

CirculationModels.jl - Reproducible, Modular Lumped Parameter Systems For Personalisation

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Objectives

1. In circulatory mechanics, lumped parameter (0D) modelling offers the unique ability to examine both cardiac function and global hemodynamics within a single model.
2. Due to the interconnected nature of the cardiovascular system, being able to quantify both is crucial for the prediction and diagnosis of cardiovascular diseases.
3. We establish a computationally efficient, modular, reproducible, open source modelling framework, which is understandable by domain experts and includes accessible analysis of lumped parameter models.

Materials

- ▶ Currently lumped parameter circulatory models are constructed through hand-derived ODEs which are often hard to understand.
- ▶ We create a framework in which domain experts define simple connect statements between compartments opening modelling to domain experts.
- ▶ Built on ModellingToolkit.jl we will build a hierarchical acausal component-based model applying the Kirchoff laws between each components.
 - ▷ CirculationModels.jl seamlessly integrates with the SciML ecosystem.
 - ▷ SciML contains tools for sensitivity analysis, uncertainty quantification and more.
 - ▷ All tools have a similar use-able common API structure
 - ▷ This reproducible approach can aid clinical decisions and diagnosis.

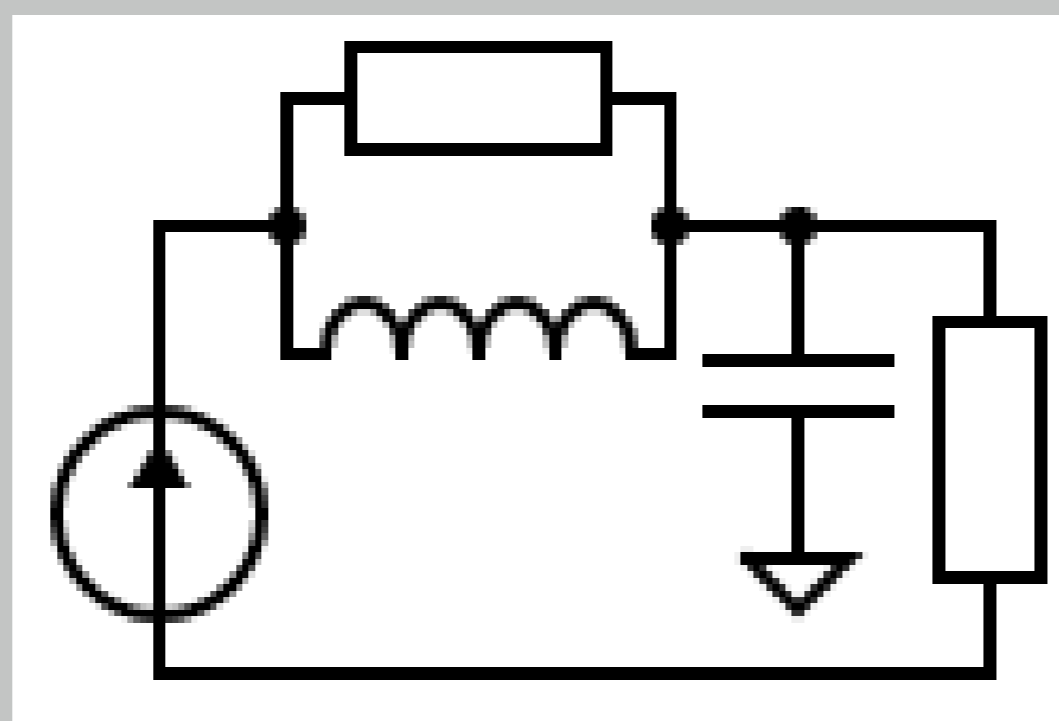


Figure 1: A 4 element windkessel model representing the arterial network [1].

Methods

```
using CirculationModels #Load the julia pkg

@named Rc = Resistor(R=R.c) #Characteristic resistance
@named Rp = Resistor(R=R.p) #Peripheral resistance
@named C = Capacitor(C=C_) #Capacitance
@named L = Inductance(L=L_) #Inertia
@named source = DrivenCurrent(I=1.0, fun=I.sin)
# Flow into arterial network
@named ground = Ground()

circ_eqs = [
    connect(source.out, Rc.in, L.in)
    connect(Rc.out, L.out, C.in, Rp.in)
    connect(Rp.out, C.out, source.in, ground.g)
]
# Here we connect the pins of the network

_circ_model = ODESystem(circ_eqs, t)
# Declare an ode system dependent on t

circ_model = compose(_circ_model, [L, Rc, Rp, C, source,
ground])
# Specify equations and component names

circ_sys = structural_simplify(circ_model)
# Simplify equations

prob = ODAEProblem(circ_sys, u0, (0, 30.0))
# ODAE allows us to only specify u0 the length of the
number of odes

sol = solve(prob)
#Solve the system

plot(sol, idxs=[C.in.p, C.in.q, Rc.q], tspan=(28, 30))
```

Complex Model

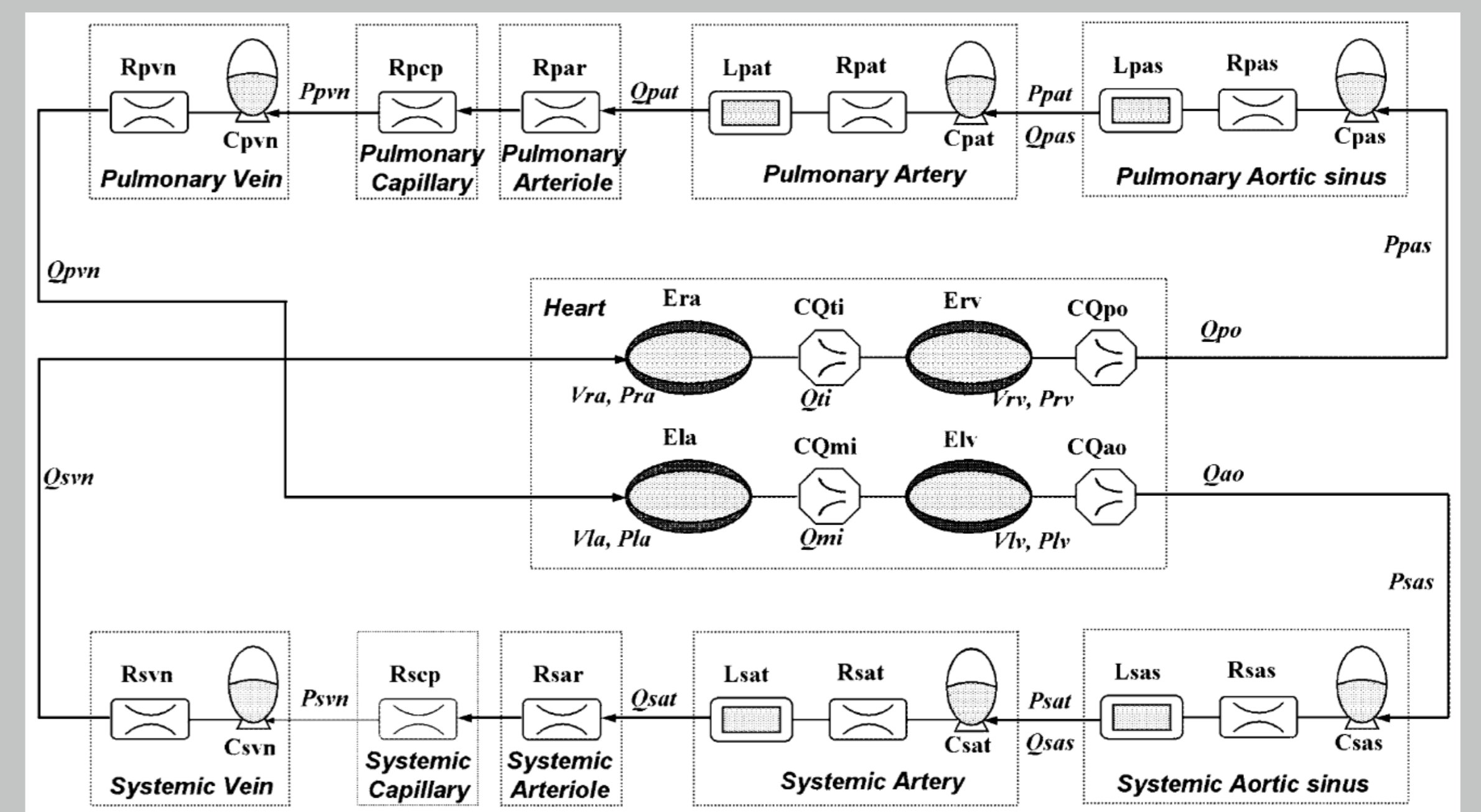


Figure 2: Full circulatory lumped parameter model from Shi et al. 2006 [2].

Results: Comparison Of Methods

- ▶ We compare the CirculationModels.jl to other open-source implementations of figure 2.
- ▶ We examine the length of code in lines and also the time to simulate 20 cardiac cycles in seconds.
- ▶ The other implementations are taken from the open source CellML Physiome Project [3]. CellMLToolkit.jl is a Julia package which allows the user to import a CellML model as it is on the repository.

Language	Length of code	Time to simulate
Python	410	42.4 (s)
Matlab	449	12 (s)
CellMLToolkit.jl	3	0.070 (s)
CirculationModels.jl (23 - 88)		0.044 (s)

Table 1: Comparison of Shi et al. model implementations

- ▶ The line length varies for CirculationModels.jl as we flexibly allow the user to specify every compartment or just focus on the parameterization.
- ▶ CellMLToolKit.jl restricts the user in not allowing them to easily specify parameters in the conventional way.

CirculationModels.jl	CellMLToolkit.jl	Matlab	Python
1x	1.6x	272.7x	963.6x

Table 2: Comparison of the time to simulate Shi et al.

- ▶ The model simulation generated by CirculationModels.jl is taken to be the one which we compare the times to simulate from

Conclusion

- ▶ We have developed a lumped parameter modelling framework which is efficient, modular, reproducible and inclusive.
- ▶ We are the first modelling framework in which domain experts can play an active role within model development. As they do not require an in-depth knowledge of ODE/DAE systems.
- ▶ The speed ups along with the seamless integration to the SciML system means model analysis on such complex systems is now possible and not limited to the number of parameters.

References

- [1] Nikos Stergiopoulos, Berend E Westerhof, and Nico Westerhof. Total arterial inductance as the fourth element of the windkessel model. *American Journal of Physiology-Heart and Circulatory Physiology*, 276(1):H81-H88, 1999.
- [2] Theodosios Korakianitis and Yubing Shi. Numerical simulation of cardiovascular dynamics with healthy and diseased heart valves. *Journal of biomechanics*, 39(11):1964-1982, 2006.
- [3] Catherine M Lloyd, Matt DB Halstead, and Poul F Nielsen. Cellml: its future, present and past. *Progress in biophysics and molecular biology*, 85(2-3):433-450, 2004.

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