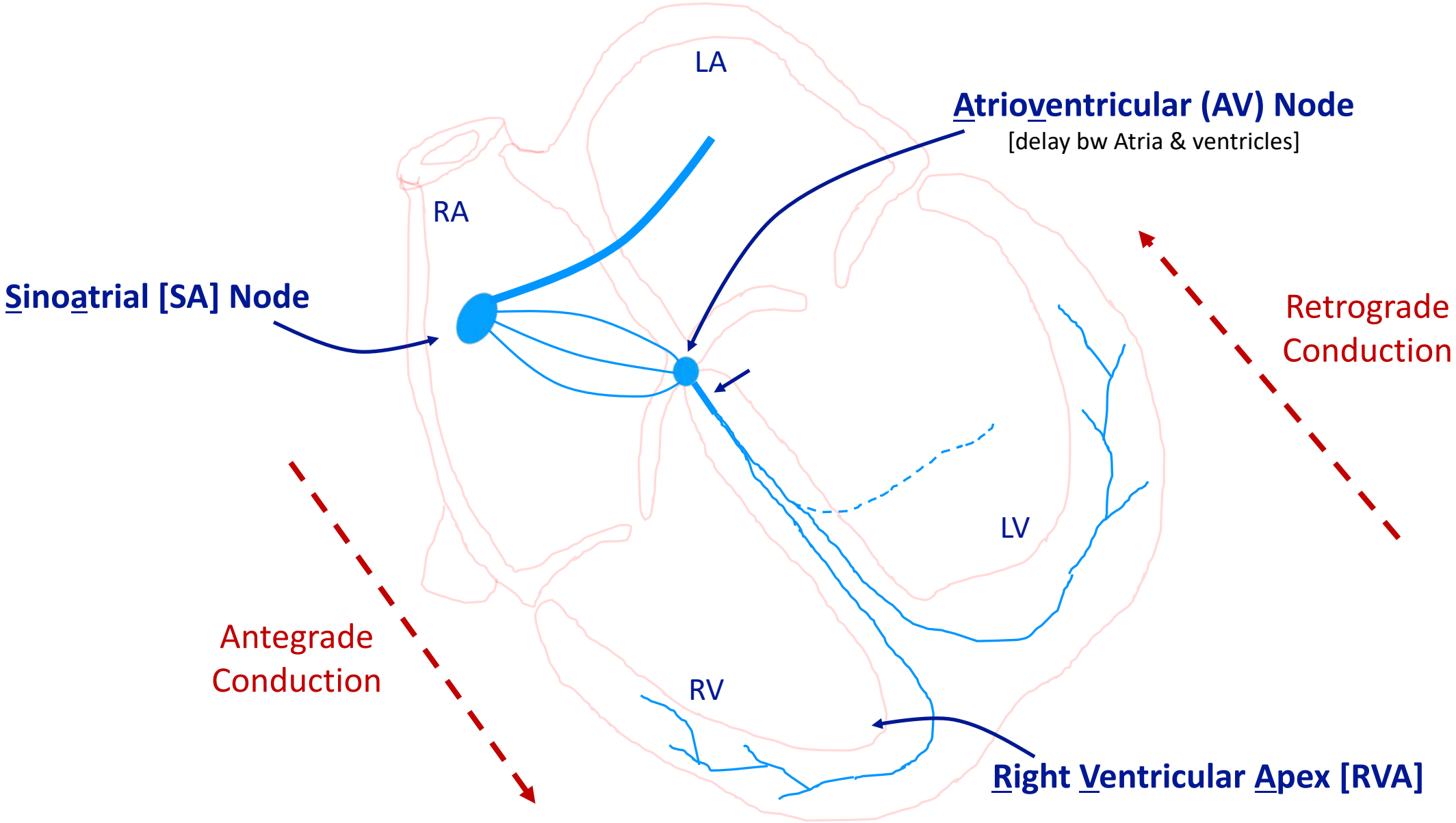
Pacemaker function

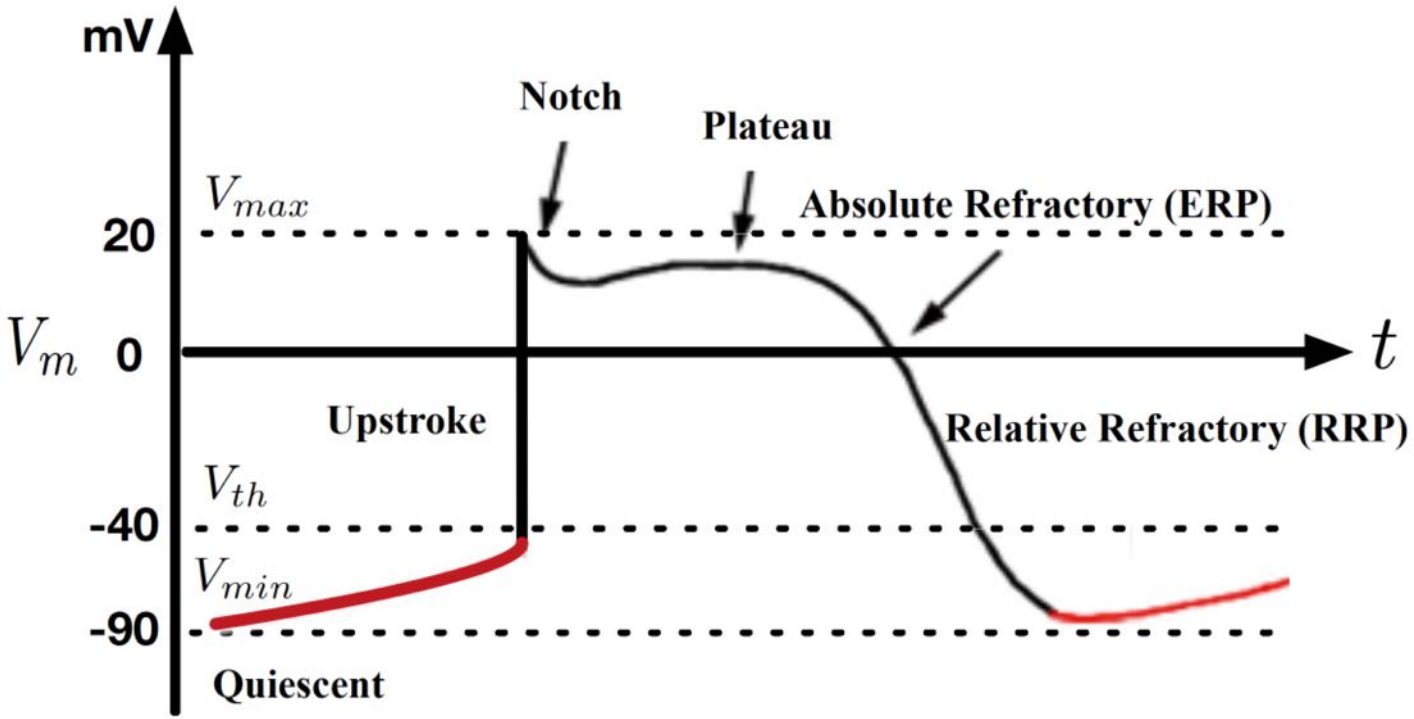
Lecture 11

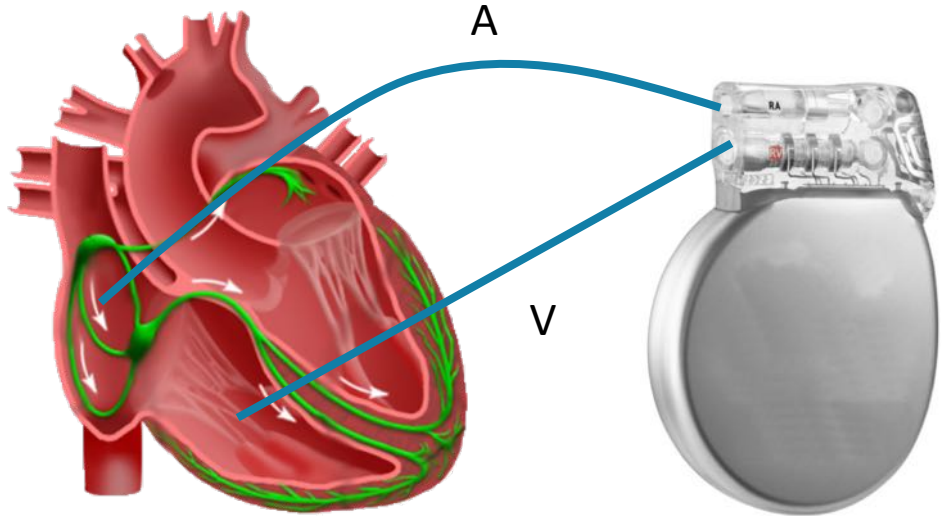
Principles of Modeling for Cyber-Physical Systems

Instructor: Madhur Behl


LA
Atrioventricular (AV) Node
[delay bw Atria & ventricles]
RA
Sinoatrial [SA] Node
Retrograde
Conduction
LV
Antegrade
Conduction
RV
Right Ventricular Apex [RVA]

Action potential in one excitable cardiac cell



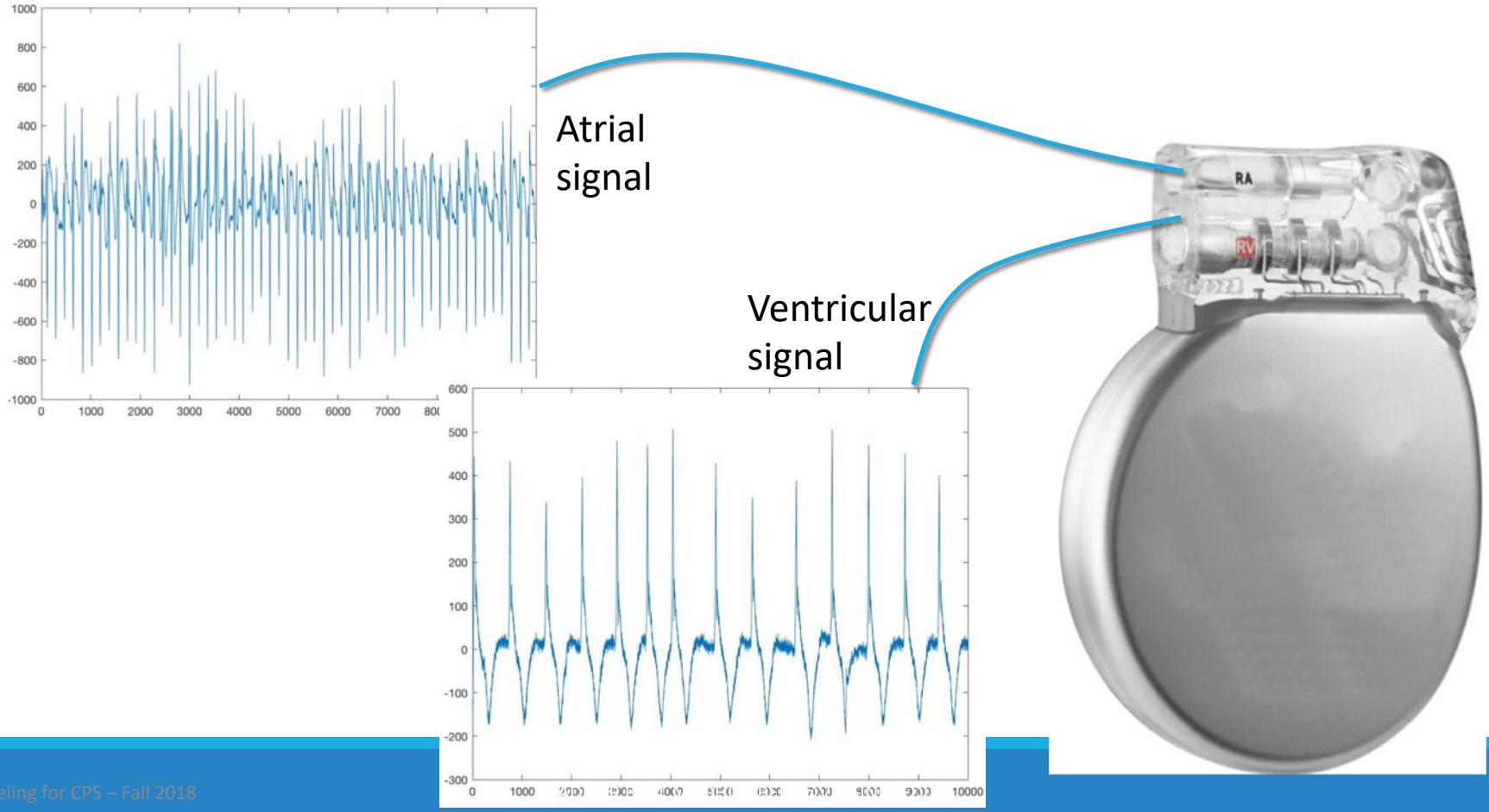



Electrocardiogram

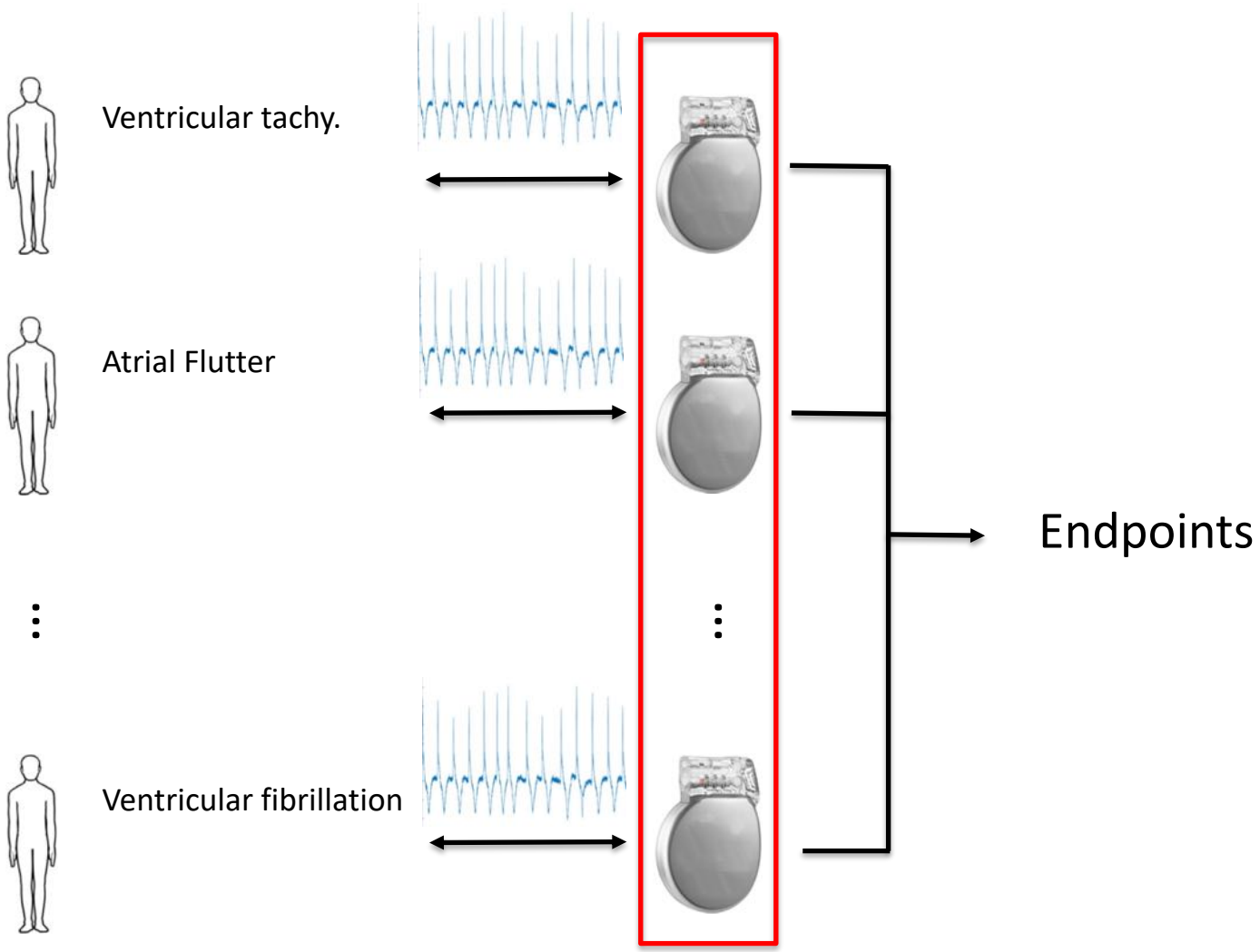

Mashable
ECG
10:09
Sinus Rhythm
i
68 BPM AVERAGE
This ECG does not show signs of atrial fibrillation.


WHAT TIME IS IT?
OOP. I'M DYING.

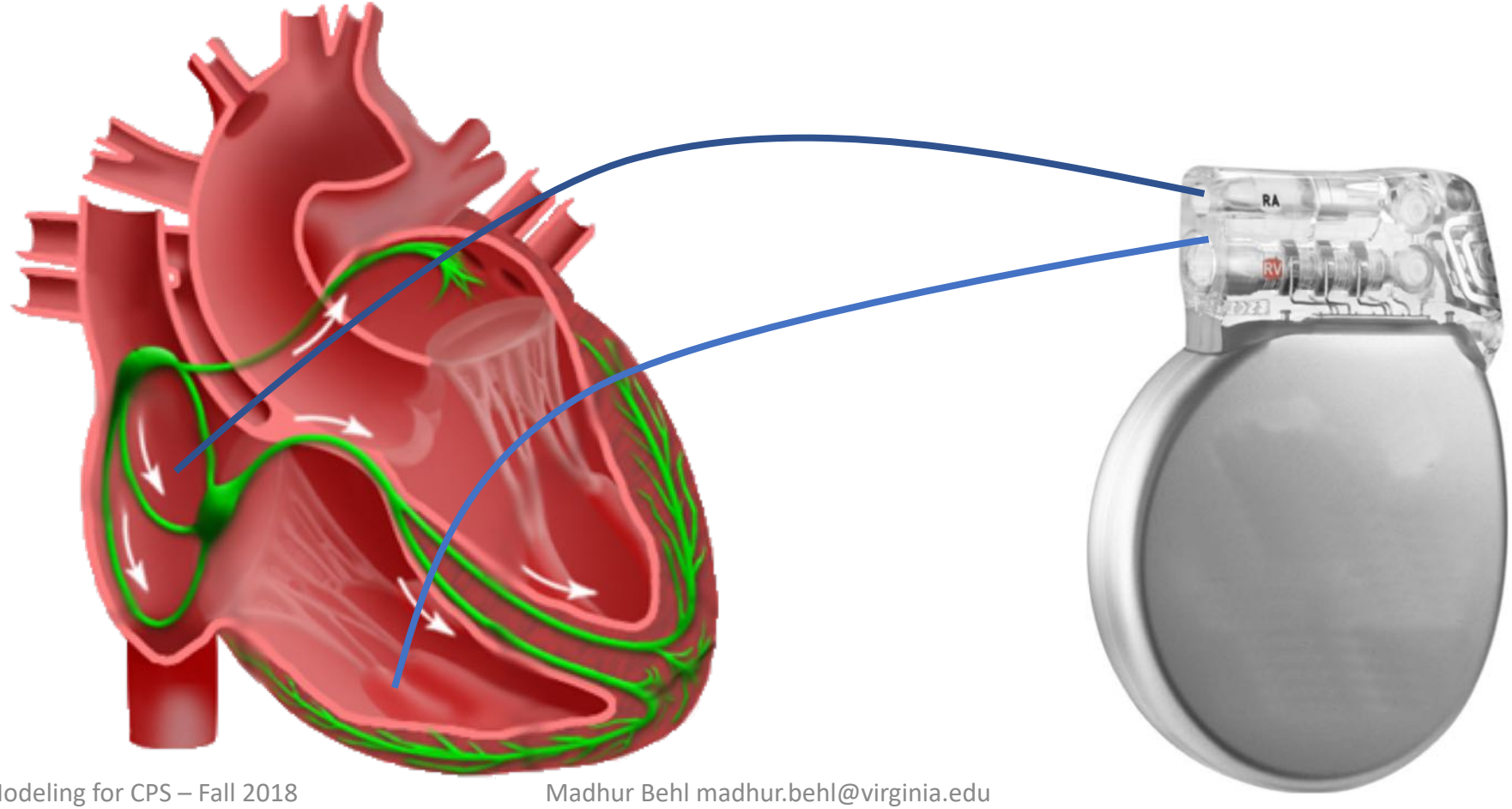
Inputs to pacemaker are intra-cardiac *electrograms [EGM]*



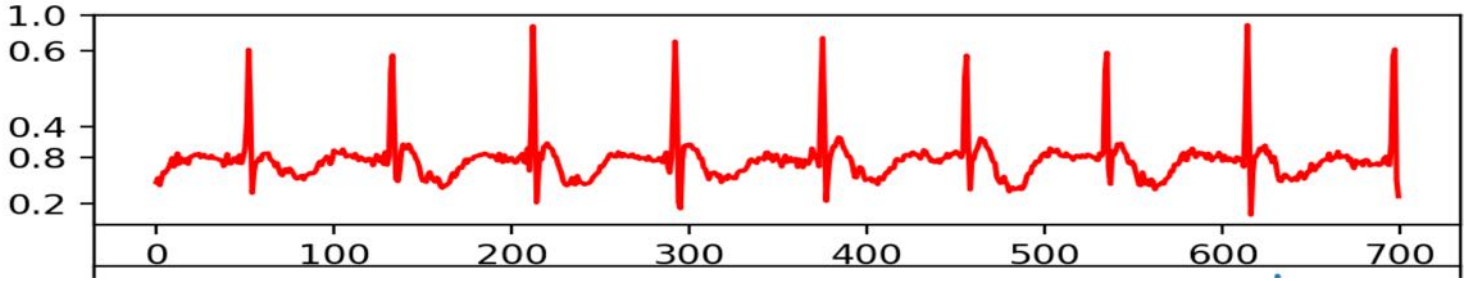
Need: a device algorithm

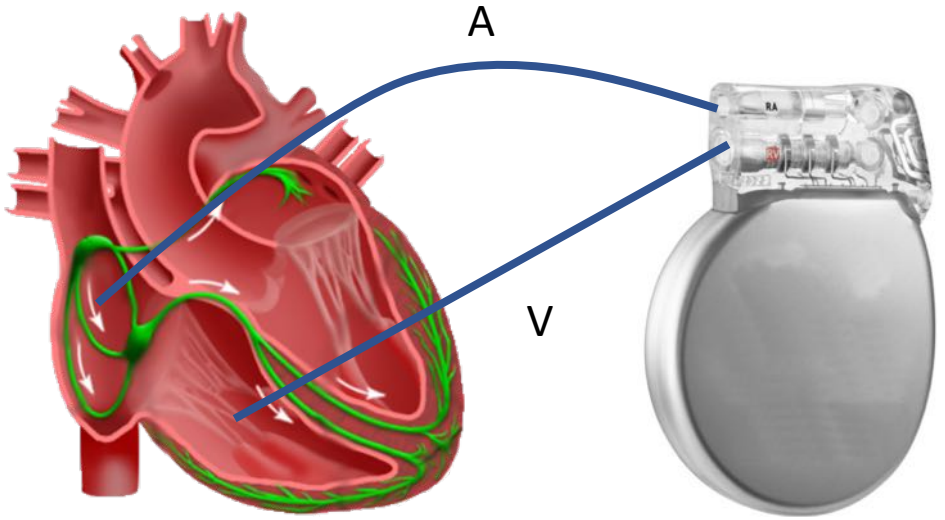


Device algorithm: Treat the symptoms

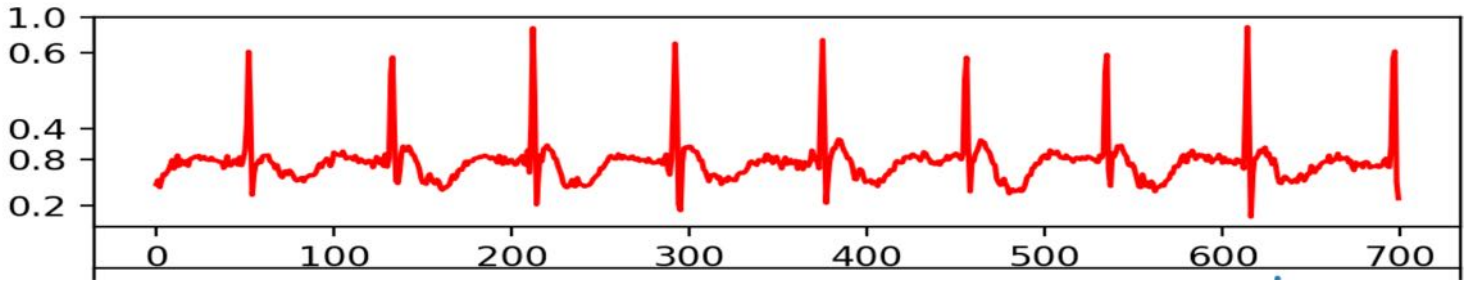


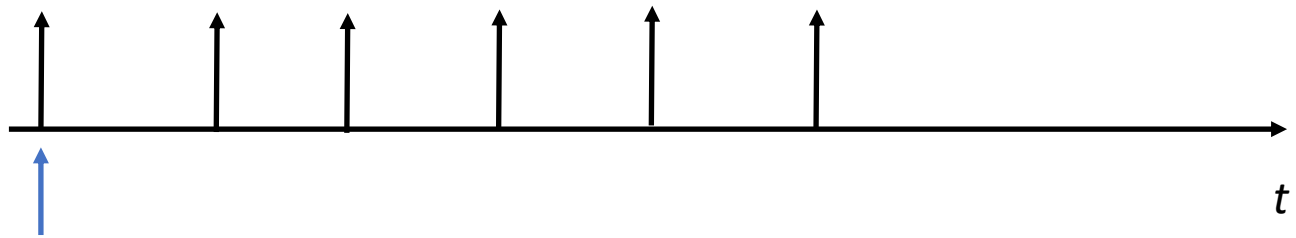
Electrogram measured by one lead

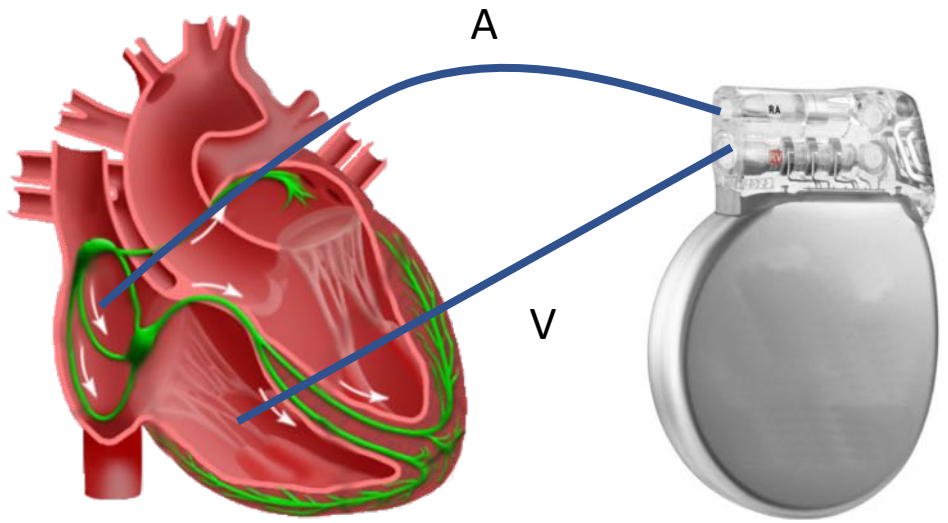




From electrogram to boolean event stream



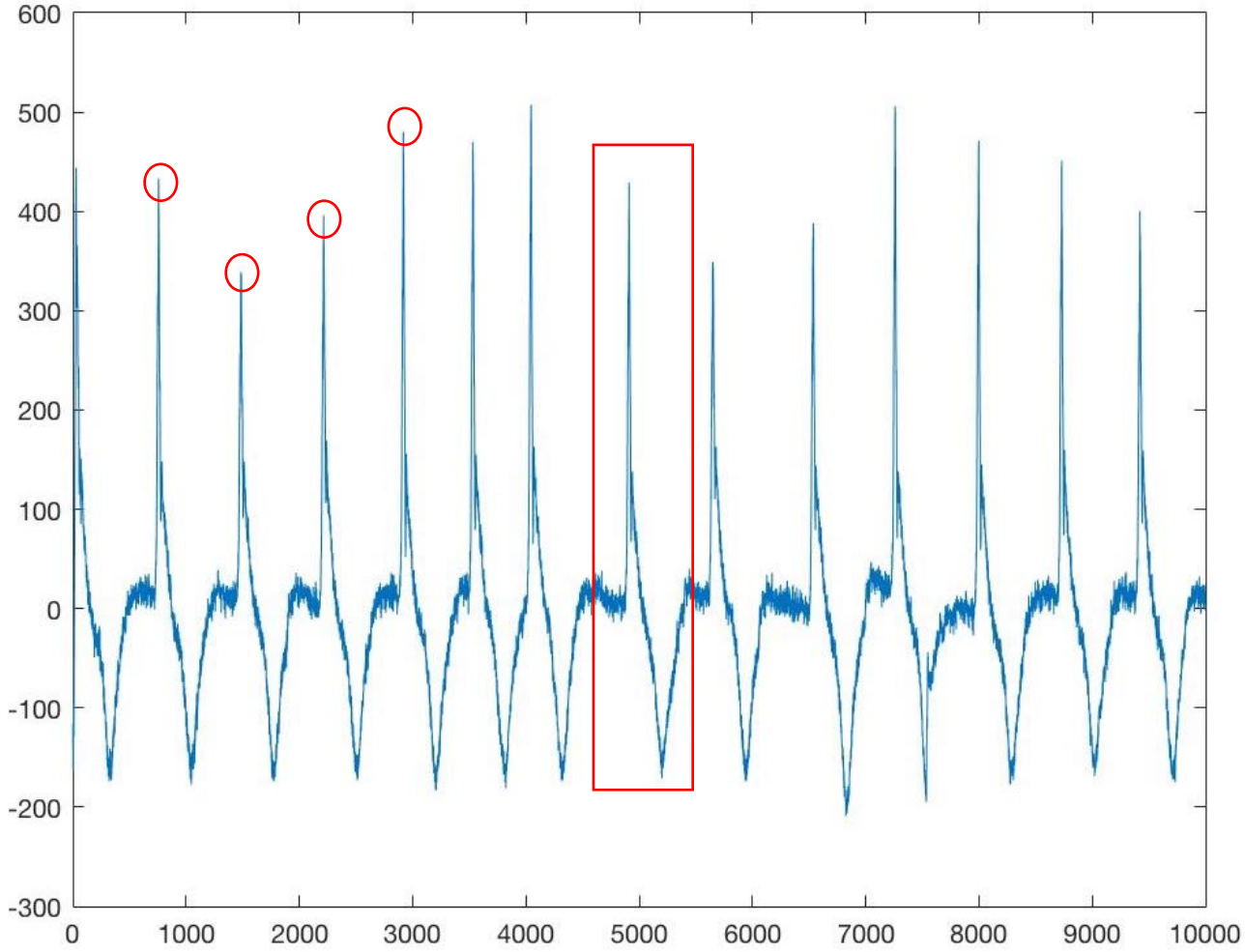




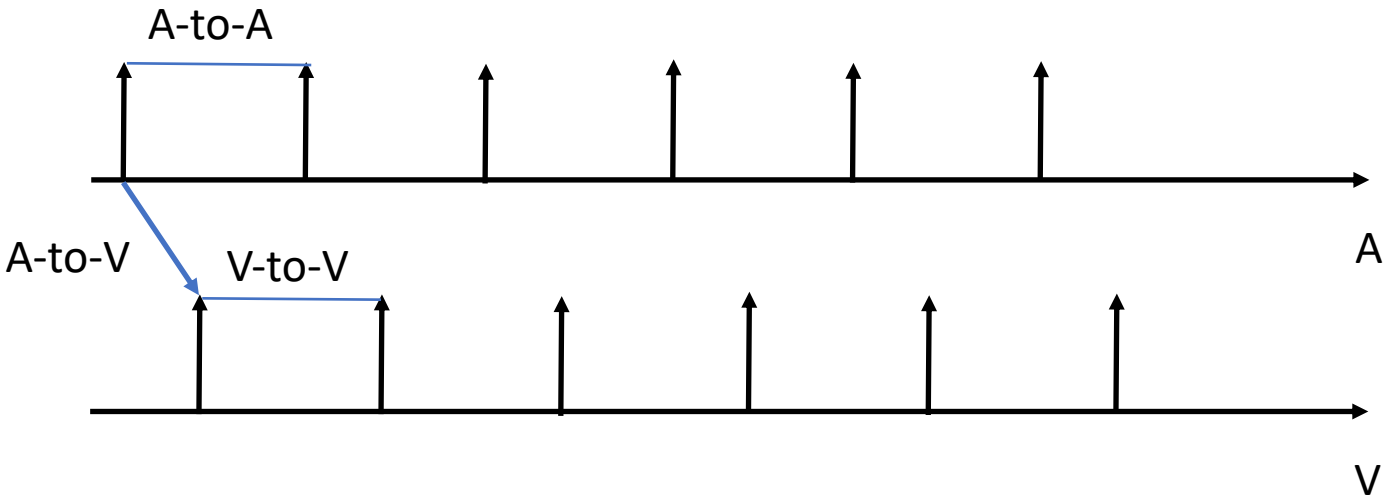
"Moment of depolarization" = "event time" = "approximate time of contraction"

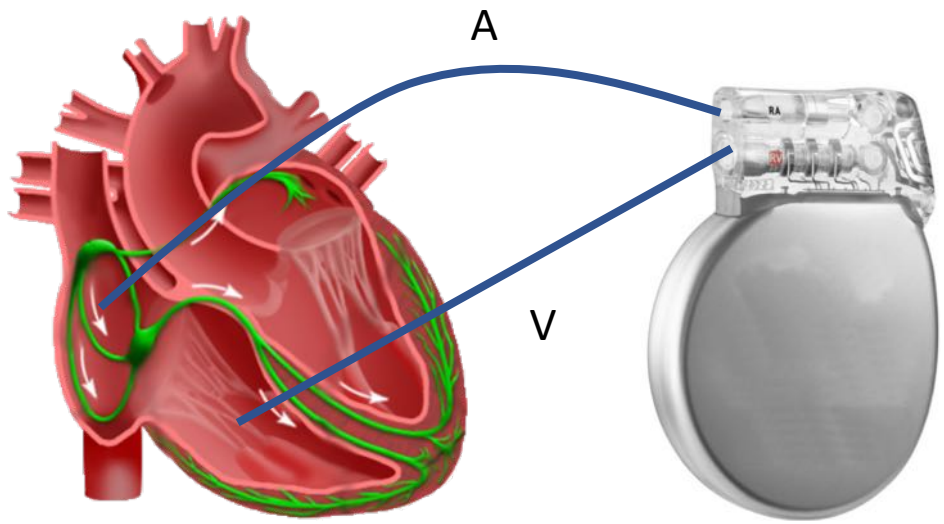
Abstraction

Pacemaker: peak detector



Normal Sinus Rhythm



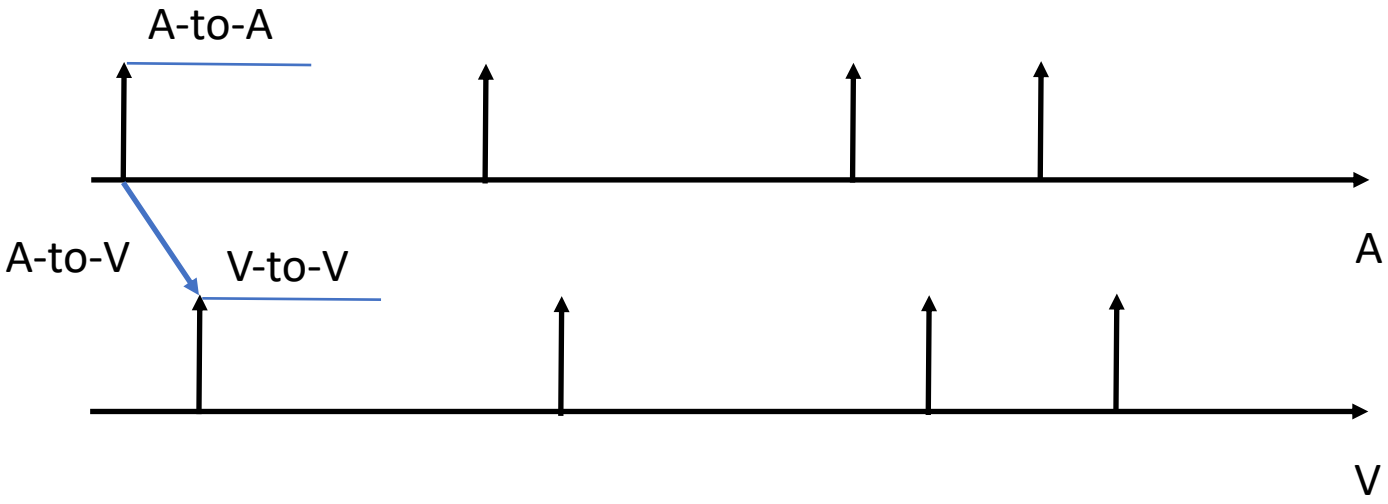


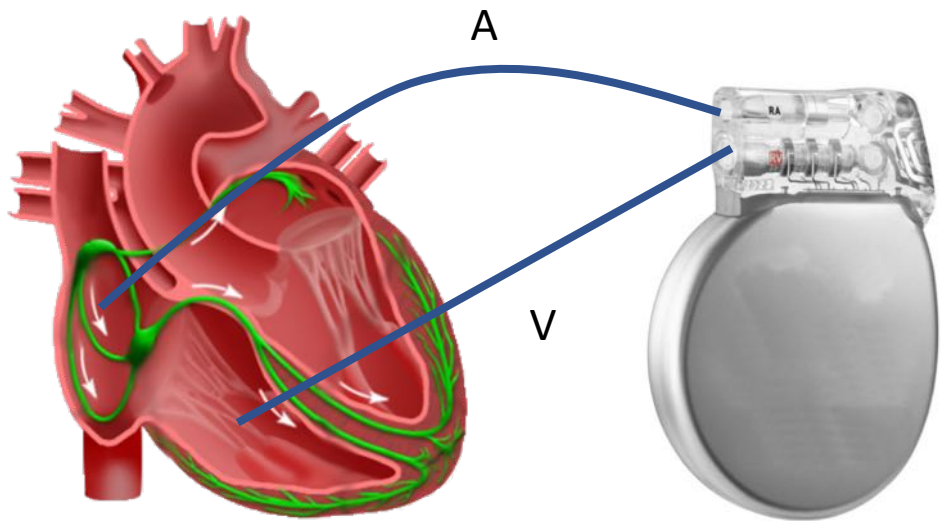
HUGE caveat: “Normal” is very patient-dependent

ASense APace

VSense VPace

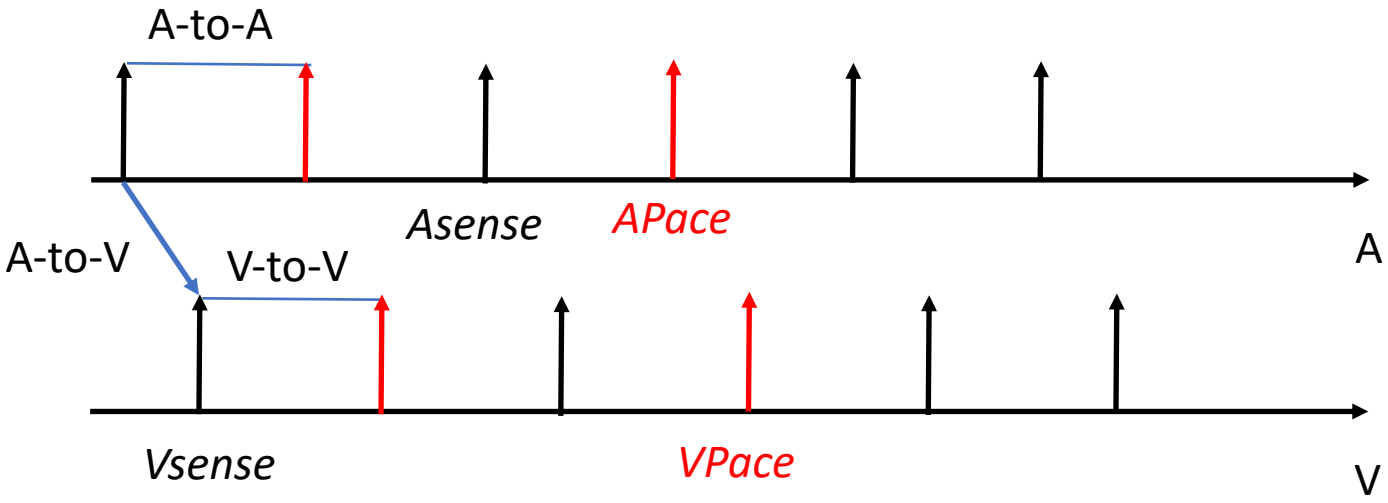
Treat the symptoms 1: SA node misses a beat (bradychardia)

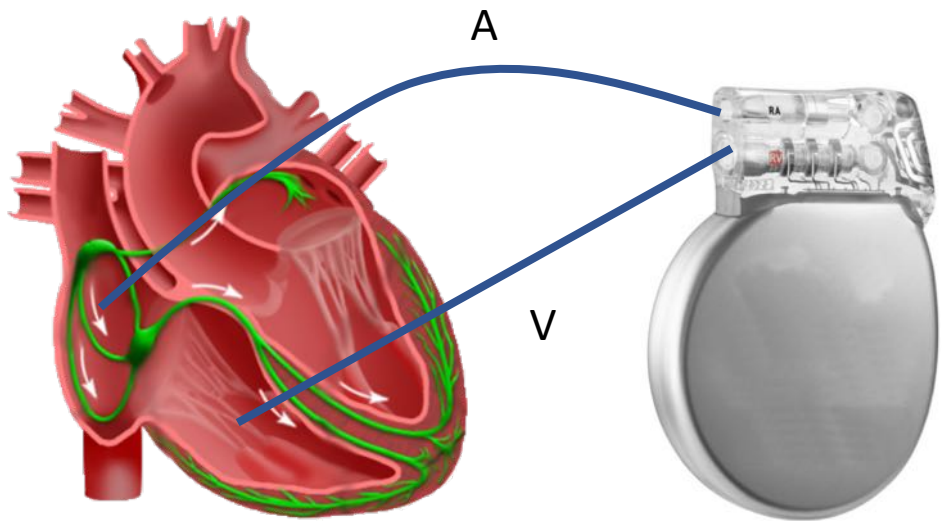




What do you do?

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

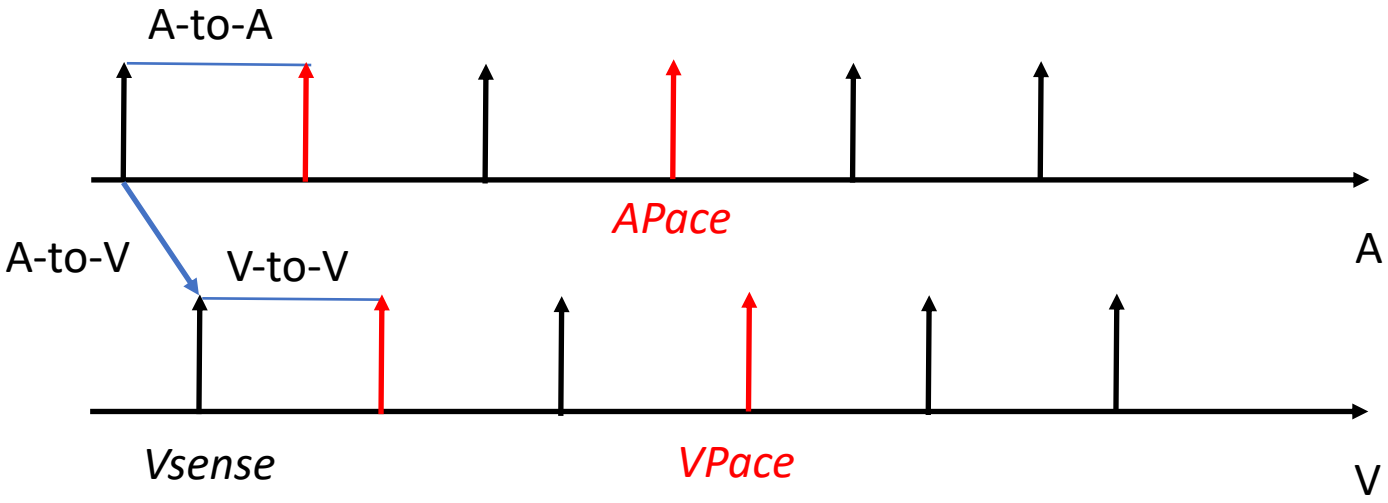


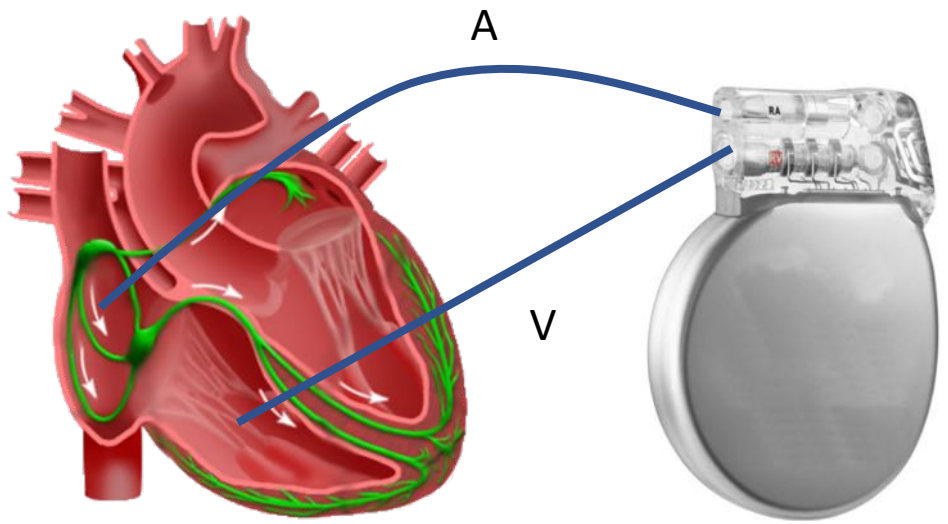


- Add an AA timer that counts down from the last time it sensed an A beat (= *Asense*). Apace when it expires
- So pacemeaker ensures AA <= A-Rate Interval

AA <= A-rate interval

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

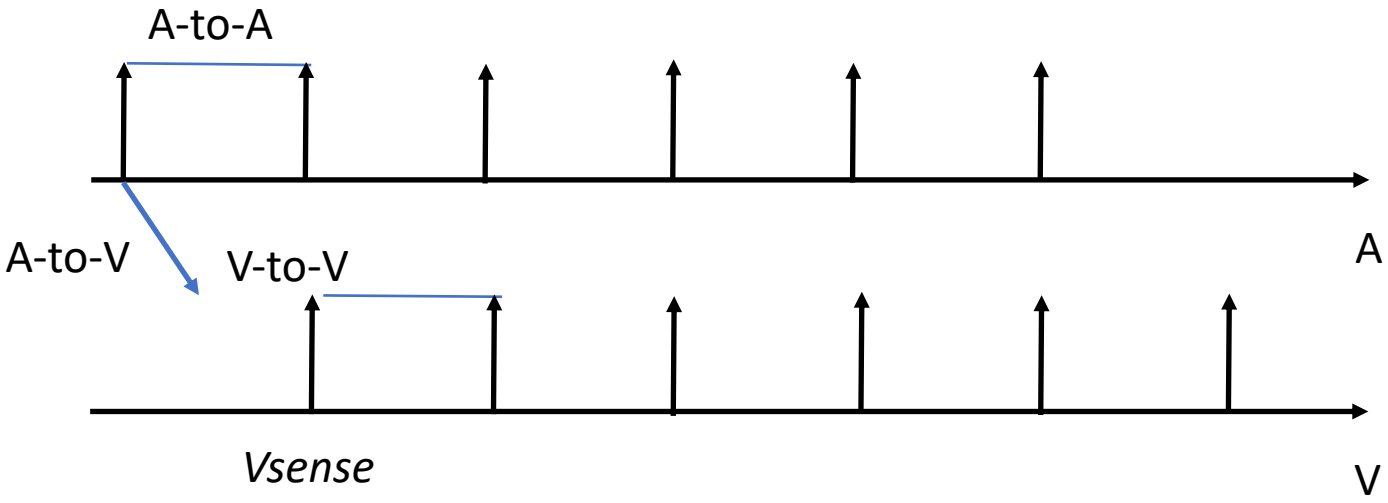


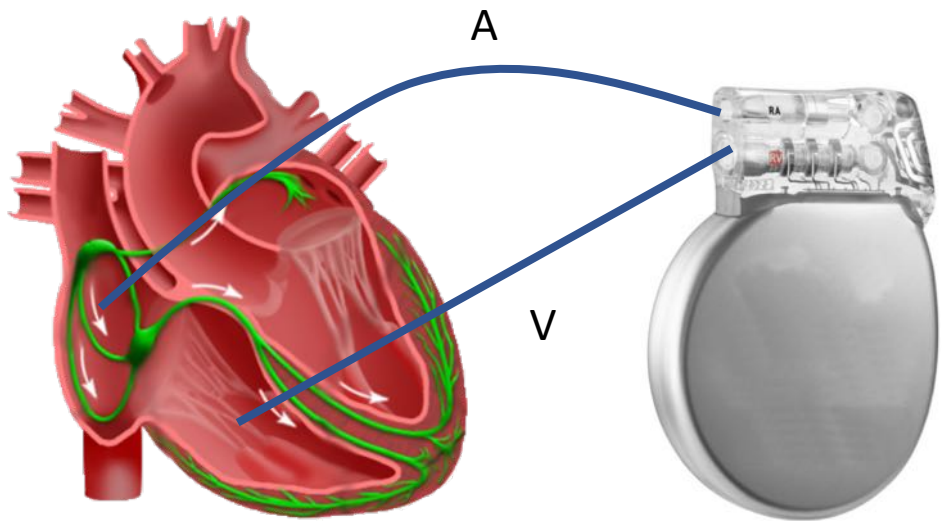


- Add a V-V timer that counts down from the last time it sensed a V beat (= *Vsense*). Vpace when it expires
- Commonly called the *Lower Rate Interval (LRI)*
- So: Device makes sure that V-V <= LRI

VV <= Lower Rate Interval
AA <= A-rate interval

Treat the symptoms 2: Delayed conduction from A to V

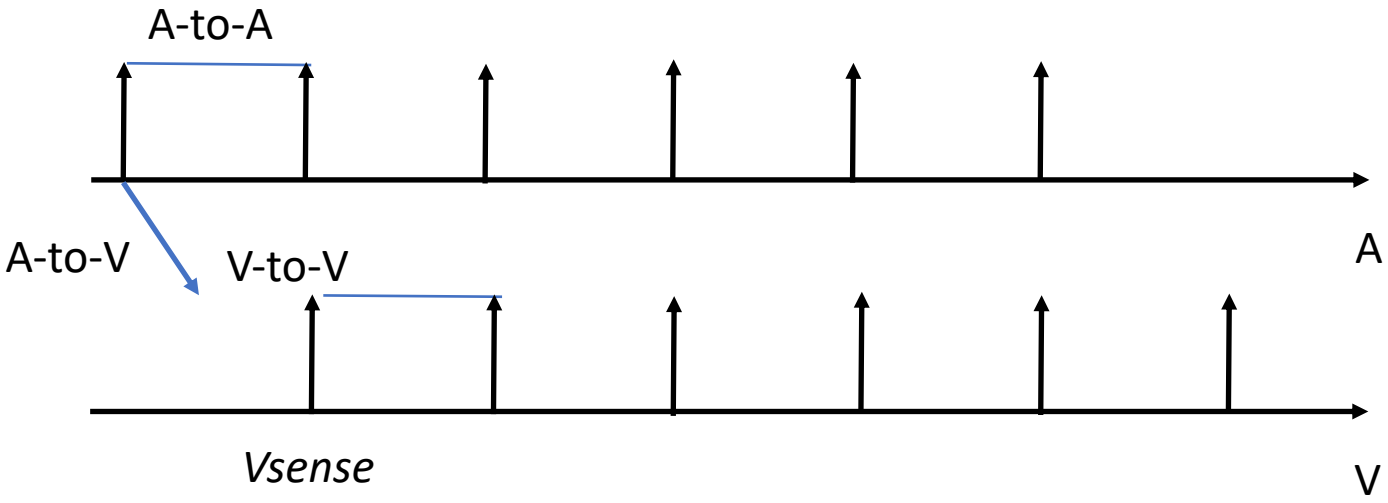


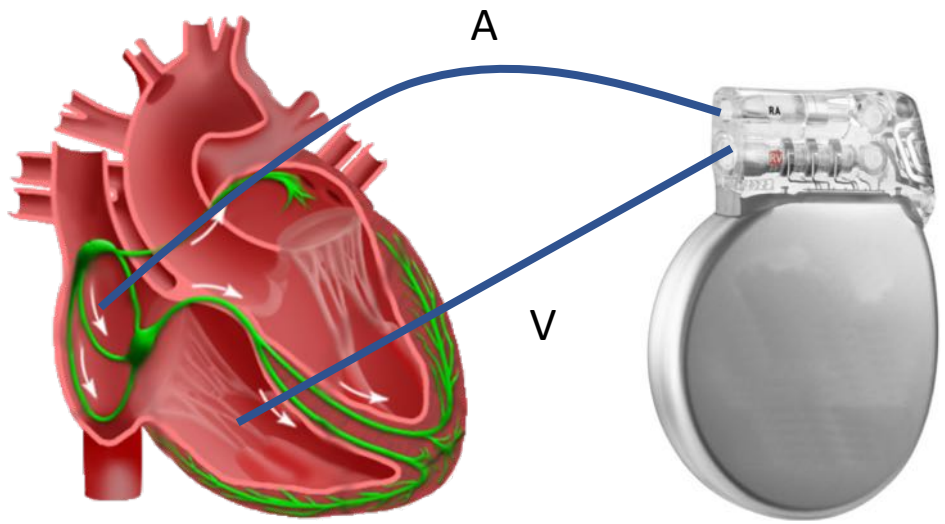


- In NSR, the ventricles are driven by the atria, so there's a relation between A events and V events.
- What do you do?

VV <= Lower Rate Interval
AA <= A-rate interval

Treat the symptoms 2: Delayed conduction from A to V

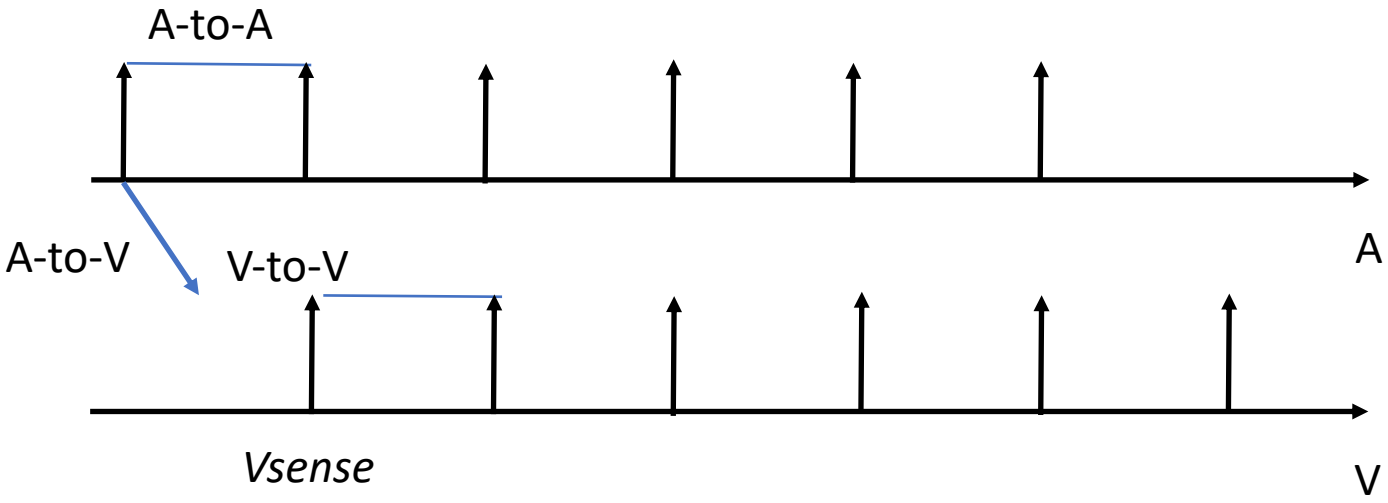


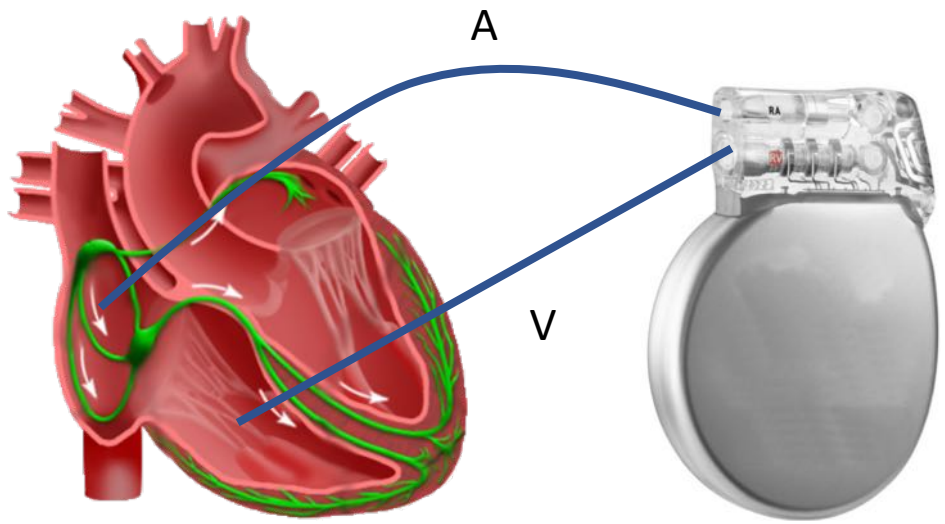


- Add an A-to-V timer, which expires after a pre-set amount of time, called the *AtrioVentricular Interval (AVI)*.
- What's the relation between LRI, A-Rate interval and AVI?

VV <= Lower Rate Interval
AA <= A-rate interval

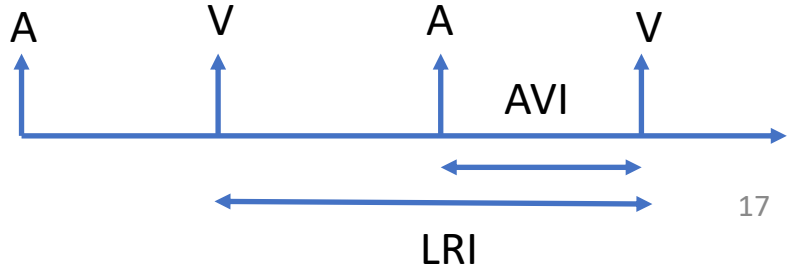
Treat the symptoms 2: Delayed conduction from A to V



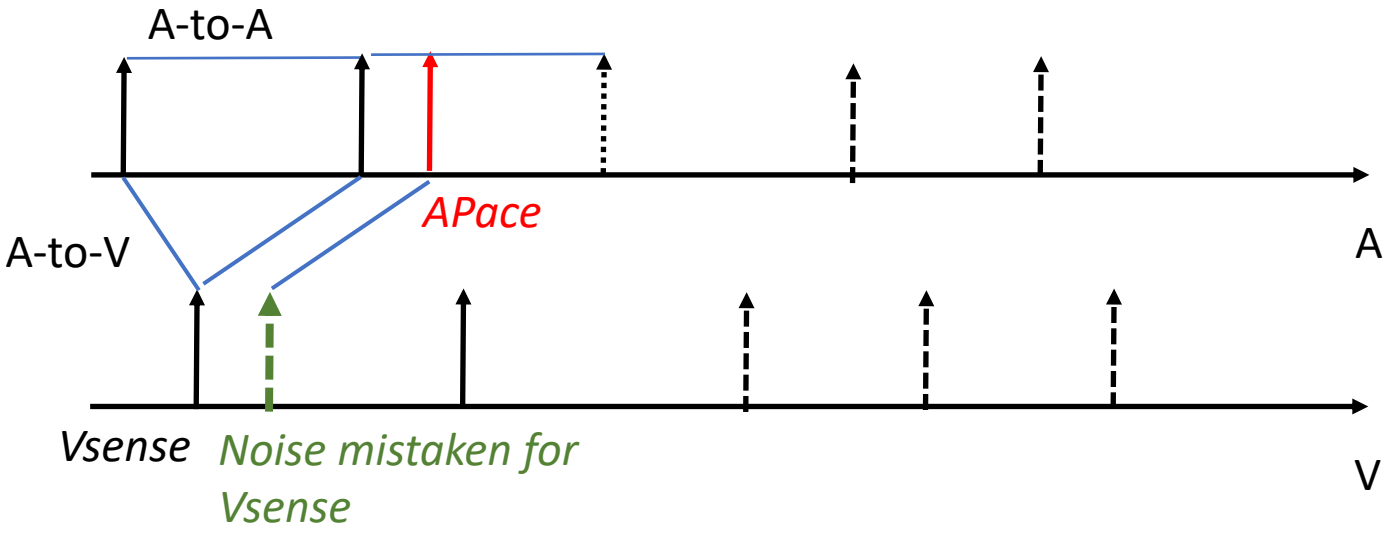


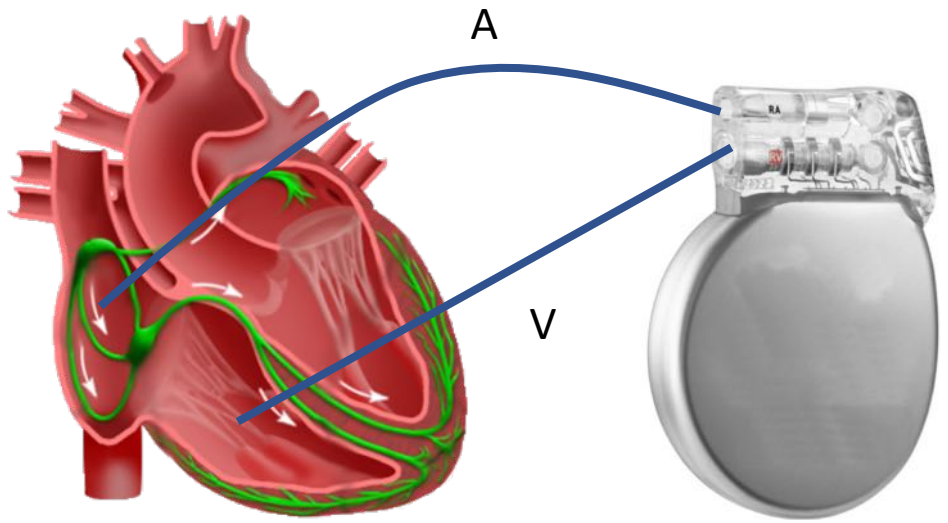
- Add an A-to-V timer, which expires after a pre-set amount of time, called the *AtrioVentricular Interval (AVI)*.
- AVI is used as a component in LRI.

VV <= Lower Rate Interval
VA <= LRI – AVI



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

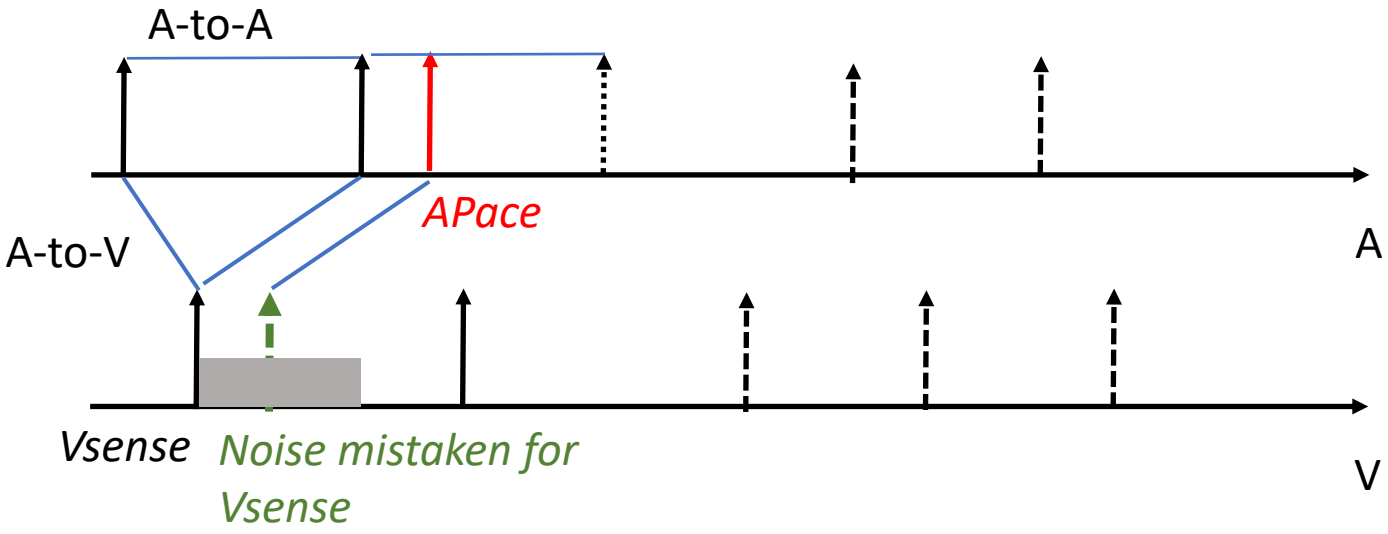


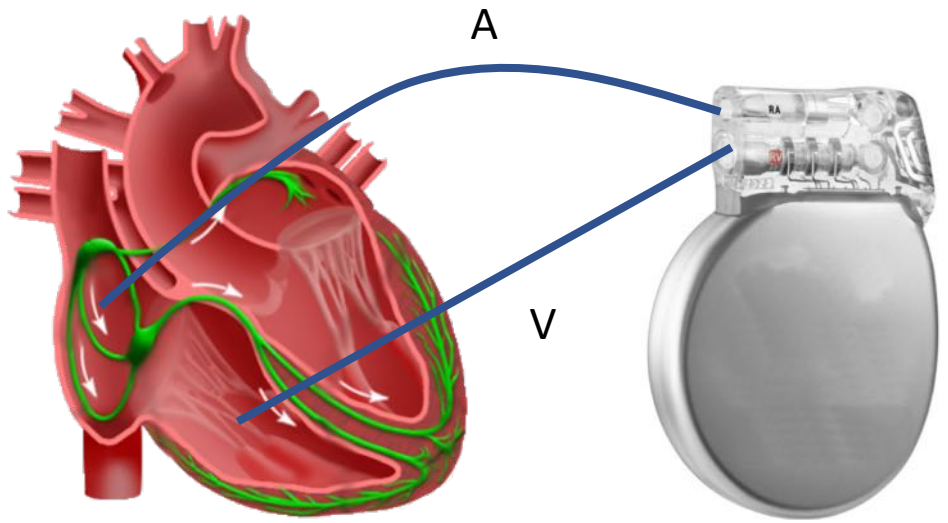


- What do you do?

VV <= Lower Rate Interval
VA <= LRI – AVI

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

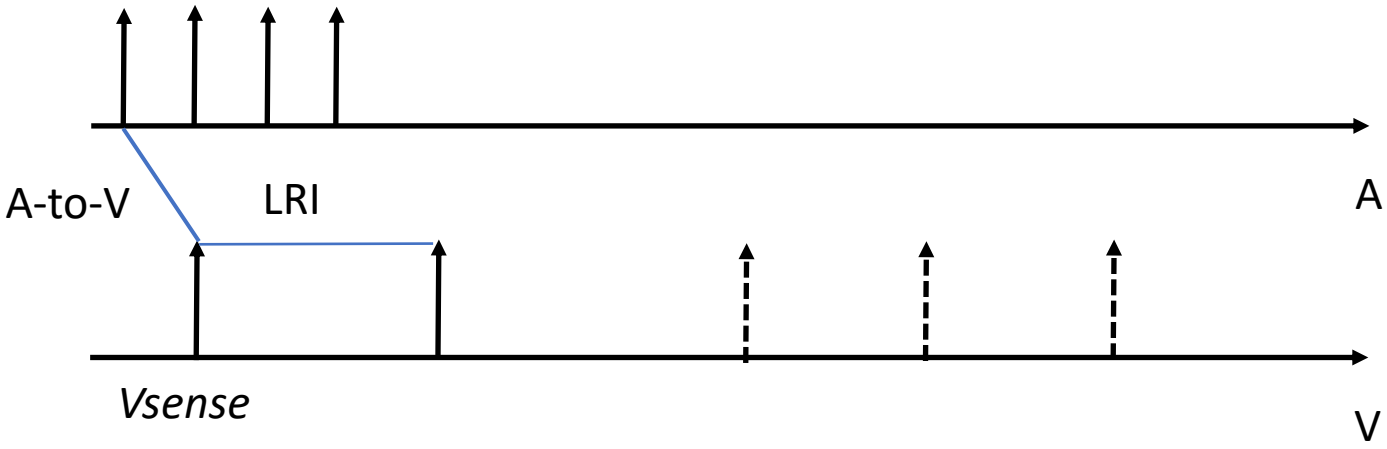


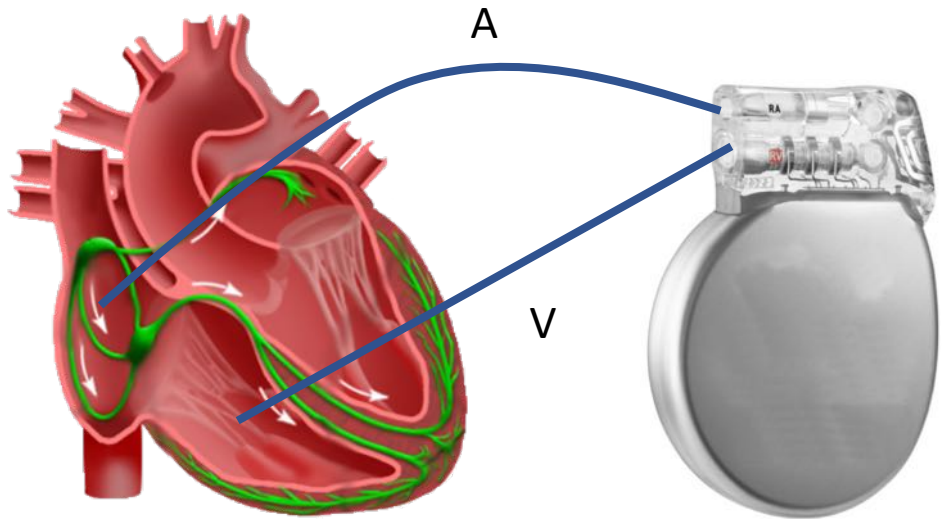


- Ventricular Refractory Period (VRP) to ignore events close to Vsense.
- Similarly, use an ARP

VV <= Lower Rate Interval
VA <= LRI – AVI
Ignore Vsense in Ventricular Refractory Period (VRP)

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

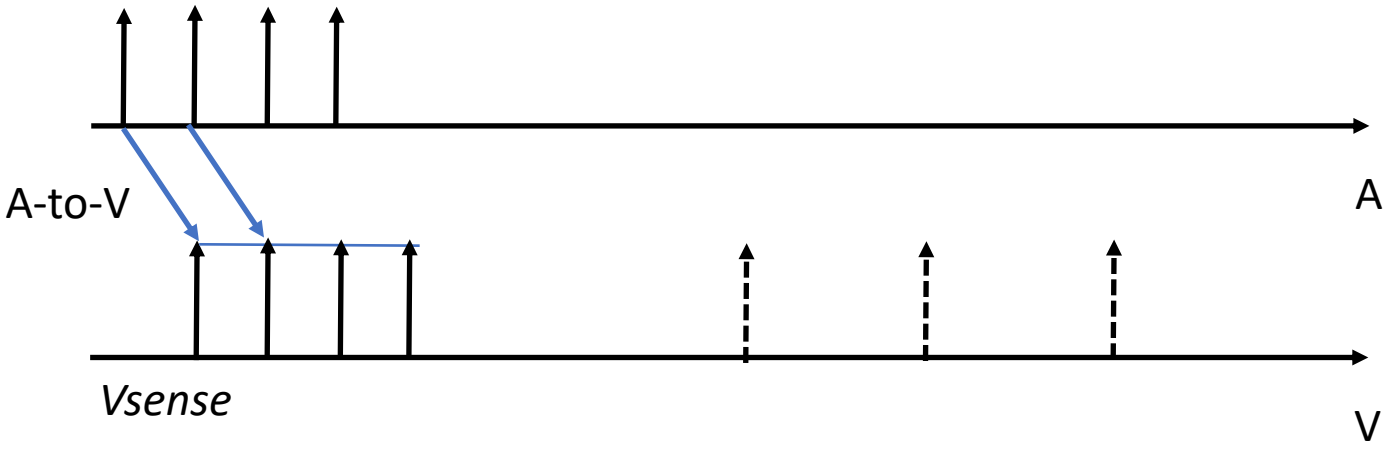


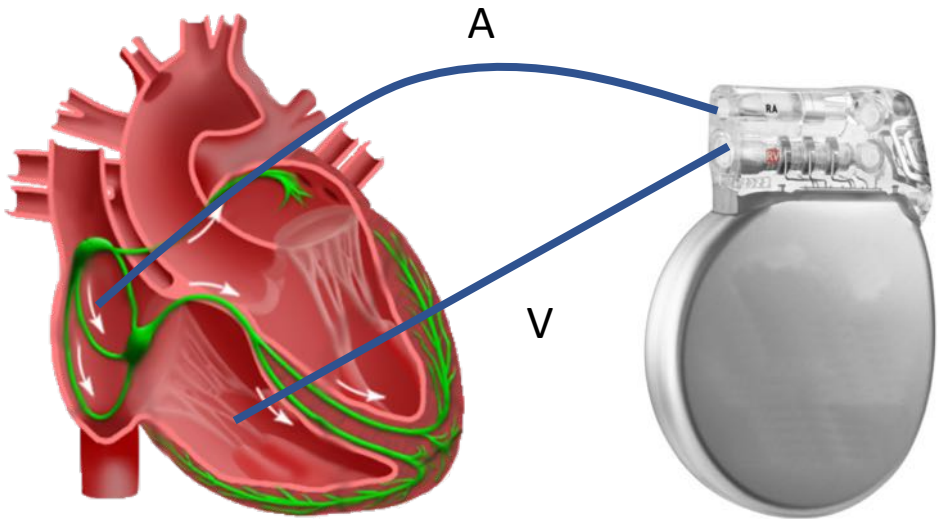


- For whatever reason, ventricles not responding to faster atrial rate.
- Pacemaker governed by LRI
- Should ventricles pace faster to keep up with atria?

VV <= Lower Rate Interval
VA <= LRI – AVI
Ignore Vsense in Ventricular Refractory Period (VRP)

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

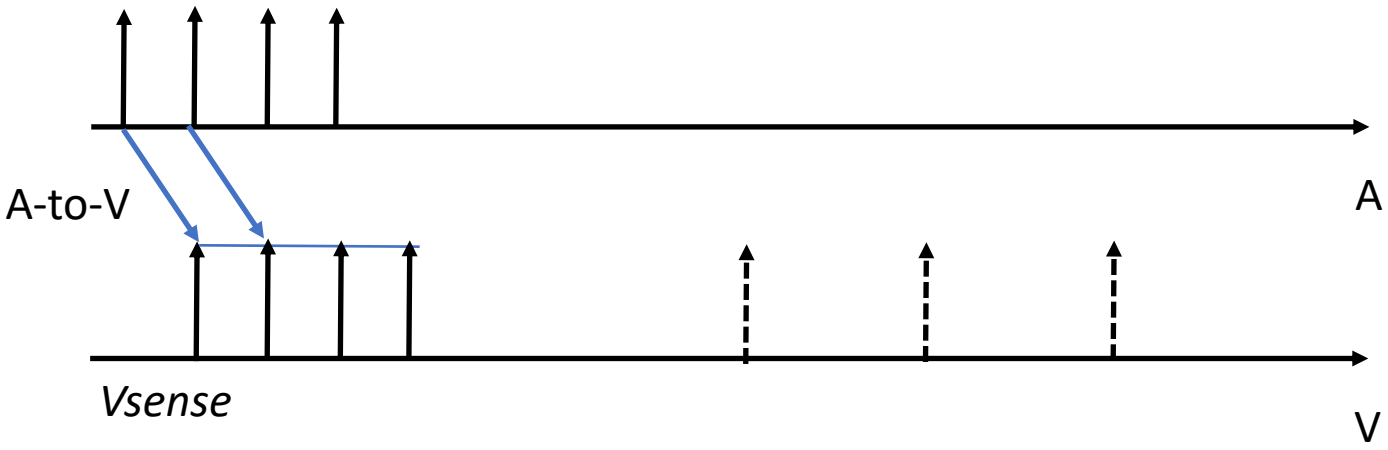


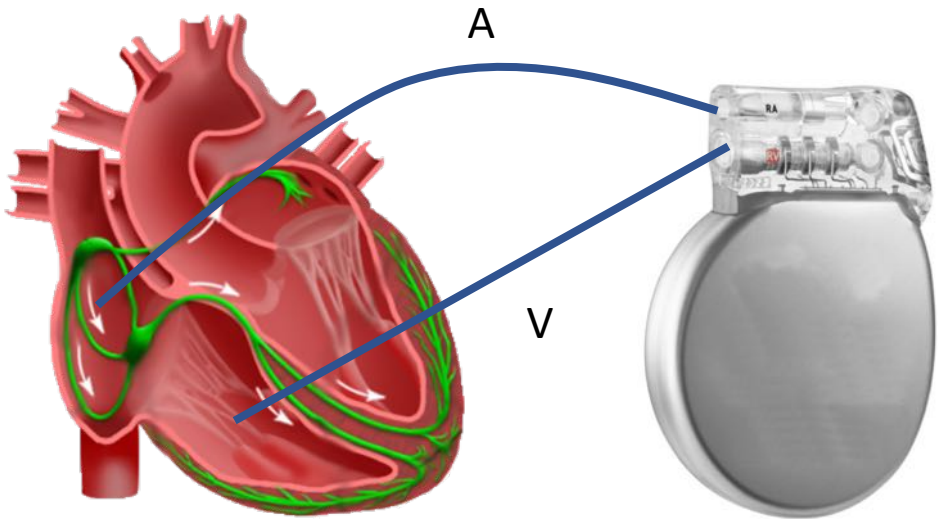


- We *should* pace the ventricles to keep up with the atria
- *Maintain an Atrio-Ventricular Interval (AVI) timer and pace when it expires*
- LRI is an *upper bound*

VV <= 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 Vpace → heart racing

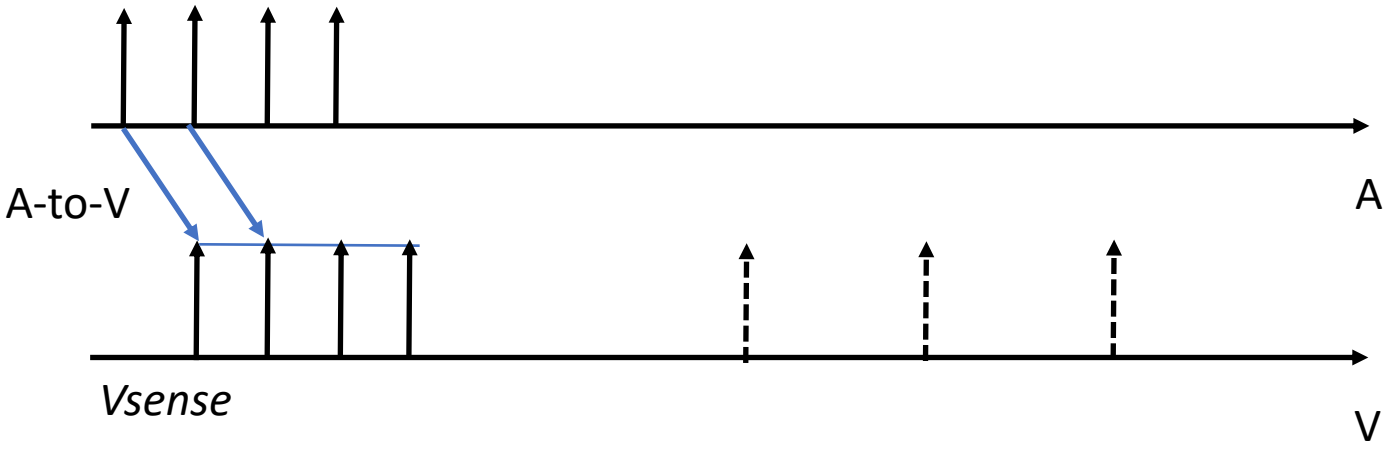


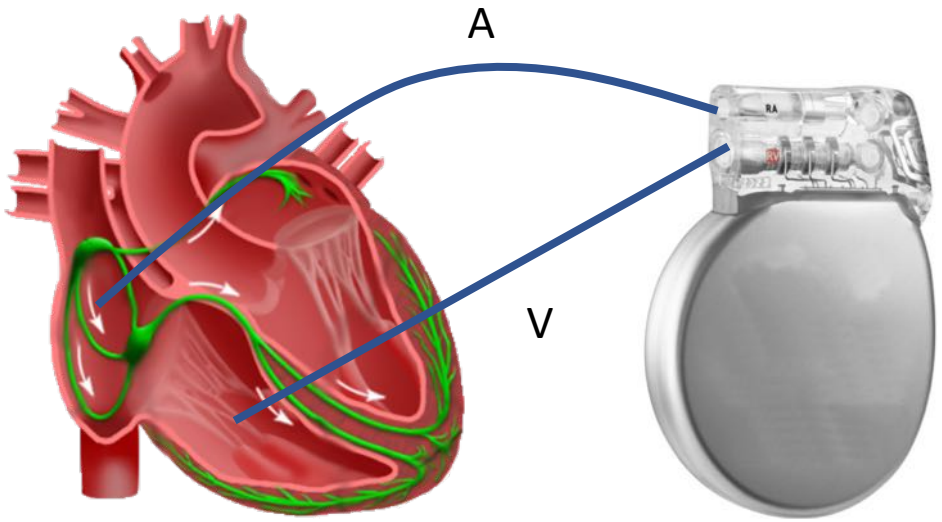


- *Tachycardia* is opposite of bradycardia: heart beats abnormally fast.
- 'Heart racing' feeling. Can result from too much coffee
- So…should we pace to keep up after all?

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 Vpace → heart racing

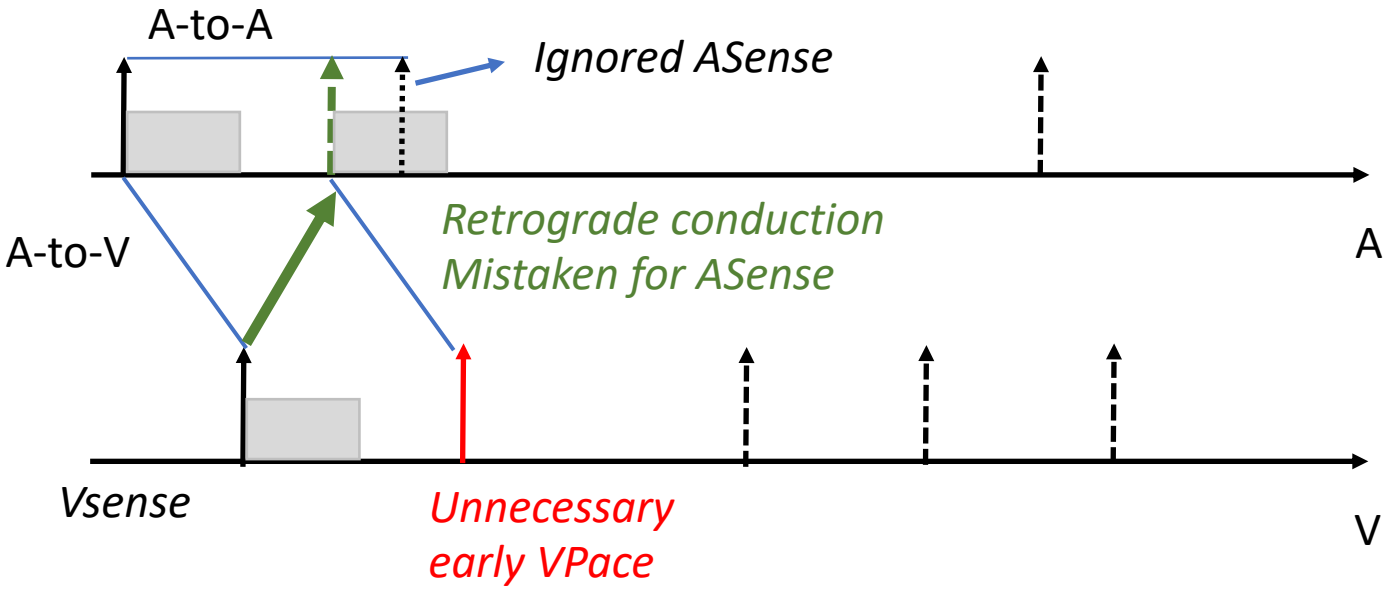


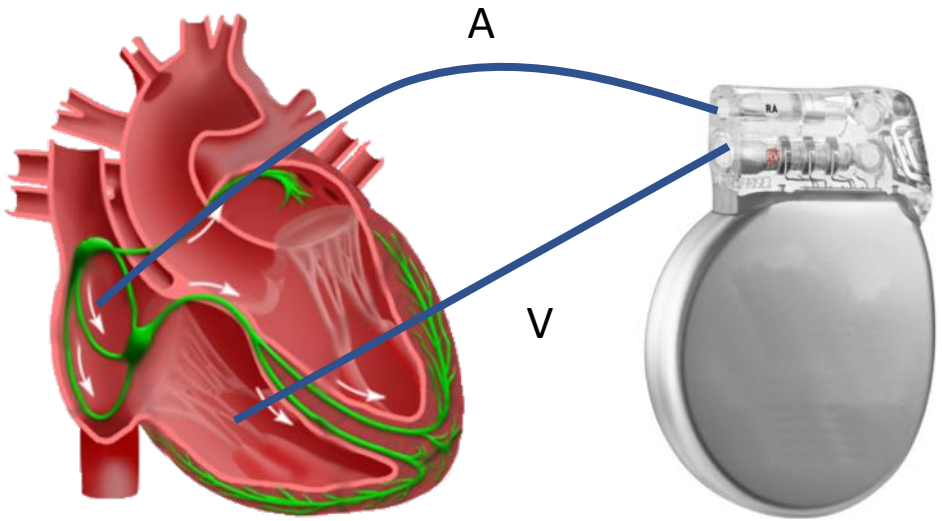


- Add accelerometers and temperature sensors to pacemaker to detect physical activity
- Not everything is solved in the same way! Think of the whole SYSTEM

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

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

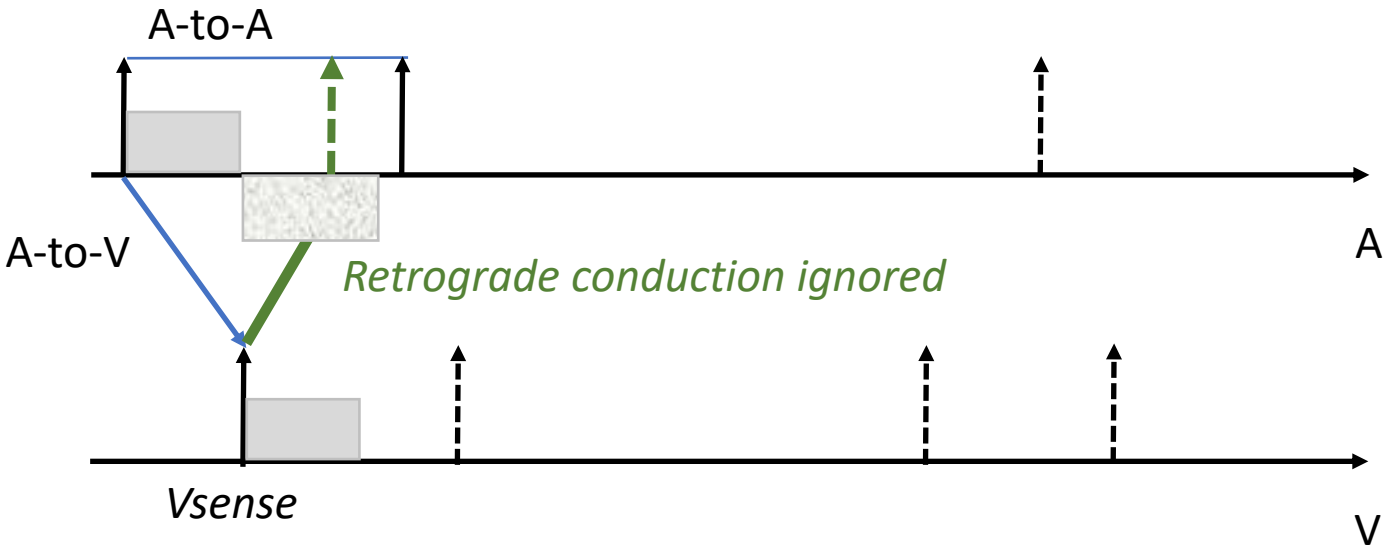


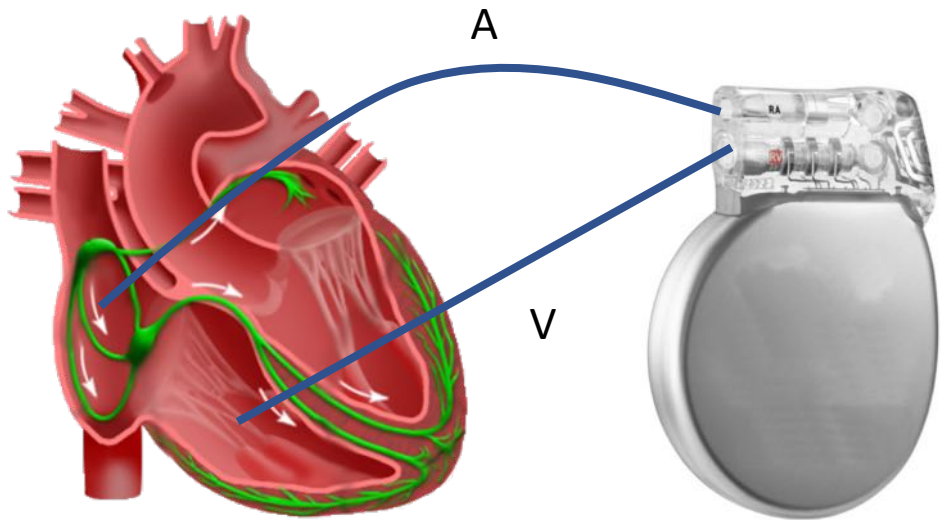


- What do you do?

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

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

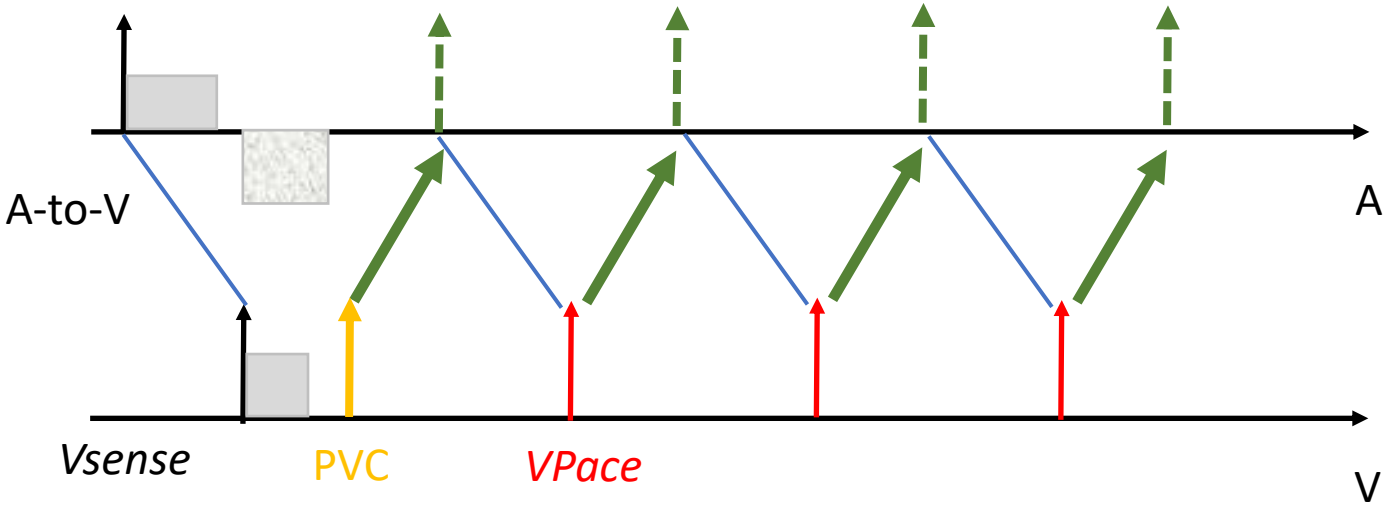


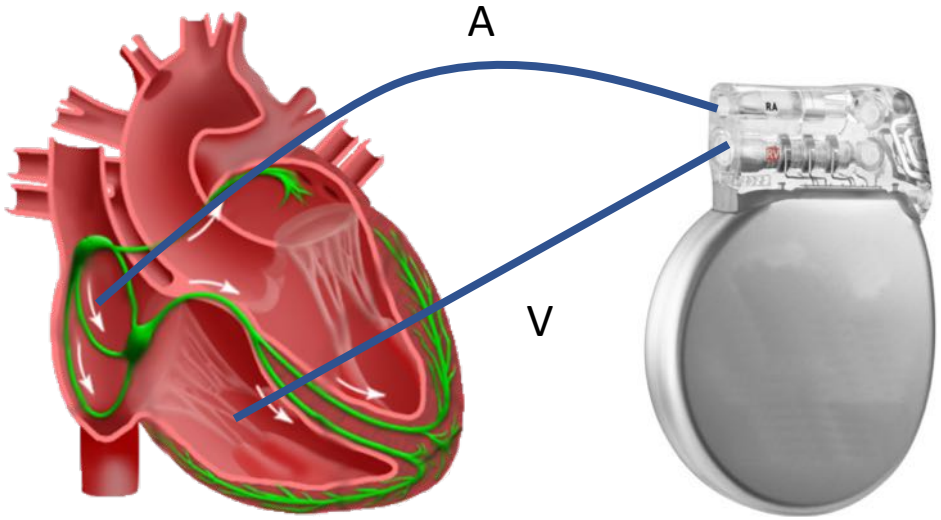


- Add a Post-Ventricular Atrial Refractory Period (PVARP)
- Ignore Asense in PVARP

VV <= Lower Rate Interval
VPace when Atrio-Ventricular Interval (AVI) expires
VA <= LRI – 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 <= Lower Rate Interval
VPace when Atrio-Ventricular Interval (AVI) expires
VA <= LRI – AVI
Ignore Vsense in Ventricular Refractory Period (VRP)
Ignore Asense 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, occuring 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

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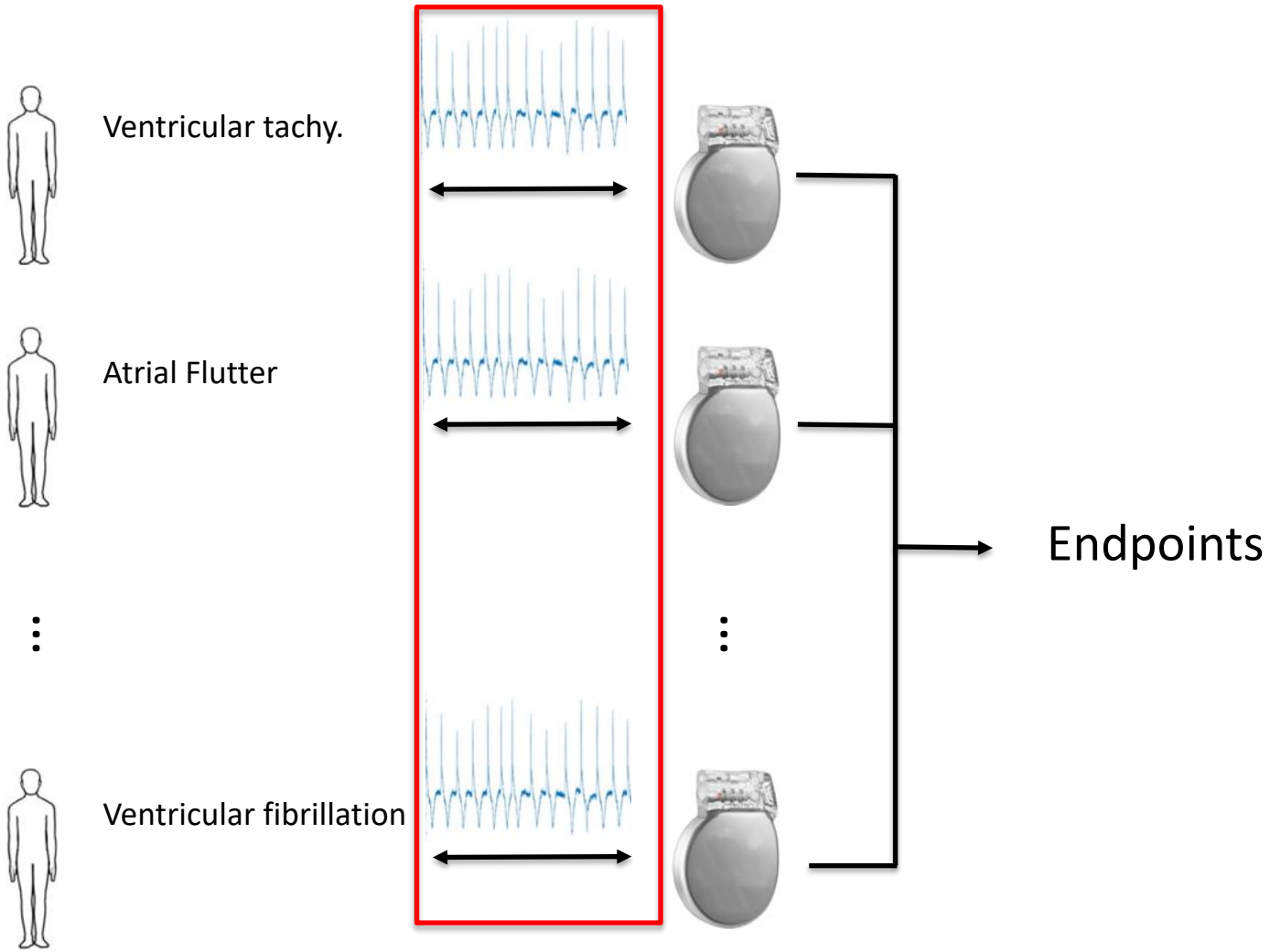
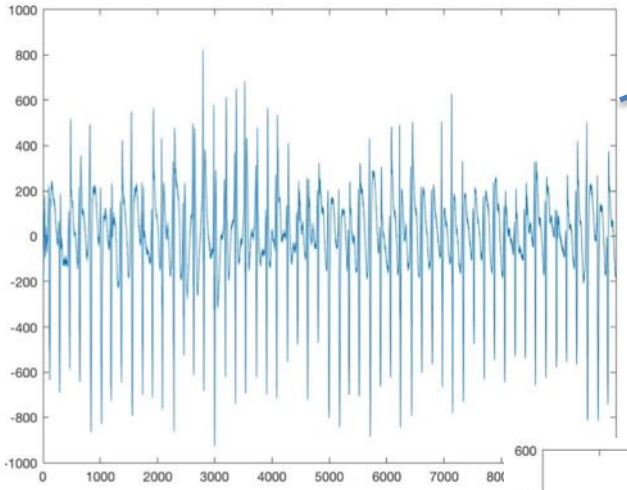
NO! "cheap" and "expensive" must be measured relative to what you are providing. 10 simulations are very cheap compared to running a model checker – but what do you learn from 10 simulations? Nothing!

Need: a model of device inputs



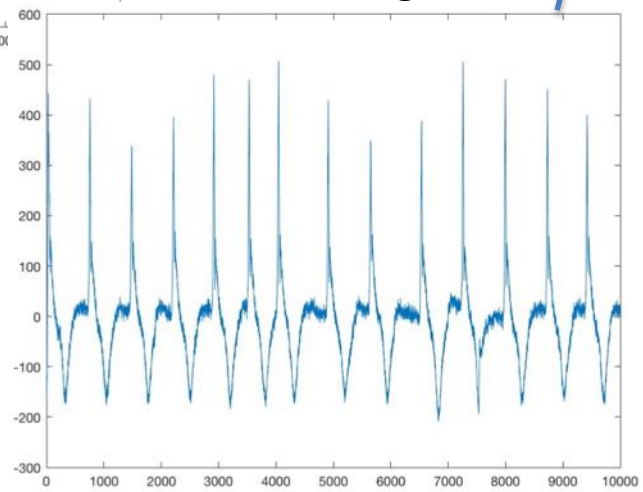
Need: a model of device inputs

Inputs to pacemaker are intra-cardiac electrograms



Atrial signal

Ventricular signal



The heart as a timed automaton

(Next lecture)