The Co-Simulation of a Cardiac Pacemaker using VDM and 20-sim

Carl Gamble, Martin Mansfield, John Fitzgerald
(Centre for Software Reliability, Newcastle University, UK)

Co-simulation of a Cardiac Pacemaker

1. Motivation
2. Co-model Development Approaches
3. Heart Modelling
4. Pacemakers and Co-Model
5. Simulation Results
6. Future Directions

Motivations for DESTECS

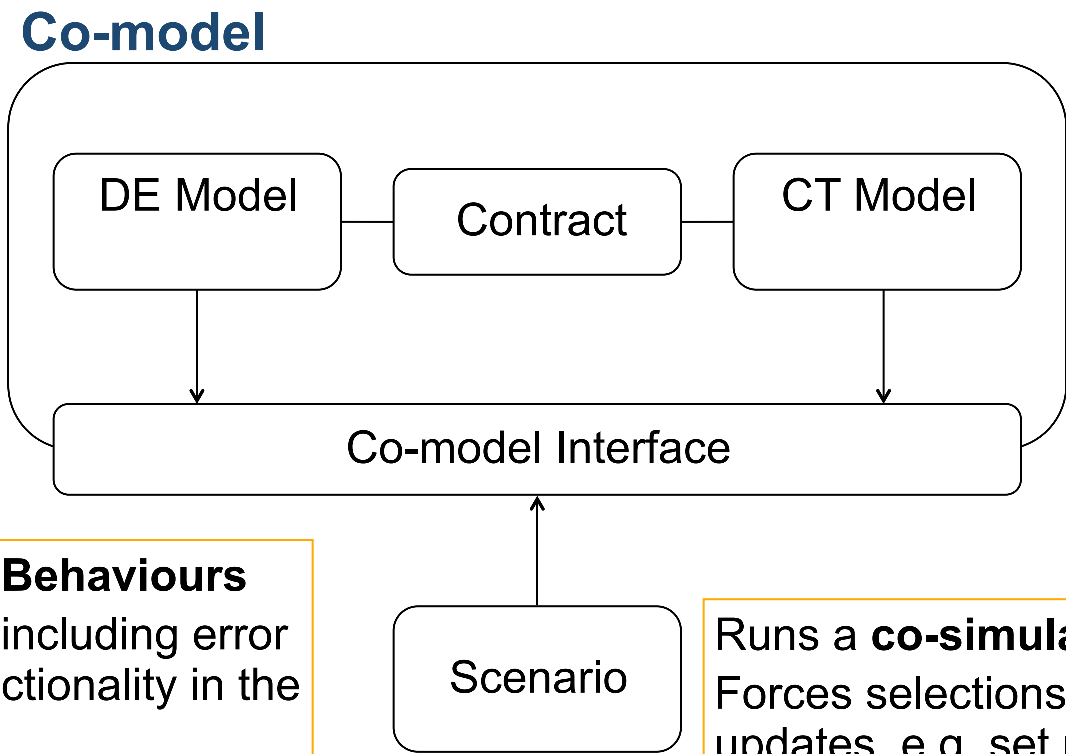
- Demanding requirements for:
  - Rapid development in competitive markets
  - Resource utilisation
  - Resilience
    - Complexity of error detection and recovery
- The need for coordinated engineering:
  - Across disciplines (cultures, abstractions, formalisms)
  - ... and models.

DESTECS Approach

(www.destecs.org)

- Bridge disciplines through co-simulation
  - Combine DE controller models and CT plant models
  - Collaboration while working with familiar formalism
- Develop methods and tools
  - Linking heterogeneous models, each in an appropriate formalism
  - A linking co-simulation engine, based on a reconciled operational semantics of the two simulations
- Patterns for modelling faults and fault tolerance mechanisms

Basic DESTECS Concepts



Ideal & Realistic Behaviours

Fault Modelling: including error states & faulty functionality in the model

Fault Injection during a simulation managed by script

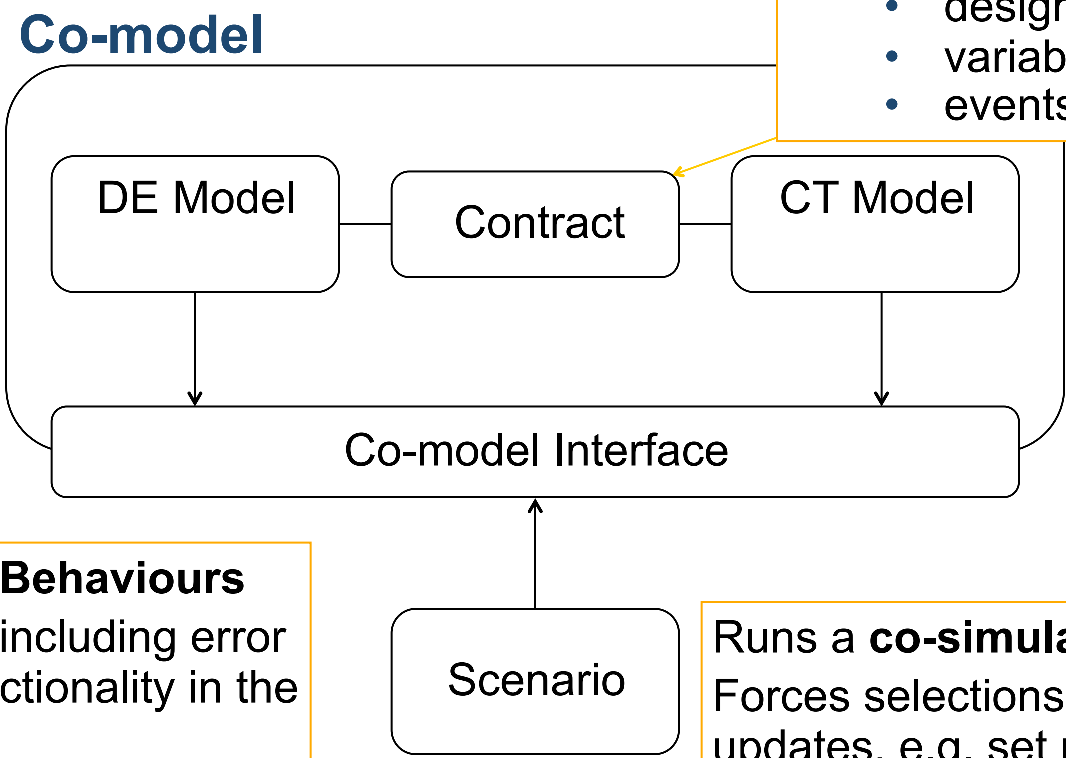
Runs a **co-simulation**

Forces selections and external updates, e.g. set point

Multiple co-simulation runs enables design space exploration

Basic DESTECS Concepts

Shared
- design parameters
- variables
- events



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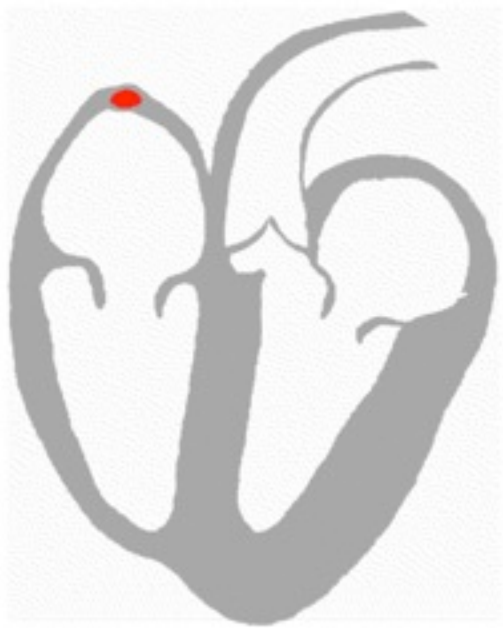
Co-model Development Approaches

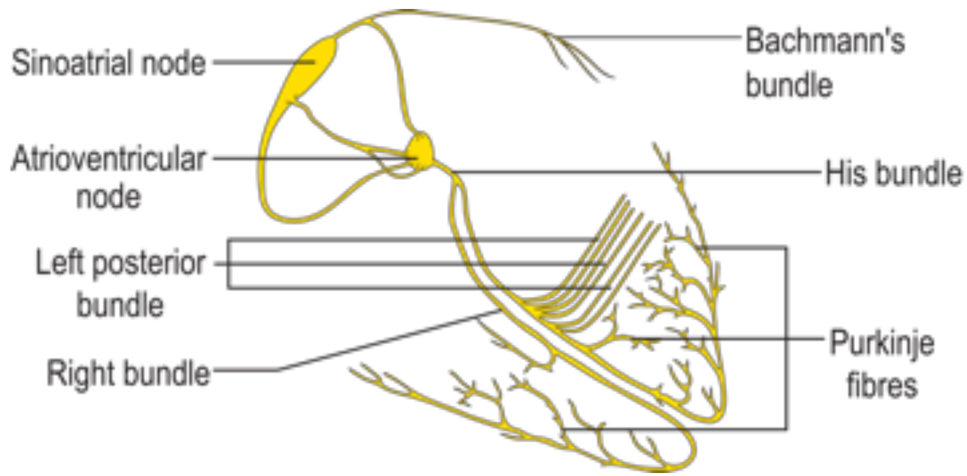
Approach	Pros	Cons	Use where ...
DE-first	• Complex controller behaviour early	• Plant dynamics over-simple; • Loop controllers not tuned; • Envt. model complexity	• Complex DE control is priority; • Legacy DE; • Mainly DE modellers
CT-first	• Plant dynamics early; loop controllers tuned	• Complex DE control not easily studied	• Plant/envt needs priority; • Legacy CT; • Mainly CT modellers
Contract-first	• Co-model from beginning; constituents co-evolve	• Constituents mutually dependent for test; restricted to tool-prescribed design	• Basic co-model can be quickly built;
Hybrid Contract-first	• Co-model early; • Constituents not mutually dependent for test	• Extra effort building constituents	•Start-up cost of basic contract-first is high •Integration of two legacy models needed

Electrophysiological Abstraction of the Heart

Images from: http://en.wikipedia.org/wiki/Electrical_conduction_system_of_the_heart

Electrophysiological Abstraction of the Heart





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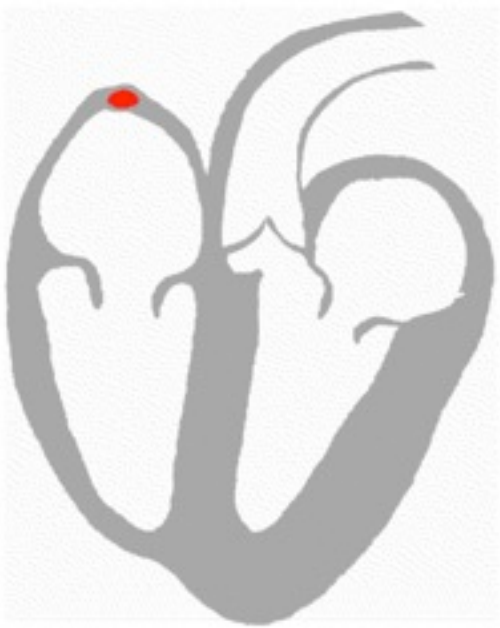

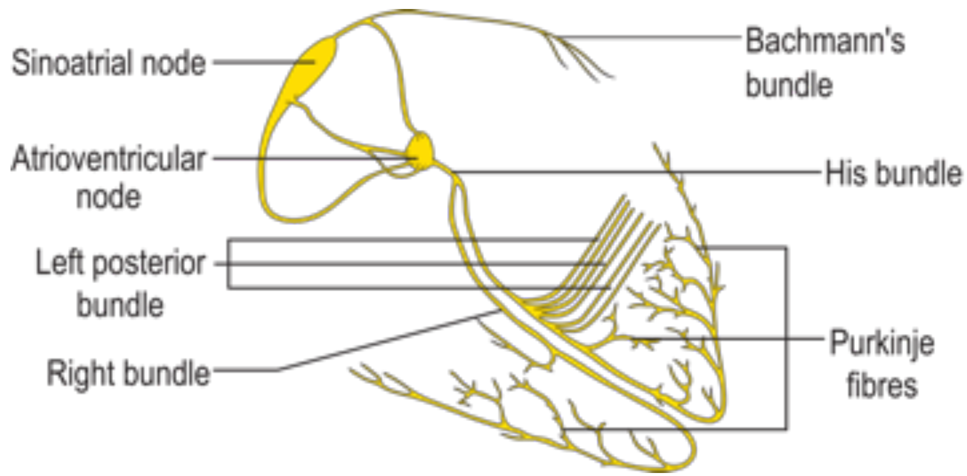

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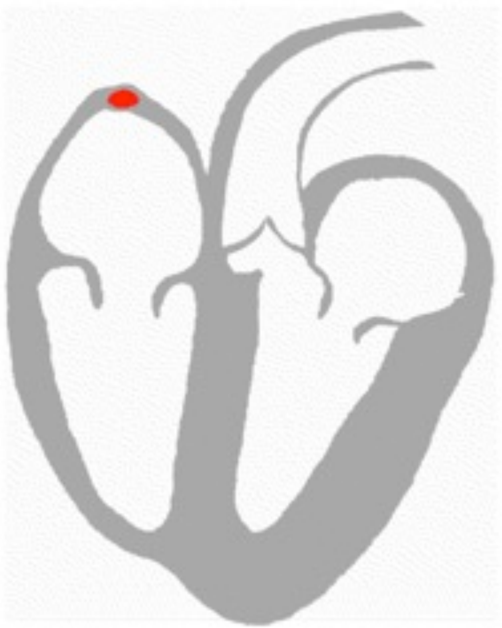
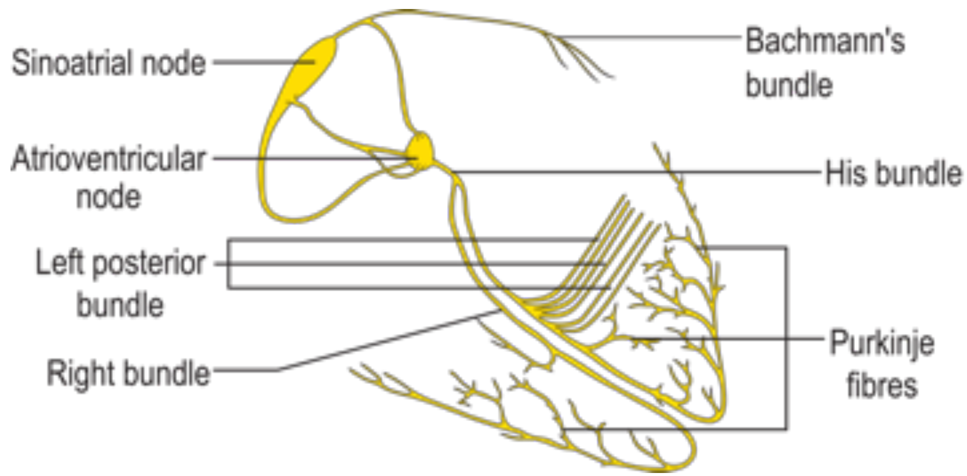




Heart Defects:

- Sinus Bradycardia: SA node fires too slowly
- Third Degree AV Block: Action potential does not reach AV node

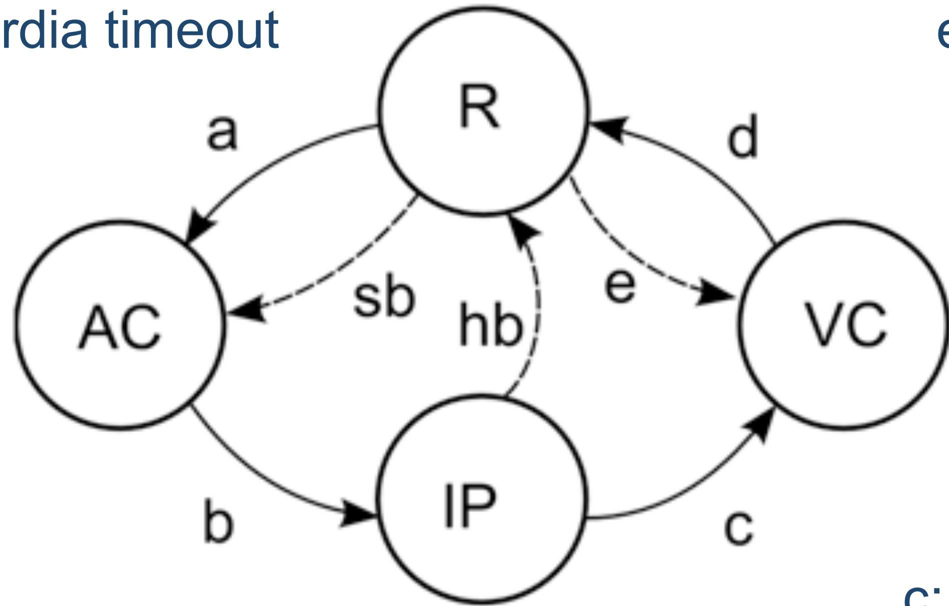
Images from: http://en.wikipedia.org/wiki/Electrical_conduction_system_of_the_heart

Modelling the Heart DE-first (VDM)

R: resting

a: SA node timeout
sb: sinus bradycardia timeout

d: ventrical contraction ends
e: AV node timeout



AC: atrial contraction

VC: Ventrical contraction

b: atrial contraction ends

c: charge conducted
hb: heart block present

IP: Internodal pathway

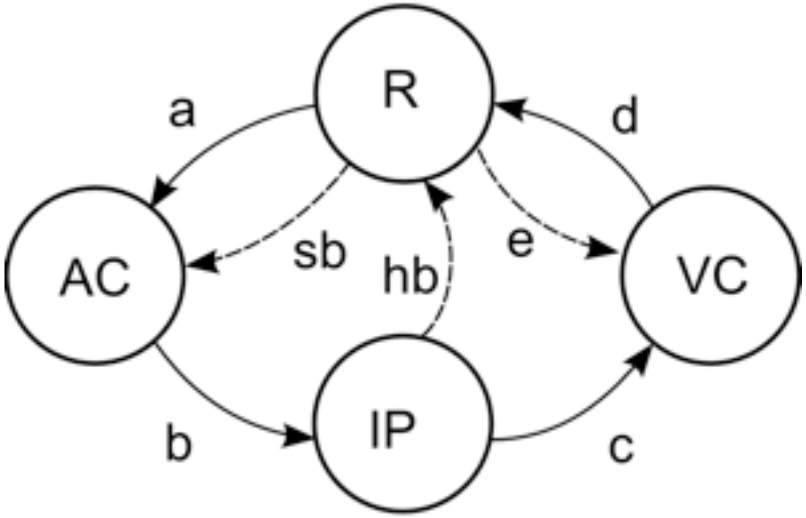
Initial Heart Approximation (VDM-SL)

VDM-SL state transition model using simple timers

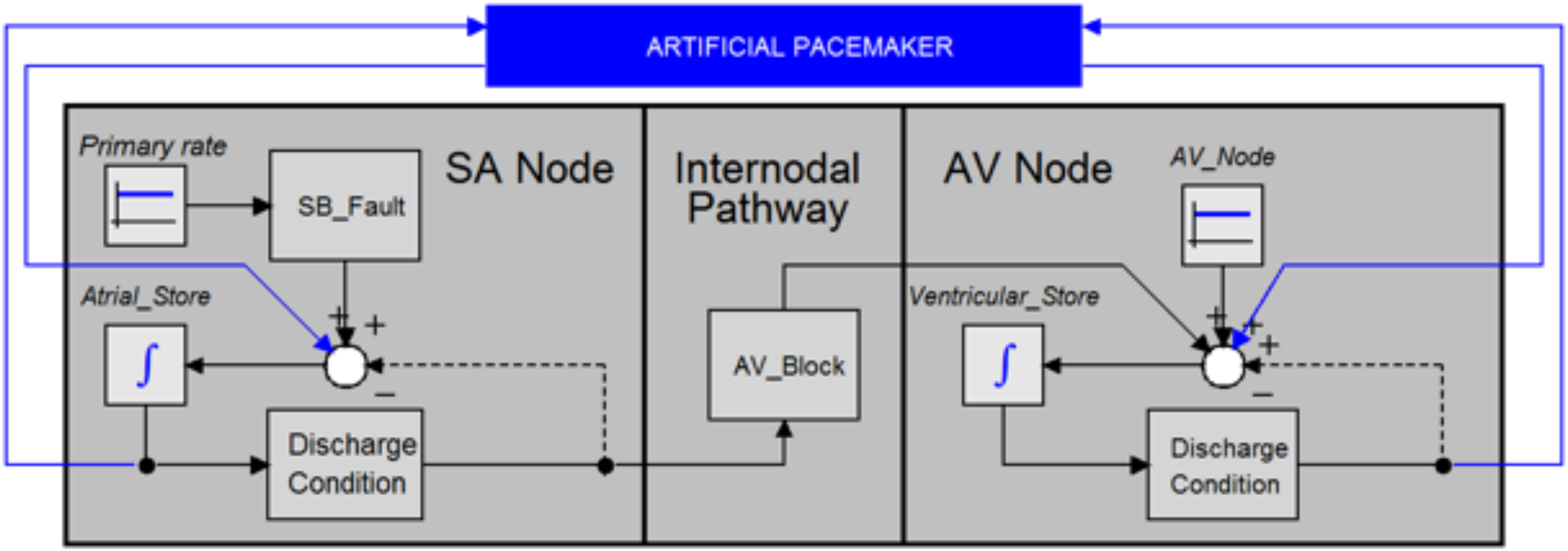
```
operations
 ProgressModel: () ==> Process
 ProgressModel() == (
    if cycle.stage = <Resting> then (
       if nodes.SA = 0 then EnterStage(<Atrial_Contraction>);
       else  if nodes.AV = 0 then EnterStage(<Ventricular_Contraction>);)
    else (
       if cycle.timer = 0 then ProgressStage();
    );

    Decrement_All_Timers();
    return cycle.stage;
 );

 …
```



Modelling the Heart (20-sim)



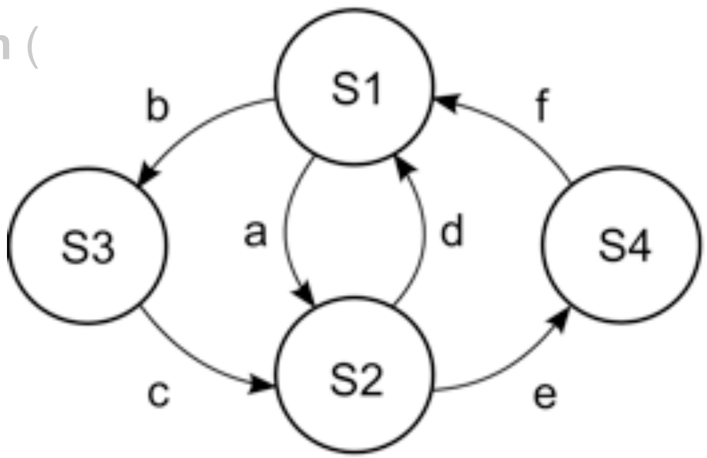
- Nodes modelled as capacitors with discharge conditions
- Faults activated via global variables

Initial Pacemaker Description (VDM-SL)

```
ProgressModel: () ==> Activity
ProgressModel() == (
   Update_Timers();

   if settings.a_sensed then (
         if Detect_Atrial_Stimulation() then A_Stimulated();
         if Atrial_Timeout() and settings.a_paced then (
            Stimulate_A();
            return “Delivered Atrial Stimulation";)
         else (
            if AV_Timeout() and settings.triggered then (
            Stimulate_V();
            return "Ventricular Stimulation";
         );
   );
…
```

VDM-SL state transition model using simple timers

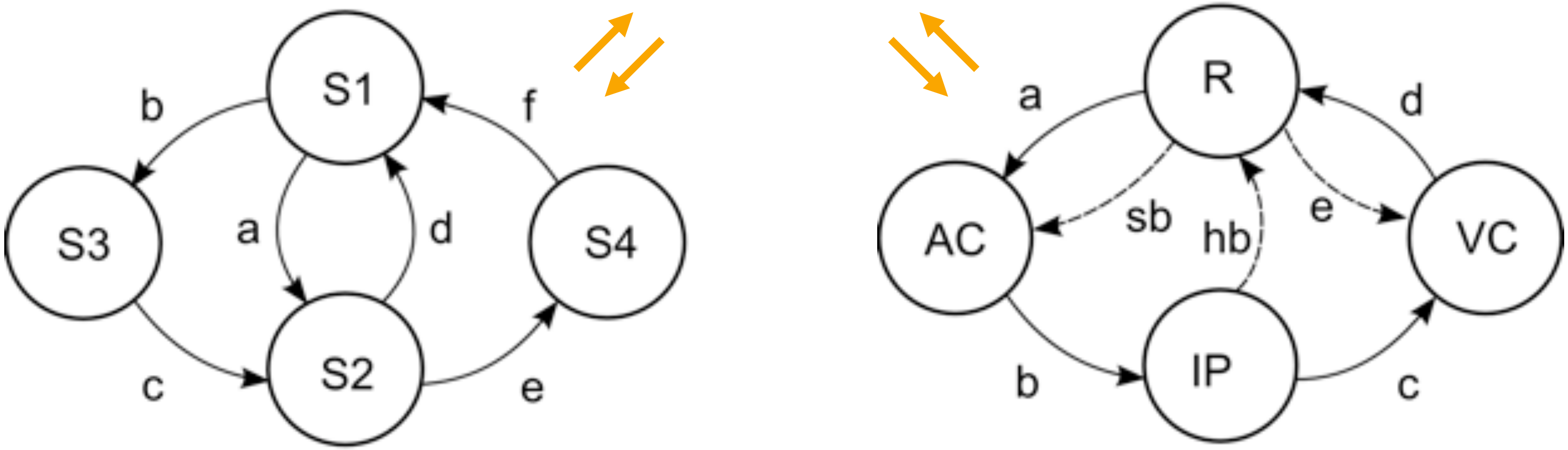


Simulating DE only Progression

DE Simulator (VDM-SL)

```
while(Active(t)) do (
  dcl stage       : Heart`Process        := DE_Heart`ProgressModel();
  dcl feedback : Pacemaker`Activity := Pacemaker`ProgressModel();

  if (feedback <> [] or StateChange(stage)) then Record_Data(t,stage,feedback);
  t := t + 1;
);
```



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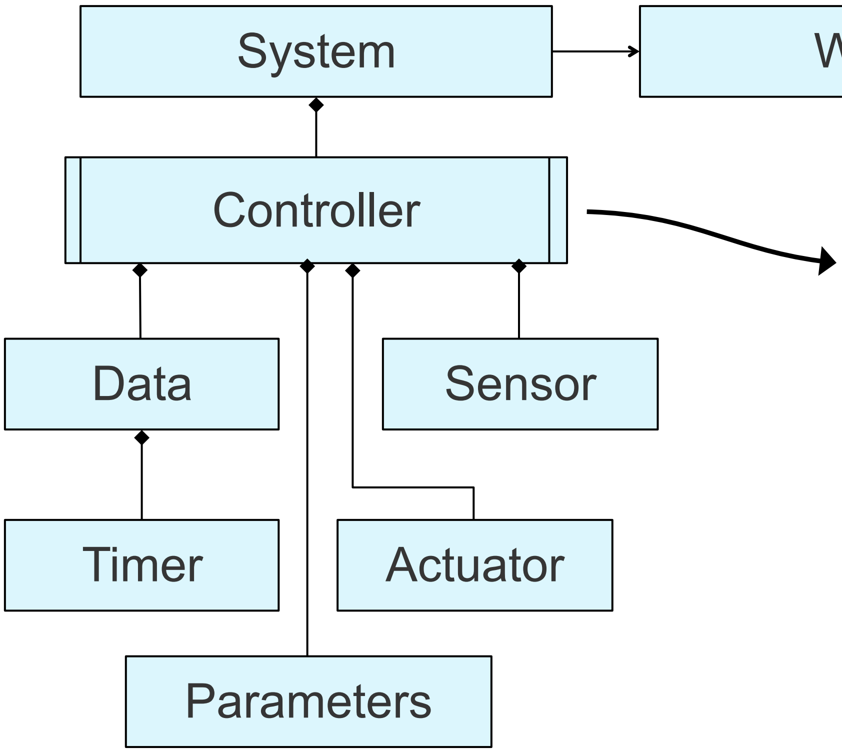
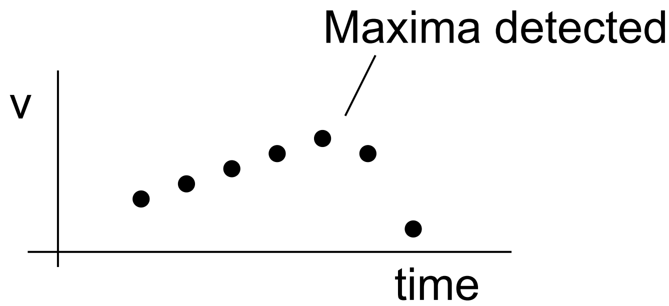
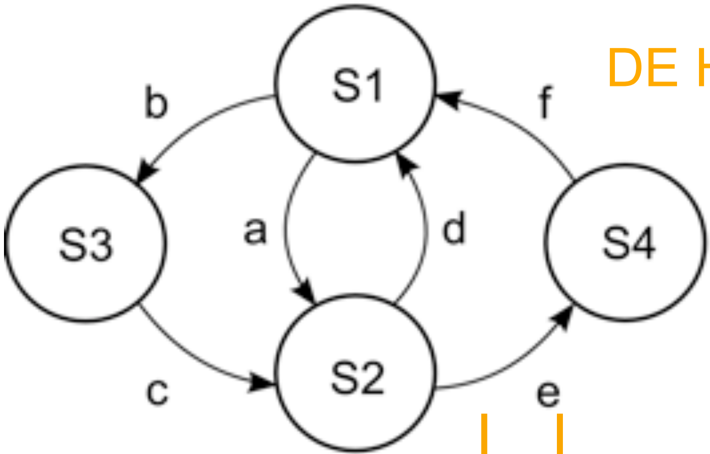
Translating Pacemaker to VDM-RT



- -- 1000Hz
  thread periodic(1E6,0,0,0)(Step);
- 

- -- Interact with external heart model to stimulate ventricals
  V_out.Fire(1500);

Establishing a Co-model

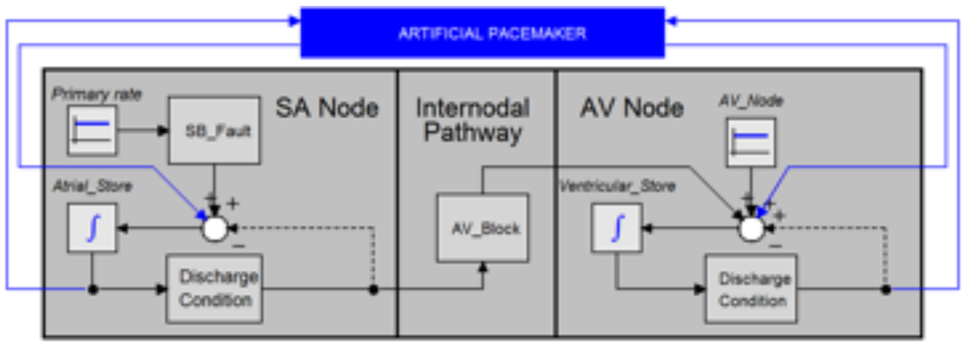


DE Heart Model (VDM-RT)

Co-model Contract

SA Charge
AV Charge
SA Pacing
AV Pacing

CT Heart Model (20-sim)



Results of DE First Model

Results of DE First Model

Normal heart trace

Time	Stage	Action
858	<Atrial_Contraction>	[]
938	<AV_Distribution>	[]
1058	<Ventricular_Contraction>	[]
1118	<Resting>	[]
1795	<Atrial_Contraction>	[]
1875	<AV_Distribution>	[]
1995	<Ventricular_Contraction>	[]
2055	<Resting>	[]
2732	<Atrial_Contraction>	[]
2812	<AV_Distribution>	[]
2932	<Ventricular_Contraction>	[]
2992	<Resting>	[]

Results of DE First Model

Normal heart trace

Time	Stage	Action
858	<Atrial_Contraction>	[]
938	<AV_Distribution>	[]
1058	<Ventricular_Contraction>	[]
1118	<Resting>	[]
1795	<Atrial_Contraction>	[]
1875	<AV_Distribution>	[]
1995	<Ventricular_Contraction>	[]
2055	<Resting>	[]
2732	<Atrial_Contraction>	[]
2812	<AV_Distribution>	[]
2932	<Ventricular_Contraction>	[]
2992	<Resting>	[]

Trace with heart block active

Time	Stage	Action
858	<Atrial_Contraction>	[]
938	<AV_Distribution>	[]
1058	<Resting>	[]
1069	<Resting>	Ventricular Stimualtion
1070	<Ventricular_Contraction>	[]
1130	<Resting>	[]
1795	<Atrial_Contraction>	[]
1875	<AV_Distribution>	[]
1995	<Resting>	[]
2006	<Resting>	Ventricular Stimualtion
2007	<Ventricular_Contraction>	[]
2067	<Resting>	[]

Results of Co-simulation

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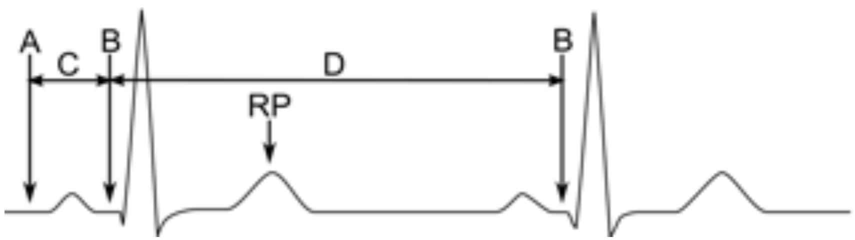
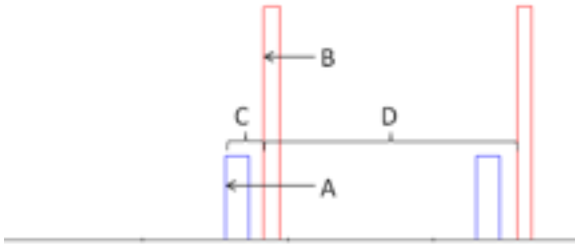
Comparison of real and simulated ECG





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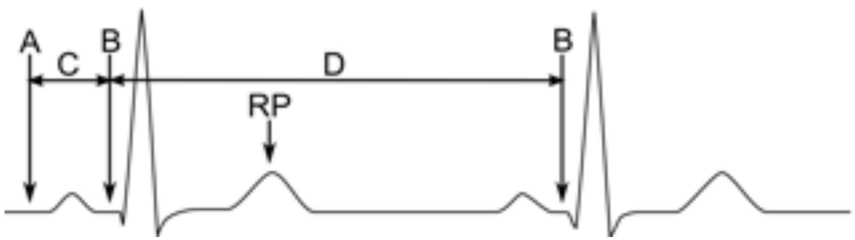
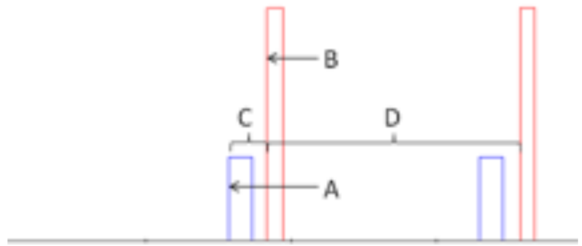
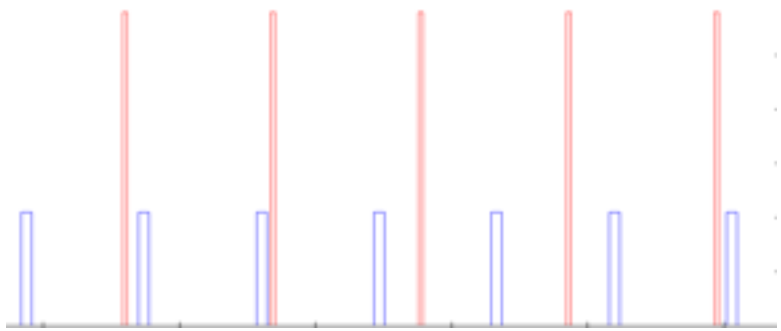




Simulated ECG with heart block



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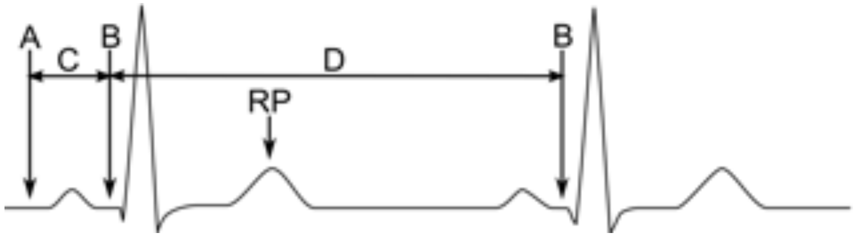

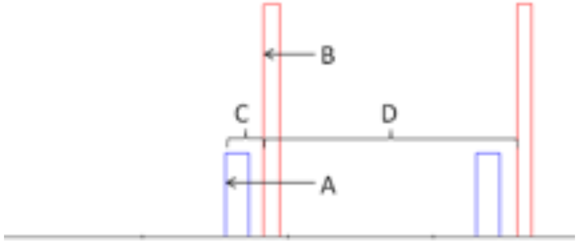

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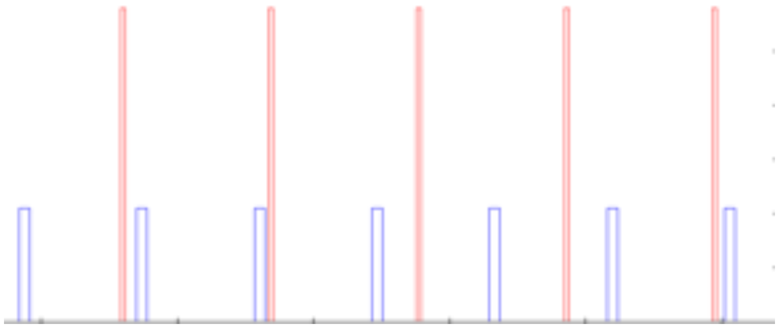
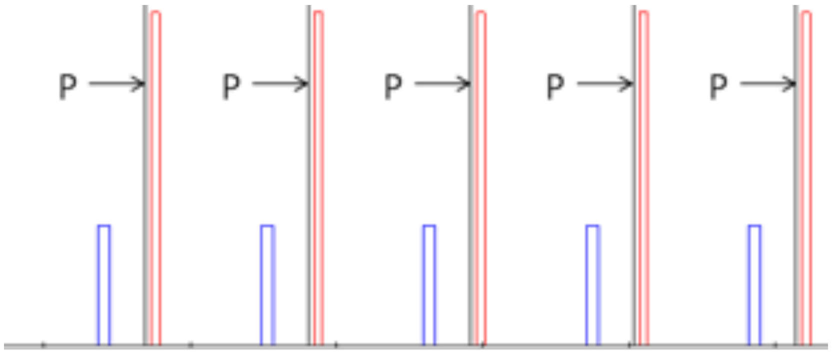


Simulated ECG with heart block and pacing



Future Directions

- Fidelity of heart model (output traces and response)

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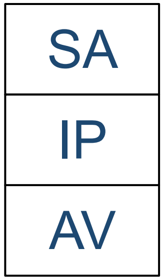
Nodes only



Key
SA – Sinoatrial node
IP – Internodal pathway
AV – Atrioventricular node
MC – Myocardia
PF – Purkinje fibres

Future Directions

- Fidelity of heart model (output traces and response)

Nodes only	Nodes and single myocardia
SA	SA
IP	MC
AV	IP
	AV
	MC

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SA – Sinoatrial node
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Future Directions

- Fidelity of heart model (output traces and response)

Nodes only

SA
IP
AV

Nodes and single myocardia

SA
MC
IP
AV
MC

Nodes, pathways and multiple myocardia (finite element)

MC	SA	MC
MC	IP	MC
MC		MC
	AV	
MC	PF	MC
MC		MC
MC		MC
MC	MC	MC

Key
SA – Sinoatrial node
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- Heart conditions modelled
  - Heart block types 1 and 2
  - Atrial Fibrilation
  - Atrial Tachycardia
  - ....

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  - Heart block types 1 and 2
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  - Atrial Tachycardia
  - ....
- Fault modelling
  - Signal noise on sensing leads
  - Imperfect stimulation
- Pacing behaviours
  - All heart conditions/modes
  - Lead noise tolerance
  - Accelerometers

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