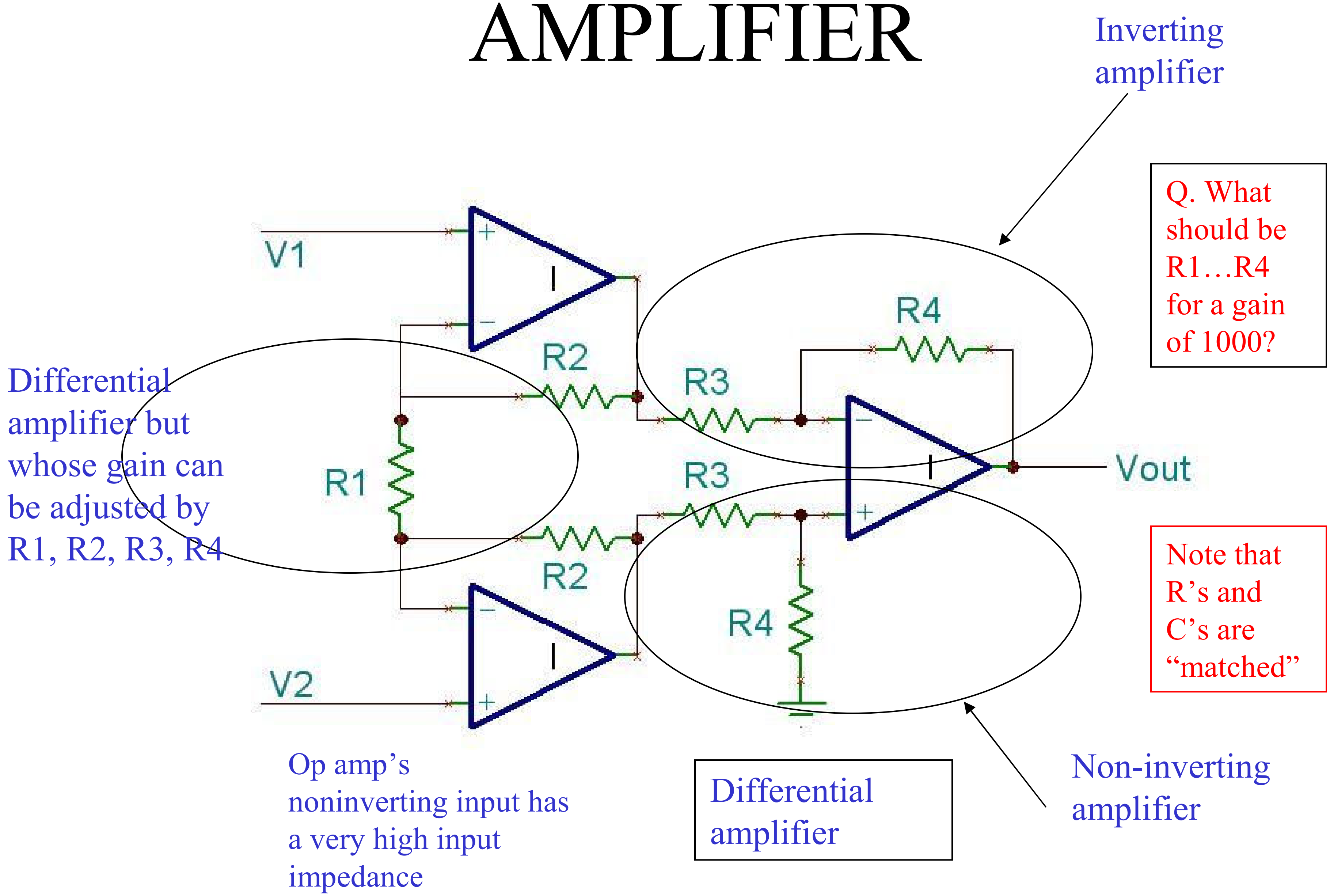
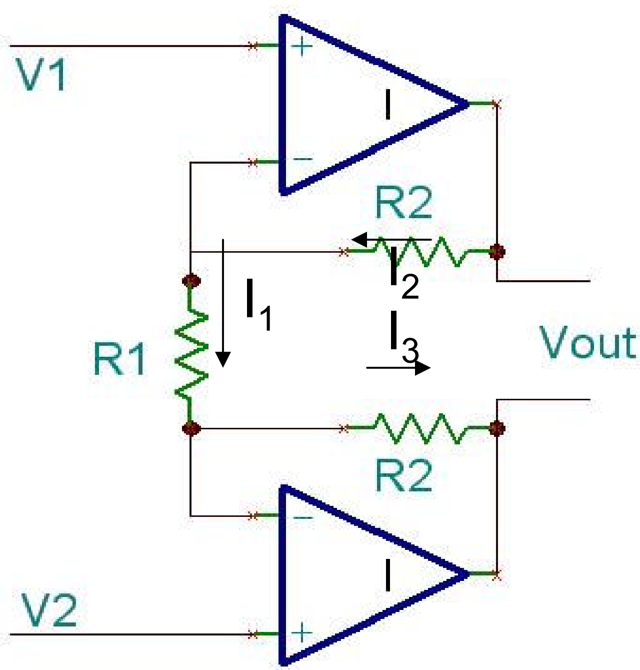
Lecture 5

Biopotential
Measurements

INSTRUMENTATION AMPLIFIER



INSTRUMENTATION AMPLIFIER: STAGE 1



Recall virtual ground of opamps

$I_1 = (V_1 - V_2)/R_1$

Recall no current can enter opamps and Kirchoff's current law

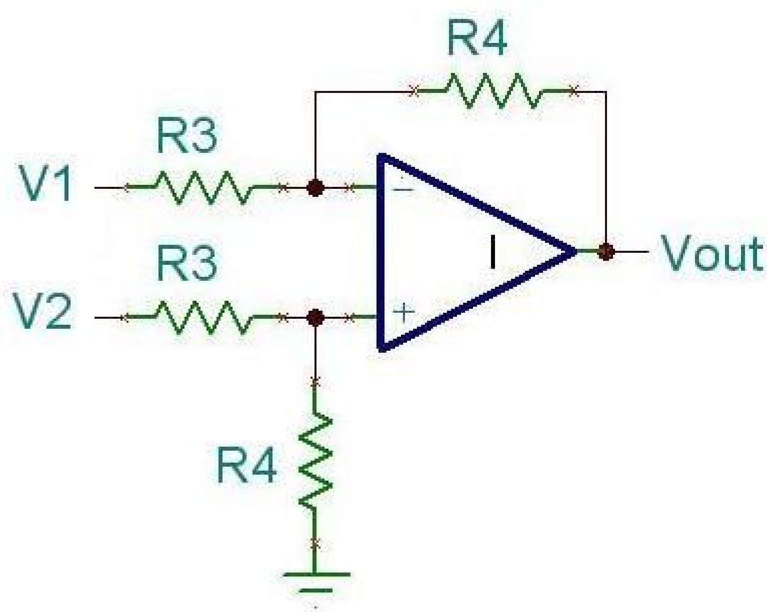
$I_2 = I_3 = I_1$

Recall Kirchoff's voltage law

$$V_{OUT} = (R_1 + 2R_2)(V_1 - V_2)/R_1$$

$$= (V_1 - V_2)(1+2R_2/R_1)$$

INSTRUMENTATION AMPLIFIER: STAGE 2



Recall virtual ground of opamps and voltage divider

$V_- = V_+ = V_2R_4/(R_3 + R_4)$

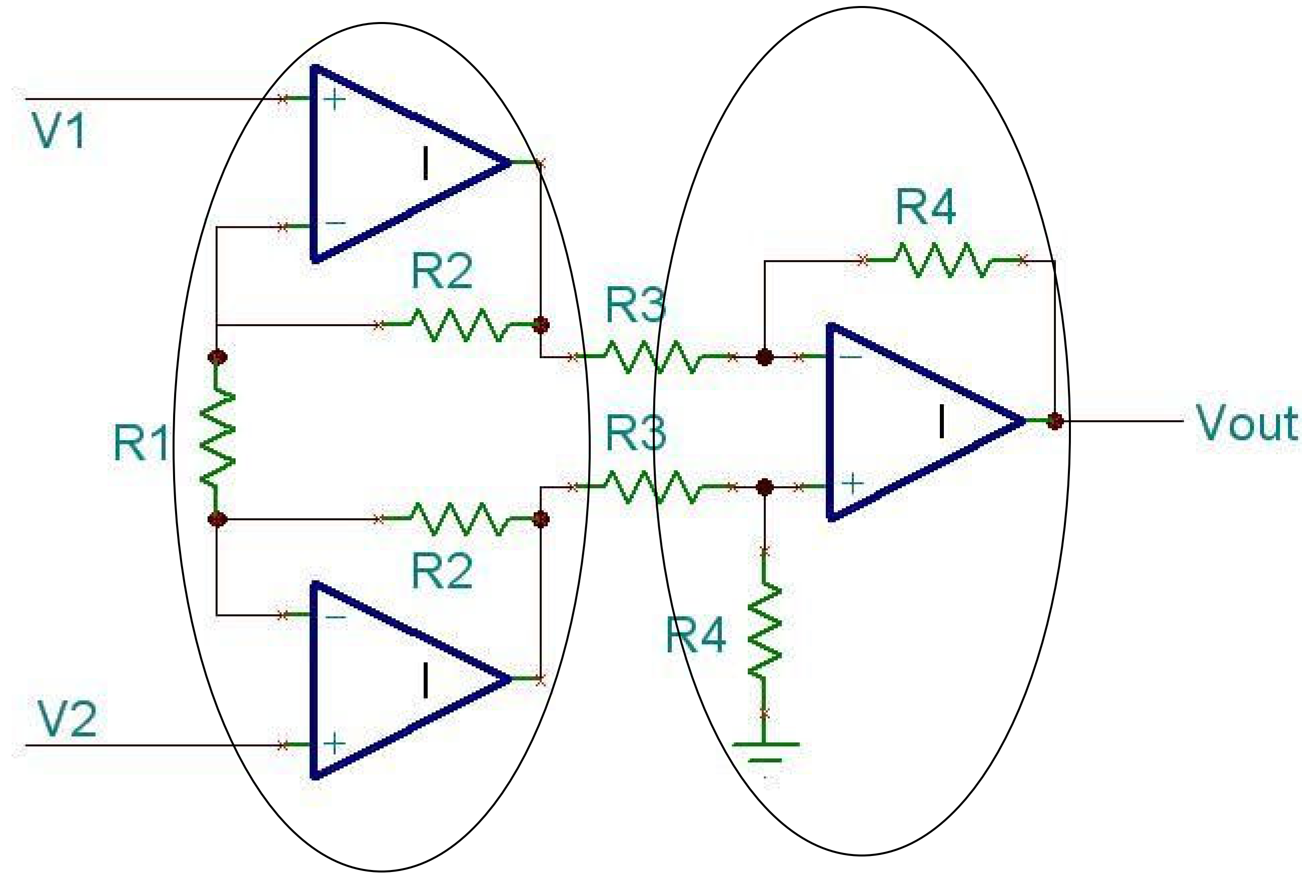
Recall no current can enter opamps

$(V_1 - V_-)/R_3 = (V_- - V_{OUT})/R_4$

Solving,

$V_{OUT} = -(V_1 - V_2)R_4/R_3$

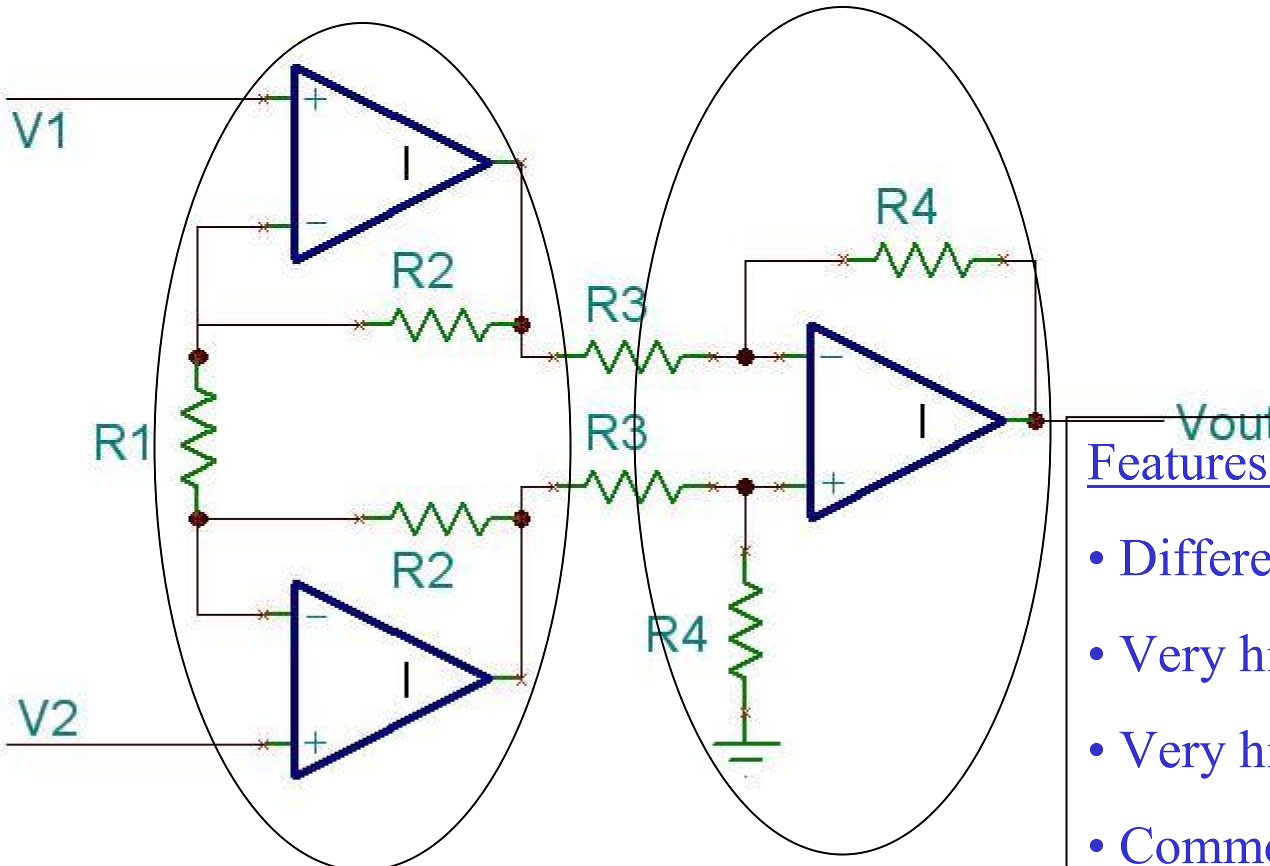
INSTRUMENTATION AMPLIFIER: COMPLETE



$$V_{OUT} = -(V_1 - V_2)(1 + 2R_2/R_1)(R_4/R_3)$$

Gain from <u>Stage I</u> and <u>Stage II</u>

INSTRUMENTATION AMPLIFIER: COMPLETE



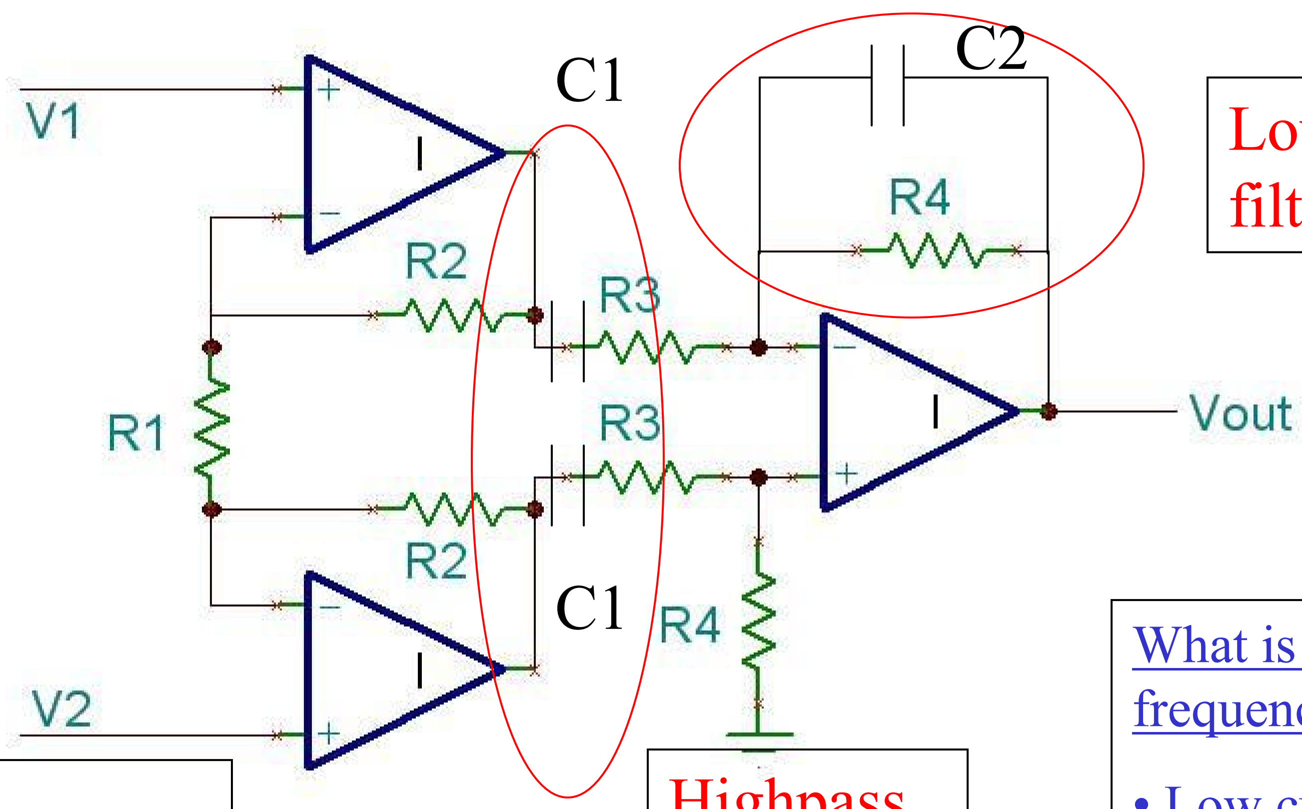
$$V_{OUT} = -(V_1 - V_2)(1 + 2R_2/R_1)(R_4/R_3)$$

Gain from <u>Stage I</u> and <u>Stage II</u>

<u>Features:</u>

- Differential amp
- Very high gain
- Very high input R
- Common mode rejection
- (we also need filters)

INSTRUMENTATION AMPLIFIER: FILTERING



Gain from Stage I and Stage II

Features:

- Bandwidth
  - Low cutoff
  - High cutoff

What is the Cut-off frequency?

- Low cutoff
- High cutoff
- f= {1/(2 pi RC)}

Signal Sources from Body

- These are all types of biopotentials
- Biopotential such as ECG can be seen as a voltage source with
  - Magntitude & direction
  - i.e. a Vector – also, a "Dipole"
- There are many other signal sources, of course
  - Cells, muscles, nerves, skin…all cells, and whole organs

ECG: Einthoven's Triangle

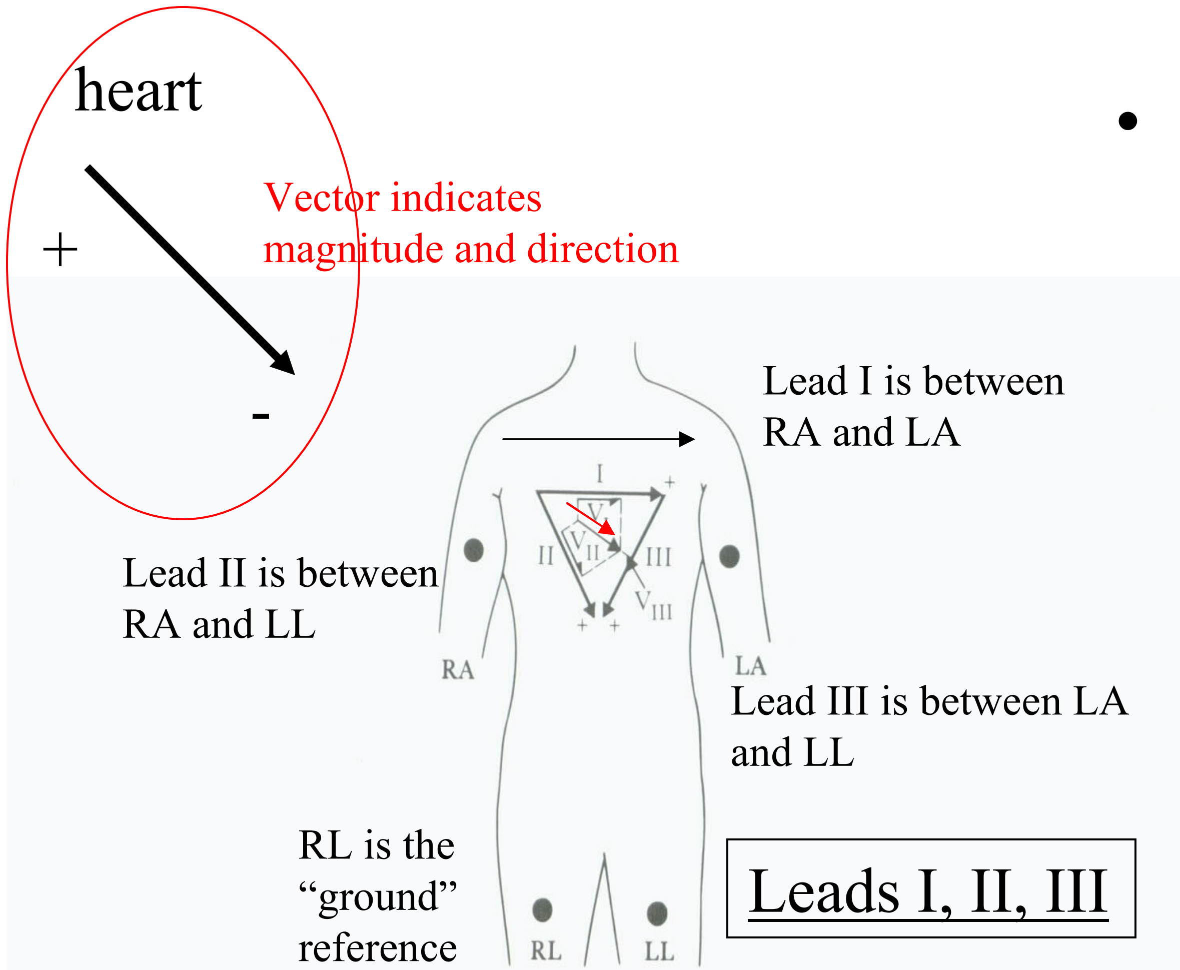


Figure 6.3 Cardiologists use a standard notation such that the direction of the lead vector for lead I is 0°, that of lead II is 60°, and that of lead III is 120°. An example of a cardiac vector at 30° with its scalar components seen for each lead is shown.

- Three vectors used to fully identify the electrical activity
  - Vector shown in frontal plane of the body

Kirchhoff's law is used for the three leads

$$I - II + III = 0$$

ECG: Electrode Placement

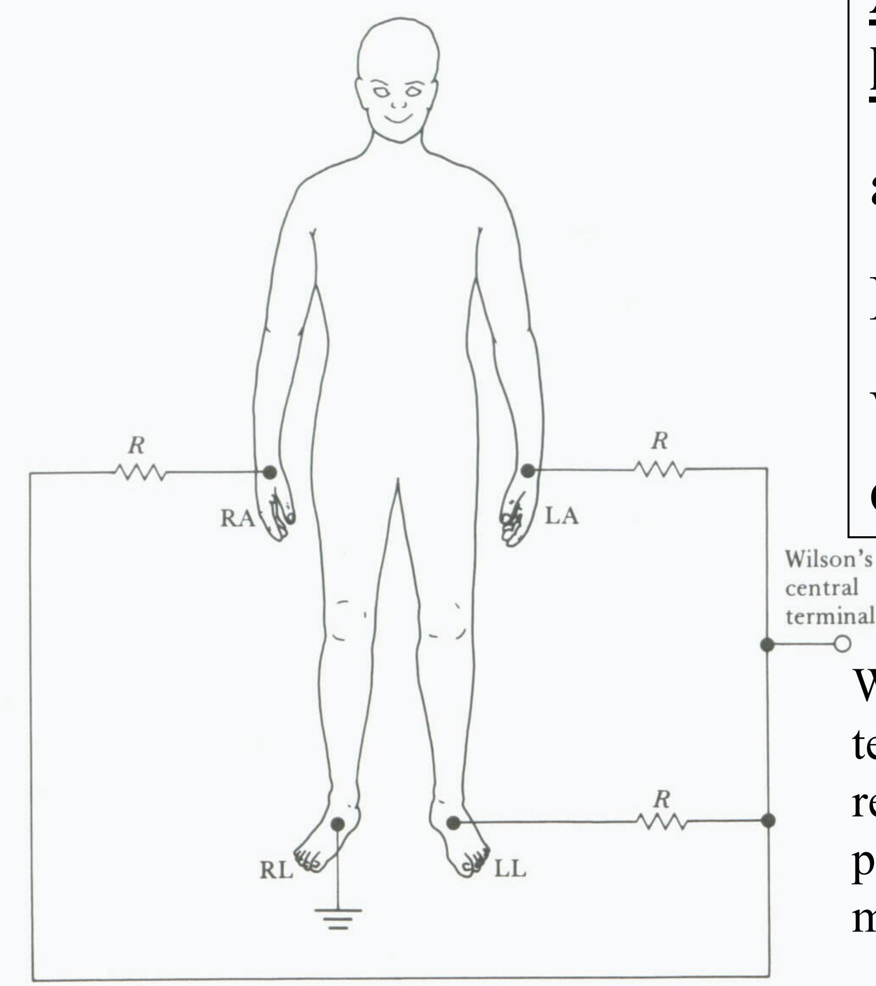


Figure 6.4 Connection of electrodes to the body to obtain Wilson's central terminal

<u>Augmented leads:</u>

aVR, aVL, aVF

Right, left, foot

With respect to central terminal

Wilson's central terminal…neutral reference against which potential of any point is measured

ECG: Transverse Plane

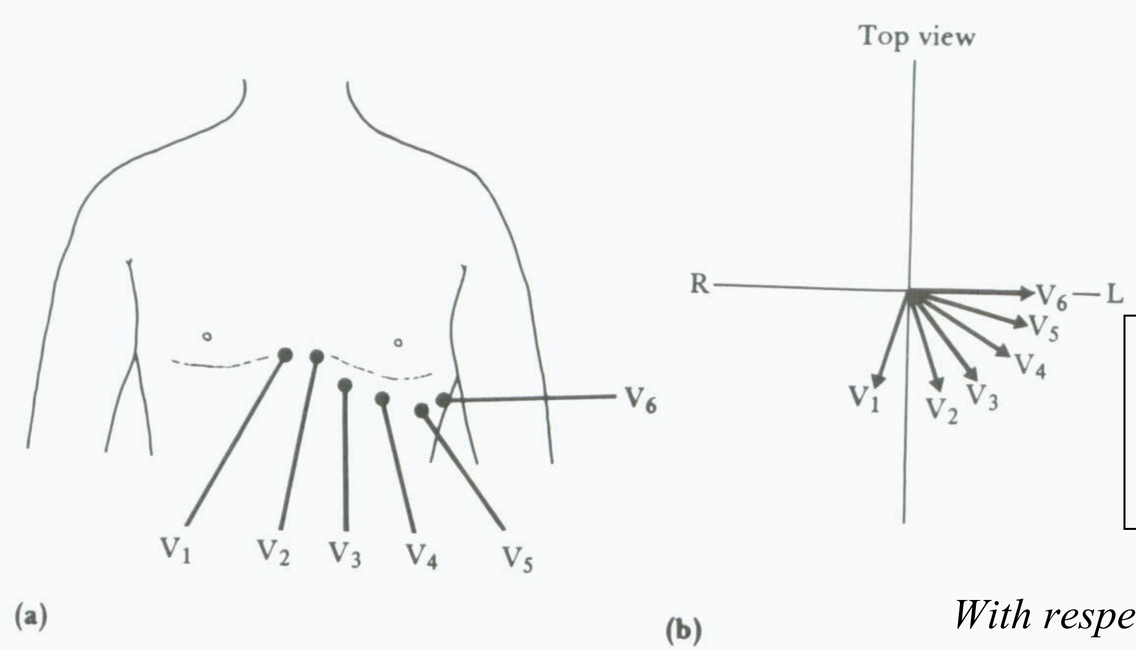


Figure 6.6 (a) Positions of precordial leads on the chest wall. (b) Directions of precordial lead vectors in the transverse plane.

With respect to central terminal

<u>Chest leads:</u>

V1,…V6

- Chest leads used to obtain the ECG in the transverse plane; Obtains ECG from the posterior side of the heart
- All together: 12 leads **(I,II,III; aVR, aVL, aVF, V1…V6)**

The 12 Lead ECG System…used in all clinical Cardiology

EEG: Electrode Recording System

- EEG recording is done using a standard lead system called 10-20 system
- Recall dipole concept to identify source of brain activity

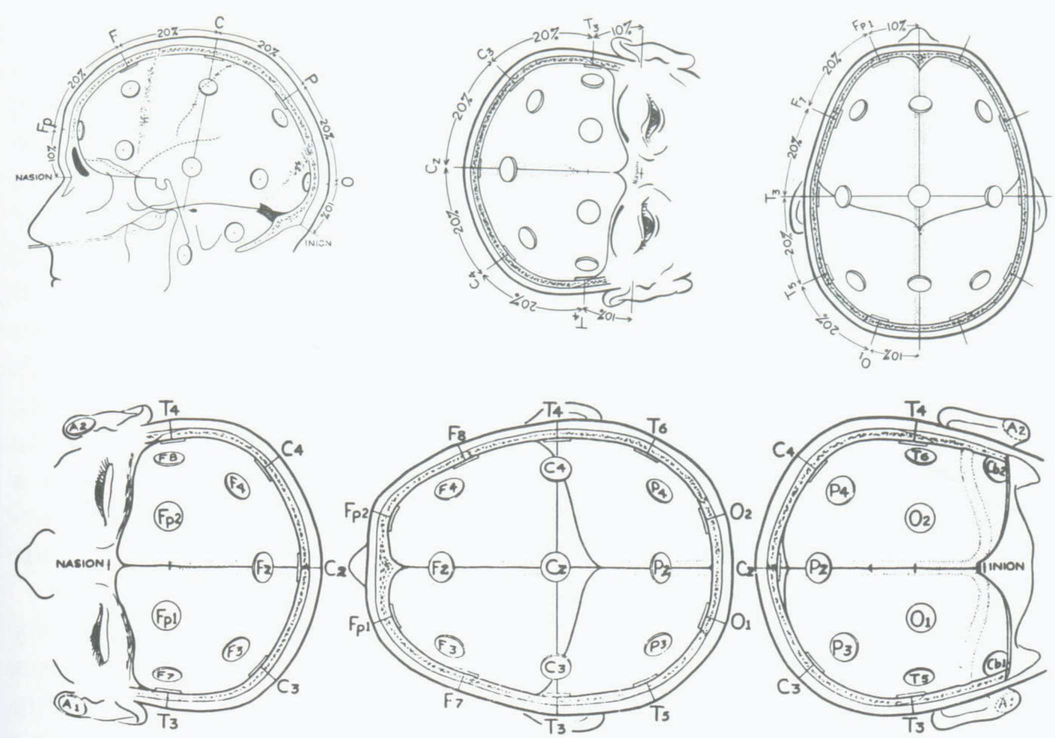


Figure 4.28 **The 10-20 electrode system** This system is recommended by the International Federation of EEG Societies. (From H. H. Jasper, "The Ten-Twenty Electrode System of the International Federation in Electroencephalography and Clinical Neurophysiology," *EEG Journal*, 1958, **10** (Appendix), 371–375.)

Other Biopotentials?

- ECG
- EEG
- EMG
- EGG
- ERG…

Other Signal Sources?

- temperature
- motion
- pH
- pO2
- chemicals…

FREQUENCIES OF BIOPOTENTIALS

Signal	Frequency range (Hz)	Amplitude range(mV)
ECG	0.01 – 100	0.05 – 3
EEG	0.1 – 80	0.001 – 1
EOG	0.01 – 10	0.001 – 0.3
EMG	50 – 3000	0.01 – 100

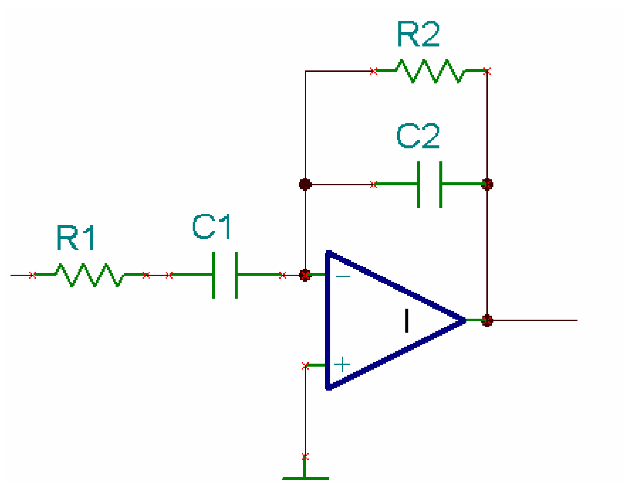
WHY FREQUENCY ?

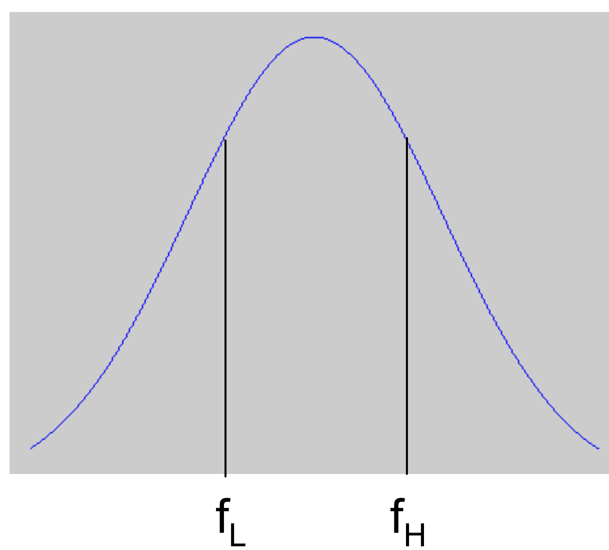
When measuring biopotentials (say ECG), EVERYTHING else

– power line interference

– even other biopotentials (like EEG, EMG, EOG)

are noise sources. These have characteristic frequencies. So use Band Pass Filters.





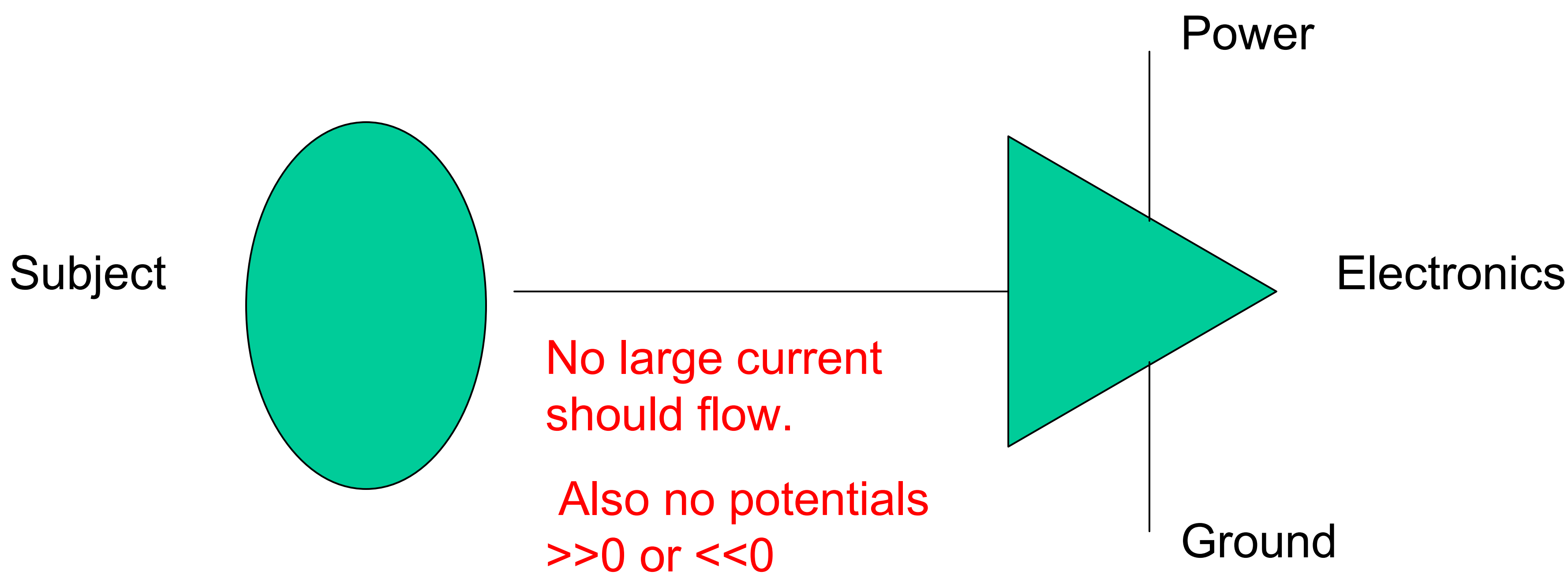
Pass only f_L to f_H attenuate the others.

NOISE

- Several sources
  - 60Hz power lines – *shielding, filtering*
    - *(and harmonics; also RF or radio frequencies)*
  - Other biopotentials
    - *e.g.EOG in EEG or EMG in ECG*
  - Motion artifacts – *relaxed subject*
  - Electrode noise – *high quality electrodes, good contacts*
  - Circuit noise – *good design, good components*
  - Common mode noise – *differential design, high CMRR*

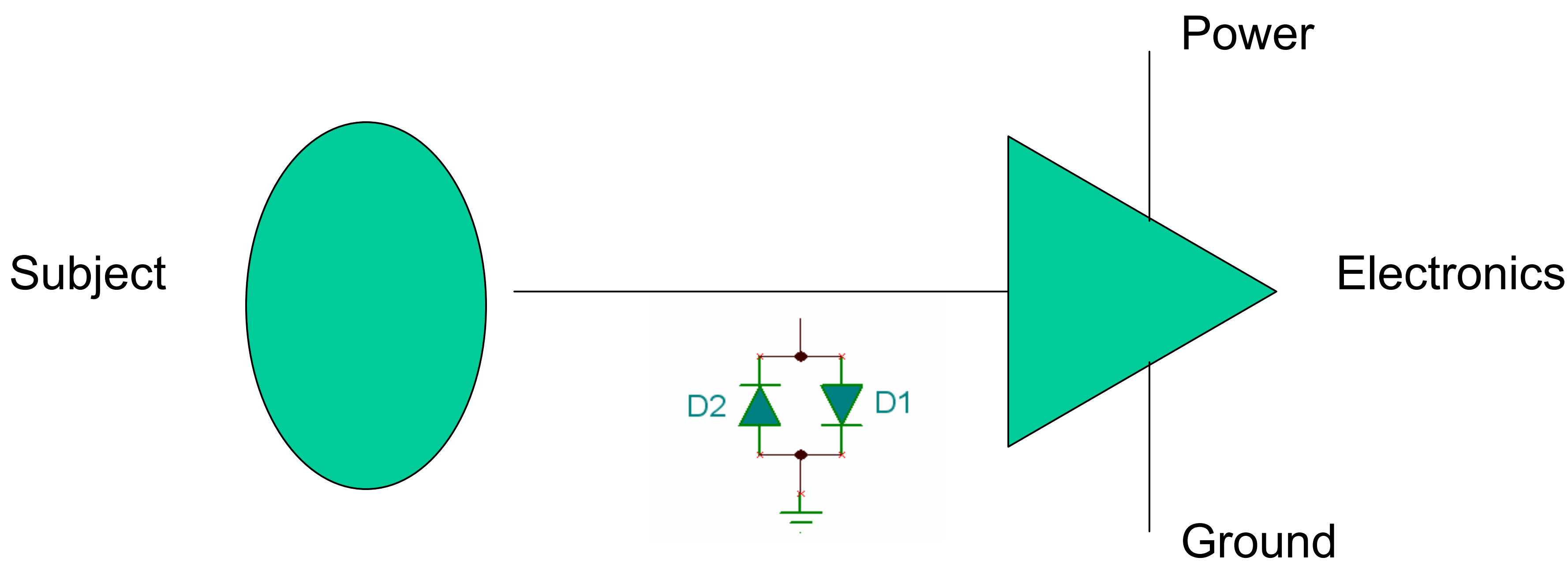
SAFETY

- Amplifiers are powered, should not shock or electrocute the subject



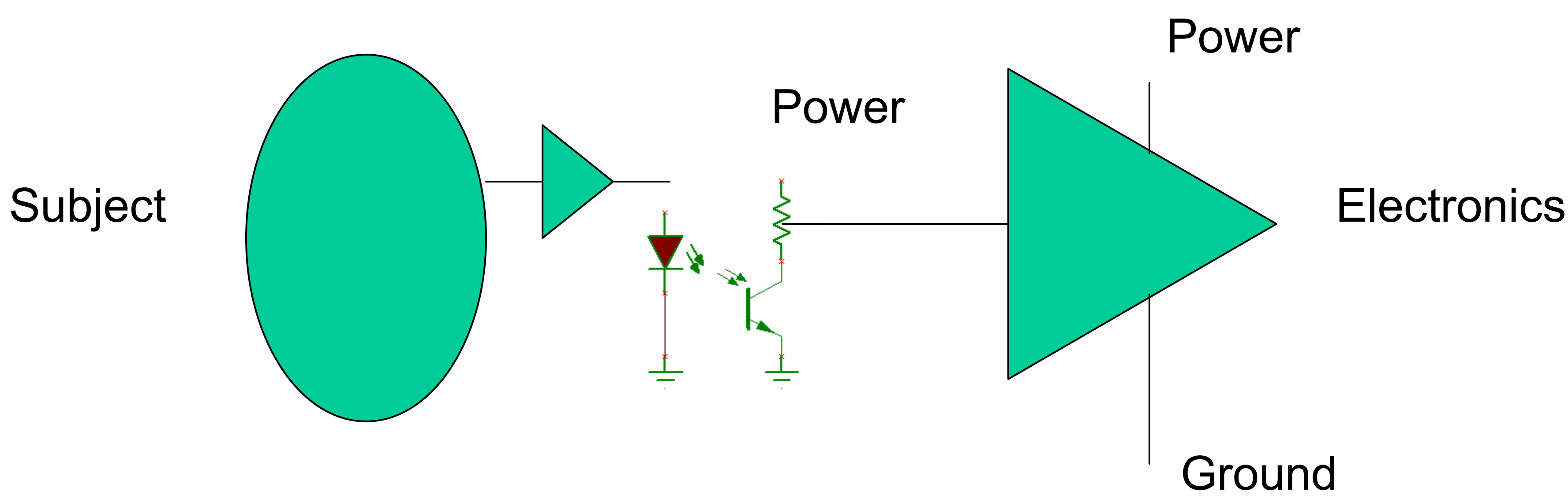
SAFETY: PROTECTION CIRCUITS

- If potential >>0, high current grounded through D1
- If potential <<0, high current grounded through D2



SAFETY: ISOLATION

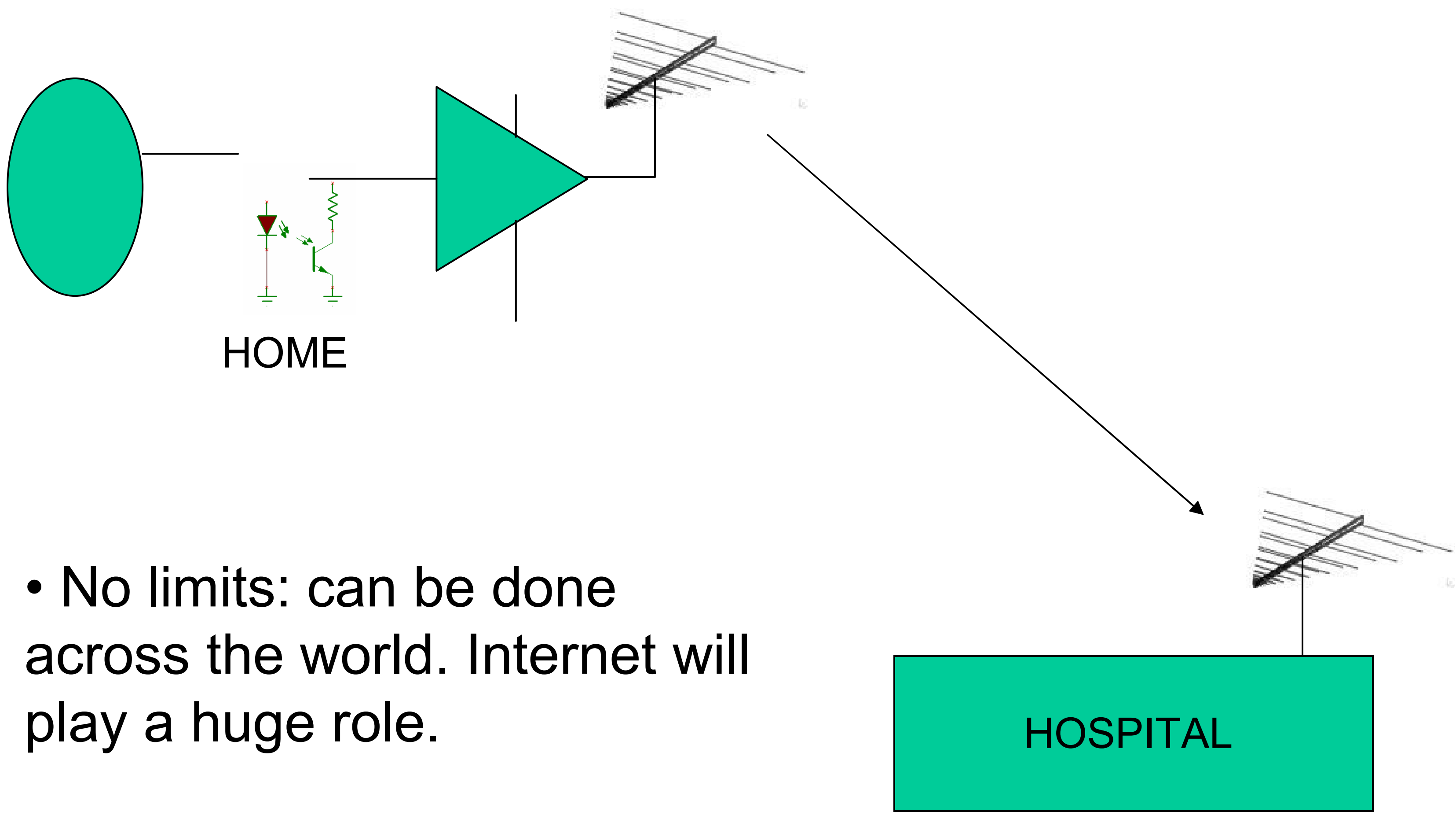
- Potential transferred through optoelectronics (shown), transformers etc.
- Circuits are electrically isolated, no current leakage



Electricity -> Light -> Electricity ➔ Provides electrical isolation

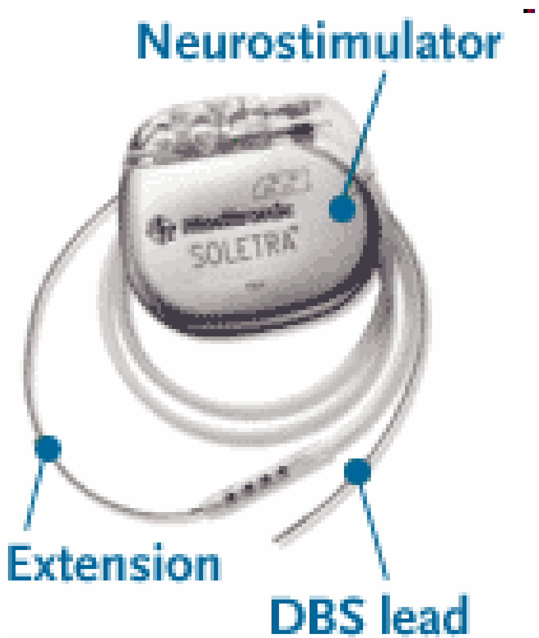
TELEMETRY

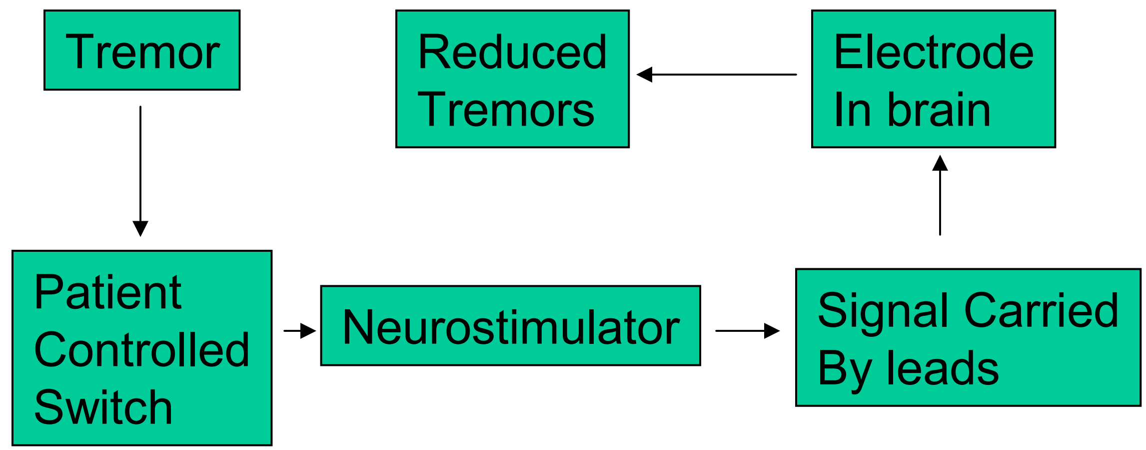
- Means wireless transmission of data from and to the device



- No limits: can be done across the world. Internet will play a huge role.

APPLICATION: Neurostimulator system by Medtronic for Parkinson's Disease



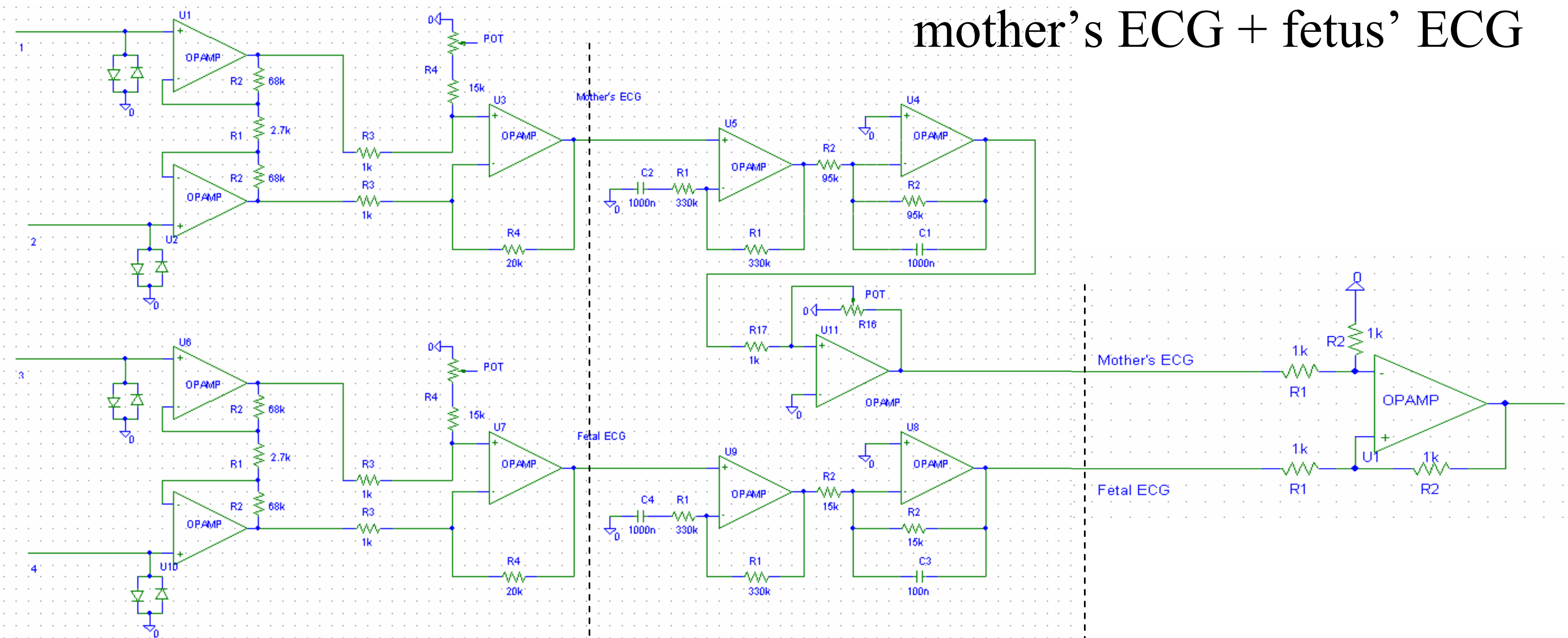


APPLICATION: Medtronic MiniMed Continuous Glucose Monitoring System

- Sensor inserted subcutaneously into abdomen.
- Connected to small pager-sized monitor (worn by patient)
- Continuous reading for up to 3 days to determine direction or trend of blood glucose levels.

APPLICATION: Fetal ECG

Problem: Recorded ECG = mother's ECG + fetus' ECG



UP: mother ECG ampl.

DN: fetus ECG ampl.

mother ECG filters

fetus ECG filters

V_{OUT} = mother's ECG – fetus' ECG

APPLICATION: Gastric Pacemaker

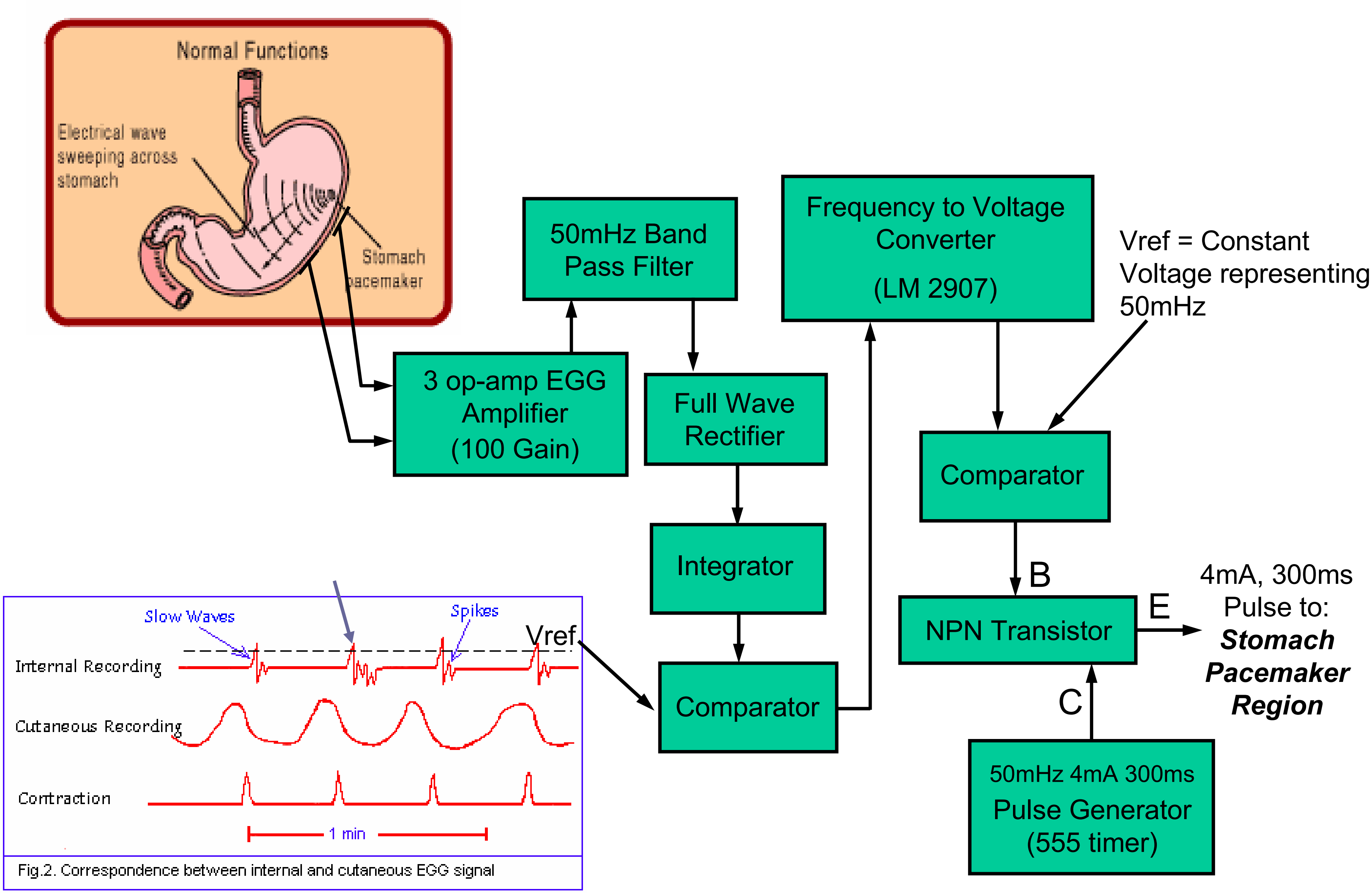


Fig.2. Correspondence between internal and cutaneous EGG signal

ECG: Einthoven's Triangle

Leads I, II, III

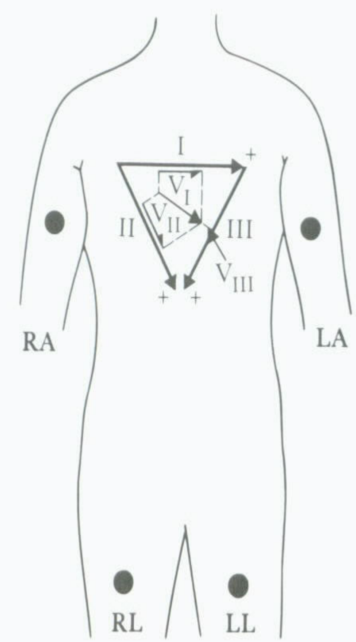


Figure 6.3 Cardiologists use a standard notation such that the direction of the lead vector for lead I is 0°, that of lead II is 60°, and that of lead III is 120°. An example of a cardiac vector at 30° with its scalar components seen for each lead is shown.

- Three vectors used to fully identify the electrical activity
  - Vector shown in frontal plane of the body
- Kirchhoff's law is used for the three leads

$$I - II + III = 0$$

ECG: Electrode Placement

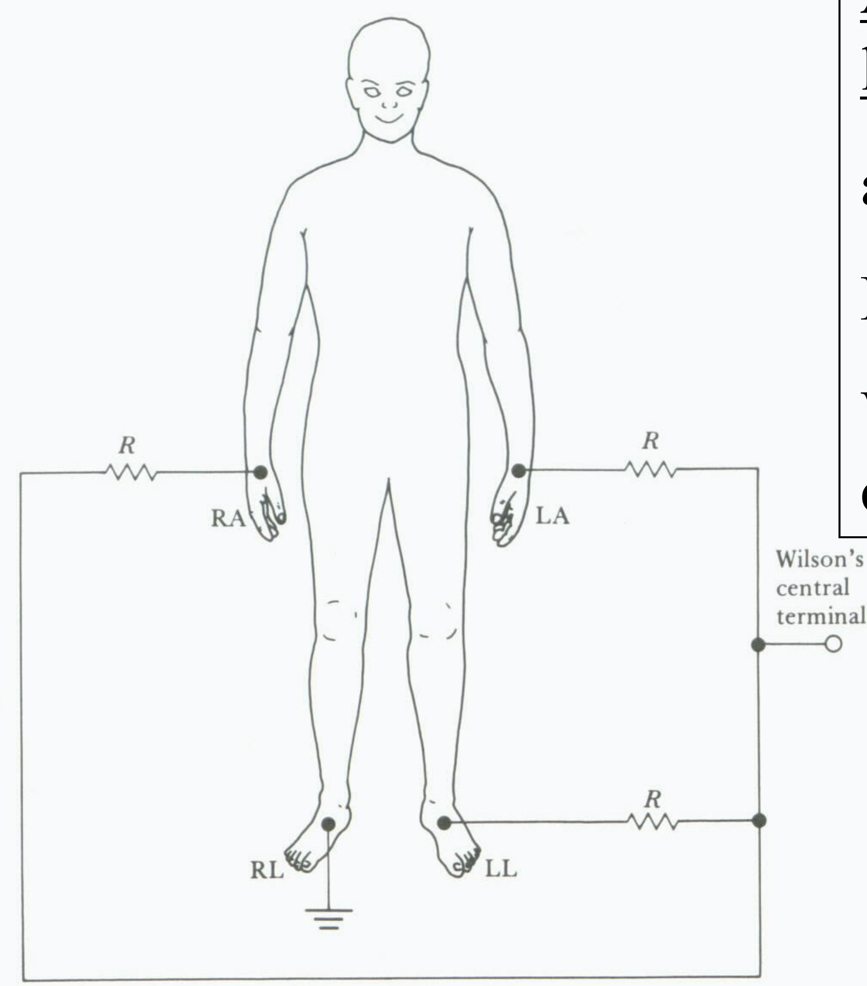


Figure 6.4 Connection of electrodes to the body to obtain Wilson's central terminal

<u>Augmented leads:</u>

aVR, aVL, aVF

Right, left, foot

With respect to central terminal

ECG: Transverse Plane

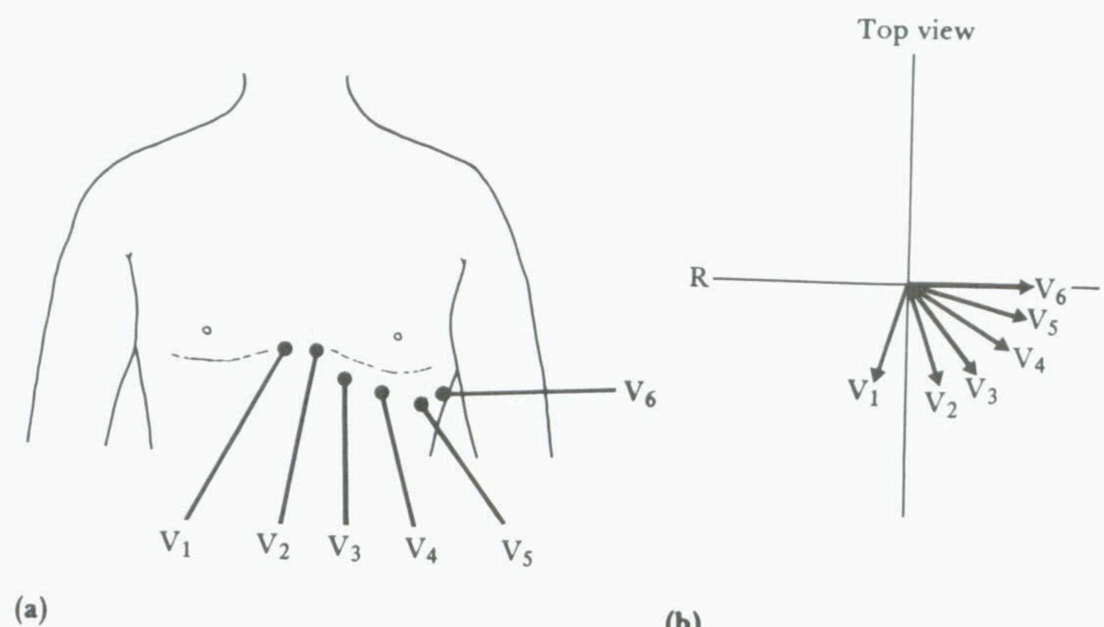


Figure 6.6 (a) Positions of precordial leads on the chest wall. (b) Directions of precordial lead vectors in the transverse plane.

Chest leads:

V1,…V6

- Chest leads used to obtain the ECG in the transverse plane; Obtains ECG from the posterior side of the heart
- All together: 12 leads **(I,II,III; aVR, aVL, aVF, V1…V6)**

EEG: Electrode Recording System

- EEG recording is done using a standard lead system called 10-20 system
- Recall dipole concept to identify source of brain activity

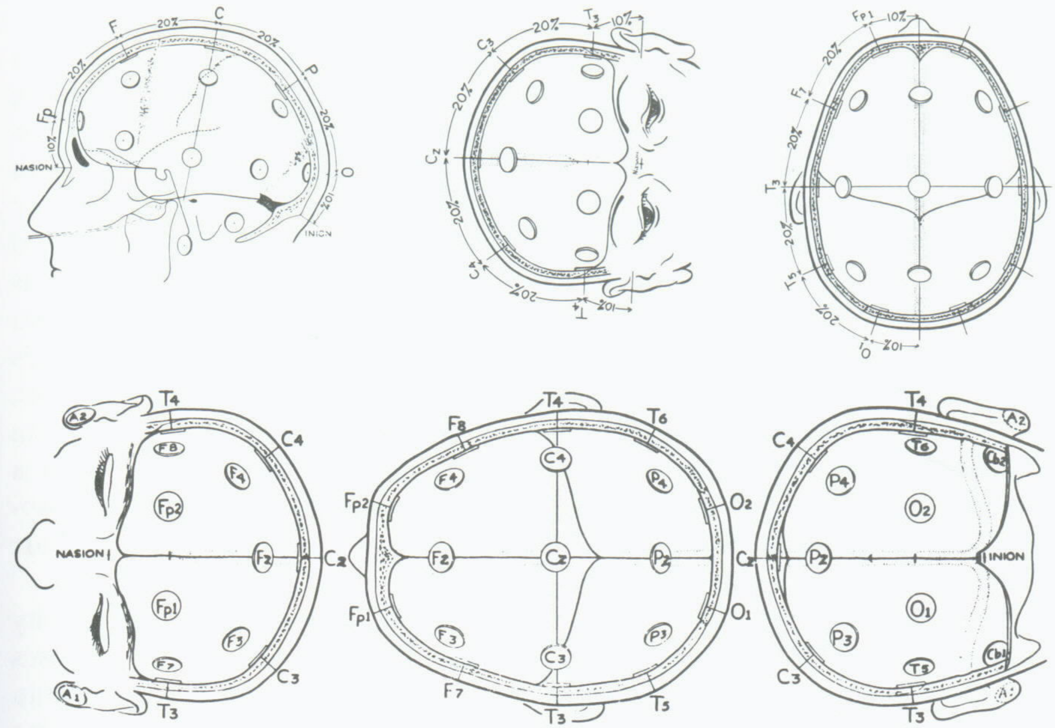


Figure 4.28 **The 10-20 electrode system** This system is recommended by the International Federation of EEG Societies. (From H. H. Jasper, "The Ten-Twenty Electrode System of the International Federation in Electroencephalography and Clinical Neurophysiology," *EEG Journal,* 1958, **10** (Appendix), 371–375.)

FREQUENCIES OF BIOPOTENTIALS

Signal	Frequency range (Hz)	Amplitude range(mV)
ECG	0.01 – 100	0.05 – 3
EEG	0.1 – 80	0.001 – 1
EOG	0.01 – 10	0.001 – 0.3
EMG	50 – 3000	0.01 – 100

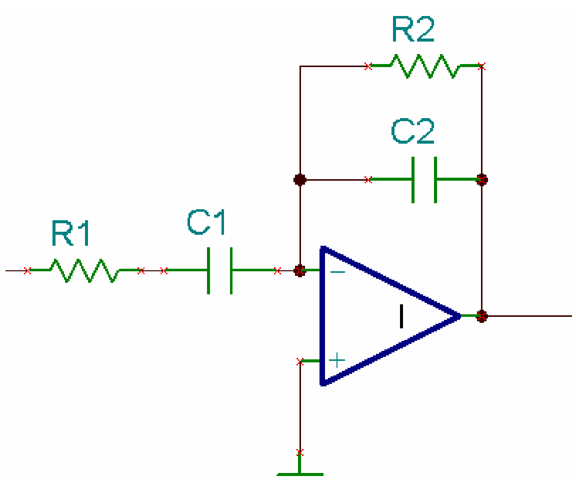
WHY FREQUENCY ?

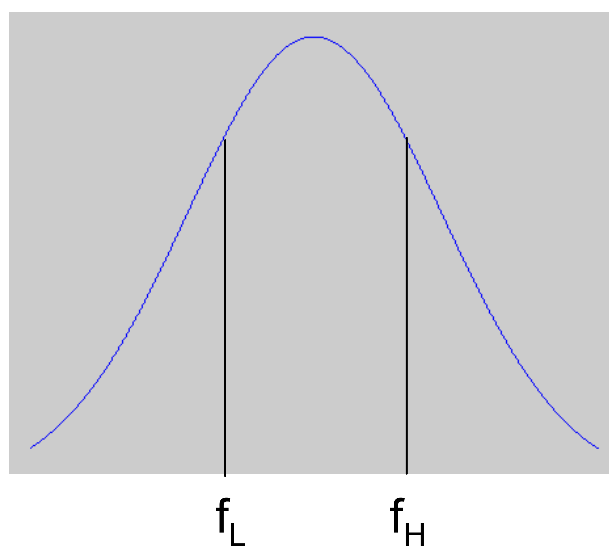
When measuring biopotentials (say ECG), EVERYTHING else

– power line interference

– even other biopotentials (like EEG, EMG, EOG)

are noise sources. These have characteristic frequencies. So use Band Pass Filters.





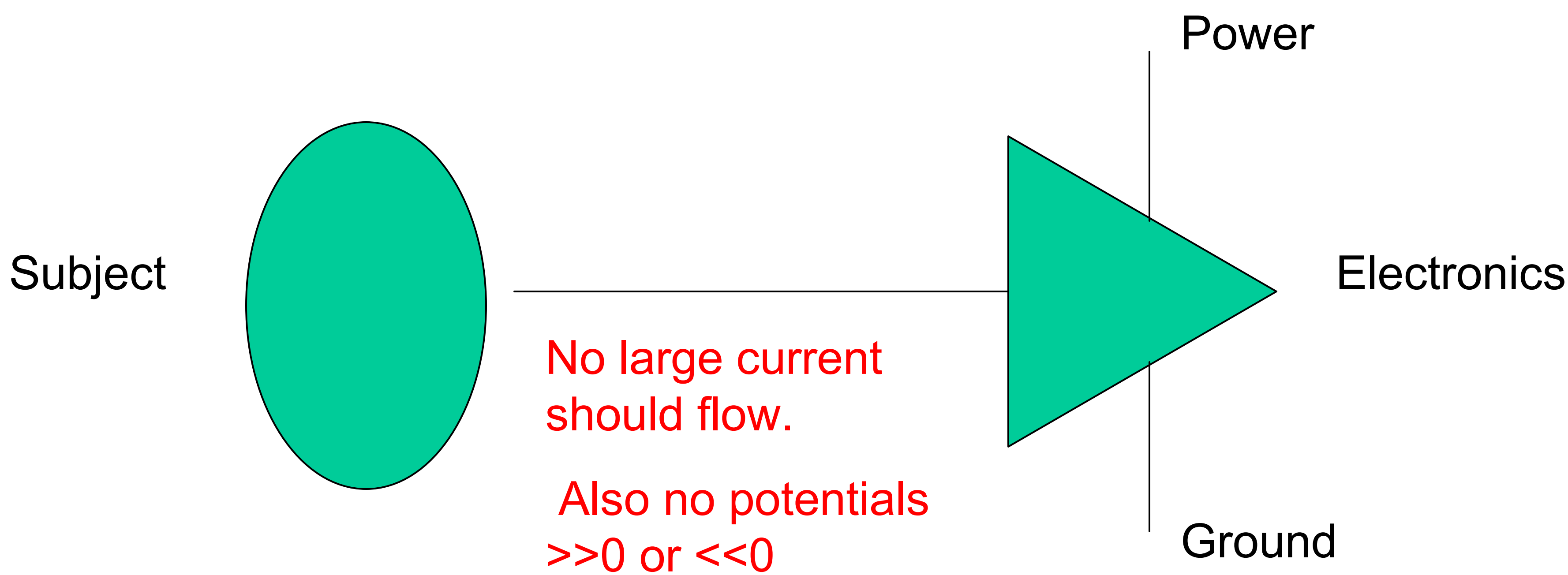
Pass only f_L to f_H attenuate the others.

NOISE

- Several sources
  - 60Hz power lines – *shielding, filtering…Faraday cage*
    - *(and harmonics; also RF or radio frequencies)*
  - Other biopotentials
    - *e.g.EOG in EEG or EMG in ECG*
  - Motion artifacts – *relaxed subject*
  - Electrode noise – *high quality electrodes, good contacts*
  - Circuit noise – *good design, good components*
  - Common mode noise – *differential design, high CMRR*

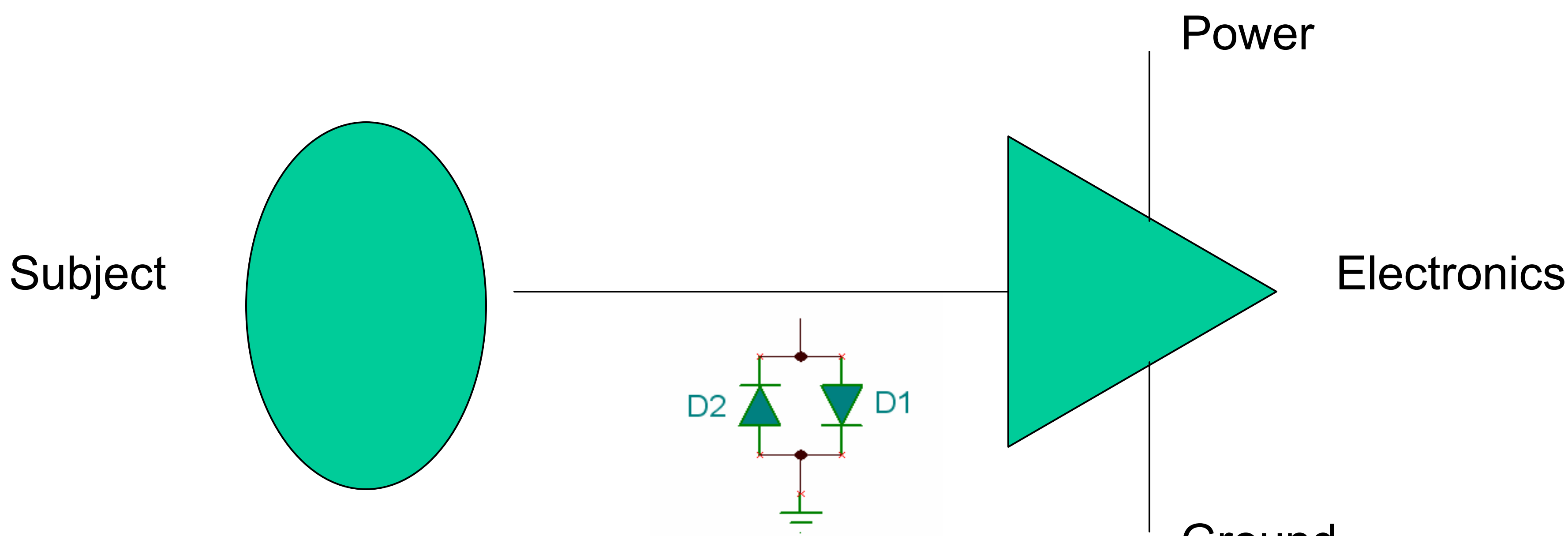
SAFETY

- Amplifiers are powered, should not shock or electrocute the subject



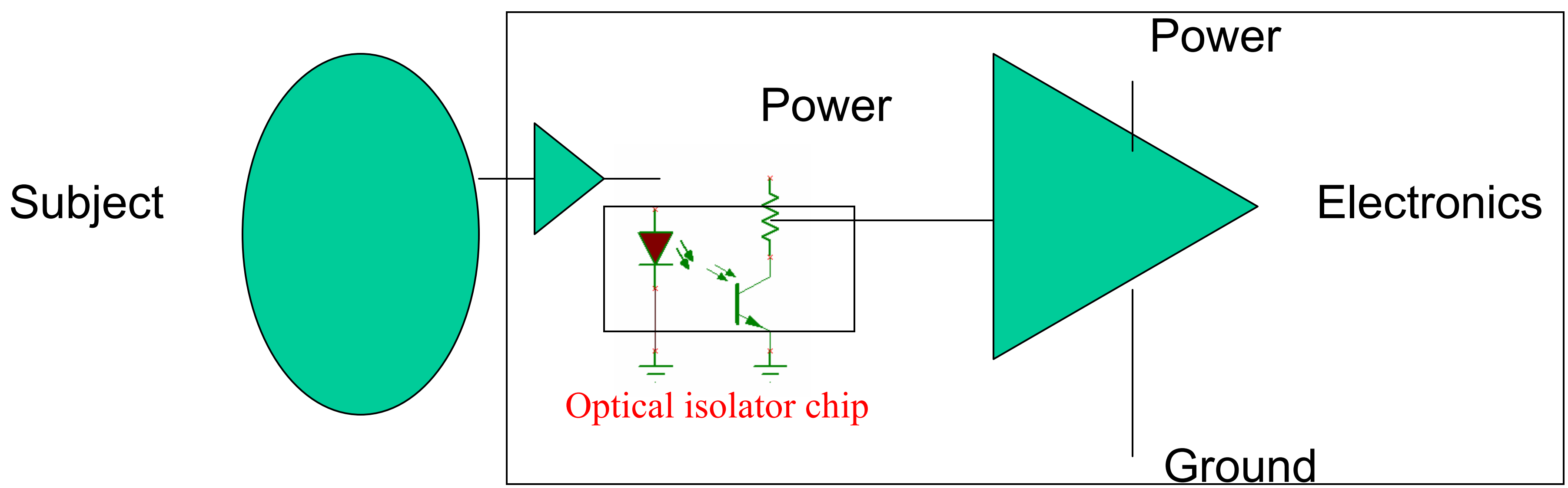
SAFETY: PROTECTION CIRCUITS

- If potential >>0, high current grounded through D1
- If potential <<0, high current grounded through D2



SAFETY: ISOLATION

- Potential transferred through optoelectronics (shown), transformers etc.
- Circuits are electrically isolated, no current leakage

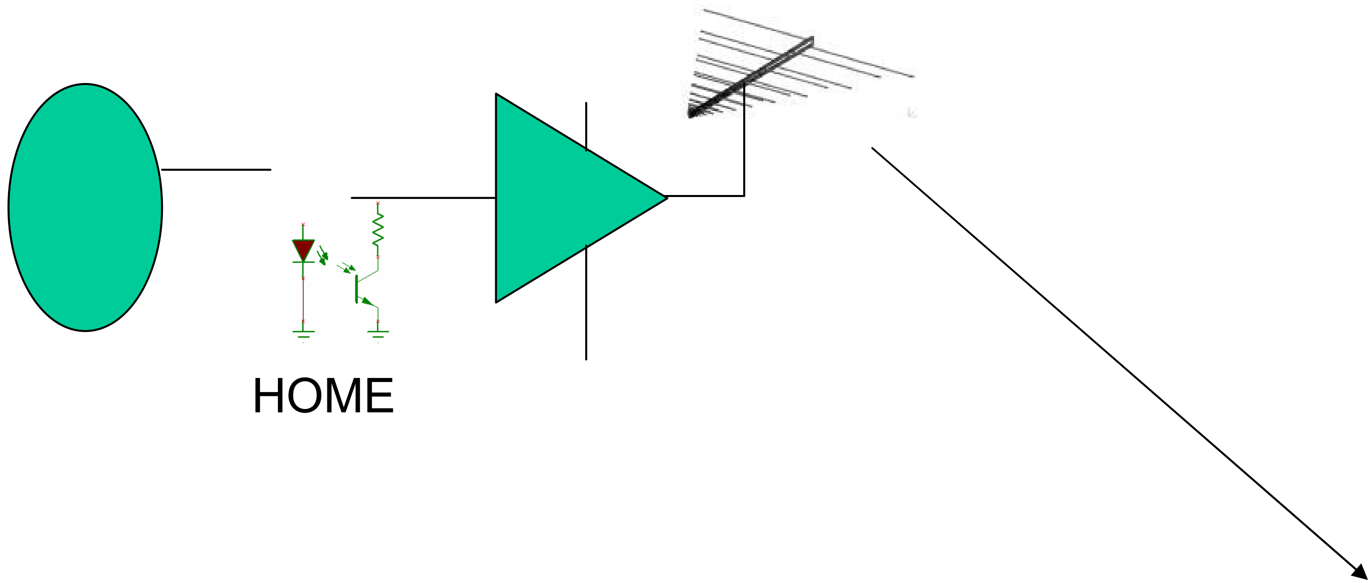


Electricity -> Light -> Electricity ➔ Provides electrical isolation

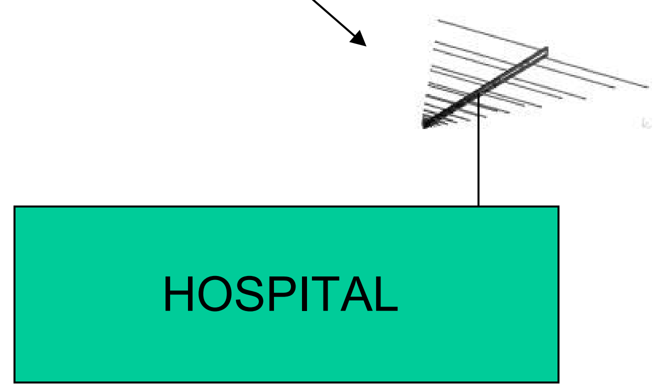
Alternately…use a transformer (its primary/secondary coils are 'isolated')

TELEMETRY

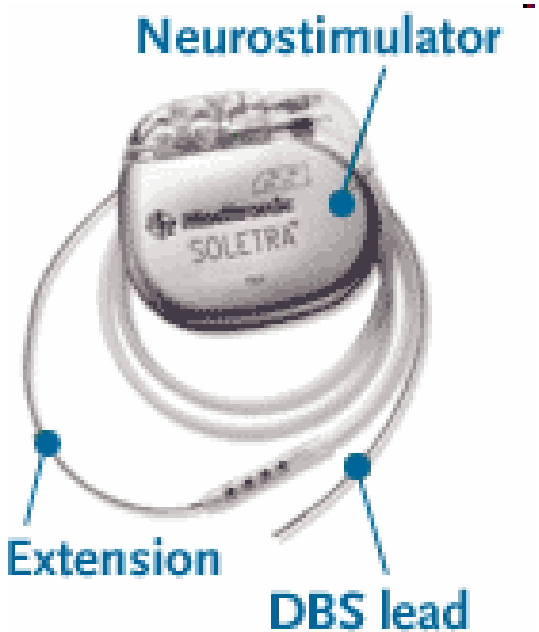
- Means wireless transmission of data from and to the device

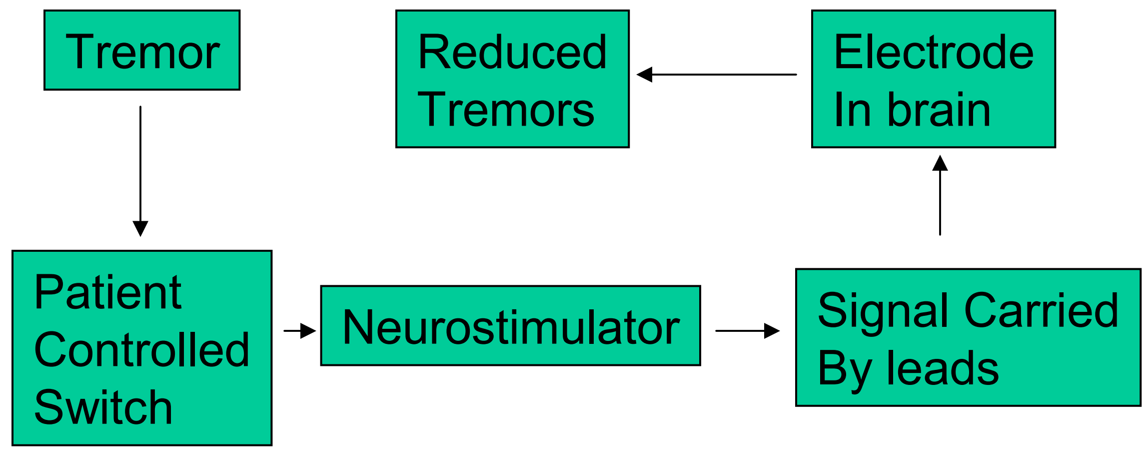


- No limits: can be done across the world. Internet will play a huge role.



APPLICATION: Neurostimulator system by Medtronic for Parkinson's Disease





APPLICATION: Medtronic MiniMed Continuous Glucose Monitoring System

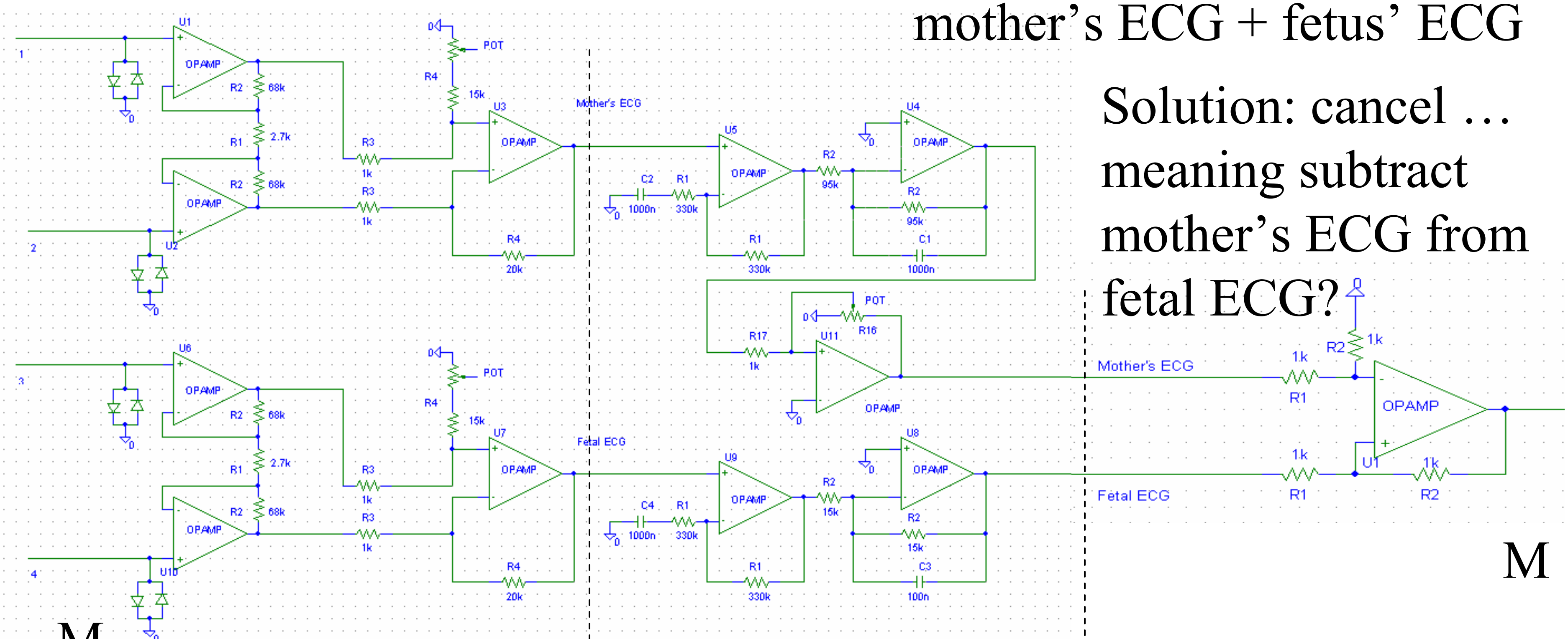
- Sensor inserted subcutaneously into abdomen.
- Connected to small pager-sized monitor (worn by patient)
- Continuous reading for up to 3 days to determine direction or trend of blood glucose levels.

APPLICATION: Fetal ECG

F+M

Problem: Recorded ECG = mother's ECG + fetus' ECG

Solution: cancel … meaning subtract mother's ECG from fetal ECG?



M

M

UP: mother ECG ampl.

DN: fetus ECG ampl.

mother ECG filters

fetus ECG filters

V_{OUT} = mother's ECG – fetus' ECG

APPLICATION: Gastric Pacemaker

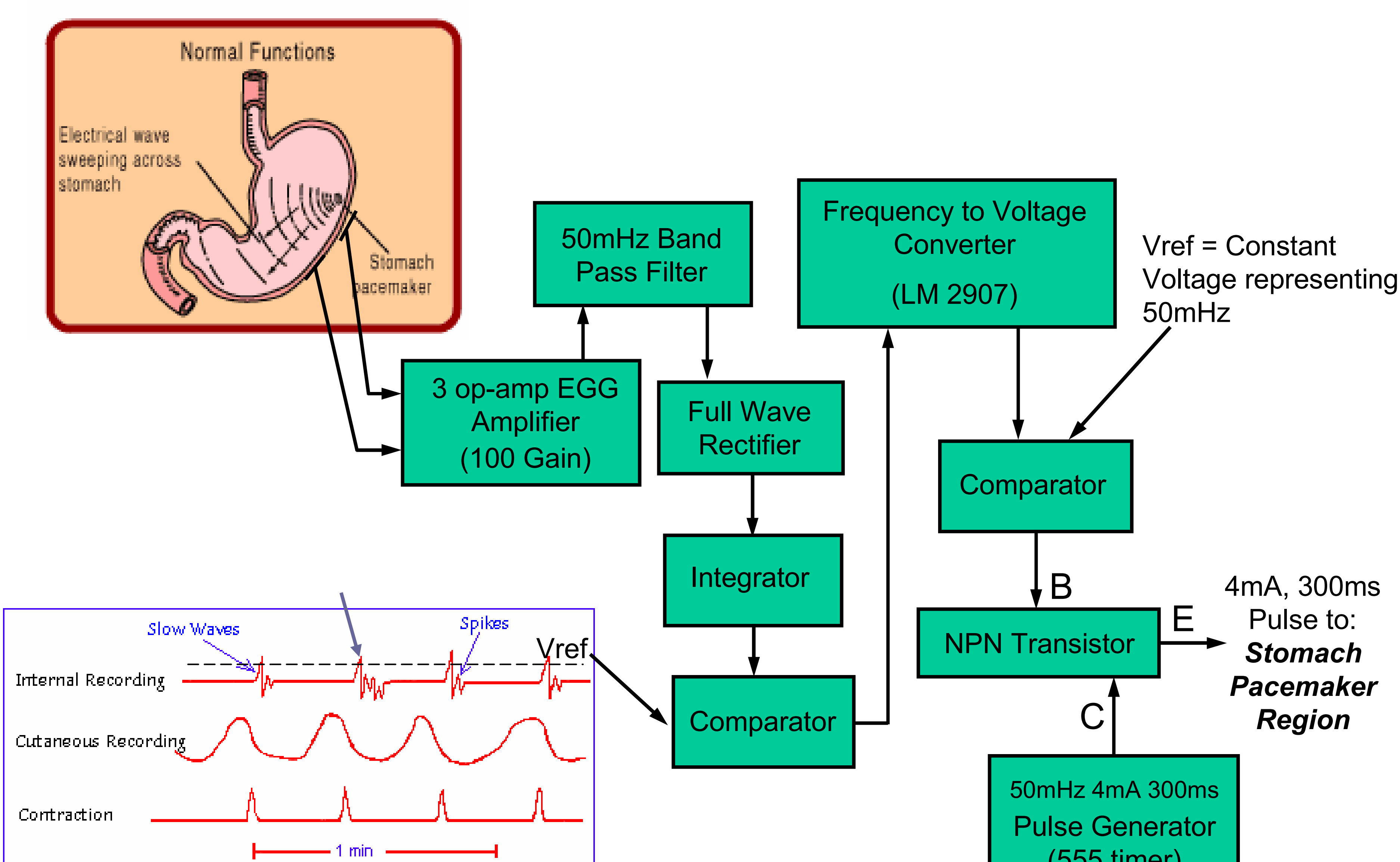
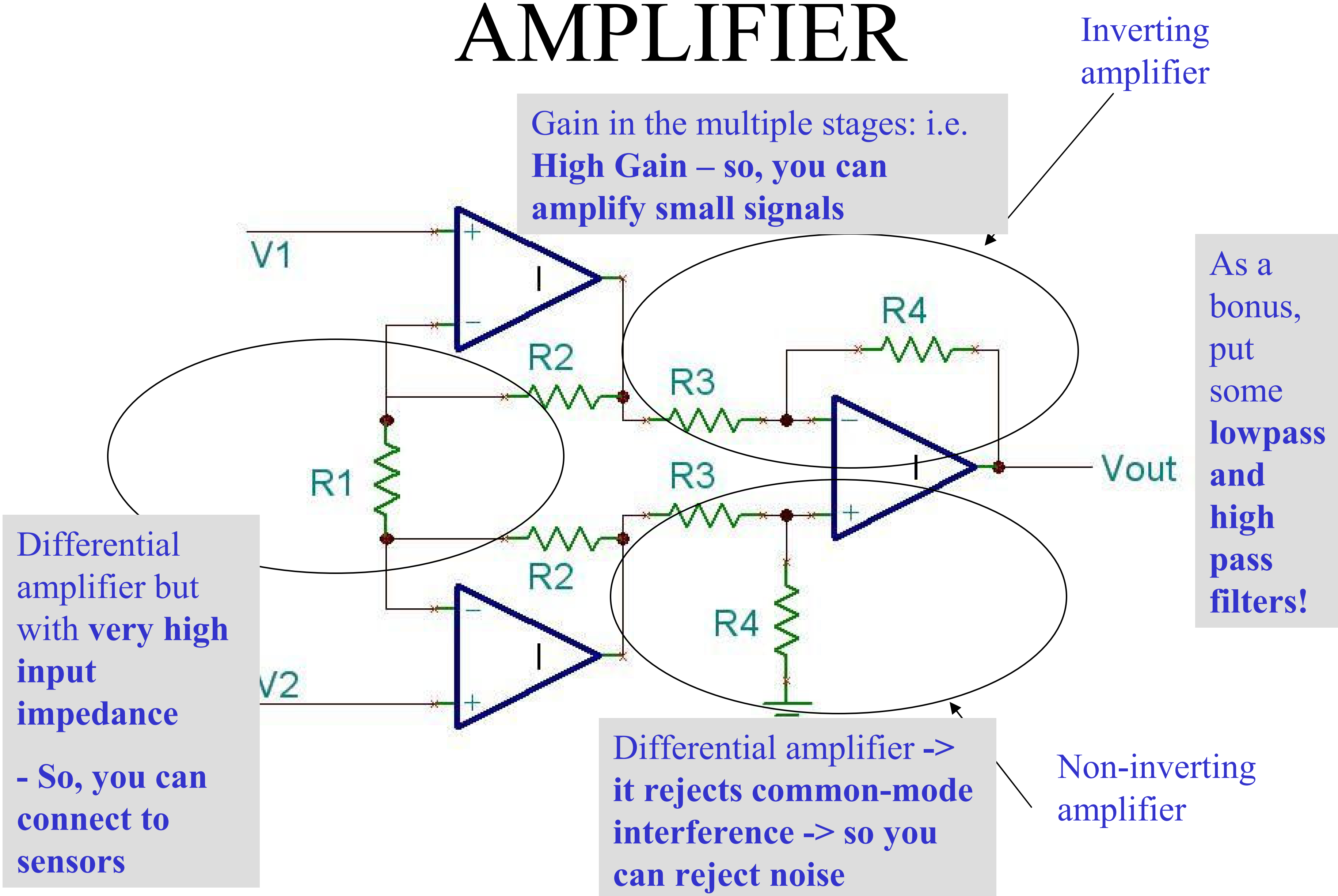
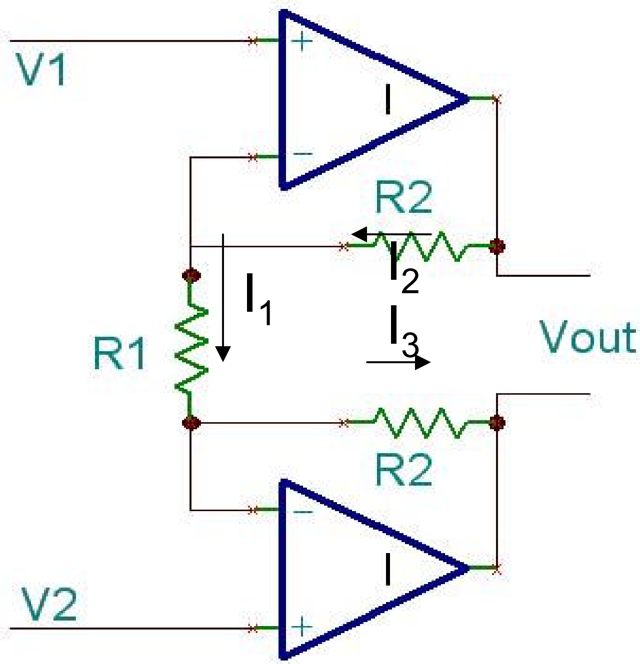


Fig.2. Correspondence between internal and cutaneous EGG signal

INSTRUMENTATION AMPLIFIER



INSTRUMENTATION AMPLIFIER: STAGE 1



Recall virtual ground of opamps

$I_1 = (V_1 – V_2)/R_1$

Recall no current can enter opamps and Kirchoff's current law

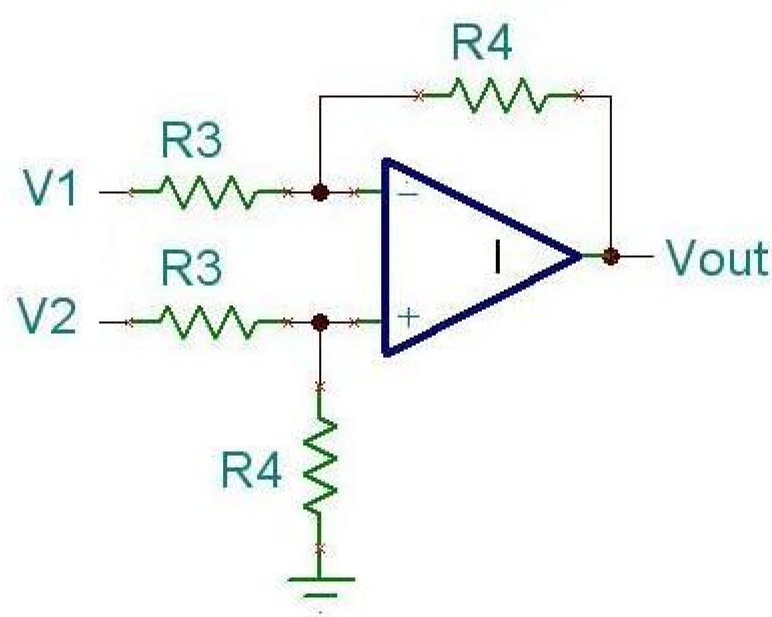
$I_2 = I_3 = I_1$

Recall Kirchoff's voltage law

$V_{OUT} = (R_1 + 2R_2)(V_1 – V_2)/R_1$

$= (V_1 – V_2)(1+2R_2/R_1)$

INSTRUMENTATION AMPLIFIER: STAGE 2



Recall virtual ground of opamps and voltage divider

$V_- = V_+ = V_2R_4/(R_3 + R_4)$

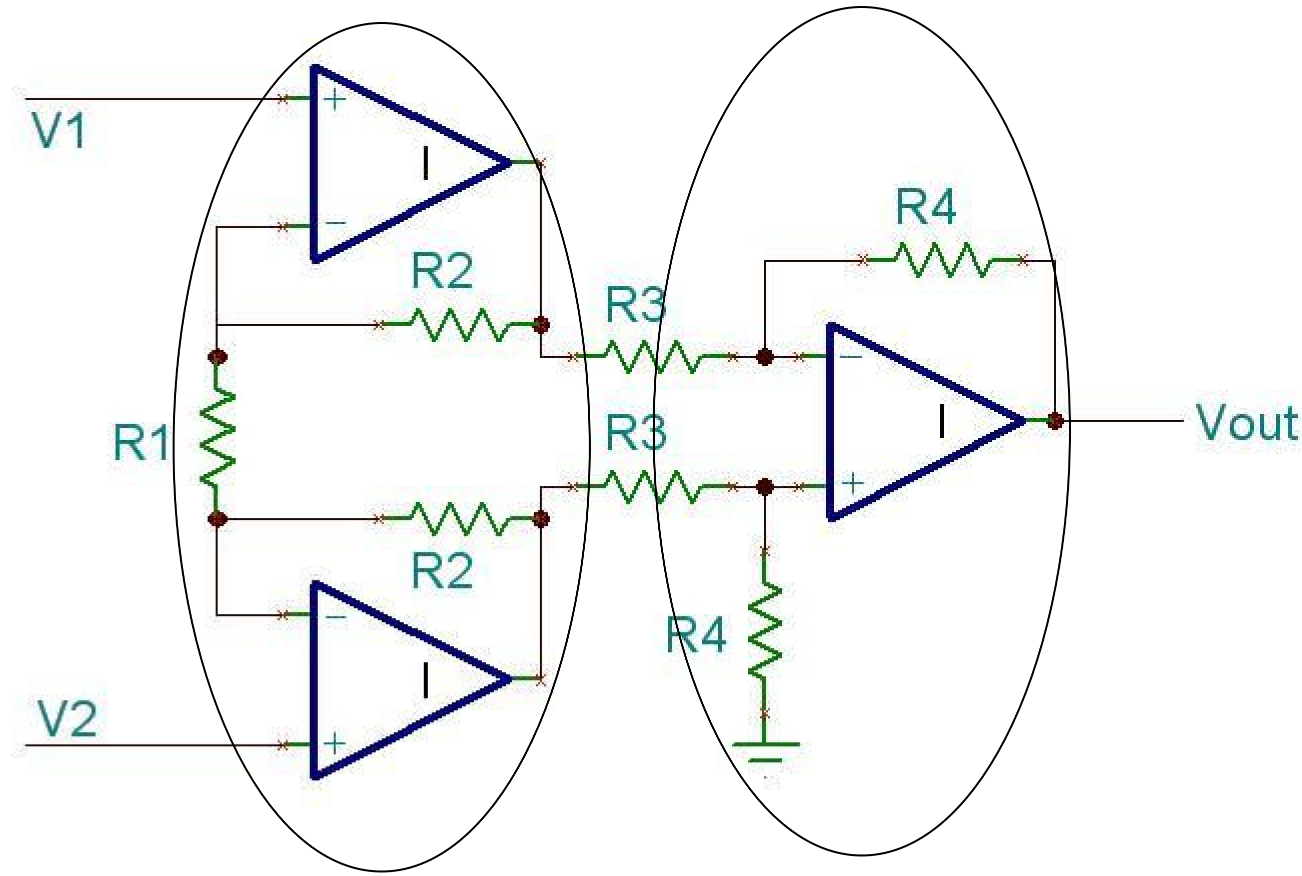
Recall no current can enter opamps

$(V_1 – V_-)/R_3 = (V_- – V_{OUT})/R_4$

Solving,

$V_{OUT} = – (V_1 – V_2)R_4/R_3$

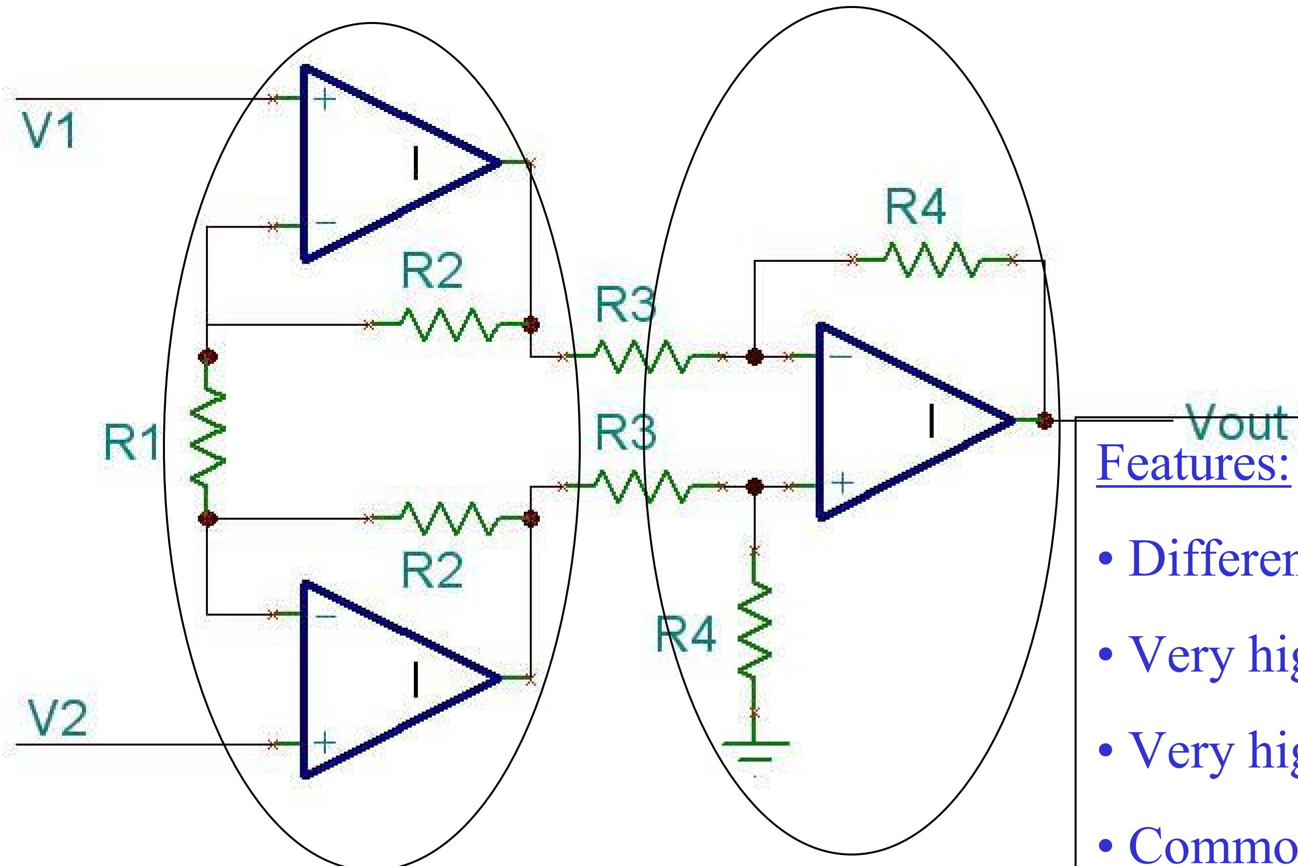
INSTRUMENTATION AMPLIFIER: COMPLETE



$$V_{OUT} = -(V_1 - V_2)(1 + 2R_2/R_1)(R_4/R_3)$$

Gain from <u>Stage I</u> and <u>Stage II</u>

INSTRUMENTATION AMPLIFIER: COMPLETE



$$V_{OUT} = -(V_1 - V_2)(1 + 2R_2/R_1)(R_4/R_3)$$

Gain from Stage I and Stage II

Features:

- Differential amp
- Very high gain
- Very high input R
- Common mode rejection
- (we also need filters)

Problems

1. This question reviews the design issues for an ECG amplifier used in monitoring a patient in an operating room or an intensive care.

(a) What are the sources of high voltage hazards? How should the amplifier be protected ? Draw a protection circuit….go beyond…diodes..what else?

(b) It is essential that the patient be further protected from leakage currents and other hazards from the instrument being connected to power and ground. Describe two alternate designs of amplifier isolation. Draw at least one of them in a circuit form.

(c) Besides the amplifier itself, list what else goes into making a full bed-side ECG monitor. You may also add “bells and whistles” to make your device more marketable. Now, itemize and estimate the cost of different materials, features, and other business-related activities that industry would add on to come up with the final instrument cost.

2. Now let us design an ECG amplifier for the pacemaker. You know how to design an ECG amplifier. Modify it for use in a pacemaker. What should be the key features or specifications for an "implanted system?

- For an implanted amplifier that goes in a pacemaker, what will be the sources of electrical interference? How should these interferences be minimized or rejected ?

- Design and draw a small circuit to detect the heart beat pulse (do not draw or design ECG amplifier; give only the pulse detection circuit).

- Research and draw an implanted pacemaker lead. Distinguish unipolar from bipolar leads.

3.1 Origins of Biopotentials, Sources and Field Modeling

The ECG signal generating from the heart can be modeled quite simply as a dipole. If a cardiac dipole has a magnitude of 1 mV and orientation of -45^{o} with respect to Lead I, then calculate, using the Einthoven triangle, the magnitude of the signal in Lead I, II, and III. Show the geometric presentation as well as the trigonometric calculations.

What does the 12-lead ECG system comprise of (sketch the different leads)? Is it superior or inferior to an orthogonal system (X, Y, and Z leads)?

What kind of a lead system would you use to record EEG from the scalp and for localizing the source of epileptic seizure? Sketch it.

What instrument is used to measure the magnetic field from the brain?
B) What are the possible advantages and disadvantages of the magnetic versus electrical measurement? C) To your knowledge, what breakthroughs in the scientific world that have are occurred (or ought to occur?) that would make magnetic field measurement more feasible and affordable? D) If you had a cheap magnetic field sensor (with a relatively lower sensitivity) available what other biomedical application would you think of (other than biopotential measurements).

Show (draw) the possible current distribution between an electrosurgical electrode, body and the return ground electrode. What would be the desirable properties of the ground reference electrode?

3.2 Origins of Biopotentials, Sources and Field Modeling

Imagine it is the beginning of the 20^{th} century. Cardiac activity is suspected as an electrical source inside the torso. Let us say that you were a contemporary of Prof. Einthoven. Prof. Einthoven recommends that to record ECG from the torso using a triangular formulation with what you now know at three leads, I, II, and III (respectively LA-RA, RA-LL, and LA-LL). However, you claim have a different theory of better presenting the cardiac vector on a different lead system (for example, you prefer not to use 3 leads arranged in the form of a triangle). Demonstrate superiority of your lead idea.

After Einthoven's original idea, a number of solutions were suggested. One of these was to put 6 leads (V1-V6) around the left ventricle. a) why around left ventricle? b) for the 6 differential amplifiers, each with one input being V1..V6 what is the other "neutral" input source?

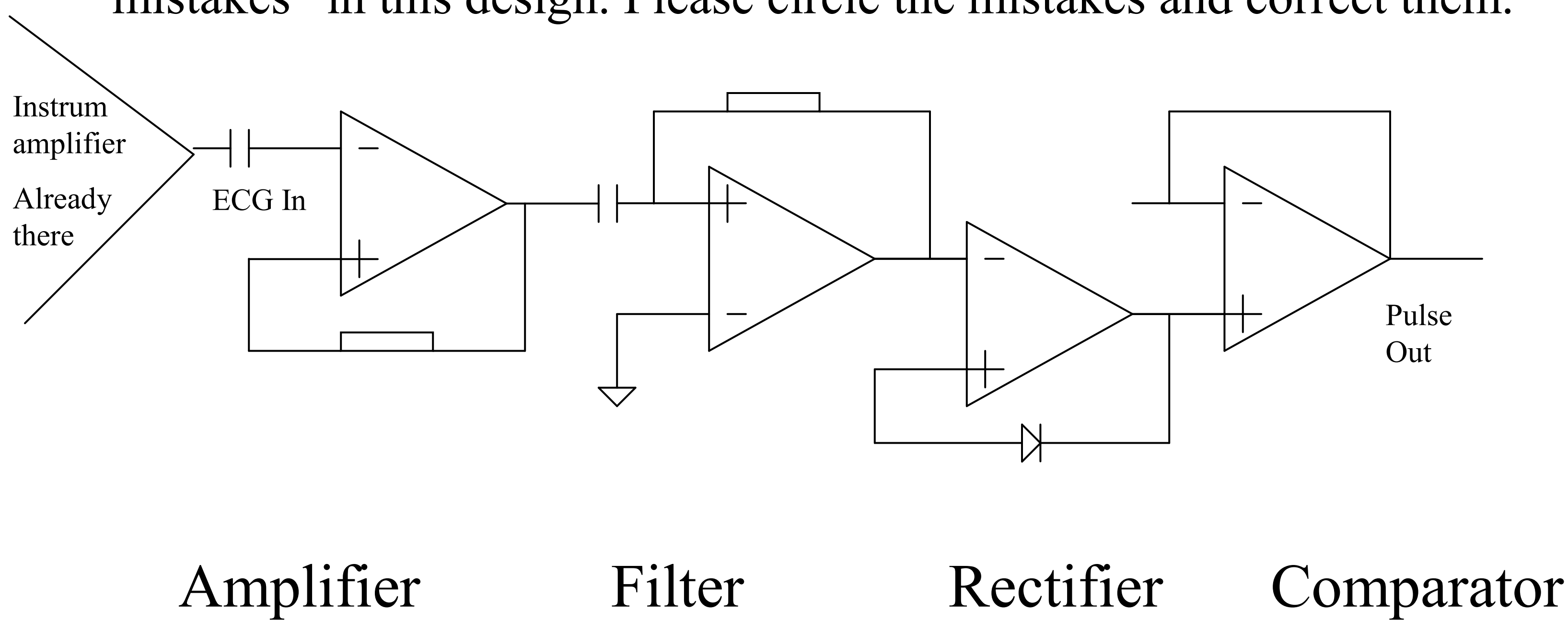
Einthoven came up with the idea of creating a triangle to come up with an experimental interpretation of the cardiac vector. In one measurement, we recorded a 5 mV signal in Lead II and 3 mV signal in lead III. (a) Calculate the Lead I signal magnitude. (b) Calculate the cardiac vector. (Hint: you may do this geometrically using the Einthoven's equilateral triangle or you may do this by calculating the vector (x, y components).

3.3 Origins of Biopotentials, Sources and Field Modeling

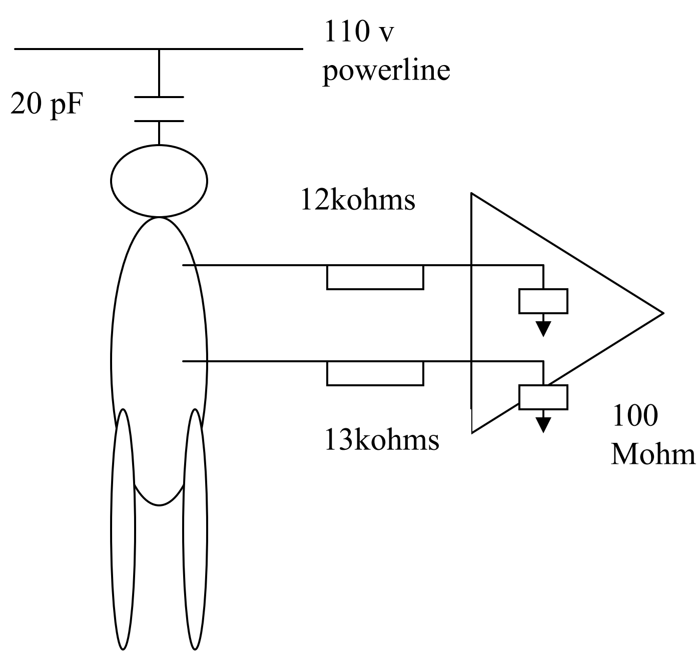
What instrument is used to measure the magnetic field from the brain? B) What are the possible advantages and disadvantages of the magnetic versus electrical measurement? C) To your knowledge, what breakthroughs in the scientific world that have are occurred (or ought to occur?) that would make magnetic field measurement more feasible and affordable? D) If you had a cheap magnetic field sensor (with a relatively lower sensitivity) available what other biomedical application would you think of (other than biopotential measurements).

We would like to record ECG of a fetus while in the womb. The main problem here is that when electrodes are placed on the mother's stomach to capture the fetal ECG, a large maternal ECG signal pulse is also picked up. A) Draw a schematic of the mother and her heart dipole/vector and fetus and its heart dipole/vector. Now, show how mother's ECG might corrupt the fetal ECG. B) How would you eliminate the maternal ECG artifact from the stomach recording? C) Someone suggests that at the most critical moment in labor, as the head of the fetus presents itself first , attach the ECG electrode to fetal scalp. Would you succeed or not in getting fetal ECG from an electrode placed on the scalp and why/why not? D) During the time of the late stage labor, what would be more likely to succeed – electrodes on the mother's stomach or an electrode on fetus's head?

4. You have already built an ECG amplifier. Now you want to build a heart beat (QRS pulse) detector. This design, consisting of a bandpass filter, rectifier and a comparator is sketched below. Unfortunately, there are several "mistakes" in this design. Please circle the mistakes and correct them.



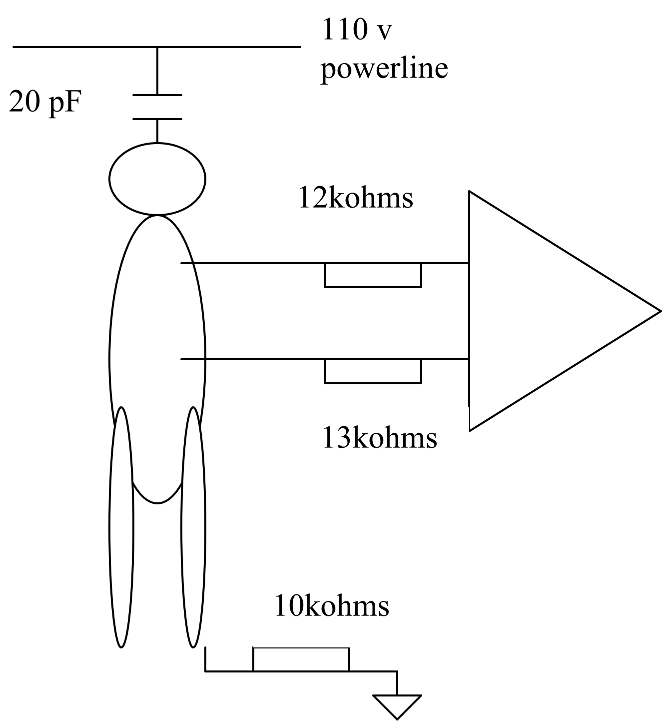
5.1 Electrical Interference Analysis



The following figure shows a person connected to an ECG amplifier via two electrodes with resistance of 12 and 13 kohms. The 110 powerline is coupled via a 20pF capacitance between the powerline and the subject. The input resistance of the amplifier is 100 Mohm (connected to ground). The student testing this set up forgets to connect the third, ground electrode on the subject.

Under the circumstances: a) what is the powerline induced current flowing into the subject? b) what is the common mode voltage produced at the amplifier input? c) What is the differential signal at the 60 Hz powerline signal?

5.2 Electrical Interference Analysis



In the following schematic, what is the current induced into the subject (note that the powerline frequency is 60 Hz)? What is the common-mode voltage? What is the differential interference voltage resulting from the induced current (note that the amplifier input resistance is 100 Mohms)?

If the environmental interference is 1V, what is the CMRR needed to detect ECG signals? B) Derive the signal output when 1 mV differential and 1V common mode signal are fed to an ECG amp with a CMRR of 10,000.

Choice of component values and Optimal Amplifier Design

- What are component values (ranges)
- For a gain of 1000, what should be the R values in an instrumentation amplifier?
- For a frequency response of 0.05 – 100 Hz what should be the filter designs in the amplifier?
- What is the amplifier noise: sqrt(4KTRBW)

Choice of R's and C's

- Cost
- Size
- Availability of the component range
- Tolerance or accuracy
- Temperature performance

Design Choices for Op Amps

- Gain……………….E.g. for small signals
- Input impedance…. E.g. for sensors
- Bandwidth……….. E.g. for video/ultrasound
- Noise…………….. E.g. for camera, EEG
- Temperature stability..E.g. for temperature sensor
- Linearity………….. E.g. for strain gauge amplifier

Noise?

- Thermal noise of resistors
  - remember noise = sqrt(4kTR*BW)
- Electronic noise of semiconductors (p-n junction; diode/transistors)
  - current and voltage noise … go look up specification sheets of commercial op amps and note voltage or current noise specification (and choose appropriate for your application)
- Environmental…other instruments (motors/generators in the building), powerline (60 Hz), lights (120 Hz), radio frequencies (MHz…GHz), …
- Biological…movement (physical activity, respiration, heart motion…), what you don't want (e.g. muscle for ECG, and ECG when recoring EEG…)
- Signal to noise ratio or SNR (although some times presented on a decibel (dB) scale which is 20*log (SNR)

Problem

- Design an EOG amplifier.
- Sensor
  - Electrodes around the eye…left-right OR up-down motion
- What do I mean by that?
  - Amplifier…what kind…differential…instrumentation amplifier?
  - Then…need gain, frequency response…
- What can I use it for
  - Track eye movement…virtual reality
  - Diagnose sleepy drivers; marketing study
  - Targeting missles…Saddam Hussein
  - Quadriplegics…eye control of cursor
  - Brain computer interface?!

Isolation

- What are the different isolation schemes?
- Optical isolation: LED & photodetector
- Problem is that these are nonlinear…so suggest an alternative method…digital!

How would you record fetal heart beats

- Does the dual amplifier scheme work?
- What other methods…
  - ECG of course is easier/better
  - Doppler….good alternative
  - Mechanical/strain guage?
  - Pulse?