

EECS 16A    Designing Information Devices and Systems I  
Fall 2016    Babak Ayazifar, Vladimir Stojanovic    Final Exam

Exam location: 145 Dwinelle, last SID# 2

PRINT your student ID: \_\_\_\_\_

PRINT AND SIGN your name: \_\_\_\_\_, \_\_\_\_\_, \_\_\_\_\_  
(last) (first) (signature)

PRINT your Unix account login: ee16a-\_\_\_\_\_

PRINT your discussion section and GSI (the one you attend): \_\_\_\_\_

Name and SID of the person to your left: \_\_\_\_\_

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Name and SID of the person in front of you: \_\_\_\_\_

Name and SID of the person behind you: \_\_\_\_\_

Section 0: Pre-exam questions (2 points)

1. What was your favorite thing about EE16A? (1 pt)

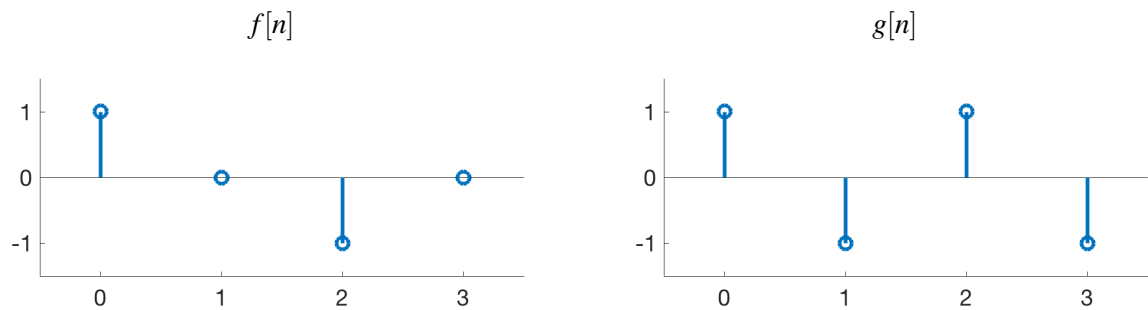
2. What are your plans for winter break? (1 pt)

## Section 1 (48 points)

### 3. Mechanical Correlation (8 points)

All cross-correlations and auto-correlations in this particular problem are circular.

- (a) (4 points) For the following calculation, please see the figures below for functions  $f$  and  $g$ . You may assume that both functions are periodic with a period of 4.



Find  $\text{corr}(f, g)$ . You may leave your answer as either a graph/plot or a vector. However, it must be clear what the precise values are.

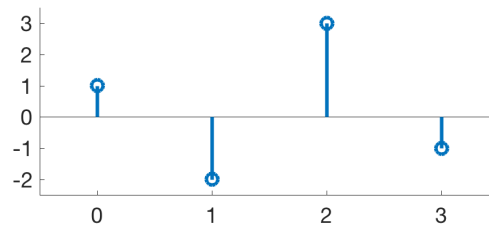
**Solutions:**

Every shift and dot product results in 0.

$$\text{corr}(f, g) = [0, 0, 0, 0]$$

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- (b) (4 points) The figure below is  $\text{corr}(x,y)$  for two signals  $x,y$ . Sketch  $\text{corr}(y,x)$ . Make sure to clearly label your axes.

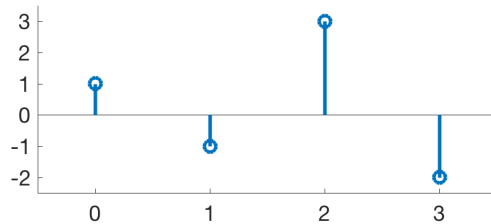


**Solutions:**

If  $z[n] = \text{corr}(x,y)$ , then  $\text{corr}(y,x) = z[-n]$ .

Above,  $z[n] = [1, -2, 3, -1]$ .

So  $z[-n] = [1, -1, 3, -2]$ .



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**4. Mechanical Gram-Schmidt (15 points)**

(a) **(5 points)** Use Gram-Schmidt to find an orthonormal basis for the following three vectors.

$$\vec{v}_1 = \begin{bmatrix} \sqrt{2} \\ -\sqrt{2} \\ 0 \end{bmatrix}, \vec{v}_2 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \vec{v}_3 = \begin{bmatrix} \sqrt{2} \\ 0 \\ -\sqrt{2} \end{bmatrix}$$

**Solutions:** A valid basis is:

$$B = \left\{ \begin{bmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \\ 0 \end{bmatrix} \right\}$$

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- (b) (5 points) Express  $\vec{v}_1, \vec{v}_2,$  and  $\vec{v}_3$  as vectors in the basis you found in part a.

**Solutions:** Using the basis above:

$$\begin{aligned}v'_1 &= \begin{bmatrix} 2 \\ 0 \\ 0 \end{bmatrix}_B \\v'_2 &= \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}_B \\v'_3 &= \begin{bmatrix} 1 \\ -\sqrt{2} \\ 1 \end{bmatrix}_B\end{aligned}$$

- (c) (5 points) Decompose the following matrix  $\mathbf{A}$  as an orthonormal matrix  $\mathbf{Q}$  and an upper-triangular matrix  $\mathbf{R}$ :

$$A = \begin{bmatrix} \sqrt{2} & 0 & \sqrt{2} \\ -\sqrt{2} & 0 & 0 \\ 0 & 1 & -\sqrt{2} \end{bmatrix}$$

**Solutions:** We've already done the work. Use the basis from part (a) and the vectors from part (c).

$$A = \begin{bmatrix} \frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ \frac{-1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 2 & 0 & 1 \\ 0 & 1 & -\sqrt{2} \\ 0 & 0 & 1 \end{bmatrix}$$

**5. Eigenvalues, Eigenvectors, and Determinants (15 points)**

- (a) (5 points) Find the eigenvalues of  $\mathbf{B} = \begin{bmatrix} 3 & 7 & 4 \\ 0 & 4 & 2 \\ 0 & 1 & 5 \end{bmatrix}$ .

**Solutions:**

$$\begin{aligned} \begin{bmatrix} 3 & 7 & 4 \\ 0 & 4 & 2 \\ 0 & 1 & 5 \end{bmatrix} &\implies |\mathbf{B} - \lambda\mathbf{I}| = \begin{vmatrix} 3-\lambda & 7 & 4 \\ 0 & 4-\lambda & 2 \\ 0 & 1 & 5-\lambda \end{vmatrix} \\ &= (3-\lambda)((4-\lambda)(5-\lambda) - 2) = (3-\lambda)((20-9\lambda+\lambda^2) - 2) = (3-\lambda)(\lambda^2 - 9\lambda + 18) \\ &= (3-\lambda)(3-\lambda)(6-\lambda) \implies \lambda = 3, 3, 6 \end{aligned}$$

- (b) (5 points) Assuming one of the eigenvalues is  $\lambda = 3$ , find its corresponding eigenvector.

**Solutions:**

$$\begin{aligned} \lambda = 3 &\implies \mathbf{B} - \lambda\mathbf{I} = \begin{bmatrix} 3-3 & 7 & 4 \\ 0 & 4-3 & 2 \\ 0 & 1 & 5-3 \end{bmatrix} = \begin{bmatrix} 0 & 7 & 4 \\ 0 & 1 & 2 \\ 0 & 1 & 2 \end{bmatrix} \\ &= \begin{bmatrix} 0 & 7 & 4 \\ 0 & 1 & 2 \\ 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 7 & 4 \\ 0 & 0 & -10 \\ 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \implies v_3 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \end{aligned}$$

- (c) (5 points) Is the matrix  $\begin{bmatrix} 3 & 7 & 4 \\ 0 & 4 & 2 \\ 0 & 1 & 5 \end{bmatrix}$  diagonalizable? Provide a succinct, but clear and convincing explanation.

**Solutions:** The eigenvalue 3 with multiplicity 2 only has one corresponding eigenvector, so this matrix will only have 2 eigenvectors, which is not enough to span  $\mathbb{R}^3$ . Therefore, it is not diagonalizable.

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**6. Block Determinants (5 points)**

The following properties may or may not be useful for this problem, and you do not need to prove them if you choose to use them.

$$\det \begin{bmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix} = \det(\mathbf{A})$$

$$\det \begin{bmatrix} \mathbf{I} & \mathbf{B} \\ \mathbf{0} & \mathbf{C} \end{bmatrix} = \det(\mathbf{C})$$

$$\det(\mathbf{AB}) = \det(\mathbf{A})\det(\mathbf{B})$$

where  $\mathbf{I}$  represents the identity matrix, and  $\mathbf{A}$ ,  $\mathbf{B}$  and  $\mathbf{C}$  are arbitrary matrices of appropriate dimension.

Determine the determinant of:

$$\mathbf{R} = \begin{bmatrix} \mathbf{P} & \mathbf{Q} \\ \mathbf{0} & \mathbf{S} \end{bmatrix}$$

as a function of the determinants of sub-matrices  $\mathbf{P}$ ,  $\mathbf{Q}$ , and  $\mathbf{S}$ , where  $\mathbf{P}$  is invertible.

**Solutions:**

$$\det \begin{bmatrix} \mathbf{P} & \mathbf{Q} \\ \mathbf{0} & \mathbf{S} \end{bmatrix} = \det \begin{bmatrix} \mathbf{P} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix} \det \begin{bmatrix} \mathbf{I} & \mathbf{P}^{-1}\mathbf{Q} \\ \mathbf{0} & \mathbf{S} \end{bmatrix} = \det(\mathbf{P})\det(\mathbf{S})$$

There is more than one way of doing this factorization. Check to make sure that their factorization is valid and that their conclusions stem from their proof using the lemmas given in Hint 1 and not intuition.

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**7. QR (5 points)**

Recall that the solution to a linear least-squares problem is a minimization of  $\|\vec{b} - A\vec{x}\|^2$ . Show that the approximation of  $\vec{x}, \hat{\vec{x}}$ , in this linear least squares formula has an equivalent representation using the  $\mathbf{A}$  matrix's  $QR$  decomposition ( $\mathbf{A} = \mathbf{QR}$ ). In other words, express  $\hat{\vec{x}}$  in terms of  $\mathbf{R}$ ,  $\mathbf{Q}$ , and  $\vec{b}$ , and show your derivation. You may assume the matrix  $\mathbf{A}$  has full column rank. Your final expression must be in the simplest form possible.

(Hint: remember that  $\mathbf{Q}$  is orthonormal)

**Solutions:**

$$\begin{aligned}A^T A \vec{x} &= A^T \vec{b} \\(QR)^T (QR) \vec{x} &= (QR)^T \vec{b} \\R^T Q^T QR \vec{x} &= R^T Q^T \vec{b} \\R^T R \vec{x} &= R^T Q^T \vec{b} \\R \vec{x} &= Q^T \vec{b} \\x &= R^{-1} Q^T \vec{b}\end{aligned}$$

(Recall that for an orthonormal matrix  $Q$ ,  $Q^T = Q^{-1}$ ; left-multiplying both sides by  $Q$  gives  $QR\vec{x} = QQ^T \vec{b}$ , which is equivalent to  $A\vec{x} = \vec{b}$ , our original objective function.)



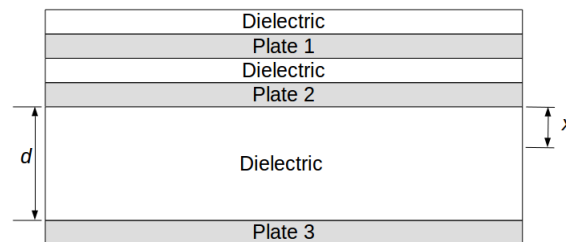
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## Section 2 (130 points)

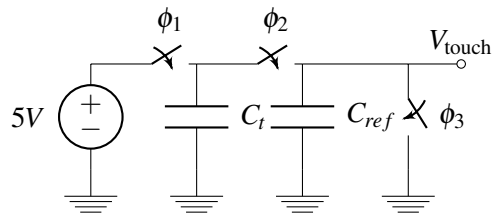
### 8. Force-Touch (30 points)

In this problem we will explore how to add force measurements to the basic touchscreen seen in lecture. Shown below is a cross section of this new touch screen. The distance between Plate 1 and Plate 2 is fixed. The distance between Plate 2 and Plate 3 is variable, and depends on the force applied on the screen. **Throughout this problem, we will call  $C_t$  the capacitance between plate 1 and 2, and  $C_f$  the capacitance between plates 2 and 3.**

Figure 1: Cross section

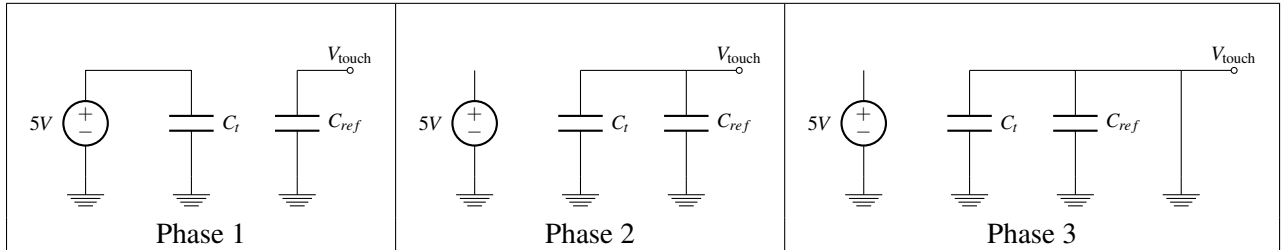


The circuit below is designed to measure a touch. Here Plate 2 is connected to ground, and  $C_t$  is the *total* capacitance, including the effect of a finger when present, between Plates 1 and 2.



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The circuit above cycles through three phases, depicted in the diagram below. For this problem, you may assume switching is controlled through a microcontroller and all capacitors reach steady state during each phase.



- (a) (5 points) Write an expression for  $C_{ref}$  such that  $V_{touch} = 2.5V$  in Phase 2 when nothing is touching the sensor. Assume  $C_t$  is some value  $C_{t,nom}$  when there is no touch. Your answer may include  $C_{t,nom}$ . Justify your answer.

**Solutions:**

In phase 1,  $C_t$  charges.  $Q_{C_t} = 5C_t$

In phase 2, The two capacitors charge share.  $Q = Q_{C_{t,nom}} + Q_{C_{ref}}$

$$Q = V_t(C_{ref} + C_{t,nom})$$

$$V_t = \frac{C_{t,nom}}{C_{ref} + C_{t,nom}} 5$$

$$C_{ref} = C_{t,nom}$$

- (b) (5 points) When a finger is touching the screen,  $C_t$  increases to twice it's nominal value, or  $2C_{t,nom}$ . Write an expression for  $V_{touch}$  in phase 2 when someone is touching the sensor. Use the value for  $C_{ref}$  you found in part a).

**Solutions:**

Using the expression from part a), we have:

$$V_{touch} = \frac{2C_{touch}}{2C_{t,nom} + C_{ref}} 5$$

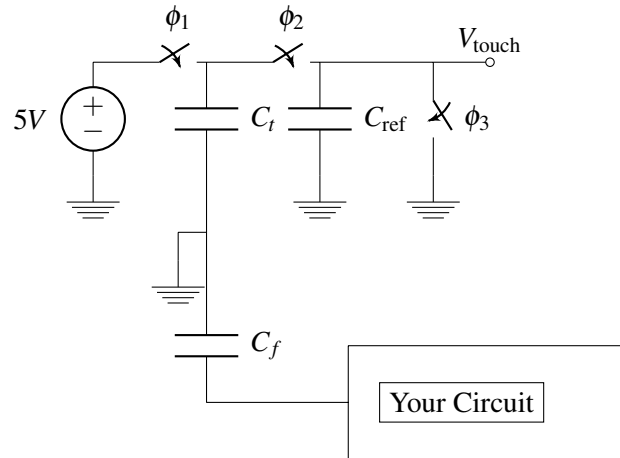
$$V_{touch} = 3.33V$$

- (c) (5 points) Let us now consider the  $C_f$ . Assume the plates have an area  $A$  and are nominally a distance  $d$  apart. When a force is applied on the screen, Plate 2 moves closer to Plate 3 by a distance  $x$ . We will ignore the capacitance between Plate 3 and Plate 1. **Find an expression for the capacitance  $C_f$  as a function of  $x$ ,  $A$ ,  $\epsilon$ , and  $d$ .**

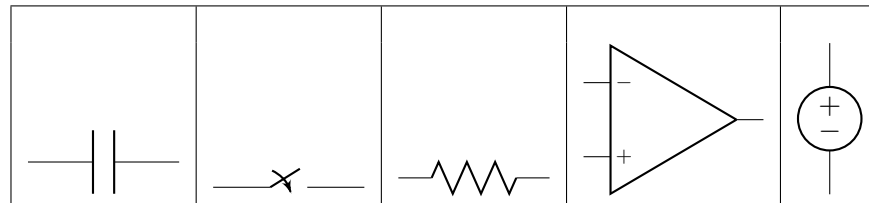
**Solutions:**  $C_{force} = \frac{A\epsilon}{d-x}$

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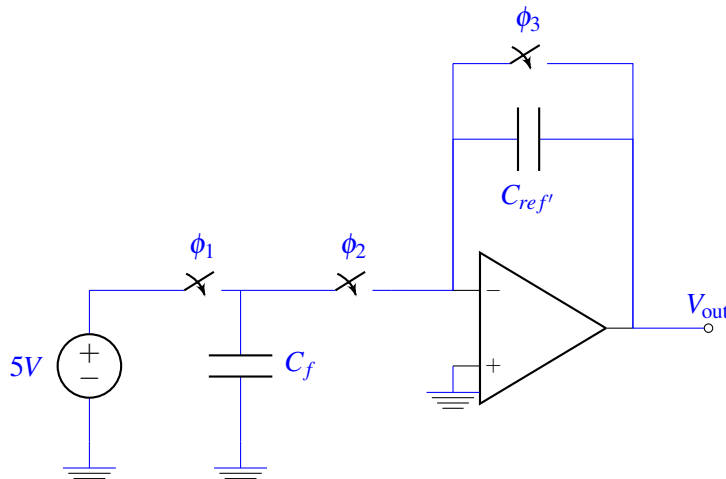
- (d) (10 points) You will now design a circuit to measure the displacement of the screen. Your circuit should connect to the touch screen as shown below:



Design a circuit using the components in the box below to output  $V_{force}$ , a voltage which is inversely proportional to  $(d-x)$ . Solutions where  $V_{force}$  is some other function of  $x$  will receive partial credit.



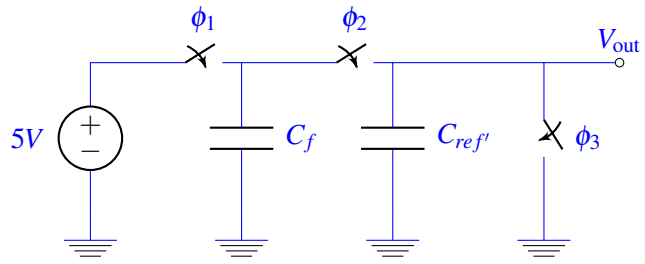
**Solutions:**



In the above circuit, in Phase 1, switches 1 and 3 are ON, charging capacitor  $C_f$  and discharging capacitor  $C_{ref'}$ . Then, Phase 2, switches 1 and 3 are OFF, and switch 2 is ON. In this circuit,  $V_{force}$  is inversely proportional to  $(d-x)$ .

$$V_{force} = \frac{\epsilon A}{C_{ref'}(d-x)}$$

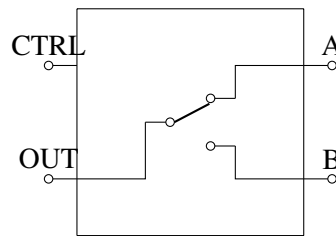
The circuit below recieved partial credit as well.



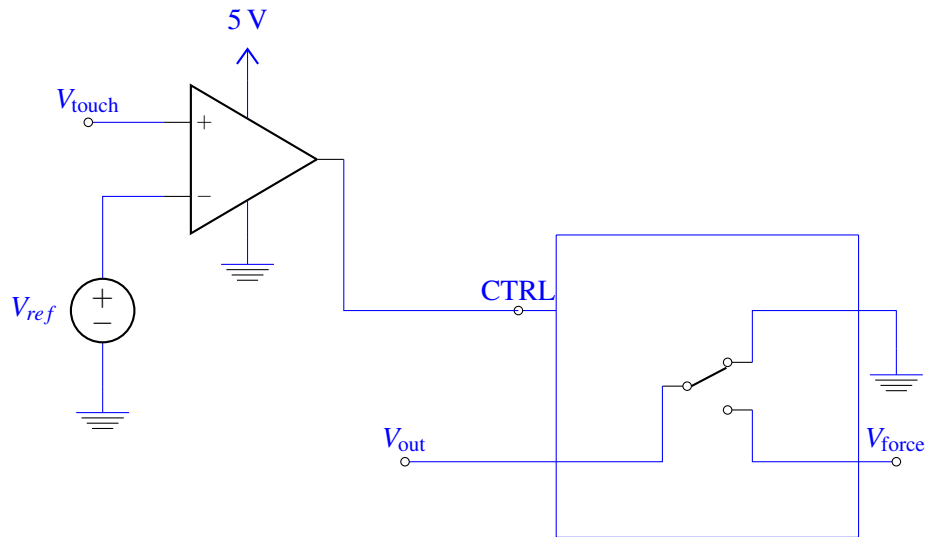
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- (e) (5 points) We now have circuits to output two voltages:  $V_{\text{touch}}$  a voltage which changes value depending on whether there is a touch or not and  $V_{\text{force}}$  a voltage which is some function of the displacement  $x$  and thus the force applied on the screen. We want to output  $V_{\text{force}}$ , but only when there is a touch. For example, this could be useful to prevent your phone from activating apps while in your pocket. Using  $V_{\text{touch}}$  the output of the touch-sensor and  $V_{\text{force}}$  the output of the force sensor as inputs to your circuit, design a circuit to output  $V_{\text{out}}$  such that  $V_{\text{out}} = V_{\text{force}}$  if there is a touch, and 0V otherwise.

In addition to the box of components from part d), you have access to a voltage controlled switch shown below. When CTRL is connected to 5V, OUT is connected to B, otherwise when CTRL is 0V out is connected to A. You cannot supply a voltage other than 0V or 5V to the CTRL input of the voltage controlled switch.



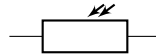
**Solutions:**



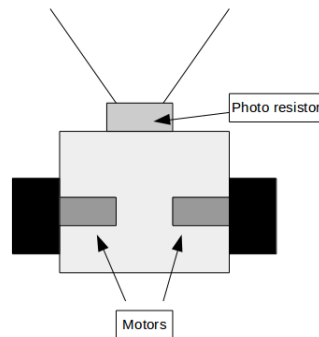
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### 9. PetBot Design (30 points)

In this problem, you will design circuits to control PetBot, a simple robot designed to follow light. PetBot measures light using photoresistors. A **photo resistor is a light-sensitive resistor. As it is exposed to more light, its resistance decreases.** Given below is the circuit symbol for a photoresistor.

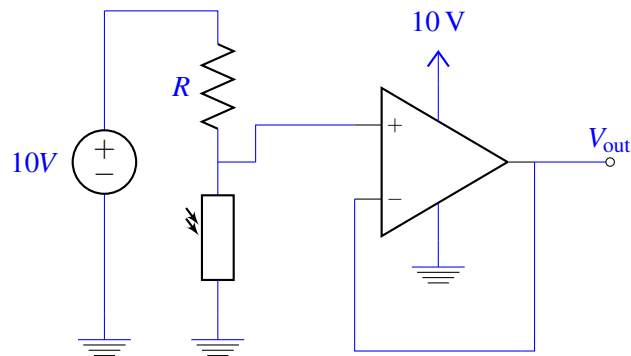


Below is the basic layout of the PetBot. It has one motor on each wheel. We will model each motor as a  $1\Omega$  resistor. When motors have positive voltage across them, they drive forward, when they have negative voltage across them, they drive backward. At zero voltage across the motors, the PetBot stops. The speed of the motor is directly proportional to the magnitude of the motor voltage. The light sensor is mounted to the front of the robot.



- (a) (5 points) **Speed control** - Let us begin by first having PetBot decrease its speed as it drives toward the flashlight. **Design a motor driver circuit that outputs a decreasing positive motor voltage as the PetBot drives toward the flashlight. The motor voltage should be at least 5V far away from the flashlight. When far away from the flashlight, the photoresistor value will be  $10K\Omega$  and dropping toward  $100\Omega$  as it gets close to the flashlight.** In your design, you may use any number of resistors and Op-Amps. You also have access to voltage sources of +10V and -10V. Based on your circuit, derive an expression for the motor voltage as a function of the circuit components that you used.

**Solutions:**



The output of the above circuit is:

$$V_{out} = \frac{R_p}{R_p + R} 10V$$

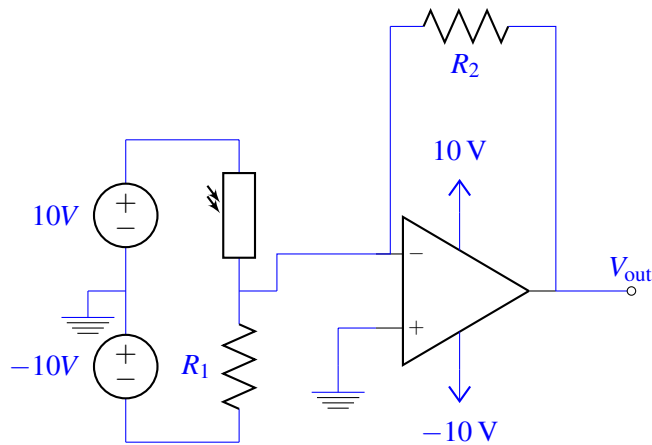
$R_p$  represents the photo resistor, and  $R \leq 10K$ .

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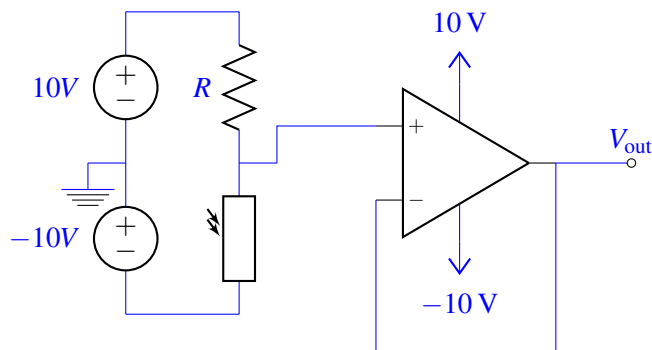
- (b) (15 points) **Distance control** - Let us now have PetBot drive up to a flashlight (or away from the flashlight) and stop at distance of 1ft away from the light. At the distance of 1ft from the flashlight, the photoresistor has a value  $1K\Omega$ .

**Design a circuit to output a motor voltage that is positive when the PetBot is at a distance greater than 1ft from the flashlight (making the PetBot move toward it), zero at 1ft from the flashlight (making the PetBot stop), and negative at a distance of less than 1ft from the flashlight (making the PetBot back-away from the flashlight).** In your design, you may use any number of resistors and Op-Amps. You also have access to voltage sources of value +10V and -10V. Based on your circuit, derive an expression for the motor voltage as a function of the values of circuit components that you used.

**Solutions:**



**Alternatively:**

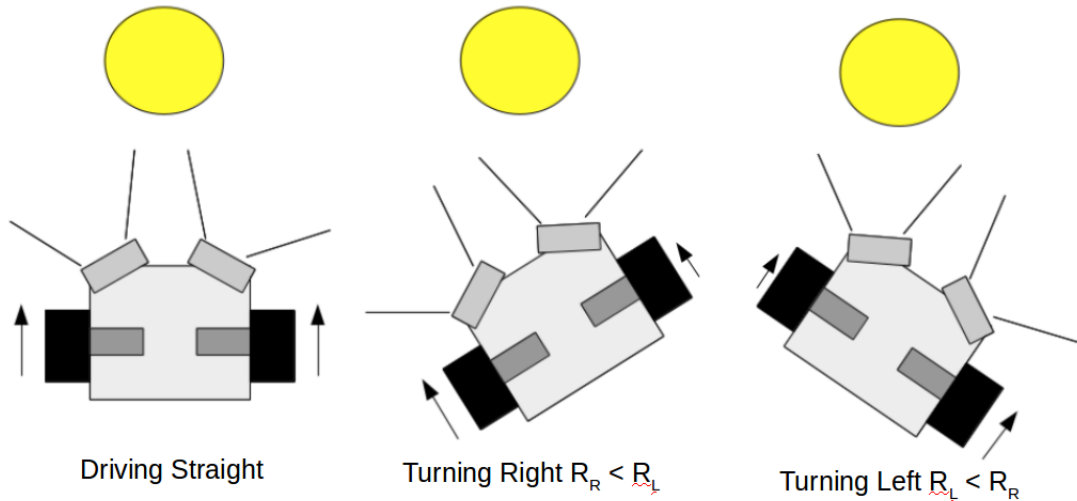




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- (c) **(10 points) Turning control** - We now want the PetBot to turn toward the flashlight that is not directly in front of it, while moving toward it and stopping at 1ft distance like before. To do so we will use two photoresistors angled slightly away from each other. In order to control the motion of the PetBot, we will use a simple control scheme described below.

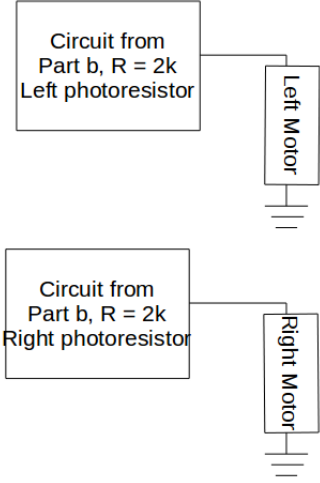
Assume there are two photoresistors,  $R_L$  and  $R_R$ . If the **left** photoresistor is pointed towards the light, and thus has less resistance, we drive the **left** motor **slower** than the right motor to turn the PetBot towards the light. A similar process occurs if the right photoresistor is pointed towards the light.



Design the control circuit for the PetBot. Your circuit should use two photoresistors and drive two motors. Both motors should only stop at distance of 1ft from the flashlight. Note that since photoresistors are angled, their value at 1ft away from the flashlight has changed to  $2K\Omega$ . **Clearly label which side of the robot each photoresistor and motor belongs on.** You have access to op-amps, resistors, and voltage sources of value +10V and -10V. For this problem, you may assume the PetBot will initially always be far away from the flashlight. You may continue your work for this problem on the next page.

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**Solutions:**



**10. A Tale of Technocrats and Three Dream Cities (30 points)**

This problem is a tale of Technocrats and three Dream Cities. The three cities are (I) San Francisco, (II) Chicago, and (III) Boston. The Technocrats don't die. They don't reproduce. In other words, their total population size is a constant from the initial time  $n = 0$  onward indefinitely (as  $n \rightarrow \infty$ ).

At the strike of every daily tick of a Universal Clock, each Technocrat chooses to either remain at the city he or she is already in, or move to another of the three Dream Cities instantaneously, but can only move in a single-hop fashion (i.e., traverse only one branch on its state-transition diagram, whether that branch is a self-loop or a branch to another node).

Let the state vector for this system be  $s[n] = \begin{bmatrix} s_1[n] \\ s_2[n] \\ s_3[n] \end{bmatrix}$ , where  $s_\ell[n]$  denotes the *fraction* of the Technocrats in City  $\ell$  at time  $n$ ; for example,  $s_3[n]$  denotes the fraction of the Technocrats who are in Boston on Day  $n$ . Accordingly, note that

$$\mathbf{1}^T s[n] = [1 \quad 1 \quad 1] \begin{bmatrix} s_1[n] \\ s_2[n] \\ s_3[n] \end{bmatrix} = s_1[n] + s_2[n] + s_3[n] = 1, \quad \forall n \in \{0, 1, 2, \dots\}.$$

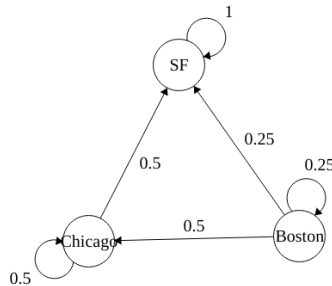
The state-evolution equation for this network is  $s[n + 1] = \mathbf{A}s[n]$ , where the state-transition matrix is

$$\mathbf{A} = \begin{bmatrix} 1 & \frac{1}{2} & \frac{1}{4} \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 0 & 0 & \frac{1}{4} \end{bmatrix}.$$

In one or more parts below, you may or may not find it useful to know that eigenvectors corresponding to distinct eigenvalues are linearly independent.

- (a) **(5 points)** Provide a *well-labeled* state-transition diagram that models the migration pattern of the Technocrats, as described above.

**Solutions:**



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- (b) (**5 points**) In this part, we're interested in a backward inference of the state vector  $s[n]$  from a future state vector, say  $s[n+1]$ . Is it possible to determine the state of the network at time  $n$  (i.e., the state vector  $s[n]$ ) from the state of the network at time  $n+1$  (i.e., the state vector  $s[n+1]$ )? Provide a succinct, but clear and convincing explanation for your answer.

**Solutions:**

Yes, because the matrix  $A$  is invertible (since by inspection, it is full rank).

- (c) (**5 points**) Without writing a single equation to derive the result, determine the limiting state vector:

$$\lim_{n \rightarrow \infty} s[n].$$

Explain your reasoning in succinct, but clear and convincing English (no mathematical derivation!).

**Solutions:**

The limiting state vector is  $\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$ .

From the state diagram, you can see that  $s_1$  is absorbing and the other states are transient.

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- (d) (**5 points**) By referring only to one or more specific aspects of the structure of the state-transition matrix  $\mathbf{A}$ , and without any complicated mathematical derivations, determine the largest eigenvalue  $\lambda_1$ . Once you've inferred the largest eigenvalue  $\lambda_1$ , determine its corresponding eigenvector  $v_1$  using whatever method suits your taste—though you should be able to determine  $v_1$ , too, with little mathematical exertion.

If you cannot see how to infer  $\lambda_1$  from the structure of the matrix  $\mathbf{A}$ , you may still receive partial credit if you determine the eigenpair  $(\lambda_1, v_1)$  as part of your derivations in the next part. If you choose to do so, simply write in the space below "*See my work in the next part.*," and otherwise leave the space for this part blank. If you write anything more for this part, we will not grade any of your work for  $(\lambda_1, v_1)$  in the next part, and we will grade only what you've written for this part.

**Solutions:**

The largest eigenvalue is 1. Since  $\mathbf{A}$  is upper triangular, we can see the eigenvalues directly from the diagonal.

The corresponding eigenvector is  $v_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$ .

The easiest way to see this is that  $\mathbf{A}$  is a transition matrix, and the steady state is  $v_1$  which corresponds to  $\lambda = 1$ . You could also derive this by finding the null space of  $\mathbf{A} - I$ .

- (e) (**5 points**) Determine the remaining eigenpairs  $(\lambda_2, v_2)$  and  $(\lambda_3, v_3)$ , where  $\lambda_2 \geq \lambda_3$ .

**Solutions:**

The other eigenvalues are  $\lambda_2 = \frac{1}{2}, \lambda_3 = \frac{1}{4}$  from the diagonal.

Solving for the null space gives us  $v_2 = \begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix}$  and  $v_3 = \begin{bmatrix} 1 \\ -2 \\ 1 \end{bmatrix}$ .

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- (f) (5 points) Suppose the initial population of Technocrats is distributed equally among the three cities. That is,

$$s[0] = \begin{bmatrix} 1/3 \\ 1/3 \\ 1/3 \end{bmatrix}$$

Express the state vector as

$$s[n] = \alpha_1[n] v_1 + \alpha_2[n] v_2 + \alpha_3[n] v_3, \quad (1)$$

where  $\alpha_1[n]$ ,  $\alpha_2[n]$ , and  $\alpha_3[n]$  are appropriate time-dependent scalar functions that you *must determine in as explicit and numerically-specific a form as possible*. If you're unsure of your numerical answers to the previous parts, you may express  $\alpha_1[n]$ ,  $\alpha_2[n]$ , and  $\alpha_3[n]$  symbolically, but still in the simplest form possible.

Explain how your expression for this part is consistent with the limiting state vector

$$\lim_{n \rightarrow \infty} s[n]$$

that you obtained previously. In particular, explain which eigenvalues of  $\mathbf{A}$  influence the limiting state, and which are irrelevant.

**Solutions:** Recall that once we diagonalize  $\mathbf{A} = \mathbf{PDP}^{-1}$  then  $s[n] = \mathbf{A}^n s[0] = \mathbf{PD}^n \mathbf{P}^{-1} s[0]$ .

We have found the eigenvalues and eigenvectors above:

$$P = \begin{bmatrix} 1 & -1 & 1 \\ 0 & 1 & -2 \\ 0 & 0 & 1 \end{bmatrix}$$

$$D = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & 0 \\ 0 & 0 & \frac{1}{4} \end{bmatrix}$$

Then  $P^{-1} = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 2 \\ 0 & 0 & 1 \end{bmatrix}$ ,  $D^n = \begin{bmatrix} 1^n & 0 & 0 \\ 0 & \frac{1}{2}^n & 0 \\ 0 & 0 & \frac{1}{4}^n \end{bmatrix}$  and we multiply out to get:

$$s[n] = 1^n v_1 + \frac{1}{2}^n v_2 + \frac{1}{3} \left( \frac{1}{4} \right)^n v_3$$

Since the second and third terms are  $< 1$ , as  $n$  approaches infinity, the second and third terms approach zero, thus the only eigenvalue influencing the limiting state is the first term, which is consistent with our previous result from part c.

**11. Inverse Power Iteration (20 points)**

In homework, we introduced the method of Power Iteration to find the dominant eigenvector of a given matrix. In this problem, we'll explore a similar method, Inverse Power Iteration, and use it to estimate eigenvectors and eigenvalues of a given matrix.

In Inverse Power Iteration, we let  $\mathbf{A}$  be an  $n \times n$  matrix and  $\mathbf{B} = (\mathbf{A} - \mu\mathbf{I})^{-1}$  where  $\mu$  is some scalar (we get to pick this scalar) and  $\mathbf{I}$  is the  $n \times n$  identity matrix.  $\mathbf{B}$  must be constructed such that it is invertible for this method to work. We begin by making a guess  $\mu$  for one of  $\mathbf{A}$ 's eigenvalue and a guess  $b_0 \neq \vec{0}$  for the corresponding eigenvector. (Assume we never pick  $b_0$  as an eigenvector of  $\mathbf{B}$ .) At each iteration we perform the update:

$$\vec{b}_{k+1} = \frac{\mathbf{B}\vec{b}_k}{\|\mathbf{B}\vec{b}_k\|}$$

As  $k$  becomes large,  $\vec{b}_k$  converges to the eigenvector of  $\mathbf{B}$  that corresponds to the eigenvalue with the largest magnitude.

- (a) (10 points) Show that if  $\vec{x}$  is an eigenvector of  $\mathbf{A}$  with the corresponding eigenvalue  $\lambda$ , then  $\vec{x}$  is also an eigenvector of  $\mathbf{B}$  with eigenvalue  $\frac{1}{\lambda - \mu}$ .

**Solutions:** Here's one possible solution:

$$\begin{aligned} \mathbf{A}\vec{x} &= \lambda\vec{x} \\ \mathbf{A}\vec{x} - \mu\vec{x} &= \lambda\vec{x} - \mu\vec{x} \\ (\mathbf{A} - \mu\mathbf{I})\vec{x} &= (\lambda - \mu)\vec{x} \\ \mathbf{B}^{-1}\vec{x} &= (\lambda - \mu)\vec{x} \\ \frac{1}{\lambda - \mu}\vec{x} &= \mathbf{B}\vec{x} \end{aligned}$$

This was not the only correct solution – we were quite happy to see a couple other creative ways to successfully tackle this proof.

Here are some common misconceptions – incorrect statements or substitutions that we noticed in quite a few proofs (In general, proofs that made any of the below errors were structured in such a way that less than 5 points were awarded.):

- i. Substituting  $AB\vec{x}$  with  $B\lambda\vec{x}$ . In general, matrix multiplication is not commutative.
- ii. Substituting  $A$  with  $\lambda$  with no  $\vec{x}$  in sight. Equating a matrix to a scalar is bad. The correct approaches instead substitute  $A\vec{x}$  with  $\lambda\vec{x}$ .
- iii. Substituting  $A$  with  $\lambda\vec{x}$ . Again, we can only apply  $A\vec{x} = \lambda\vec{x}$  when there is a vector attached.
- iv. Substituting  $(A - \mu I)^{-1}$  with  $A^{-1} - (\mu I)^{-1}$ . In general, matrix inversion is not distributive.
- v. Substituting  $(A - \mu I)^{-1}\vec{x}$  with  $(A\vec{x} - \mu I\vec{x})^{-1}$ . In general, we cannot distribute a vector into a matrix inversion. (What does it mean to take the inverse of a vector, namely  $(A\vec{x} - \mu I\vec{x})^{-1}$ ?)
- vi. Stating  $B = \frac{1}{\lambda - \mu}$ . Again, this is equating a matrix to a scalar. The correct statement looks like  $B\vec{x} = \frac{1}{\lambda - \mu}\vec{x}$ .

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- (b) (5 points) Let  $\mathbf{A}$  have unique eigenvalues  $\lambda_1, \lambda_2, \dots, \lambda_i$ . For a given choice of  $\mu$ , where  $\mu \neq \lambda_i$  show that with large  $k$ ,  $\vec{b}_k$  converges to the eigenvector of  $\mathbf{A}$  whose eigenvalue  $\lambda_i$  is closest to  $\mu$ .

**Solutions:**

In part (a), we showed that  $\mathbf{B}$ 's eigenvalues can be expressed as  $\frac{1}{\lambda_i - \mu}$ , where  $\lambda_i$  is an eigenvalue of  $\mathbf{A}$ . The eigenvalue of  $\mathbf{B}$  with the largest magnitude equivalently has the smallest  $|\lambda_i - \mu|$ . Because  $\vec{b}_k$  converges to the eigenvector of  $\mathbf{B}$  that corresponds with  $\mathbf{B}$ 's eigenvalue with largest magnitude, and by part (a),  $\vec{b}_k$  converges to the eigenvector of  $\mathbf{A}$  that corresponds to the  $\lambda_i$  that is closest to  $\mu$ .

In other words, power iteration maximizes  $\frac{1}{|\lambda_i - \mu|}$ , which is equivalent to minimizing  $|\lambda_i - \mu|$ , which means that  $\lambda_i$  will be the eigenvalue of  $\mathbf{A}$  closest to  $\mu$ .

- (c) (5 points) Let  $\mathbf{A}$  be a PageRank transition matrix. To find its steady state behavior we're looking for  $\mathbf{A}$ 's eigenvector that corresponds to the eigenvalue  $\lambda = 1$ . Argue that we should **not** use  $\mu = 1$  to perform inverse power iteration to estimate  $\mathbf{A}$ 's eigenvector.

**Solutions:**

If we choose  $\mu = \lambda = 1$ , then  $\mu$  is an eigenvalue of  $A$ , so  $\det(\mathbf{A} - \mu\mathbf{I}) = \det(\mathbf{A} - \lambda\mathbf{I}) = 0$ , which means  $\mathbf{A} - \lambda\mathbf{I}$  is no longer invertible. If  $\mathbf{A} - \lambda\mathbf{I}$  is not invertible,  $\mathbf{B}$  is undefined.

By this result and part (b),  $\mu$  should be chosen as close to the desired  $\lambda$  as possible, but not exactly  $\lambda$ .



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## 12. Patient Classification (15 points)

Consider a set of patients. Patient  $i$  can be represented by an attribute vector  $\vec{x}^{(i)} = \begin{bmatrix} x_1^{(i)} \\ x_2^{(i)} \end{bmatrix}$  as well as a known value  $y^{(i)} \in \{+1, -1\}$  indicating whether they have the disease Dragon Pox. We want to design a simple classifier that can use the information from the data we have in order to predict whether a patient with attributes  $x_1^{(i)}$  and  $x_2^{(i)}$  and unknown diagnosis status has Dragon Pox. To do this, we will use our knowledge of least squares linear regression. We would like to design a linear function

$$f(\vec{x}^{(i)}) = \vec{w}^T \vec{x}^{(i)}$$

that takes in a vector  $\vec{x}^{(i)}$  for a patient  $i$  and computes  $y^{(i)} = \text{sign}(f(\vec{x}^{(i)}))$  to predict whether the patient has Dragon Pox.

- (a) (10 points) Given that we are trying to minimize  $\left[ f(\vec{x}^{(i)}) - y^{(i)} \right]^2$  for each patient  $i$  and classification value  $y^{(i)}$ , what is the overall cost function  $J(\vec{w})$  we are trying to minimize if we have  $n$  patients? Given a matrix  $\mathbf{X}$  with each row vector corresponding to a patient and each column vector corresponding to an attribute and a vector  $\vec{y}$  corresponding to the patient's illness status, what is the vector that minimizes this cost function? You may define the cost function in terms of a sum of individual terms, or as a matrix expression.

**Solutions:**

$$J(\vec{w}) = \sum_{i=1}^n (y^i - w^T x^{(i)})^2$$

is the cost function. We could write this as:

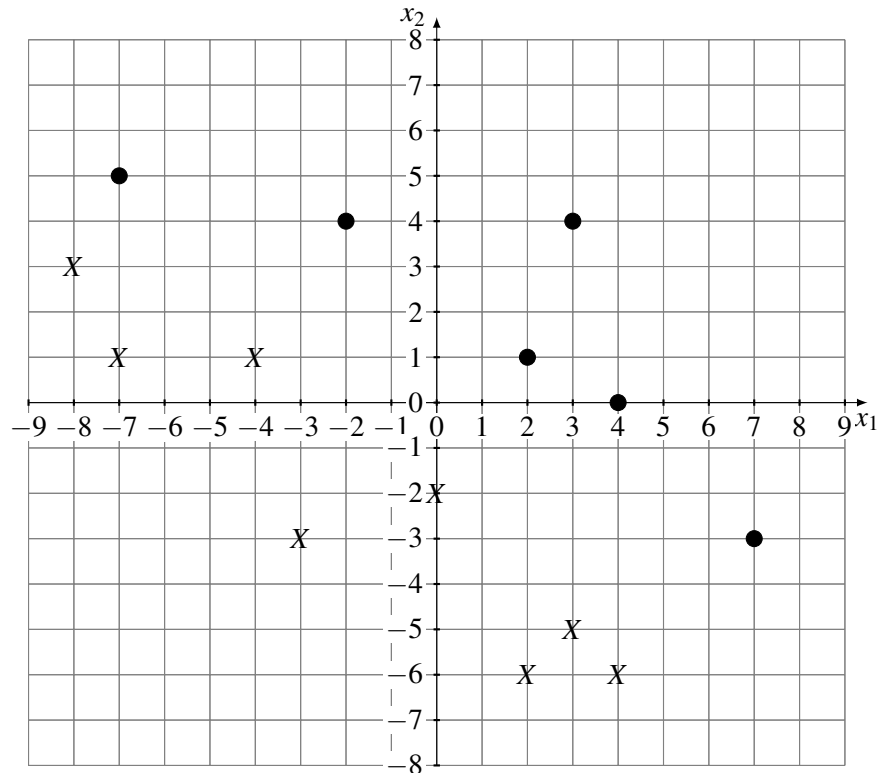
$$J(\vec{w}) = (\mathbf{X}\vec{w} - \vec{y})^T (\mathbf{X}\vec{w} - \vec{y})$$

The optimal vector  $\vec{w}$  is:

$$\vec{w} = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \vec{y}$$

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- (b) (5 points) Suppose we have brand new set of data points as shown on the graph below. Dots represent positive diagnoses (+1) and crosses represent negative diagnoses (-1).



Let  $w = [2, 3]^T$ . Draw the line corresponding to the decision boundary on the graph.

Given the following information, predict whether each patient has the disease. Fill in the last column of the table with "yes", "no", or "inconclusive".

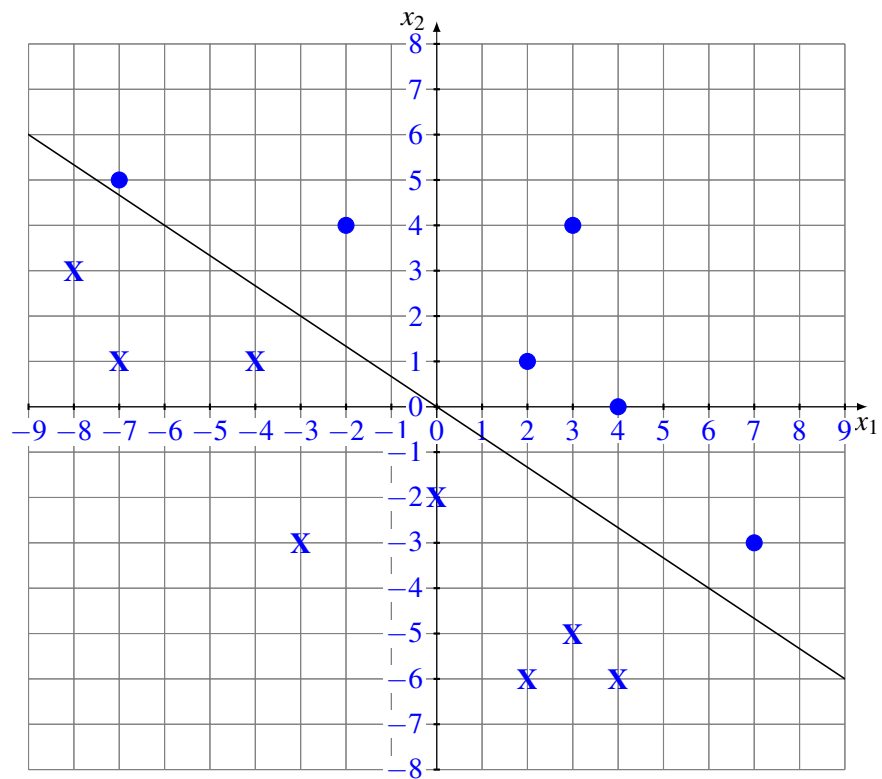
Patient	$x_1$	$x_2$	Disease?
1	1	0	
2	-6	1	
3	-5	-5	
4	9	-6	

**Solutions:** Since 0 is the boundary for classifying a patient with or without a disease, set  $f(x) = 0$

$$f(x) = w^T x^{(i)}$$

$$0 = 2x_1 + 3x_2$$

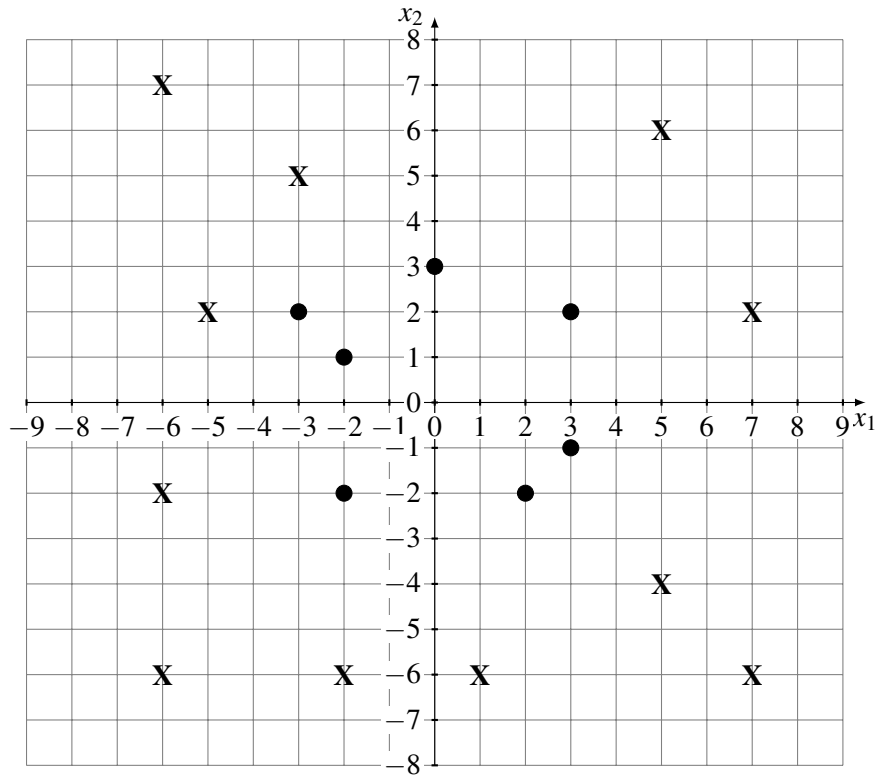
$$x_2 = \frac{-2}{3}x_1$$



A patient is predicted to have the disease if  $f(x) > 0$ , or alternatively above the decision boundary on the graph. Substituting values in the function or using the graph results in the following table:

Patient	$x_1$	$x_2$	Disease?
1	1	0	yes
2	-6	1	no
3	-5	-5	no
4	9	-6	inconclusive

(c) (5 points) Suppose the patient data looked like this:



Given that we still know our original attribute vector for each patient, how can we change it to classify this data correctly, such that their classes can be separated by a circle centered at the origin? Fill in the blanks with the new feature vector below:

Remember that we would like to design a linear function  $f(\vec{x}^{(i)}) = \vec{w}^T \vec{x}^{(i)}$  such that  $y^{(i)} = \text{sign}(f(\vec{x}^{(i)}))$ .

$$\vec{x}^{(i)} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$\vec{x}_{\text{new}}^{(i)} = \begin{bmatrix} \text{_____} \\ \text{_____} \end{bmatrix}$$

**Solutions:** Since the decision boundary is a circle around the origin with a certain radius, we would need the features  $1, x_1^2 + x_2^2$

$$\vec{x}_{\text{new}} = \begin{bmatrix} x_1^2 + x_2^2 \\ 1 \end{bmatrix}$$

You may use this page for scratch work but **it will not be graded.**