# 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


FANDANGO
MOVIECLIPS

# 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

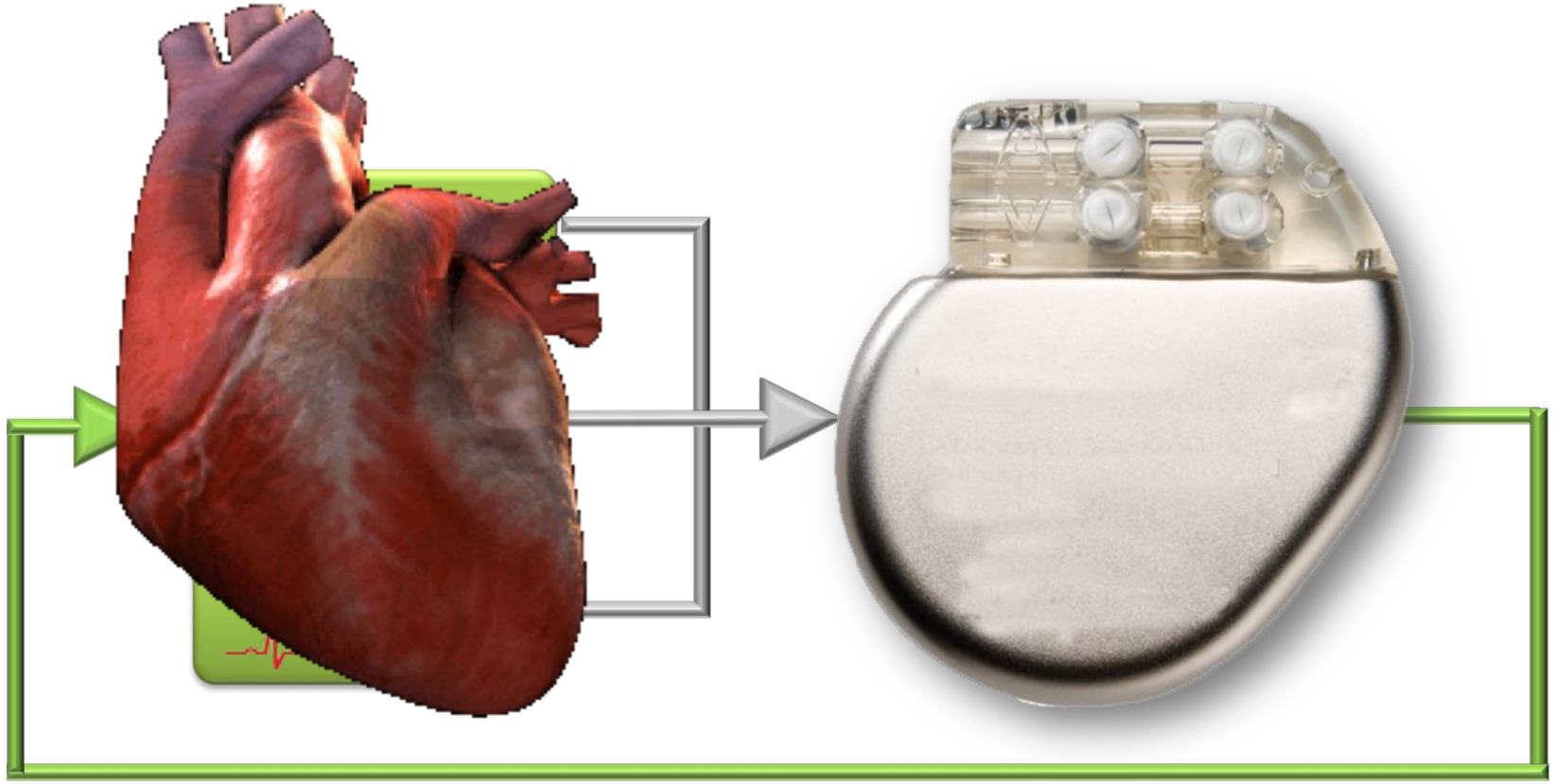
**Implantable Pacemaker**

**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

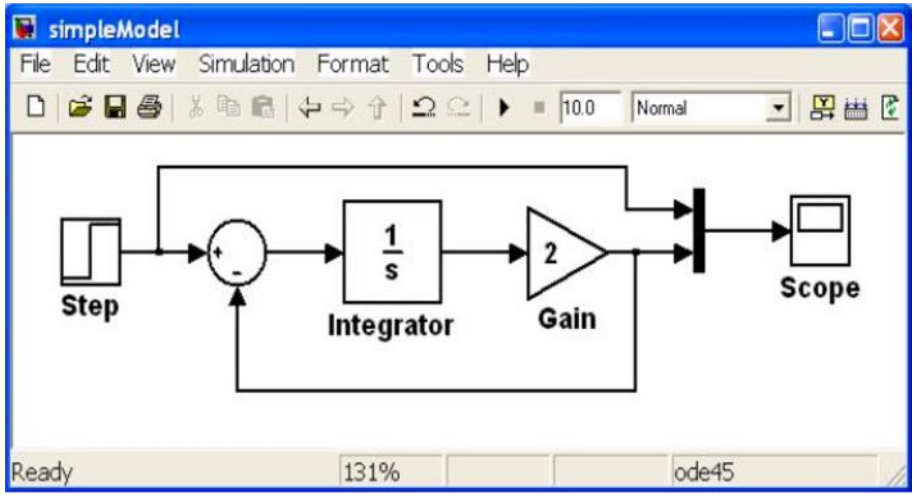
Check if pacemaker is ‘safe’ for different heart conditions

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

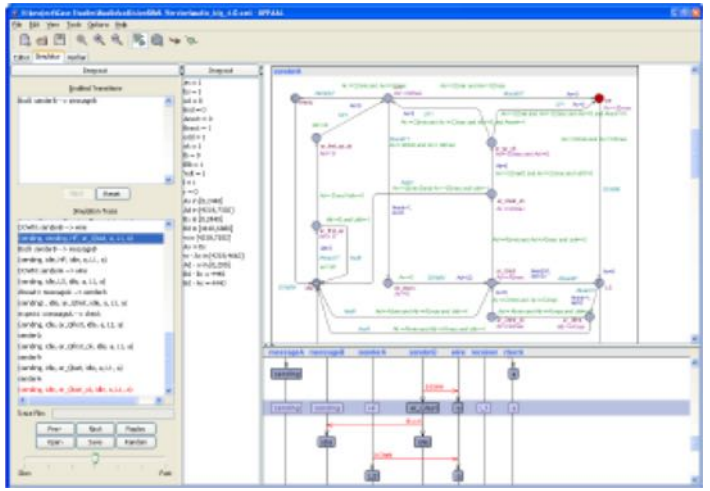
# This Module

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.

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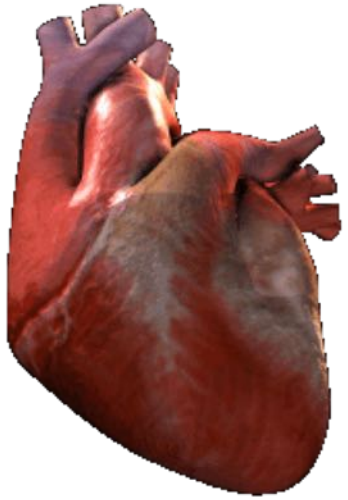
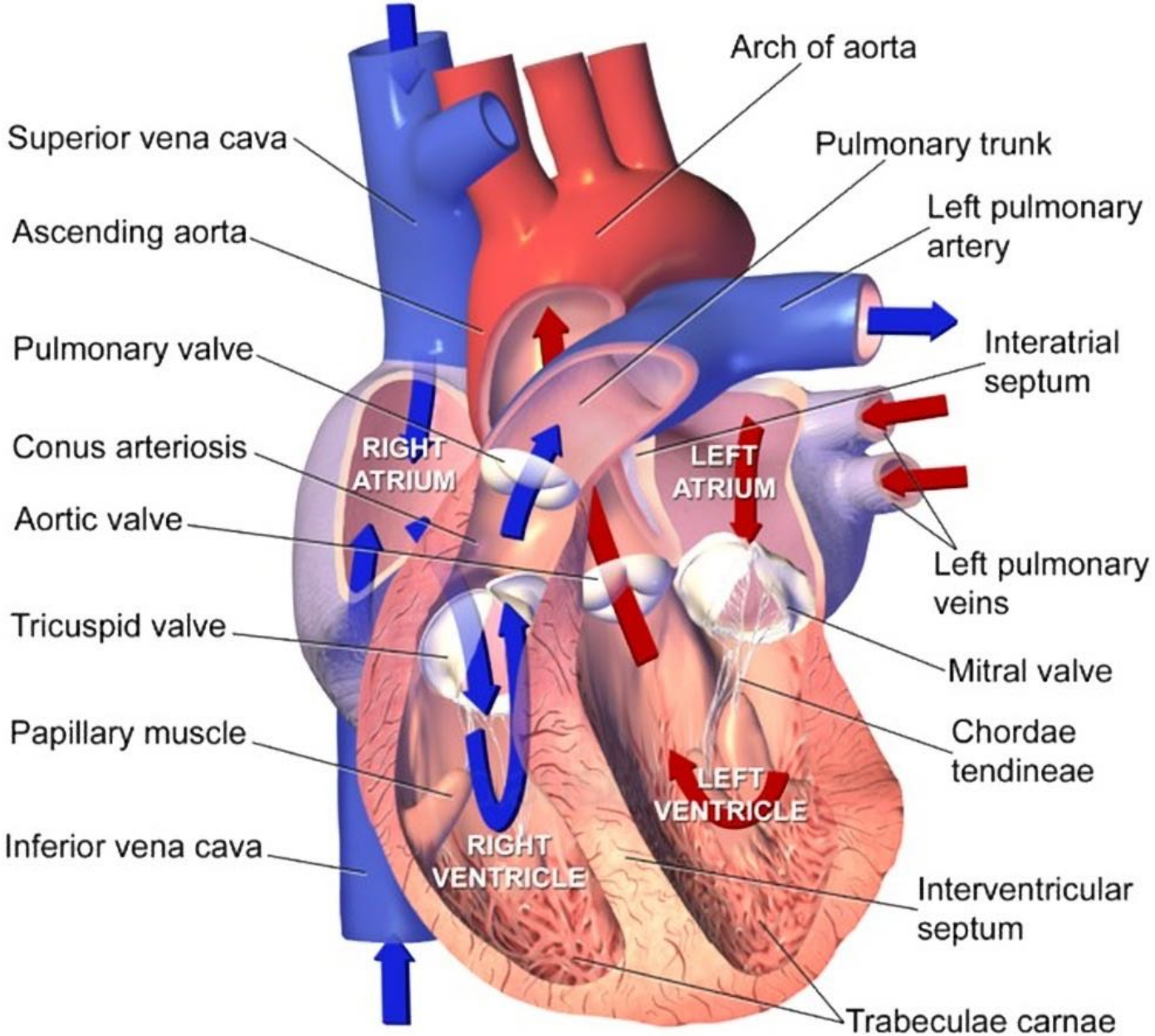
Remember....modeling choices and ‘usefulness’ depend on the problem at hand.

# Electrophysiology of the heart



aka ..talking like a cardiologist without attending med school

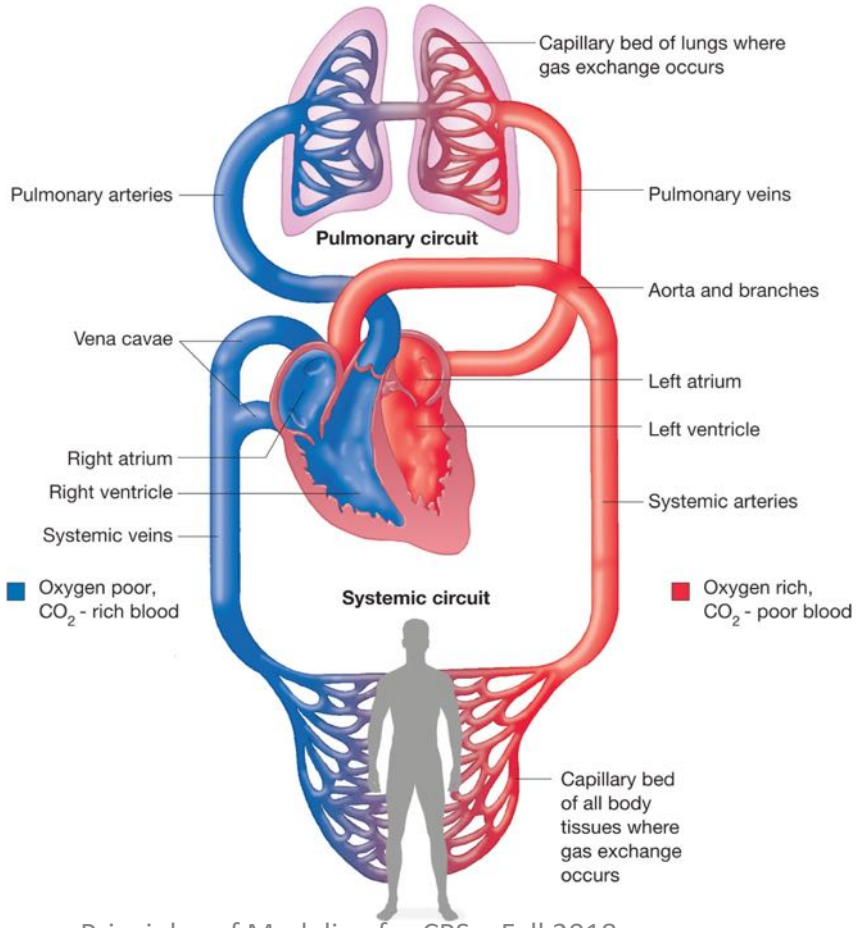
# First, let's examine the human heart

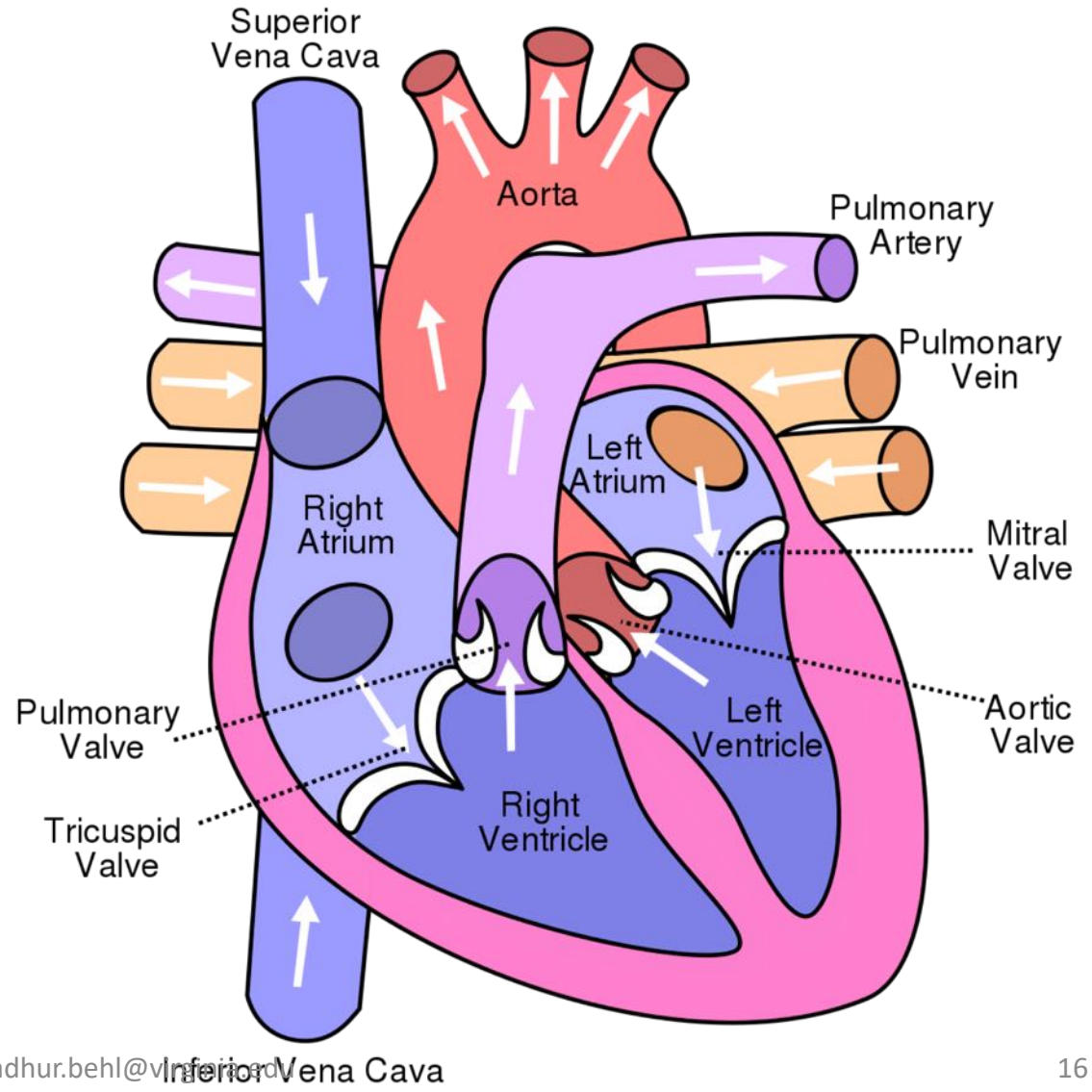



**Sectional Anatomy of the Heart**

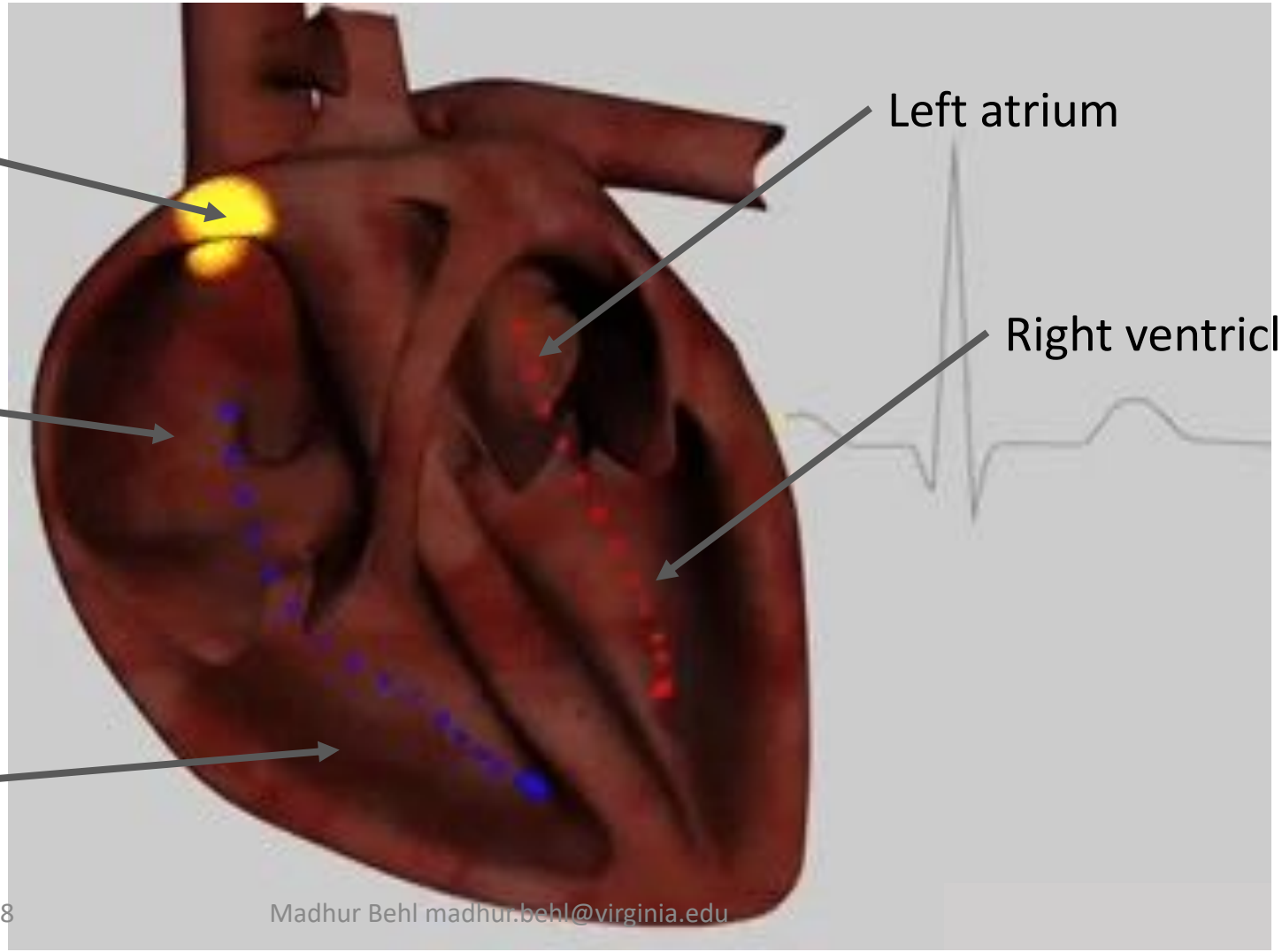
# Circulatory system and heart function

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

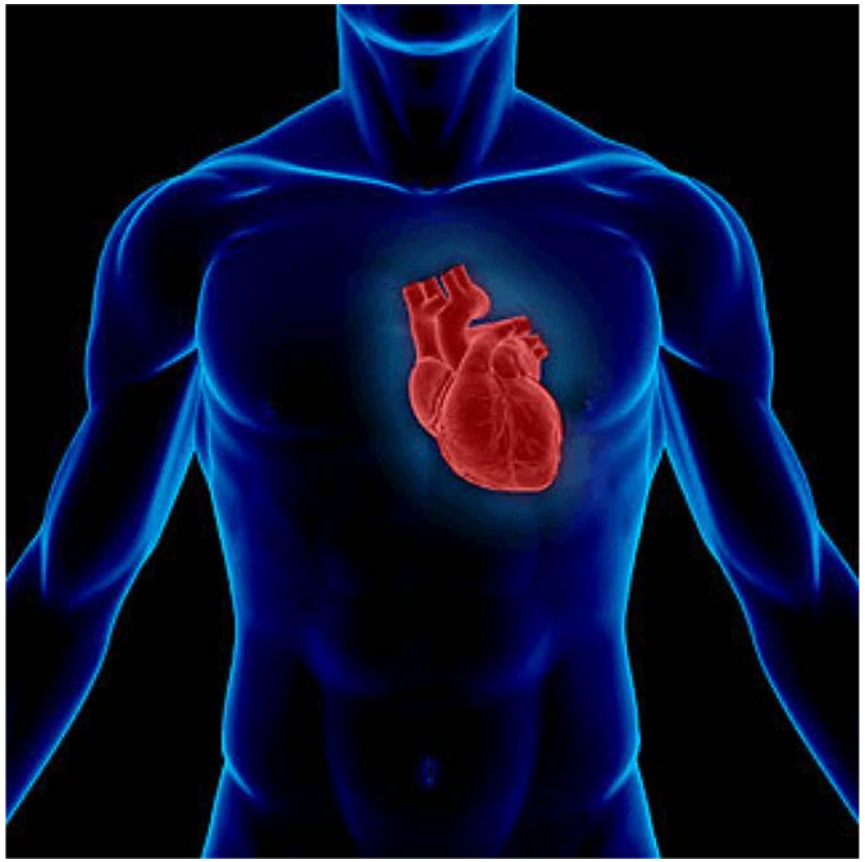


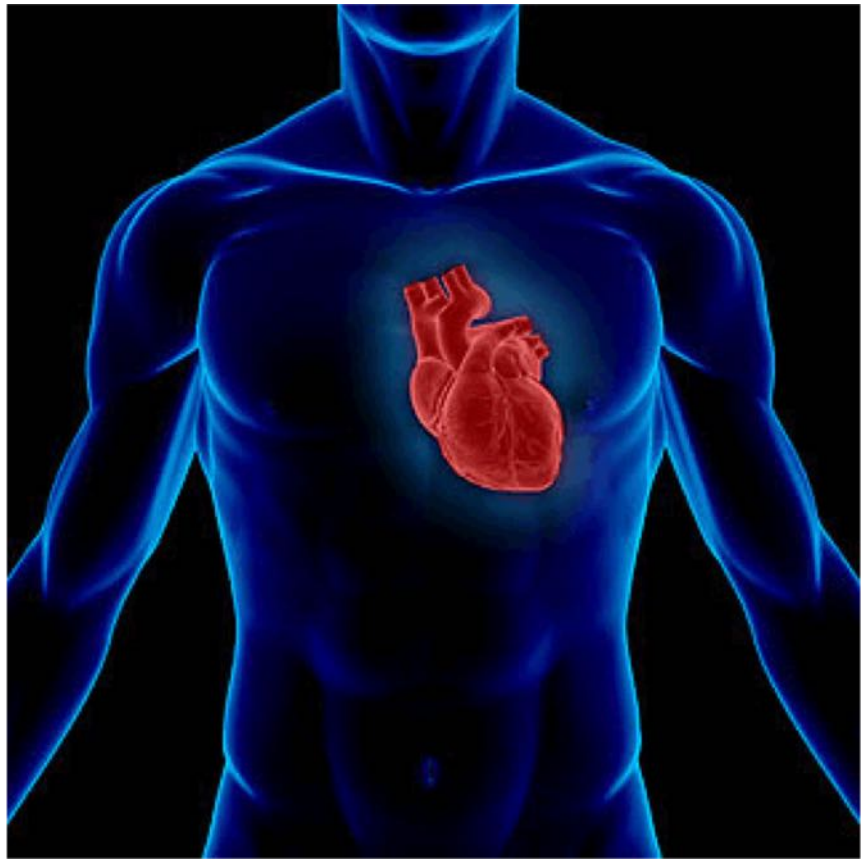



# Electrical generation and propagation

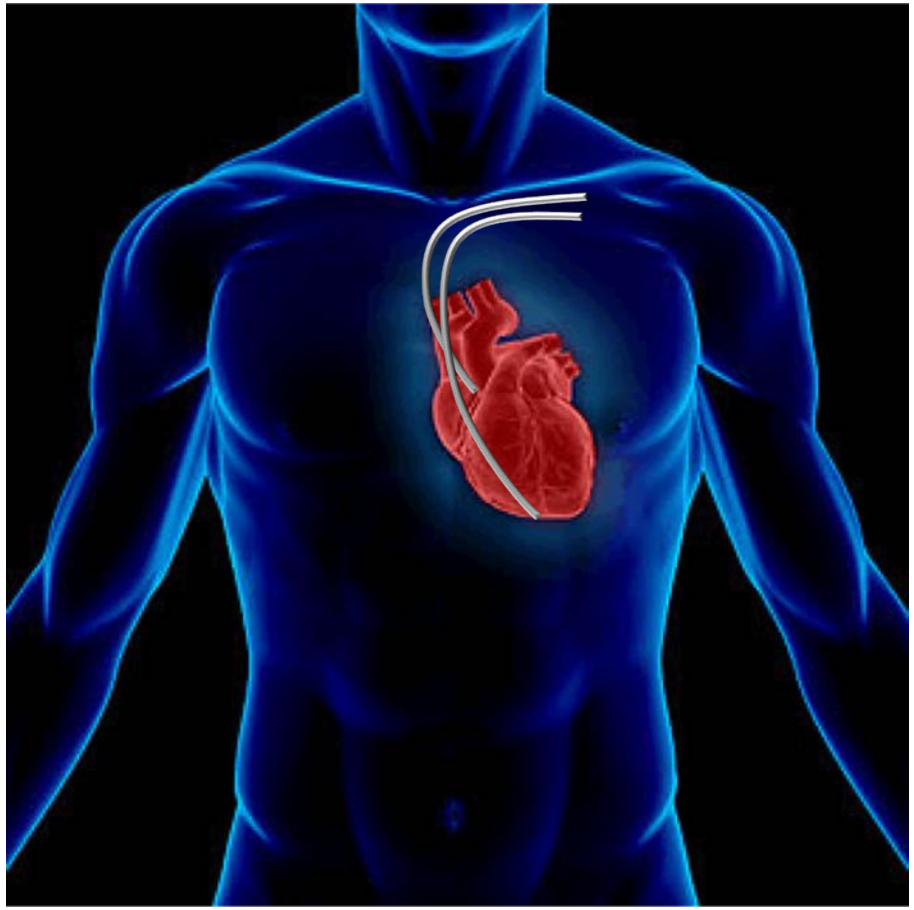


# Bradycardia: bradus (slow) + kardia (heart)





# Implantable Pacemaker

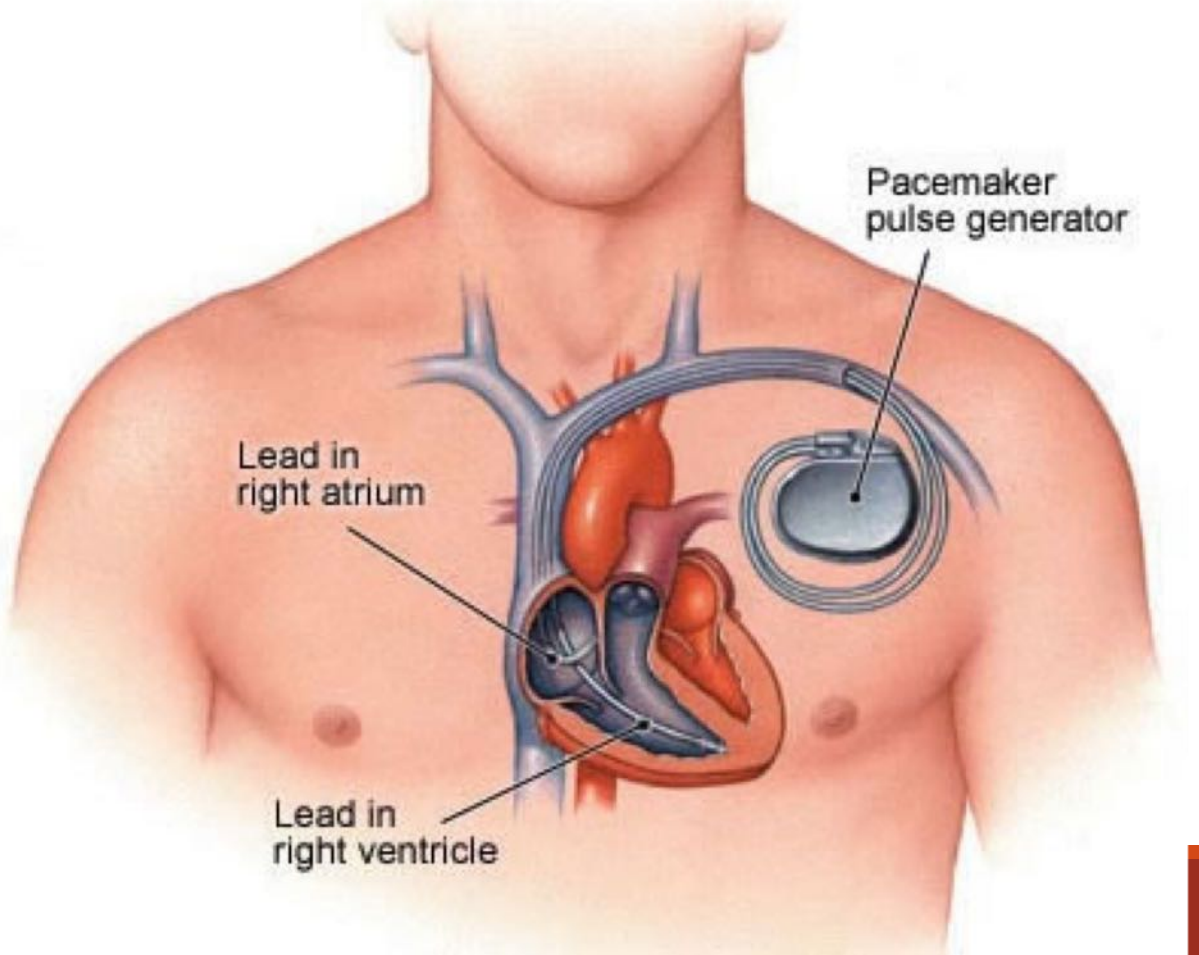


Two leads in heart chambers

# 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**



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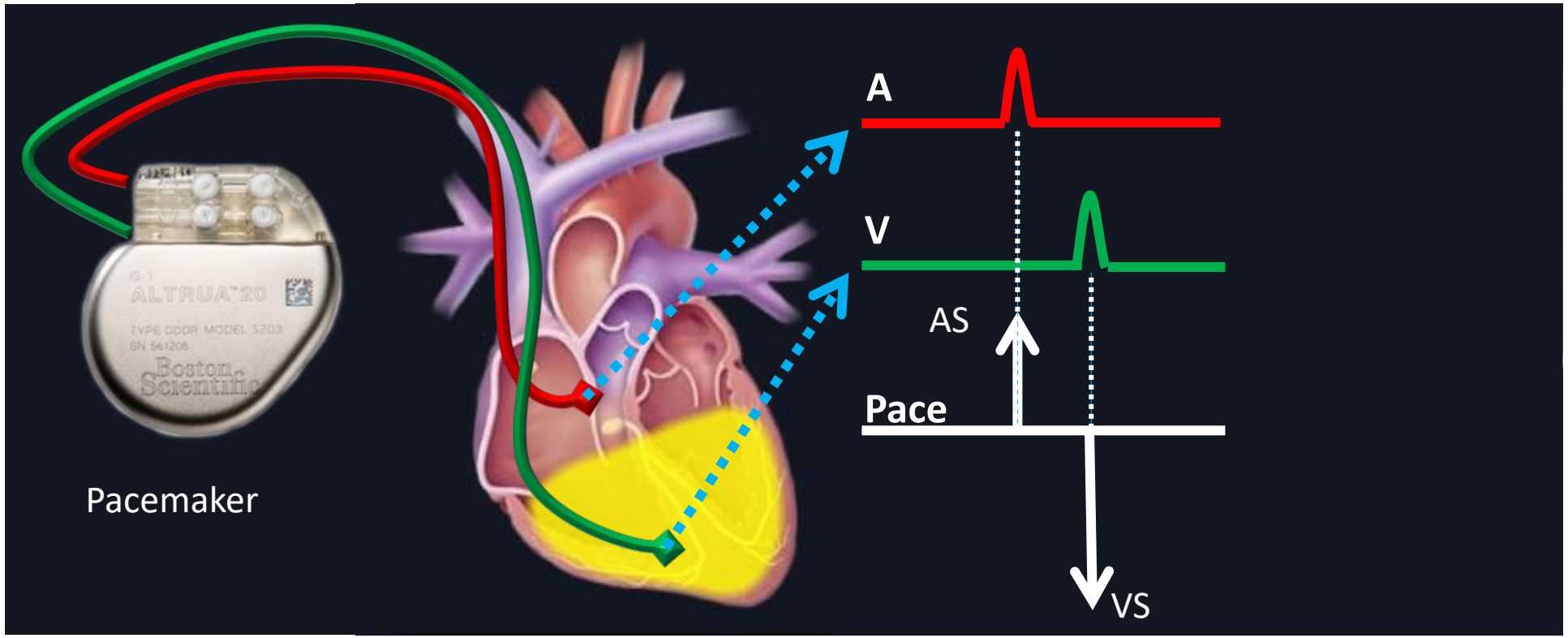
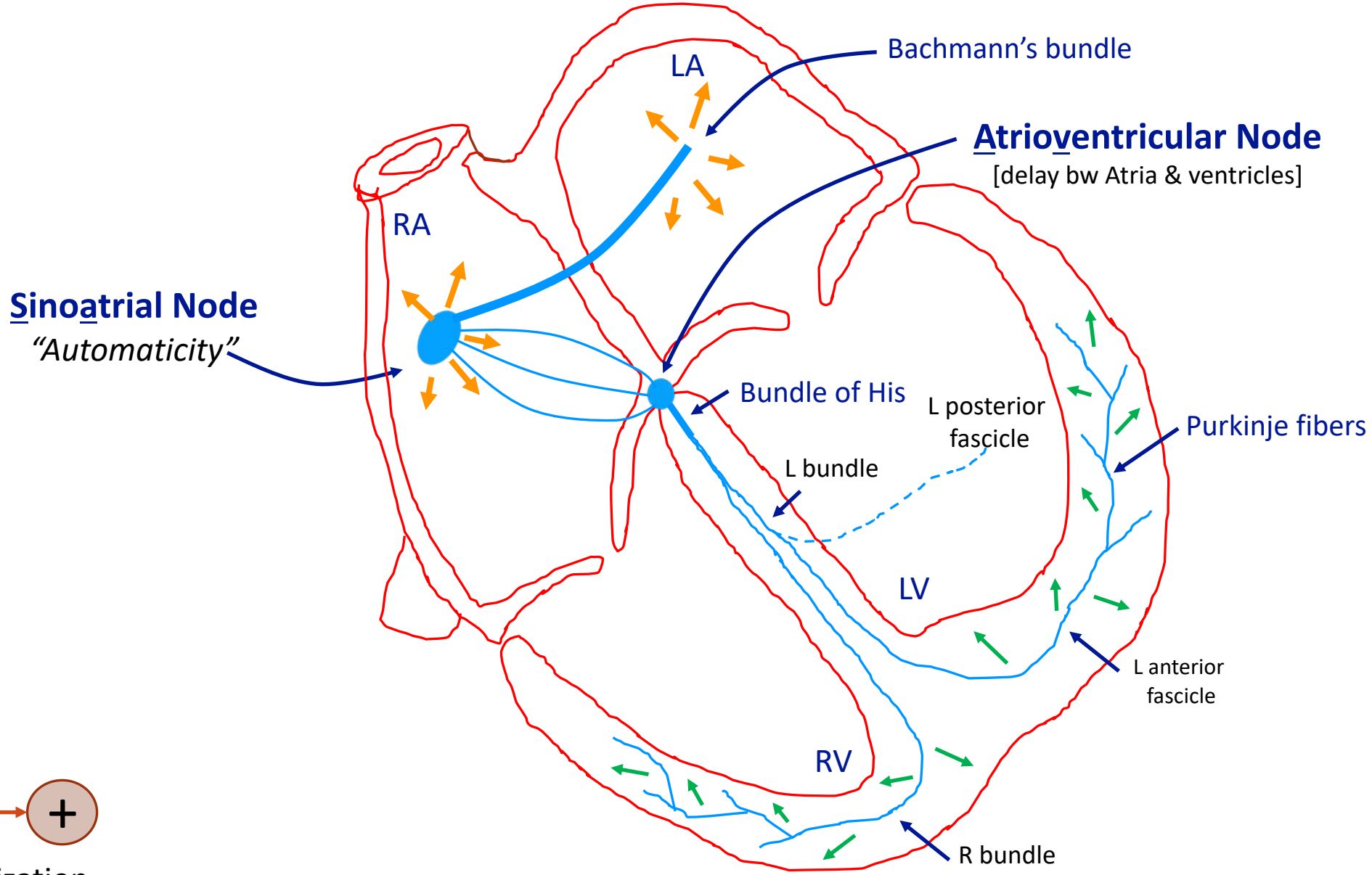
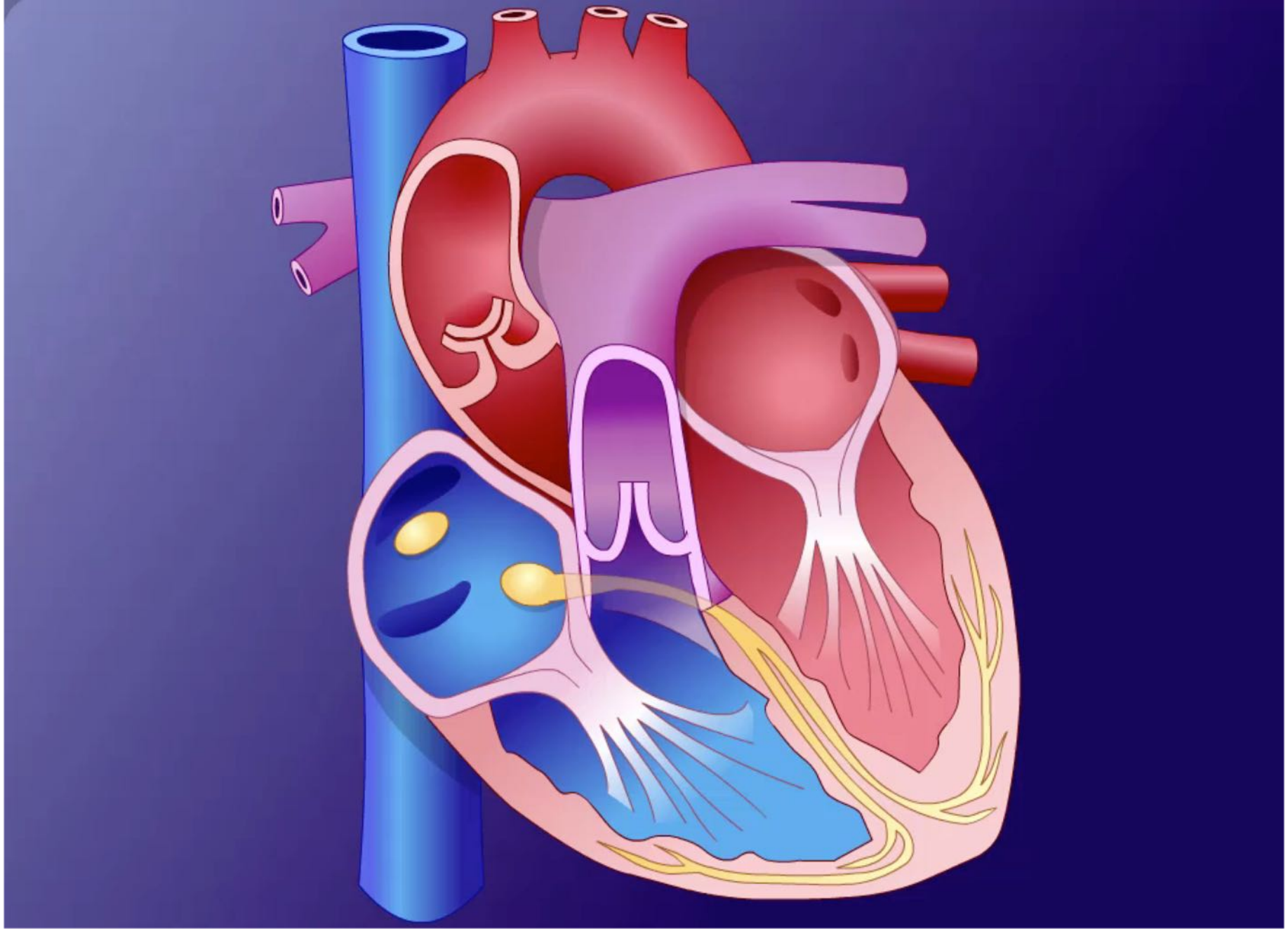






Depolarization



**Pacemaker cells** (naturally pace the atria and ventricles)

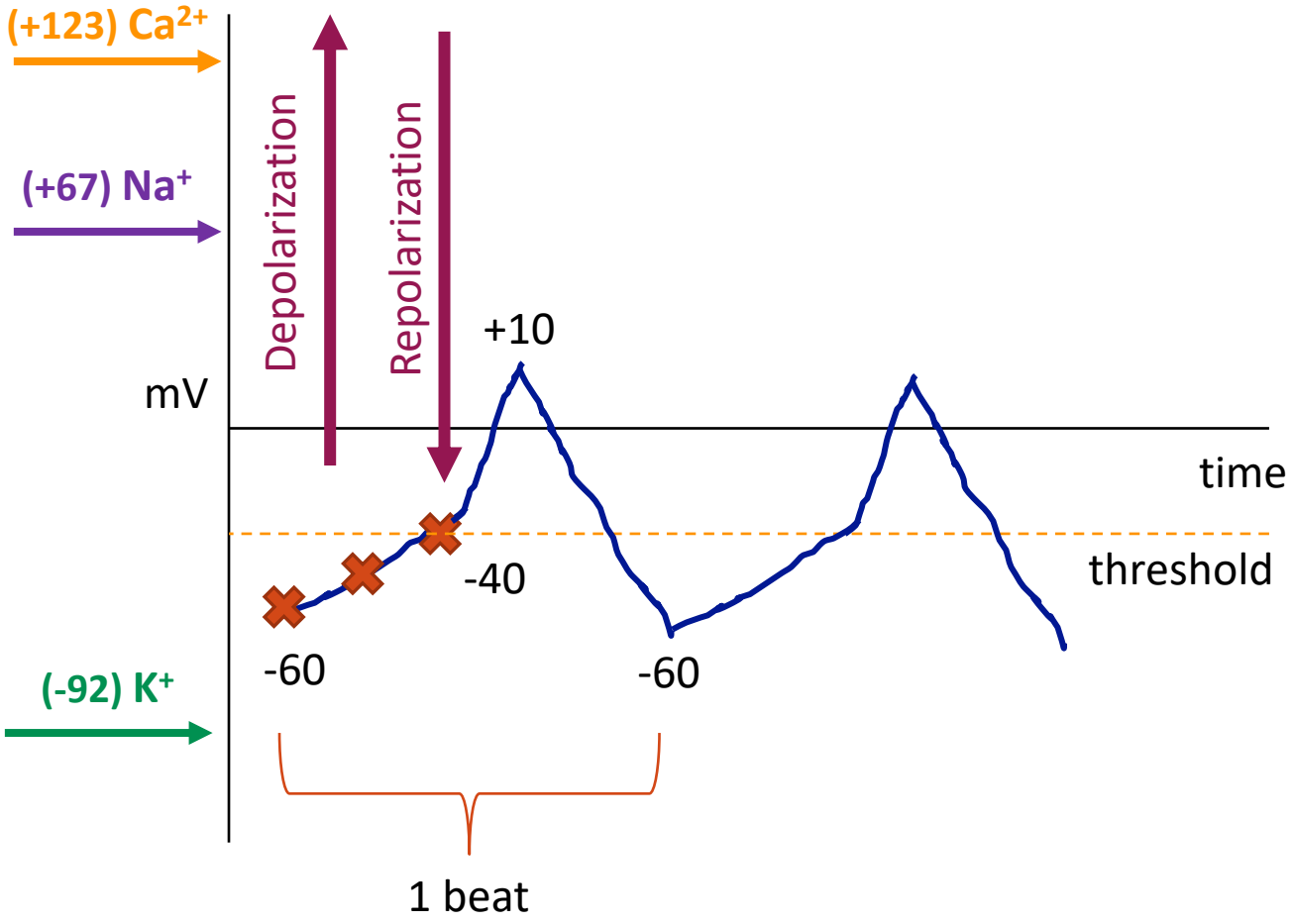
and

**Cardiac myocytes cells** ("squeezing" the heart)

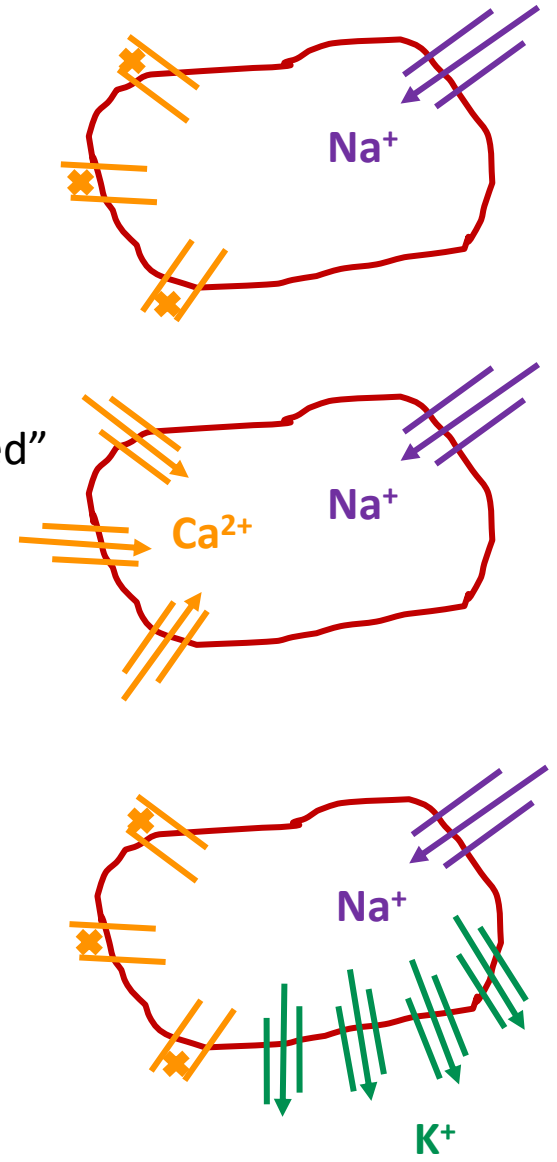
# Pacemaker cells – "Automaticity"

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

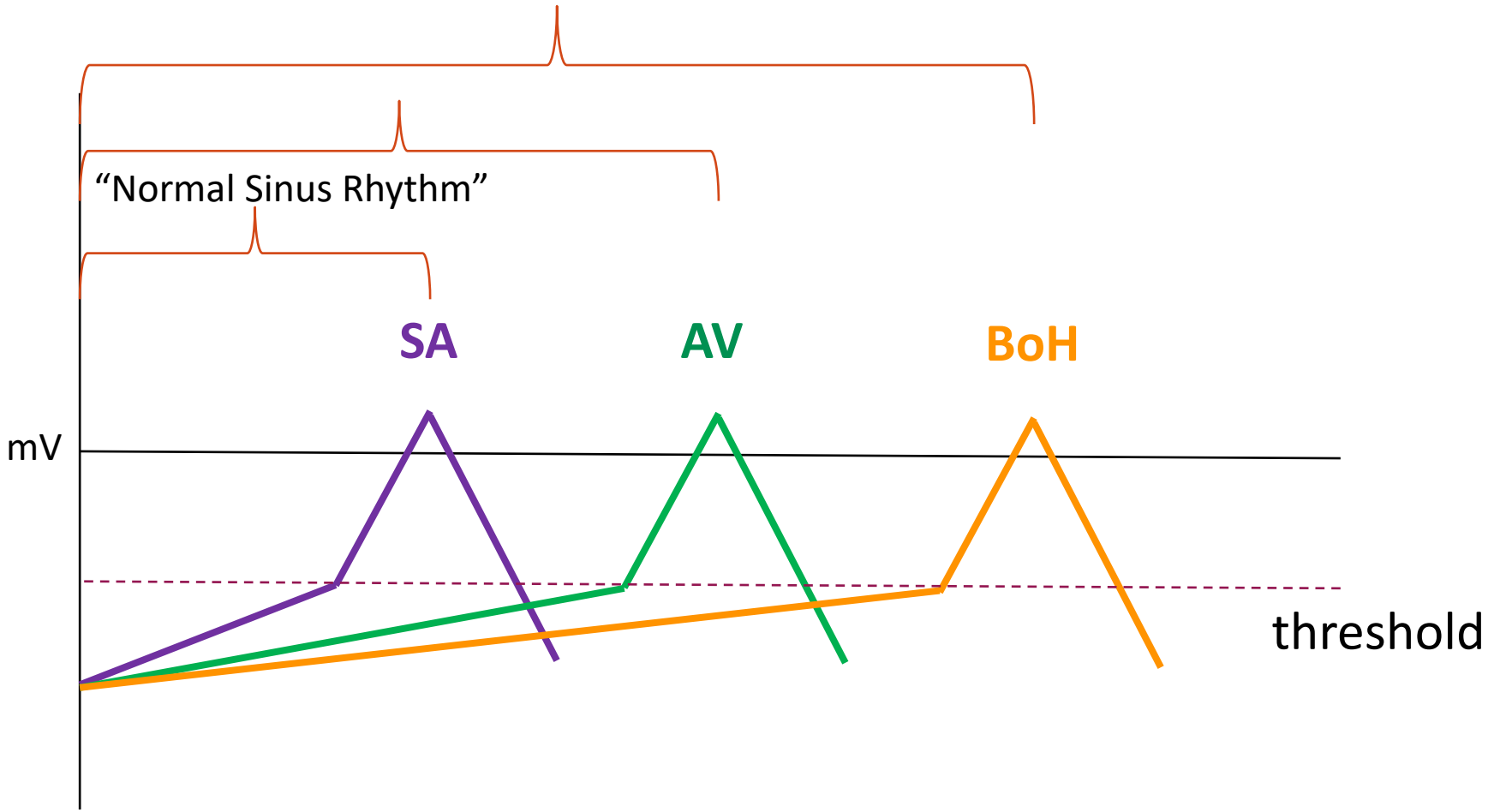
# Pacemaker cells




"Voltage-gated"



# Race to keep pace !



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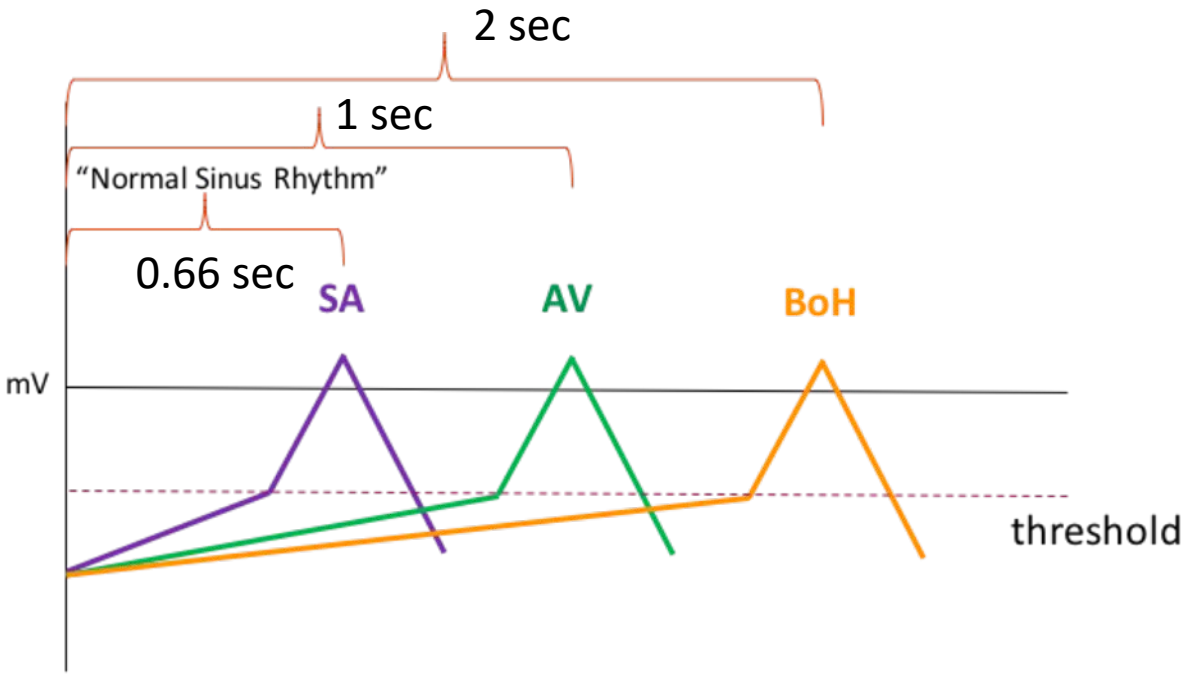
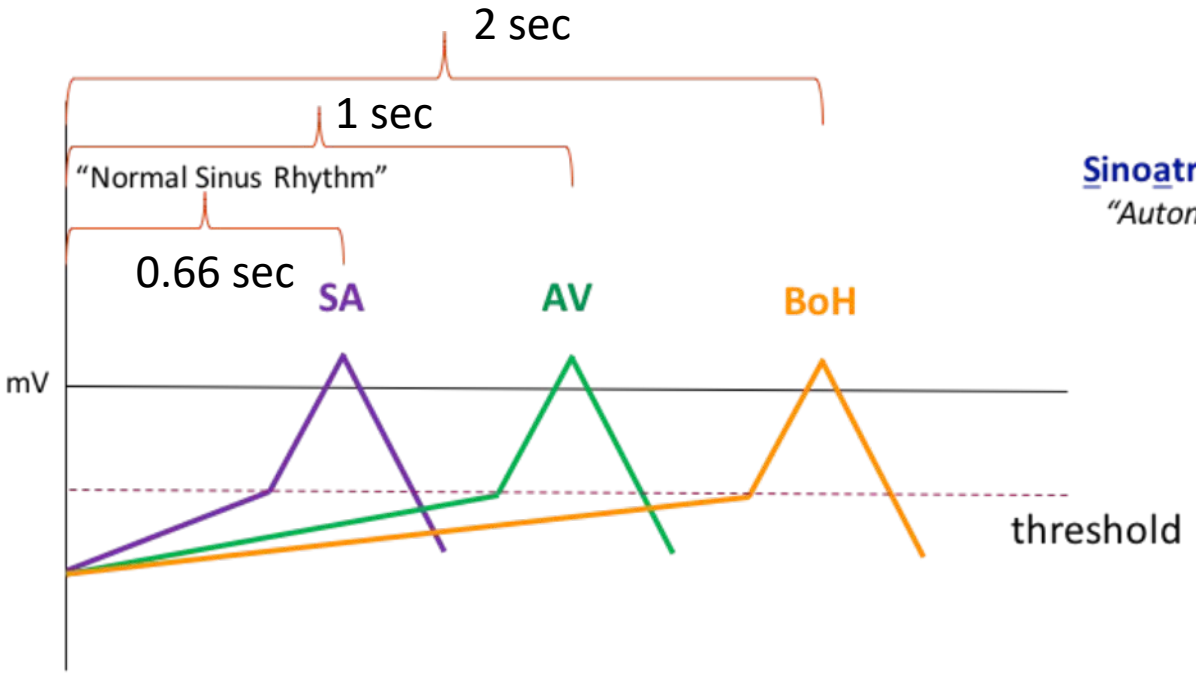
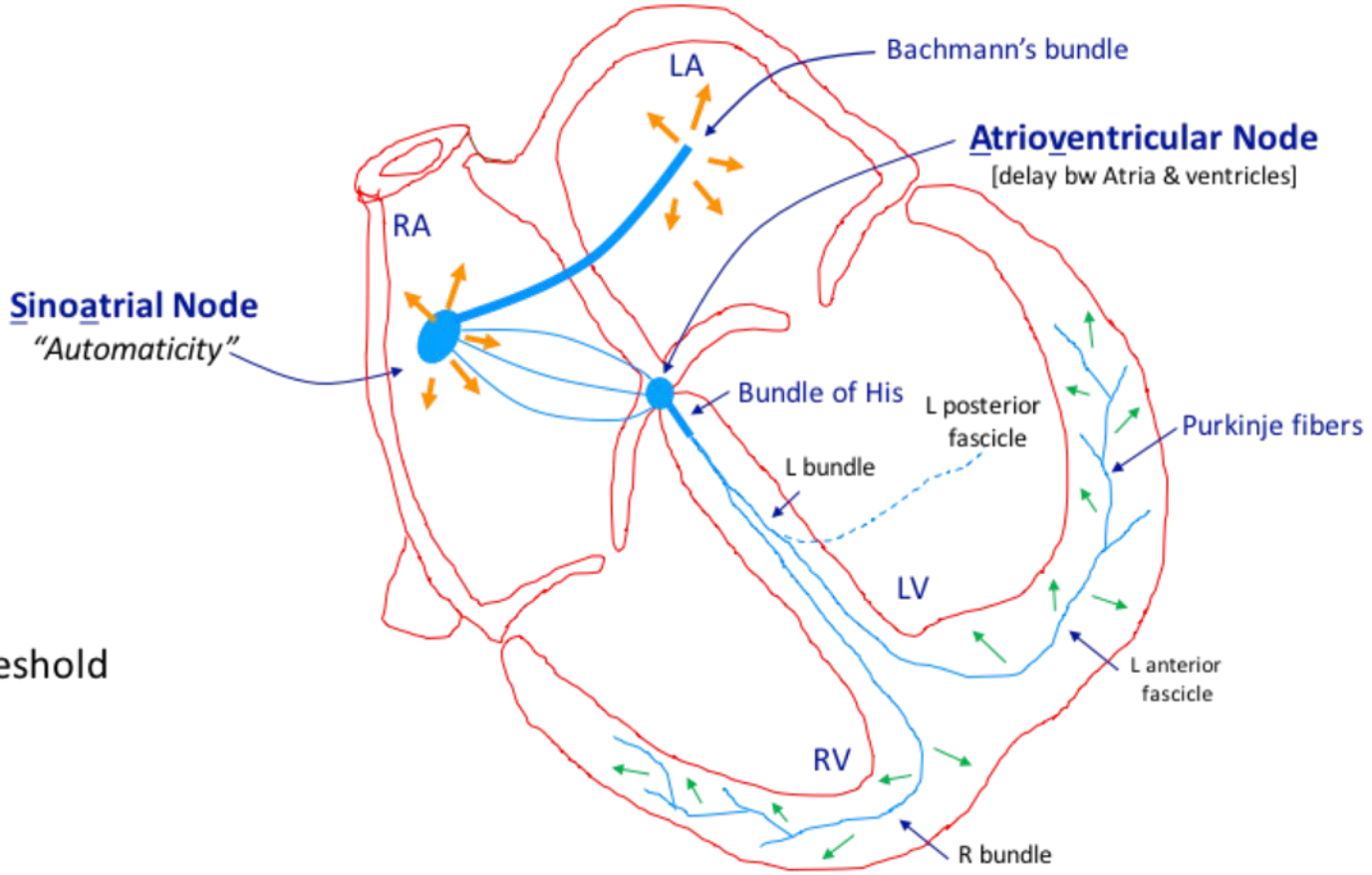



| | Heart Rate (beats/min) | 1 beat (sec) |
|---|---|---|
| SA | 60-90 | 0.66 sec |
| AV | 40-60 | 1 sec |
| BoH | 20-30 | 2 sec |

# Race to keep pace !



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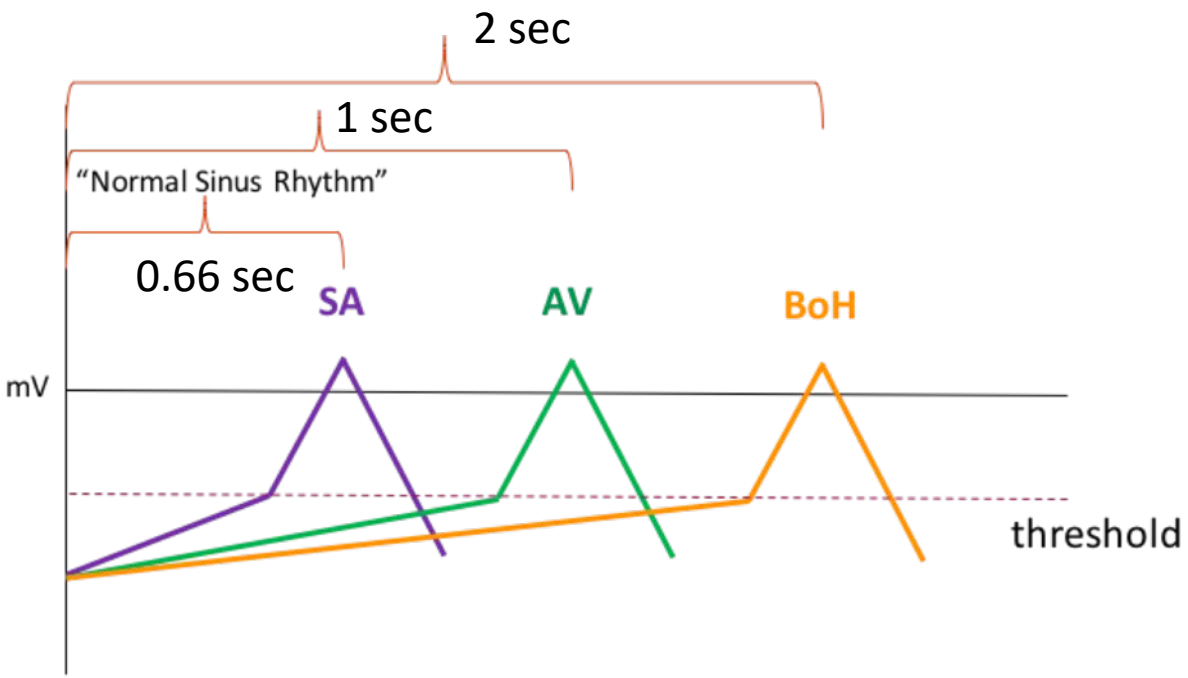
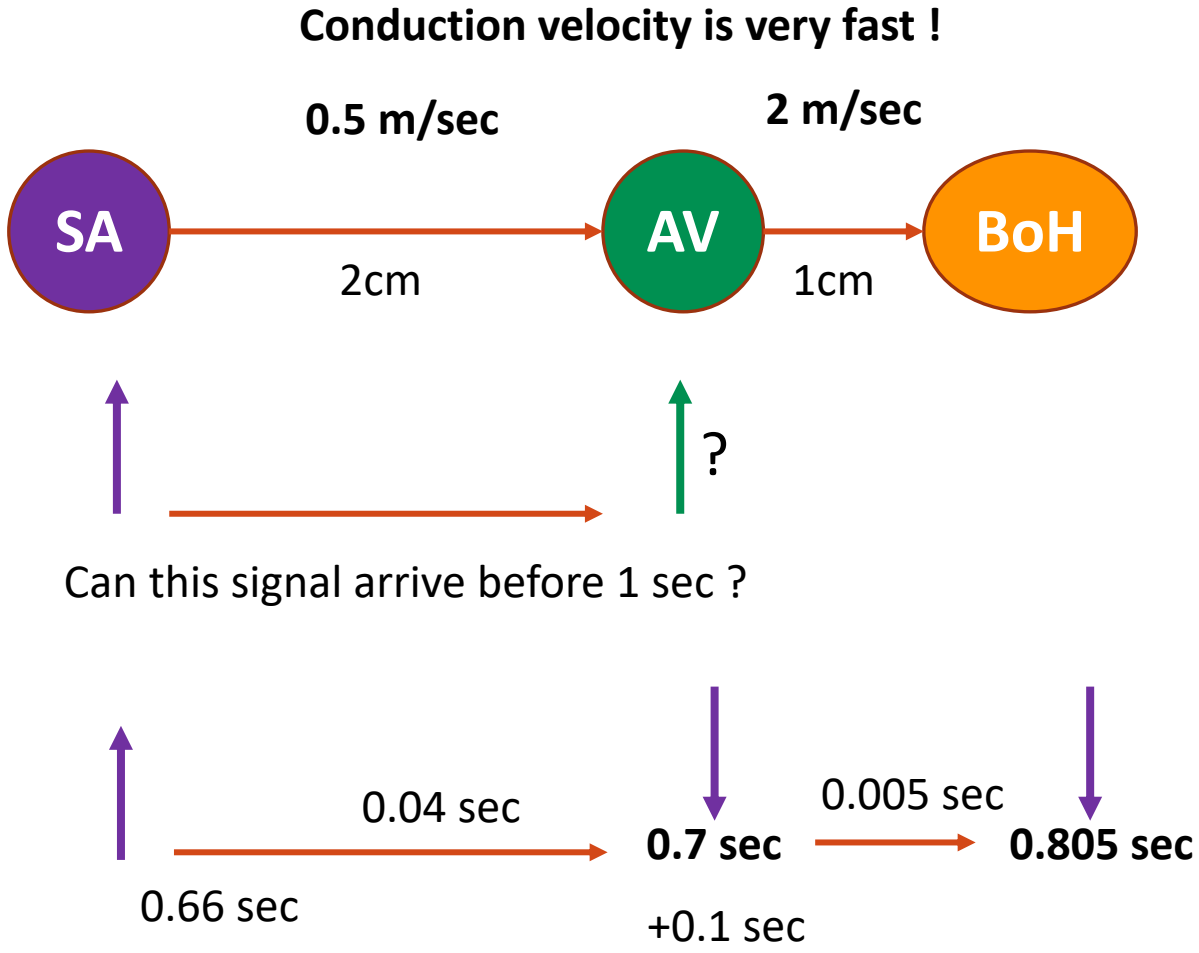
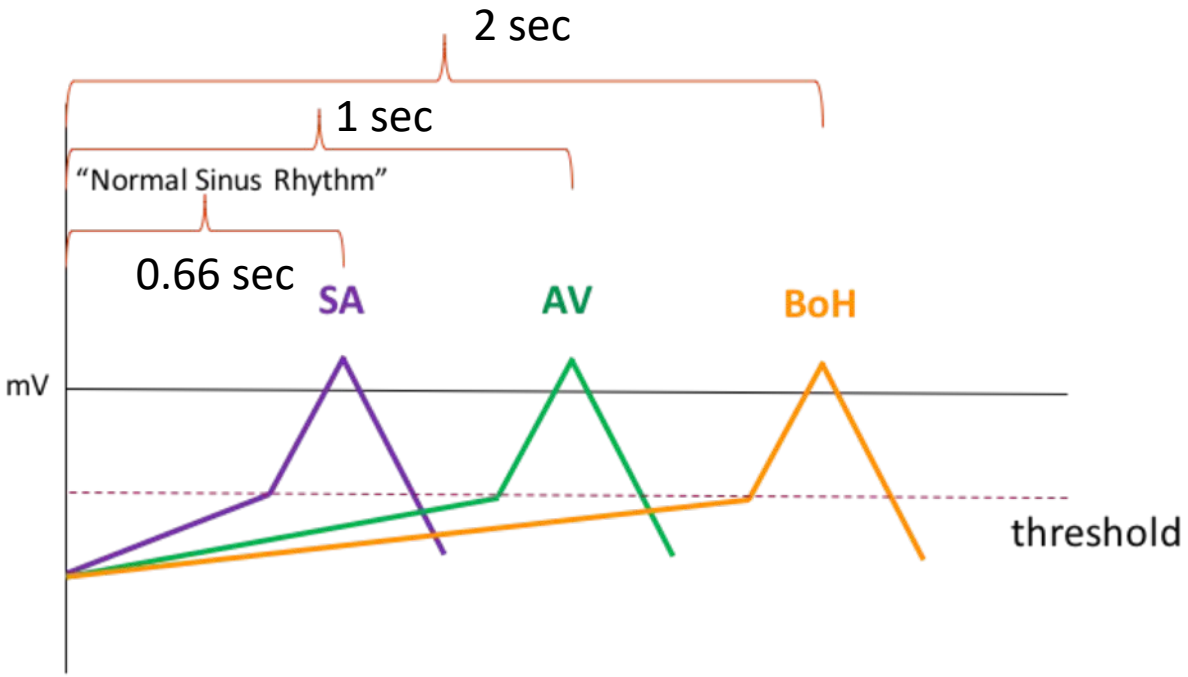



How does SA node control the heart beat ?

"Normal Sinus Rhythm"

# Race to keep pace !

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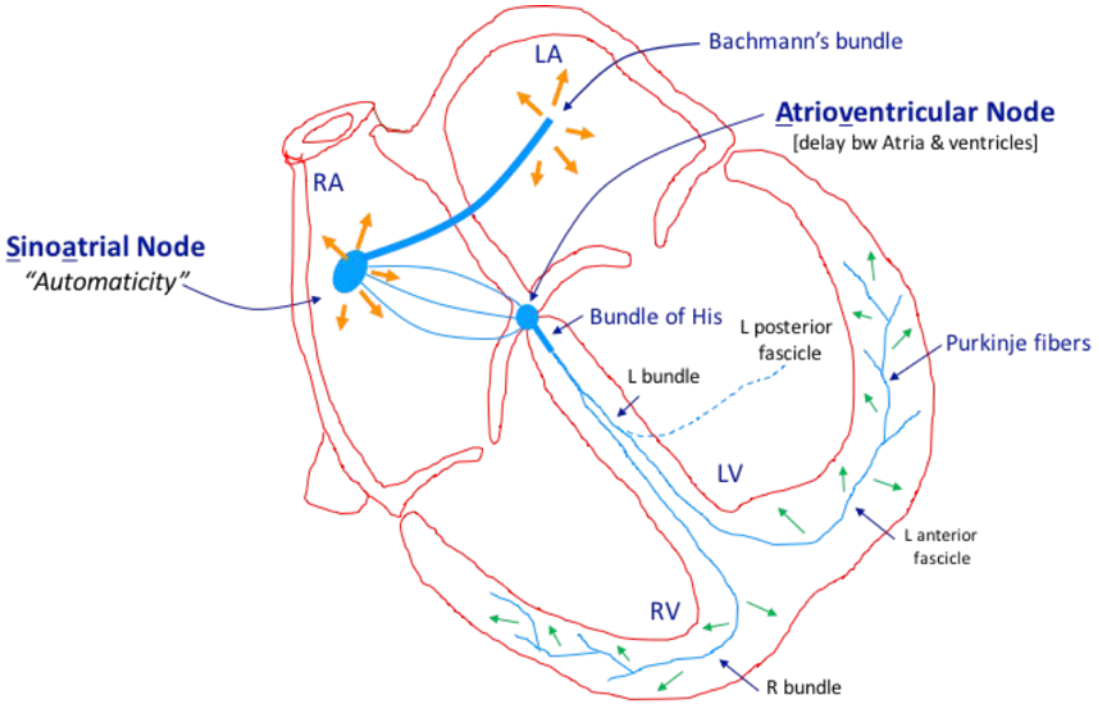


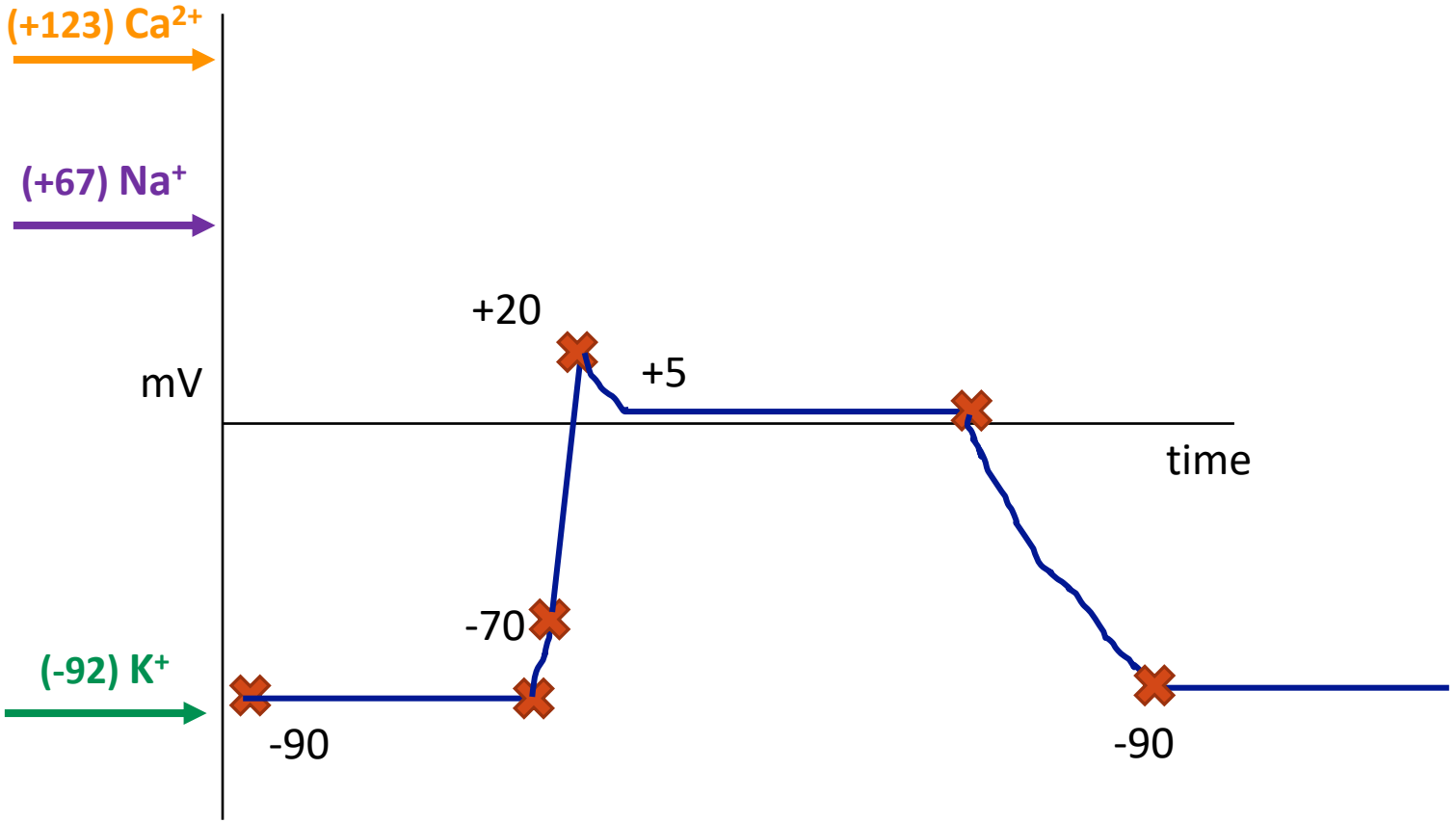

- SA node – Plan A
- AV node – Plan B
- BoH – Plan C

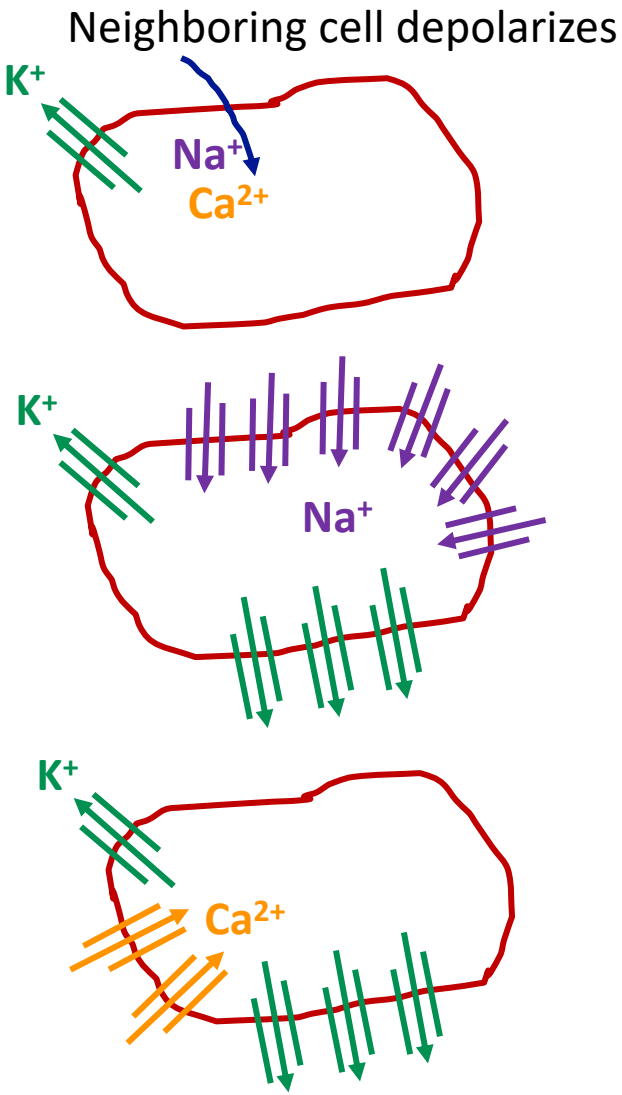
**Pacemaker cells** (naturally pace the atria and ventricles)

and

**Cardiac myocytes cells** ("squeezing" the heart)

# Cardiac Myocytes – How does the heart squeeze



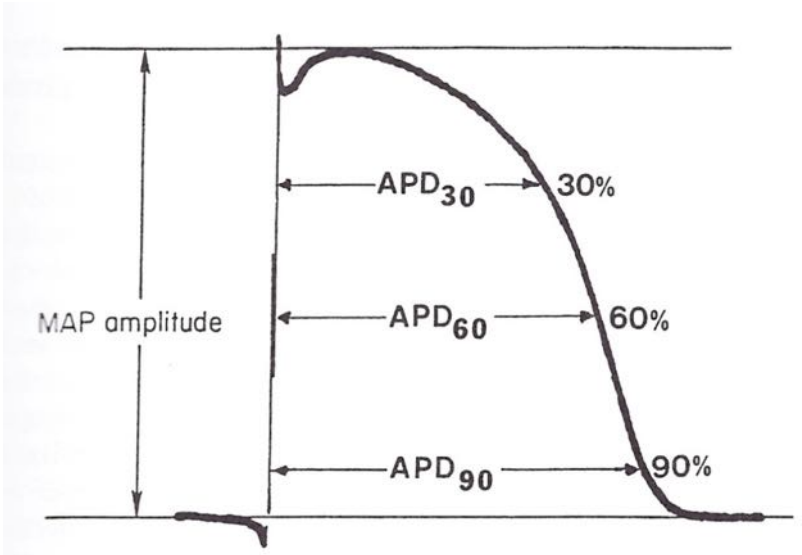



# Action Potential - Tissue

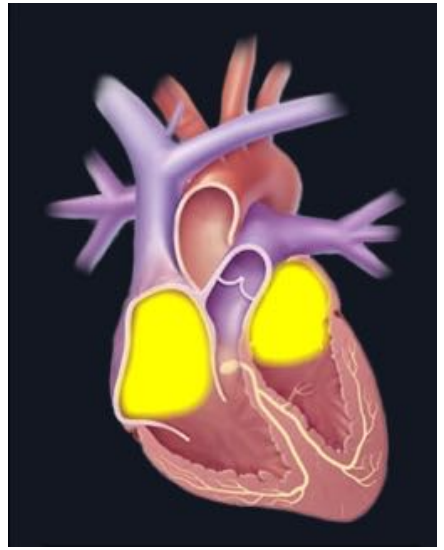
The elementary signal of the heart

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

Closely related to most cardiac diseases.




APD: Action Potential Duration



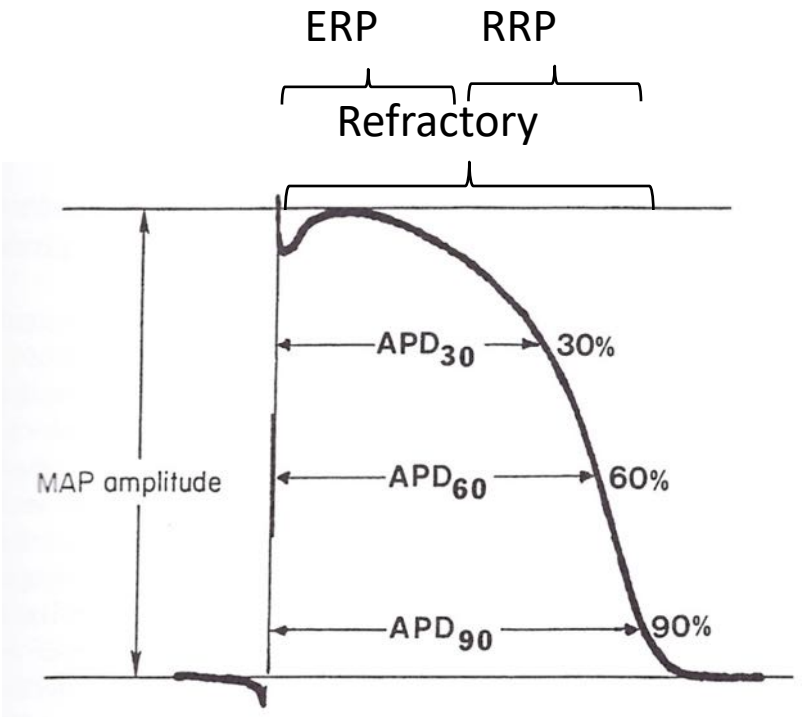
Functional syncytium

# Cellular Level - Action potential

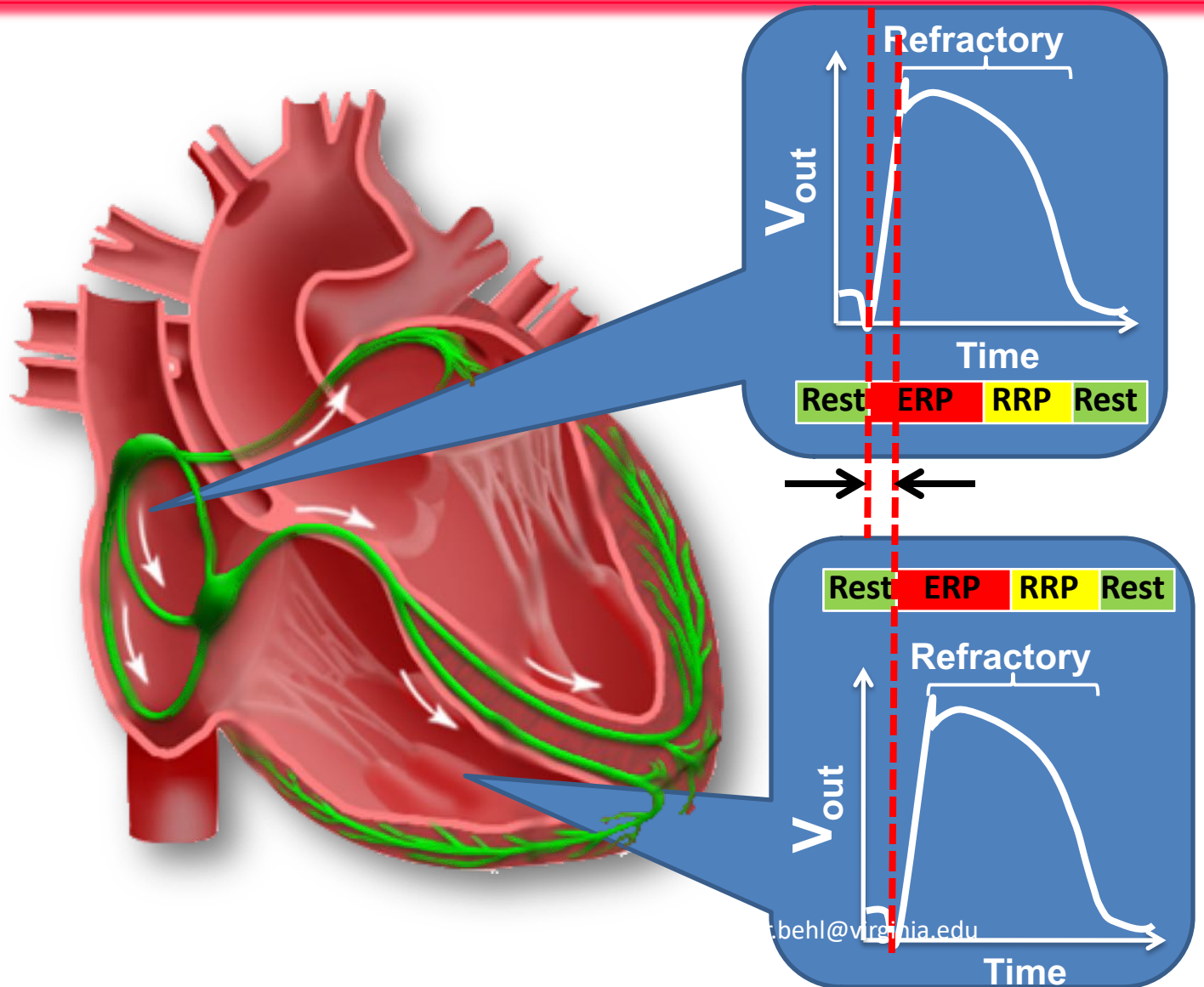
Ions refill

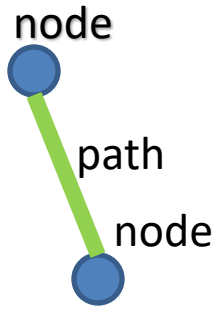
Divided into *Effective Refractory Period(ERP)* and *Relative Refractory Period(RRP)* for activation with certain strength

Block Interval during ERP, abnormal new action potential during RRP



# Refractory period



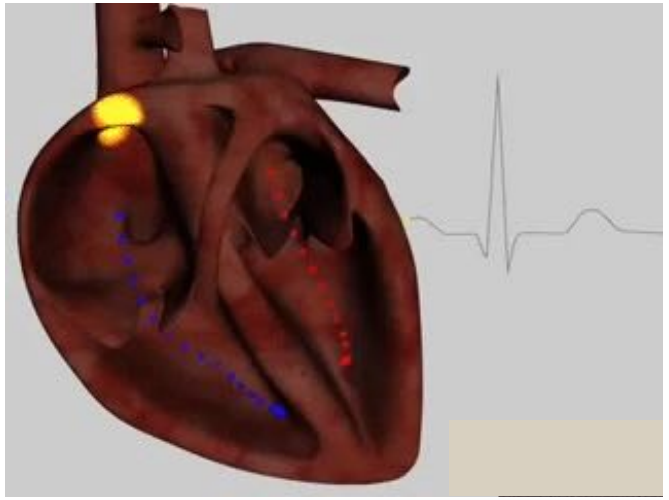

t.behl@virginia.edu

# 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:

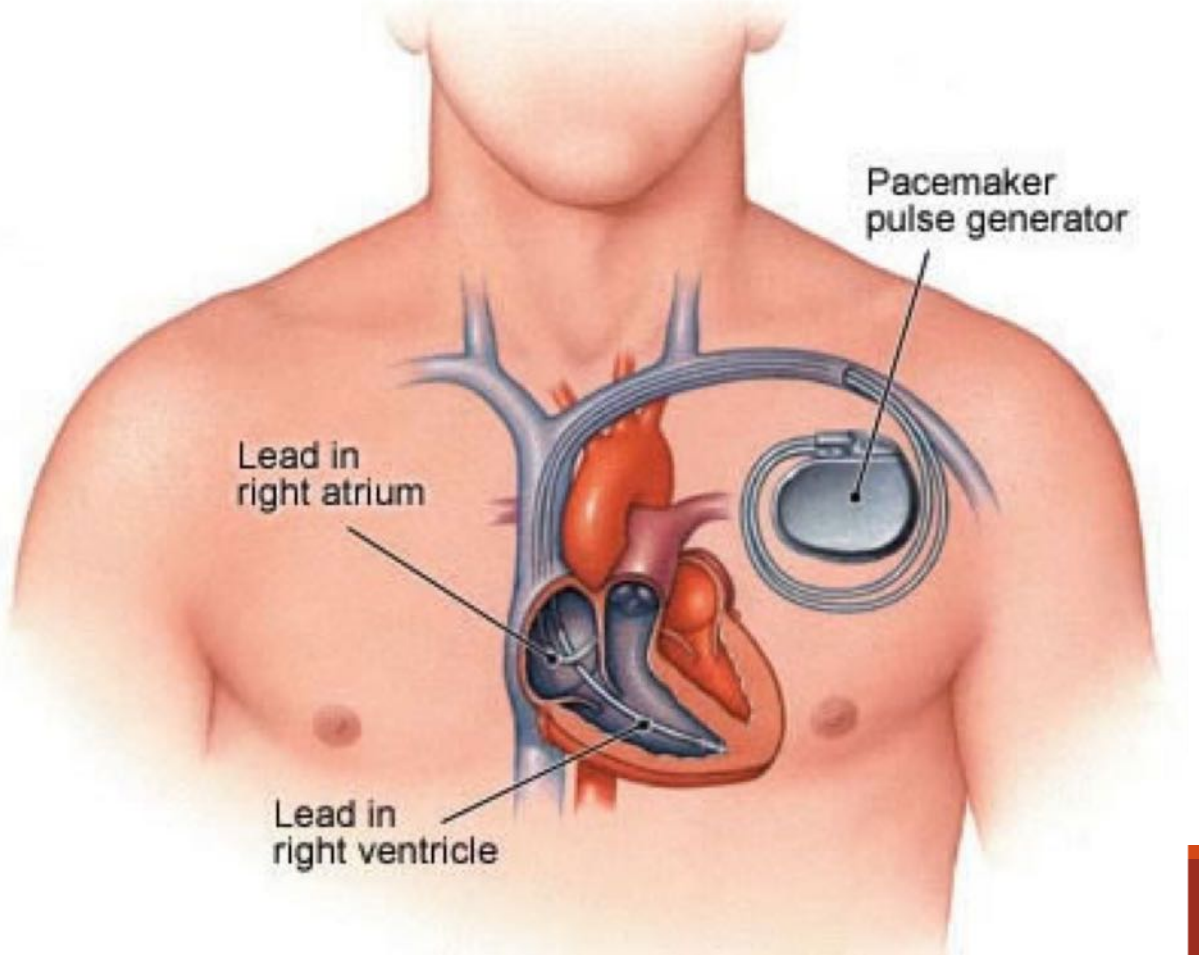
- We know that usually, the atria contract together, and the ventricles contract together → sense only in right atrium and ventricles
- Usually, depolarization is synchronous with contraction → measure the electrical activity as a proxy for the mechanical activity
- Usually, depolarization in part of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

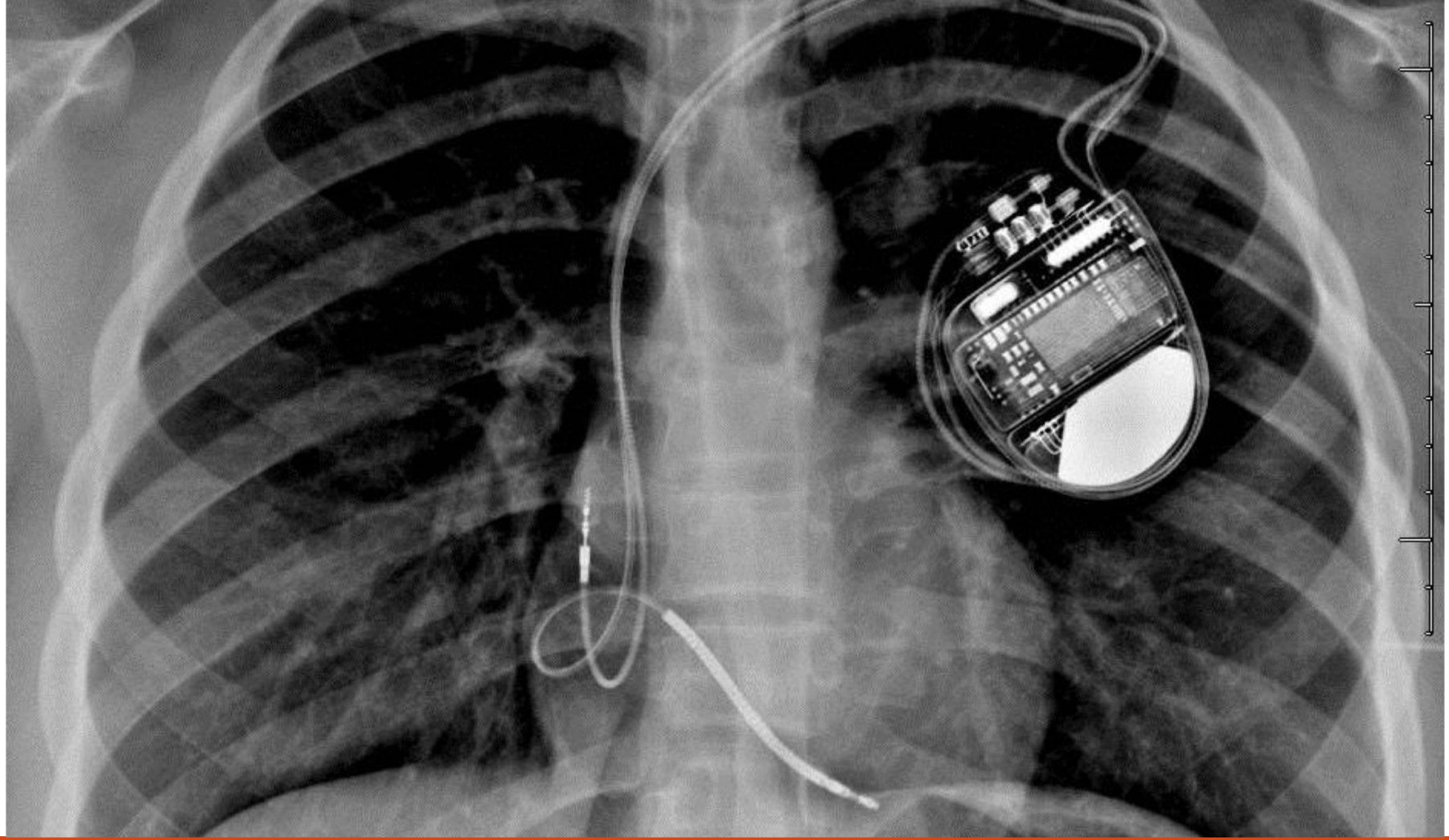


# Implantable Pacemaker

Two leads are placed in the right atrium and right ventricle

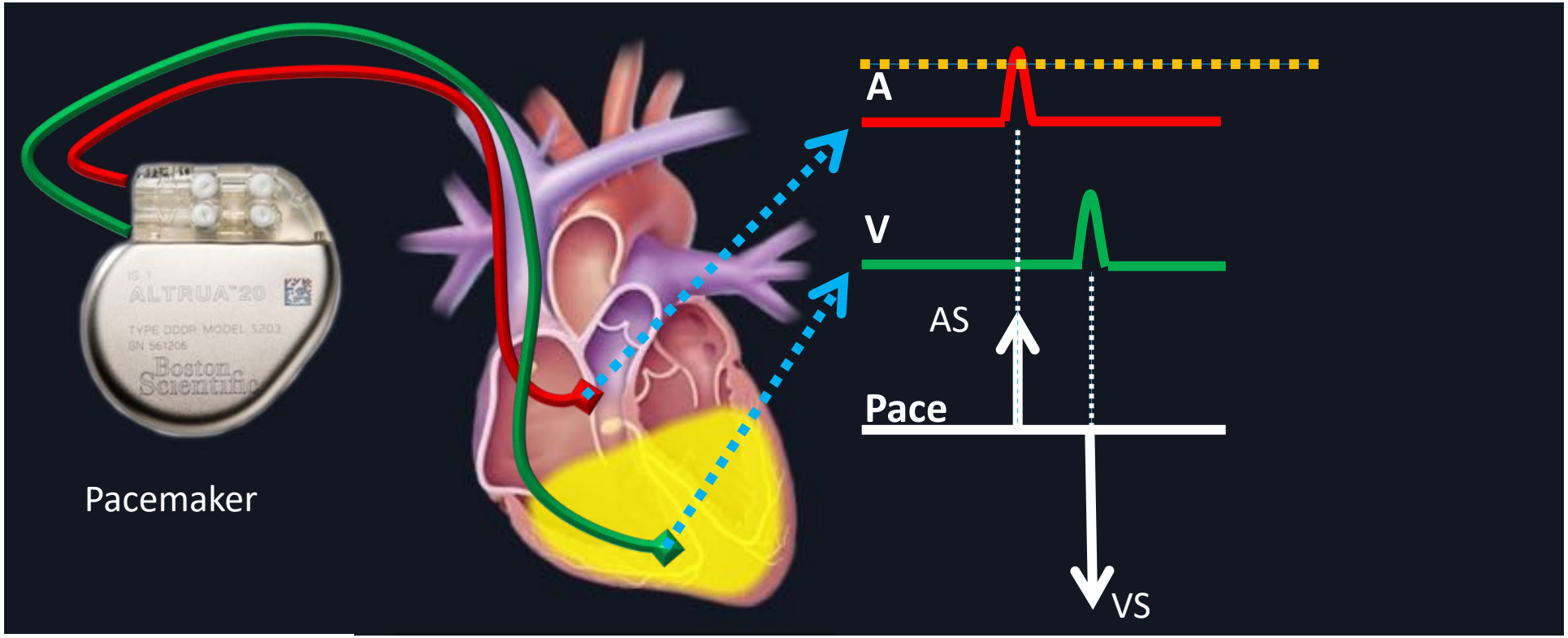
Monitors the local electrical activities of the heart and deliver therapy according to the **timing information**





# 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