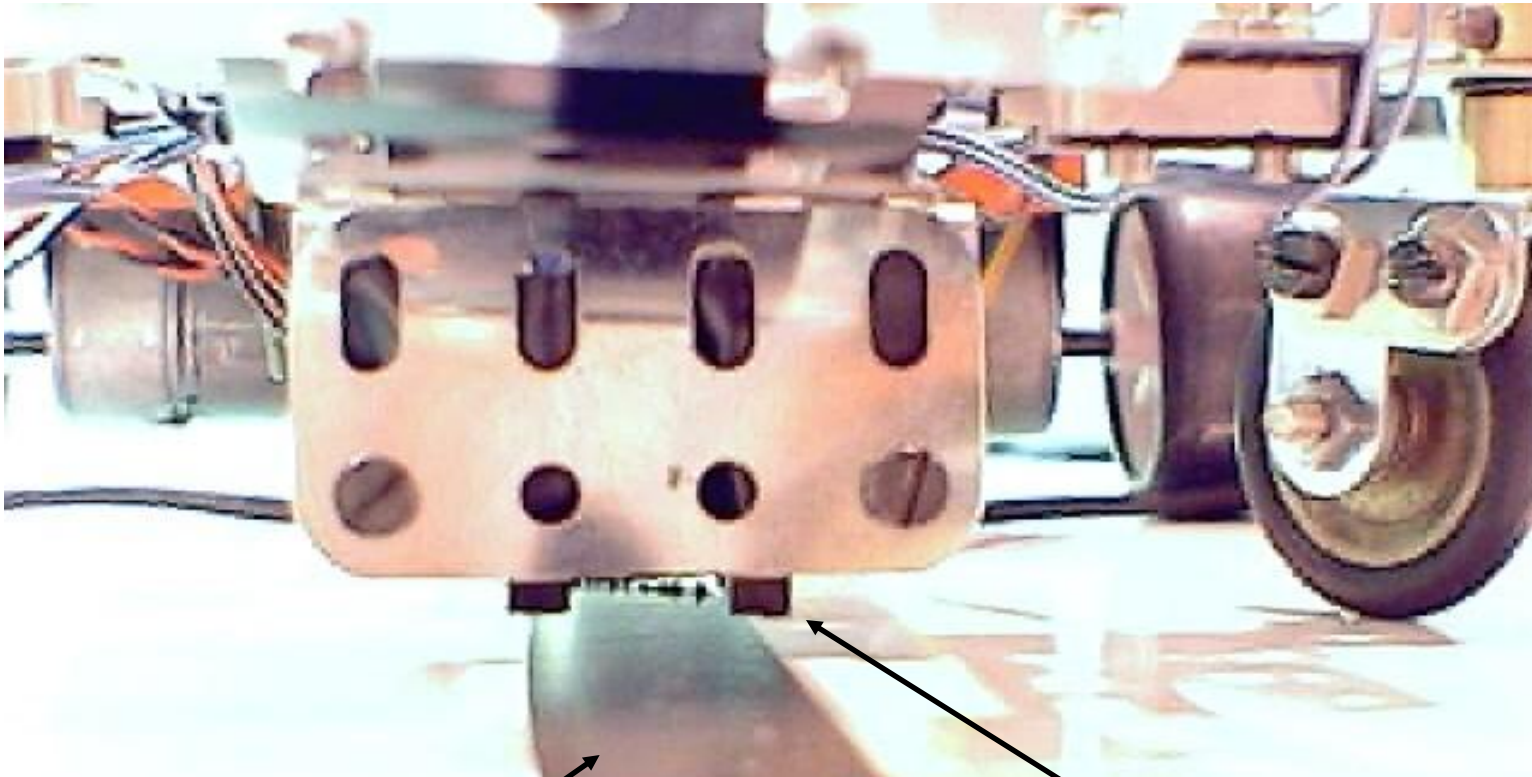
- Set $P=I=D=0$
- **USE external pots or menus to adjust!!!!**
- Increase P slightly and ensure that the sign of the gains is correct.
- Increase P until oscillations begin
- Increase D to dampen oscillations
- Iterate increasing P and D until fast response is achieved with little overshoot
- Increase I to remove any Steady State error.
- If overshoot is too large try decreasing P and D.
- Test with step response:



Control: Introduction

How to measure X (distance from tape):

Use QRD1114 reflectance sensors to detect lack of reflectance from tape.



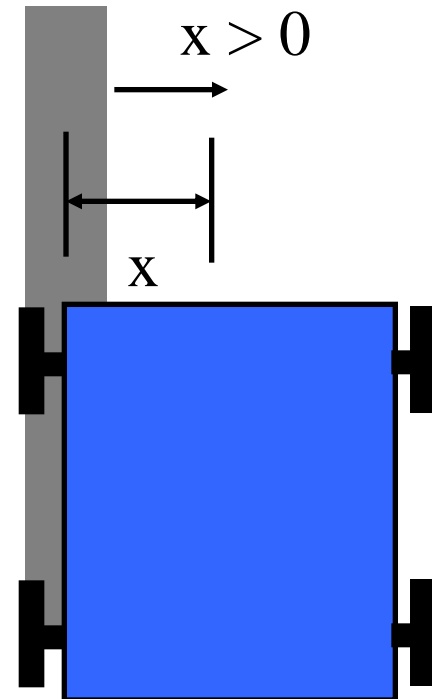
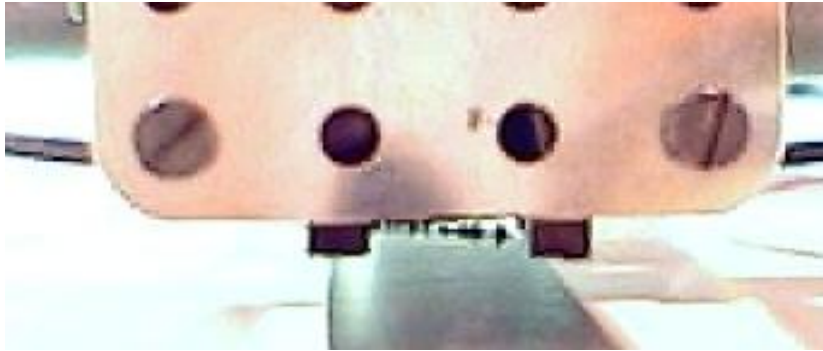
tape

sensor

Control: Introduction

How to measure X:

X = distance between center of robot and center of tape

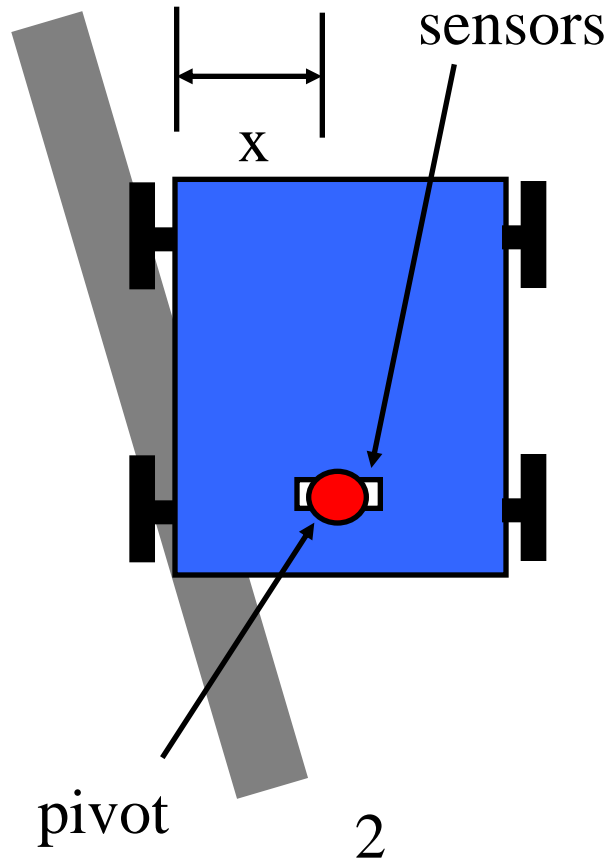
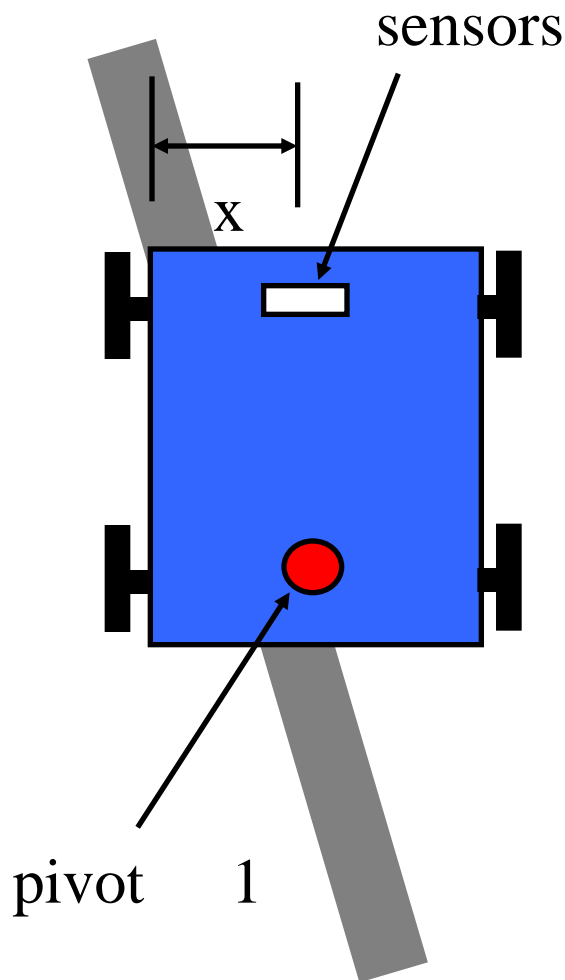


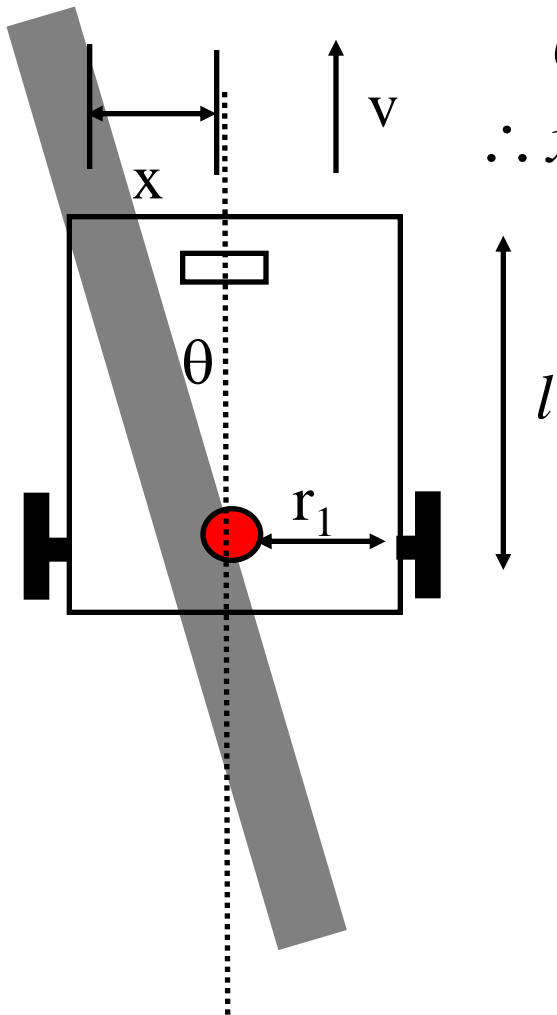
You can form a rough approximation of X by digital to analog conversion of your digital inputs with history:

Situation	Left sensor	Right Sensor	X
Both sensors on tape	1	1	0
Left sensor off tape, right on	0	1	-1
Right sensor off tape, left on	1	0	+1
Both sensors off (right was last on)	0	0	-5
Both sensors off (left was last on)	0	0	+5

Please consider the following problem for a robot with differential rear drive steering:

Which robot configuration has more poles in the transfer function between I (current to motors) and x (distance of sensors from tape)?





$\theta_{in} = 0$ (we want robot to follow tape)

$\therefore x_{in} = 0$

Actual x value in time domain:

$$x = l \sin \theta + \int v \sin \theta dt$$

$$\approx l\theta + \int v\theta dt$$

Actual X in frequency domain:

$$X \approx l\theta + \frac{v\theta}{s} \quad \begin{matrix} \nearrow X \sim l\theta \\ \searrow X = \frac{v\theta}{s} \end{matrix} \quad \text{at low } v$$

$$X = \frac{v\theta}{s} \quad \text{for } l = 0$$

$$\theta = \frac{K_{bot} I_{pwm}}{s(s+a)}$$

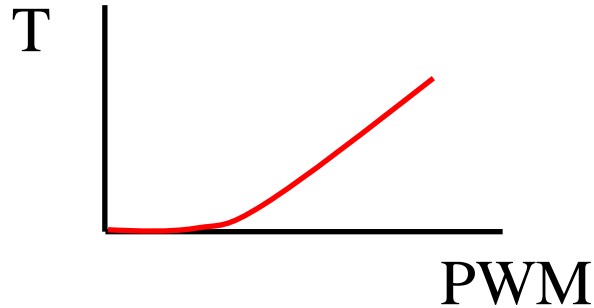
where $a \propto \frac{1}{I_{bot}}$

I_{bot} is the chassis moment of inertia

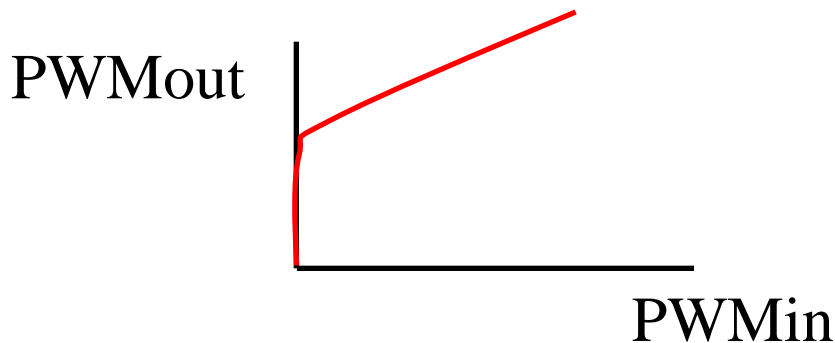
Linearization of non-linear functions

Control can be very difficult if G is non-linear.

PWM drive (combined with friction) yields a very non-linear torque curve:



Solution: Linearize this curve in software by mapping PWM to desired Torque



Analog PID in software (Servo control)

loop

```
pot = analog(6);
```

Feedback potentiometer

```
set = knob();
```

Set point

```
error = set-pot;
```

```
p=kp*error;
```

Proportional

```
d=kd*(error-lasterr);
```

Derivative

```
i=ki*error+i;
```

Integration

```
    if (i>maxi) i = maxi;
```

```
    if (i<-maxi) i = -maxi;
```

Anti-windup

```
g = p+i+d;
```

```
motor(3,g);
```

```
lasterr=error;
```

Because i is an integral, it will build up to large values over time for a constant error. An anti-windup check must be put in place to avoid it overwhelming P and D control when the error is removed.

Digital PID in software (Tape following)

```
left=analog(5);  
right=analog(6);
```

QRD sensors

```
if ((left>thresh)&&(right>thresh)) error = 0;  
if ((left>thresh)&&(right<thresh)) error = -1;  
if ((left<thresh)&&(right>thresh)) error = +1;  
if ((left<thresh)&&(right<thresh))
```

History

```
{  
  if (lerr>0) error = 5;  
  if (lerr<=0) error=-5;  
}
```

Derivative approximation

```
if (!(error==lerr))  
{  
  recerr=lerr;  
  q=m;  
  m=1;  
}
```

Proportional / Derivative

```
p=kp*error;  
d=(int)((float)kd*(float)(error-recerr)/(float)(q+m));  
con = p+d;
```

Display status

```
if (c==30)  
{  
  printf("%d %d %d %d %d %d\n",right,left,kp,kd,p,d);  
  c=0;  
}
```

Motor control

```
c=c+1;  
m=m+1;  
motor(0,-speed+con);  
motor(3,+speed+con);  
lerr=error;
```

Special care needs to be taken for the derivative to approximate its real value.