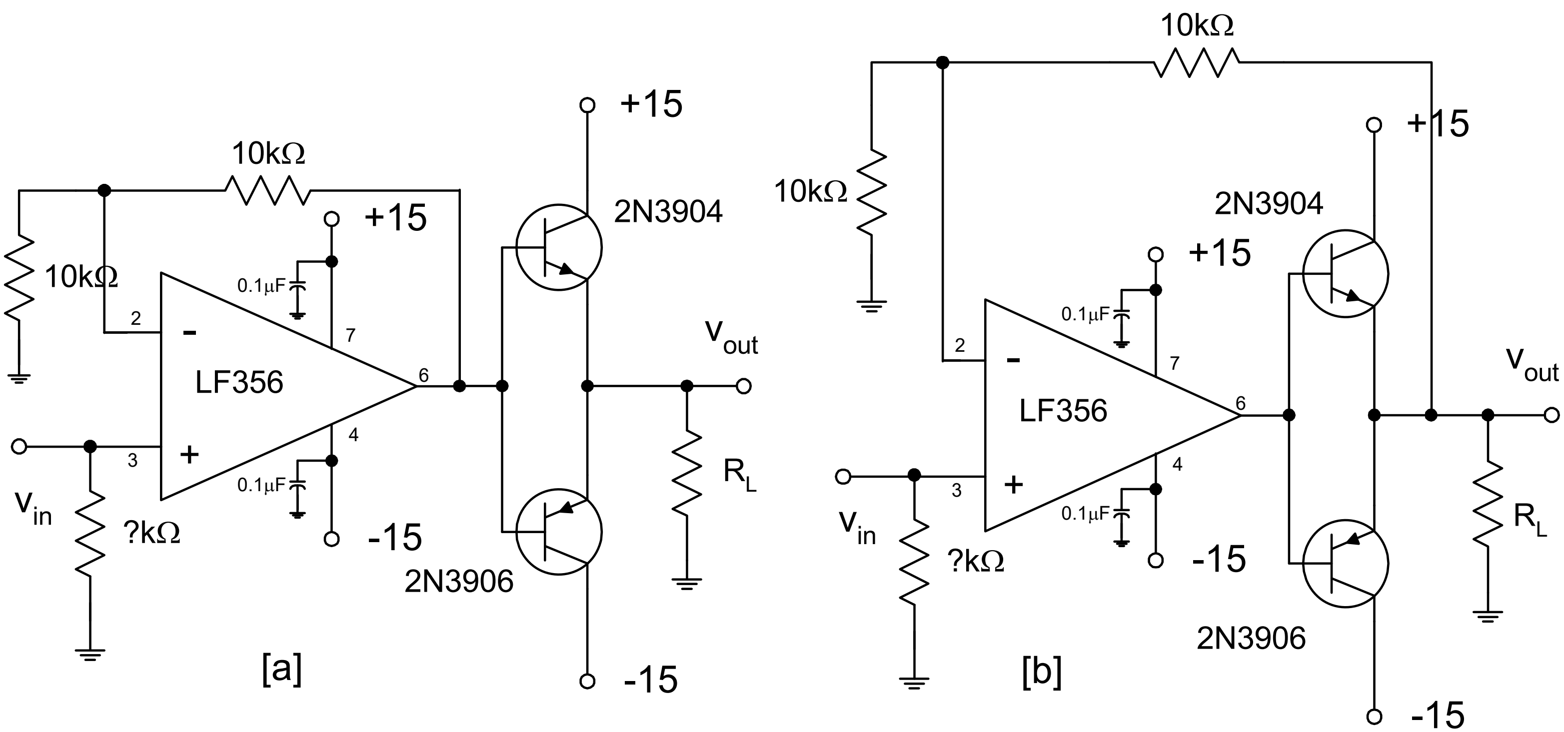
- Amplifiers: Class A, B, AB, D
- Op-amp Application: ECG

Acknowledgements:
Ron Roscoe

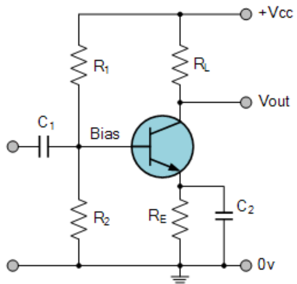
Crossover Distortion (hole)



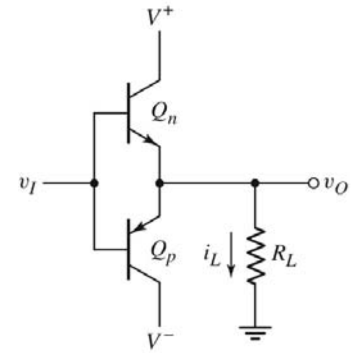
Why is [b] better?

Amplifier Classification

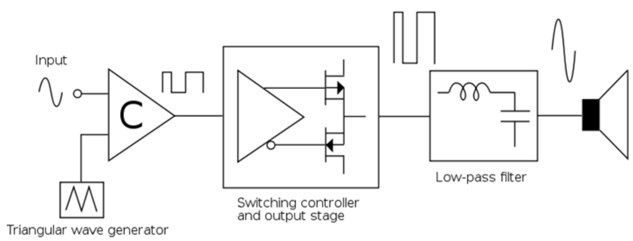
- Class A: output transistors are biased with a quiescent current – common emitter



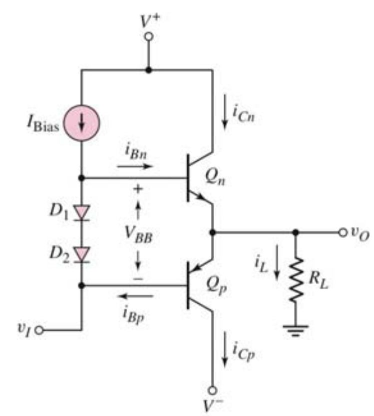
- Class B: output transistors conduct for only one half of each sine wave input - push pull



- Class D: output transistors are switched on/off with PWM*



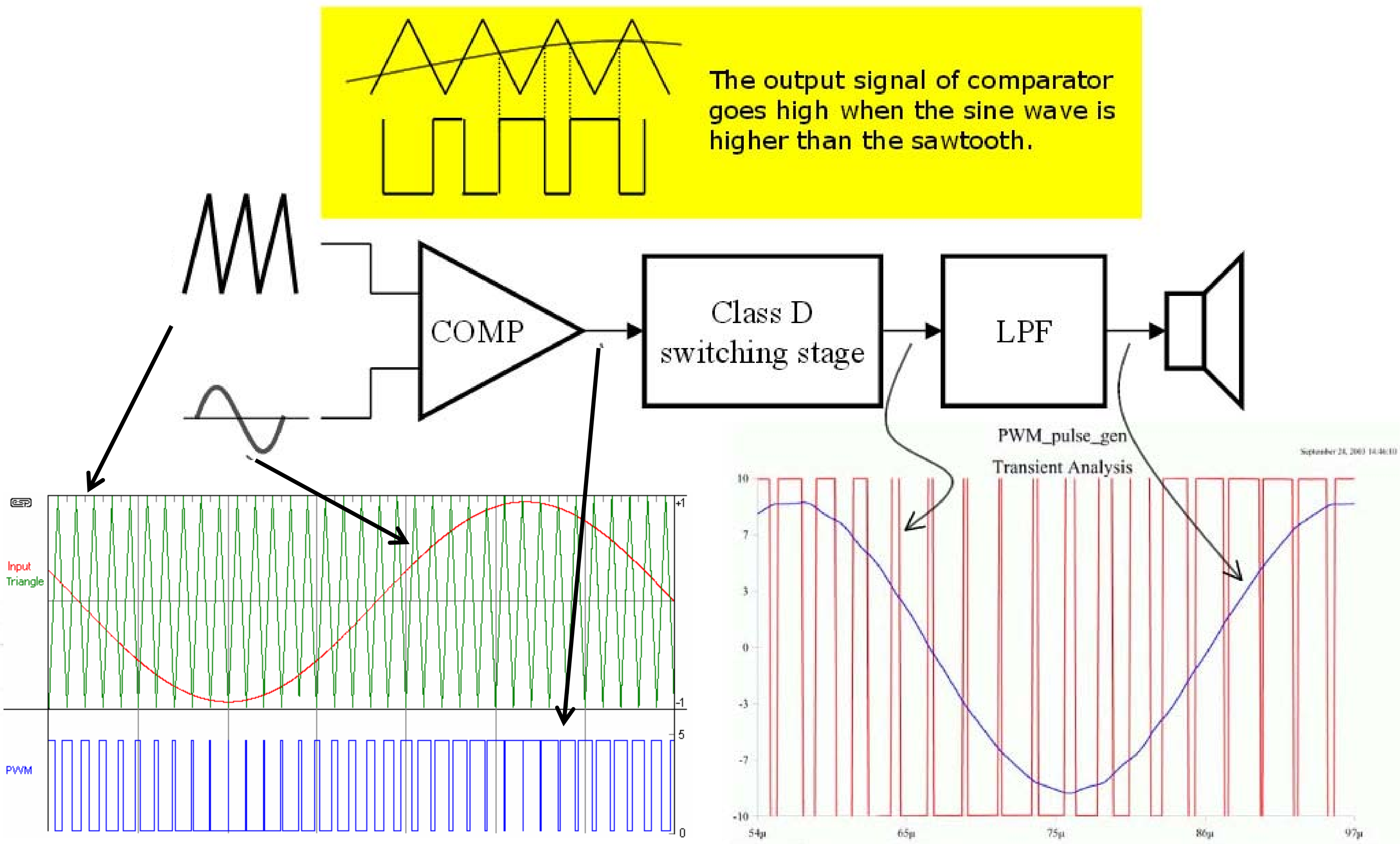
- Class AB: output transistors are biased at a small quiescent current



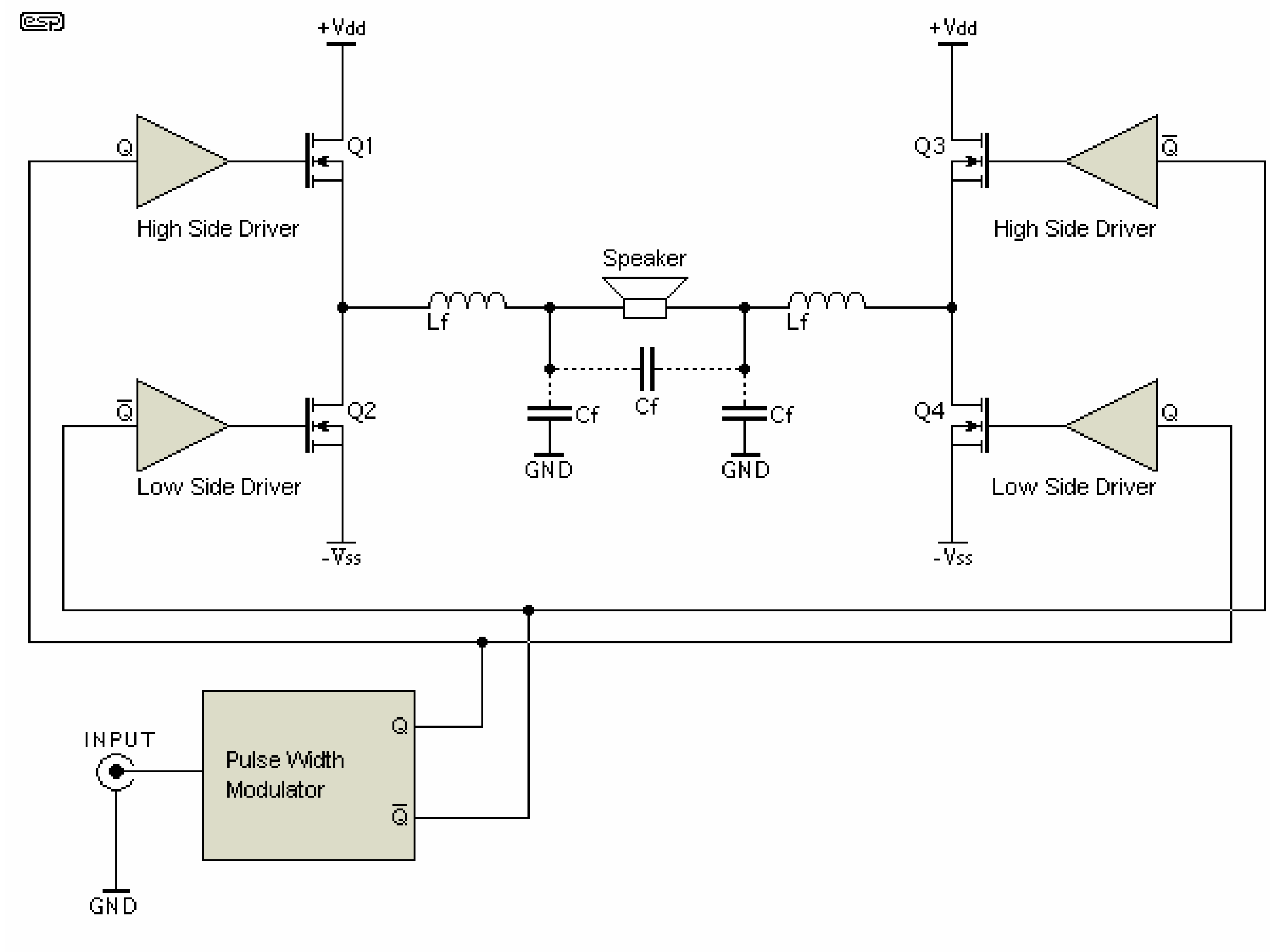
- Class G: output transistors operated with multiply power supply rails

* http://upload.wikimedia.org/wikipedia/commons/thumb/4/4c/Pwm_amp.svg/800px-Pwm_amp.svg.png

Basic PWM Operation

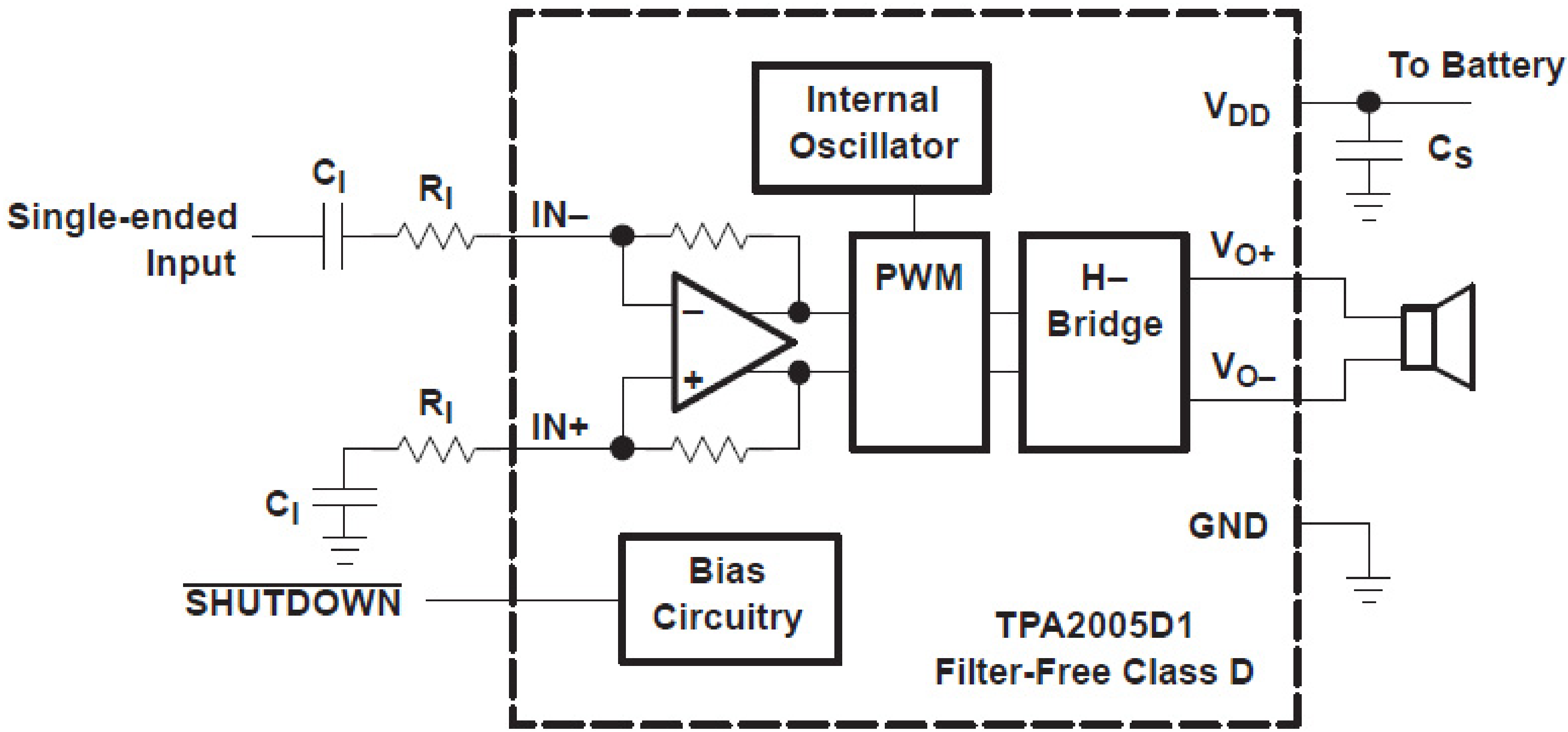


Class D Output Stage*

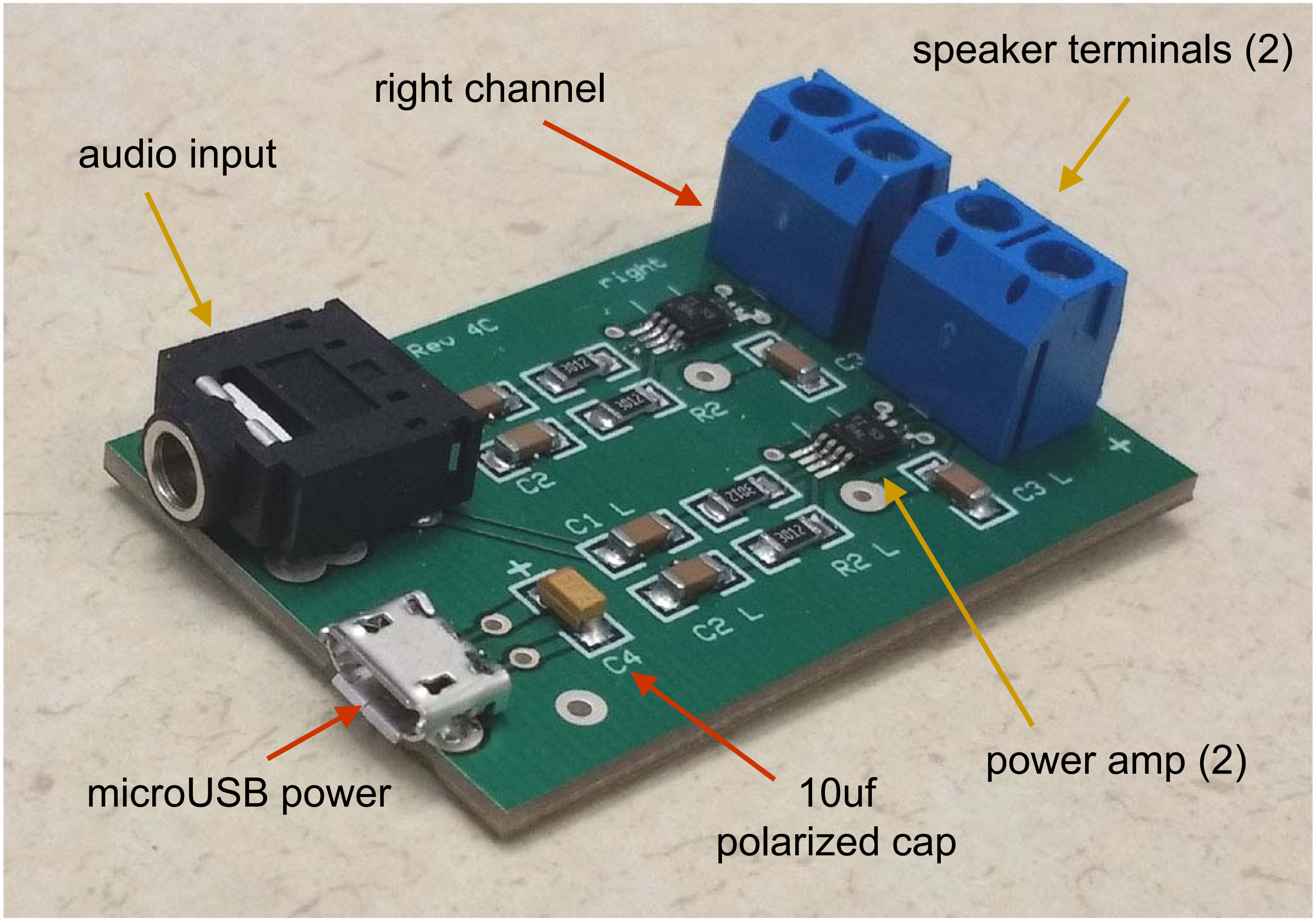


*sound.wethost.com/pwm.htm

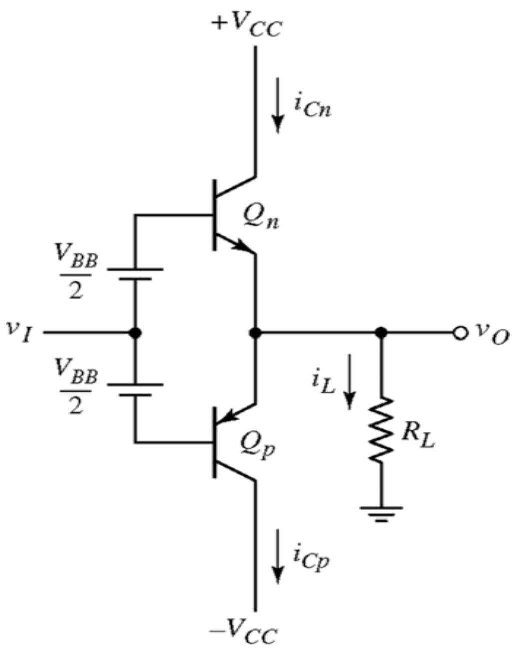
TPA2005 – Integrated Class D Amplifier
Surface Mount

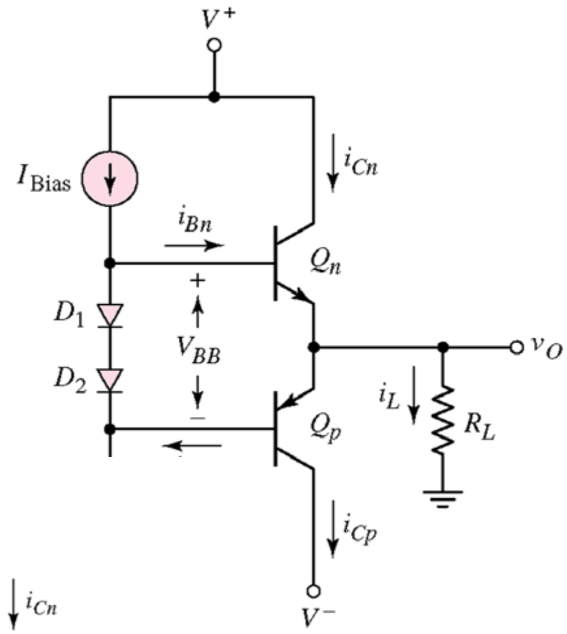


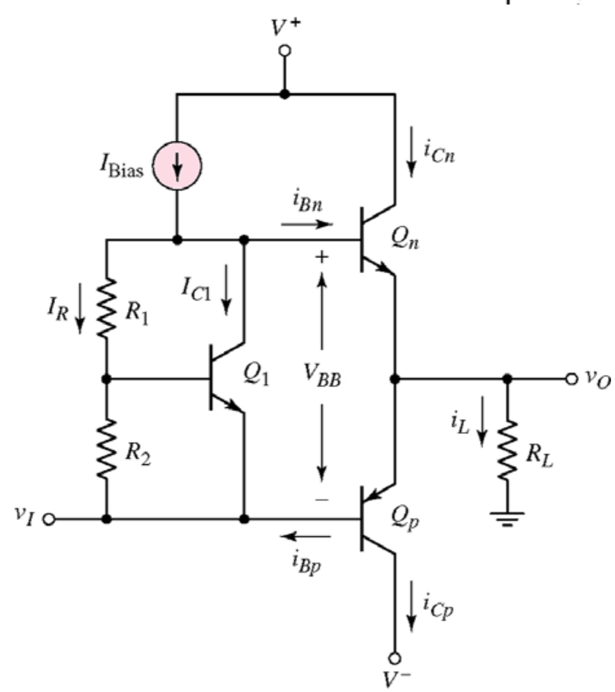
USB Power Amplifier



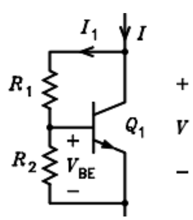
Class AB Biasing



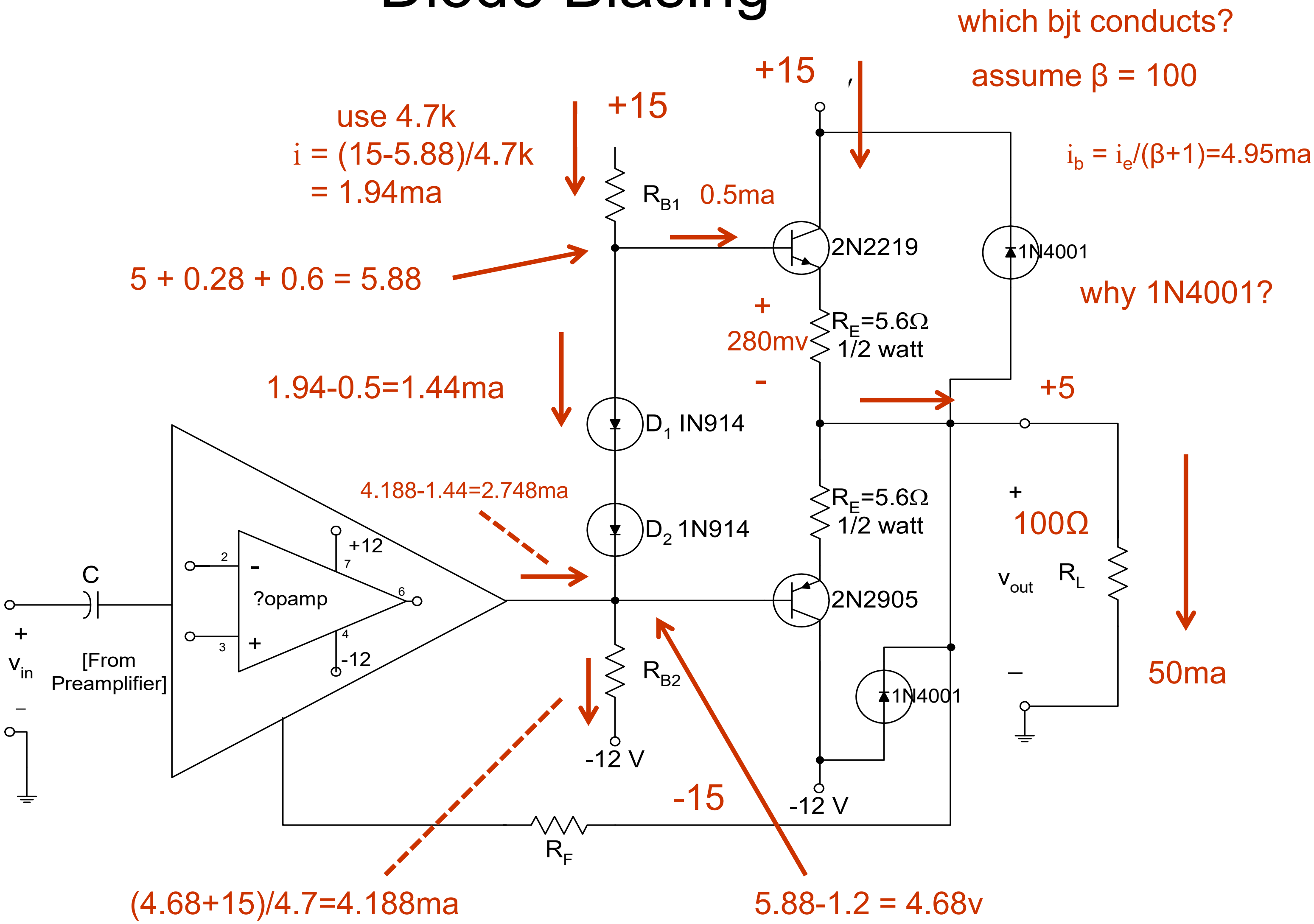




$$V = \frac{(R_1 + R_2)}{R_2} V_{BE}$$



Diode Biasing



Cardiac Electrophysiology

- Contraction of the heart results from depolarization and polarization (change in voltage) of myocardial cells.
- Sinoatrial (SA) node acts as pacemaker initiates atrial depolarization.

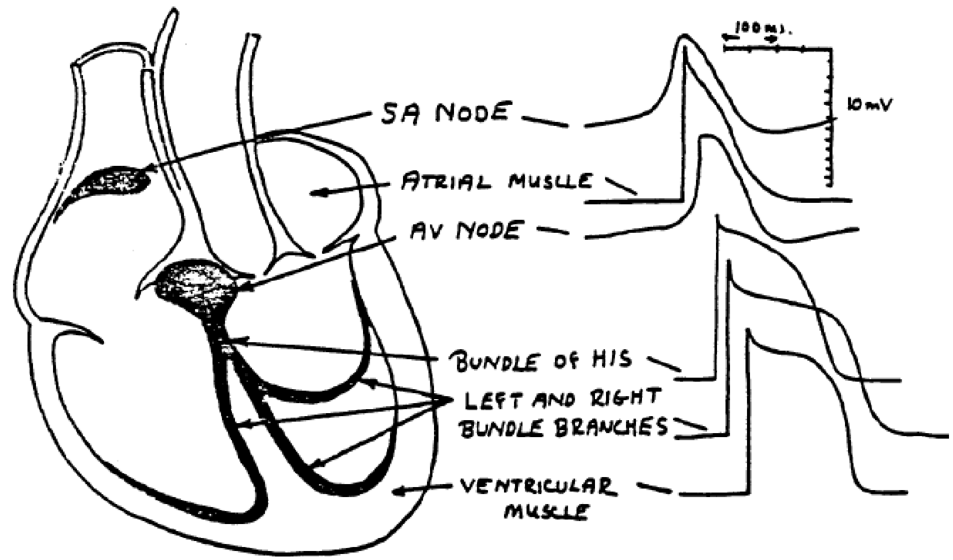


Diagram from 6.022

- Electrical signal propagates to the ventricles by the atrioventricular (AV) node through a specialized conducting tissue, the Bundle of His.
- Voltage sensed by electrodes on skin surface typically 0.5 - 2.0 millivolts.

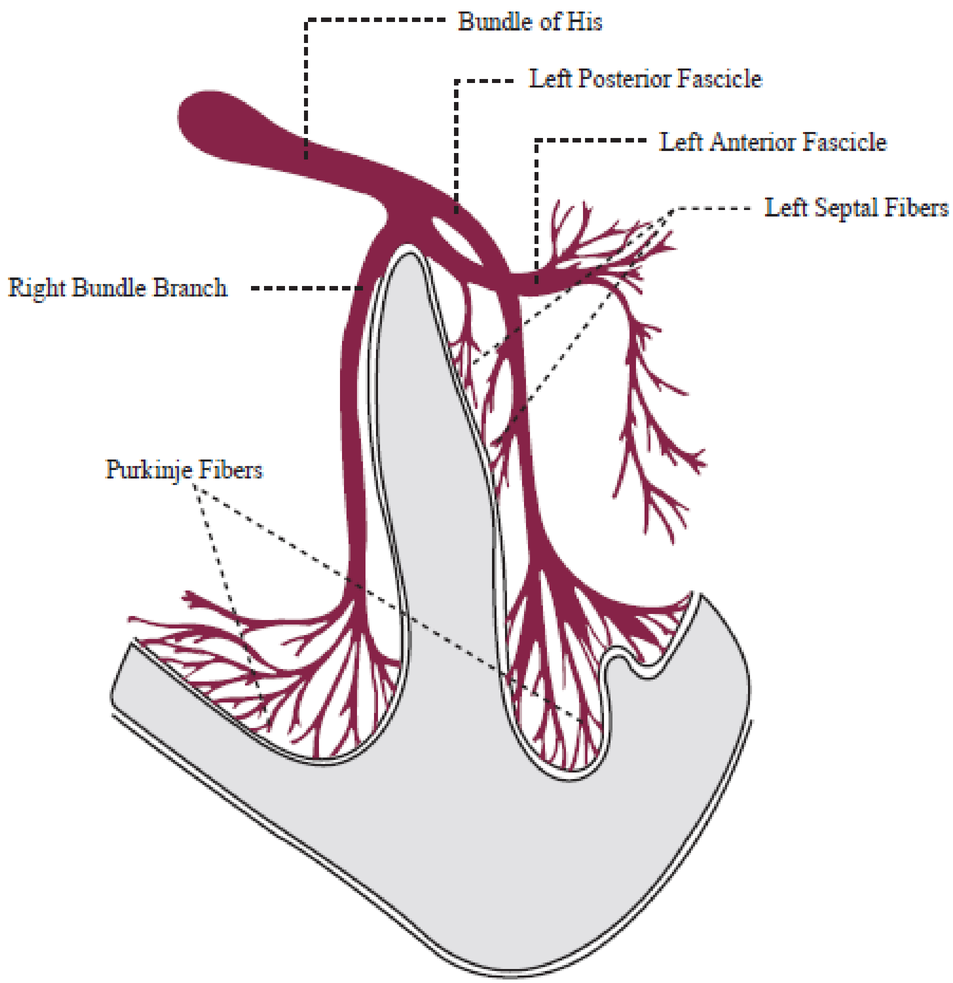


Figure by MIT OCW. After M. J. Goldman, *Principles of Clinical Electrocardiography.* 8th ed (1973), p. 37.

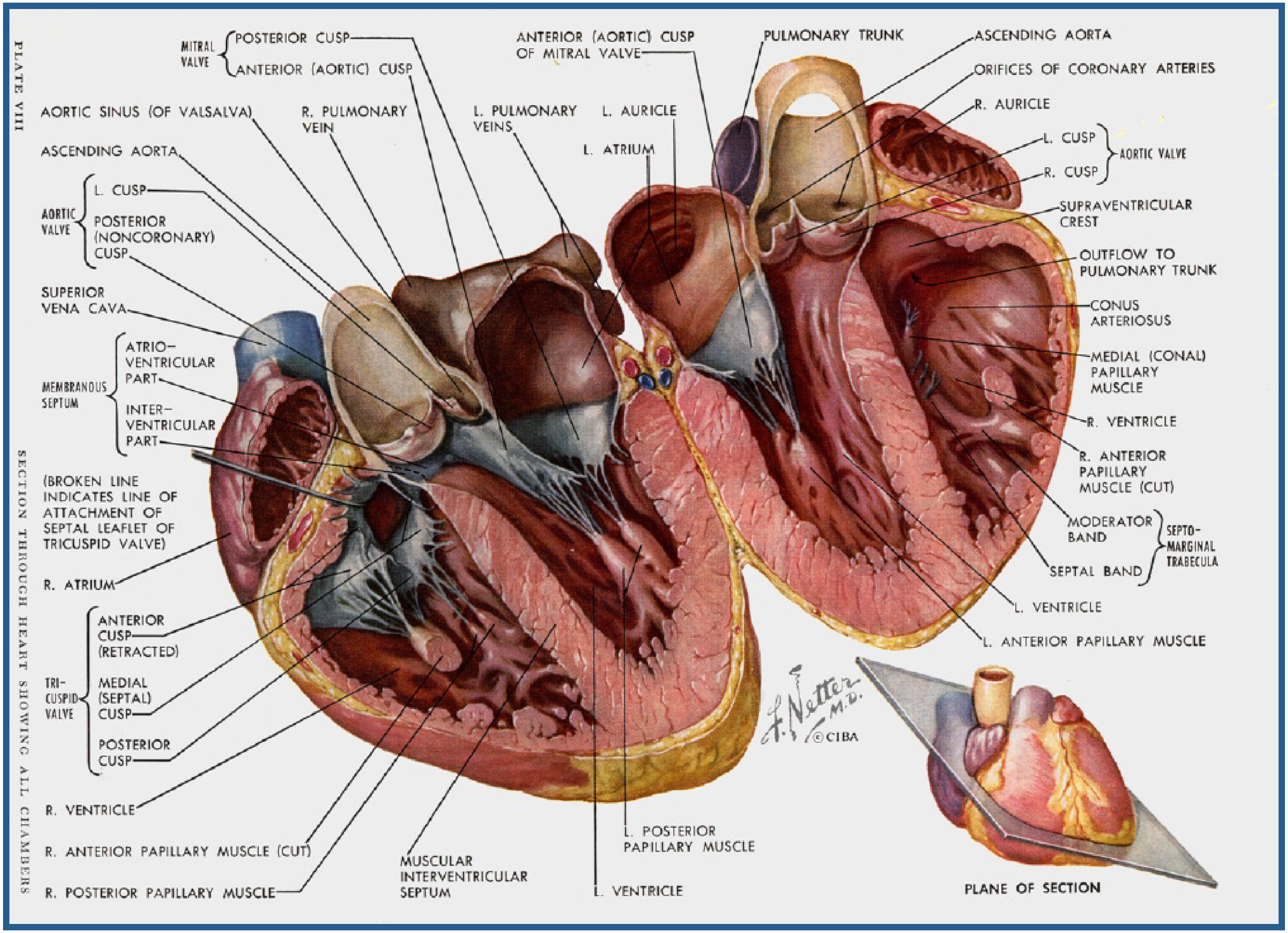


PLATE VIII
SECTION THROUGH HEART SHOWING ALL CHAMBERS
MITRAL VALVE
POSTERIOR CUSP
ANTERIOR (AORTIC) CUSP
ANTERIOR (AORTIC) CUSP OF MITRAL VALVE
PULMONARY TRUNK
ASCENDING AORTA
ORIFICES OF CORONARY ARTERIES
R. AURICLE
L. CUSP
R. CUSP
AORTIC VALVE
SUPRAVENTRICULAR CREST
OUTFLOW TO PULMONARY TRUNK
CONUS ARTERIOSUS
MEDIAL (CONAL) PAPILLARY MUSCLE
R. VENTRICLE
R. ANTERIOR PAPILLARY MUSCLE (CUT)
MODERATOR BAND
SEPTAL BAND
SEPTO-MARGINAL TRABECULA
L. VENTRICLE
L. ANTERIOR PAPILLARY MUSCLE
AORTIC SINUS (OF VALSALVA)
R. PULMONARY VEIN
L. PULMONARY VEINS
L. AURICLE
L. ATRIUM
ASCENDING AORTA
AORTIC VALVE
L. CUSP
POSTERIOR (NONCORONARY) CUSP
SUPERIOR VENA CAVA
MEMBRANOUS SEPTUM
ATRIO-VENTRICULAR PART
INTER-VENTRICULAR PART
(BROKEN LINE INDICATES LINE OF ATTACHMENT OF SEPTAL LEAFLET OF TRICUSPID VALVE)
R. ATRIUM
TRI-CUSPID VALVE
ANTERIOR CUSP (RETRACTED)
MEDIAL (SEPTAL) CUSP
POSTERIOR CUSP
R. VENTRICLE
R. ANTERIOR PAPILLARY MUSCLE (CUT)
R. POSTERIOR PAPILLARY MUSCLE
MUSCULAR INTERVENTRICULAR SEPTUM
L. VENTRICLE
L. POSTERIOR PAPILLARY MUSCLE
F. Netter M.D.
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PLANE OF SECTION

"Electric Current" in the Body

- A cell normally is polarized (excess of Na+ in the extracellular space; excess of K+ intracellular space);

- Movement of ions leads to easing of electrochemical gradients, causing a lessening of the magnitude of polarization (i.e., depolarization).

- Key points:
  - Current is propagated through the myocardium;
  - Current does not refer to movement of electrons, but rather movement of ions;
  - Movement of ions causes a "current dipole" – movement of dipoles throughout myocardium

13

Dipole Field In Myocardial Cell

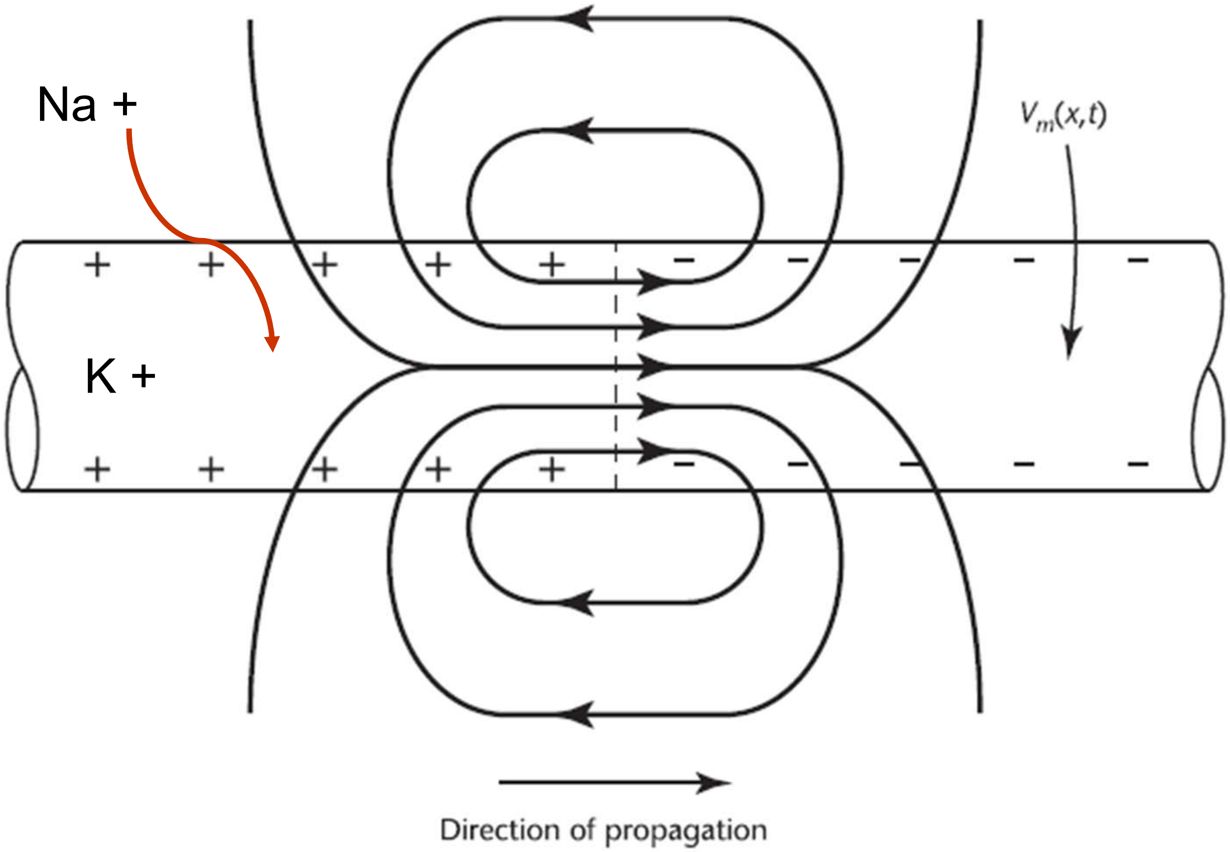


Figure 1.2 The dipole field due to current flow in a myocardial cell at the advancing front of depolarization. V_m is the transmembrane potential. (*From*: [2]. © 2004 MIT OCW. Reprinted with permission.)

Terminology

- Surface potential – the electric potential energy at a point arising from the surface charge

- ECG Lead – difference in the surface potential at two points. Uses 10 electrodes.

- 12 leads place on body & orientation
  - Right to Left,
  - Superior to Inferior,
  - Anterior to Posterior
  - RA = right arm; LA = left arm, LL = left foot

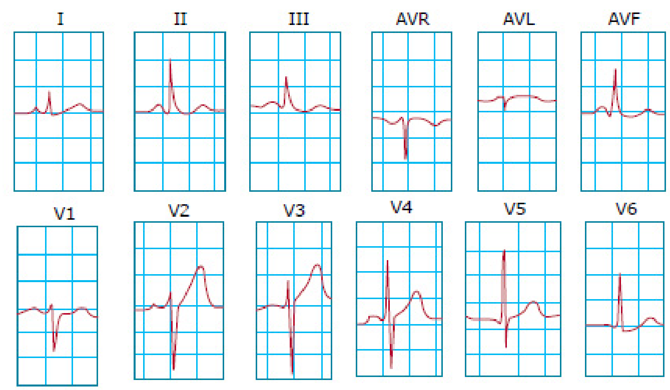
- Bipolar limb leads (frontal plane):
  - Lead I: RA (-) to LA (+) (Right Left, or lateral)
  - Lead II: RA (-) to LL (+) (Superior Inferior)
  - Lead III: LA (-) to LL (+) (Superior Inferior)

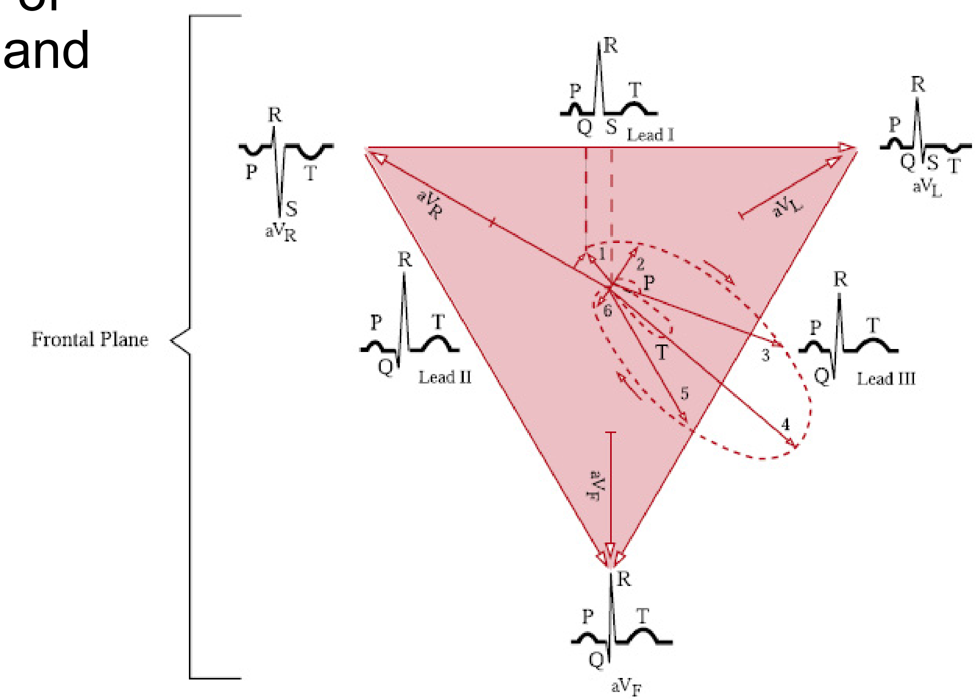
- Augmented unipolar limb leads (frontal plane):
  - Lead aVR: RA (+) to [LA & LL] (-) (Rightward)
  - Lead aVL: LA (+) to [RA & LL] (-) (Leftward)
  - Lead aVF: LL (+) to [RA & LA] (-) (Inferior)

- Unipolar (+) chest leads (horizontal plane):
  - Leads V1, V2, V3: (Posterior Anterior)
  - Leads V4, V5, V6:(Right Left, or lateral)

Medical Grade ECG

- Medical grade ECG uses 6 or 10 monitoring electrodes.
- Three lead ECG circuit used to show a ECG signal and demonstration operation of instrumentation op-amp and low pass filter.



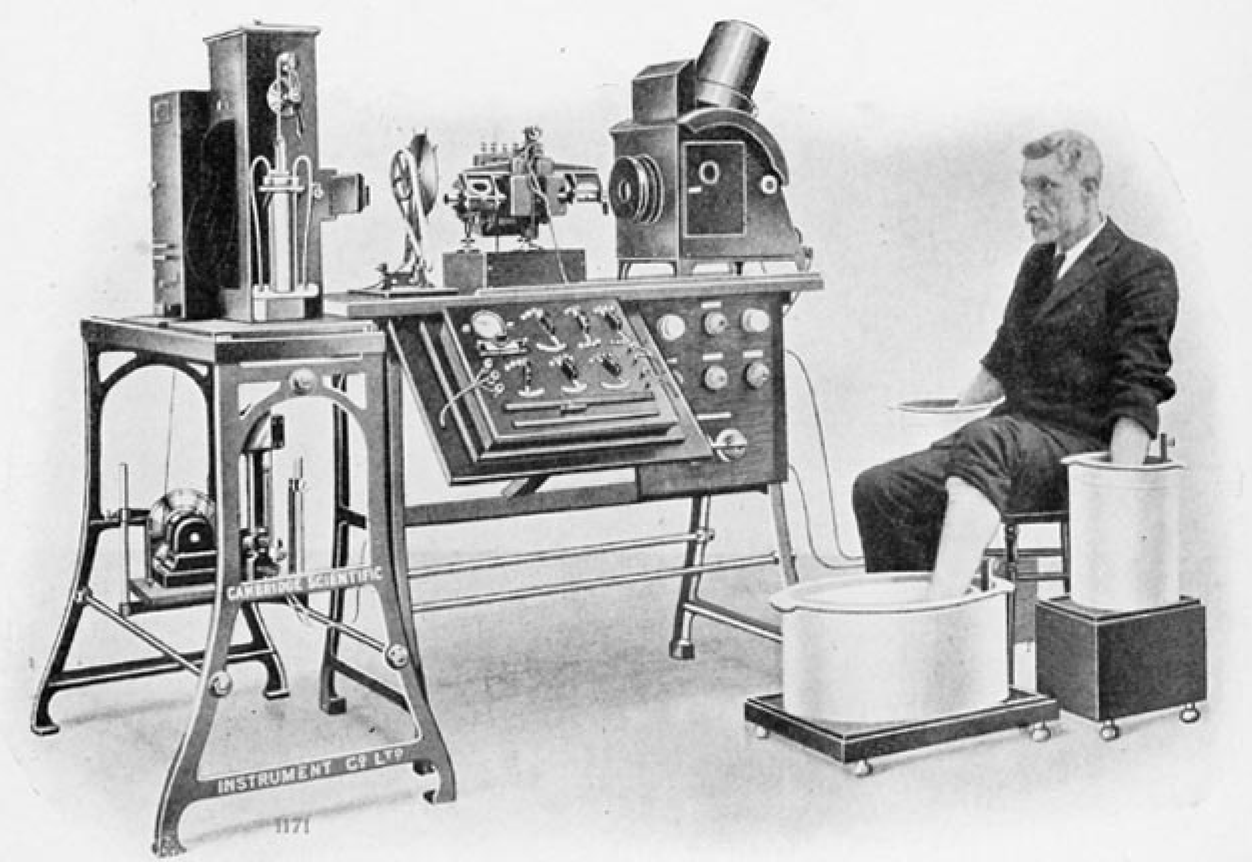


6.022 OCW Figure

ECG Measurement

- Human tissue is electrically conductive; necessary for muscle control
- Place electrodes at multiple points on the body.
  - Electrode is metal contact with conductive gel and an adhesive backing.
  - Hand lotion and KY jelly are conductive
- Measure potential difference (voltage) between two points.

The Nobel Prize Medicine 1924 Willem Einthoven
"discovery of the mechanism of the electrocardiogram"



PHOTOGRAPH OF A COMPLETE ELECTROCARDIOGRAPH, SHOWING THE MANNER IN WHICH THE ELECTRODES ARE ATTACHED TO THE PATIENT, IN THIS CASE THE HANDS AND ONE FOOT BEING IMMERSED IN JARS OF SALT SOLUTION

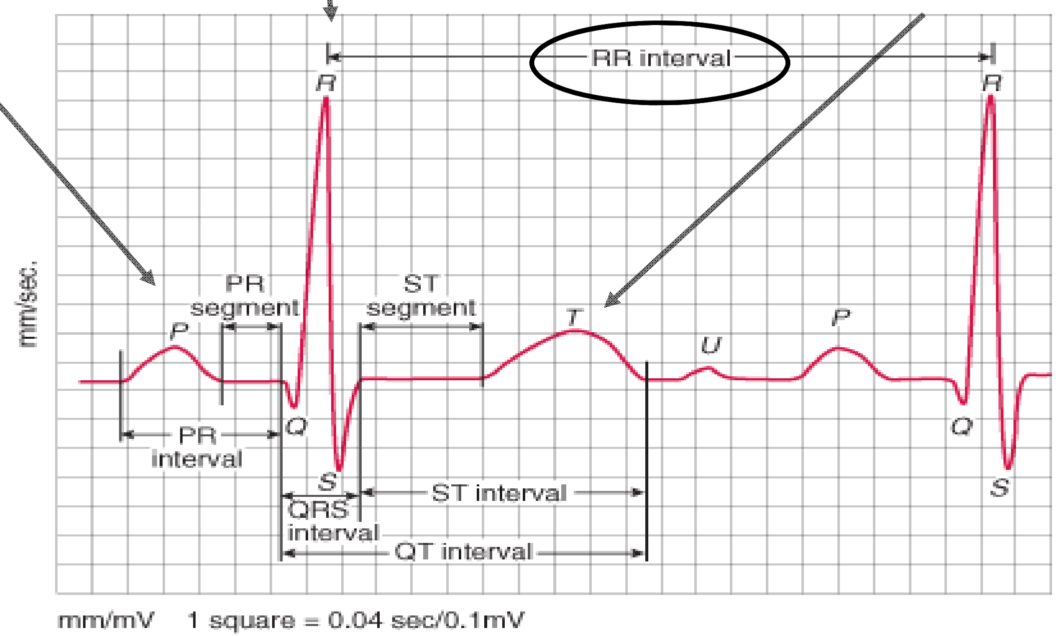

Goldfinger

ECG Characteristics

QRS complex: ventricular contraction

P wave: atrial contraction

T wave: ventricular recovery
repolarization

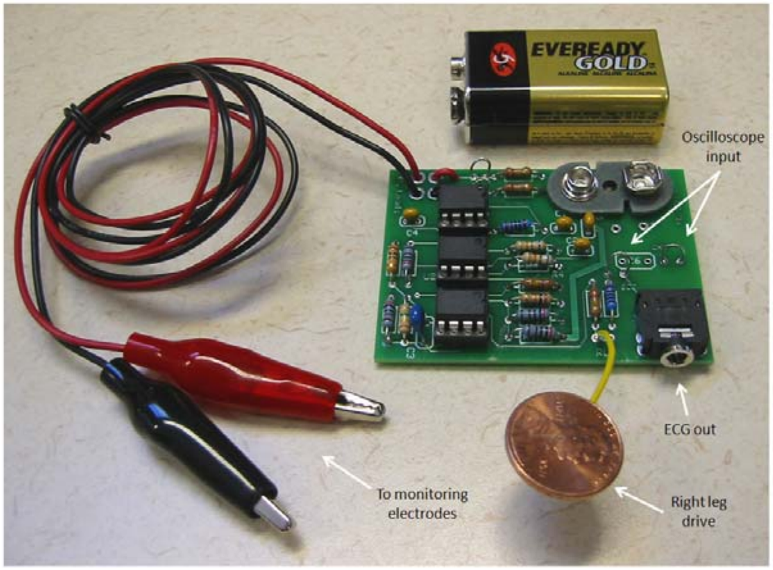


Functional ECG Design - Uninspired

- Dual supply op-amp, instrumentation amplifier
- Oscilloscope display
- Data export for MATLAB analysis
- Or AD interface to PC

ECG Circuit Design Goals

- Powered by 9V battery for safety
- Use inexpensive commercial parts
- Use thru hole two layer PCB
- Display ECG (lead 1) signal
- Direct attach to PC for demonstration and analysis



Used in 6.03 lab

Where is my ECG?

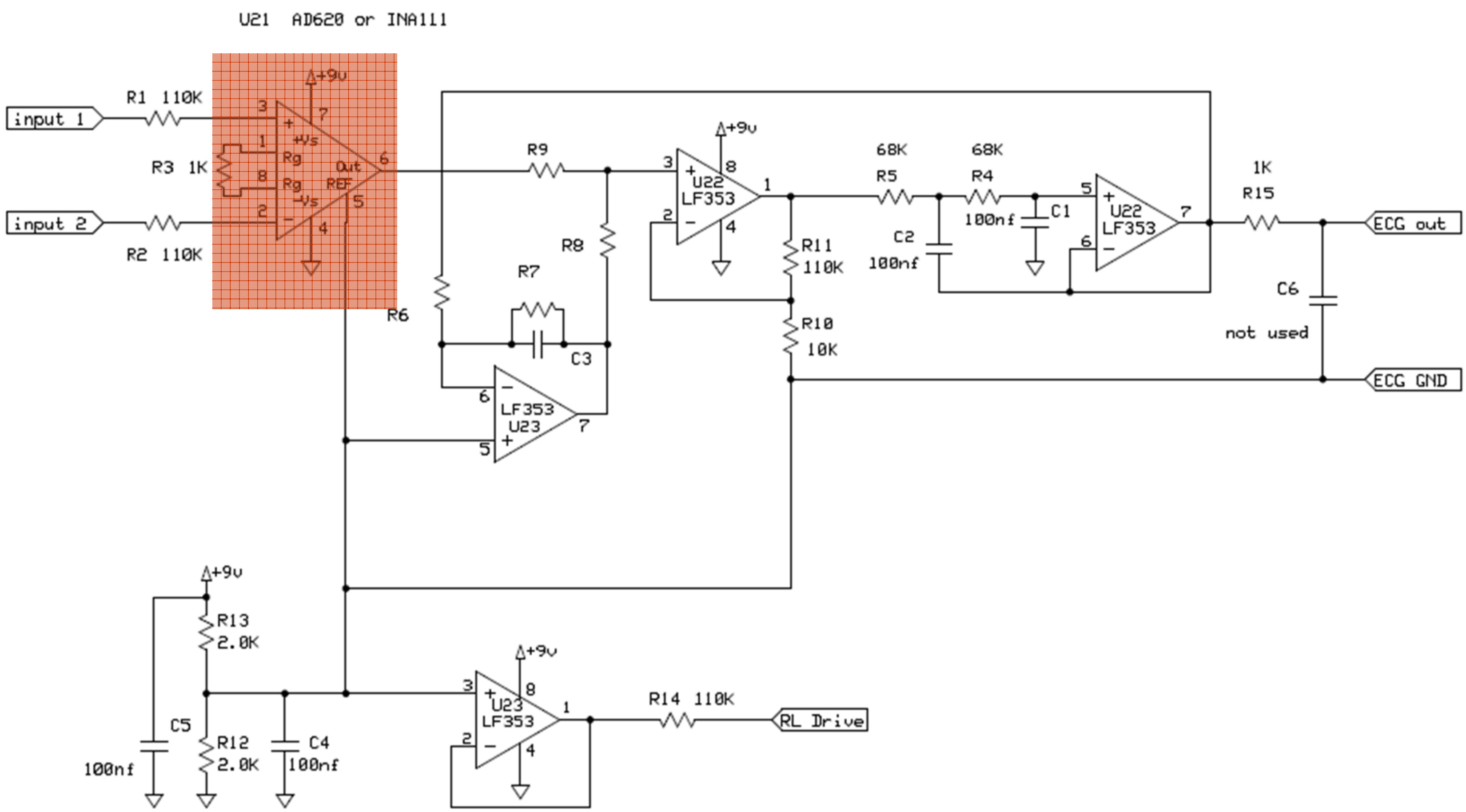
Skin Signal Composition

- Electromagnetic interference (EMI) and other noise pickup. Common mode and differential mode noise
- 50-60hz ac line noise
- ECG Heart signal ~ 1mv
- DC offset (signals originate from different parts of the body) ~ up to 500mv

ECG Signal Processing Steps

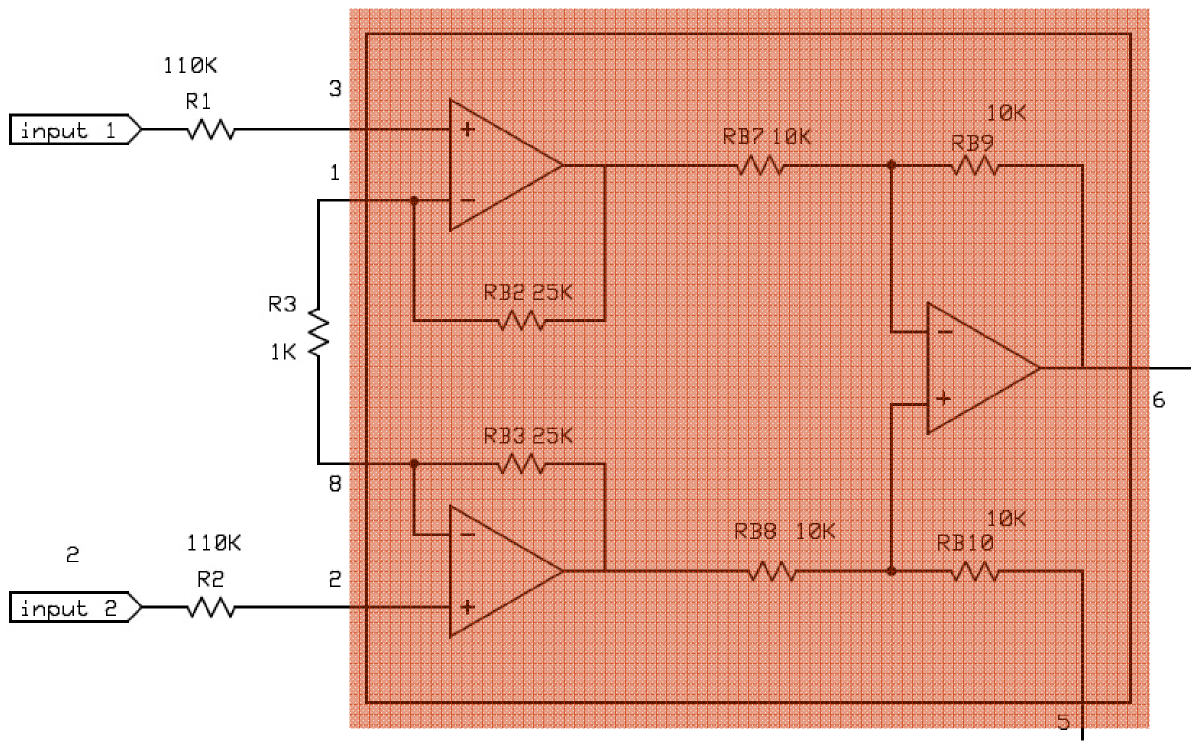
- Amplify signal from electrodes
- Remove common mode noise, amplify signal
- Remove noise above 23hz with low pass filter
- Apply bias for single supply operation and improve common mode rejection
- Compensate for DC offset

ECG Board

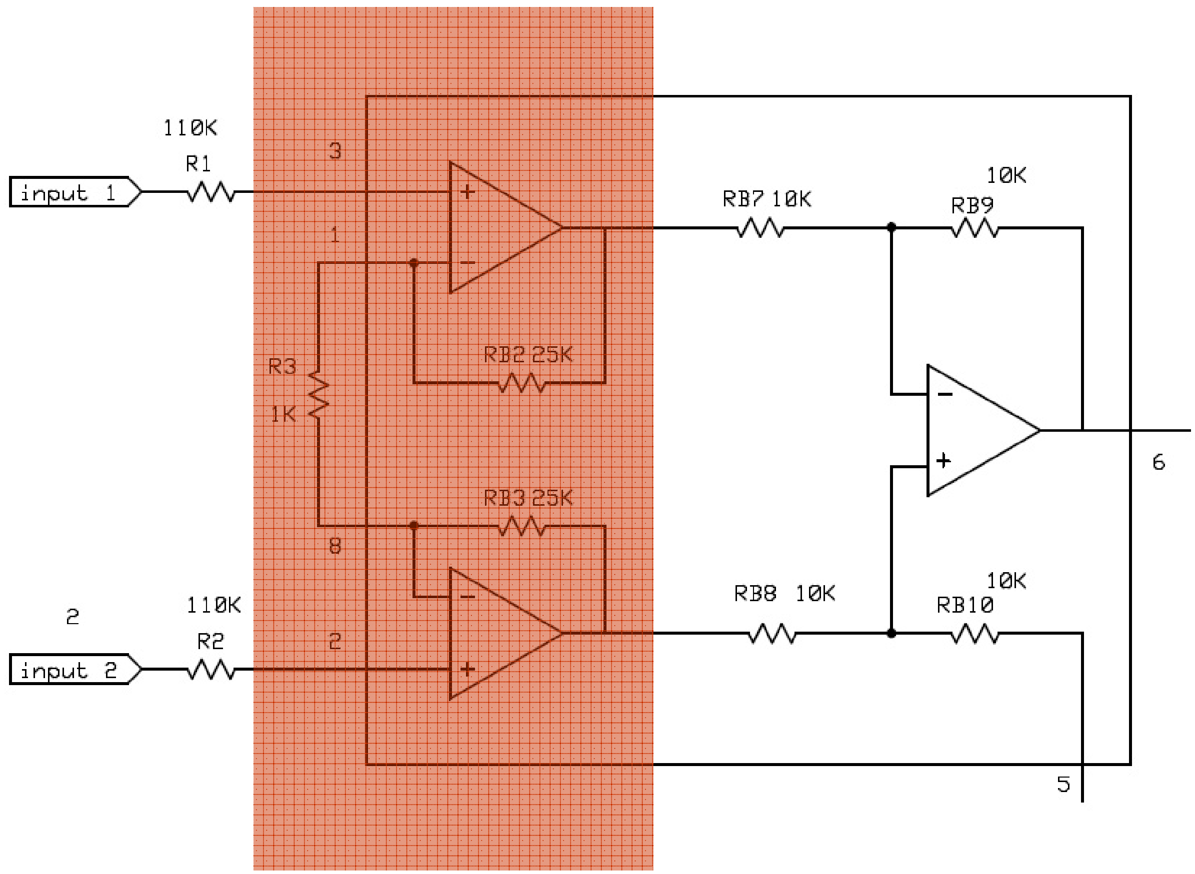


U21 AD620 or INA111
+9v
R1 110K
input 1
input 2
R2 110K
R3 1K
Rg
Rg
+Vs
-Vs
Out
REF
R6
R7
R8
R9
C3
LF353
U23
+9v
U22
LF353
R11
110K
R10
10K
68K
R5
68K
R4
C2
100nf
100nf
C1
U22
LF353
1K
R15
ECG out
C6
not used
ECG GND
+9v
R13
2.0K
R12
2.0K
C5
100nf
C4
100nf
+9v
U23
LF353
R14 110K
RL Drive

1NA 111 Instrumentation Amplifier

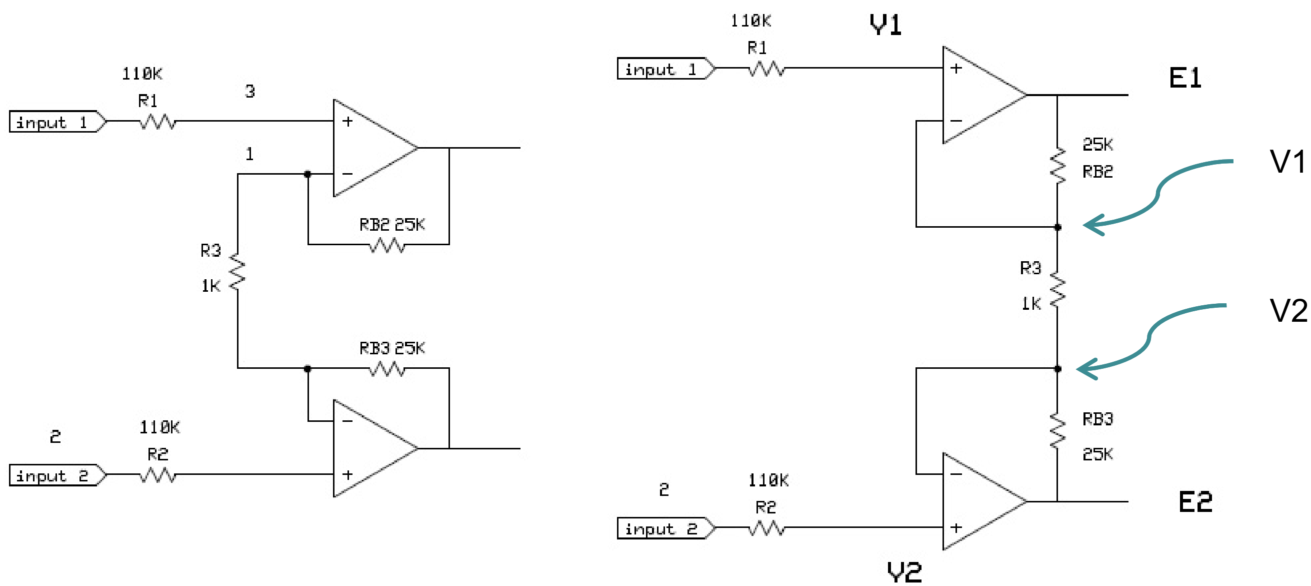


1NA 111 Instrumentation Amplifier



Instrumentation Op Amp Front End

Equivalent circuits – differential mode signal



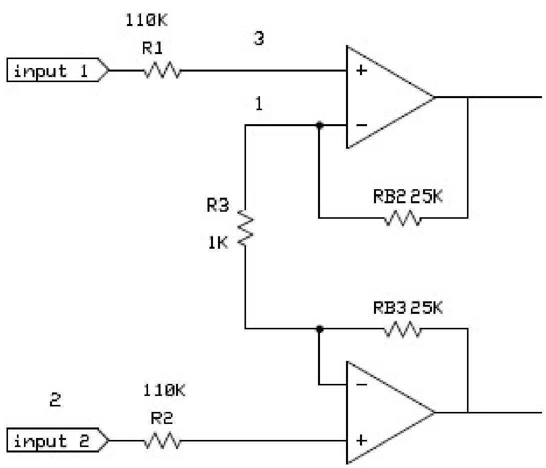
$$i_{R3} = \frac{V1 - V2}{1k} \qquad (E1 - E2) = i_{R3}(RB2 + R3 + RB3)$$

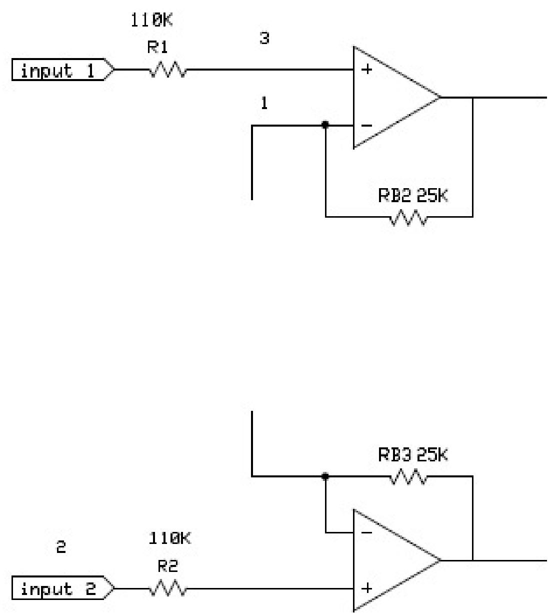
$$(E1 - E2) = \frac{(V1 - V2)}{R3}(RB2 + R3 + RB3) = (V1 - V2)\left(1 + \frac{2RB}{R3}\right)$$

Gain = 51

Instrumentation Op Amp Front End

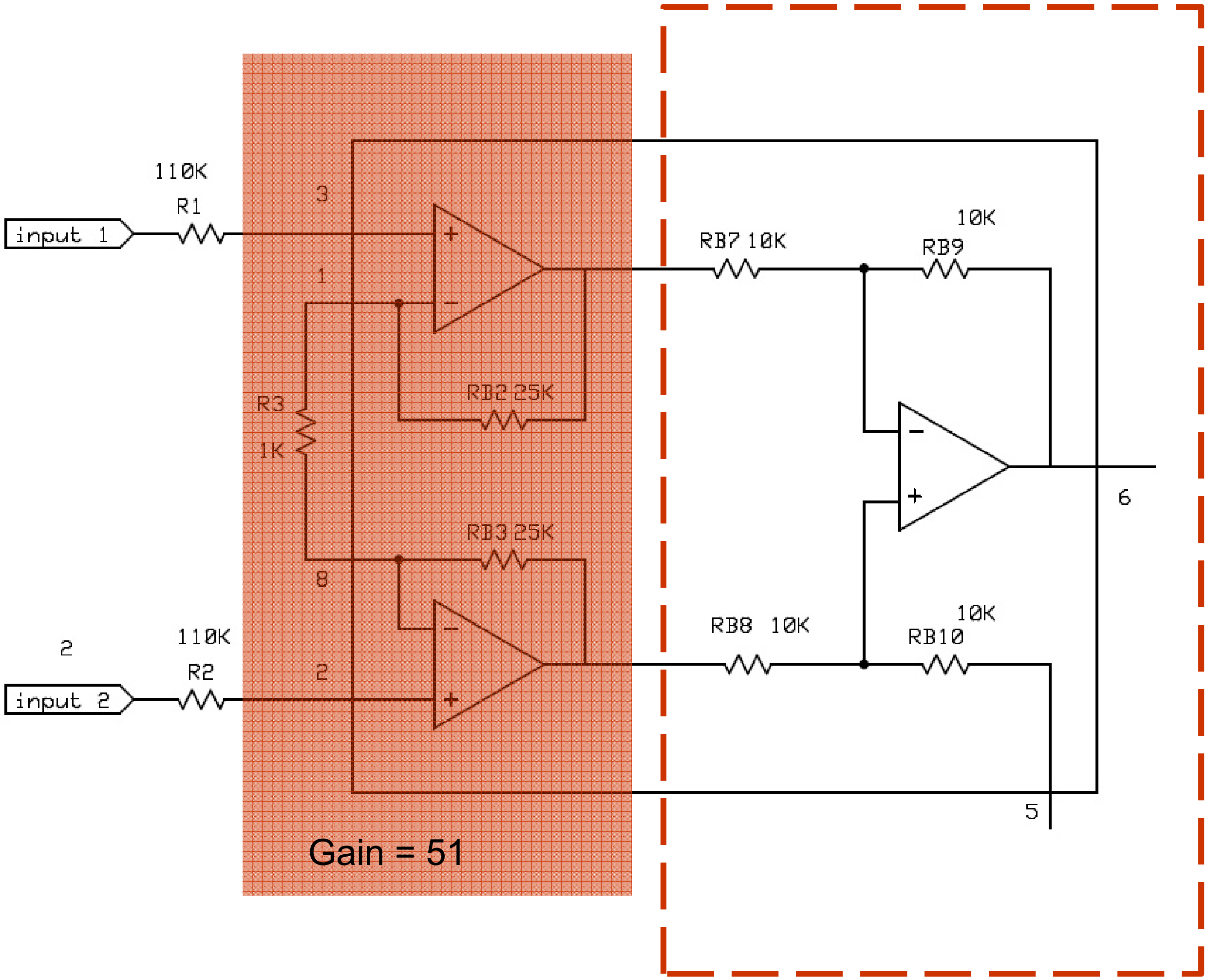
Equivalent circuits – Common mode signal



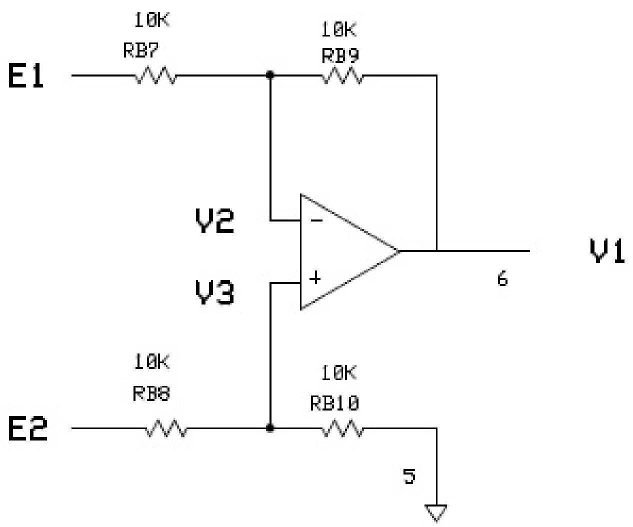


Common mode gain = 1

1NA 111 Instrumentation Amplifier



Elimination of Common Mode Noise



$$V2 = V3$$

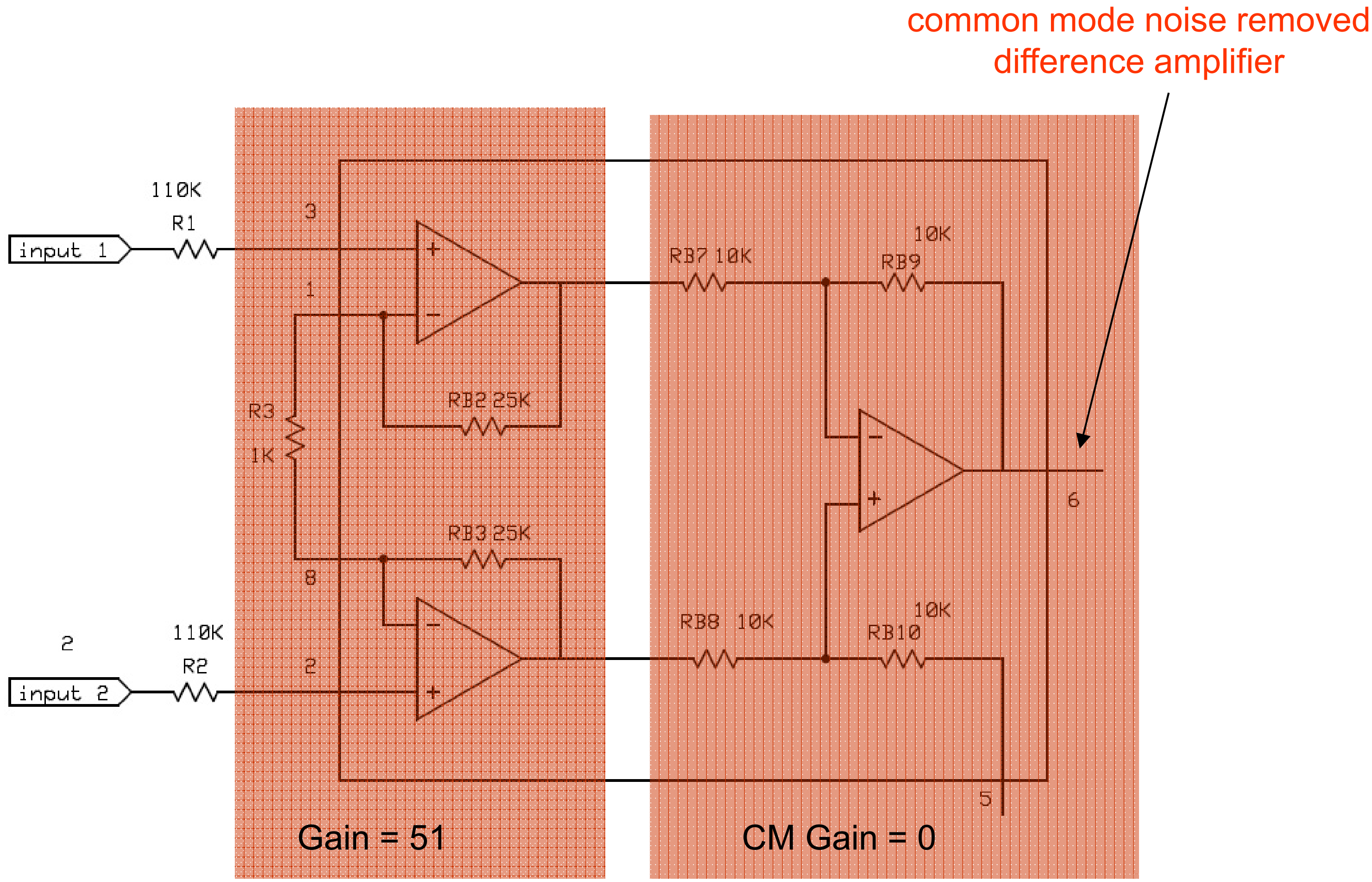
$$V3 = E2 \times \frac{RB10}{RB8 + RB10}$$

$$V2 = E1\left(\frac{RB9}{RB7 + RB9}\right) + V1\left(\frac{RB7}{RB7 + RB9}\right)$$

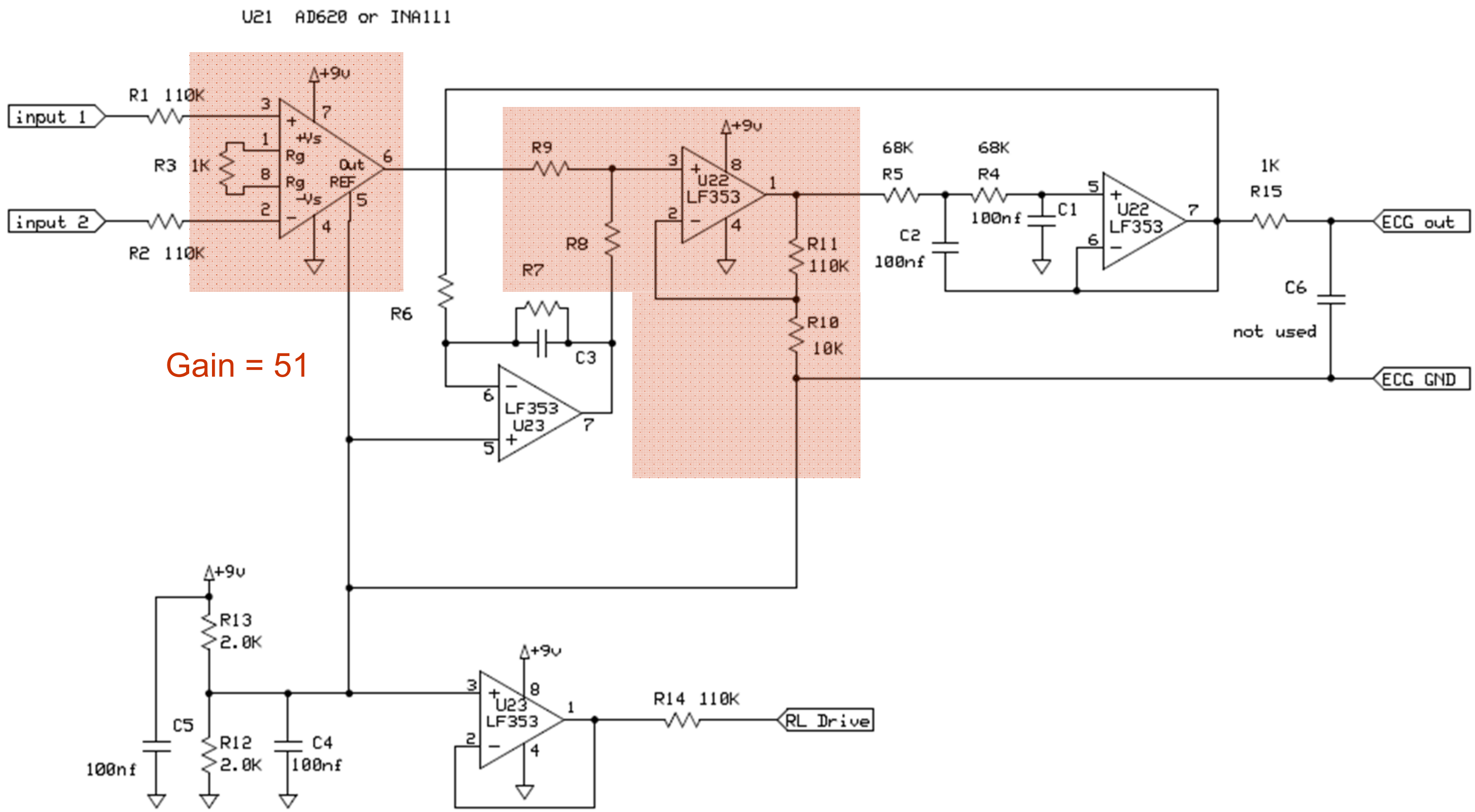
$$RB7 = RB8 = R9 = R10 = 10K$$

$$V1 = (E2 - E1)$$

1NA111 Instrumentation Amplifier

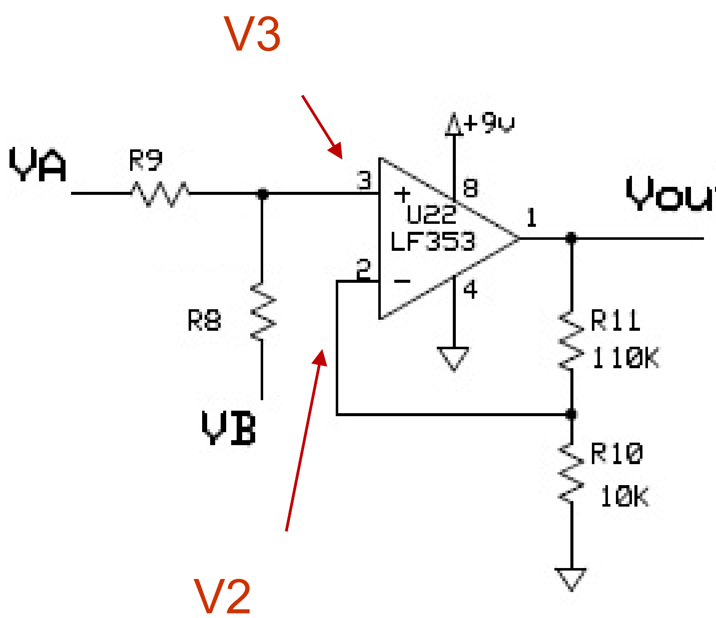


ECG Board



U21 AD620 or INA111
input 1
input 2
R1 110K
R2 110K
R3 1K
+9v
+Vs
Rg
Rg
Out
REF
-Vs
R9
R8
R7
R6
C3
U22
LF353
LF353
U23
R11
110K
R10
10K
68K
R5
68K
R4
C2
100nf
100nf
C1
1K
R15
ECG out
C6
not used
ECG GND
R13
2.0K
R12
2.0K
C5
100nf
C4
100nf
R14 110K
RL Drive
Gain = 51

Adder Circuit

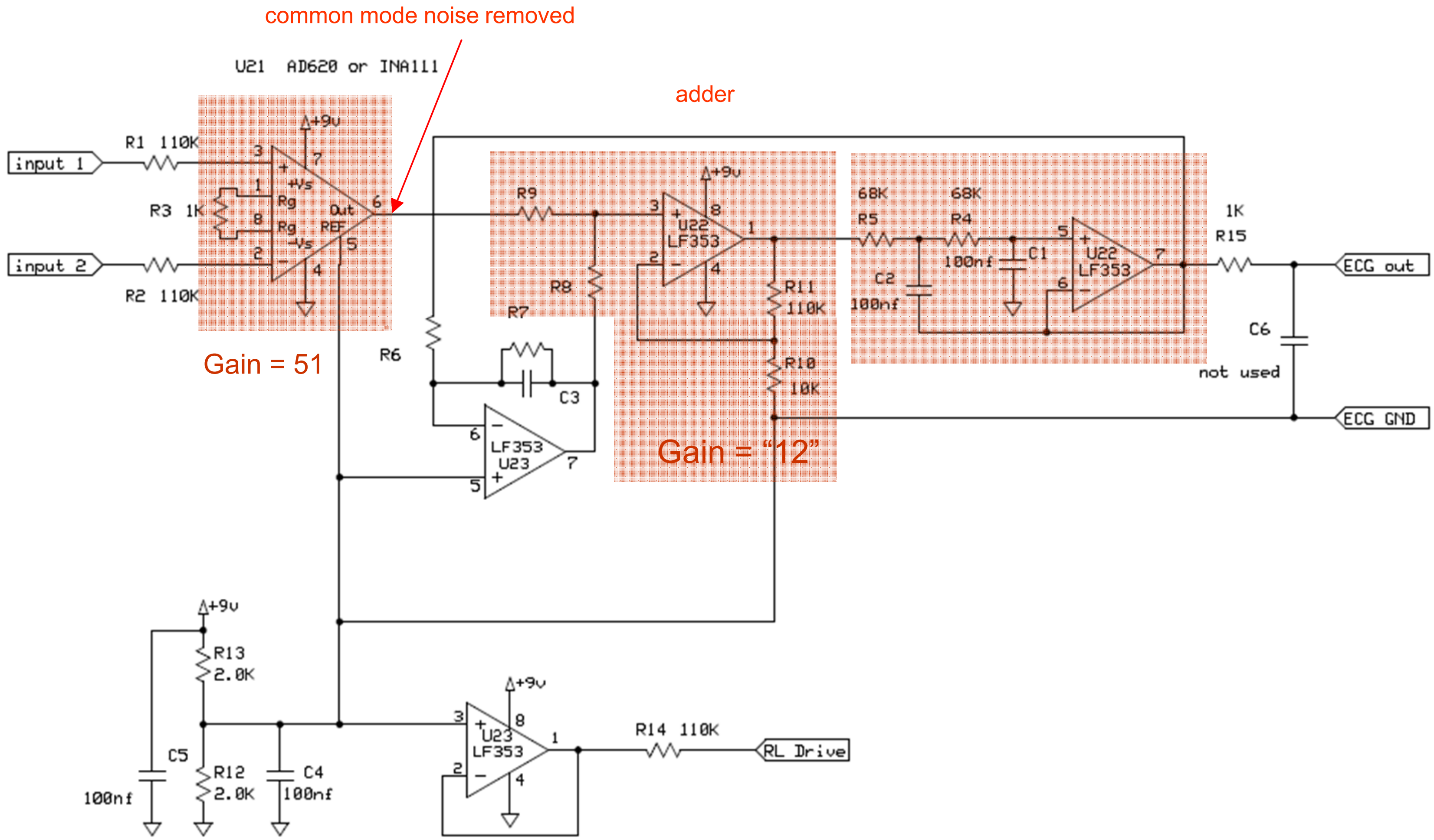


$$V3 = VA(\frac{R8}{R8+R9}) + VB(\frac{R9}{R8+R9})$$

$$V2 = Vout(\frac{R10}{R10+R11})$$

$$Vout = \left(VA(\frac{R8}{R8+R9}) + VB(\frac{R9}{R8+R9}) \right)\left(\frac{R10+R11}{R10} \right)$$

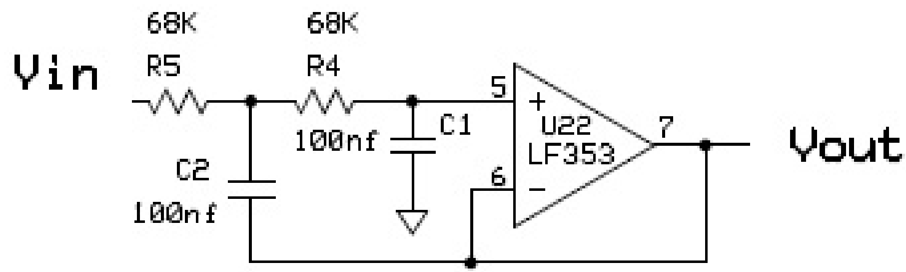
ECG Board



common mode noise removed
U21 AD620 or INA111
adder
input 1
input 2
R1 110K
R2 110K
R3 1K
+9v
Gain = 51
R6
R7
R8
R9
C3
LF353
U23
U22
R11 110K
R10 10K
Gain = "12"
68K
R5
68K
R4
C2 100nf
100nf
C1
1K
R15
ECG out
C6
not used
ECG GND
R13 2.0K
R12 2.0K
C5
100nf
C4 100nf
R14 110K
RL Drive

Elimination of High Frequency Noise

- Use low pass filter (LPF). Sallen-Key filter is a second order filter. (A second order filter attenuates by a factor of one fourth for every doubling of frequency.)



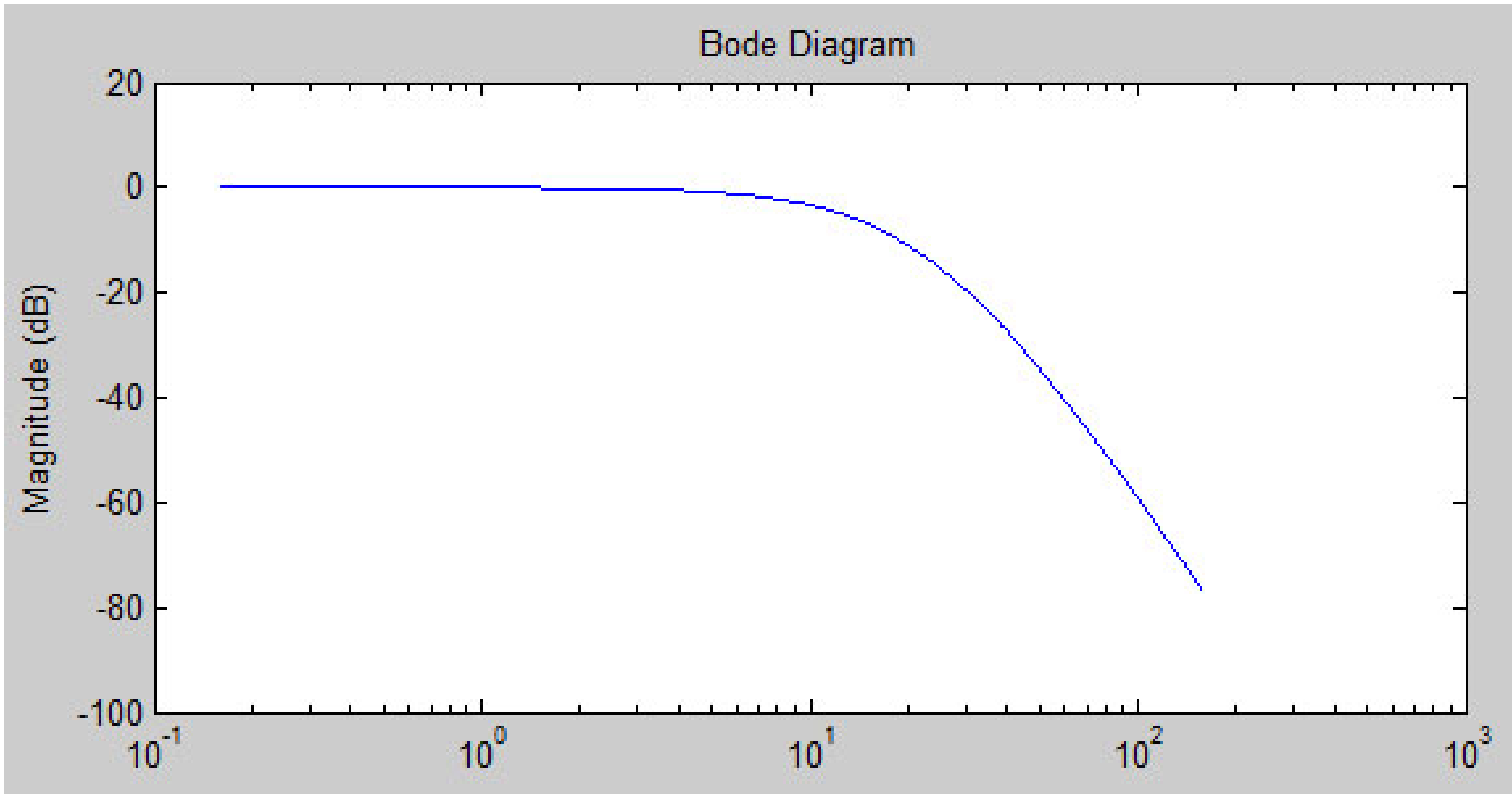
- For low frequencies, C1, C2 are open circuit – op amp feeds signal through.

- For high frequencies, C1, C2 act as shorts.

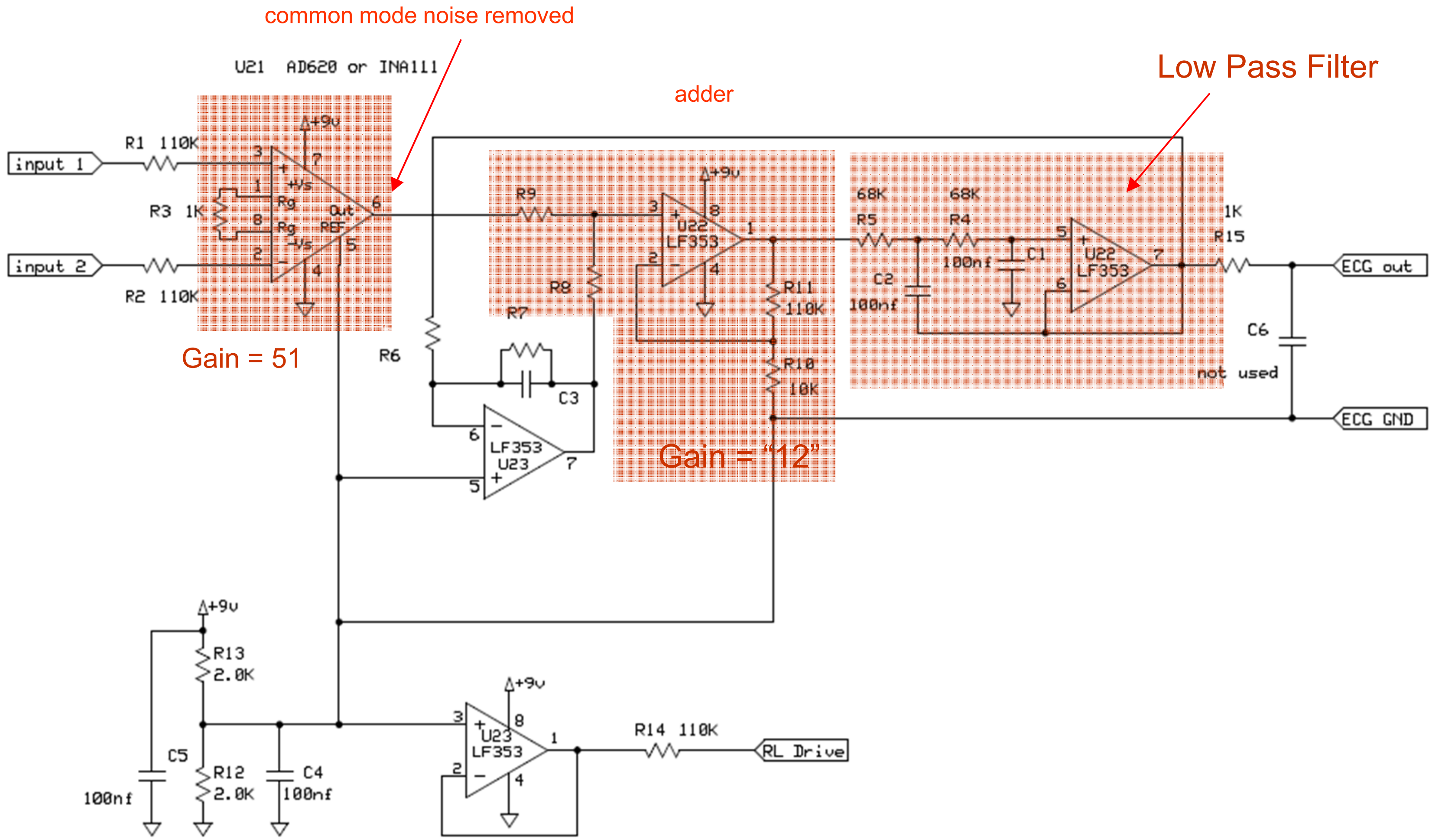
$$f_c = \frac{1}{2\pi RC}$$

R5 = R4 = 68K
C1= C2 = 100nf
f_c= 23.4 Hz

Sallen Key Bode Diagram

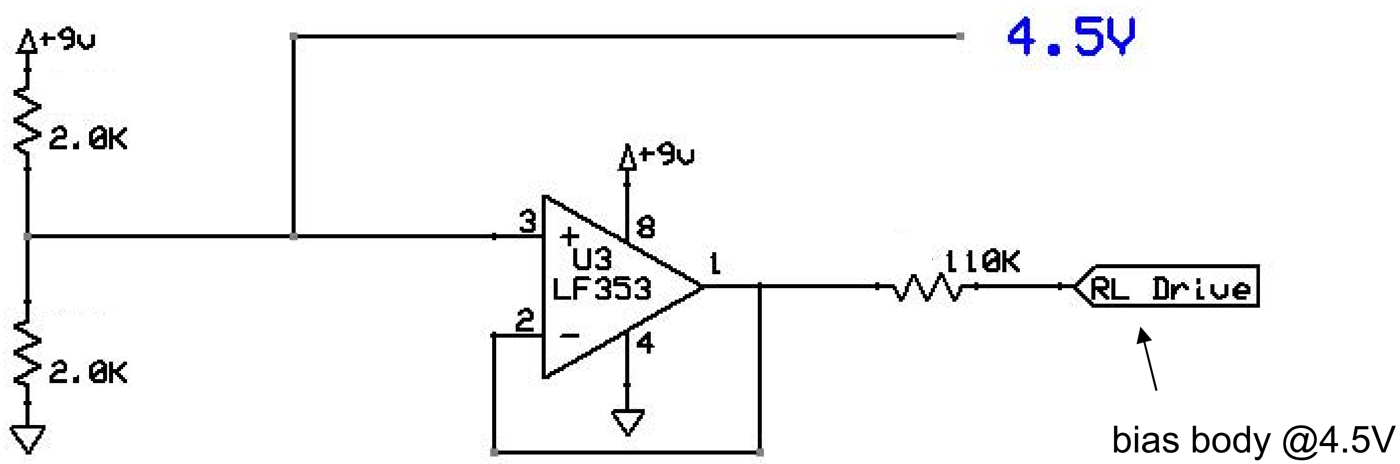


ECG Board



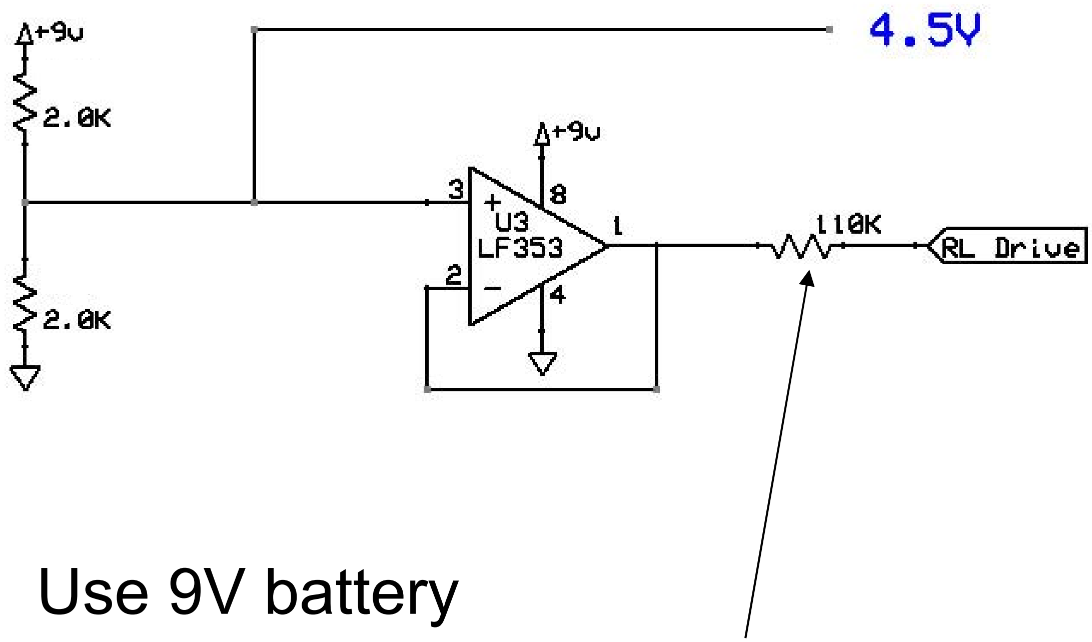
common mode noise removed
U21 AD620 or INA111
adder
Low Pass Filter
input 1
input 2
R1 110K
R2 110K
R3 1K
+9v
+Vs
-Vs
Rg
Out
REF
Gain = 51
R6
R7
R8
R9
U22
LF353
R11
110K
R10
10K
Gain = "12"
C3
U23
68K
R5
68K
R4
C2
100nf
C1
1K
R15
ECG out
C6
not used
ECG GND
R13
2.0K
R12
2.0K
C5
C4
R14 110K
RL Drive

Operation from 9V source
Right Leg Drive



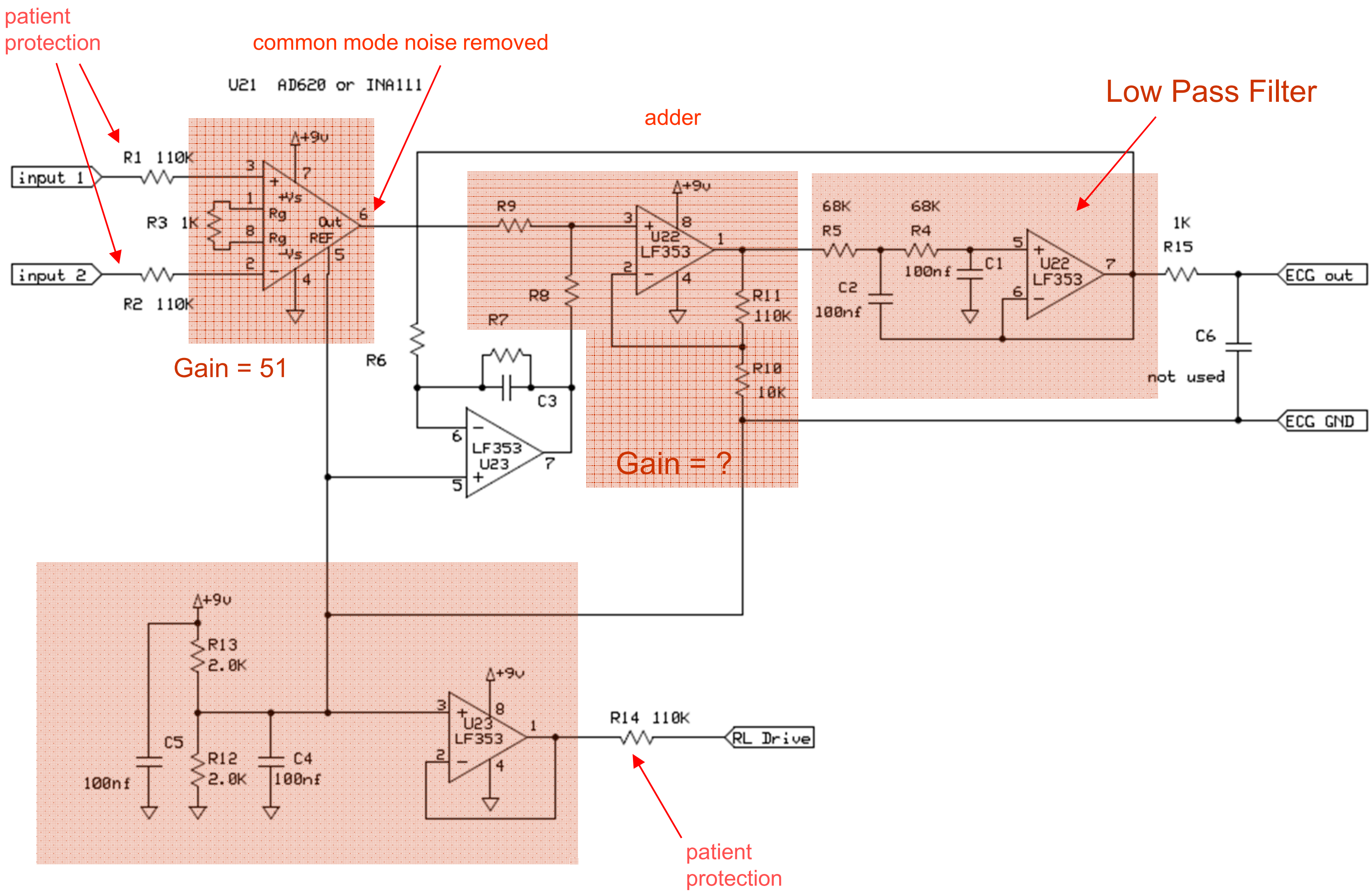
- LF353 (but not all op amps) need a plus/minus voltage source
- Set the reference voltage (typically ground) to 4.5V.
- Op amps sees +4.5 and -4.5
- Improves CMRR by shunting noise to “ground”

Patient Protection



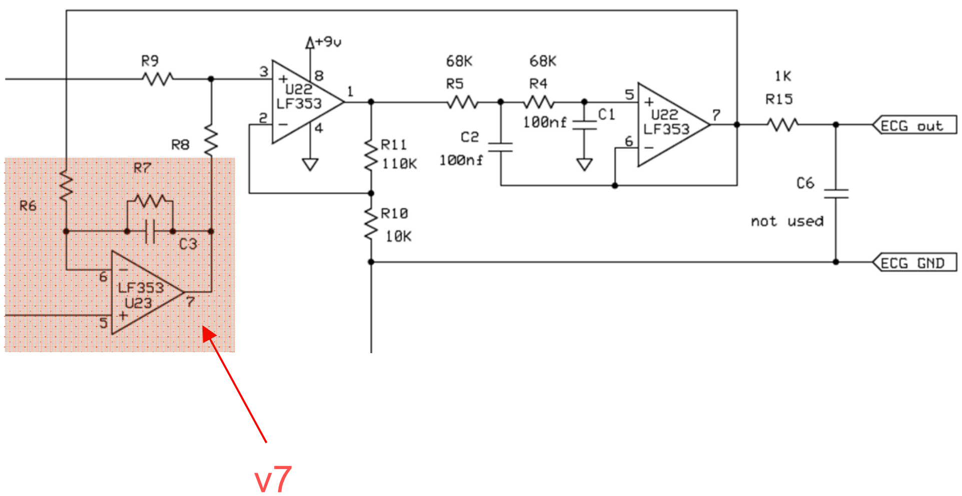
- Use 9V battery
- 110K resistor in series with all leads connecting to patient

ECG Board



patient protection
common mode noise removed
U21 AD620 or INA111
Low Pass Filter
adder
input 1
input 2
R1 110K
R2 110K
R3 1K
+9v
+Vs
Rg
Rg
Out
REF
-Vs
R9
R8
R7
R6
U22 LF353
R11 110K
R10 10K
C3
LF353 U23
Gain = 51
Gain = ?
68K
R5
68K
R4
C2
100nf
100nf
C1
U22 LF353
1K
R15
ECG out
C6
not used
ECG GND
R13 2.0K
R12 2.0K
C5
100nf
C4
100nf
U23 LF353
R14 110K
RL Drive
patient protection

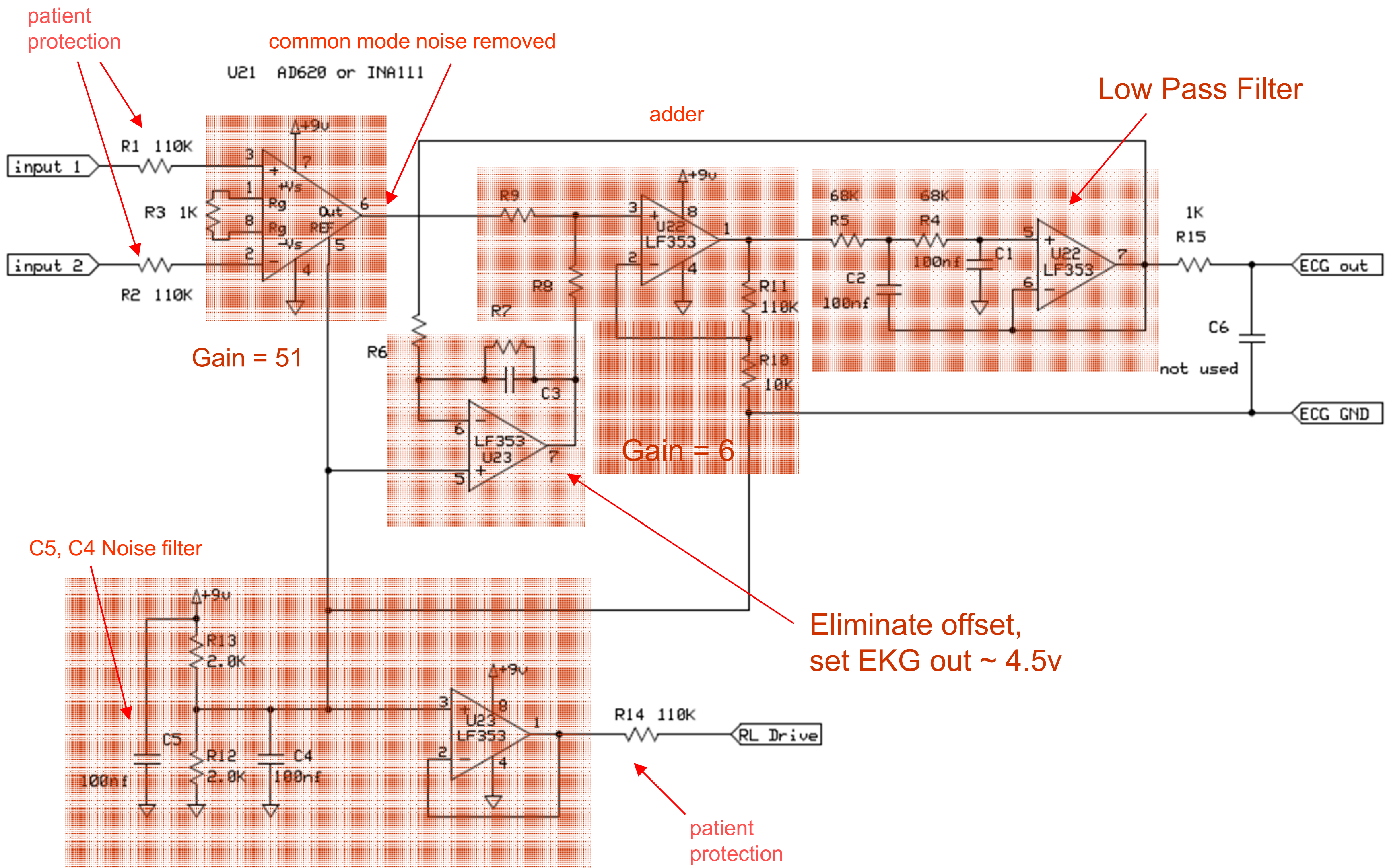
Elimination of DC Offset*



v7 added to amplified ECG signal to maintain ECG_{out} at 4.5 V

- This block, a LPF, integrates the output voltage over time and compensates for any DC offset
- Determine transfer function
- Select R6, R7 and C3 values.

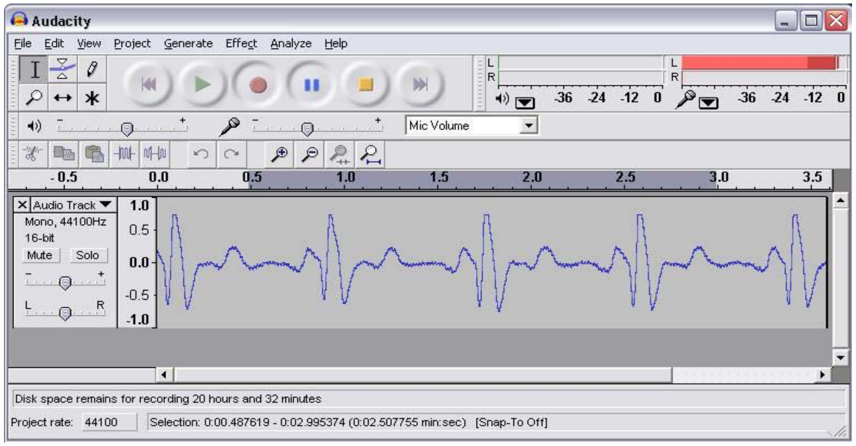
ECG Board



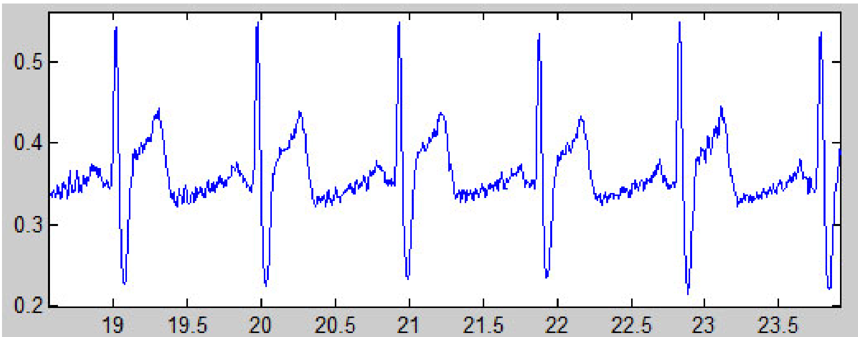
patient
protection
common mode noise removed
U21 AD620 or INA111
adder
Low Pass Filter
input 1
input 2
R1 110K
R2 110K
R3 1K
+9v
Gain = 51
R9
R8
R7
R6
C3
U22
LF353
R11
110K
R10
10K
U23
LF353
Gain = 6
68K
68K
R5
R4
100nf
C1
C2
100nf
1K
R15
ECG out
C6
not used
ECG GND
C5, C4 Noise filter
R13
2.0K
R12
2.0K
C5
100nf
C4
100nf
R14 110K
RL Drive
Eliminate offset,
set EKG out ~ 4.5v
patient
protection

Displaying ECG

- PC audio uses AC-97 chip with 20 bit A-D converter (DAC) for microphone/line input.
- Display using Audacity, open source recording/editing software with ECG as microphone input



- Display using MATlab

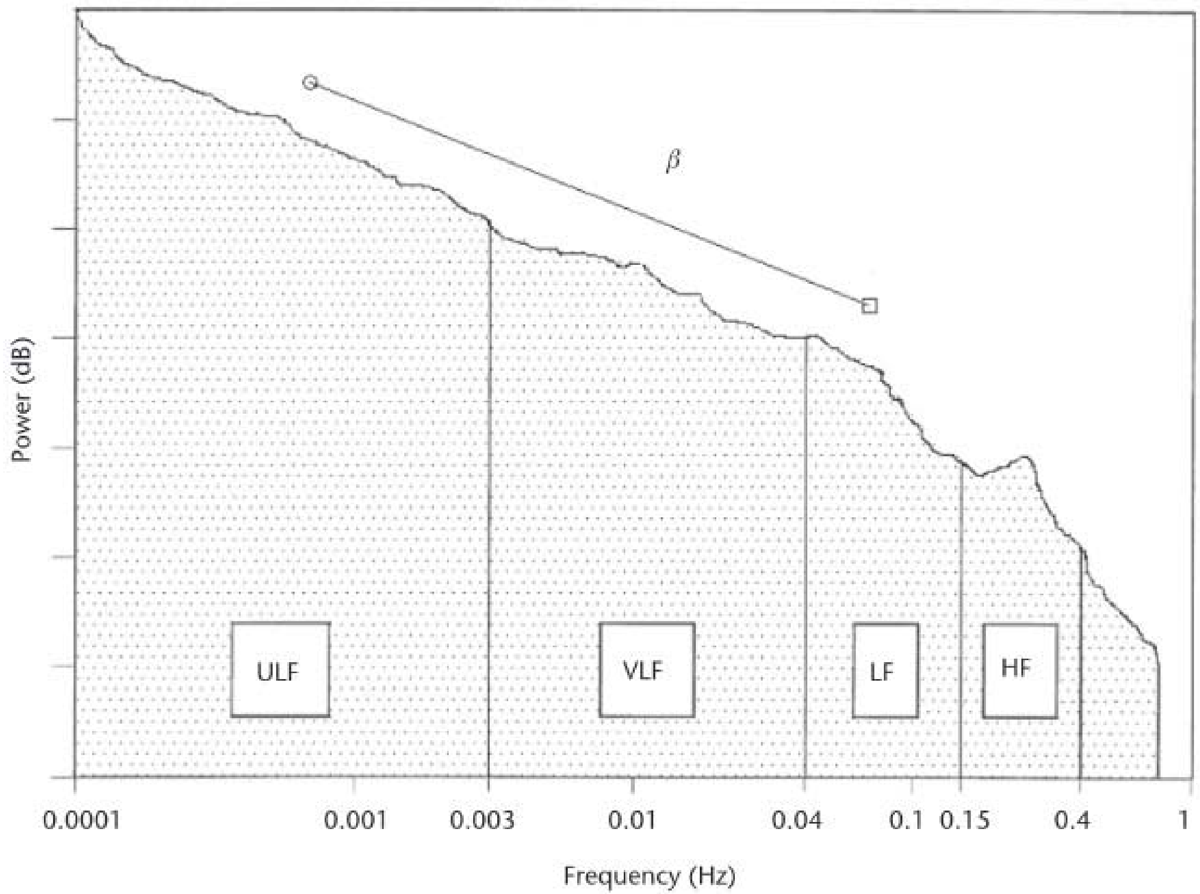


ECG Variability Analysis

- Time domain analysis – Time series
  - NN series: beat to beat interval also called RR series.
  - SDNN: standard deviation of NN interval
  - RMSSD: root mean square of successive differences
  - NN50: number of NN pairs differing by 50ms

- Frequency domain analysis – power spectral density
  - Frequency bands
    - High frequency (HF) 0.15-0.4 Hz
    - Low frequency (LF) 0.04-.015 Hz
    - Very low frequency (VLF) 0.0033-.04 Hz

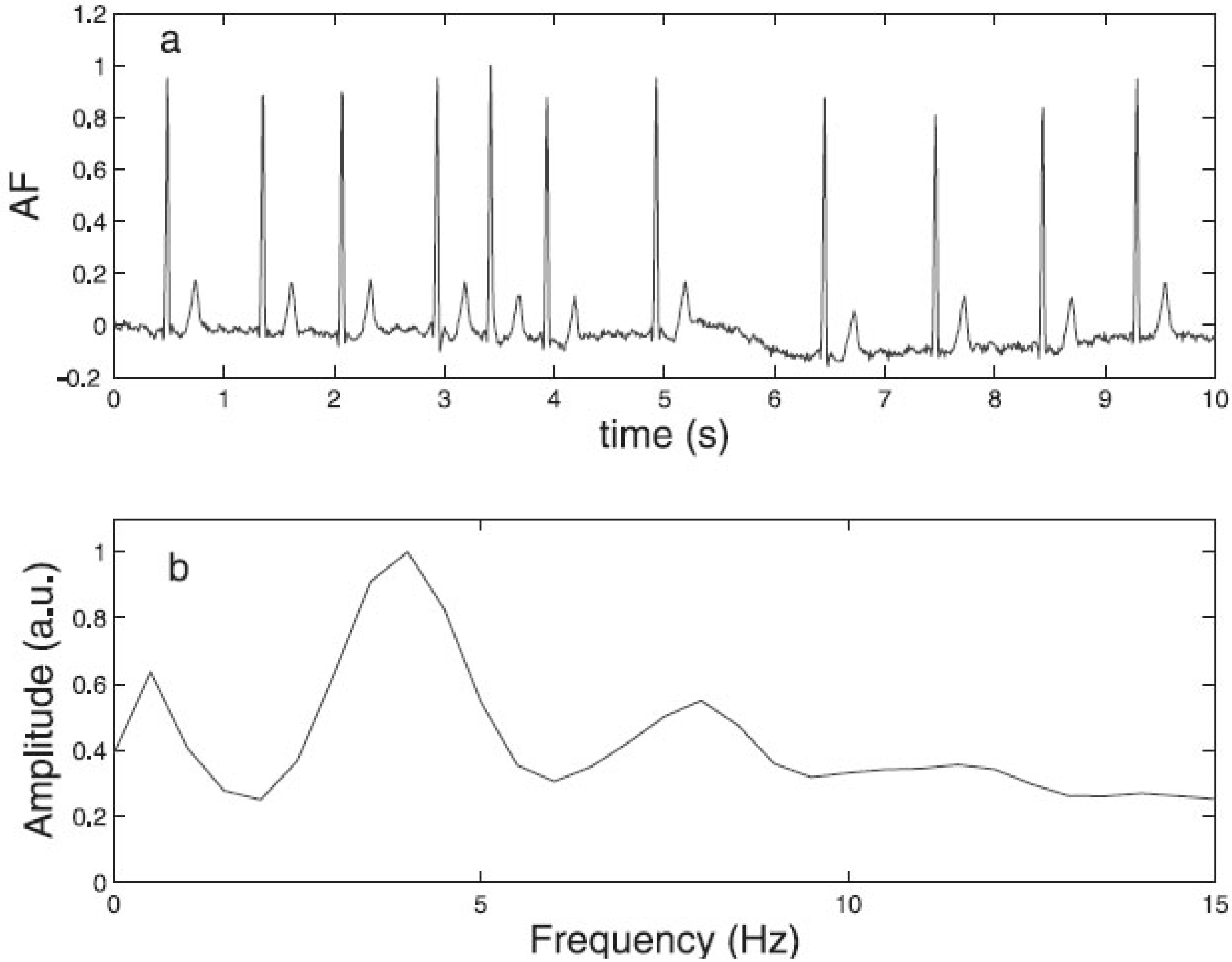
ECG PSD - Frequency Domain



PSD: Power spectral density

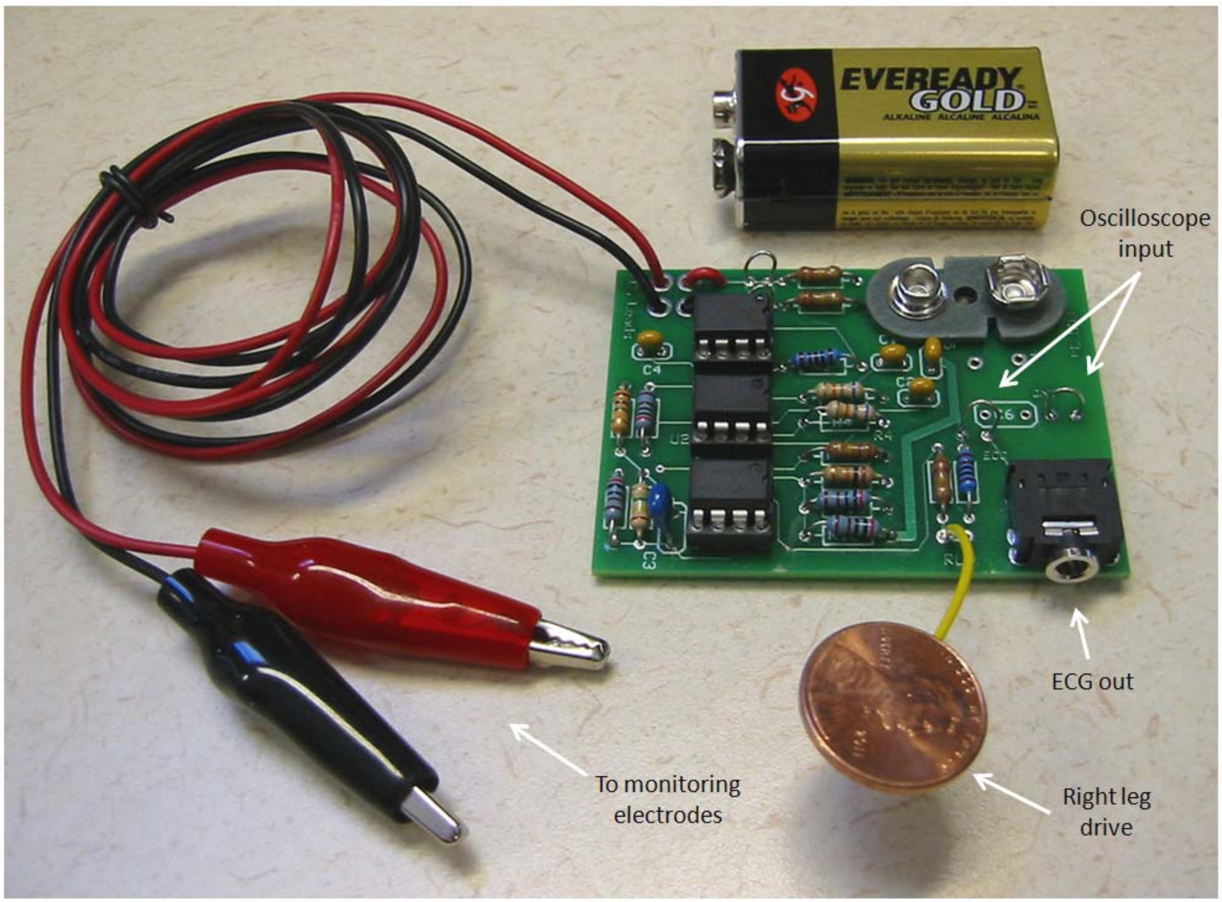
ECG*

Atrial
Fibrillation

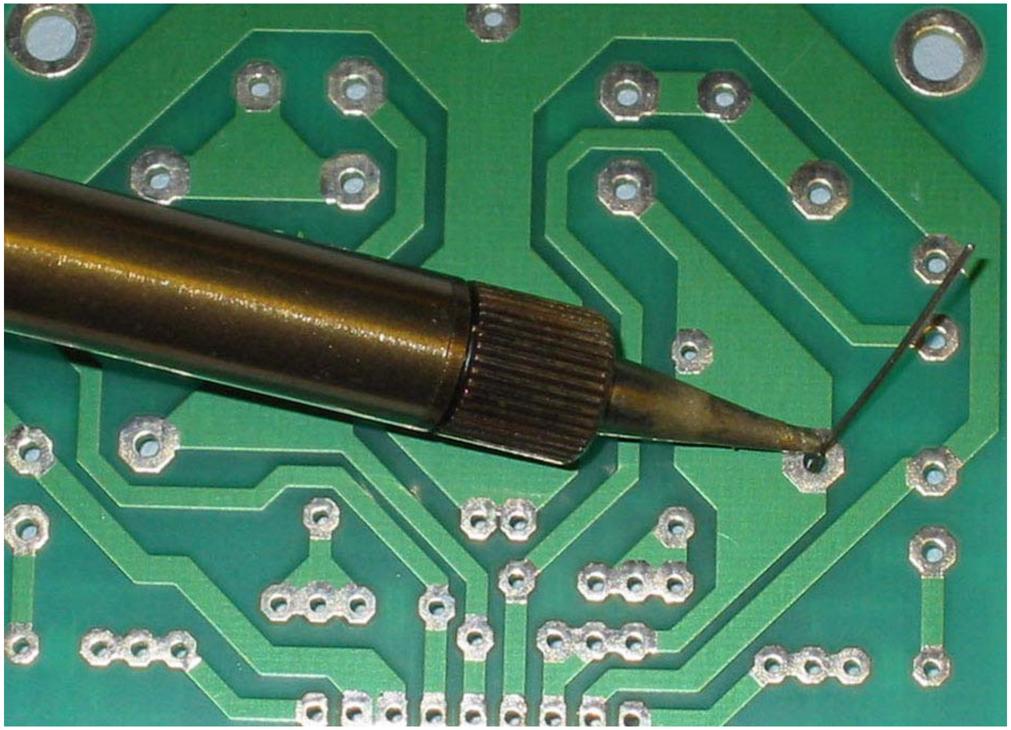


* Clifford, Gari ECG Book

Lab Exercise

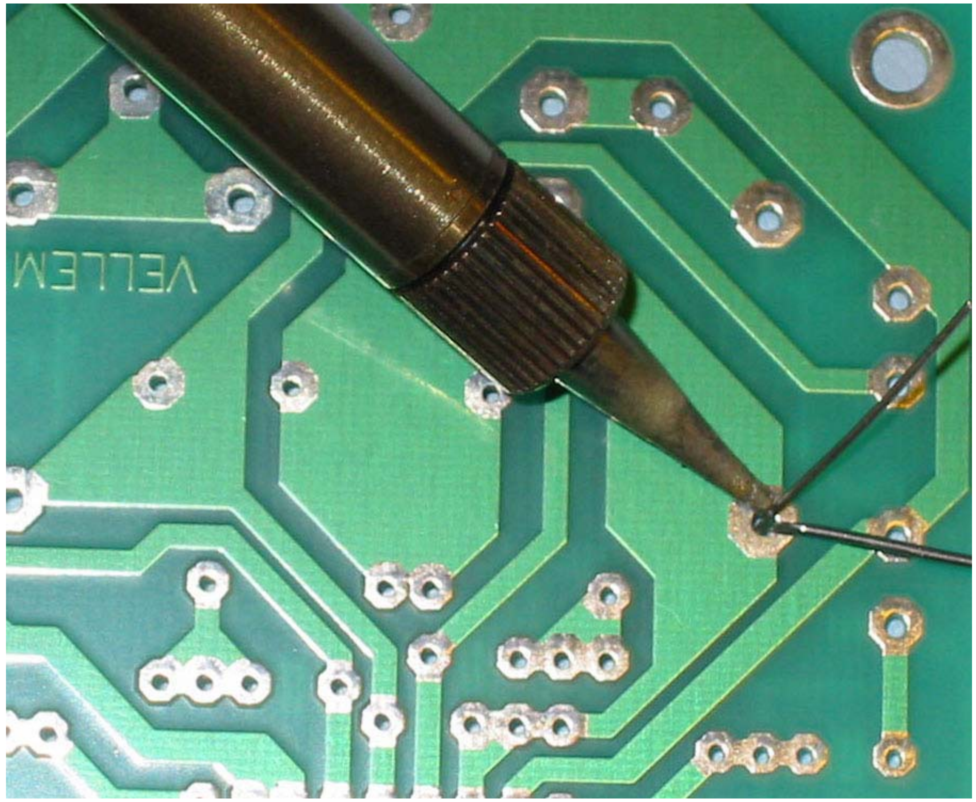


- Build ECG circuit
- Display ECG waveform on oscilloscope
- Perform MATlab analysis
- Follow lab write up carefully!



Turn on exhaust fan

Apply heat to the circuit board but ok to initially melt a little bit of solder on the iron to improve heat conduction.



Apply solder to the component, not to the soldering.

ECG Exercise

- Sample ECG for 60 sec using MATLAB script; using your laptop or Win7 PC in 38-530
- Store data using save command
  - save(FILENAME) stores all variables from the current workspace in a MATLAB formatted binary file (MAT-file) called FILENAME.
  - load(FILENAME) restores saved variables.
- Calculate average heart rate in a 60 second interval.

ECG Acquisition

```
%%
recObj = audiorecorder(1000,16, 1);
% 1000 sample rate, 16 bits, 1 channel

record_time = 5;
disp('Start ECG.')
recordblocking(recObj, record_time);
disp('End of Recording.');

% Store data in double-precision array.
myECG = getaudiodata(recObj);

% create x axis in 1/1000 interval
t = [0:1/1000:record_time-1/1000];

% Plot the waveform.
plot(t,myECG);
% label x axis in seconds
xlabel ('sec');
%%
save('mydata')
```

ECG Figures

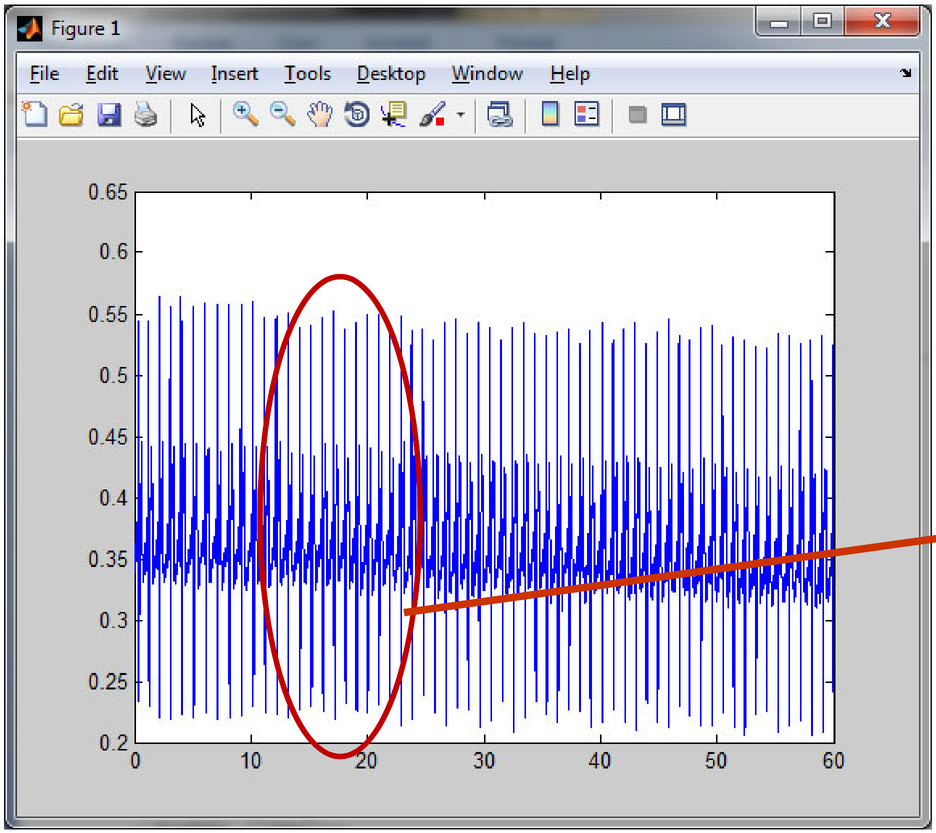
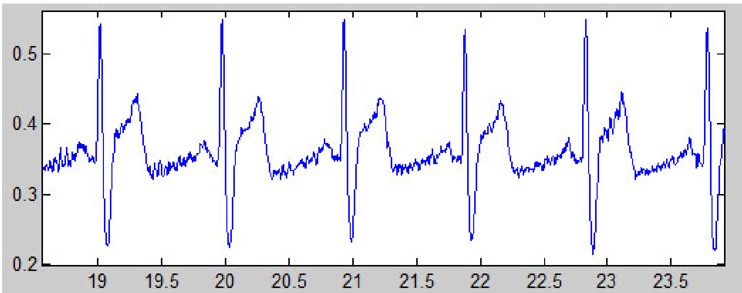


Figure 1
File Edit View Insert Tools Desktop Window Help
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0
10
20
30
40
50
60


0.5
0.4
0.3
0.2
19
19.5
20
20.5
21
21.5
22
22.5
23
23.5

Useful MATLAB commands

- title ('ECG 60 seconds') % set title of graph
- xlabel ('time ms'), ylabel…
- save(FILENAME) stores all variables from the current workspace in a MATLAB formatted binary file (MAT-file) called FILENAME.
- length(X) returns the length of vector X.
- [peaks, loc]= findpeaks(v) % gives peaks and location of peaks
- diff_data = diff(X), for a vector X, is [X(2)-X(1), X(3)-X(2) ... X(n)-X(n-1)
- mean(X) is the mean value of the elements in X
- linspace(X1, X2, N) generates N points between X1 and X2.

Built-in Matlab function "findpeaks".

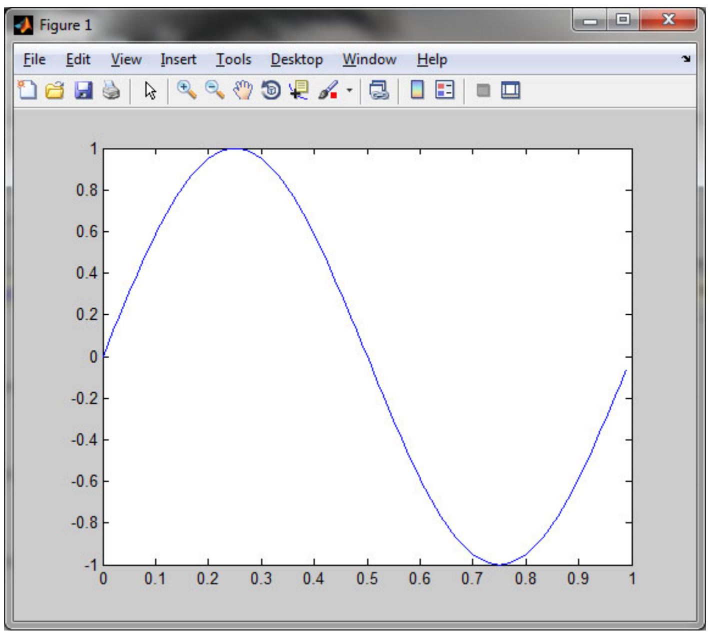
`[pks,locs]= findpeaks (X)` returns the indices "locs" at which the peaks occur as well as the value of the peaks "pks"

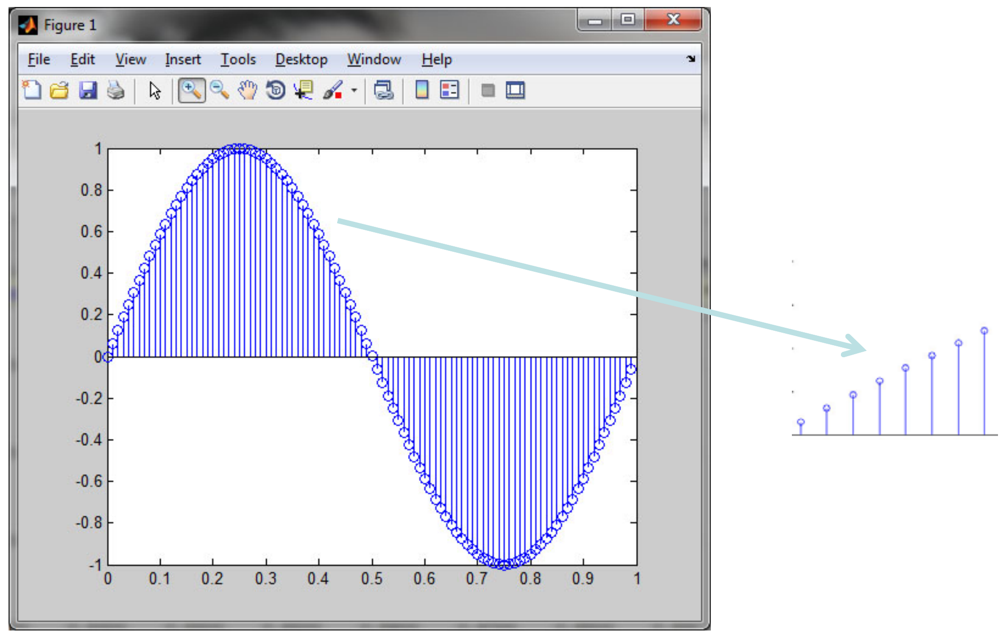
`findpeaks` also allows the user to specify the minimum peak height (MinPeakHeight) and the minimum peak distance (MinPeakDistance). For example:

```
[peaks,locs] = findpeaks(myECG, ' MinPeakHeight ',MPH)
```
%enter a value for MPH

MATLAB example sin(x)

```
>> t=[0:1/100:1-1/100]; % create t from 0 to .99,  100 values
>> x=sin(2*pi*t);
>> plot(t, x);
>> stem(t,x);
>> shg
```

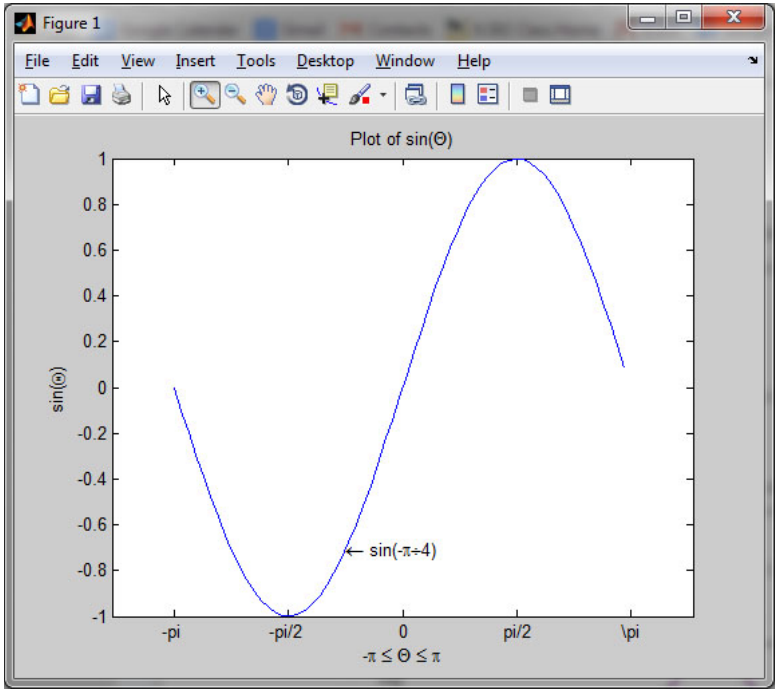




MATLAB plot commands

- Example y=sin(x)
  x = -pi:.1:pi;   %   -pi < x < pi in .1 increments
  y = sin(x);
  plot(x,y)
  set(gca,'XTick',-pi:pi/2:pi)   % gca = graphics current axis; label x axis   in pi/2 increment
  set(gca,'XTickLabel',{'-pi','-pi/2','0','pi/2','pi'}) % label the x axis

- add axis labels and draw an arrow that points
  to the location on the graph where y = sin(-pi/4):
  xlabel('-\pi \leq \Theta \leq \pi')
  ylabel('sin(\Theta)')
  title('Plot of sin(\Theta)')
  text(-pi/4,sin(-pi/4),'\leftarrow sin(-\pi\div4)',
       'HorizontalAlignment','left')



A Matlab Cheat-sheet (MIT 18.06, Fall 2007)

Basics:

`save 'file.mat'`	save variables to *file.mat*
`load 'file.mat'`	load variables from *file.mat*
`diary on`	record input/output to file *diary*
`diary off`	stop recording
`whos`	list all variables currenly defined
`clear`	delete/undefine all variables
`help command`	quick help on a given *command*
`doc command`	extensive help on a given *command*

Defining/changing variables:

`x = 3`	define variable x to be 3
`x = [1 2 3]`	set x to the 1×3 row-vector (1,2,3)
`x = [1 2 3];`	same, but don't echo x to output
`x = [1;2;3]`	set x to the 3×1 column-vector (1,2,3)
`A = [1 2 3 4;5 6 7 8;9 10 11 12];`	set A to the 3×4 matrix with rows 1,2,3,4 etc.
`x(2) = 7`	change x from (1,2,3) to (1,7,3)
`A(2,1) = 0`	change $A_{2,1}$ from 5 to 0

Arithmetic and functions of numbers:

`3*4, 7+4, 2-6 8/3`	multiply, add, subtract, and divide numbers
`3^7, 3^(8+2i)`	compute 3 to the 7th power, or 3 to the 8+2i power
`sqrt(-5)`	compute the square root of –5
`exp(12)`	compute e^{12}
`log(3), log10(100)`	compute the natural log (ln) and base-10 log ($\log_{10}$)
`abs(-5)`	compute the absolute value |–5|
`sin(5*pi/3)`	compute the sine of 5π/3
`besselj(2,6)`	compute the Bessel function $J_2(6)$

Arithmetic and functions of vectors and matrices:

`x * 3`	multiply every element of x by 3
`x + 2`	add 2 to every element of x
`x + y`	element-wise addition of two vectors x and y
`A * y`	product of a matrix A and a vector y
`A * B`	product of two matrices A and B
`x * y`	not allowed if x and y are two column vectors!
`x .* y`	element-wise product of vectors x and y
`A^3`	the square matrix A to the 3rd power
`x^3`	not allowed if x is not a square matrix!
`x.^3`	every element of x is taken to the 3rd power
`cos(x)`	the cosine of every element of x
`abs(A)`	the absolute value of every element of A
`exp(A)`	e to the power of every element of A
`sqrt(A)`	the square root of every element of A
`expm(A)`	the matrix exponential e^A
`sqrtm(A)`	the matrix whose square is A

Constructing a few simple matrices:

`rand(12,4)`	a 12×4 matrix with uniform random numbers in [0,1)
`randn(12,4)`	a 12×4 matrix with Gaussian random (center 0, variance 1)
`zeros(12,4)`	a 12×4 matrix of zeros
`ones(12,4)`	a 12×4 matrix of ones
`eye(5)`	a 5×5 identity matrix I ("eye")
`eye(12,4)`	a 12×4 matrix whose first 4 rows are the 4×4 identity
`linspace(1.2,4.7,100)`	row vector of 100 equally-spaced numbers from 1.2 to 4.7
`7:15`	row vector of 7,8,9,…,14,15
`diag(x)`	matrix whose diagonal is the entries of x (and other elements = 0)

Portions of matrices and vectors:

`x(2:12)`	the 2nd to the 12th elements of x
`x(2:end)`	the 2nd to the last elements of x
`x(1:3:end)`	every third element of x, from 1st to the last
`x(:)`	all the elements of x
`A(5,:)`	the row vector of every element in the 5th row of A
`A(5,1:3)`	the row vector of the first 3 elements in the 5th row of A
`A(:,2)`	the column vector of every element in the 2nd column of A
`diag(A)`	column vector of the diagonal elements of A

Solving linear equations:

`A \ b`	for A a matrix and b a column vector, the solution x to $Ax=b$
`inv(A)`	the inverse matrix A^{-1}
`[L,U,P] = lu(A)`	the LU factorization $PA=LU$
`eig(A)`	the eigenvalues of A
`[V,D] = eig(A)`	the columns of V are the eigenvectors of A, and the diagonals `diag(D)` are the eigenvalues of A

Plotting:

`plot(y)`	plot y as the y axis, with 1,2,3,… as the x axis
`plot(x,y)`	plot y versus x (must have same length)
`plot(x,A)`	plot columns of A versus x (must have same # rows)
`loglog(x,y)`	plot y versus x on a log-log scale
`semilogx(x,y)`	plot y versus x with x on a log scale
`semilogy(x,y)`	plot y versus x with y on a log scale
`fplot(@(x) …expression…,[a,b])`	plot some expression in x from $x=a$ to $x=b$
`axis equal`	force the x and y axes of the current plot to be scaled equally
`title('A Title')`	add a title *A Title* at the top of the plot
`xlabel('blah')`	label the x axis as *blah*
`ylabel('blah')`	label the y axis as *blah*
`legend('foo','bar')`	label 2 curves in the plot *foo* and *bar*
`grid`	include a grid in the plot
`figure`	open up a new figure window

Transposes and dot products:

`x.', A.'`	the transposes of x and A
`x', A'`	the complex-conjugate of the transposes of x and A
`x' * y`	the dot (inner) product of two *column* vectors x and y
`dot(x,y), sum(x.*y)`	…two other ways to write the dot product
`x * y'`	the *outer* product of two *column* vectors x and y

ECG Project Ideas

- Transmit ECG wirelessly
  - RF (AM, FM)
  - Laser beam
- Display ECG using galvanometer or TFT Teensy
- Add sound, alarm
- 2014 Project Video
  - Send ECG via fiber optic cable
  - Display heart rate via analog meter
  - Set alarms
  - Output tone proportional to heart rate