Medical Cyber-Physical Systems

Electrophysiology basics

Lecture 10

Principles of Modeling for Cyber-Physical Systems

Instructor: Madhur Behl

Many thanks to:
Zhihao Jiang,
Houssam Abbas, and
Rahul Mangharam,
For help with preparing this module.

Why explore cardiac modeling?

Cardiac disease is the **leading cause of death in the US**

Around the world, **17.5 million people** die of Cardiovascular Diseases (CVD) yearly

That's an estimated **31%** of all deaths

More than 75% of CVD deaths occur in low income and middle income countries

Implanted devices are a leading method of treating some CVDs

Why study cardiac devices?

These devices are life-critical → must function correctly

Are constrained in their energy consumption → must be low-power

Are implanted in the body → very special design considerations (e.g., materials used, must be ex-plantable…)

Are regulated by the FDA → must follow certain best practices, but also have some inertia

These are life-critical embedded systems

Its shocking! Cardiac devices can have bugs

Implantable Cardiac Devices Recalls

- Over 600,000 cardiac medical devices recalled from 1990-2000
  - 40% of which were due to software issues
- 2008-12: **15% of *all*** the medical device recalls due to software

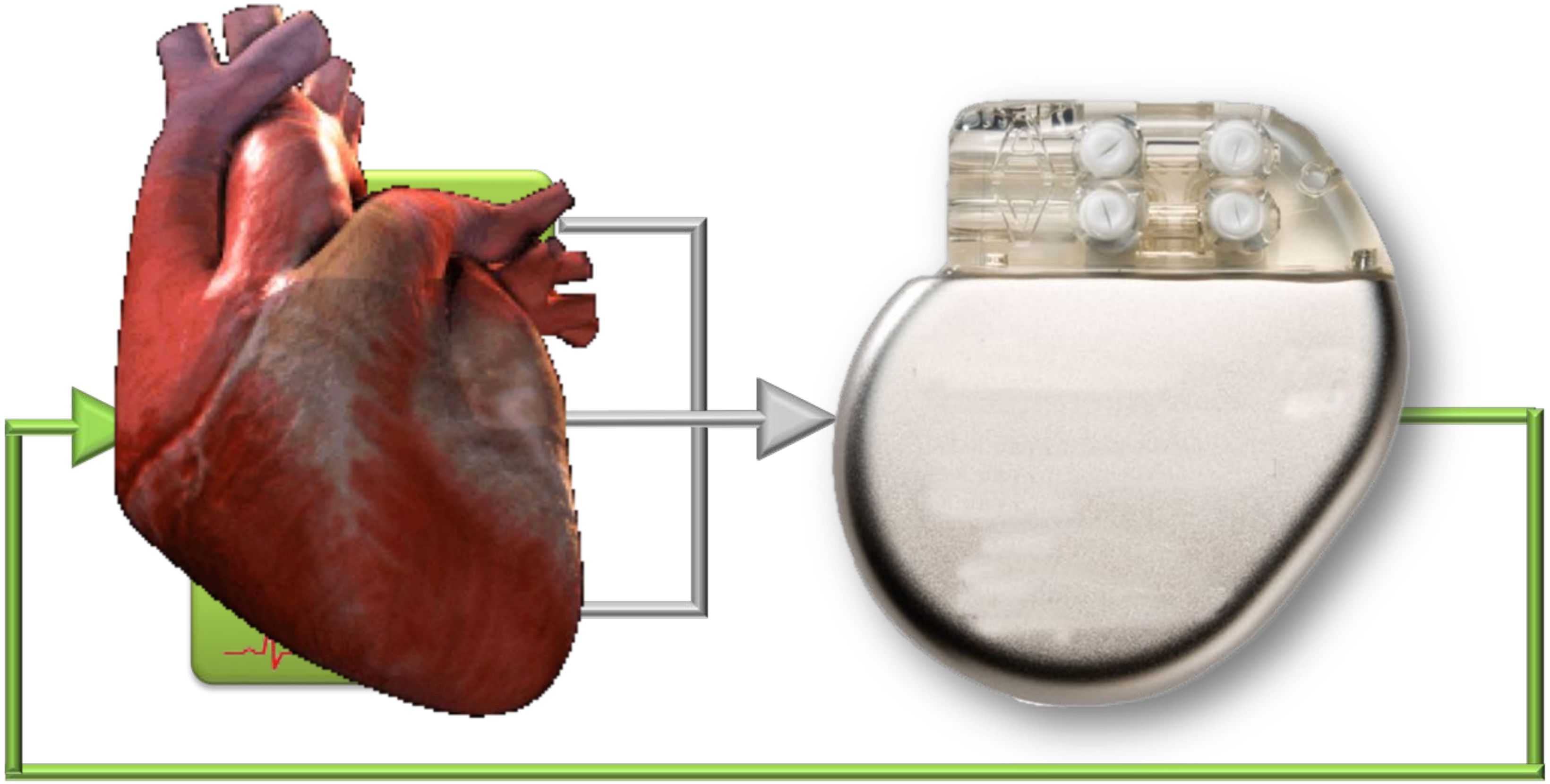
Implantable Pacemaker

Implantable Cardioverter-Defibrillator (ICD)

The consequences of incorrect algorithms and implementations

Filmed and shared with patient's consent

Closed-Loop Evaluation



Need a model of the heart which can capture the physiological conditions of the heart and respond to pacemaker outputs.

Model/implement the pacemaker

Check if pacemaker is ‘safe’ for different heart conditions

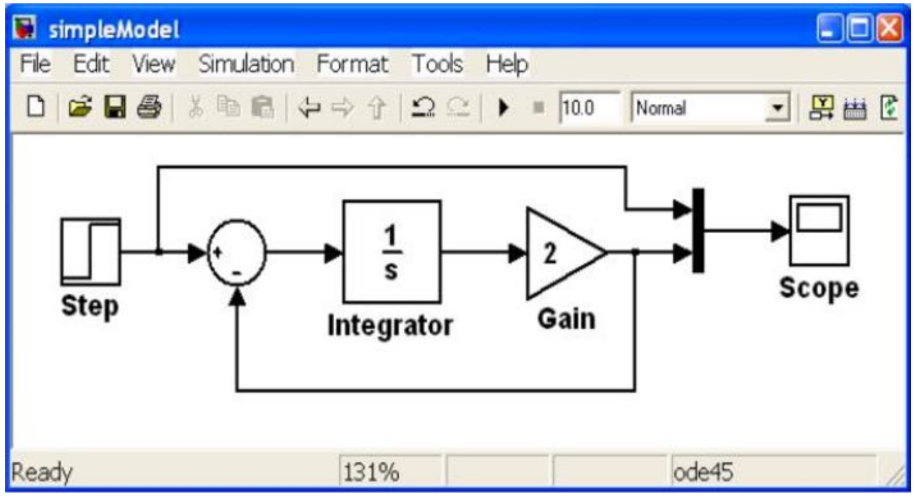
Let our heart (model) catch the bugs before your heart does

Madhur Behl madhur.behl@virginia.edu

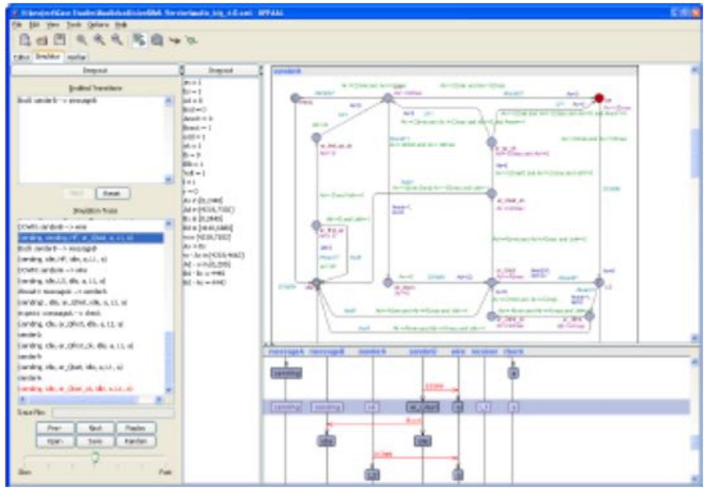
This Module

Will be challenging:

- New domain (electrophysiology)
- New tools (Simulink and UPPAAL)
- New theory (timed automata)
- New concepts (model checking)



Simulink



UPPAAL

How do we go about understanding the heart?

Understand the electrical system as a circuit?

Understand the cellular activity?

Understand the molecular activity?

What does one heart tell us about other hearts?

What does a healthy heart tell us about an unhealthy heart?

What *is* a healthy heart?

What is the purpose of our enquiry?

Need to understand the domain.

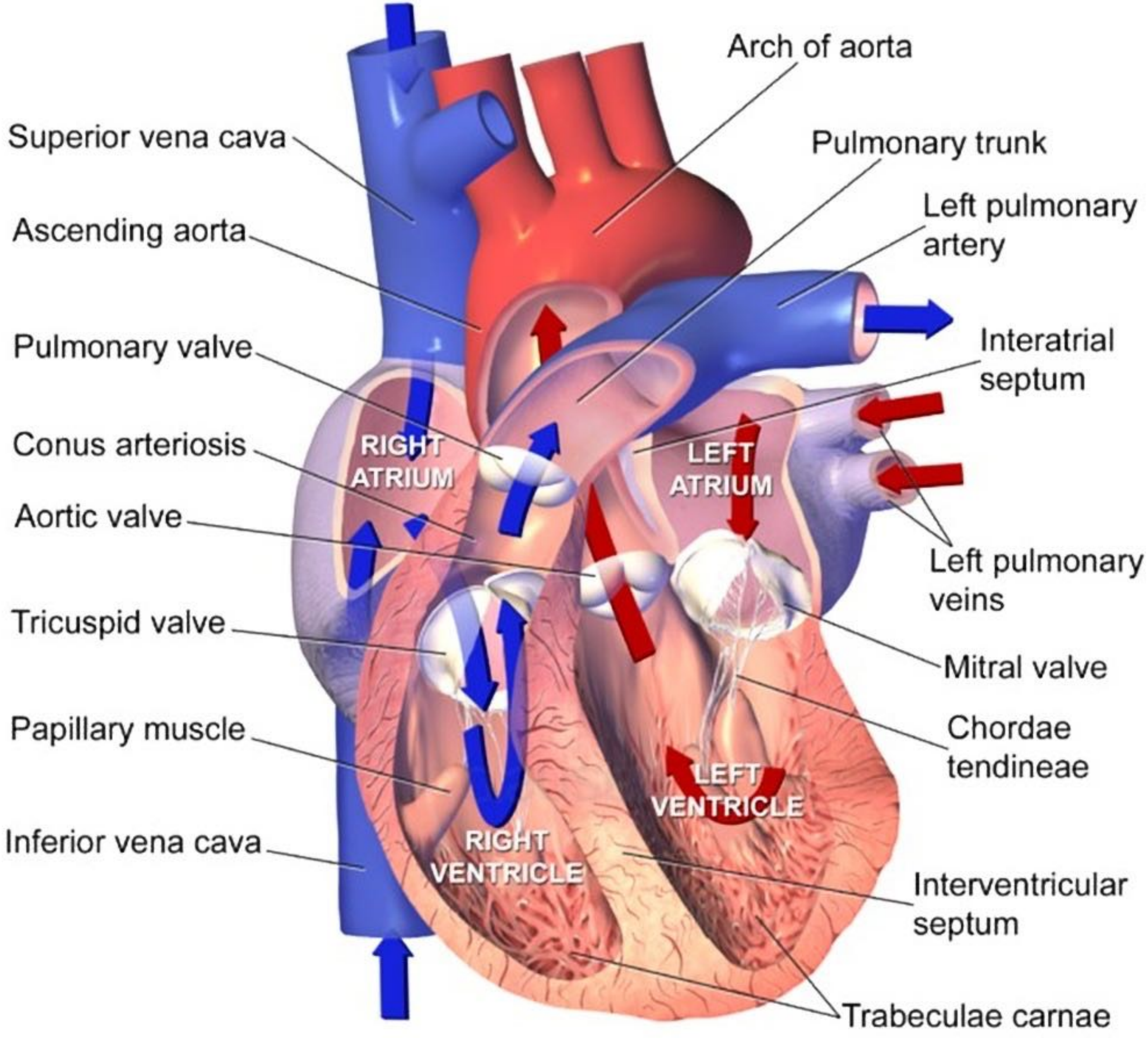
Speak the same language as the domain experts.

Remember….modeling choices and ‘usefulness’ depend on the problem at hand.

Electrophysiology of the heart

aka ..talking like a cardiologist without attending med school

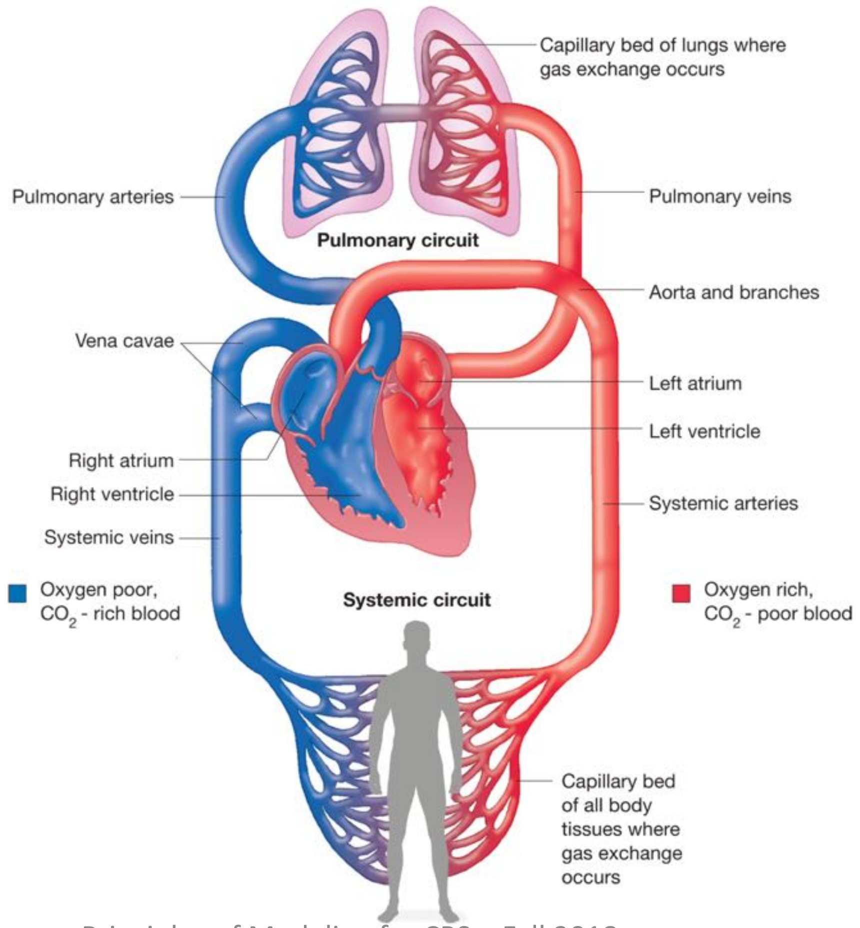
First, let’s examine the human heart

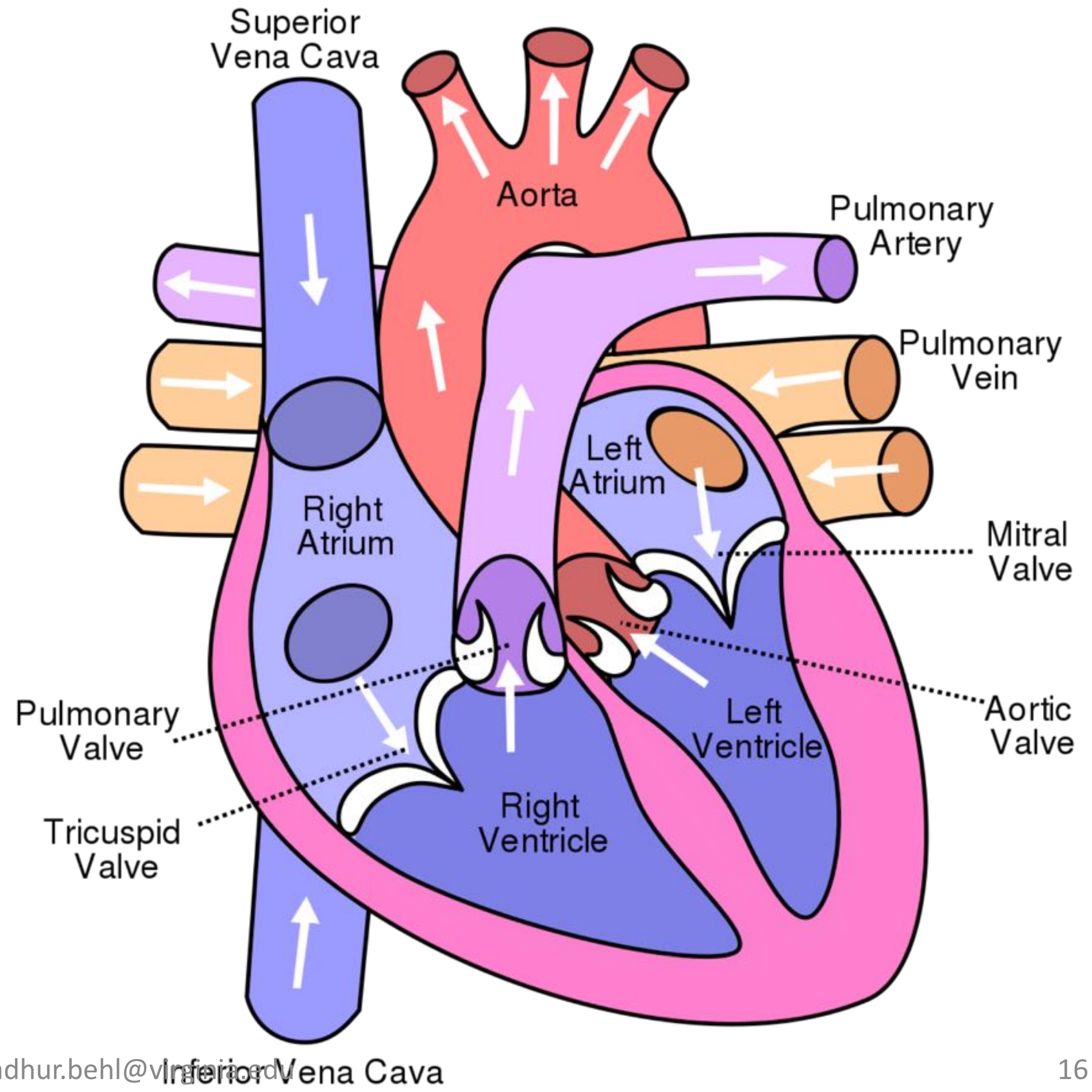


Sectional Anatomy of the Heart

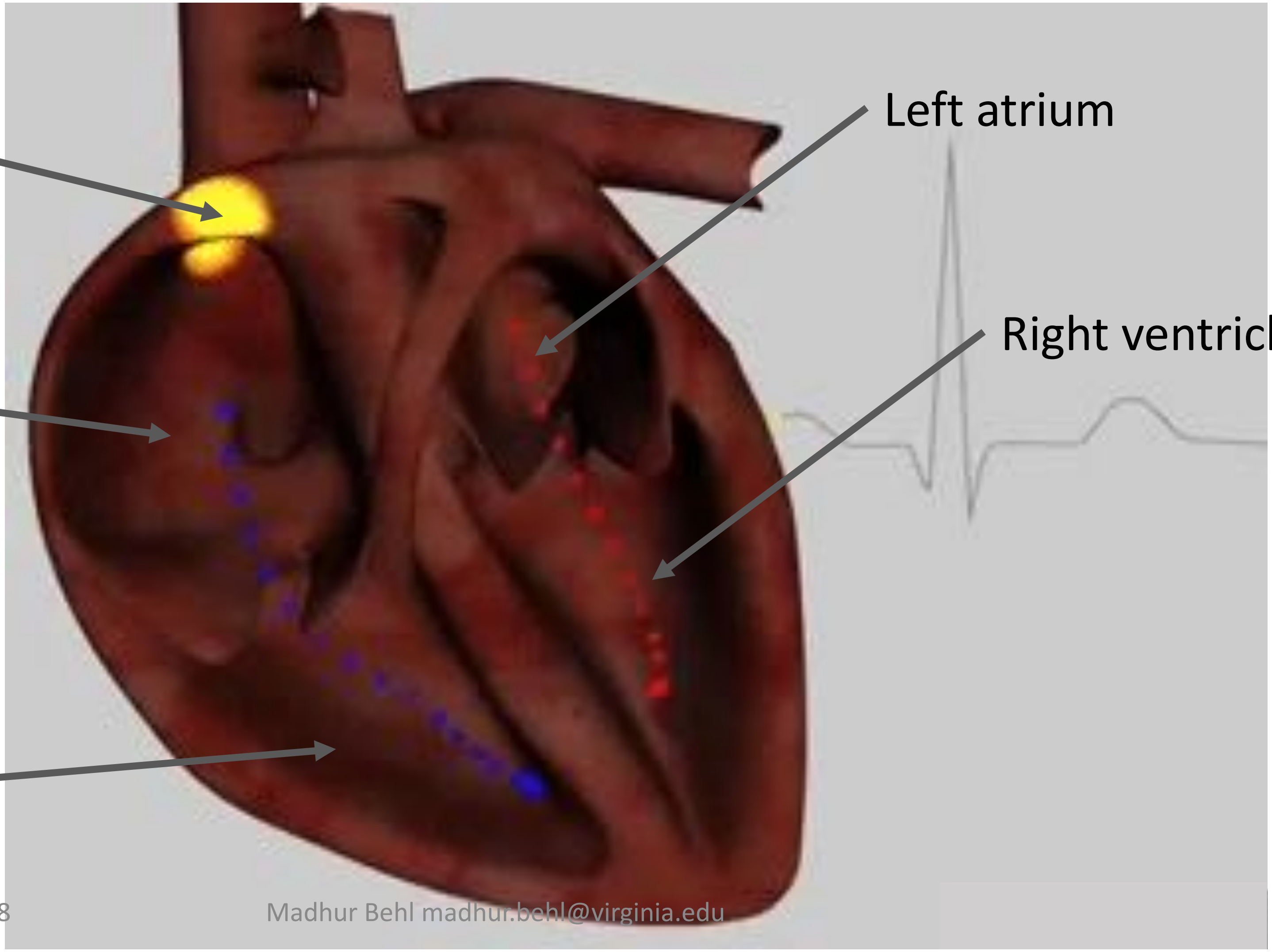
Circulatory system and heart function

Vein: towards the heart.
Artery: away from the heart

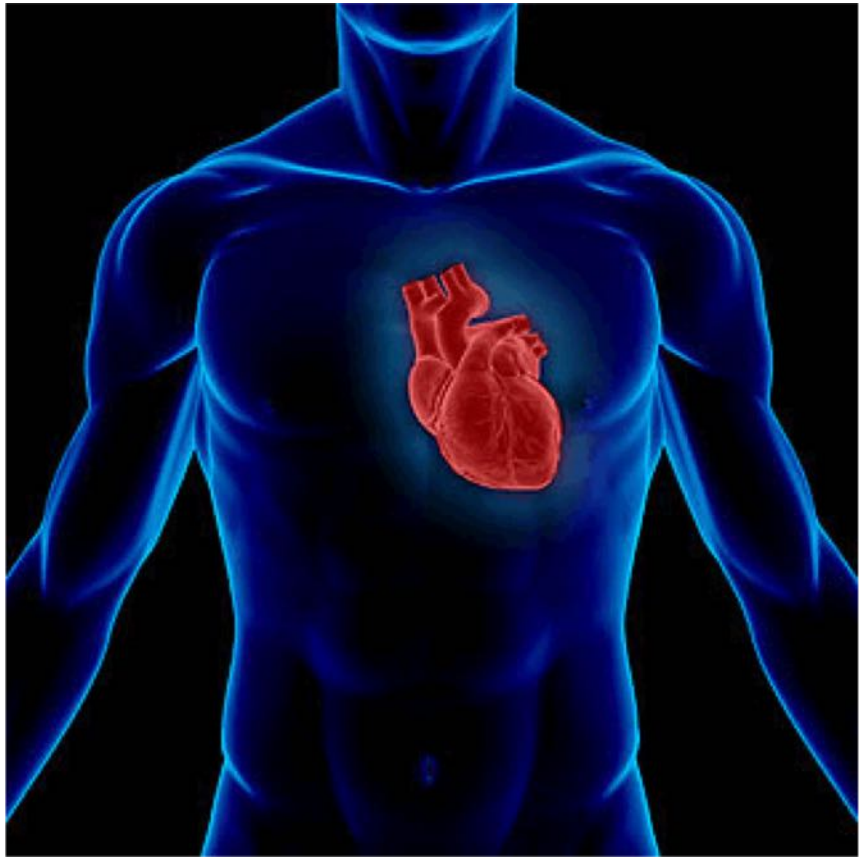


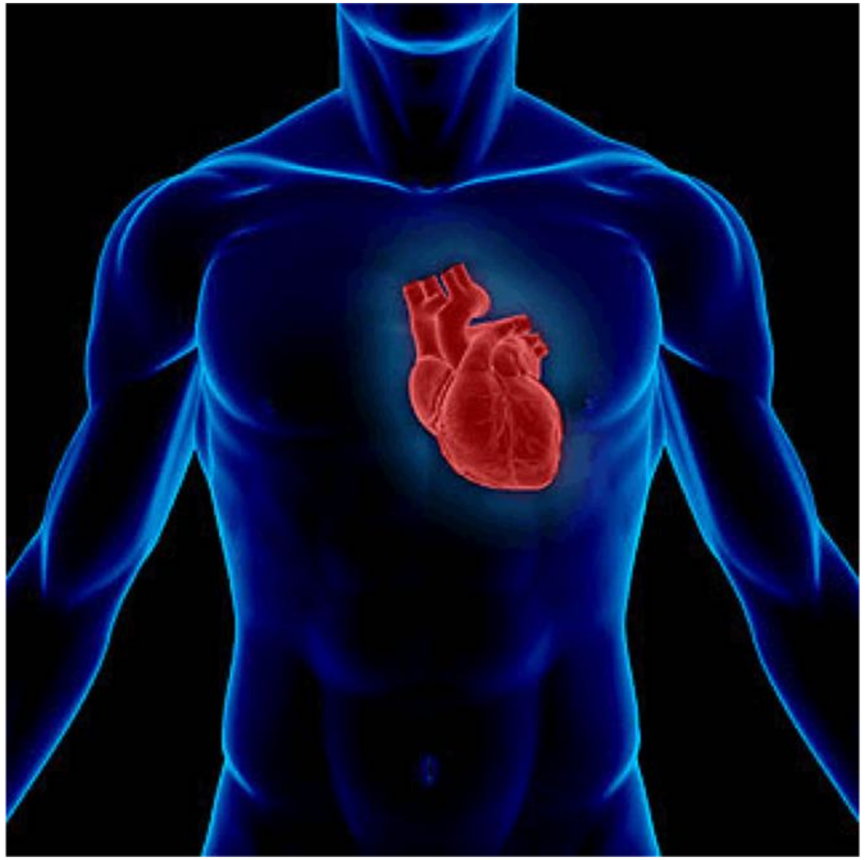


Electrical generation and propagation



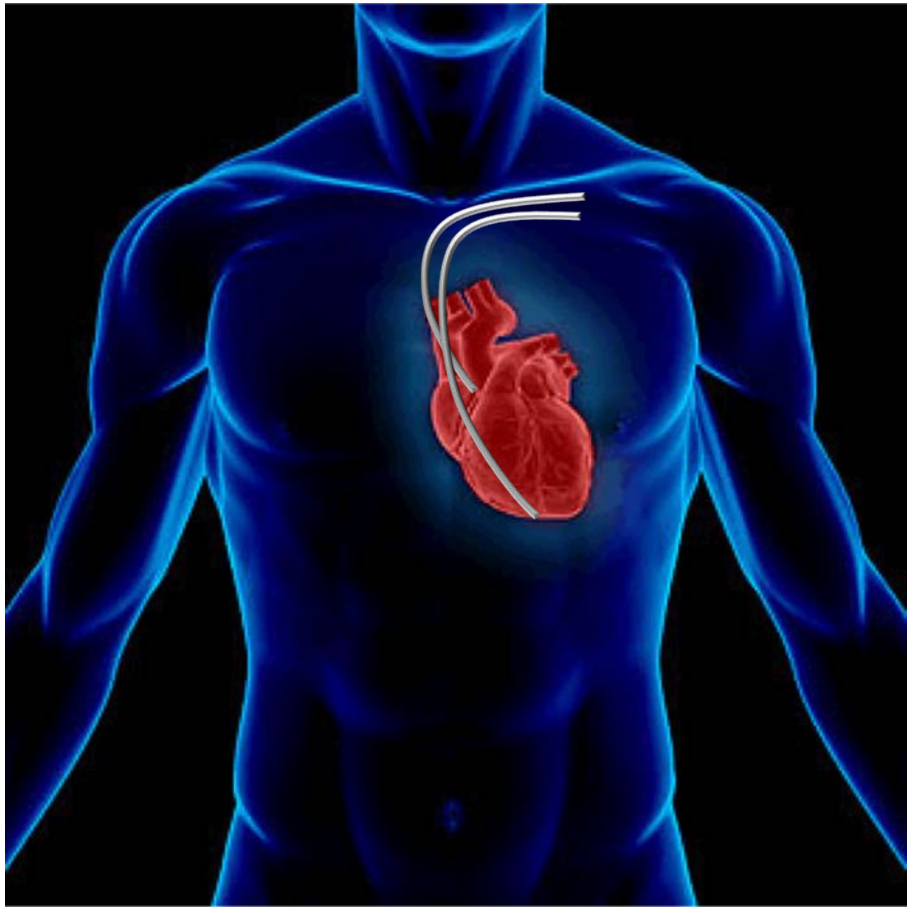
Bradycardia: bradus (slow) + kardia (heart)





Madhur Behl madhur.behl@virginia.edu

Implantable Pacemaker



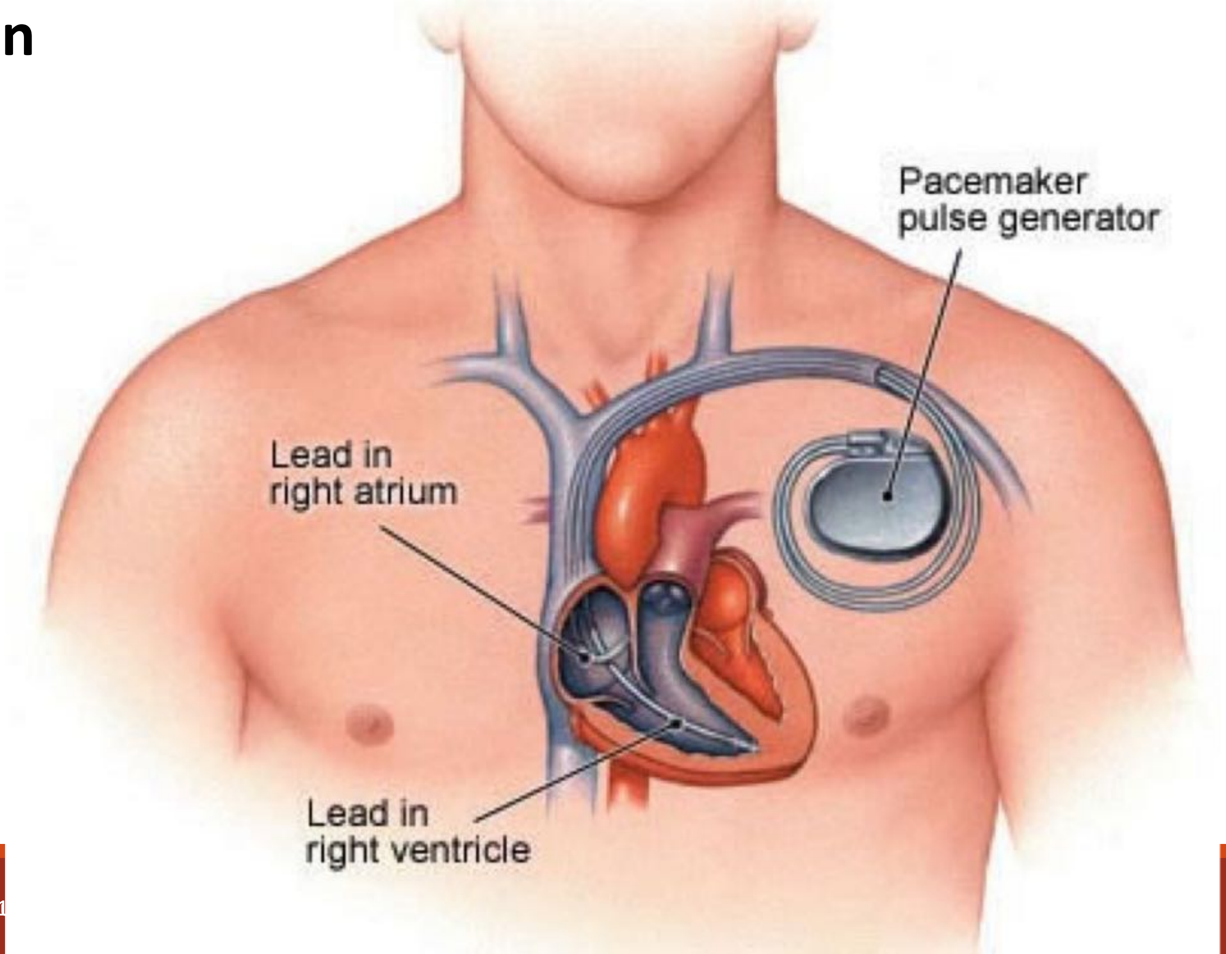
Two leads in heart chambers

Madhur Behl madhur.behl@virginia.edu

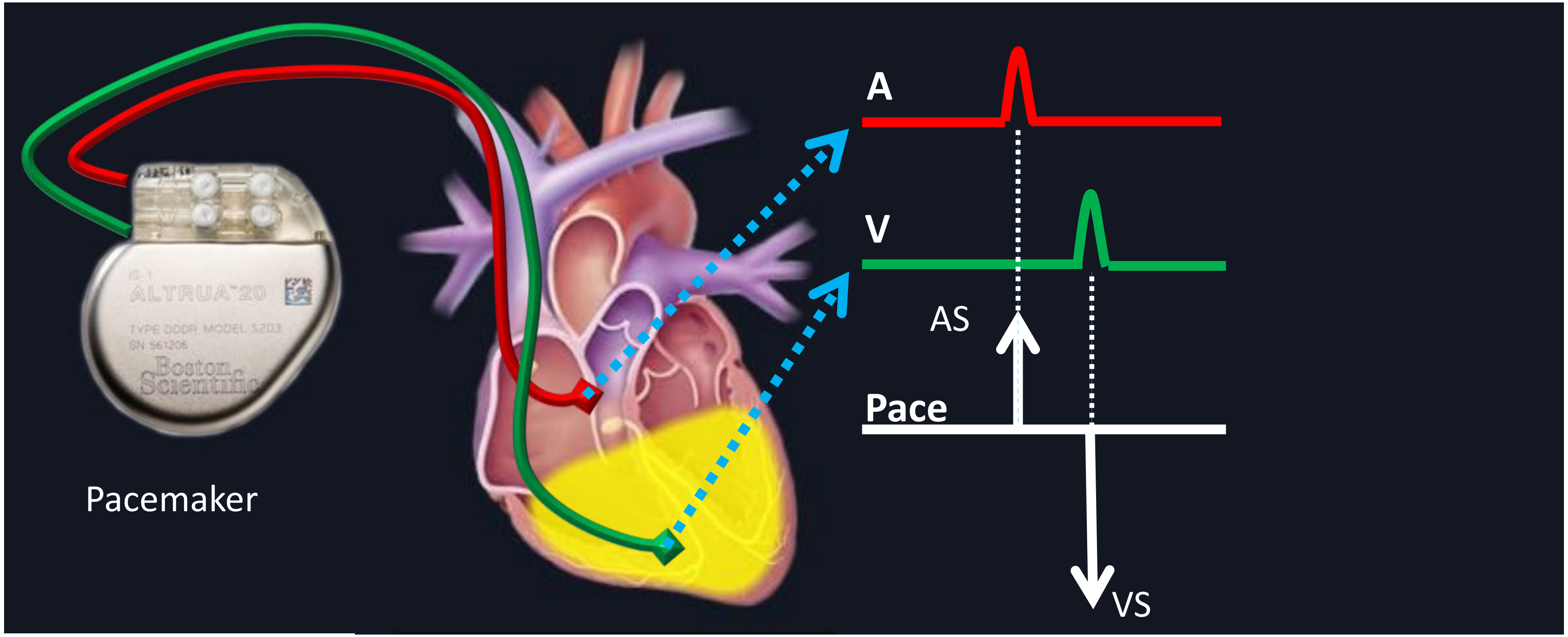
Implantable Pacemaker

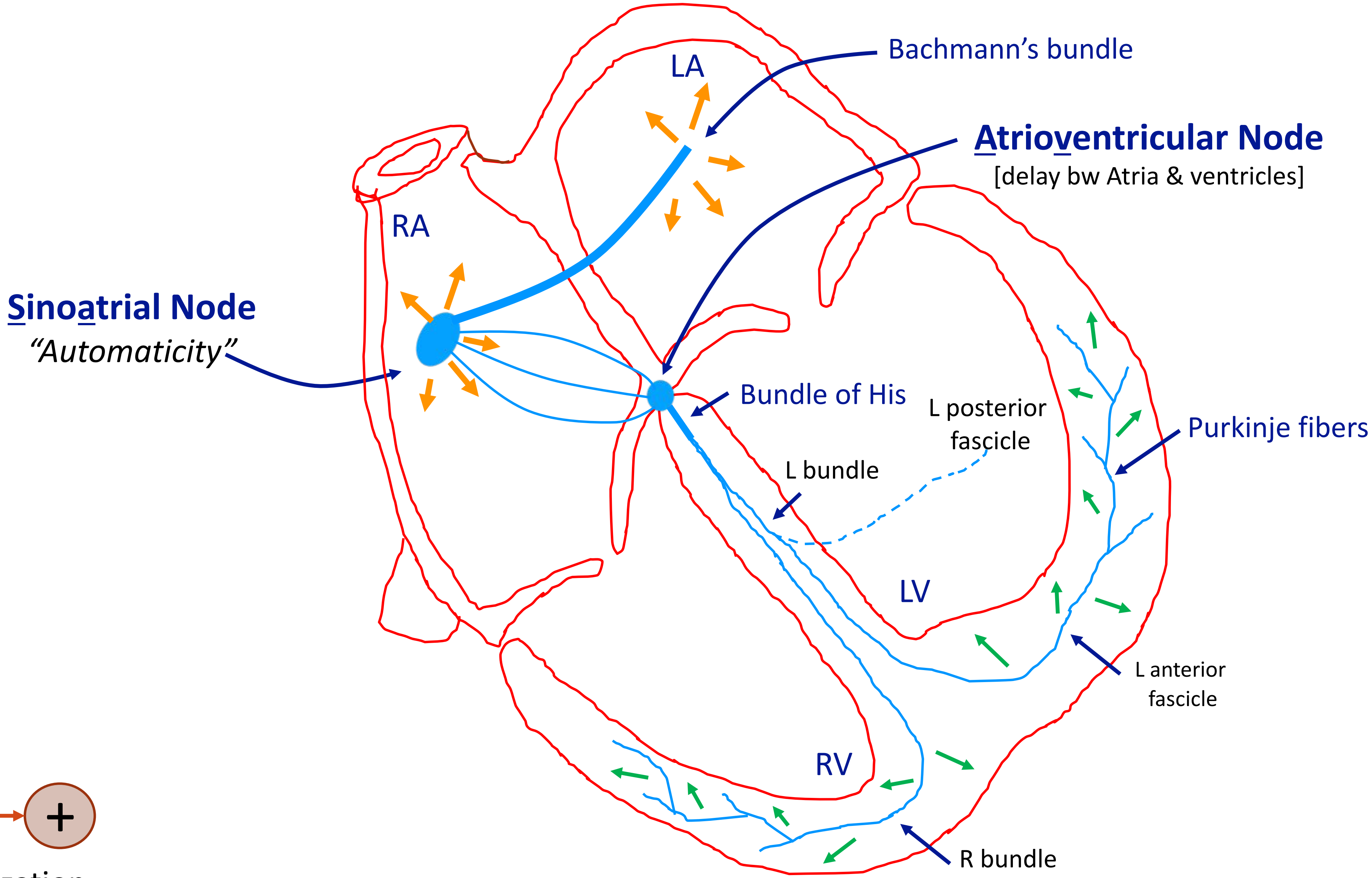
Two leads are placed in the right atrium and right ventricle

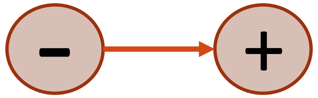
Monitors the local electrical activities of the heart and deliver therapy according to the **timing information**



Implantable Pacemaker

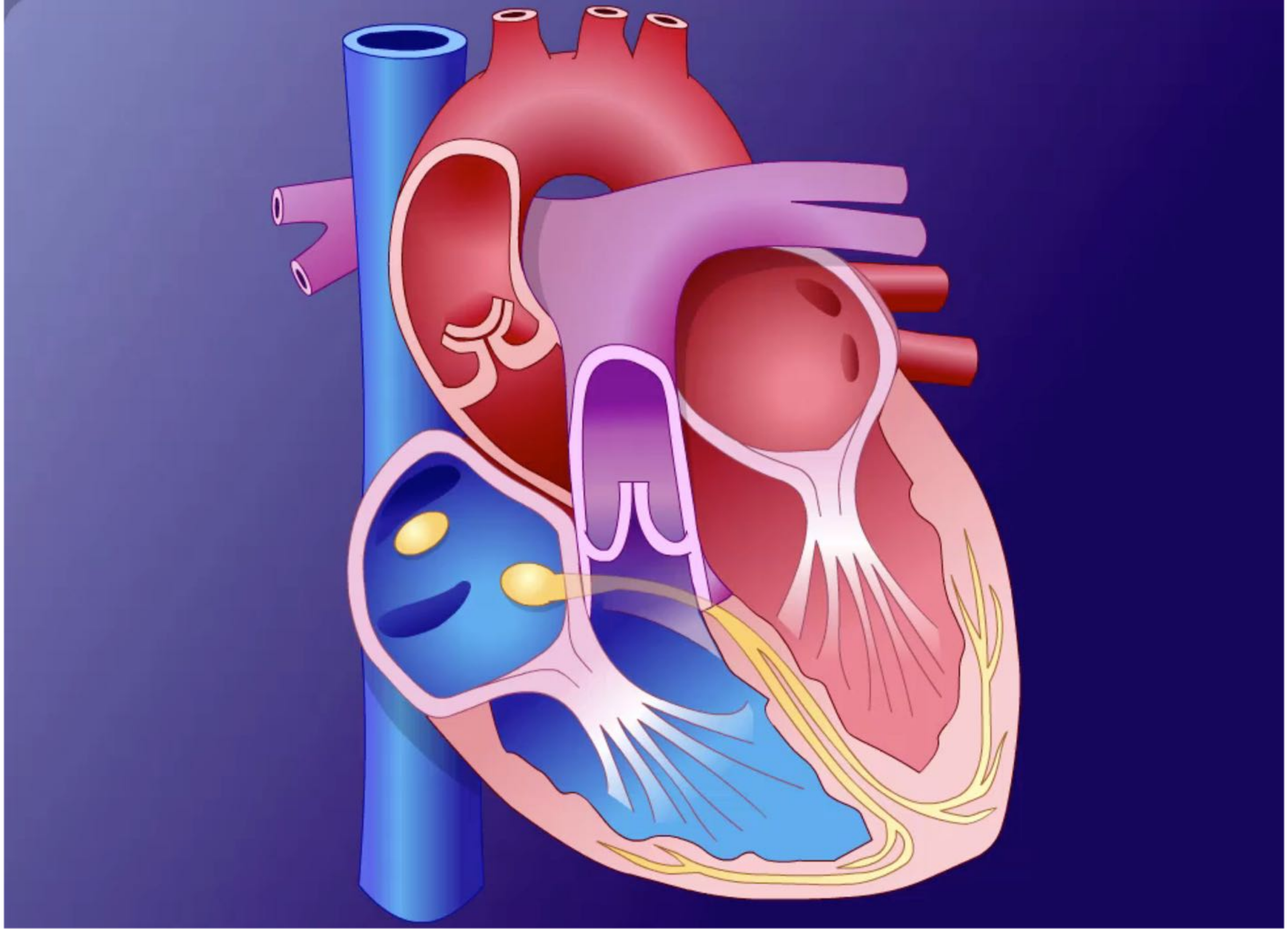






Depolarization

Madhur Behl madhur.behl@virginia.edu



Pacemaker cells (naturally pace the atria and ventricles)

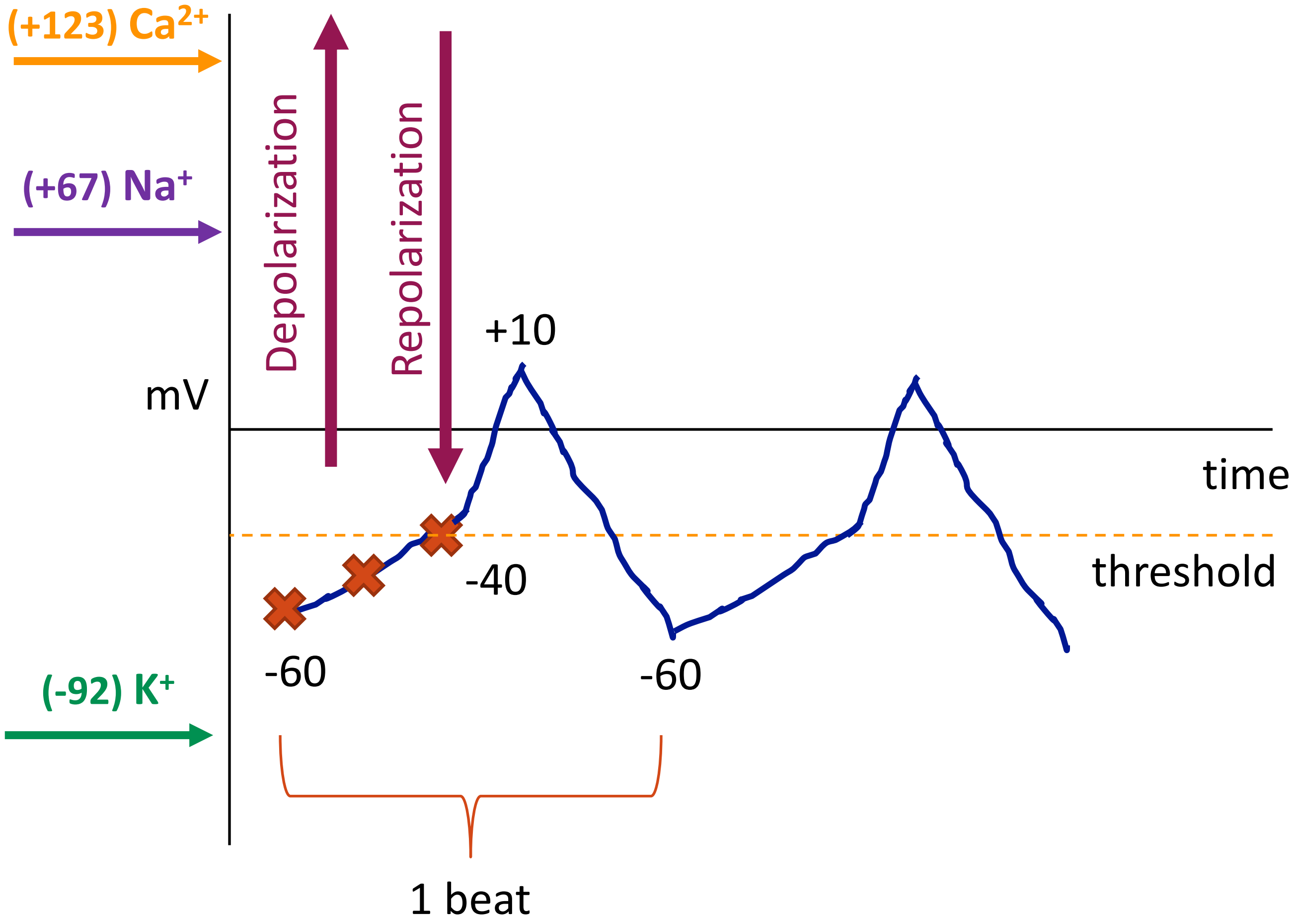
and

Cardiac myocytes cells (“squeezing” the heart)

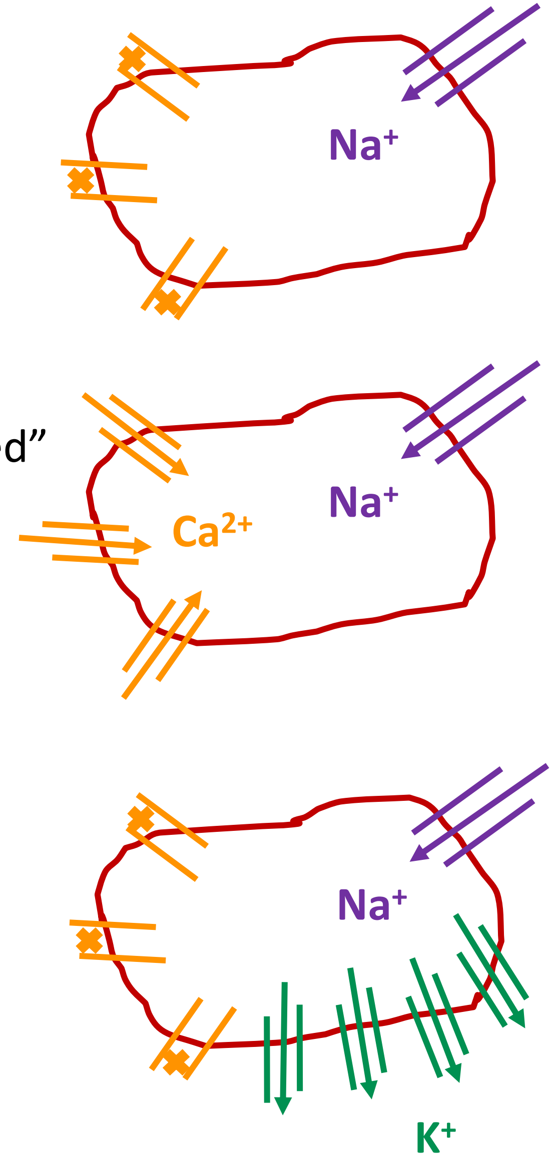
Pacemaker cells – “Automaticity”

1) Sino-Atrial (SA) node
2) Atrioventricular (AV) node
3) Bundle of His / Purkinje fibers

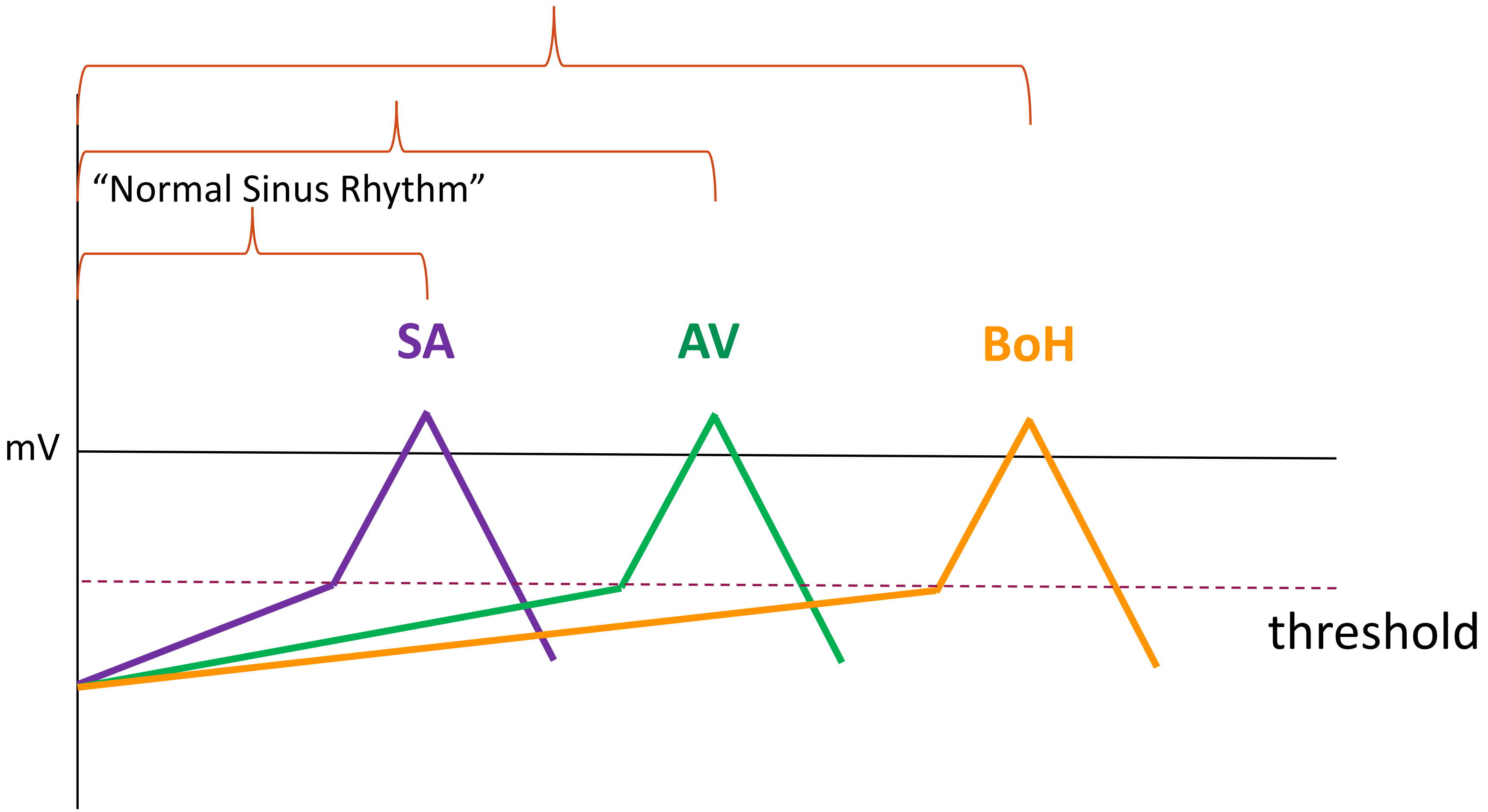
Pacemaker cells



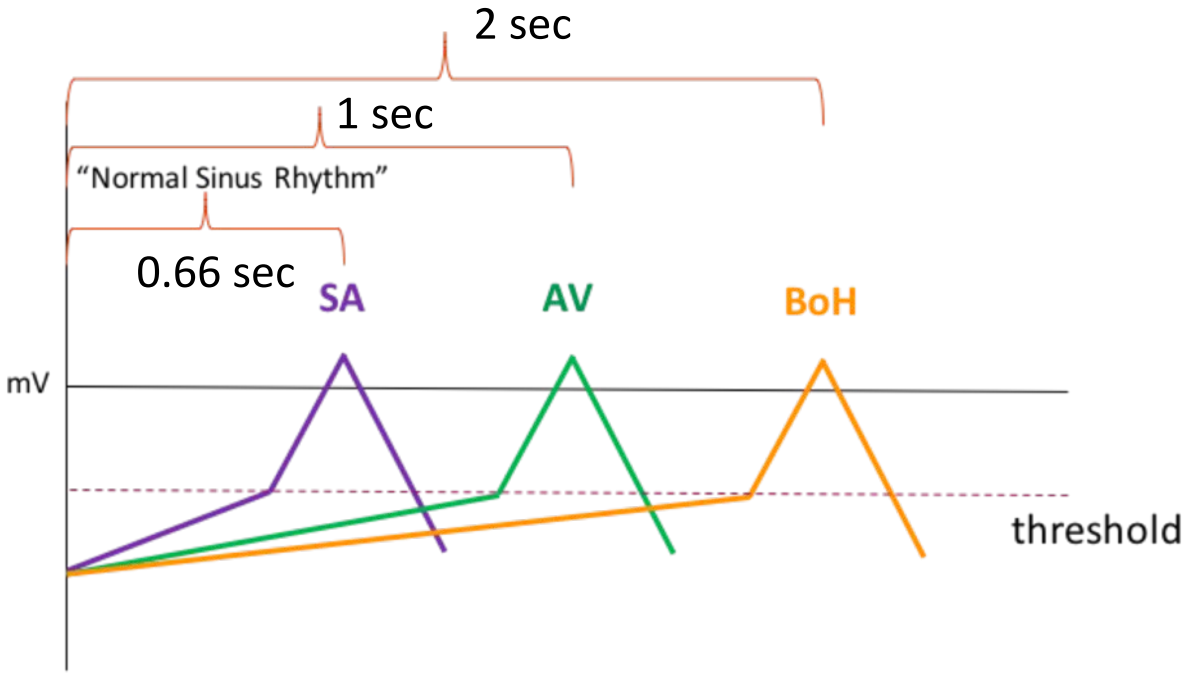
“Voltage-gated”



Race to keep pace !

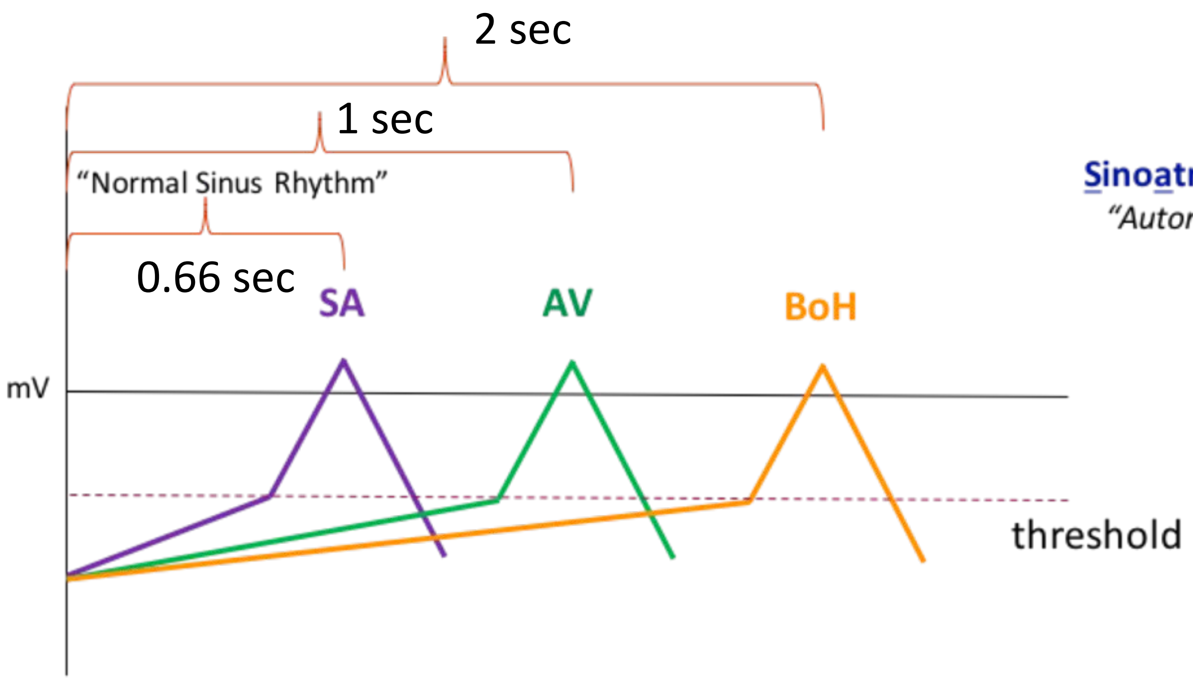


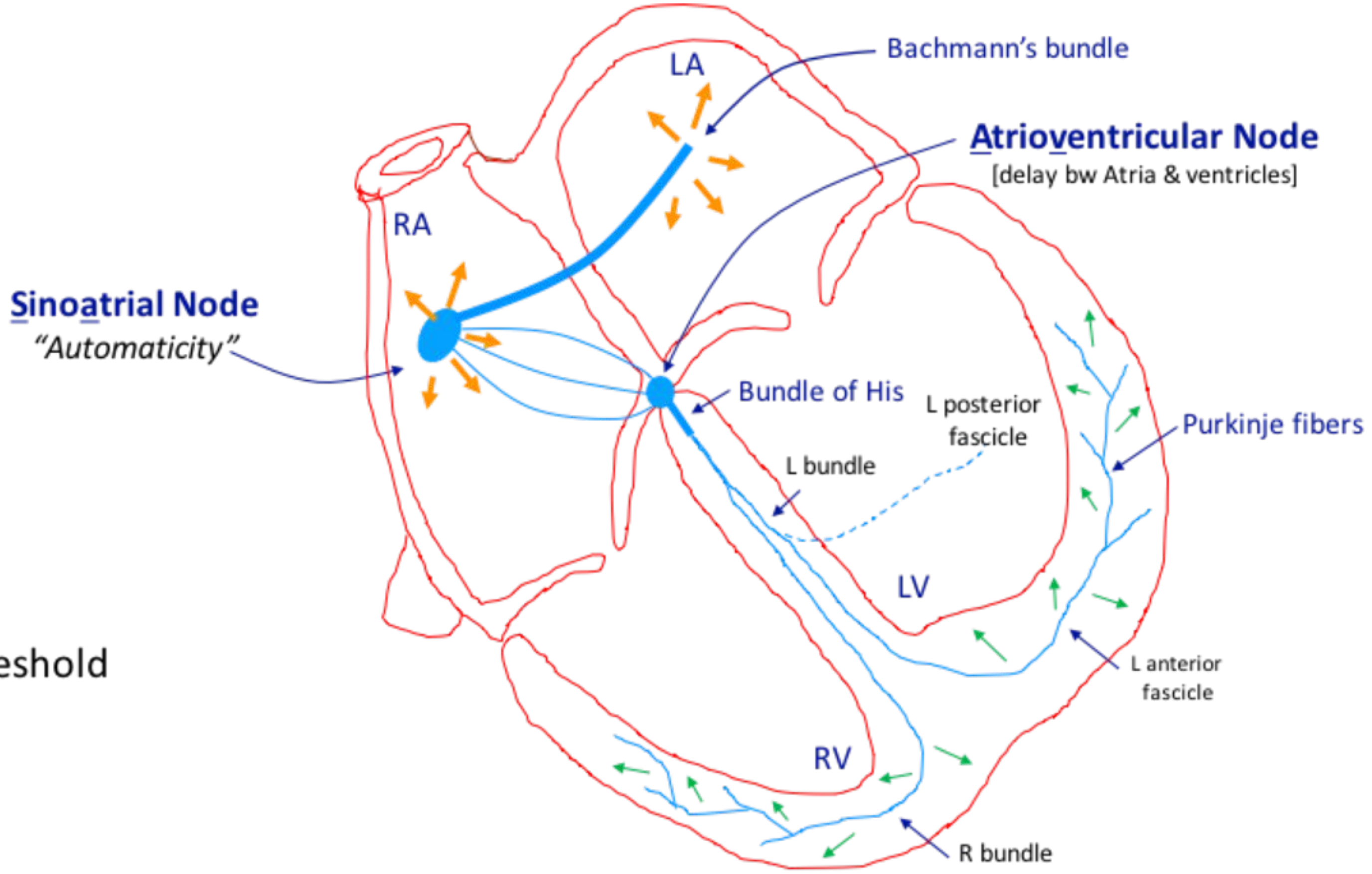
Race to keep pace !



	Heart Rate (beats/min)	1 beat (sec)
SA	60-90	0.66 sec
AV	40-60	1 sec
BoH	20-30	2 sec

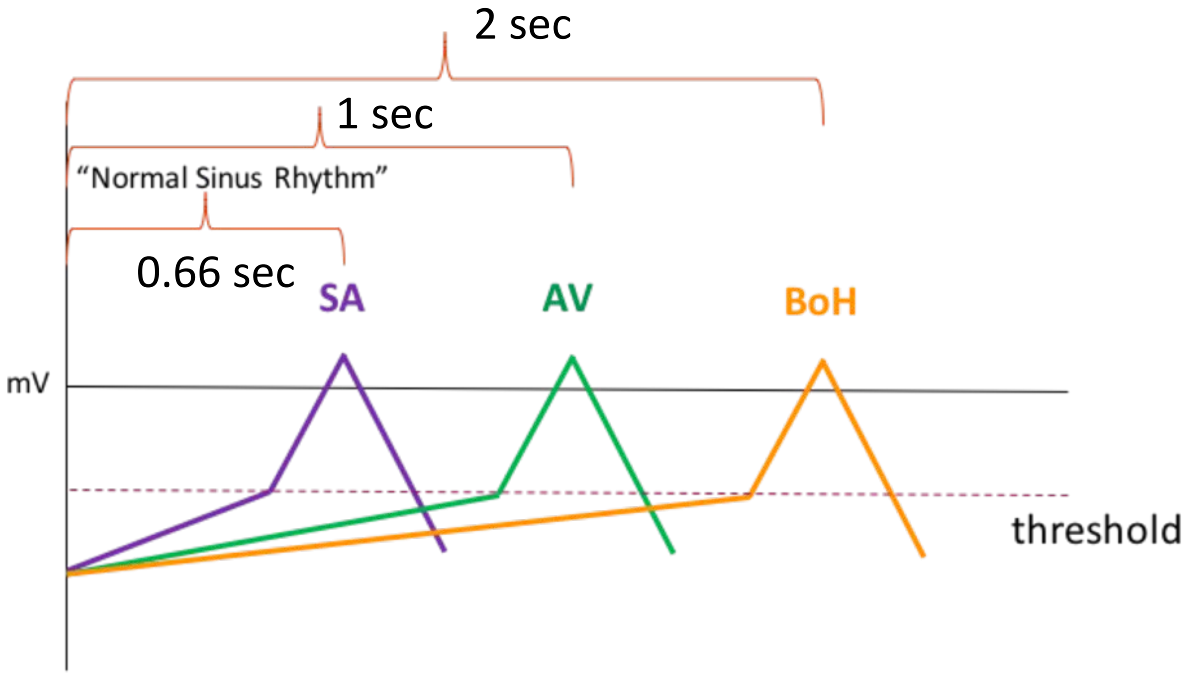
Race to keep pace !





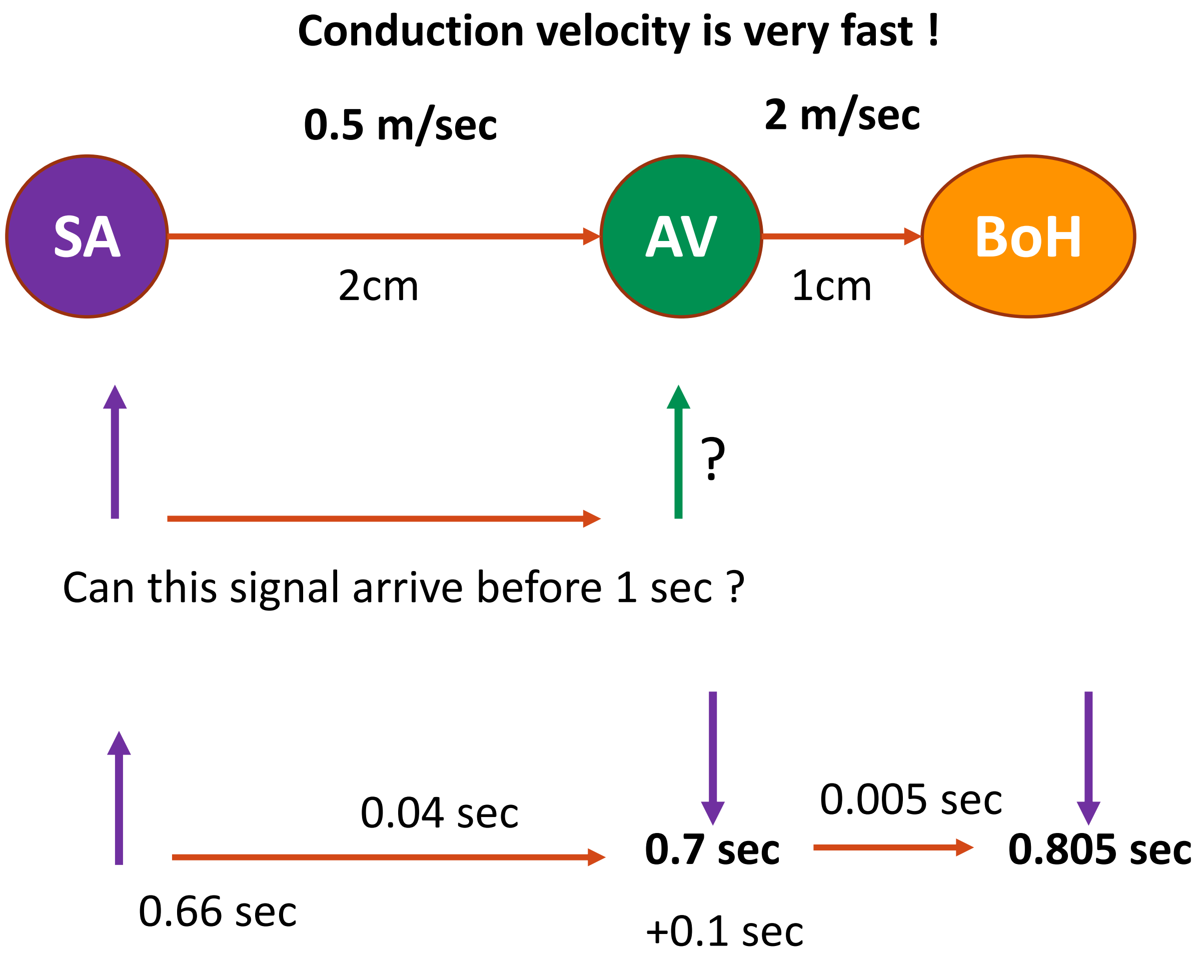
Madhur Behl madhur.behl@virginia.edu

Race to keep pace !

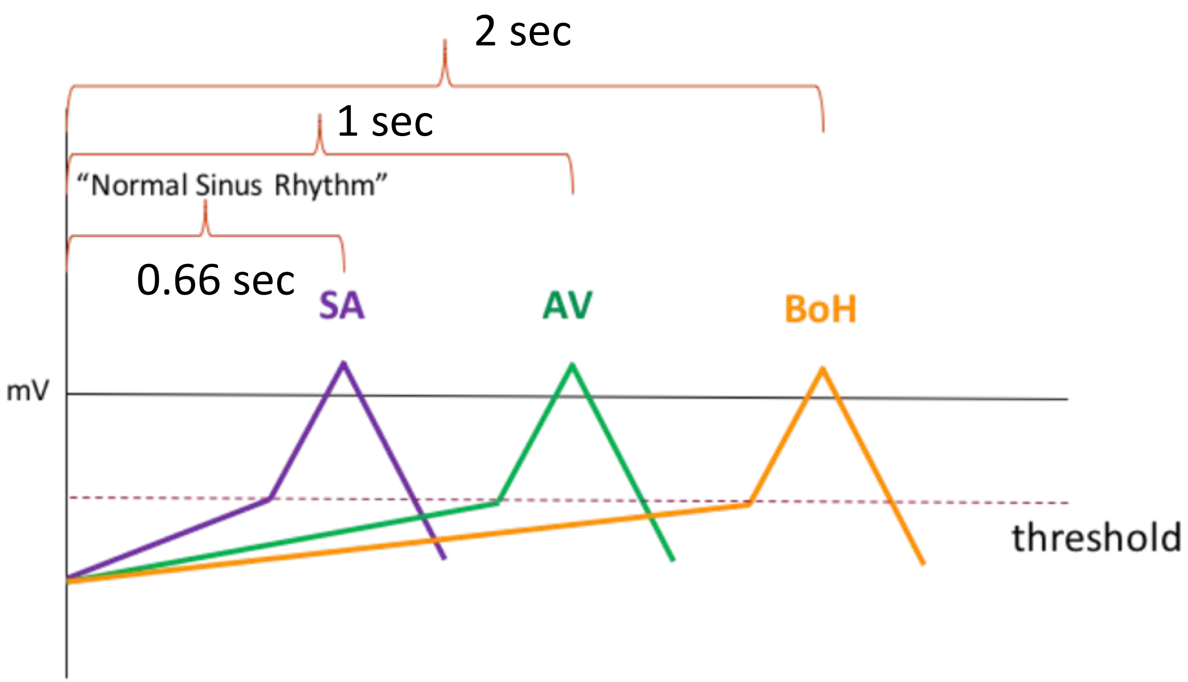


How does SA node control the heart beat ?

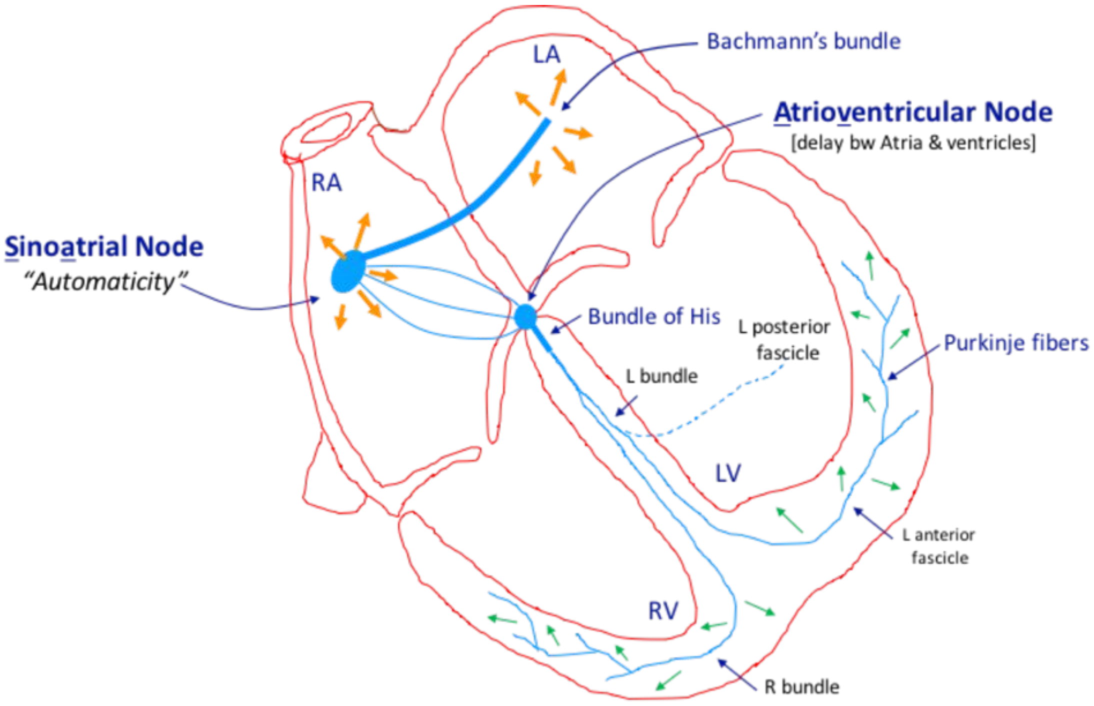
"Normal Sinus Rhythm"



Race to keep pace !



	Heart Rate (beats/min)	1 beat (sec)
SA	60-90	0.66 sec
AV	40-60	1 sec
BoH	20-30	2 sec



- SA node – Plan A
- AV node – Plan B
- BoH – Plan C

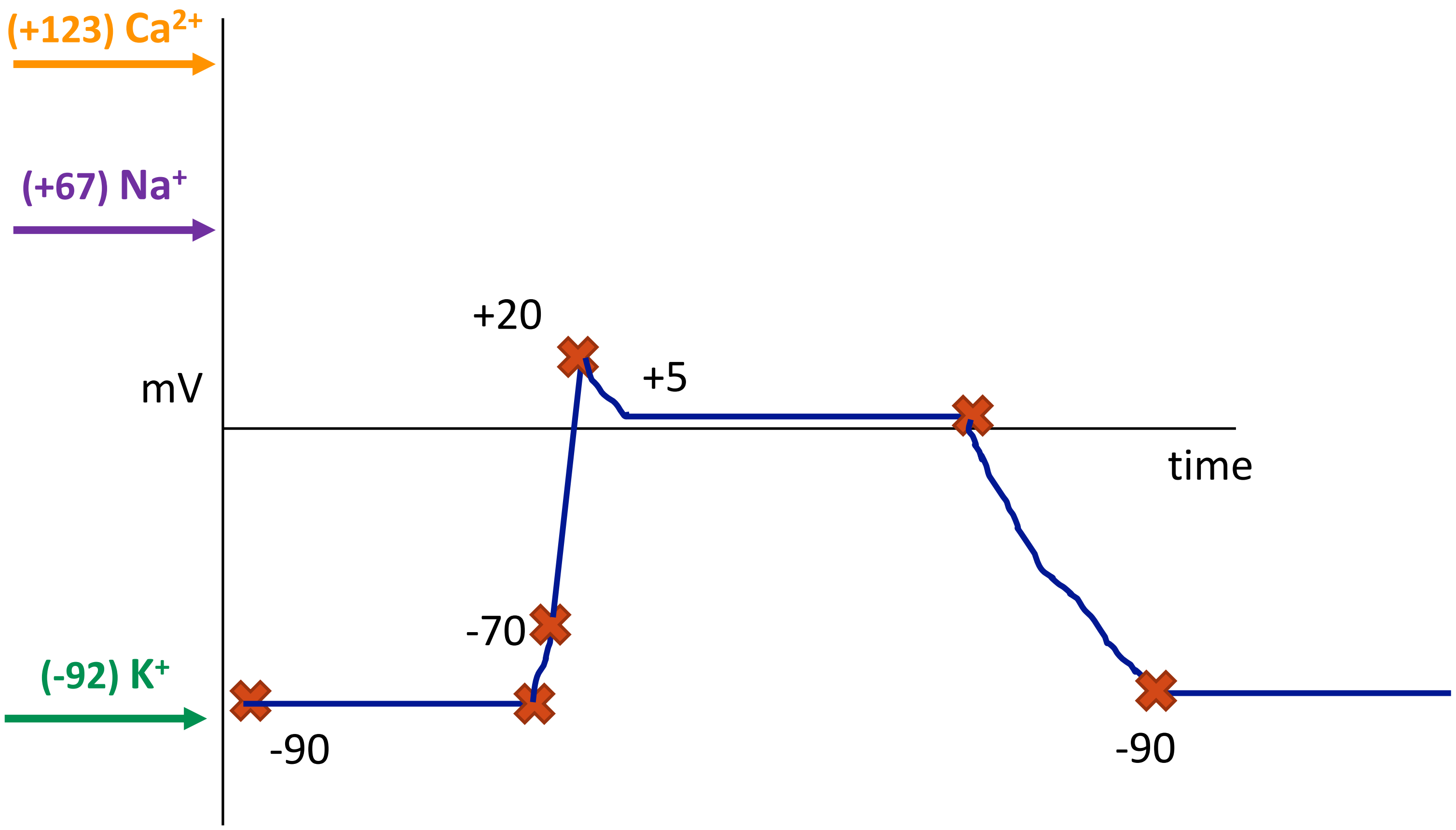
Pacemaker cells (naturally pace the atria and ventricles)

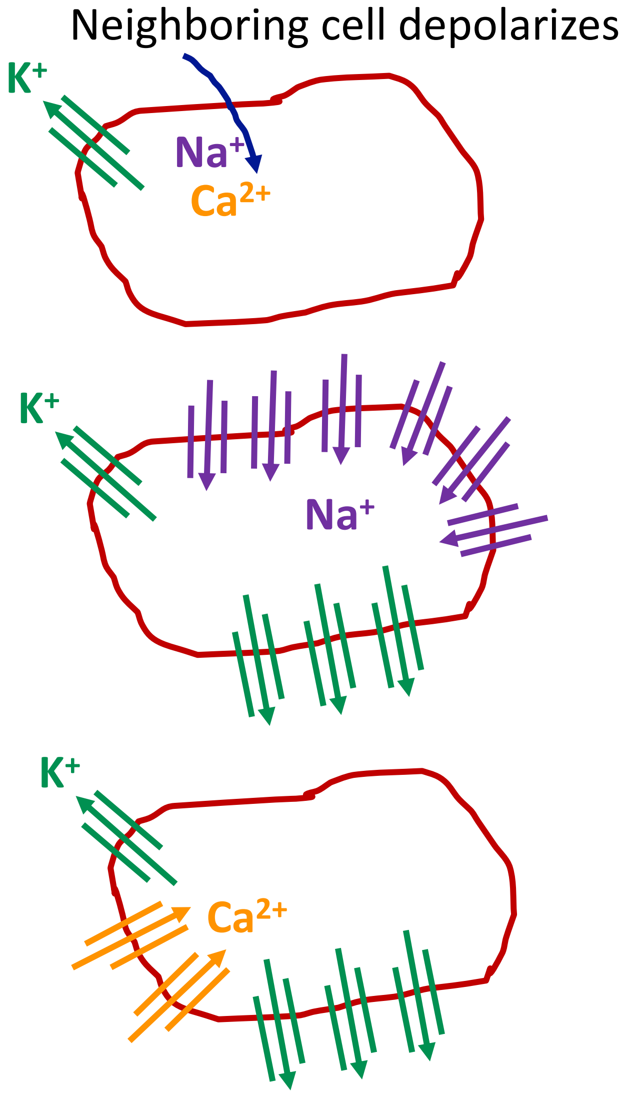
and

Cardiac myocytes cells ("squeezing" the heart)

Madhur Behl madhur.behl@virginia.edu

Cardiac Myocytes – How does the heart squeeze



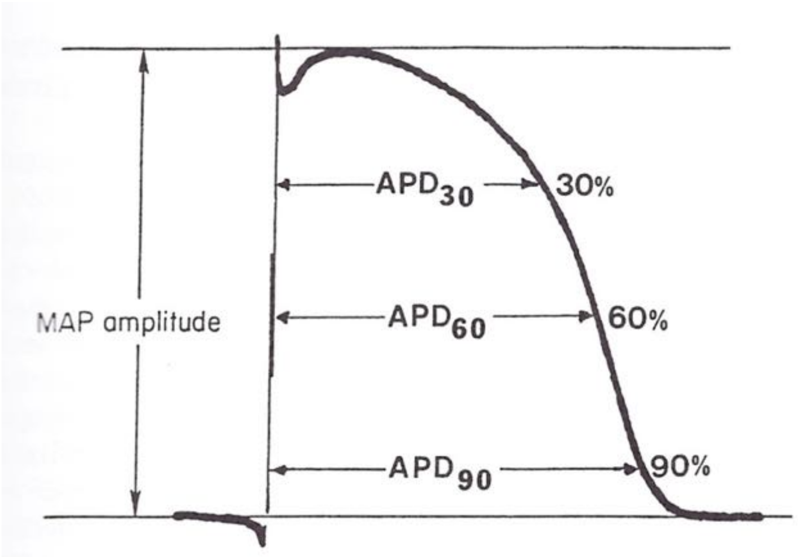


Action Potential - Tissue

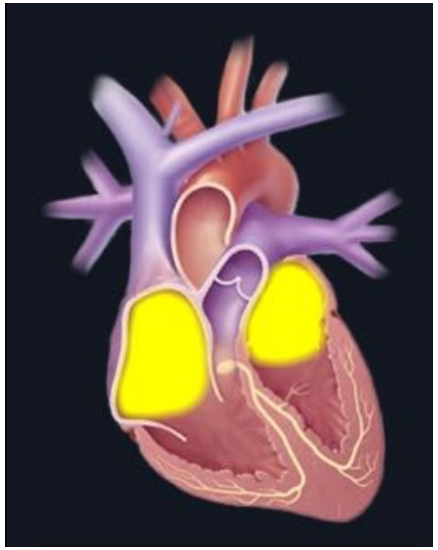
The elementary signal of the heart

It affects the *conduction velocity* and *signal passage* of the tissue.

Closely related to most cardiac diseases.



APD: Action Potential Duration



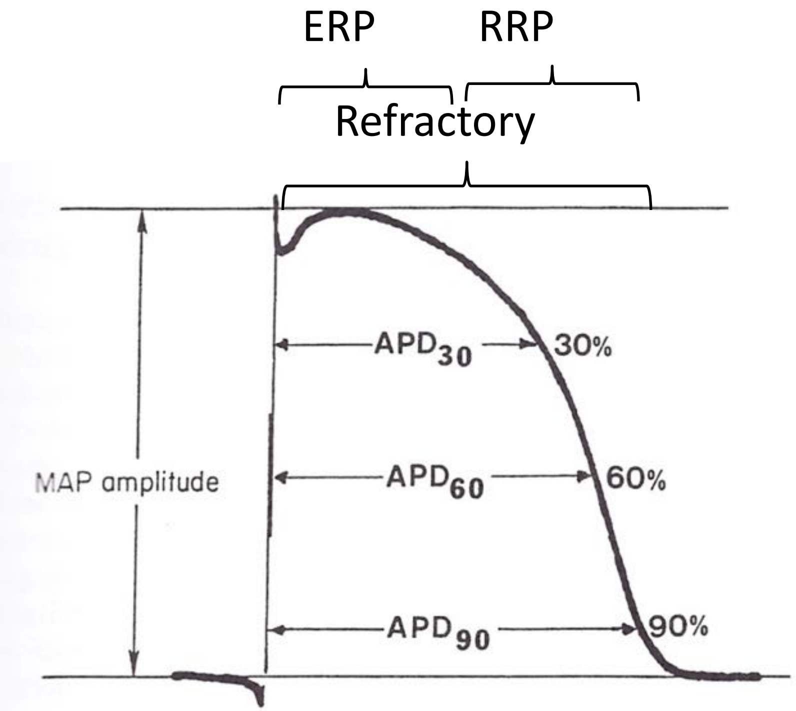
Functional syncytium

Cellular Level - Action potential

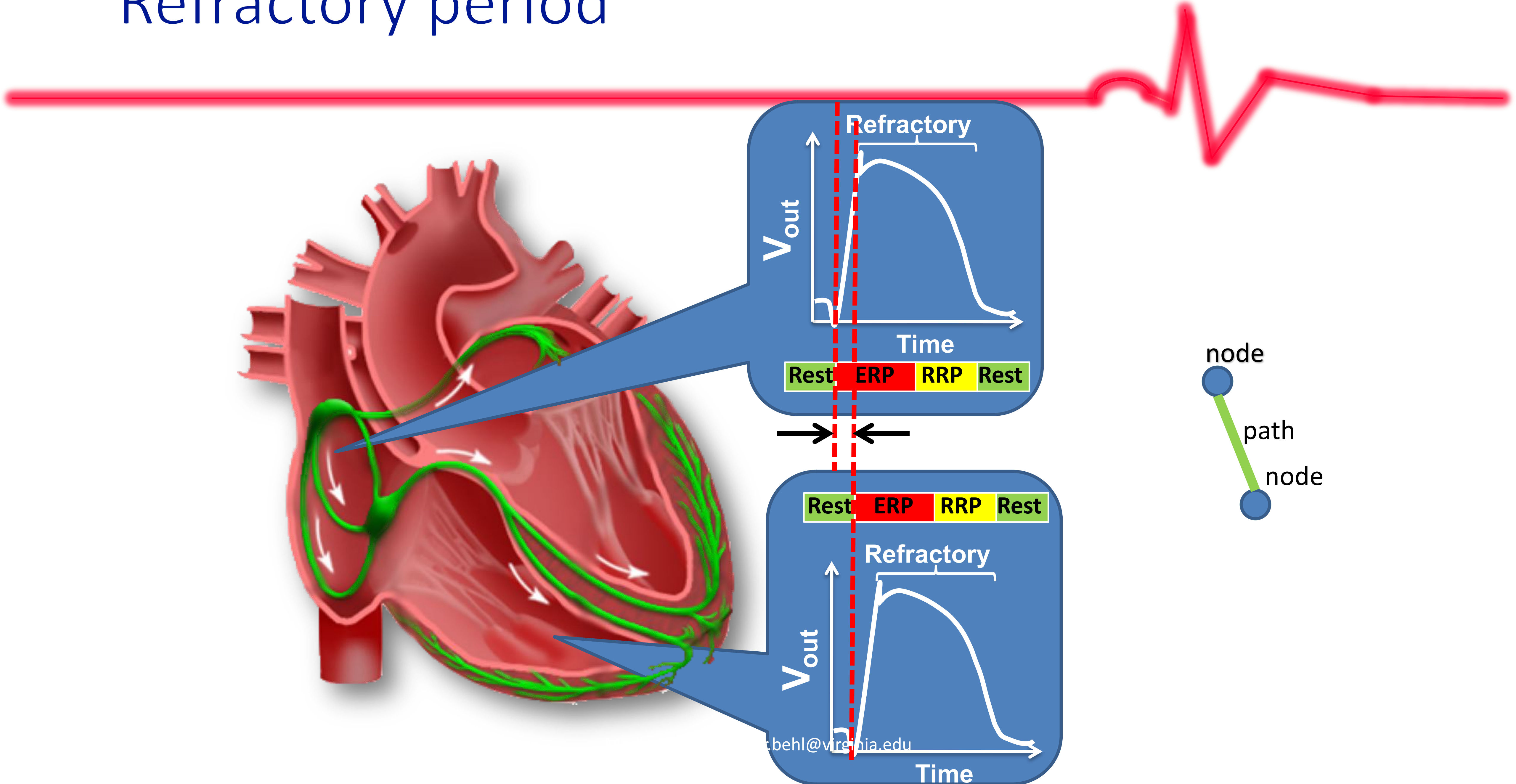
Ions refill

Divided into *Effective Refractory Period(ERP)* and *Relative Refractory Period(RRP)* for activation with certain strength

Block Interval during ERP, abnormal new action potential during RRP



Refractory period



Treating bradycardia

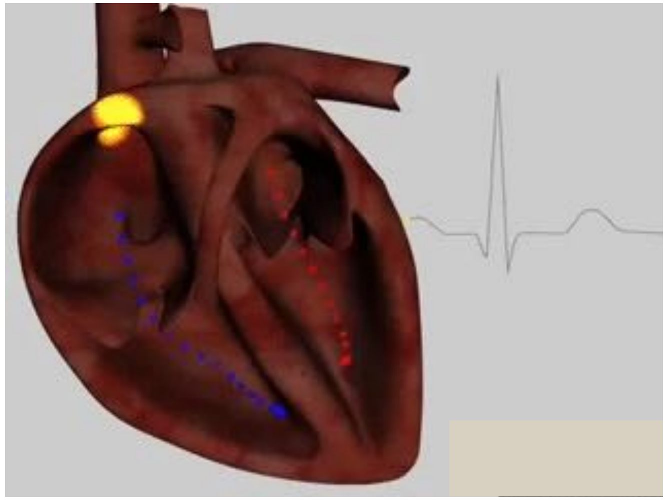
We want to detect when the atria or the ventricles miss a beat, and pace the chambers when that happens

Start small and simple:

- We know that usually, the atria contract together, and the ventricles contract together → sense only in right atrium and ventricles
- Usually, depolarization is synchronous with contraction → measure the electrical activity as a proxy for the mechanical activity
- Usually, depolarization in part of the atrium (or ventricle) is

  propagated to the rest of that chamber → measure only in

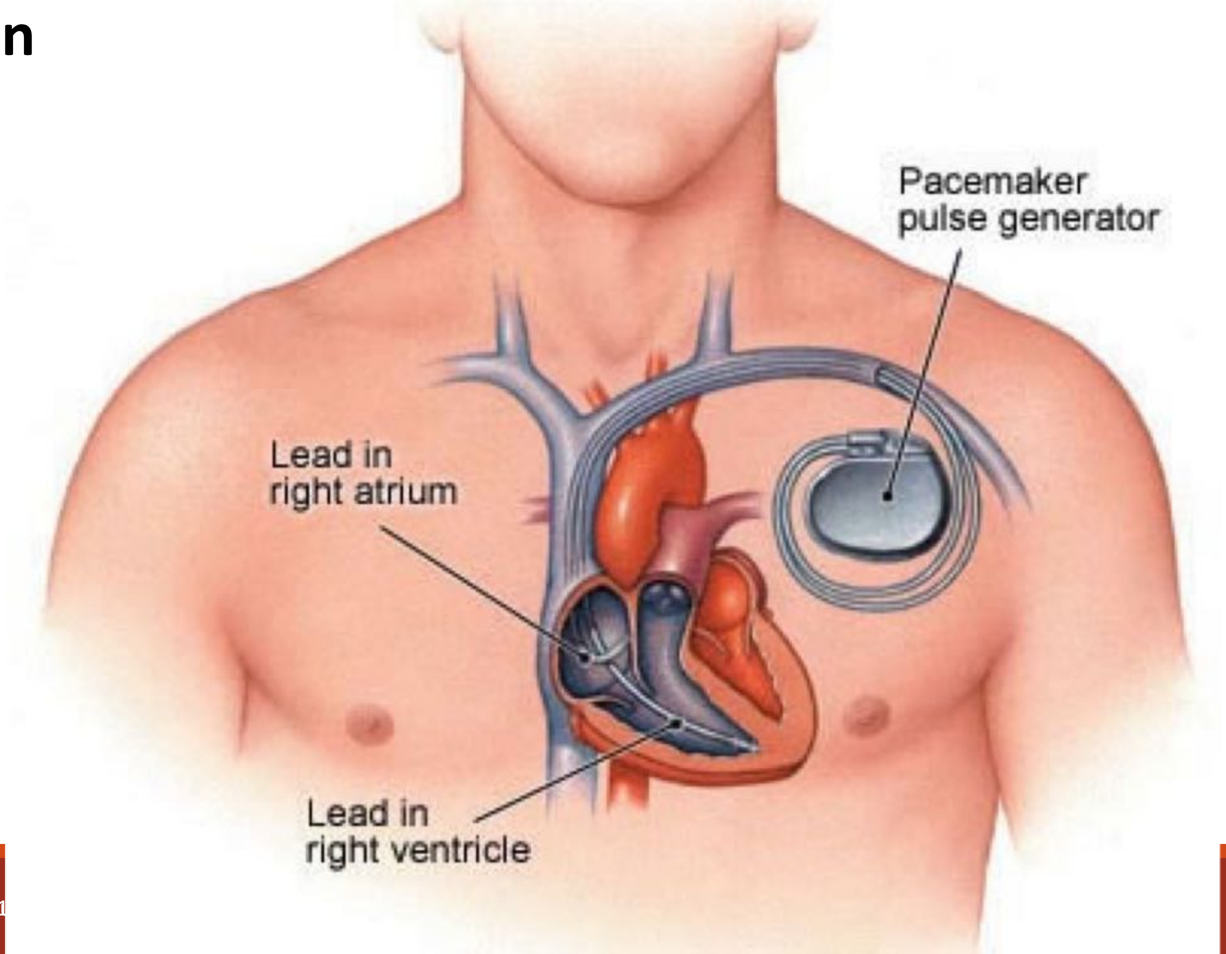
  one location of the chamber

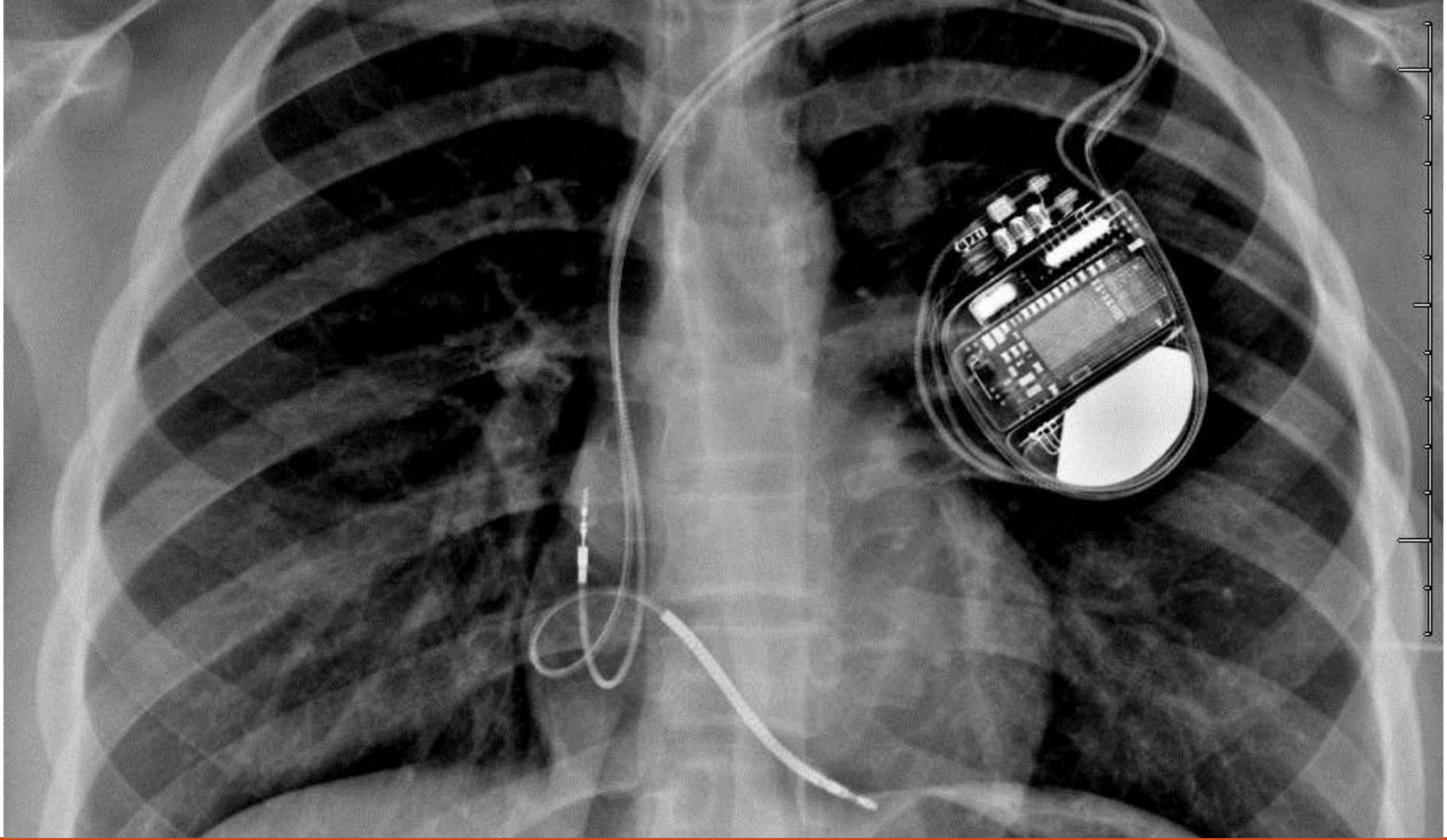


Implantable Pacemaker

Two leads are placed in the right atrium and right ventricle

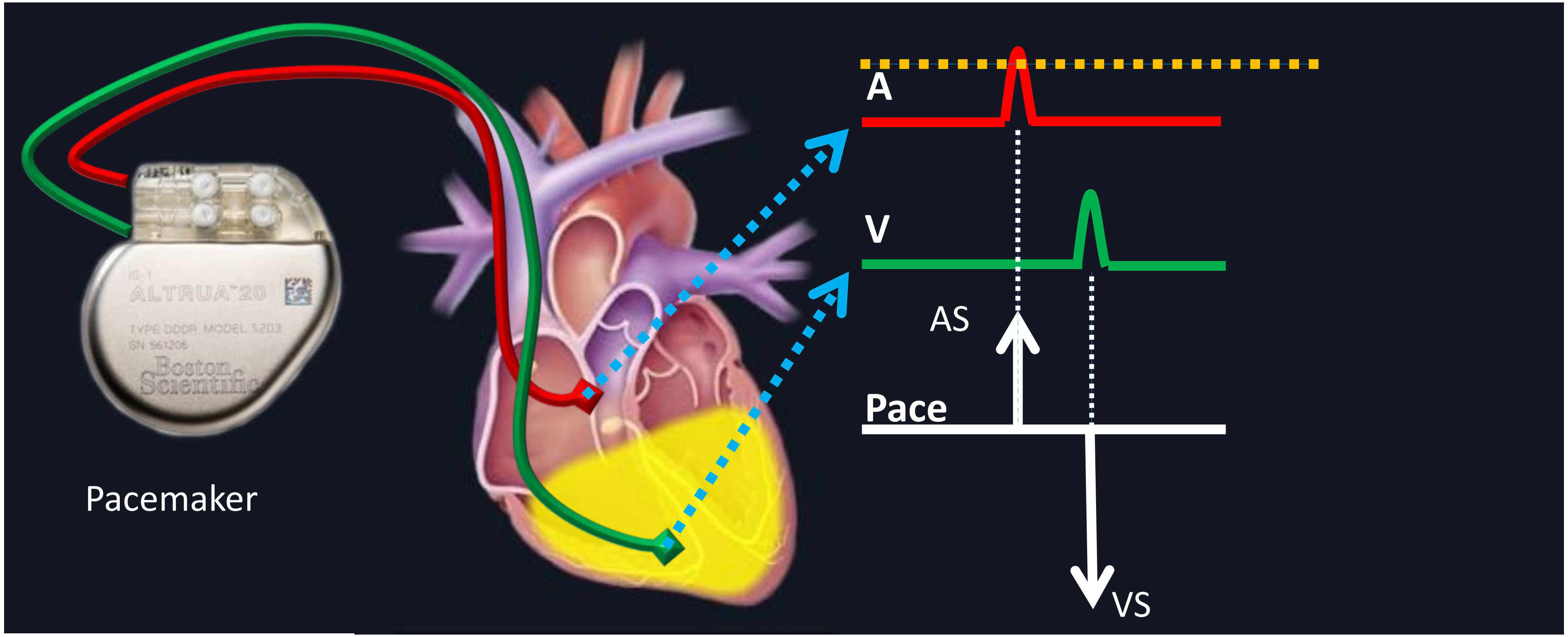
Monitors the local electrical activities of the heart and deliver therapy according to the **timing information**





Implantable Pacemaker

Timing info for local activation



- Simulink and State-flow tutorials have been posted on the course website.
- Not graded. No submission required.
- One week to brush up on Simulink/Stateflow.
- Go through the tutorials before the Simulink/Stateflow model walkthrough lecture next week

Next Lecture:

- Pacemaker operation and heart conditions
- Model checking vs Model testing
- Heart modeling using timed automata