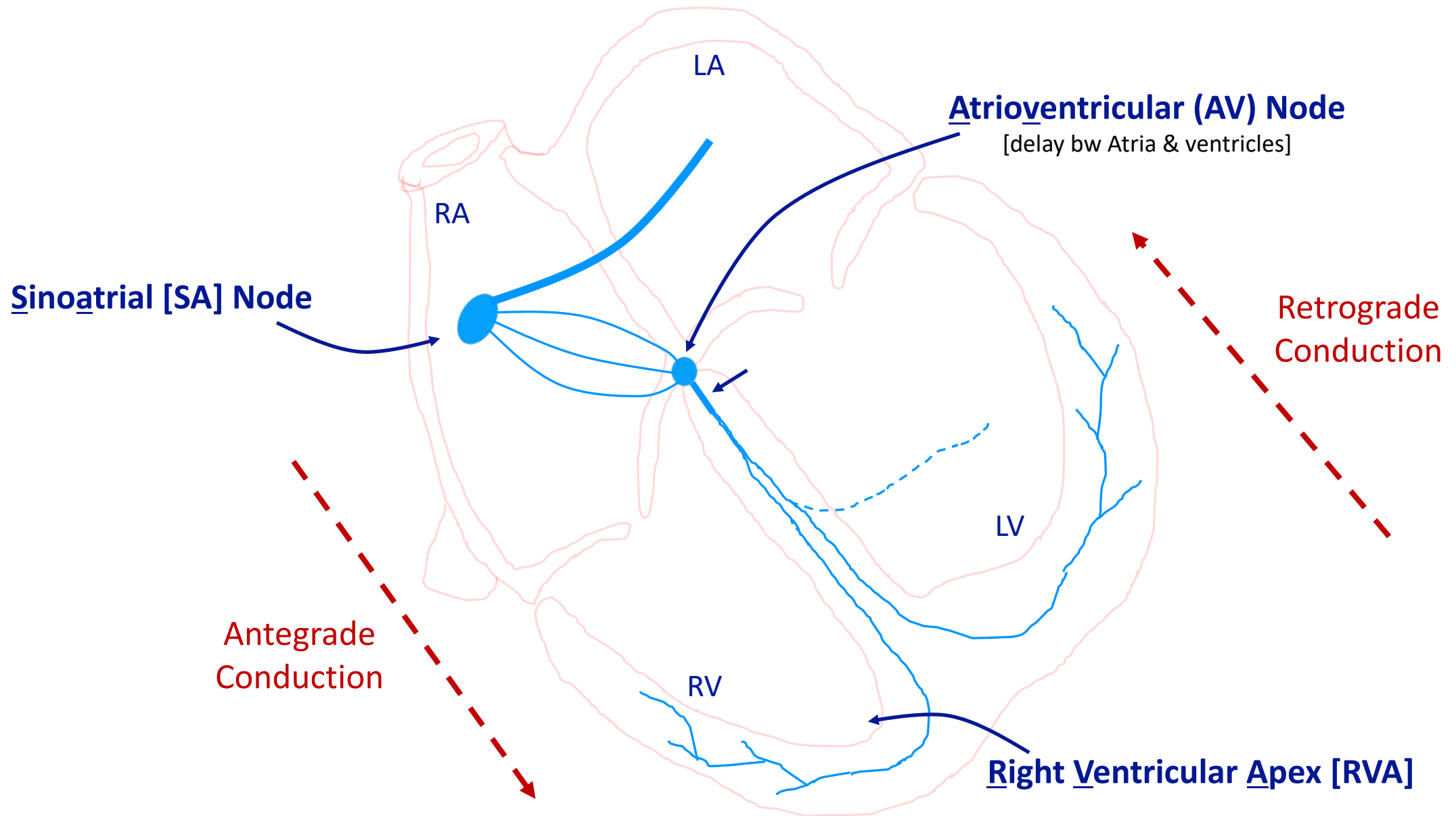


# Pacemaker function

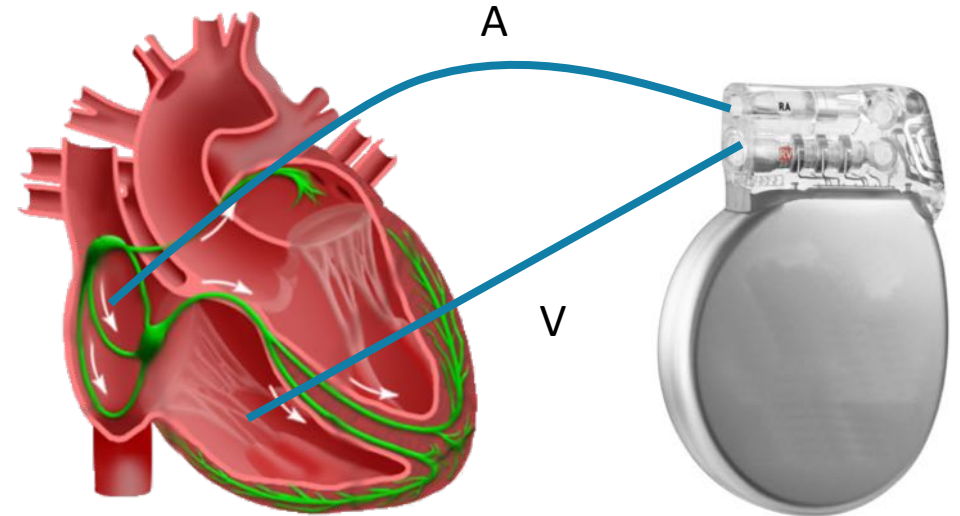
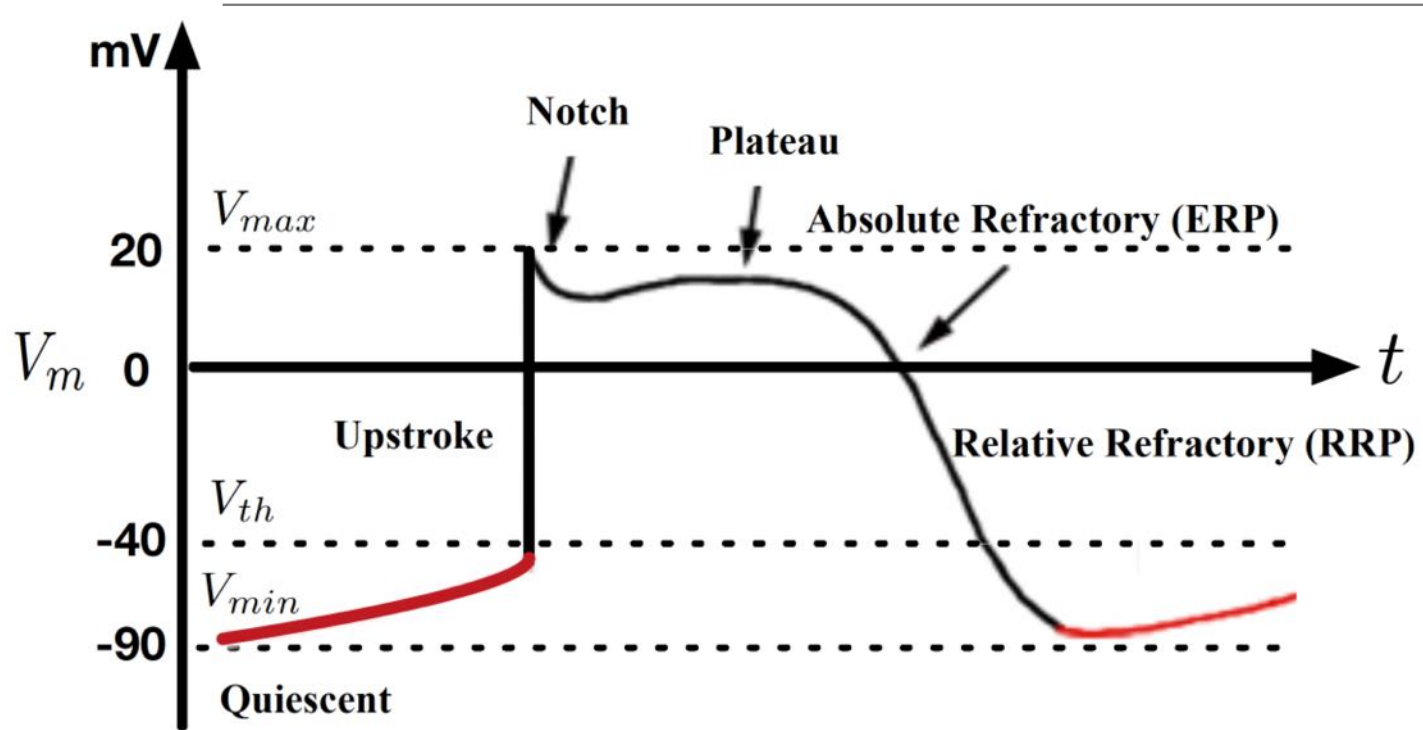
Lecture 11

Principles of Modeling for Cyber-Physical Systems

Instructor: Madhur Behl



# Action potential in one excitable cardiac cell



# Electrocardiogram



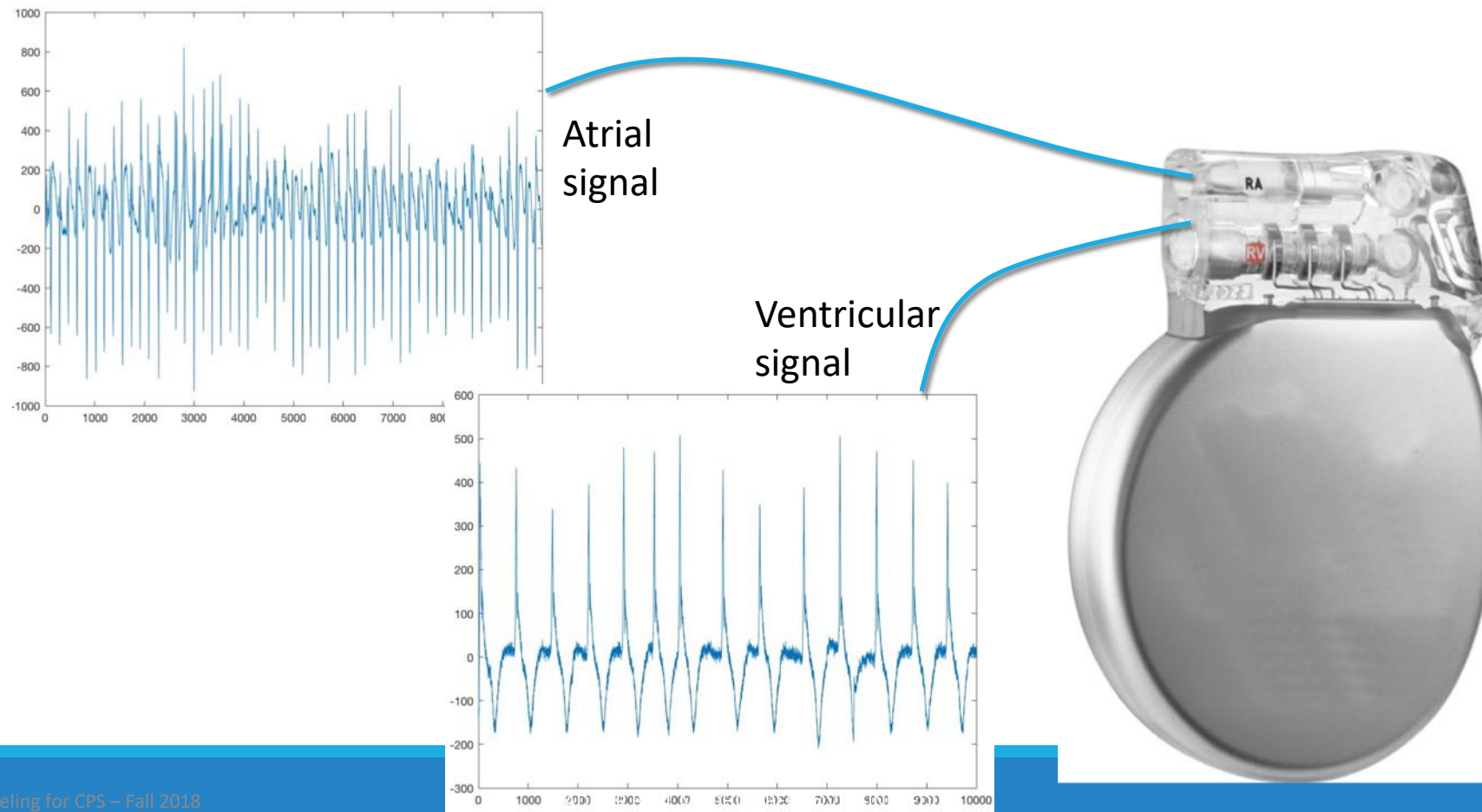
Mashable

# WHAT TIME IS IT?

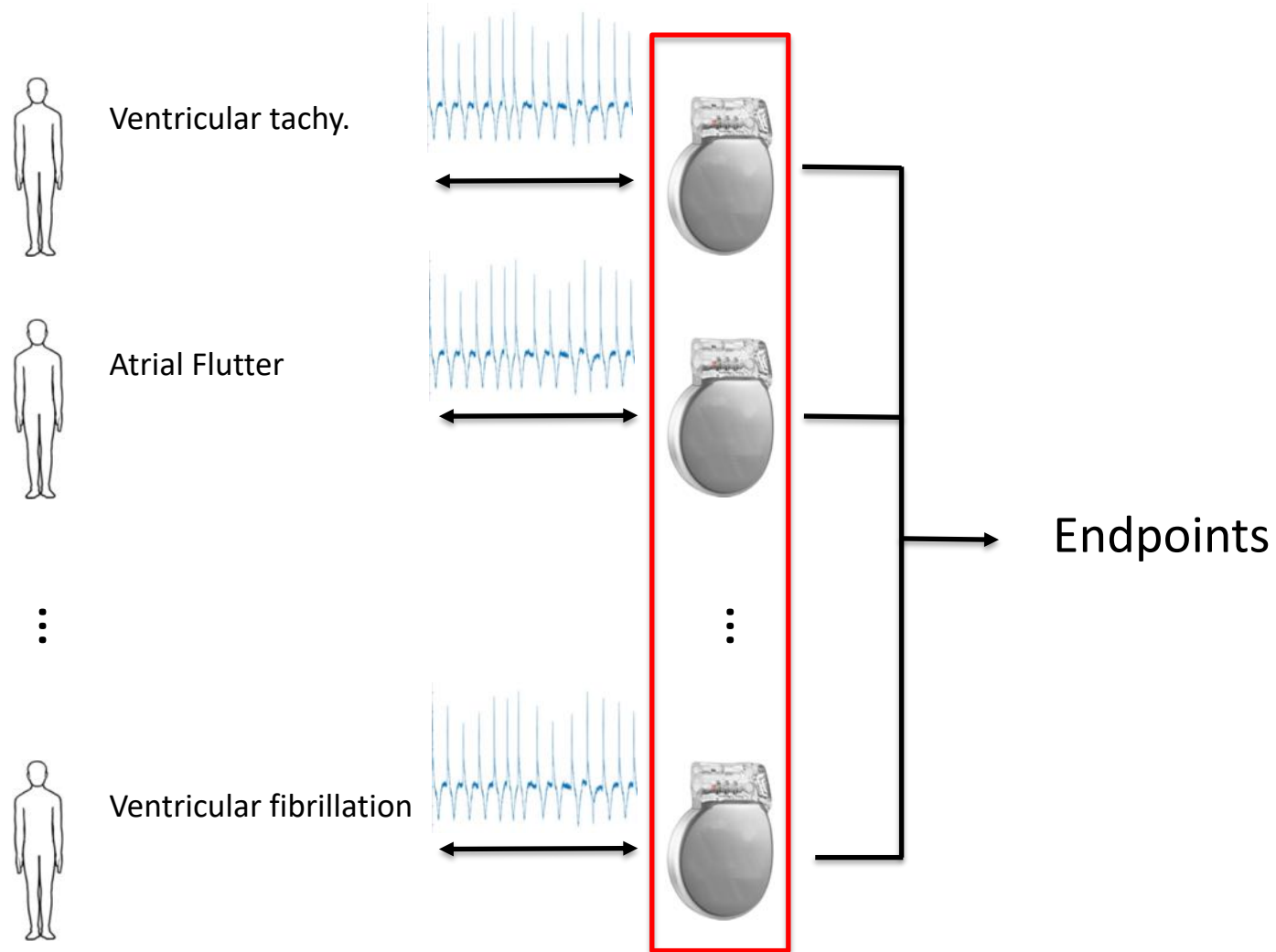


# OOP. I'M DYING.

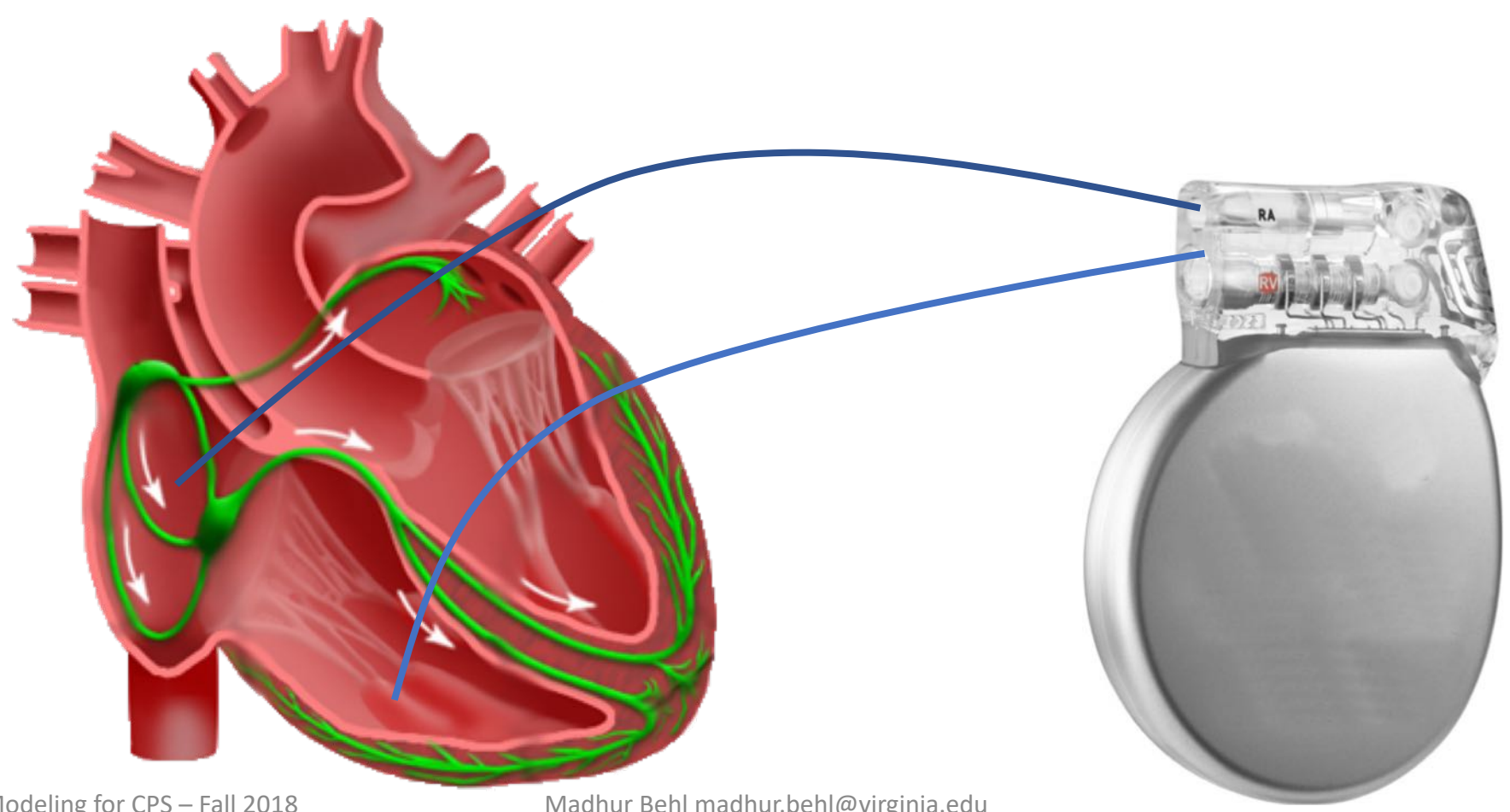
# Inputs to pacemaker are intra-cardiac *electrograms [EGM]*



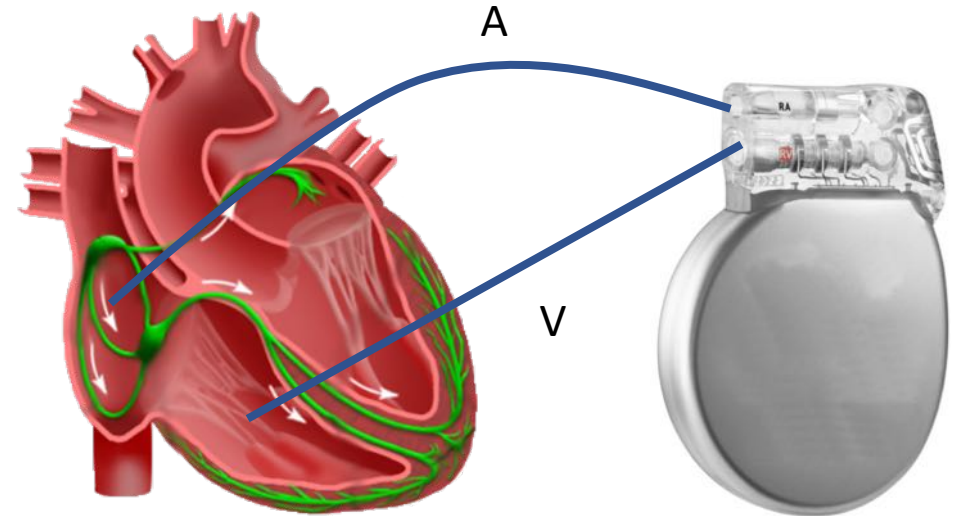
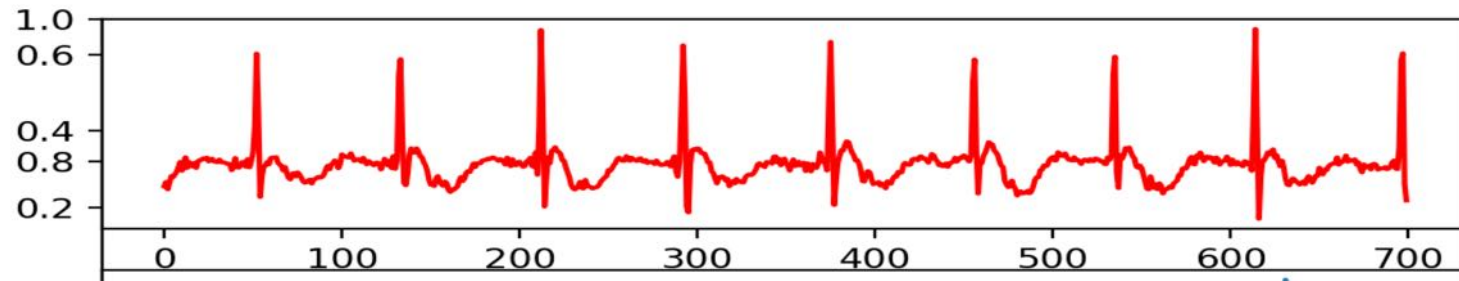
# Need: a device algorithm



# Device algorithm: Treat the symptoms

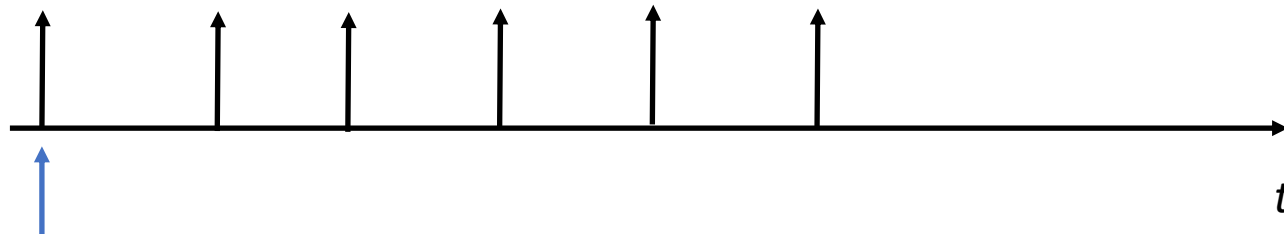
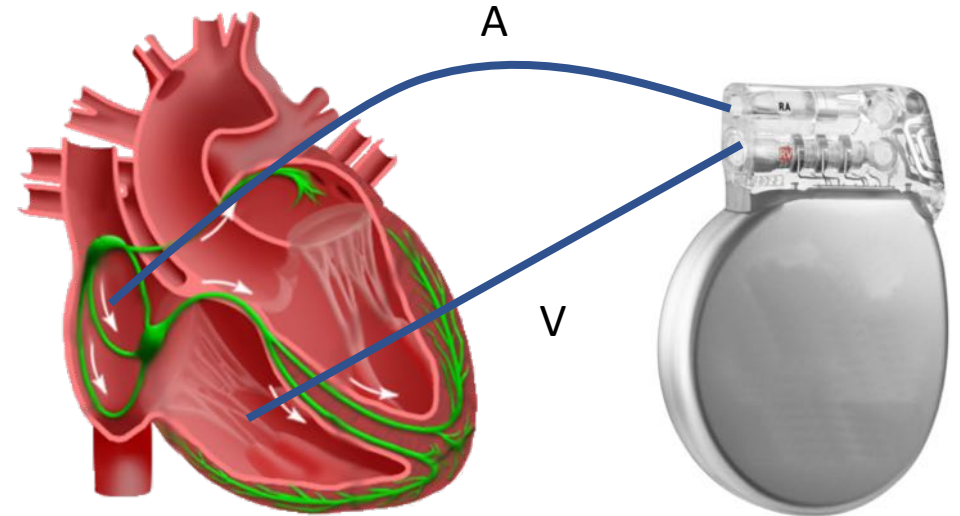
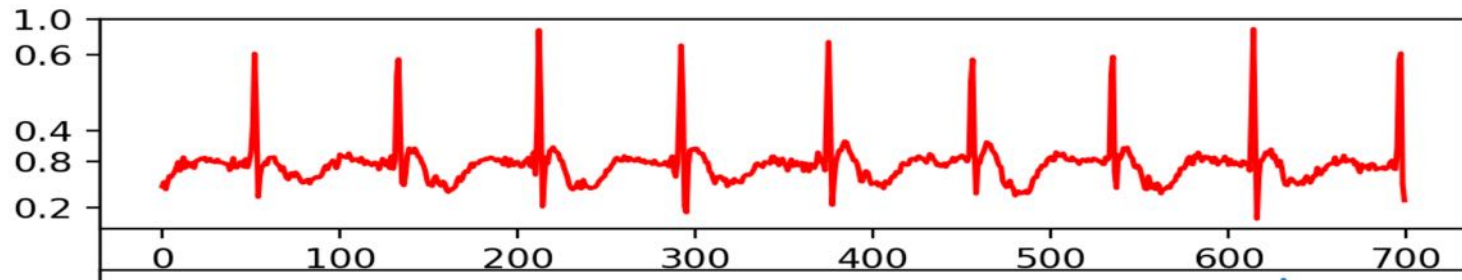


# *Electrogram* measured by one lead





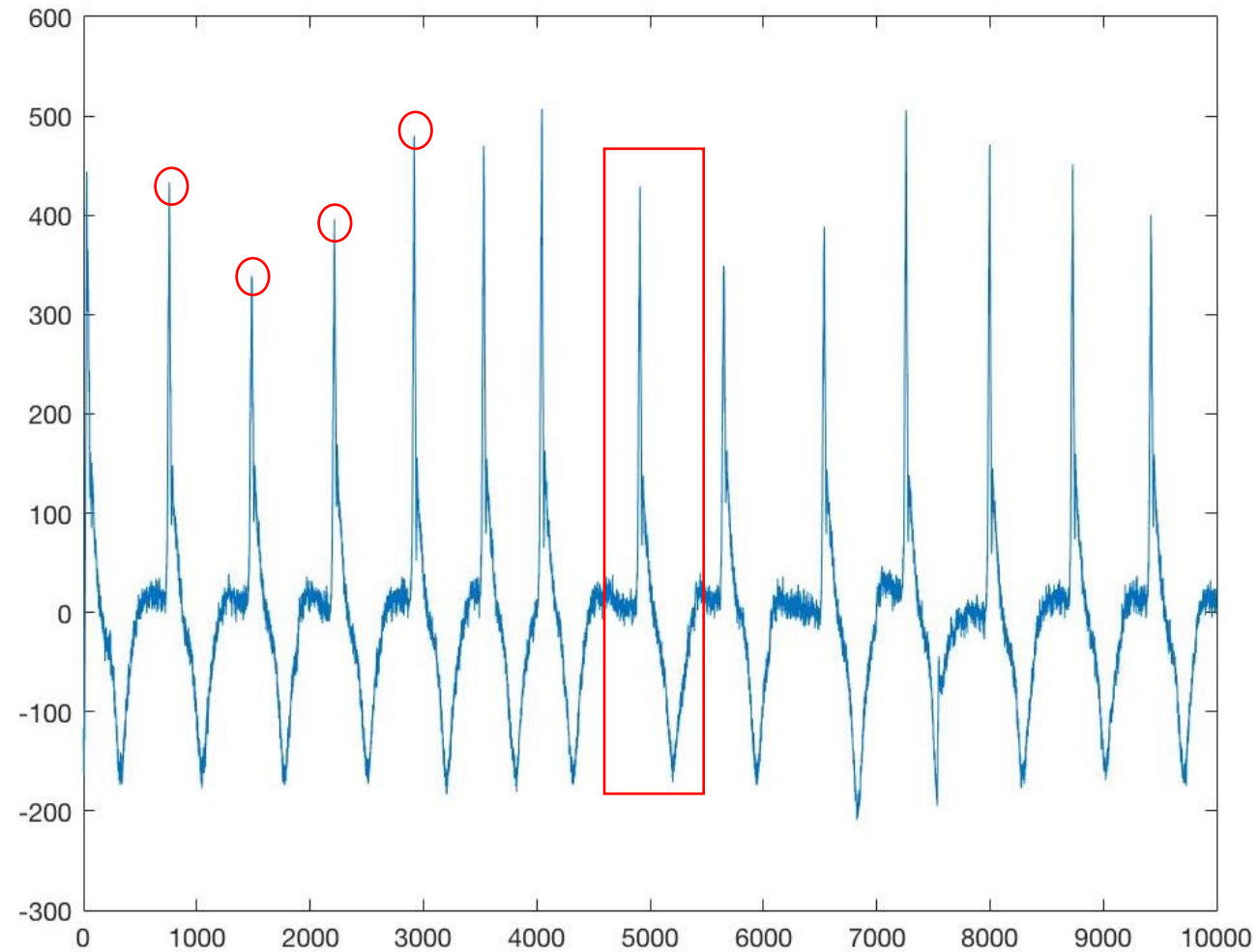
# From electrogram to boolean event stream



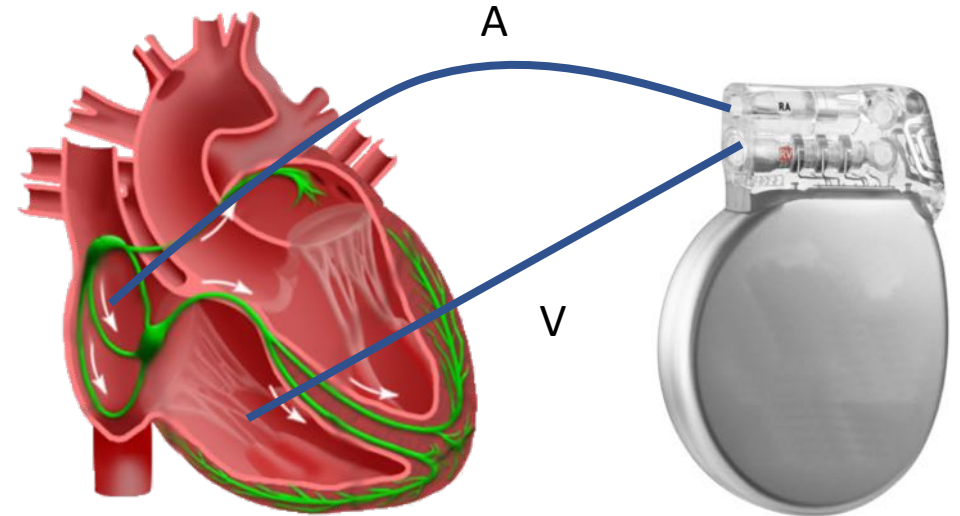
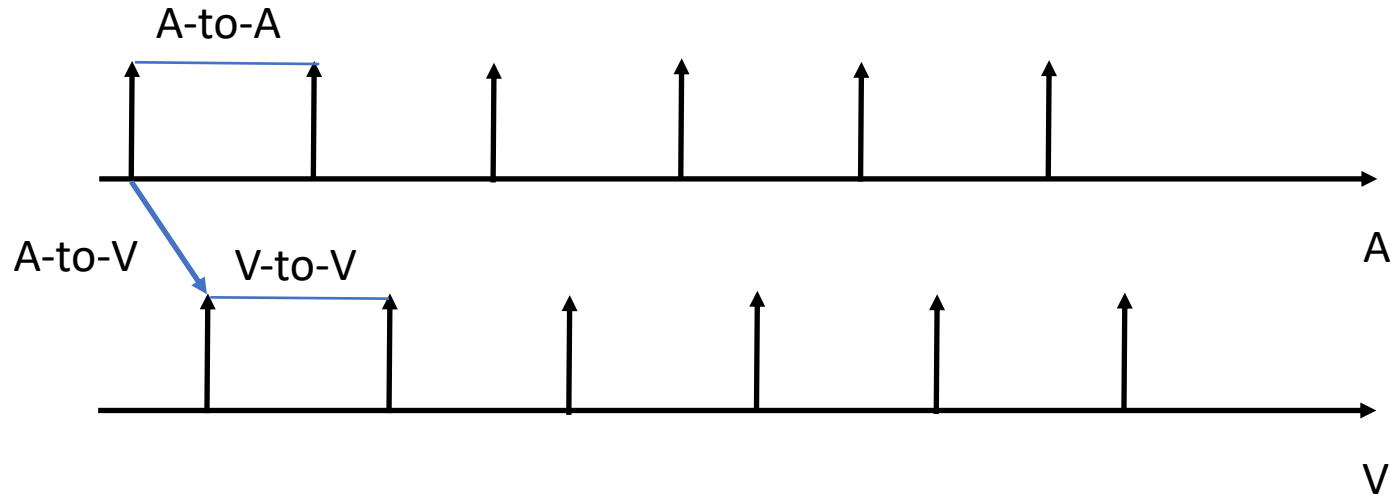
“Moment of depolarization” =  
“event time” = “approximate  
time of contraction”

Abstraction

# Pacemaker: peak detector



# Normal Sinus Rhythm

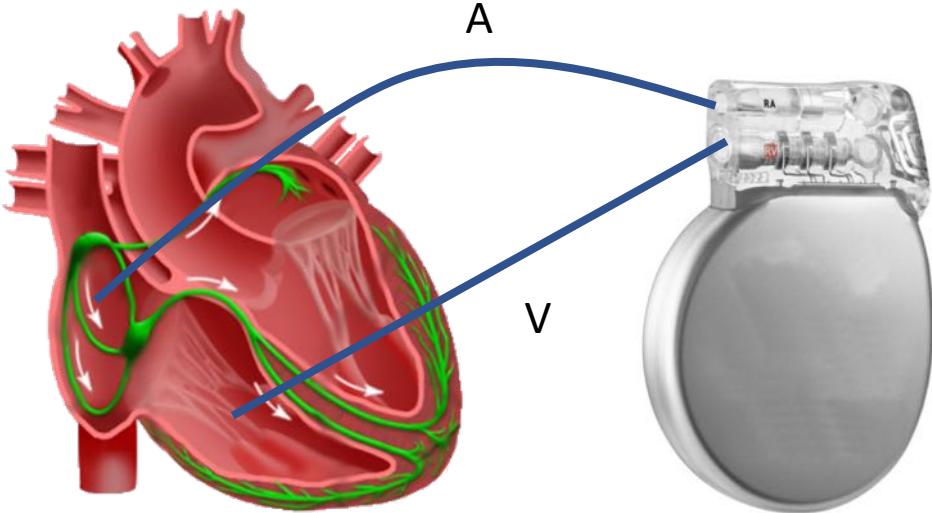
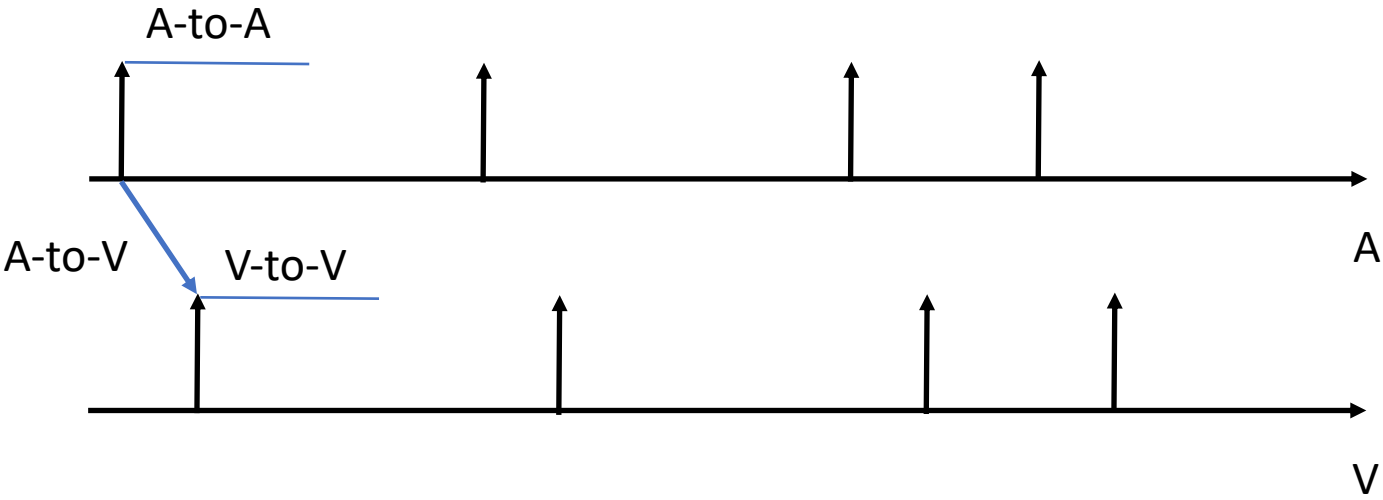


HUGE caveat: “Normal” is very patient-dependent

ASense      APace

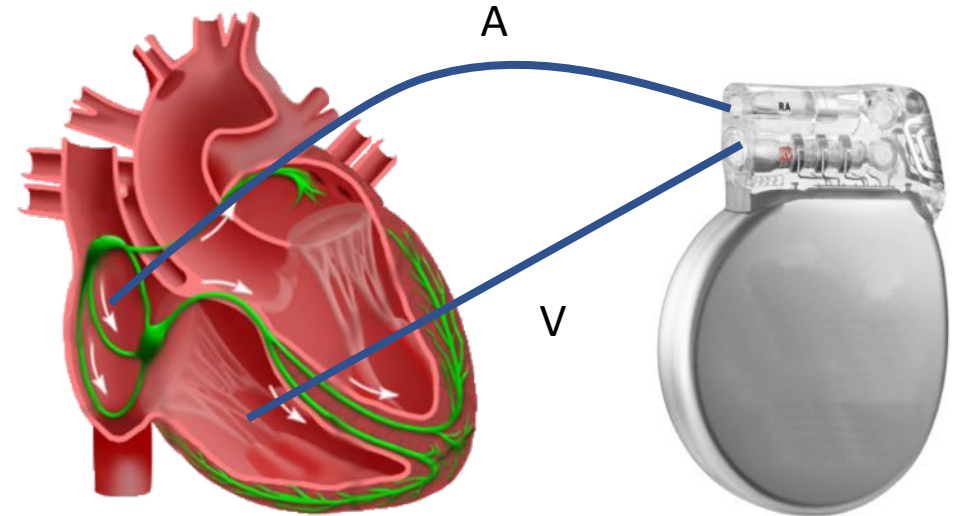
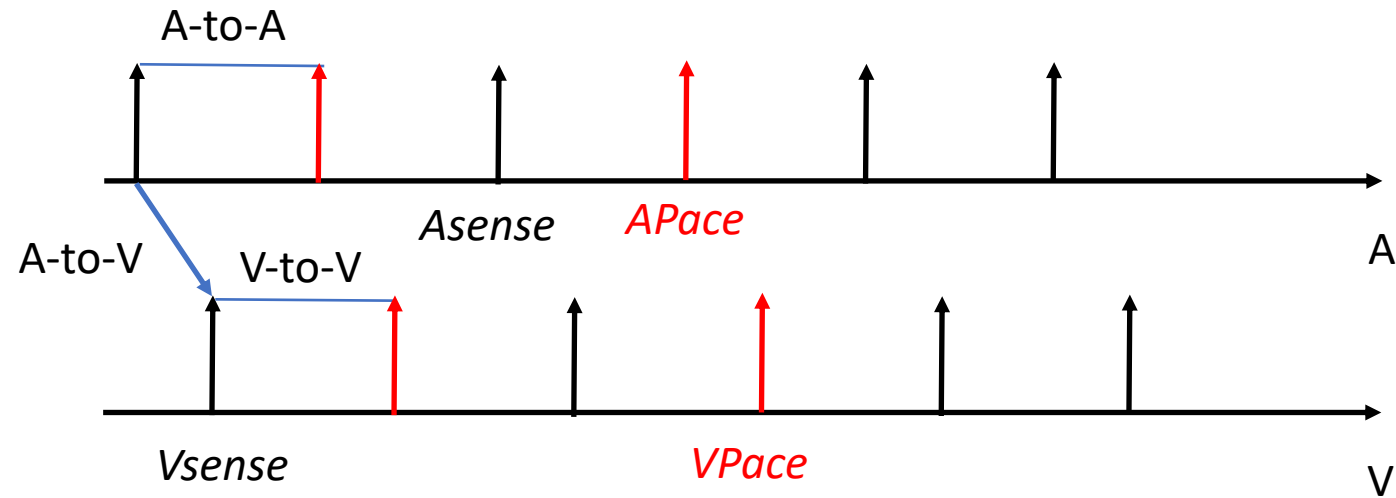
VSense      VPace

# Treat the symptoms 1: SA node misses a beat (bradychardia)



What do you do?

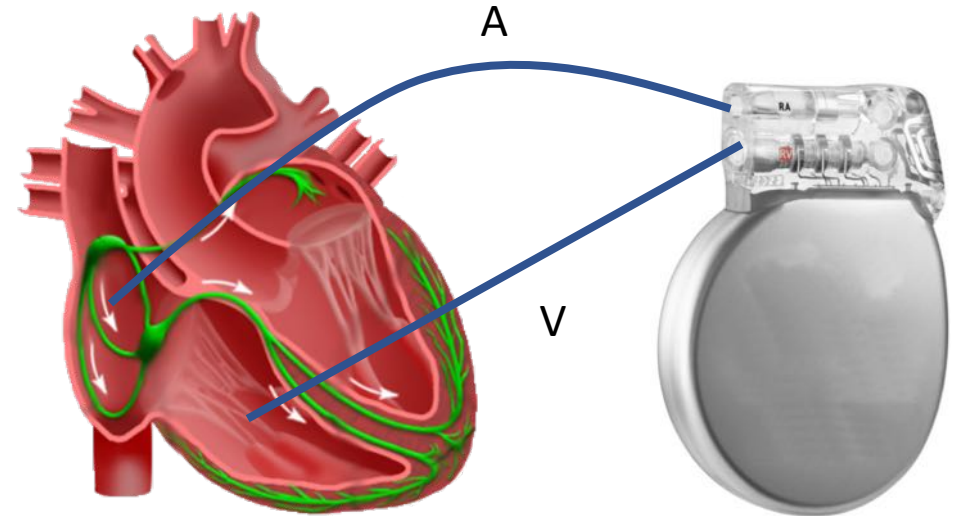
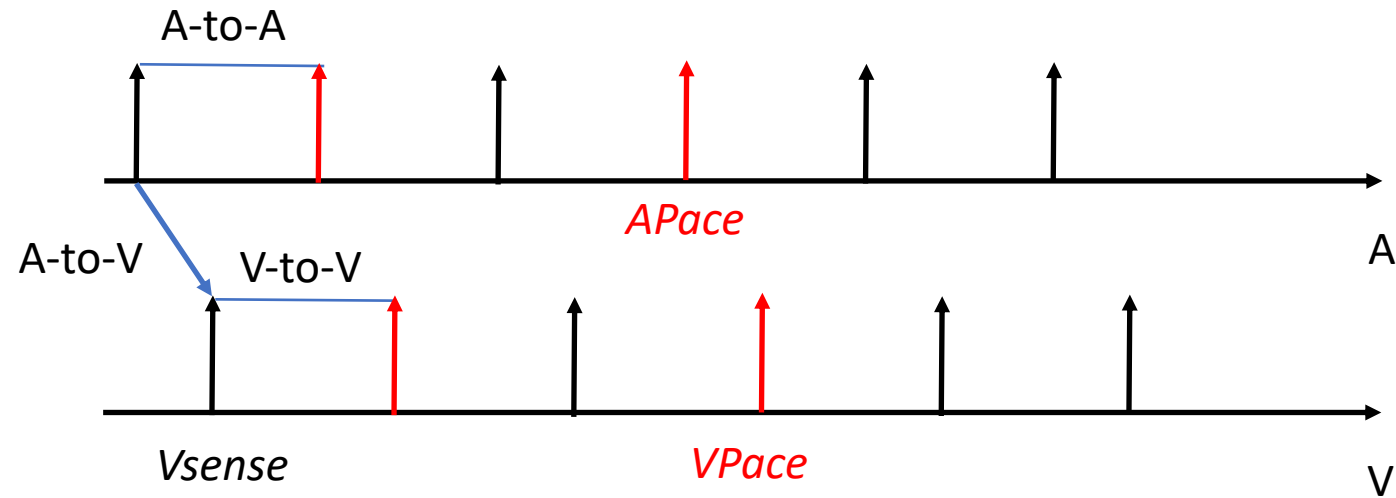
# Treat the symptoms 1: SA node misses a beat (bradychardia)



$AA \leq A\text{-rate interval}$

- Add an AA timer that counts down from the last time it sensed an A beat ( = *Asense*). *APace* when it expires
- So pacemaker ensures  $AA \leq A\text{-Rate Interval}$

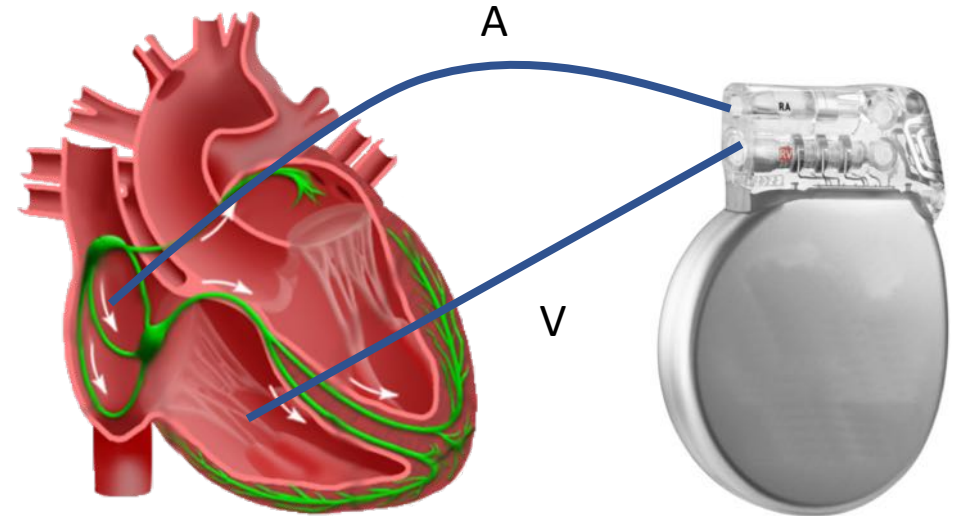
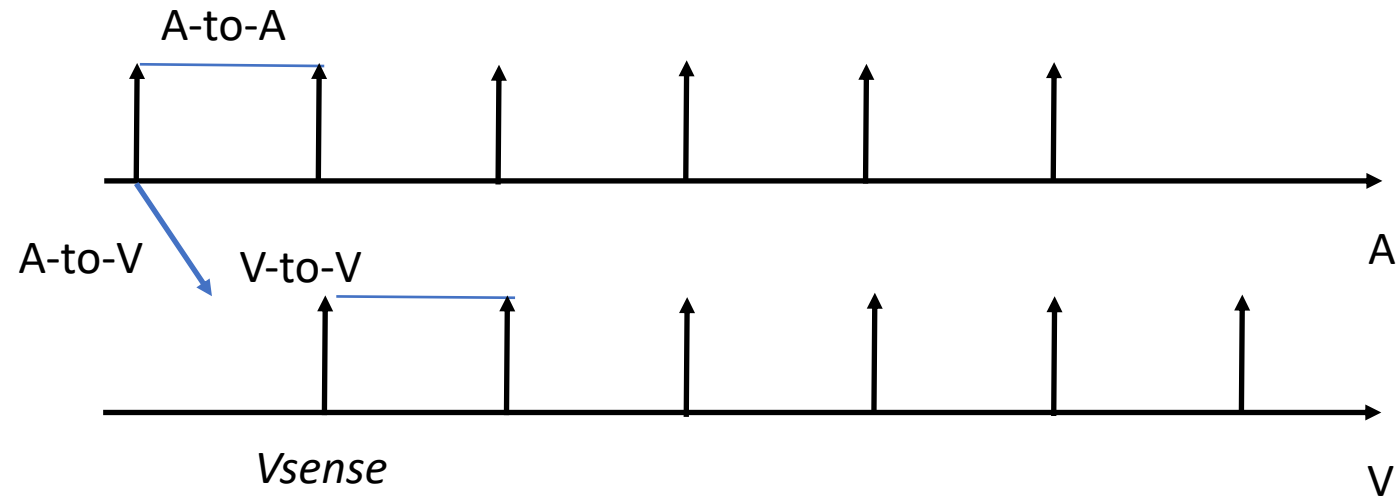
# Treat the symptoms 1: SA node misses a beat (bradychardia)



- Add a V-V timer that counts down from the last time it sensed a V beat ( =  $V_{sense}$ ).  $V_{pace}$  when it expires
- Commonly called the *Lower Rate Interval (LRI)*
- So: Device makes sure that  $V-V \leq LRI$

$VV \leq$  Lower Rate Interval  
 $AA \leq$  A-rate interval

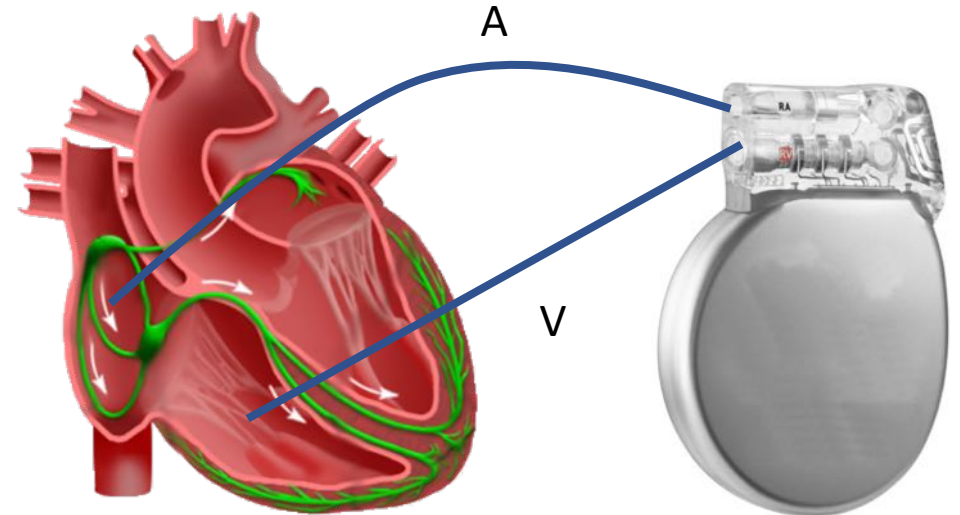
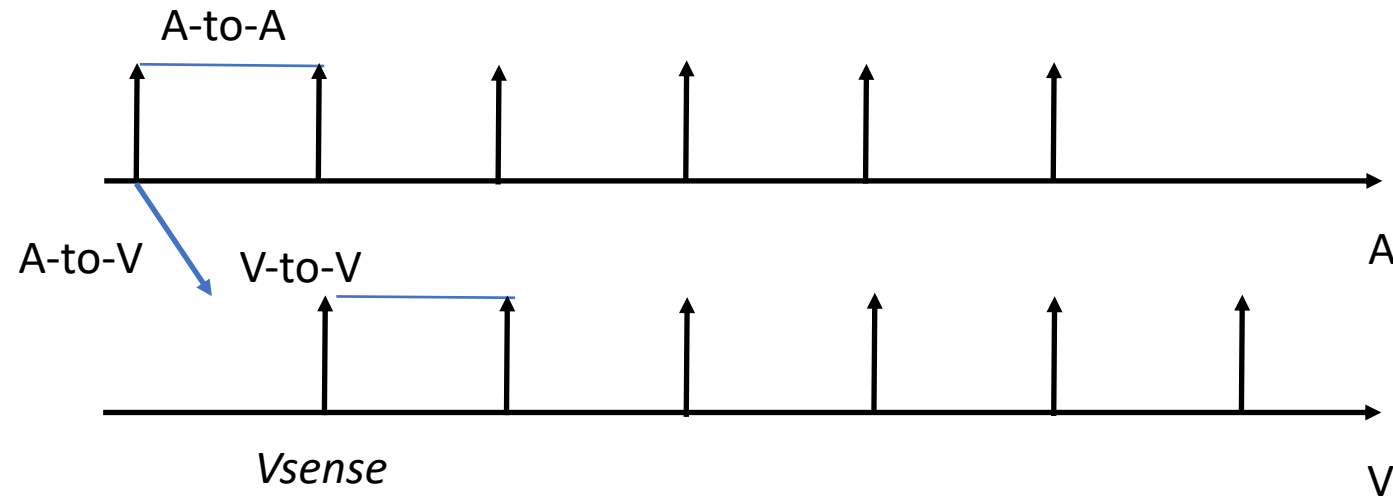
## Treat the symptoms 2: Delayed conduction from A to V



- In NSR, the ventricles are driven by the atria, so there's a relation between A events and V events.
- What do you do?

VV  $\leq$  Lower Rate Interval  
AA  $\leq$  A-rate interval

## Treat the symptoms 2: Delayed conduction from A to V

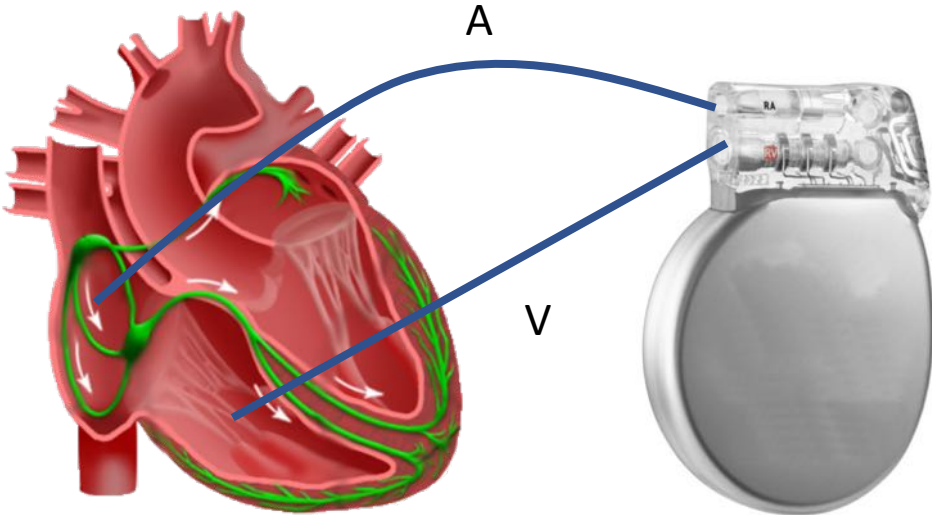
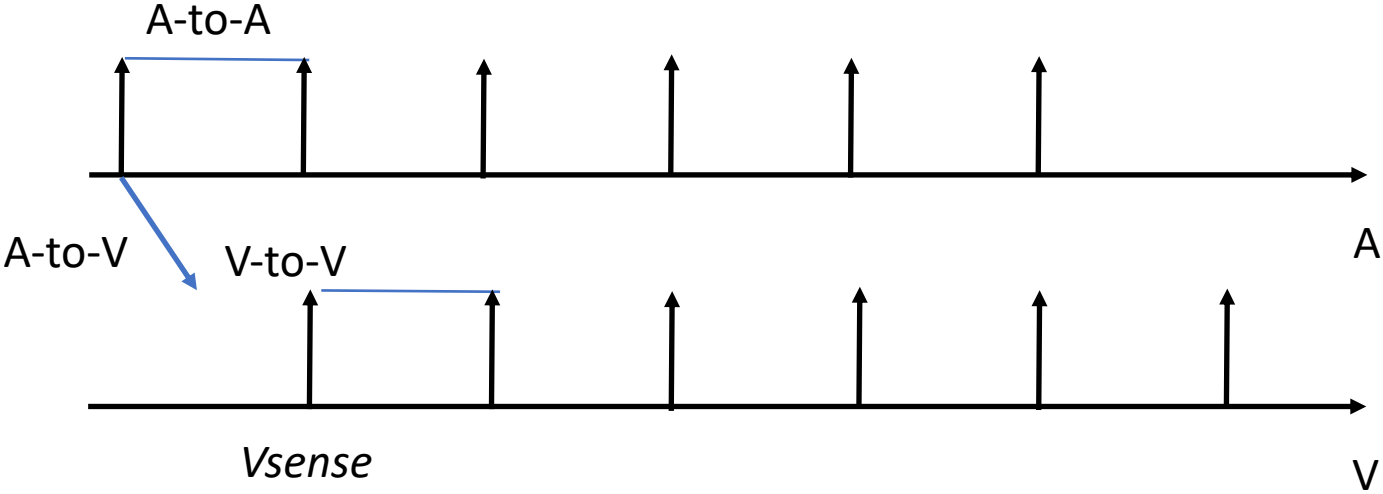


- Add an A-to-V timer, which expires after a pre-set amount of time, called the *AtrioVentricular Interval (AVI)*.
- What's the relation between LRI, A-Rate interval and AVI?

$VV \leq$  Lower Rate Interval  
 $AA \leq$  A-rate interval



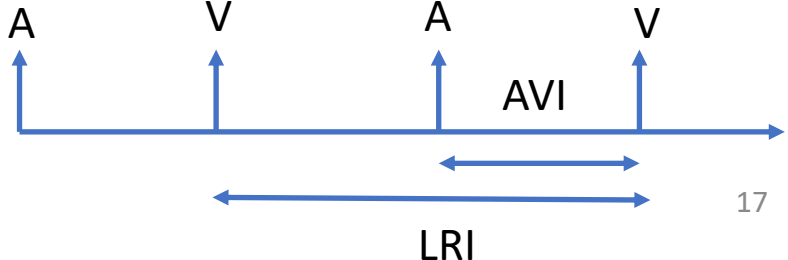
# Treat the symptoms 2: Delayed conduction from A to V



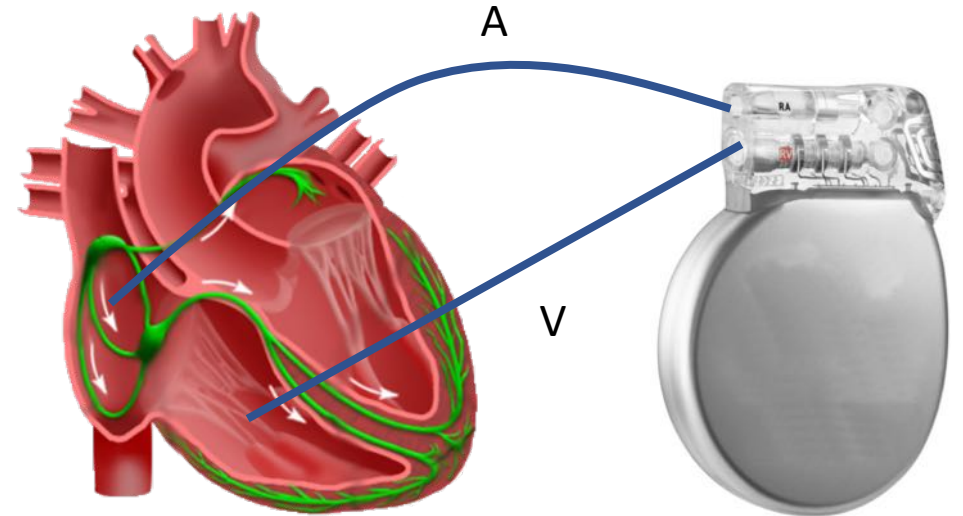
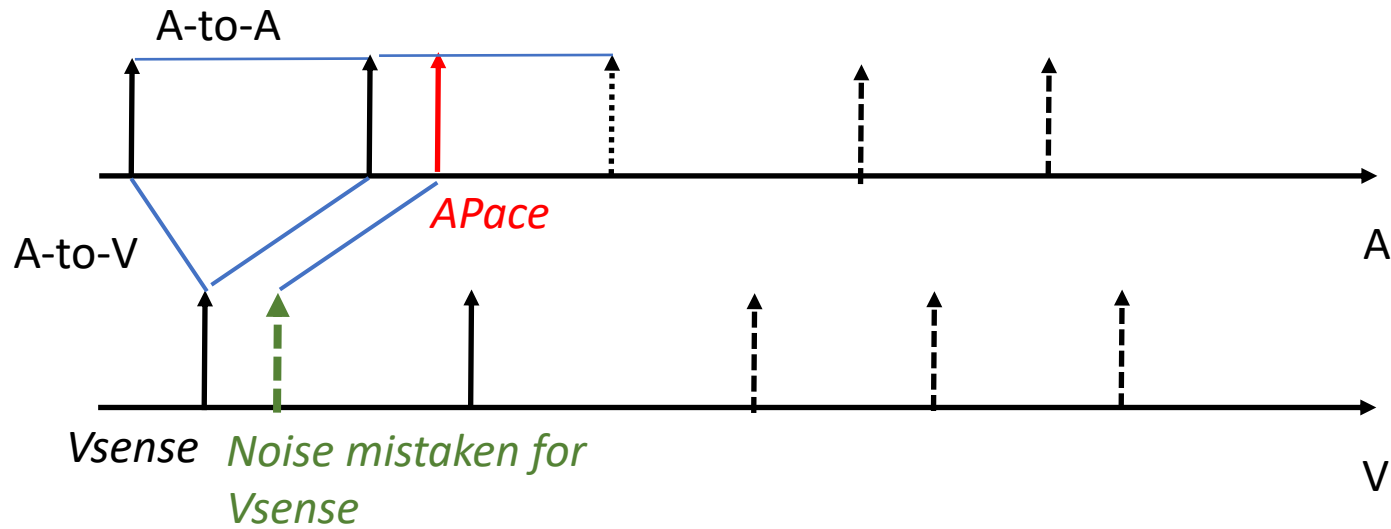
- Add an A-to-V timer, which expires after a pre-set amount of time, called the *AtrioVentricular Interval (AVI)*.
- AVI is used as a component in LRI.

$$VV \leq \text{Lower Rate Interval}$$

$$VA \leq LRI - AVI$$



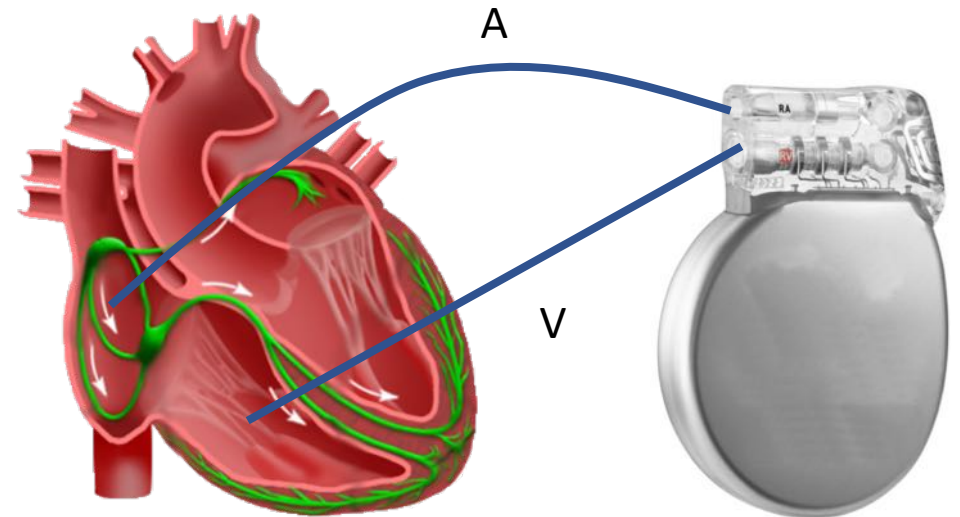
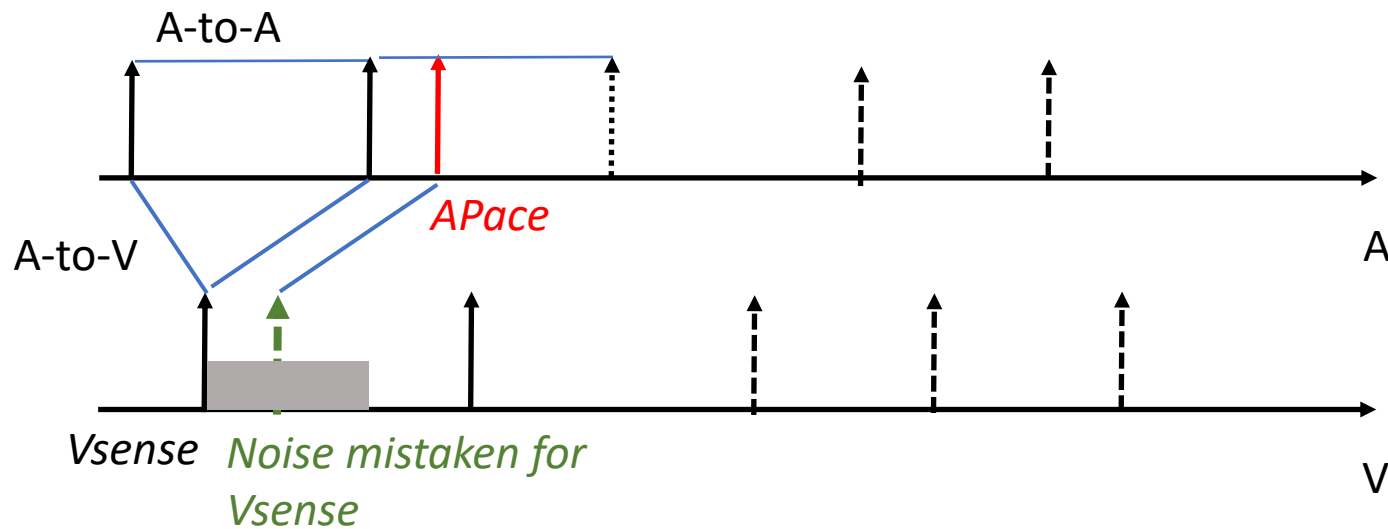
# Treat the symptoms 3: Noise on V lead occurring soon after a Vsense → Apace too soon



- What do you do?

$VV \leq \text{Lower Rate Interval}$   
 $VA \leq \text{LRI} - \text{AVI}$

# Treat the symptoms 3: Noise on V lead occurring soon after a $V_{sense}$ $\rightarrow$ Apace too soon



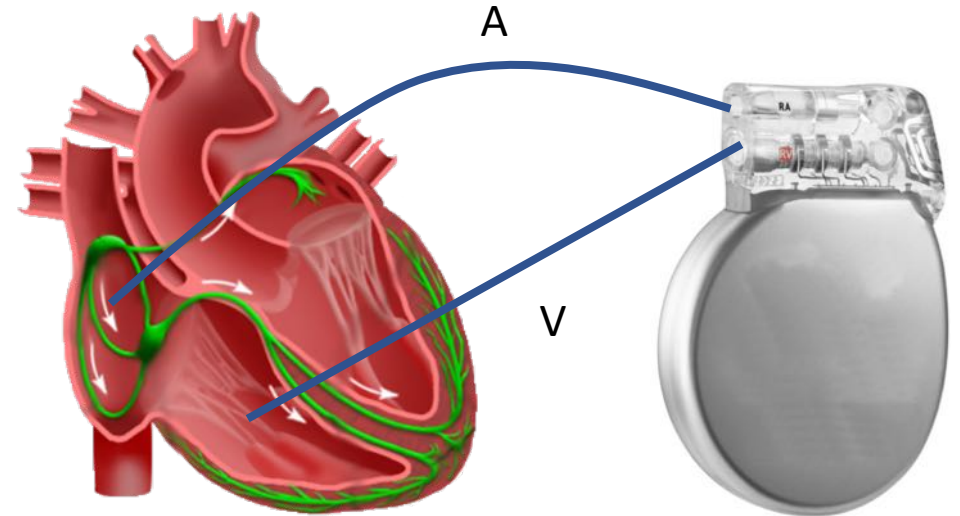
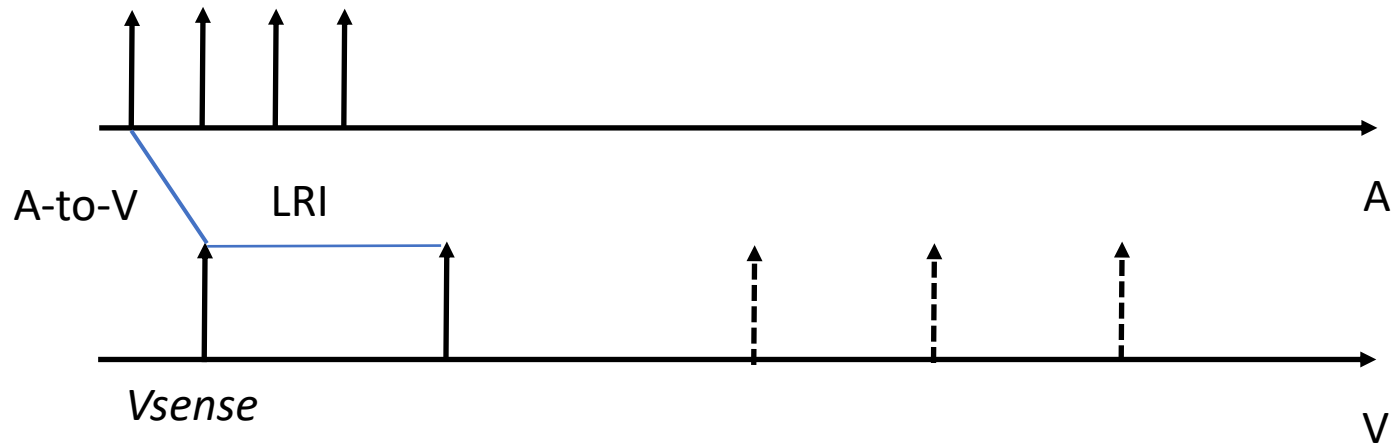
- Ventricular Refractory Period (VRP) to ignore events close to  $V_{sense}$ .
- Similarly, use an ARP

$VV \leq$  Lower Rate Interval

$VA \leq$  LRI - AVI

Ignore  $V_{sense}$  in Ventricular Refractory Period (VRP)

# Treat the symptoms 4: Subject is exercising – should we pace faster?



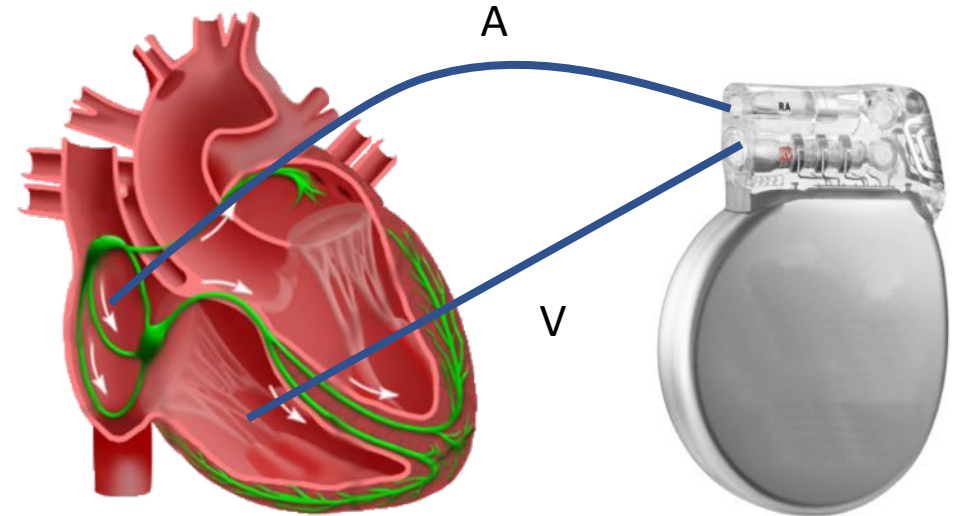
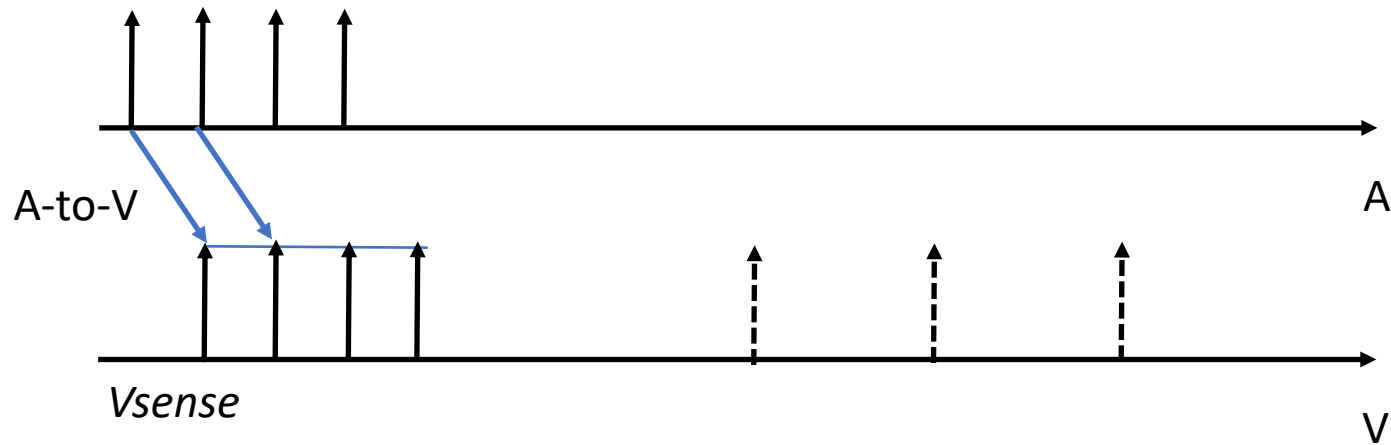
- For whatever reason, ventricles not responding to faster atrial rate.
- Pacemaker governed by LRI
- Should ventricles pace faster to keep up with atria?

$VV \leq \text{Lower Rate Interval}$

$VA \leq \text{LRI} - \text{AVI}$

Ignore Vsense in Ventricular Refractory Period (VRP)

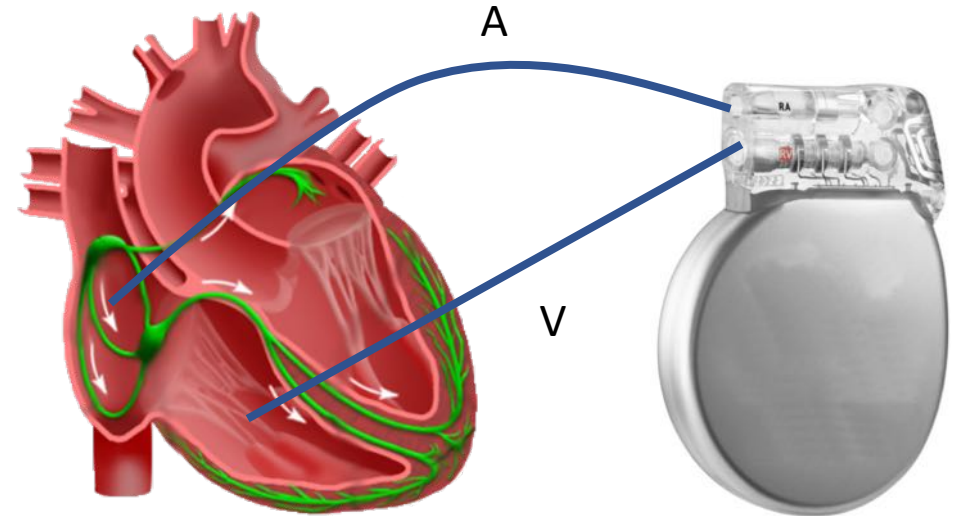
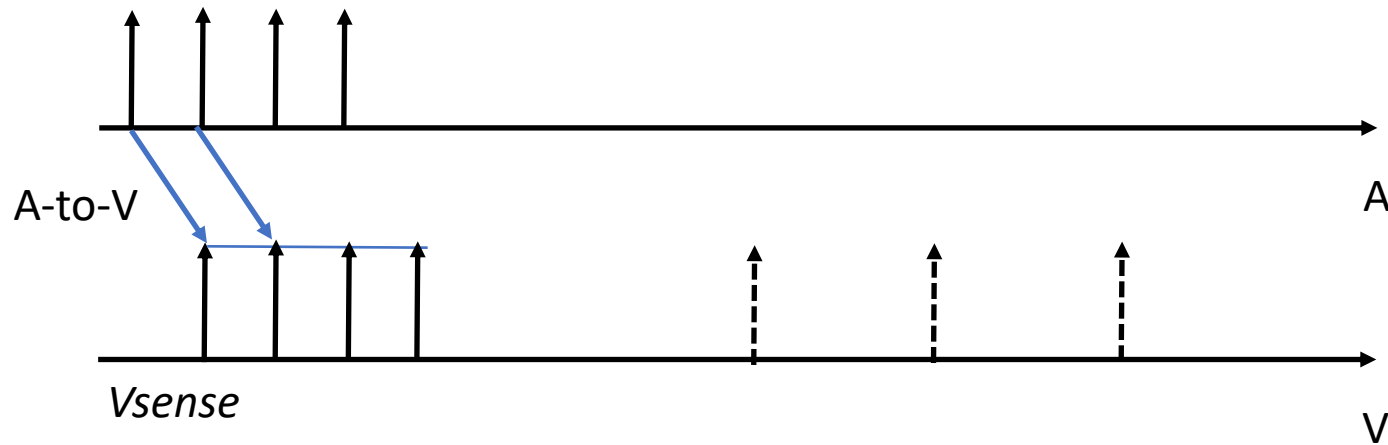
# Treat the symptoms 4: Subject is exercising – should we pace faster?



- We *should* pace the ventricles to keep up with the atria
- *Maintain an Atrio-Ventricular Interval (AVI) timer and pace when it expires*
- LRI is an *upper bound*

VV  $\leq$  Lower Rate Interval  
VPace when Atrio-Ventricular Interval (AVI) expires  
VA  $\leq$  LRI – AVI  
Ignore Vsense in Ventricular Refractory Period (VRP)

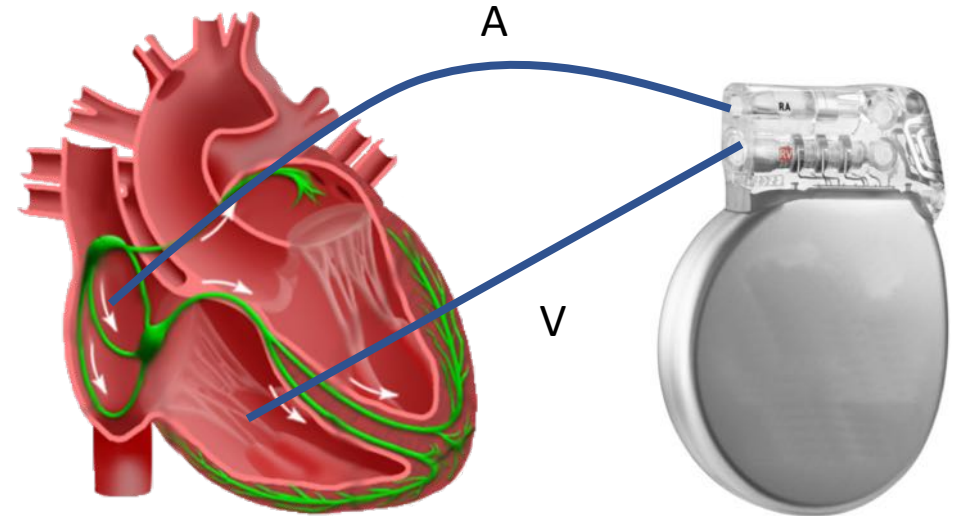
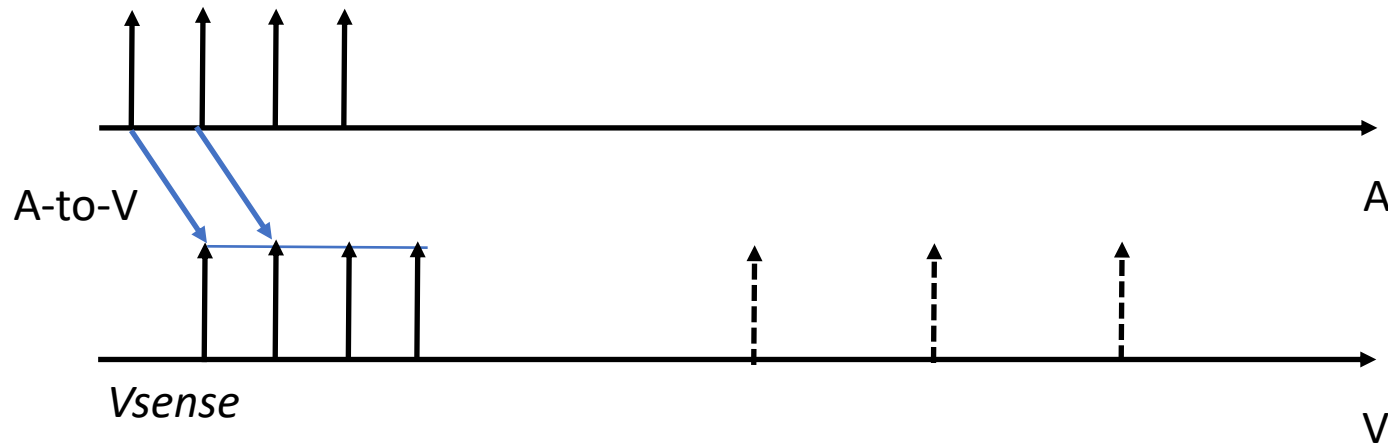
# Treat the symptoms 5: Atrial tachycardia leads to accelerated V<sub>pace</sub> → heart racing



- *Tachycardia* is opposite of bradycardia: heart beats abnormally **fast**.
- ‘Heart racing’ feeling. Can result from too much coffee
- So...should we pace to keep up after all?

VV ≤ Lower Rate Interval  
VPace when Atrio-Ventricular Interval (AVI) expires  
VA ≤ LRI – AVI  
Ignore Vsense in Ventricular Refractory Period (VRP)

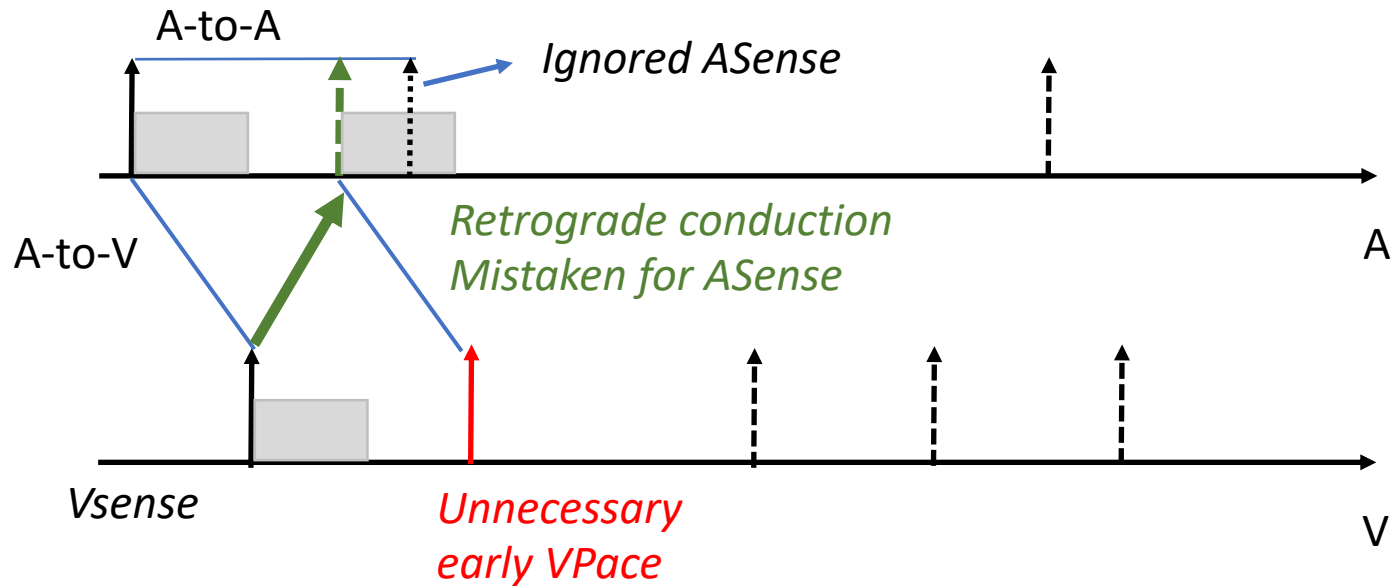
# Treat the symptoms 5: Atrial tachycardia leads to accelerated V<sub>pace</sub> → heart racing



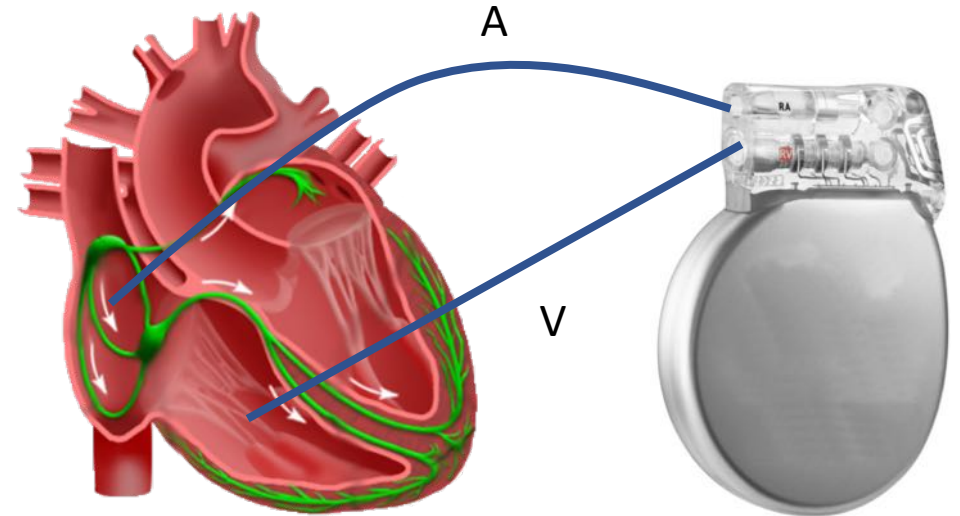
- Add accelerometers and temperature sensors to pacemaker to detect physical activity
- Not everything is solved in the same way! Think of the whole SYSTEM

$VV \leq \text{Lower Rate Interval}$   
 $V_{\text{Pace}}$  when Atrio-Ventricular Interval (AVI) expires  
 $VA \leq \text{LRI} - \text{AVI}$   
Ignore  $V_{\text{sense}}$  in Ventricular Refractory Period (VRP)

# Treat the symptoms 6: Retrograde V-to-A conduction → Asense → VPace



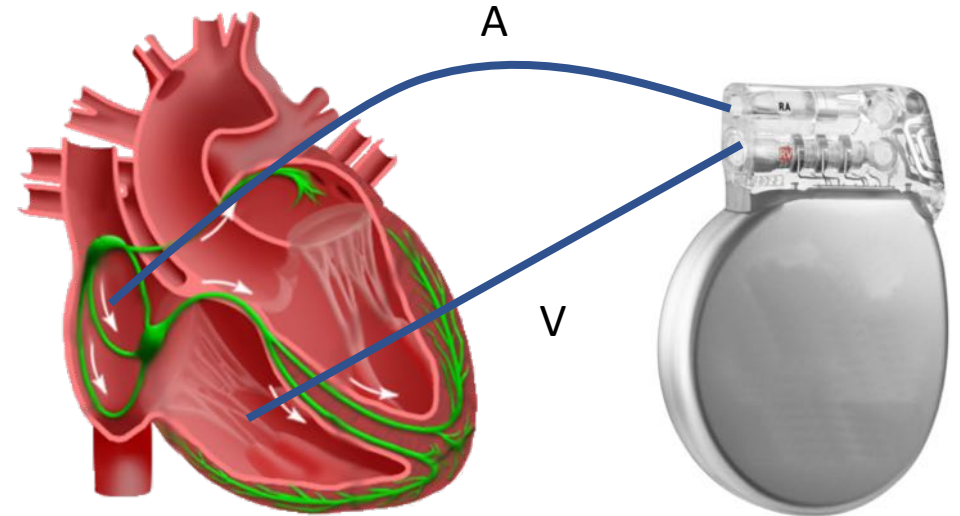
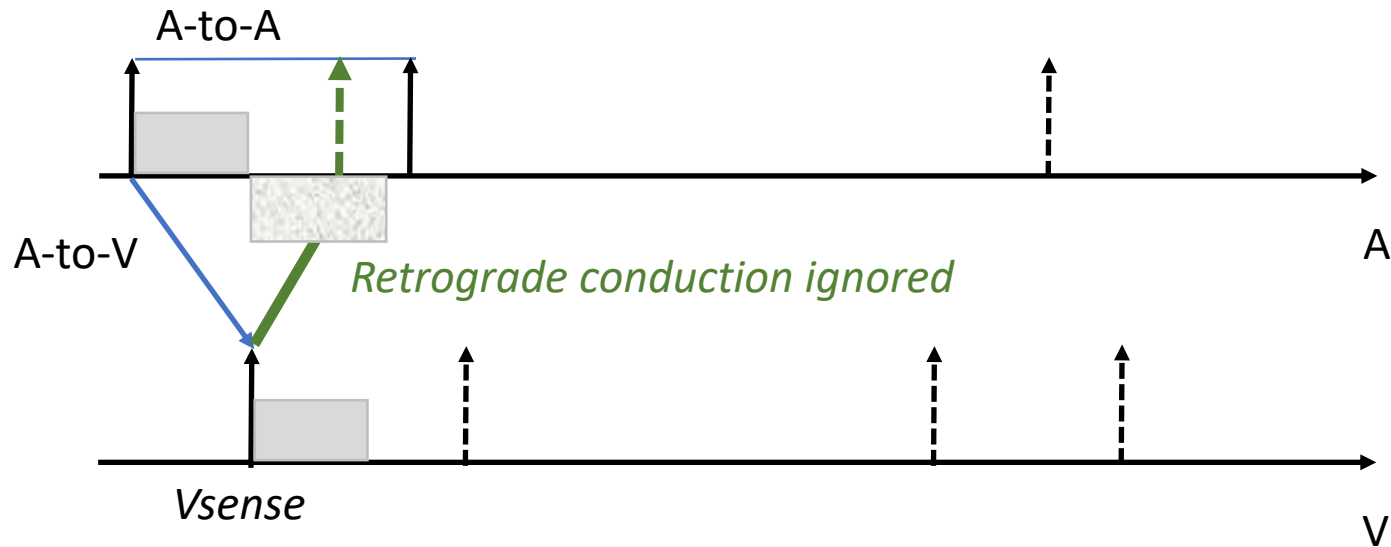
- What do you do?




$VV \leq \text{Lower Rate Interval}$   
 $VPace \text{ when Atrio-Ventricular Interval (AVI) expires}$   
 $VA \leq LRI - AVI$   
 Ignore Vsense in Ventricular Refractory Period (VRP)



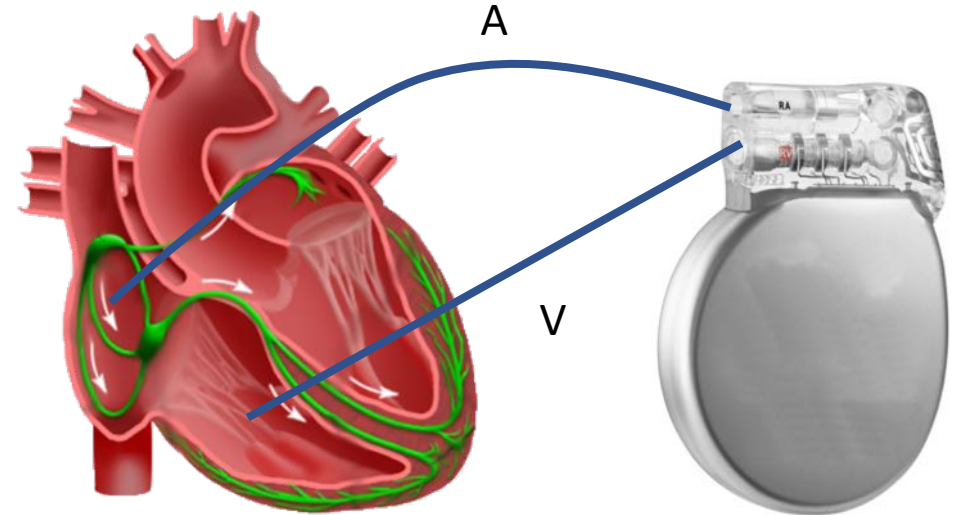
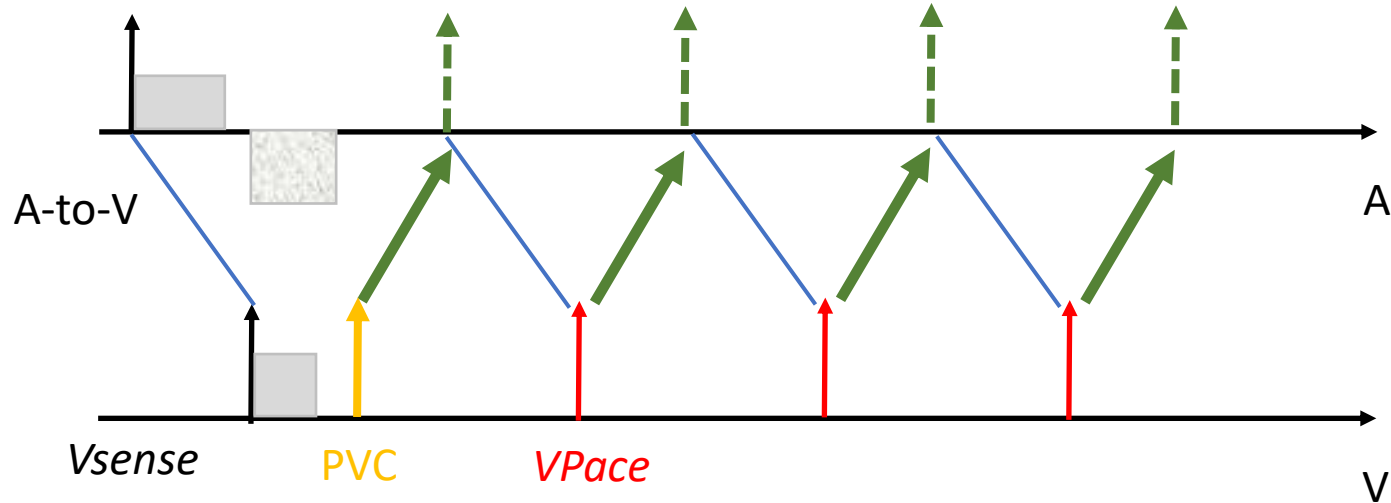
# Treat the symptoms 6: Retrograde V-to-A conduction → Asense → VPace



- Add a Post-Ventricular Atrial Refractory Period (PVARP) 
- Ignore Asense in PVARP

$VV \leq \text{Lower Rate Interval}$   
 VPace when Atrio-Ventricular Interval (AVI) expires  
 $VA \leq \text{LRI} - \text{AVI}$   
 Ignore Vsense in Ventricular Refractory Period (VRP)  
 Ignore Asense in Post-Ventricular Atrial Refractory Period (PVARP)

# Treat the symptoms 7: Rhythm Hijack (PVC)



- *Premature Ventricular Complex (PVC)* is a spontaneous depolarization in the ventricles that occurs 'too soon', i.e. before the conducted A-to-V waveform arrives
- It is caused by irritable tissue
- **Endless-Loop Tachycardia**

$VV \leq \text{Lower Rate Interval}$   
 $VPace$  when Atrio-Ventricular Interval (AVI) expires  
 $VA \leq LRI - AVI$   
Ignore  $V_{sense}$  in Ventricular Refractory Period (VRP)  
Ignore  $A_{sense}$  in Post-Ventricular Atrial Refractory Period (PVARP)

# Solution built so far

1. The SA node skips beats (—> keep a VV timer and pace when it expires - Lower Rate Interval)
2. Delayed conduction from A to V (—> keep a VA timer and pace when it expires - AtrioVentricular Interval)
3. Noise on A lead perceived as an ASense, occurring shortly after a true Abeat, would cause a V pace too soon (—> Atrial Refractory Period to ignore events close to Abeat. Similarly, use a VRP)
4. Retrograde conduction from V to A causing an ASense, in turn causing a VPace (—> Post-Ventricular ARP to ignore these things).
5. Atrial tachy leading to fast VP results in decreased blood pumping (—> establish an Upper Rate Limit)
6. Subject is exercising, shouldn't we pace faster? (—> activity measurement and adaptive rate setting. How is the rate measured? Temperature sensors, accelerometers, pacemaker form factor)
7. PVC occurring outside the VRP: what can go wrong? if it conducts retrogradely...leads to ASense...leading to another VPace after the AV delay...conducts retrogradely again...what is governing the heart rate now? (—> the retrograde delay+AV delay). Is this bad? Well, If the subject wants to sleep, her heart rate will stay this fast. it's been hijacked. this is called Pacemaker-Induced Tachycardia.
8. How should the pacemaker stop it? —> if tracked rate is at the Upper Rate Limit for a while, blank the next ASense, e.g., by increasing the PVARP temporarily
9. And so on...
10. And so forth...
11. Ultimately, it's all about keeping the heart rate in an appropriate range.

# Modeling

- This ad hoc approach can only take us so far
- We need to **understand** the relevant phenomena of the human heart...
- ...**model** them...
- ...design our device so its correctness is **shown** on the model...
- ...and **automatically implement** the tested device algorithm so the implementation is correct.

# Testing vs. Model checking

## Testing

- Debugging process: objective is to find a bug
- Can test a model of the system, or the system itself.
- Incomplete: might not find a bug, even though it exists
- Little up-front effort: just need to be able to simulate
- Cheap

## Model checking

- Verification process: objective is to prove absence of bugs
- Requires a model of the system
- Complete: if it returns “Correct”, then the model is correct
- More up-front effort to create an appropriate model
- Expensive

# Testing vs. Model checking

## Testing

- Debugging: find a bug
- Can test a model of the system, or the system itself.
- Incomplete: might not find a bug, even though it exists
- Little up-front effort: just need to be able to simulate
- Cheap

## Model checking

- Verification: prove is bug-free
- Requires a model of the system
- Complete: if it returns “Correct”, then the model is correct
- More up-front effort to create an appropriate model
- Expensive

# Testing vs. Model checking

## Testing

- Debugging: find a bug
- Can test a model of the system, or the system itself.
- Incomplete: might not find a bug, even though it exists
- Little up-front effort: just need to be able to simulate
- Cheap

## Model checking

- Verification: prove is bug-free
- Requires a model of the system
- Complete: if it returns “Correct”, then the model is correct
- More up-front effort to create an appropriate model
- Expensive

# Testing vs. Model checking

## Testing

- Debugging: find a bug
- Can test a model of the system, or the system itself.
- Incomplete: might not find a bug, even though it exists
- Little up-front effort: just need to be able to simulate
- Cheap

## Model checking

- Verification: prove is bug-free
- Requires a model of the system
- Complete: if it returns “Correct”, then the model is correct
- More up-front effort to create an appropriate model
- Expensive



# Testing vs. Model checking

## Testing

- Debugging: find a bug
- Can test a model of the system, or the system itself.
- Incomplete: might not find a bug, even though it exists
- Little up-front effort: just need to be able to simulate
- Cheap

## Model checking

- Verification: prove is bug-free
- Requires a model of the system
- Complete: if it returns “Correct”, then the model is correct
- More up-front effort to create an appropriate model
- Expensive

# Testing vs Model checking

**NO! “cheap” and “expensive” must be measured relative to what you are providing. 10 simulations are very cheap compared to running a model checker – but what do you learn from 10 simulations?**

**Nothing!**

- Debugging

- Incomplete

- Little up-front effort. just need to be able to simulate

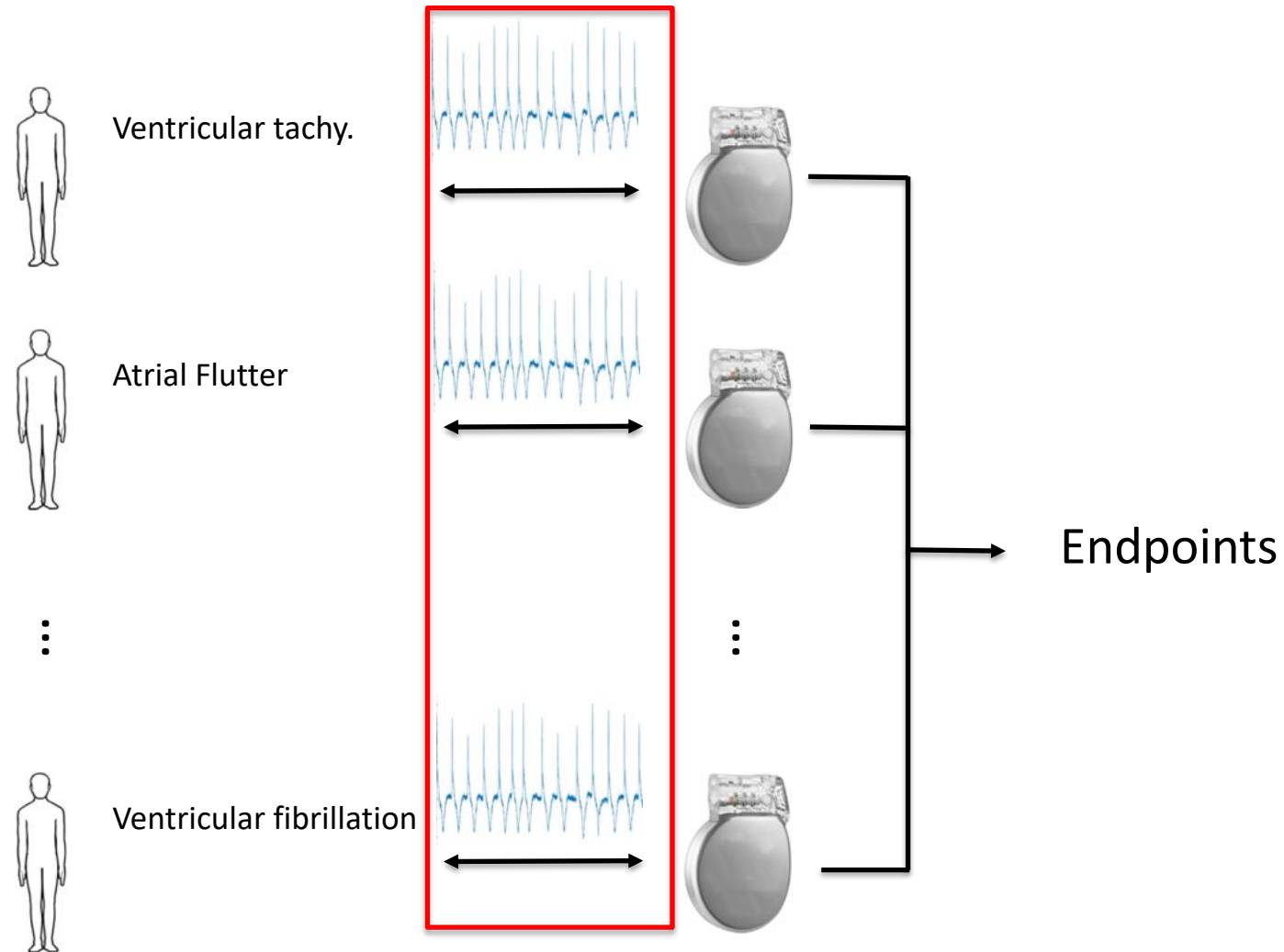
- ~~Cheap~~

are up-front effort to create an appropriate model

- ~~Expensive~~

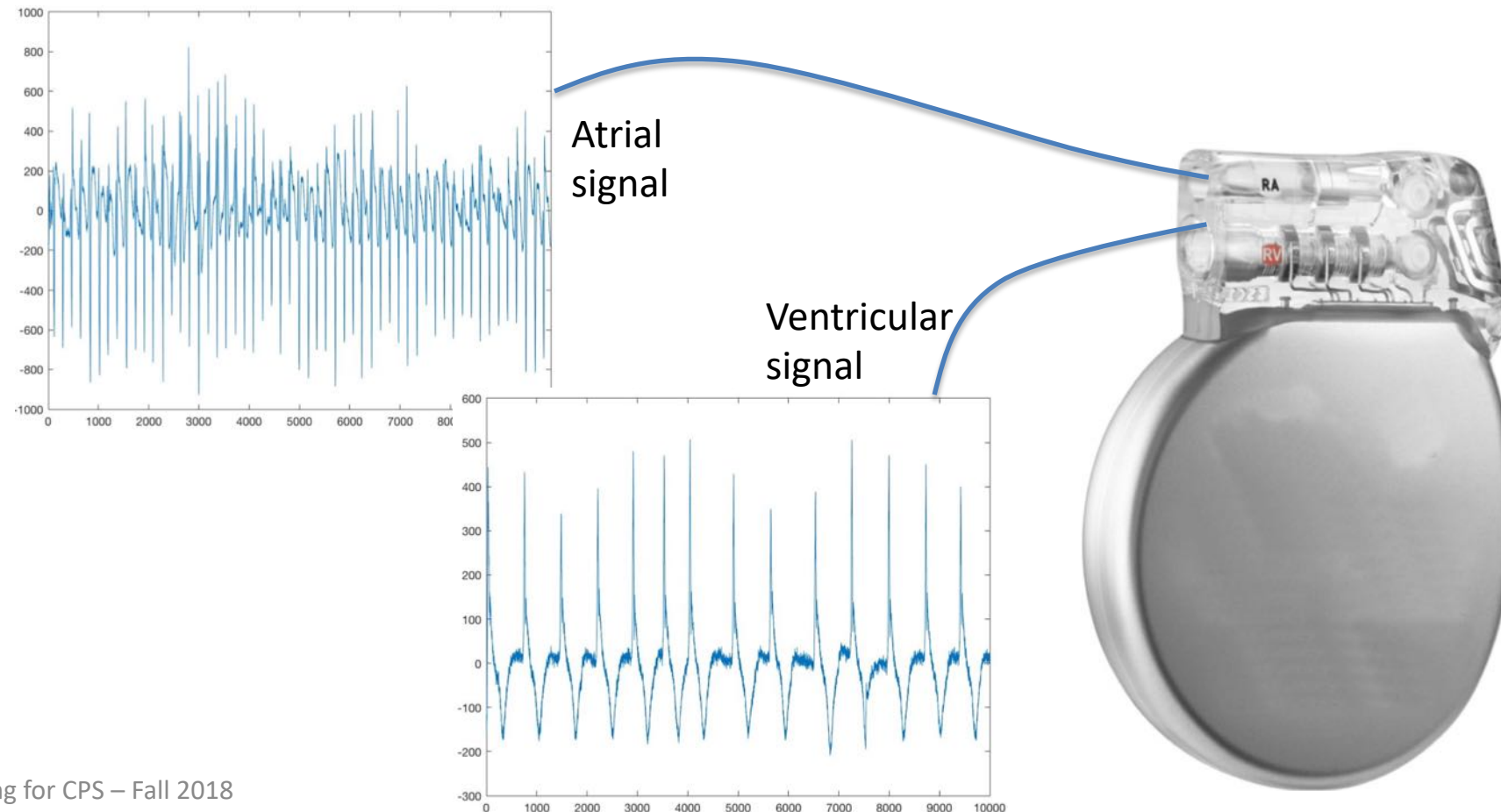
returns “act”, is correct

# Need: a model of device inputs



# Need: a model of device inputs

Inputs to pacemaker are intra-cardiac electrograms



# The heart as a timed automaton

(Next lecture)