$q \rightarrow$ quantity $\begin{cases} m \rightarrow \text{mechanics} \\ \text{mole and entropy} \rightarrow \text{bio chemistry \& heat flow} \\ \text{columb and candela} \rightarrow \text{electromagnetism} \\ \end{cases}$

~~potential~~

$\vartheta = \frac{dq}{dt} = \dot{q} \rightarrow$ flow

$\mu \rightarrow$ potential $= \frac{\text{Joules}}{\text{quantity}}$

$[\vartheta] = \left[\frac{J}{\text{quantity} \cdot s}\right]$

$q \rightarrow$ can be stored in 'capacitor'

$$\begin{cases} \mu = E q \rightarrow \text{capacitor} \\ \mu = L a = R \vartheta \rightarrow \text{inductor} \\ \vartheta = \underbrace{\frac{1}{R}}_{K} \mu \rightarrow \text{Resistance} \end{cases}$$

$a = \frac{d\vartheta}{dt} =$ شتاب جریان $= \frac{d^2q}{dt^2}$

$$\begin{tikzcd} q \arrow[r, "\frac{d}{dt}"] \arrow[dr, "E"'] & \vartheta \arrow[r, "\frac{d}{dt}"] \arrow[d, "R"] & a \arrow[dl, "L"] \\ & \mu & \end{tikzcd}$$

$$\begin{cases} F = ma \rightarrow a = \frac{dv}{dt},\ v = \frac{dx}{dt} \\ V = L\frac{di}{dt} \end{cases}$$

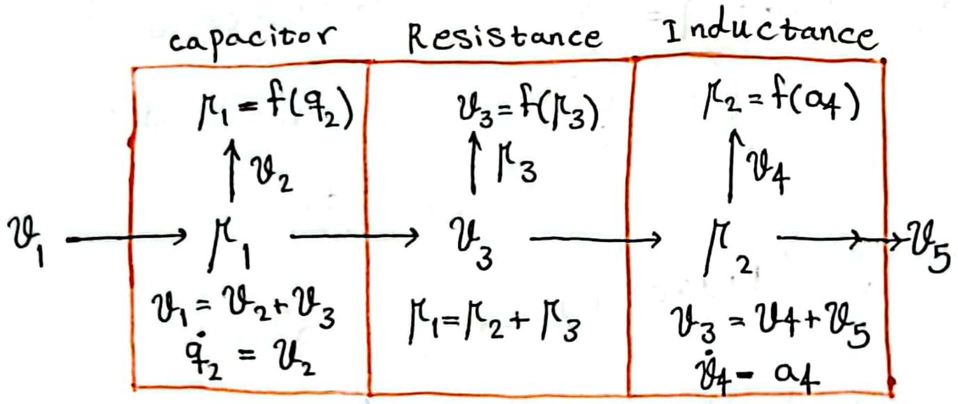
$q = x$

$i = v \rightarrow q \rightarrow$ charge

$\boxed{L \equiv m}$

$$\begin{cases} p = \int \mu \, dt \\ p = L \vartheta \end{cases}$$

mass in mechanics



BG = Bond Graph

$\sum \mu_i \cdot \vartheta_i = \mu \sum \vartheta_i = 0$

0-nodes

1-nodes

$\sum \mu_i \cdot \vartheta_i = \vartheta \sum \mu_i = 0$

0-nodes

$$\begin{cases} \text{Linear constraint} \rightarrow \text{conservation laws} \\ \text{constitutive laws} \rightarrow \text{nonlinear or Linear} \end{cases}$$

Electrical → Voltage$(J \cdot C^{-1})$ × current$(C \cdot s^{-1})$ = Power$\left(\frac{J}{s}\right)$

Mechanical → force$\left(\frac{J}{m}\right)$ × Velocity$\left(\frac{m}{s}\right)$ = power$\left(\frac{J}{s}\right)$

Hydraulics → pressure$\left(\frac{J}{m^3}\right)$ × Volume flow$\left(\frac{m^3}{s}\right)$ = power$\left(\frac{J}{s}\right)$

Thermodynamis → temperature$\left(\frac{J}{e^{-1}}\right)$ × entropy flow$\left(\frac{e}{s}\right)$ = power$\left(\frac{J}{s}\right)$

$\downarrow \mu$ $\qquad \downarrow \upsilon = \frac{dq}{dt}$ $\qquad \downarrow$ power $= \mu\upsilon$

$q = \{C, m, m^3, e\}$

C ↙ culumb

m ↘ meter

m^3 ↘ Volume

e ↘ entropy

Static Storage (capacitor) → $\boxed{\mu = Eq}$

Elastance $= \frac{1}{C}$ ← ظرفیت خازن

Capacitor → $\int \upsilon\, dt = \int C \frac{d\mu}{dt} dt \rightarrow q = C\mu$

$\boxed{E = \frac{1}{C}}$ → $\boxed{\mu = Eq}$

Dynamic storage (Inductor) → $\boxed{\mu = La}$

inductance

Inductor → $\mu = L\frac{d\upsilon}{dt} = La$

Dissipation (Resistor) → $\boxed{\upsilon = k\mu}$

$k = \frac{1}{R}$

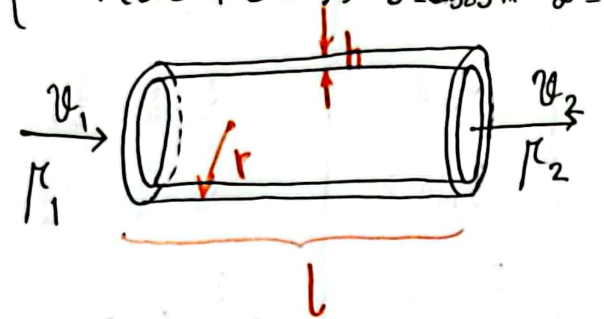
Fluid Dynamics

pressure → $p\ [J/m^3]$, $q = m^3$ Volume , $v = \frac{dq}{dt} = \left[\frac{m^3}{s}\right]$ Volume Rate

$p \cdot v =$ power → $[J/s]$

q ← اضافه حجم براثر اتساع است.

$\left\{ h = r(ae^{br} + ce^{dr}), \quad \begin{matrix} a = 0.28 & c = 0.13 \\ b = 0.505\ m^{-1} & d = -11\ m^{-1} \end{matrix} \right\}$ Watanabe(2013)



$L = \frac{\rho l}{\pi r^2}\ (Js^2/m^6)$ یا I
بعضی جاها

$R = \frac{8\eta l}{\pi r^4}\ (Js/m^6)$

E : modulus E
ضریب الاستیسیته

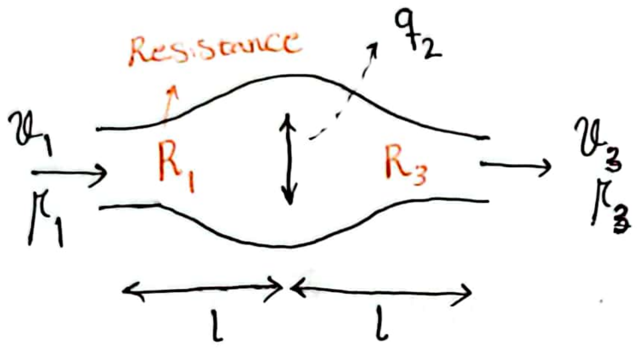
$E = \frac{\varepsilon h}{2\pi r^3 l}$, $C = \frac{1}{E}$

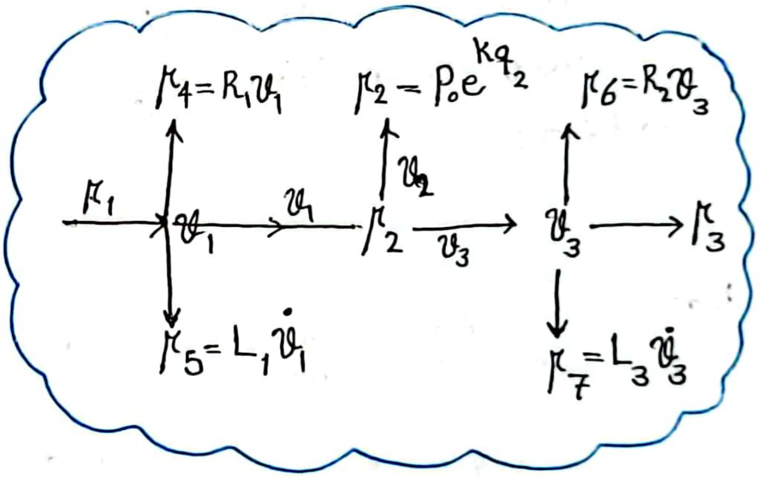
Viscosity ← η

$p = p_0 e^{kq}$

$\boxed{\Delta p = R v}$

فشار در حالتی که $q = 0$ (بدون اتساع)





$p_1 = p_4 + p_5 + p_2$

$v_1 = v_2 + v_3$

$p_2 = p_6 + p_7 + p_3$

$\dot{q}_2 = v_2$

Two Boundary conditions are needed

for example : v_1 , p_3

	name	Solid Mech	Fluid	Biochemical
Potential	μ	force($J/_m$ -N)	$\frac{J}{m^3}$ (pa)	J/mol = M
Quantity	q	m	m^3	M
Flow	$v = \dot{q}$	$\frac{m}{s}$	$\frac{m^3}{s}$	$\frac{M}{s}$
Rate of Flow	$a = \dot{v} = \ddot{q}$	$\frac{m}{s^2}$	$\frac{m^3}{s^2}$	$\frac{M}{s^2}$
Elastance	$E\left(\frac{\mu}{q}\right)$	$J/_{m^2}$	$J/_{m^6}$	$\frac{J}{M} \cdot \frac{1}{M} = \frac{J}{M^2}$
Resistance	$R\left(\frac{\mu}{v}\right)$	$(J/_{m^2}) \cdot s$	$J/_{m^6} \cdot s$	$\frac{J}{M} \cdot \frac{s}{M} = \frac{Js}{M^2}$
Inductance	$L\left(\frac{\mu}{a}\right)$	$\frac{J}{m^3} \cdot \frac{s^2}{m^2} = \frac{Js^2}{m^2}$	$\frac{J}{m^3} \times \frac{s^2}{m^3}$	$\frac{J}{M} \times \frac{s^2}{M} = \frac{Js^2}{M^2}$

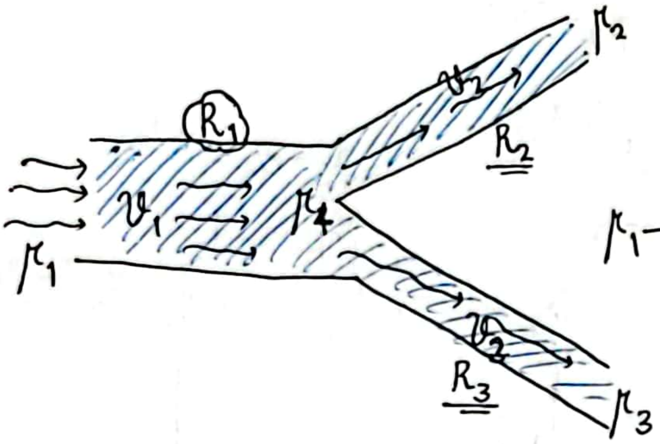
Define a Unit in CellML file:

```
def unit Js2_per_m2 as
    unit joule;
    unit second{expo: 2};
    unit metre{expo:-2};
enddef;
```

$\rightarrow \left[\frac{\text{Joule} \cdot s^2}{m^2}\right]$

note: $\underset{\text{mass}}{1\,kg} = \frac{J}{m^2} s^2$ pressure $= 1\,Pa = \frac{J}{m^3}$

$1\,N = \frac{J}{m}$ Voltage $= \frac{J}{C}$



$$\begin{tikzcd}
 & v_1 = \frac{P_1 - P_4}{R_1} & P_4 = P_0 e^{Kq_4} & v_2 = \frac{P_4 - P_2}{R_2} & \\
P_1 \arrow[r] & v_1 \arrow[u, "P_1 - P_4"'] \arrow[r] & P_4 \arrow[u, "v_4 = \dot{q}_4"'] \arrow[r, "v_2"'] \arrow[d, "v_3"'] & v_2 \arrow[u, "P_4 - P_2"'] \arrow[r] & P_2 \\
 & & v_3 \arrow[r] \arrow[d] & v_3 = \frac{P_4 - P_3}{R_3} & \\
 & & P_3 & &
\end{tikzcd}$$

$$9\ \underline{\underline{\text{par.}}} \left\{ \begin{array}{ll} v_1 & q_4 \\ v_2 & P_1 \\ v_3 & P_2 \\ v_4 & P_3 \\ & P_4 \end{array} \right.$$

$$\left\{ \begin{array}{l} \dot{q}_4 = v_4 \\ P_4 = P_0 e^{Kq_4} \\ v_1 = \dfrac{P_1 - P_4}{R_1} \\ v_3 = \dfrac{P_4 - P_3}{R_3} \end{array} \right.$$

$$v_2 = \frac{P_4 - P_2}{R_2}$$

$$v_1 = v_2 + v_3 + v_4$$

6 equ.

+ 3 B.C.

$$\text{for} \left\{ \begin{array}{l} P_2, P_3, P_1 \\ v_1, v_2, v_3 \end{array} \right.$$

BC = Boundry condition

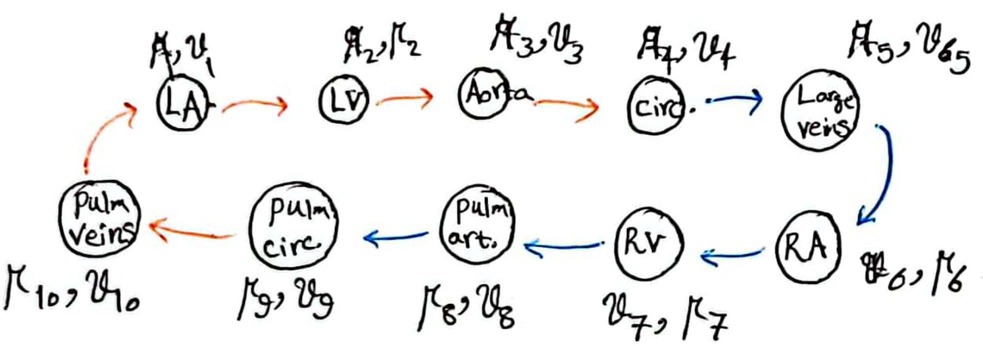
Circulation system:

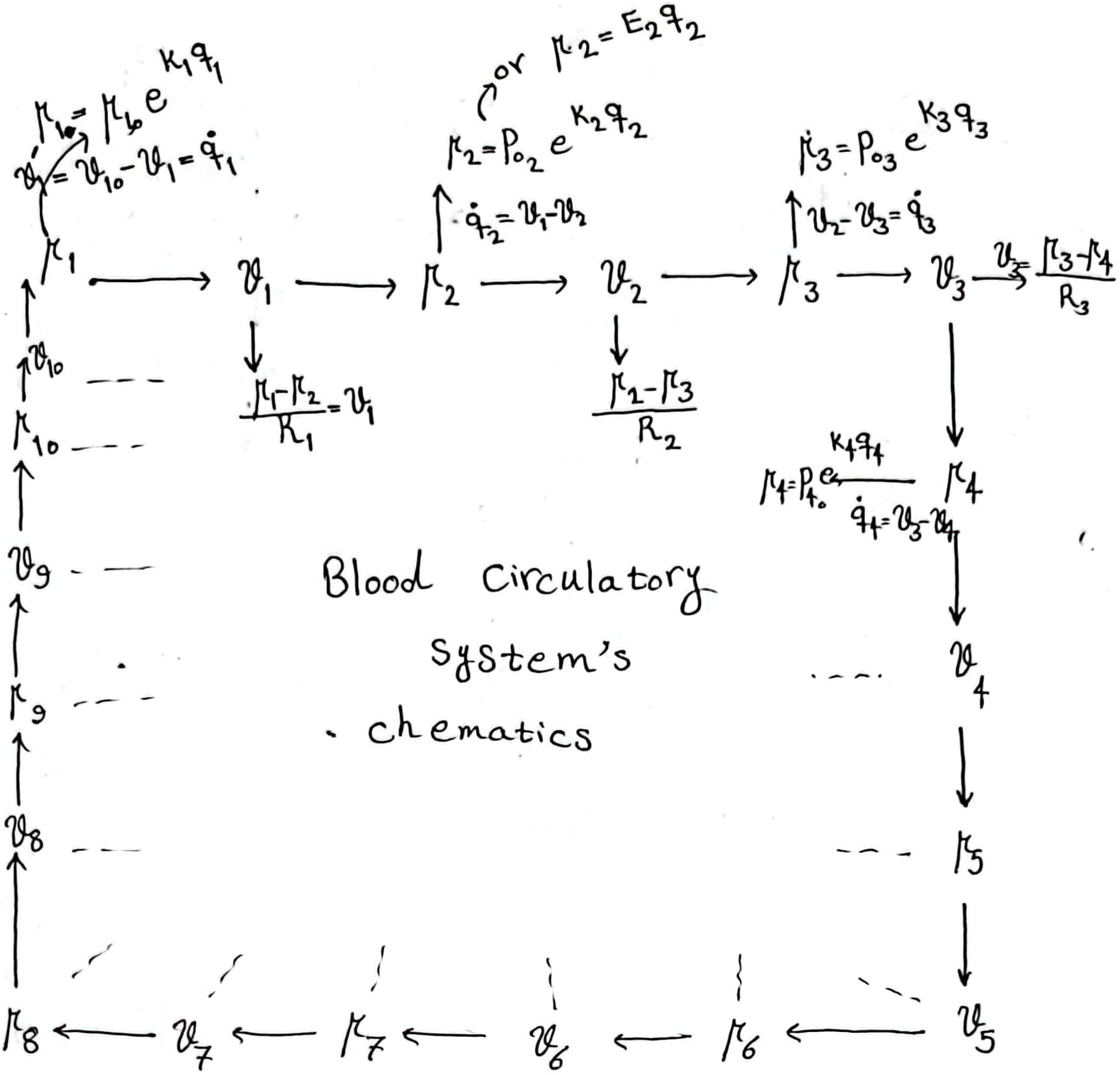
LA : Left Atrium

Lv : Left ventricle

RA : Right Atrium

RV : Right ventricle

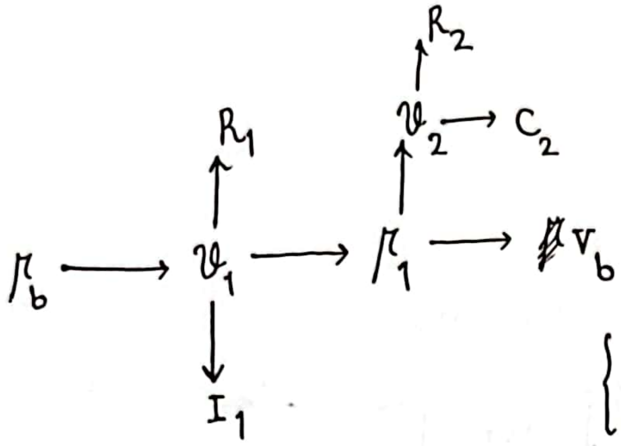


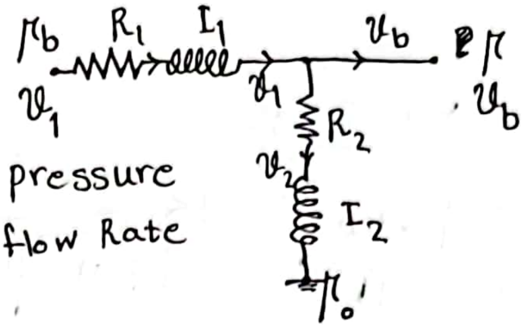


Blood circulatory
system's
chematics

30 equations and 30 variables

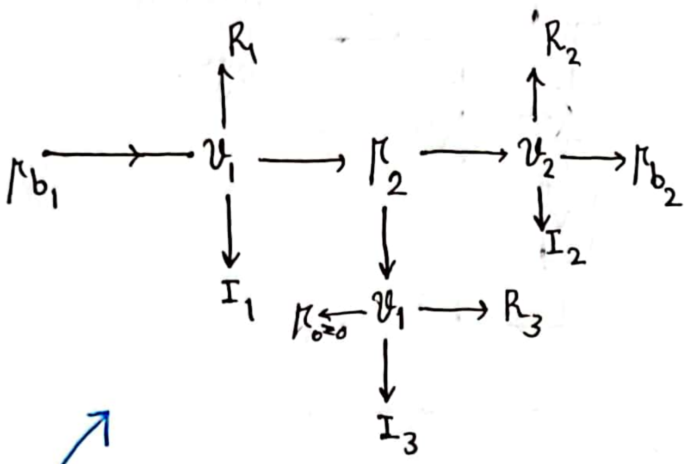
all types of B.C. :

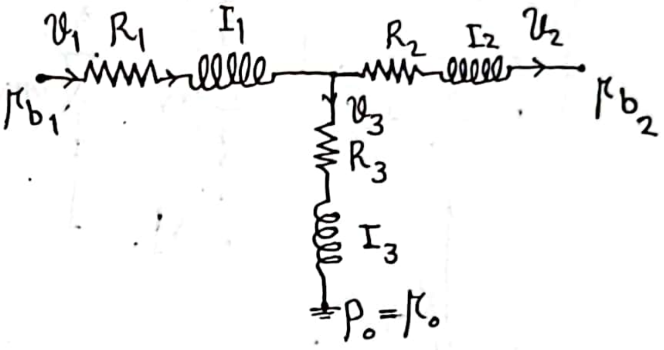




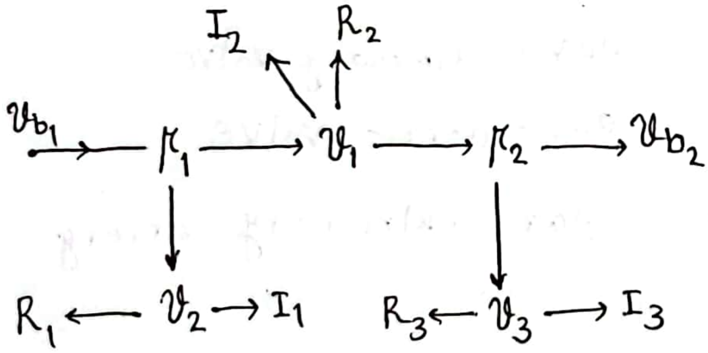
p : pressure
v : flow Rate

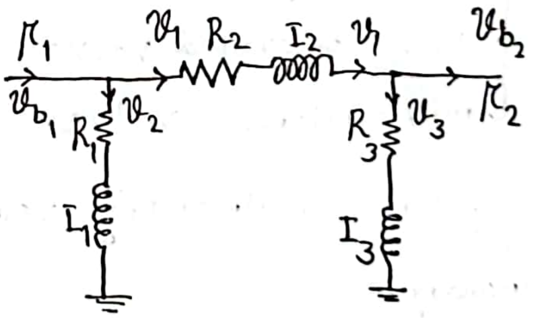
pv type : pressure - ~~current~~ flow



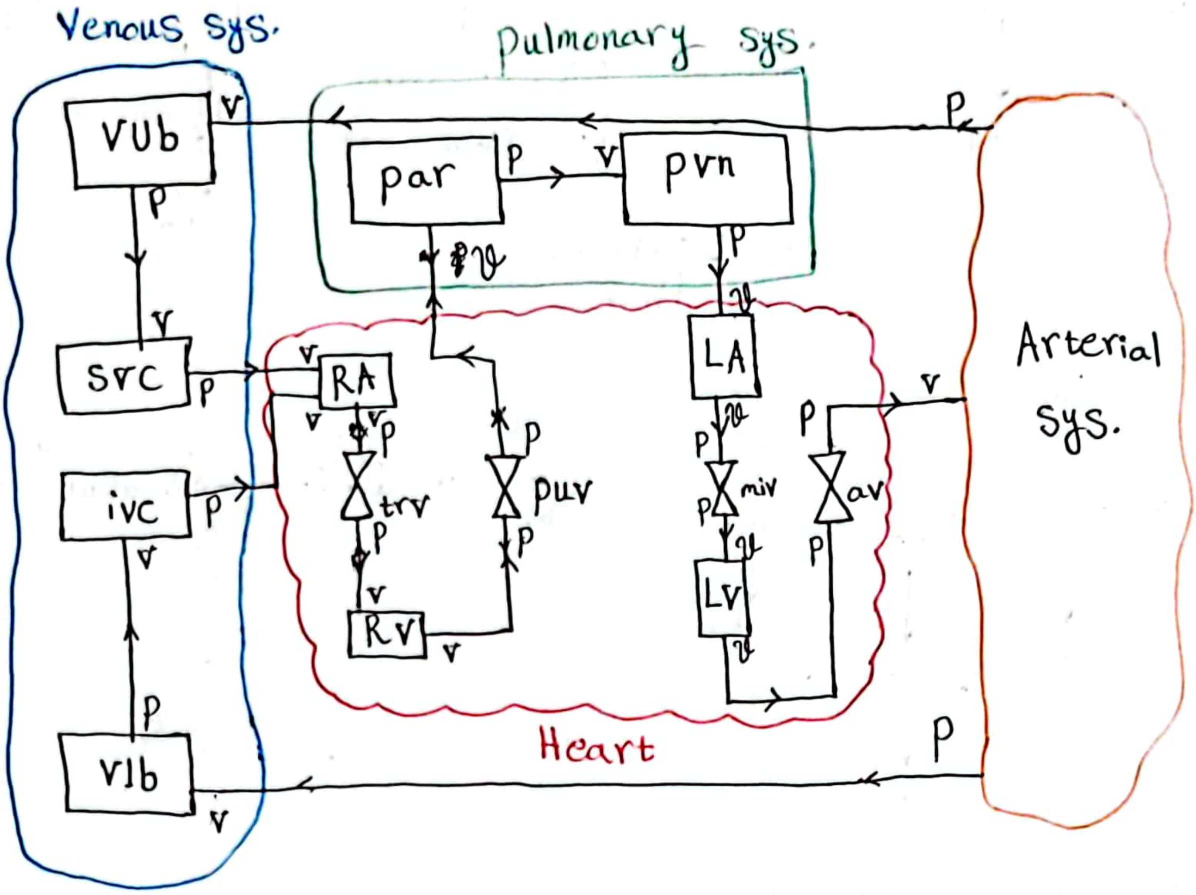


pp type : pressure - pressure





vv type : flow - flow



Heart

RA : Right Atrium

RV : Right ventricle

trv : tricuspid valve

miv : mitral valve

LA : Left Atrium

LV : Left ventricle

puv : pulmonary valve

aov : aortic valve

pulmonary sys.

pvn : pulmonary vein

par : pulmonary artery

Venous sys.

vub : venous upper body

svc : superior vena cava ~ بزرگ سیاهرگ بالایی

vlb : venous lower body

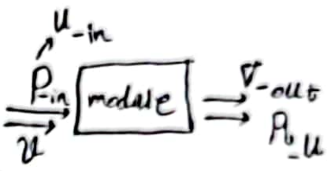
ivc : inferior vena cava

بزرگ سیاهرگ زیرین

```
def import using "testRun_modules.cellml" for
        comp X using comp y:
 enddef
```

X	Y
pvn_module	vp_simple_type
par_module	vp_simple_type
heart_module	heart_new_valve
aortic_root_module	vv_simple_type
systemic_T_module	pp_tT_type
venous_svc_module	vp_simple_type
zero_flow_module	zero_flow

PV module



pablic

BC: inputs: u_in, v_out

pub outputs: u, q_c, u_c, v

Vessel mapping:

```
def map between par_module and pvn_module for
      vars u_out and u;
      vars v and v_in;
enddef;
,
:
```

Left   Right

{ آنهایی که _in و _out دارند
شرایط مرزی BC هستند. } ★

Modules:

def comp

pv_0D_1D_coupler_type
imposter_1D
heart_simple_wcont
heart_simple
heart_new_valve
heart_simple_Lvprop
constant_flow_BC_type
constant_flow_2_BC_type
constant_pressure_BC_type
P_observer_type
f_observer_type
controller_type
controller2_type
pv_type
vp_type
pp_type
vv_type
pv_simple_type
pp_simple_type
vv_simple_type
vp_simple_type
pp_T_type
→ pp_T_wcont_type
pv_split_type
vv_2in2out_type
vv_merge_type
vp_merge_type
zero_flow

flow_sum_2_type
baroreceptor_type
chemoreceptor_type
afferent_to_vagal_efferent_type
afferent_to_syp---.
efferent_resistance_--
efferent_heart_--
⋮

gas_transport_simple_type
temp