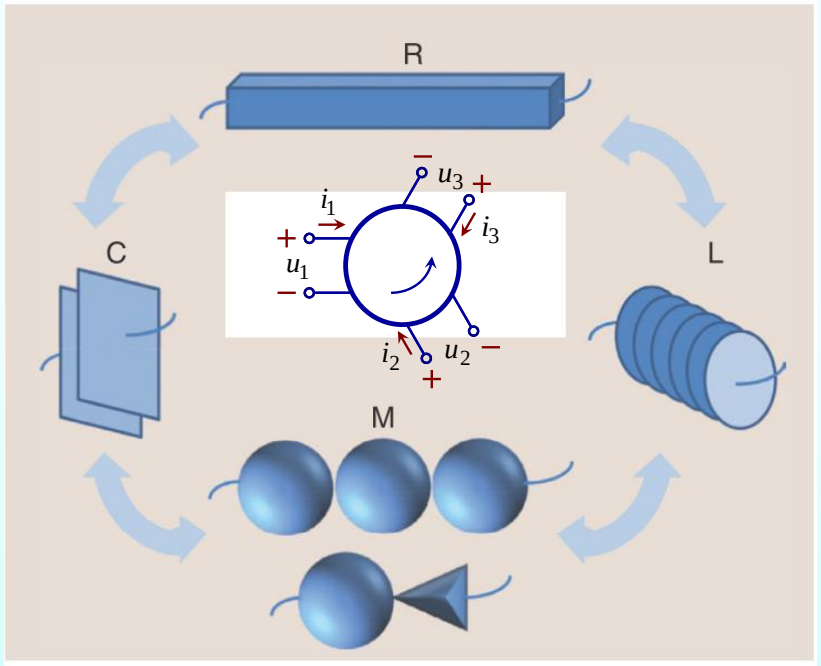
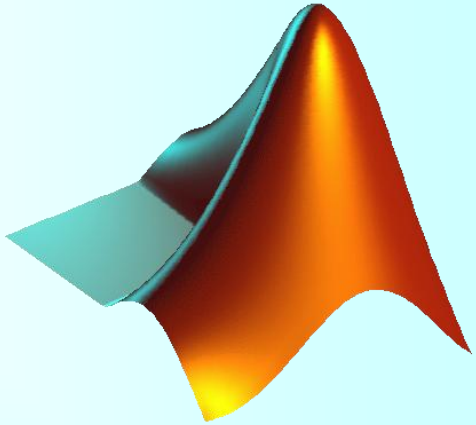
др Милка Потребић Иваниш, ред. проф., др Никола Баста, доцент, *Практикум из рачунарске анализе кола*, Универзитет у Београду – Електротехнички факултет, 2022.

Практикум из рачунарске анализе кола





Милка Потребић Иваниш

Никола Баста

Практикум из рачунарске анализе кола 13Е072ПРК3, 19Е072ПРК

- **Настава се изводи према текућем студијском програму који је Електротехнички факултет акредитовао** http://www.etf.bg.ac.rs
- Студијски програм: **Електротехника и рачунарство**
- Изборно подручје (модул): **Физичка електроника, Сигнали и системи, Телекомуникације и информационе технологије**
- **Циљ.** Излагање основних концепата анализе помоћу рачунара који се користе у софтверским пакетима за симулацију електричних кола са гледишта инжењера и истраживача електротехнике. Увођење основа за анализу модела електротехничких система и направа за нумеричку и симболичку анализу у временском и фреквенцијском домену. Изградња основних знања аналогне обраде сигнала помоћу електричних кола.
- **Исход.** Разумевање основних концепата анализе електричних кола помоћу рачунара и одговарајућих математичких алгоритама. Решавање линеарних електричних кола у временском и фреквенцијском домену помоћу система компјутерске алгебре.
- **Садржај.** Основни концепти рачунарске симулације електричних кола помоћу савремених софтверских алата. Фазорска анализа. Одзив на почетне услове, побуду и потпун одзив. Резонанција. Фреквенцијски одзив. Бодеови дијаграми. Трофазна кола. Симболичко решавање електричних кола. Водови.
- **Наставници.** Др **Милка Потребић Иваниш**, редовни професор, соба 64 (milka_potrebic@etf.rs);
  Др **Никола Баста**, доцент, соба 63 (nbasta@etf.rs).
- **Демонстратори. Ања Ковачевић**, дипл. инж., **Филип Нешковић**, дипл. инж.
- Белешке са предавања и лаб. вежби, примери испитних задатака и питања, **http://tek.etf.rs**
- **Додатни материјали и консултације биће организовани преко канала на MS Teams платформи** (линкови за канале су на адреси **http://tek.etf.rs**)
- **Начин одржавања наставе.** Рачунски центар.
- **Начин полагања испита.** 1) Решавање задатака на рачунару у пару (или смостално) у РЦ, или алтернативно 2) издрада два домаћа задатка у пару (или самостално) са пратећим извештајем у виду презентецајује која се усмено брани.
  Испит се може полагати у сваком испитном року.
  Усмена одбрана домаћих задатака се заказује са предметним наставницима.
  За издраду домаћих задатака јавити се е-поштом Милки Потребић Иваниш.
- **Пратити** званично представљање предмета и објављивање општих службених порука на адреси **http://tek.etf. rs/**

Рачунарски (софтверски) алати

- *Mathematica*, WolframAlpha, MuPAD, **Maxima**, **SymPy**, **SymPy Live**, **SymPy Gamma**
- MATLAB, **Scilab**, **Octave**, **FreeMat**, **Julia**
- LTspice, **QucsStudio**, **ngspice**, **Xyce**, **XCircuit**
- **Python**, MathCAD, MAPLE, GeoGebra, Sage
- Symbolab, SpeQ Mathematics, meta-calculator, Desmos, …
- Android apk: NCalc+, CalcES, SymJa CAS, Scientific Calculator Pro, CYZSoft Scientific Calculator Plus

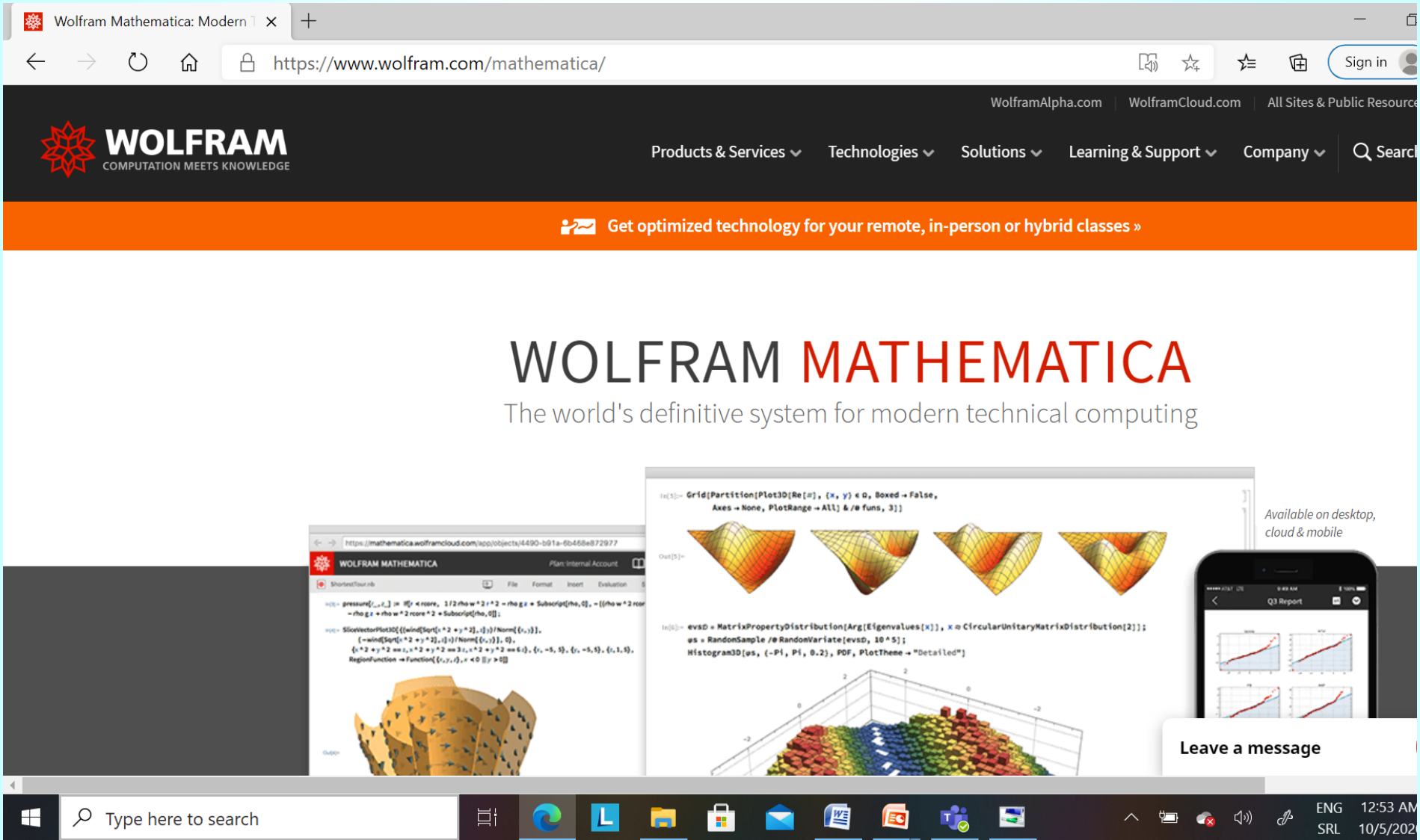
Free/Libre Open Source Software (FLOSS)

Моделовање електричних кола

- PSpice, ngSpice, Xcos, SciLab, TINA-TI, Micro-Cap, Plexim, 5Spice…
- **Online Circuit Simulator**: DoCircuits, Circuit Lab, PartSim, EasyEda, Multisim, PartQuest (SystemVision Cloud)...
- **Android circuit simulator:**
  Electric Circuit Studio,
  Circuit Safari SPICE Simulator...

Mathematica

https://www.wolfram.com/mathematica/



Mathematica free on every Raspberry Pi!

https://www.wolfram.com/raspberry-pi/

www.wolframalpha.com

Give your brain a quick workout with Wolfram Problem Generator.

WolframAlpha computational knowledge engine

y' +1000 * y = 10000, y(0)=-10

Examples Random

Input:

$\{y'(x) + 1000\, y(x) = 10\,000,\ y(0) = -10\}$

ODE classification:

first-order linear ordinary differential equation

Alternate forms:

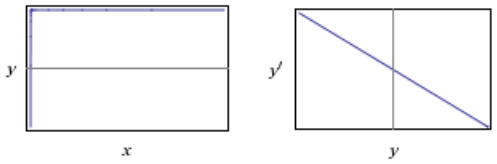
$\{y'(x) = 10\,000 - 1000\, y(x),\ y(0) = -10\}$

$\{y'(x) + 1000\,(y(x) - 10) = 0,\ y(0) = -10\}$

Differential equation solution: Approximate form | Step-by-step solution

$y(x) = 10 - 20\, e^{-1000\, x}$

Plots of the solution:



New to Wolfram|Alpha?

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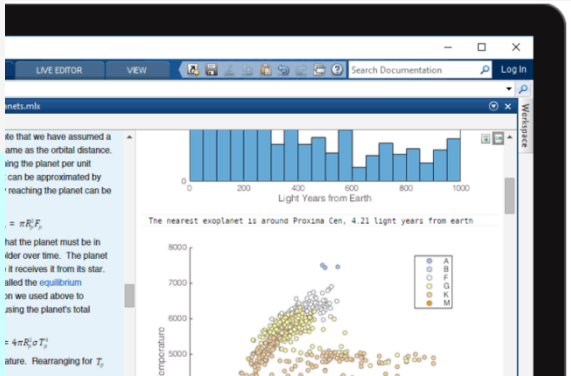
Design AI models and AI-driven systems



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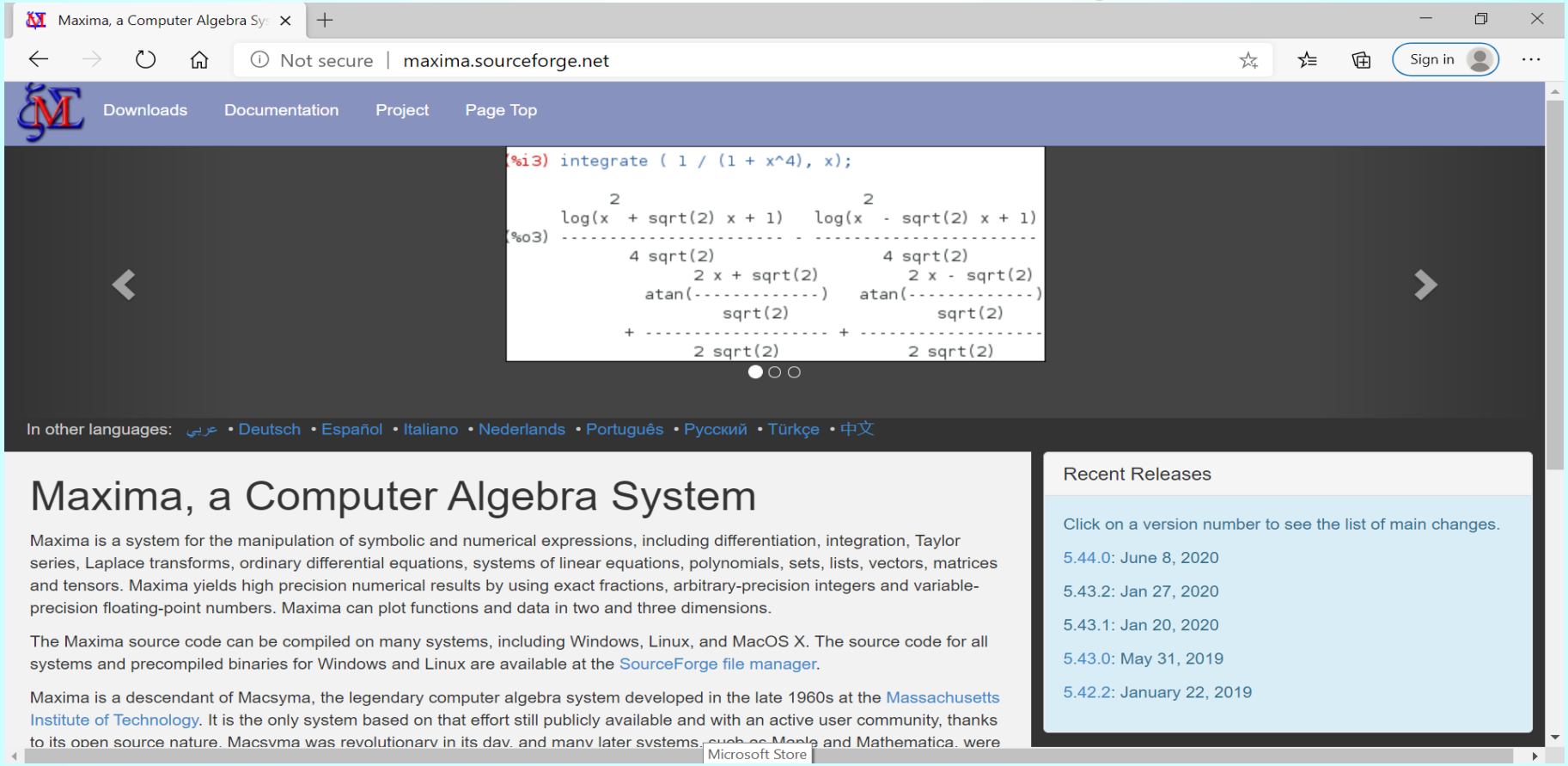
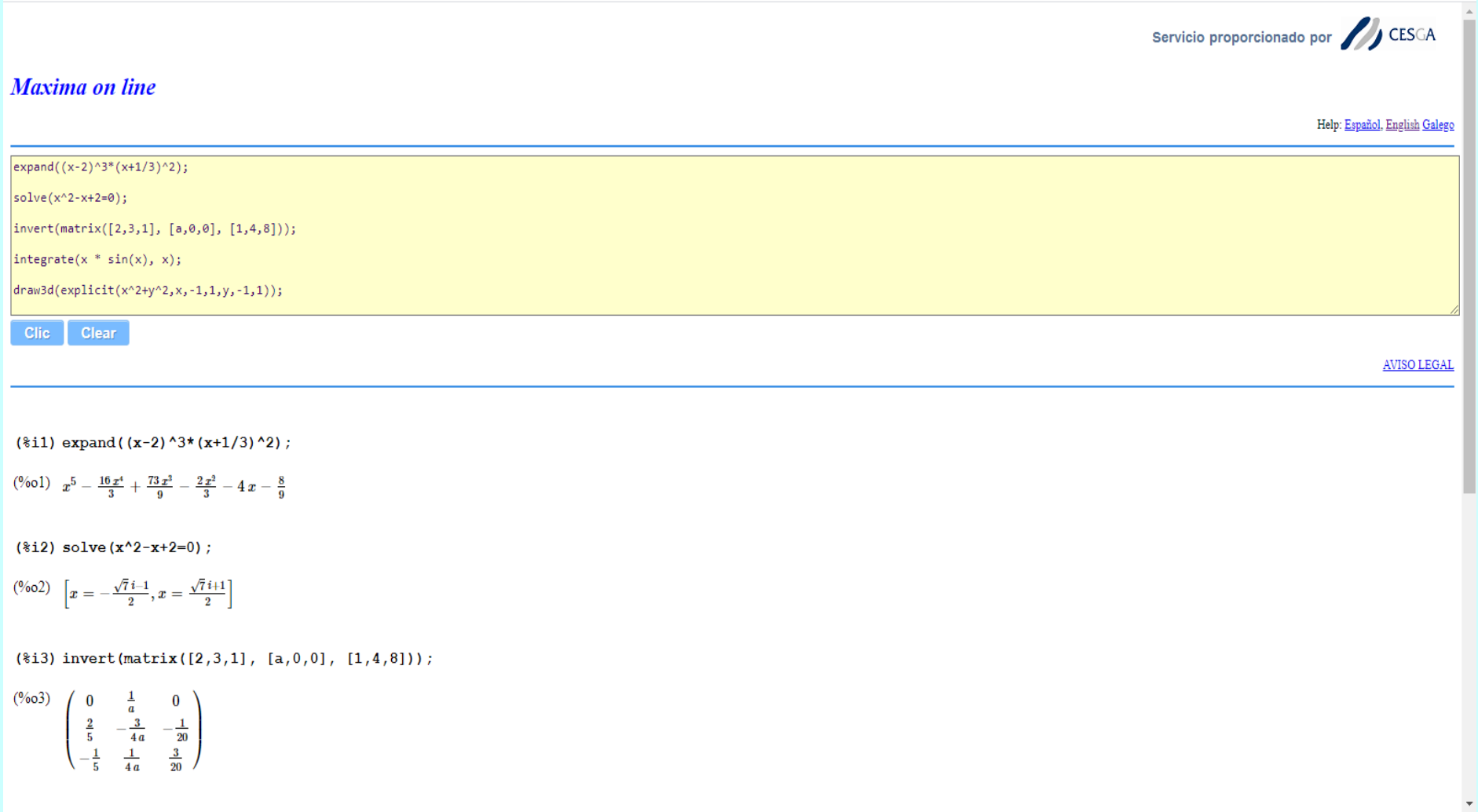
Maxima

http://maxima.sourceforge.net/



Maxima on line

http://maxima.cesga.es/



Maxima on Android

https://play.google.com/store/apps/details?id=jp.yhonda&hl=en_US&gl=US

https://play.google.com/store/apps/details?id=jp.yhonda&hl=en_US&gl=US

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Yasuaki Honda Education

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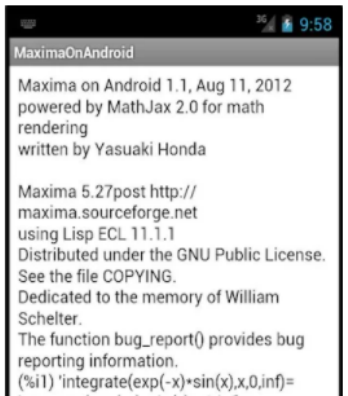
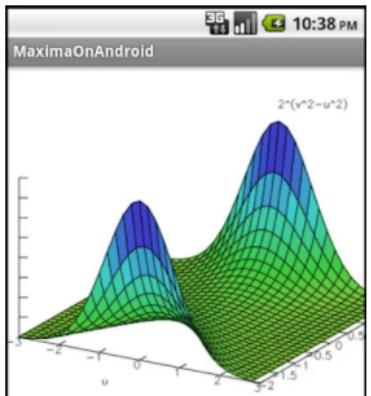
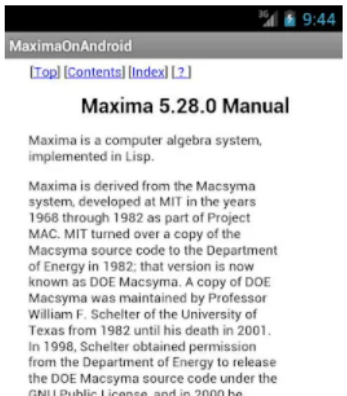
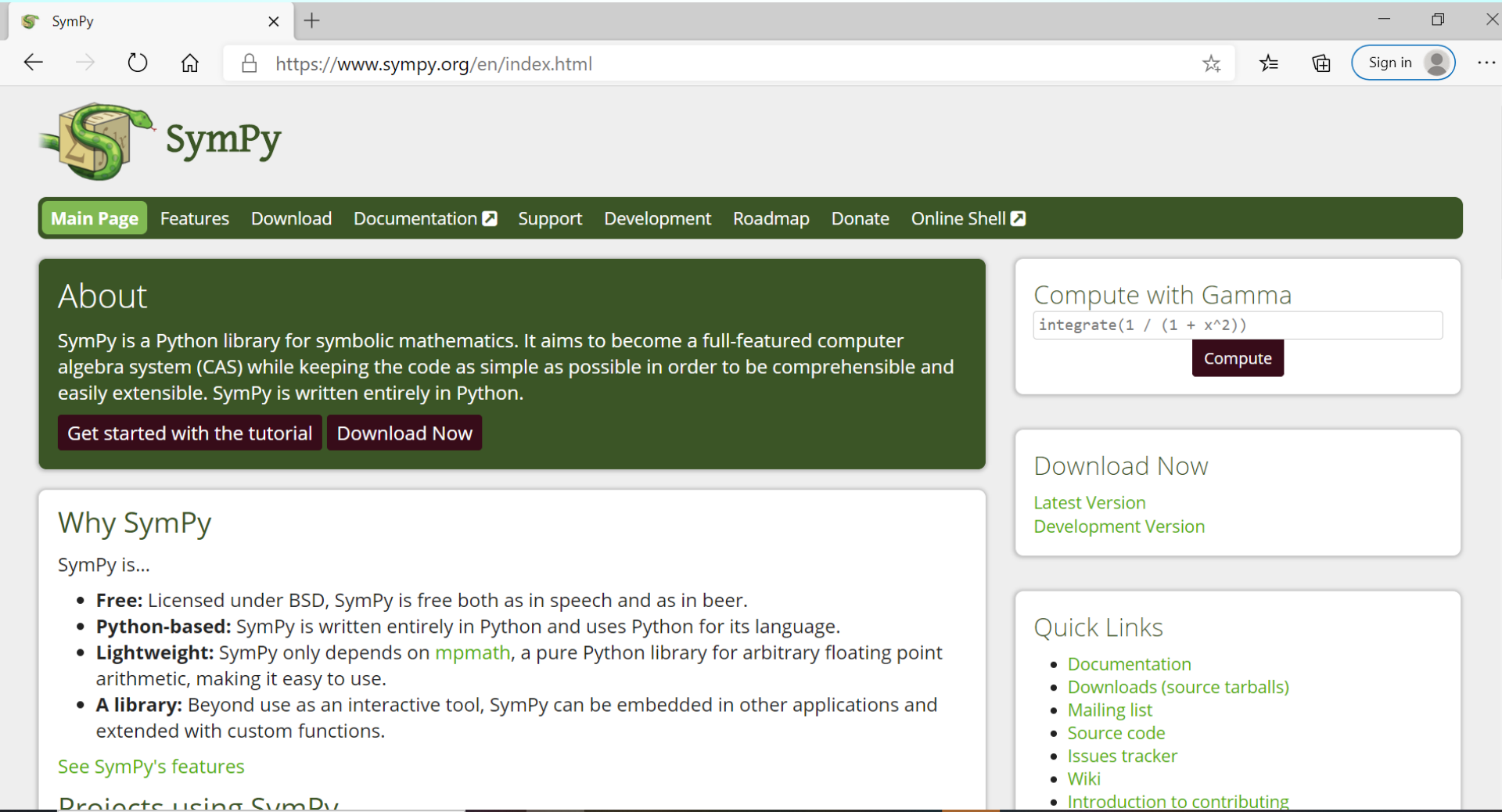






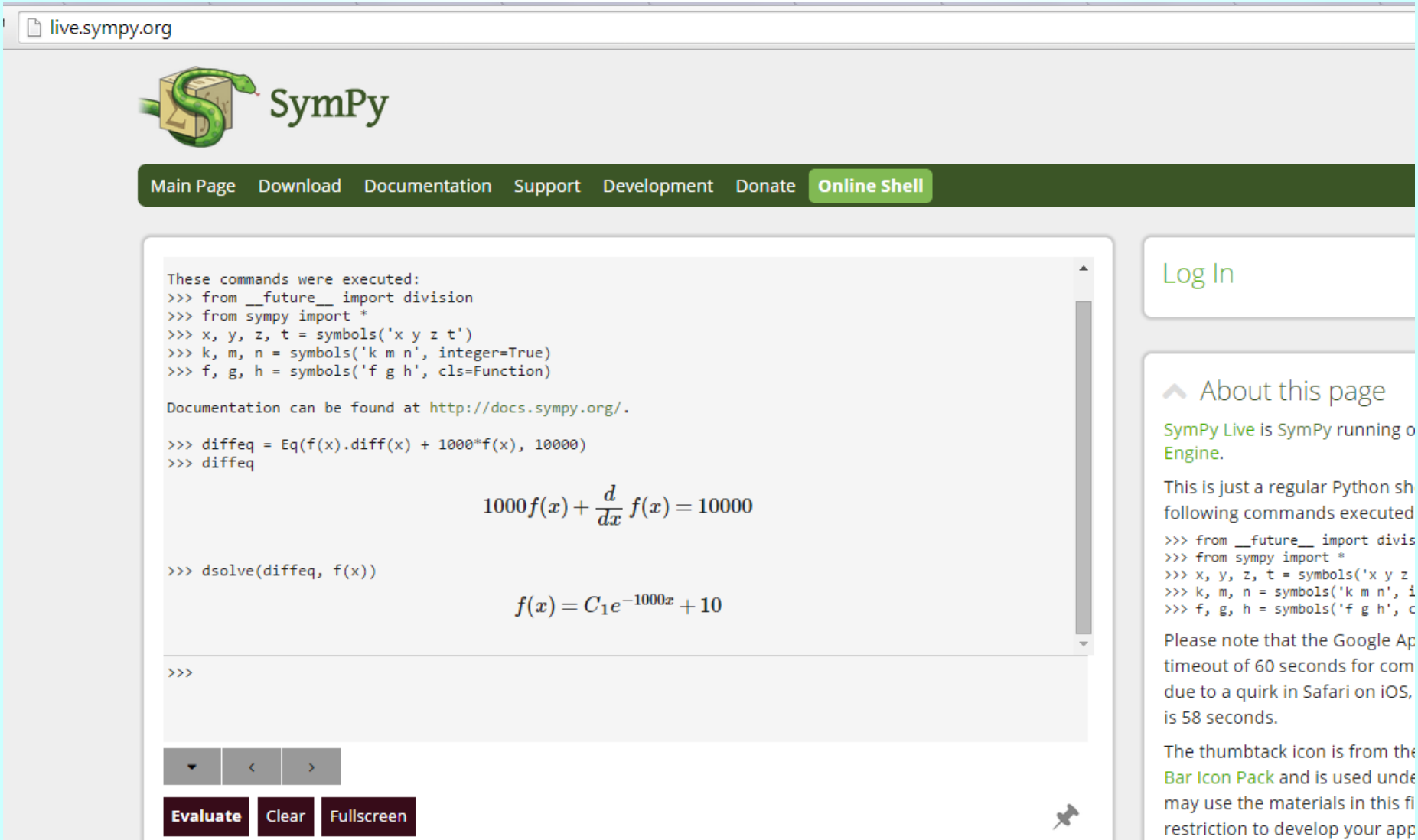
SymPy

www.sympy.org/



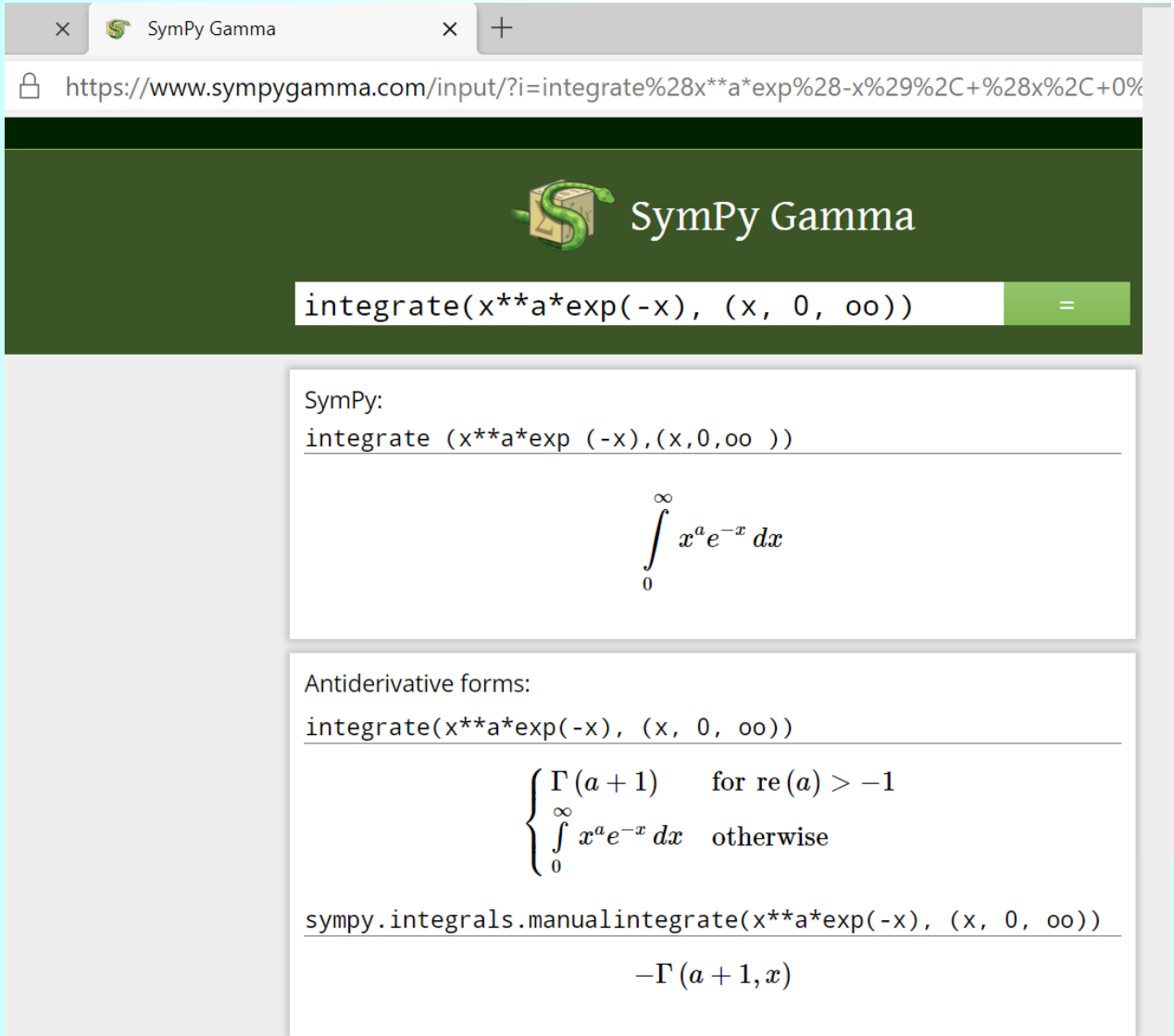
SymPy live

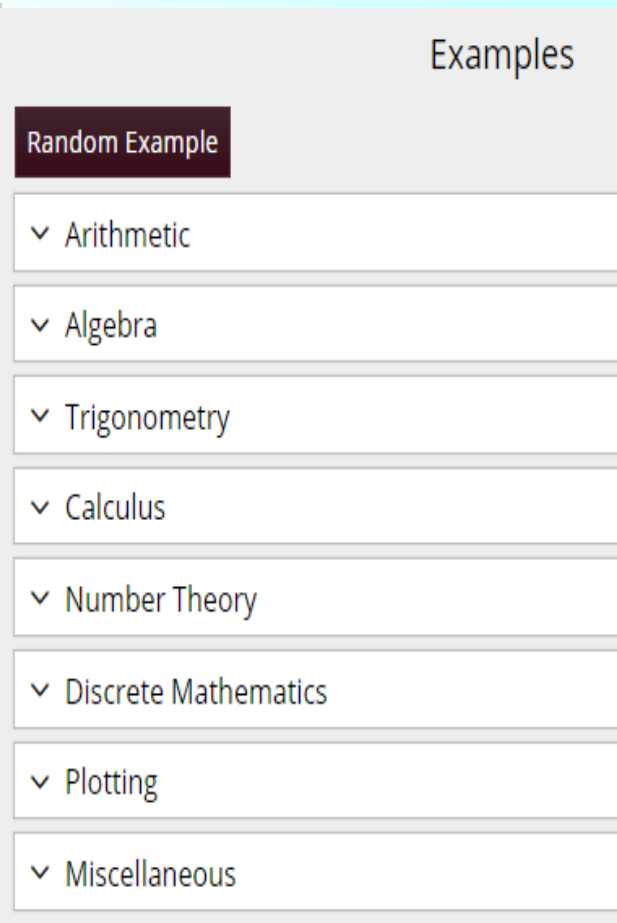
live.sympy.org



SymPy Gamma

https://www.sympygamma.com/





```
[1]: from sympy import *
     x = symbols('x')
     import sympy;sympy.__version__
[1]: '1.4'
[2]: Integral(exp(-x**2), (x, -oo, oo))
[2]: ∫_{-∞}^{∞} e^{-x^2} dx
[3]: _.doit()
[3]: √π
```

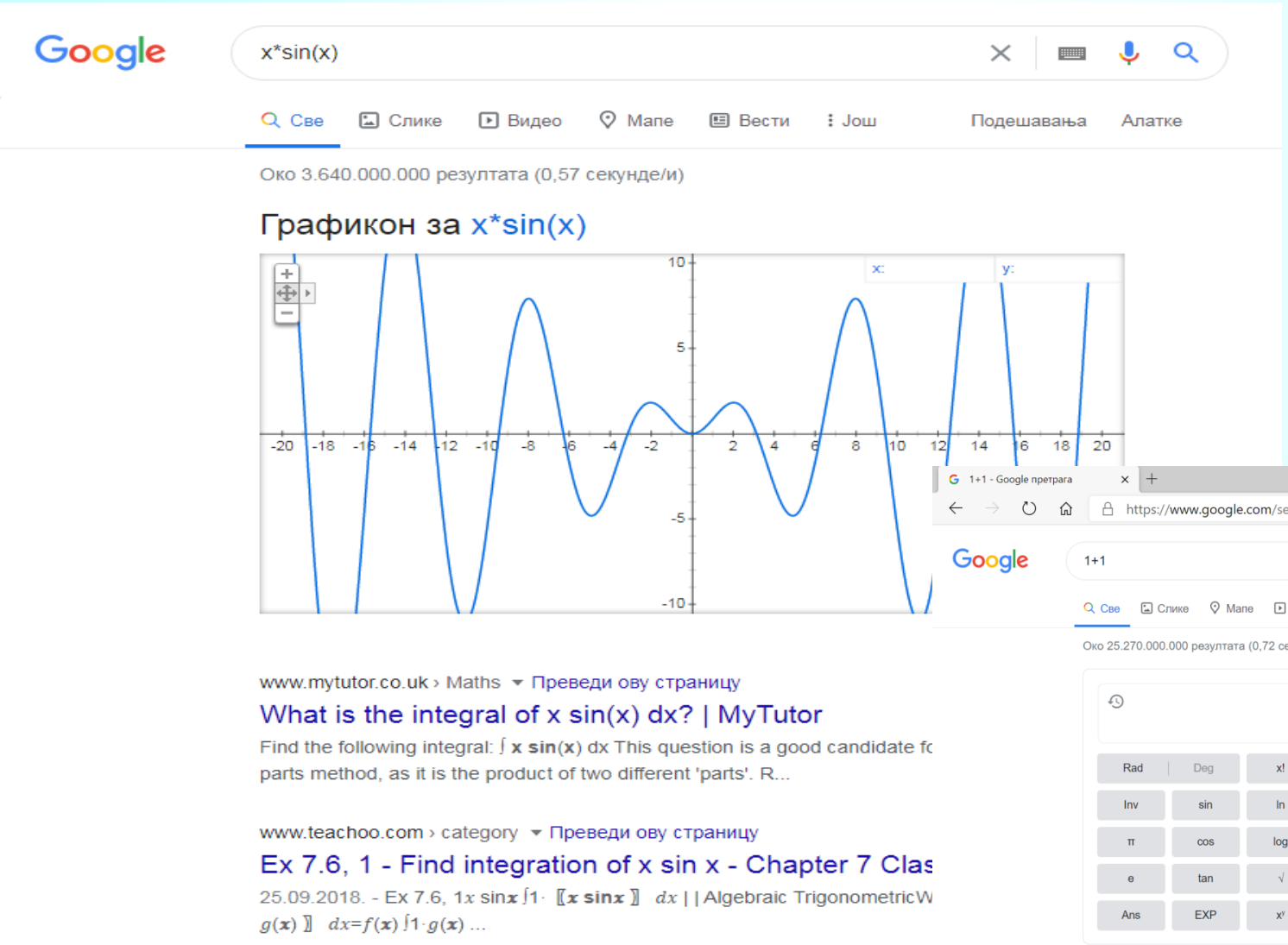
https://jupyter.org

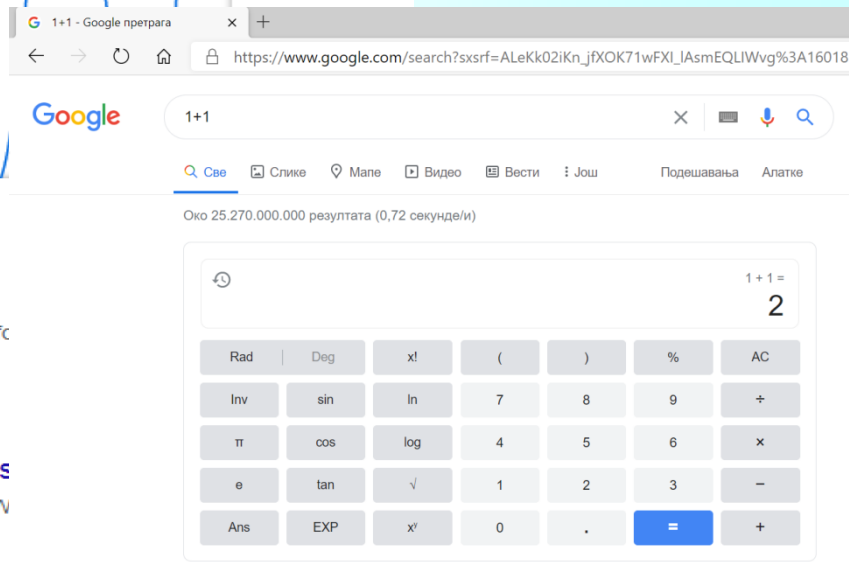
jupyter Install About Us Community Events Do

Sympy and the Jupyter Notebook for engineering calculations

Project Jupyter exists to develop open-source software, open-standards, and services
interactive computing across dozens of programming languages.

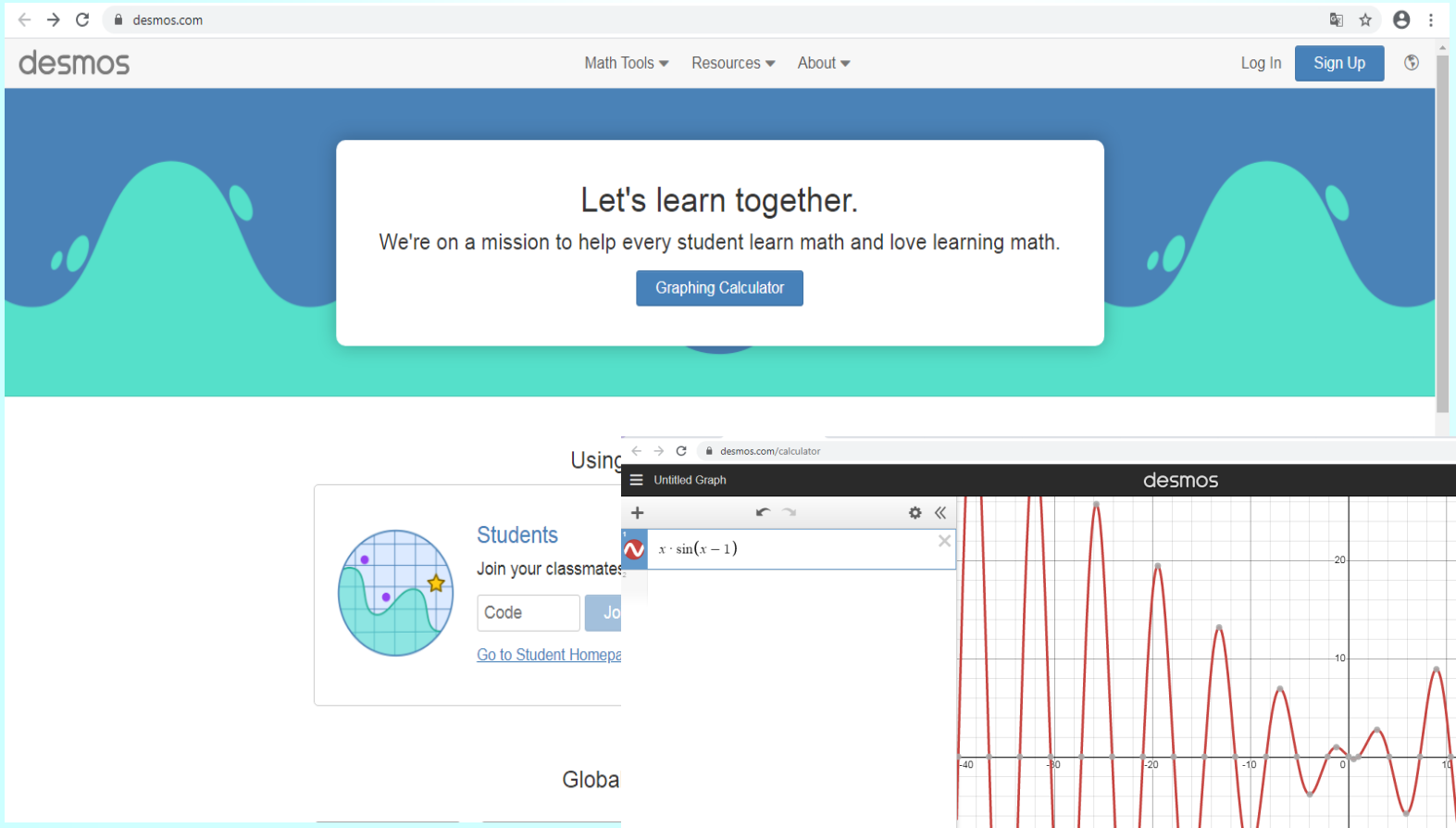
Google kalkulator

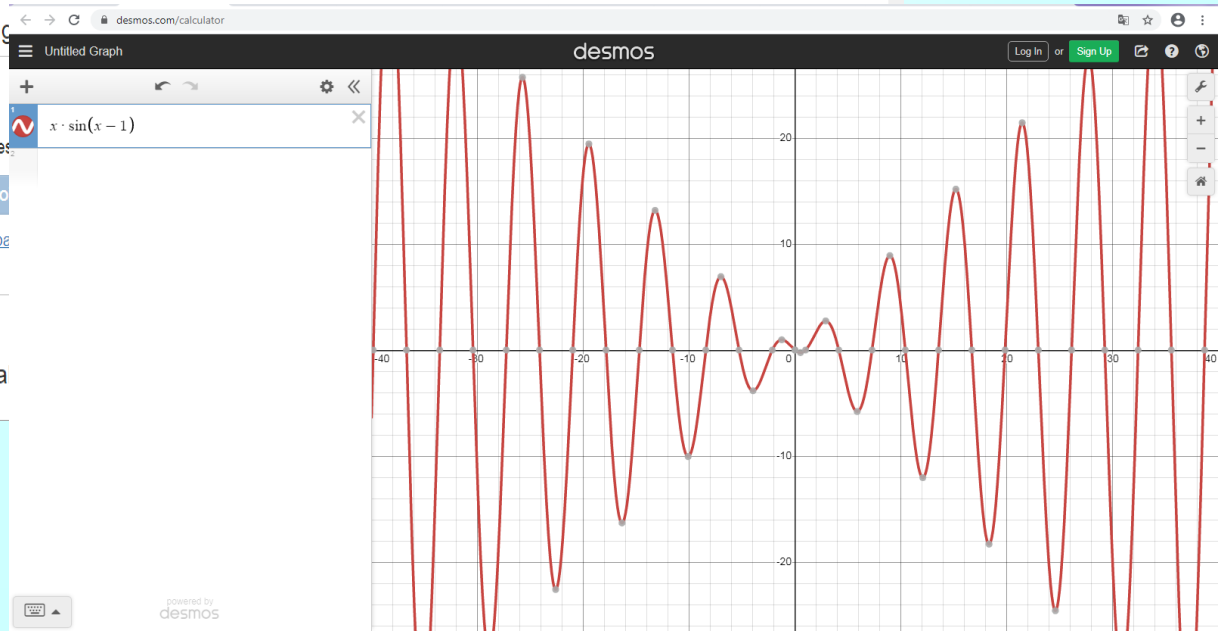




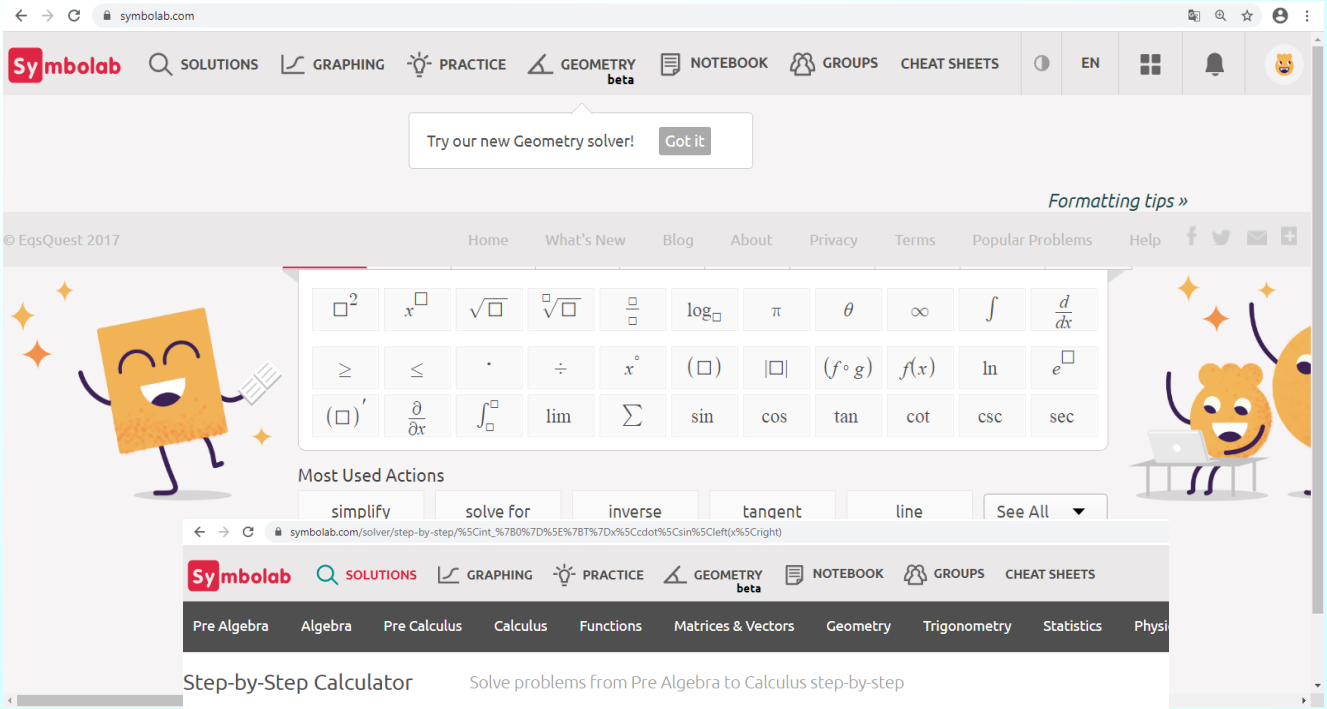
Graphing Calculator – Desmos

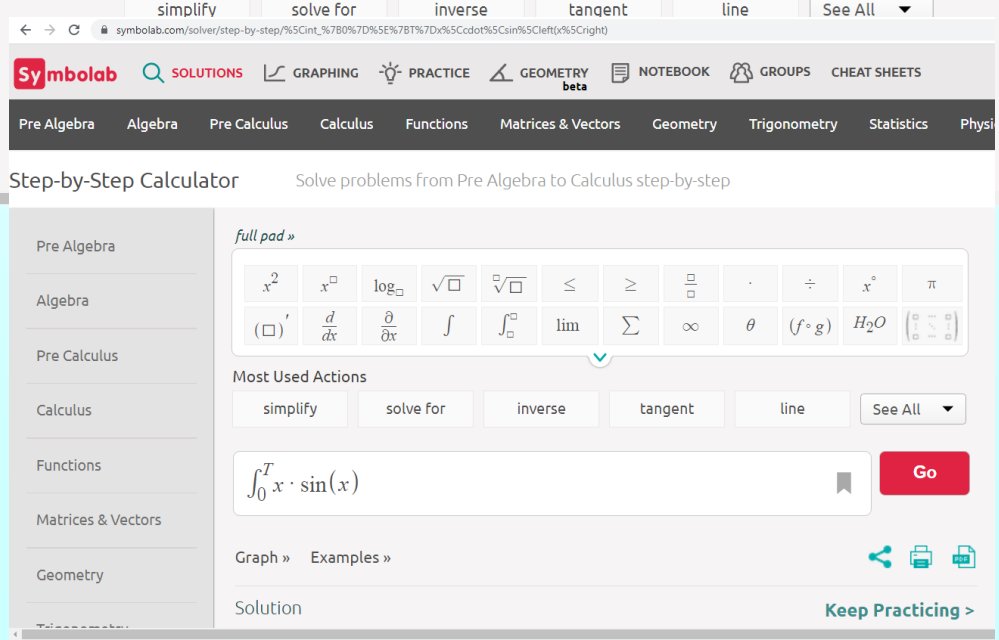
https://www.desmos.com/calculator

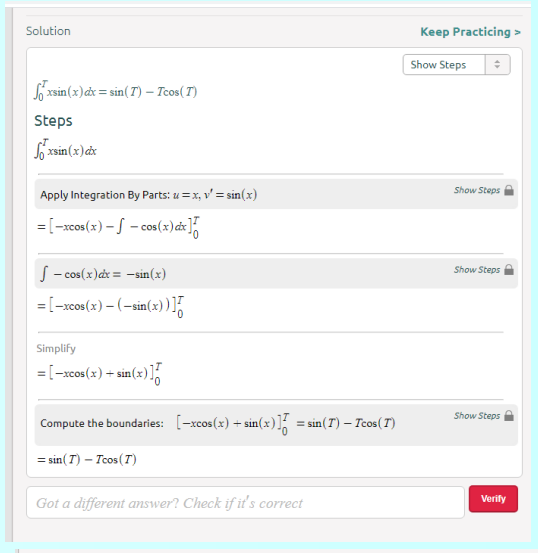


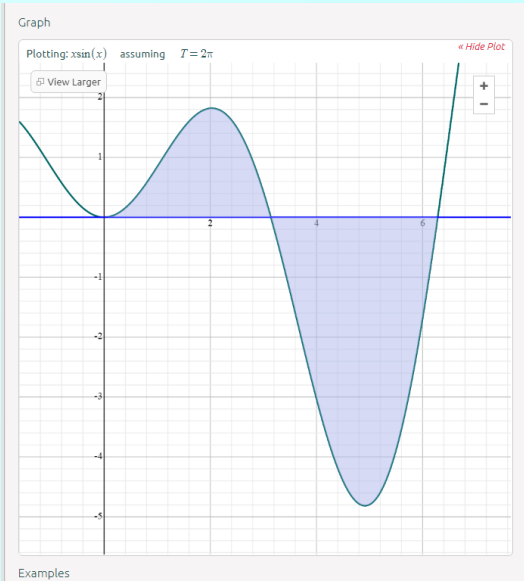


Symbolab Math Solver - Step by Step calculator
https://www.symbolab.com/



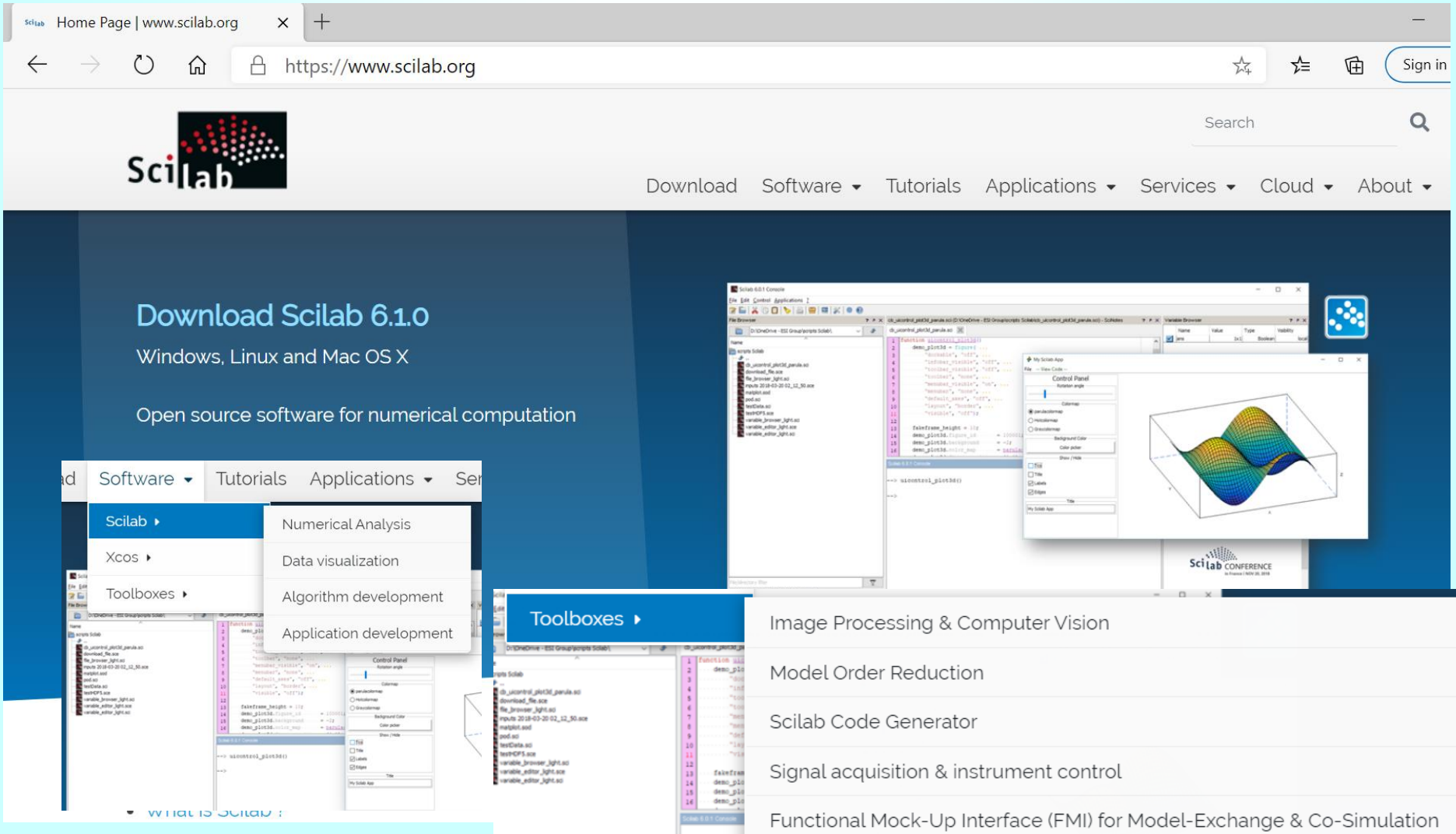






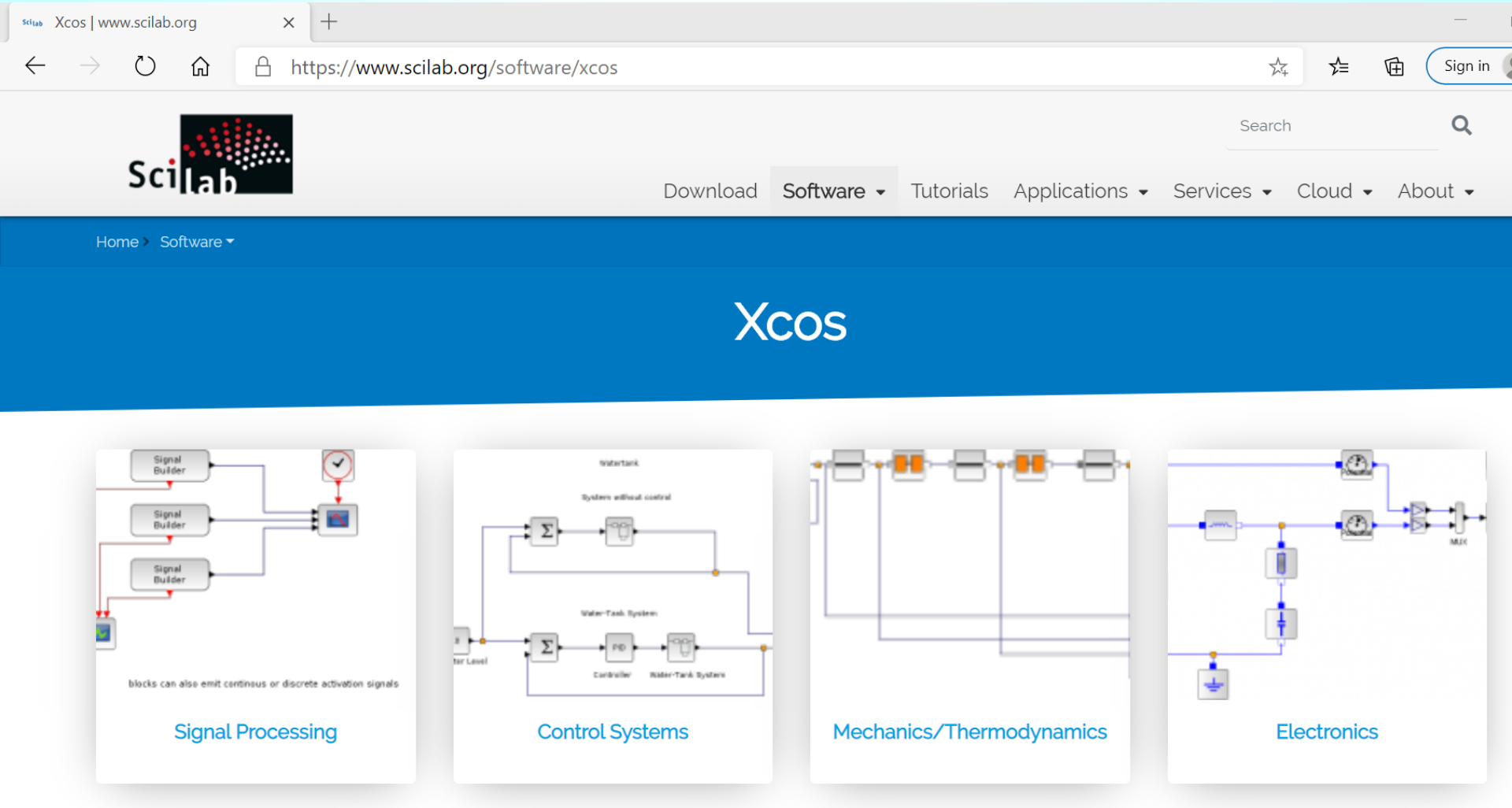
SciLab

https://www.scilab.org/



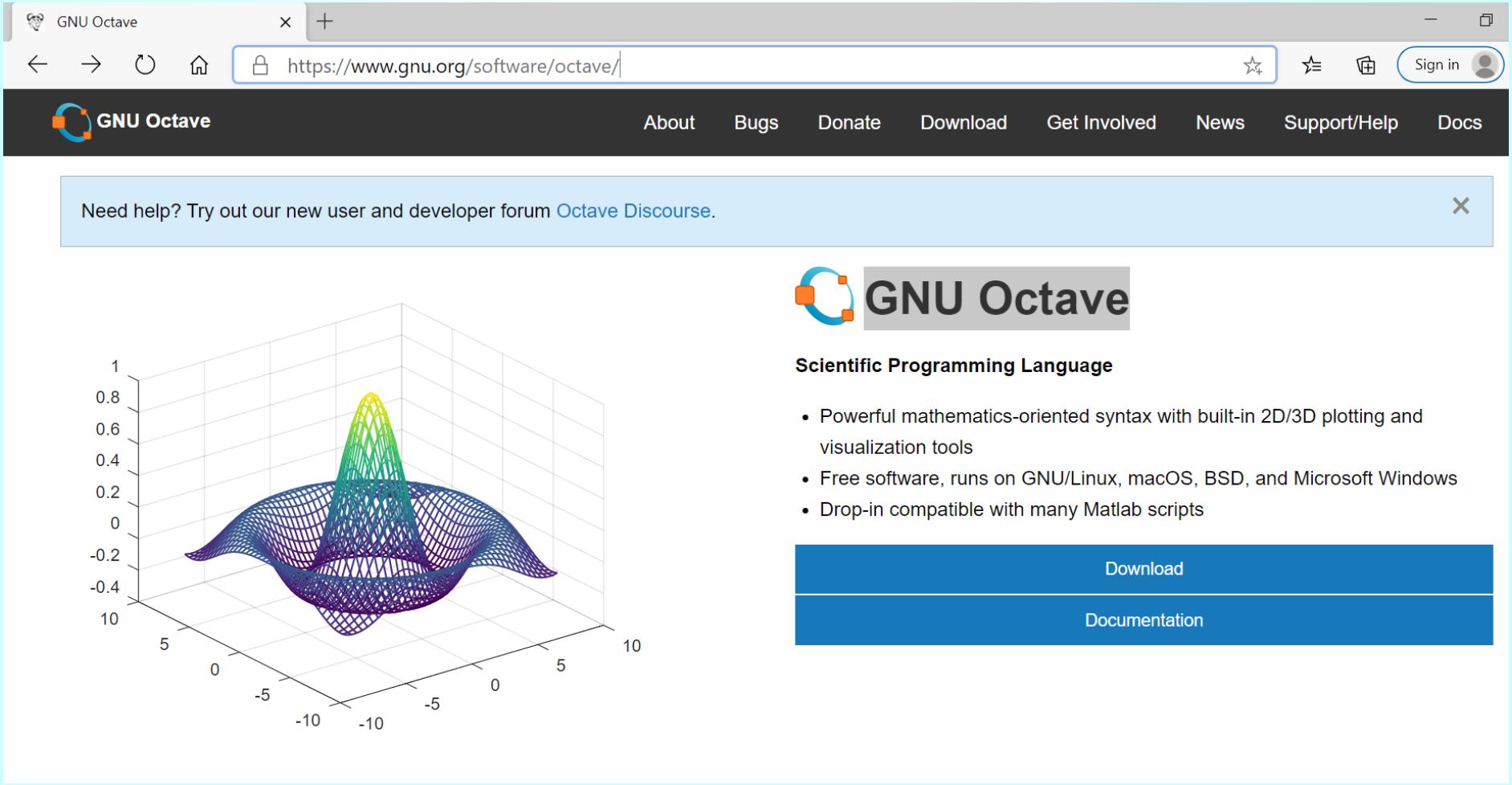
Xcos

https://www.scilab.org/software/xcos



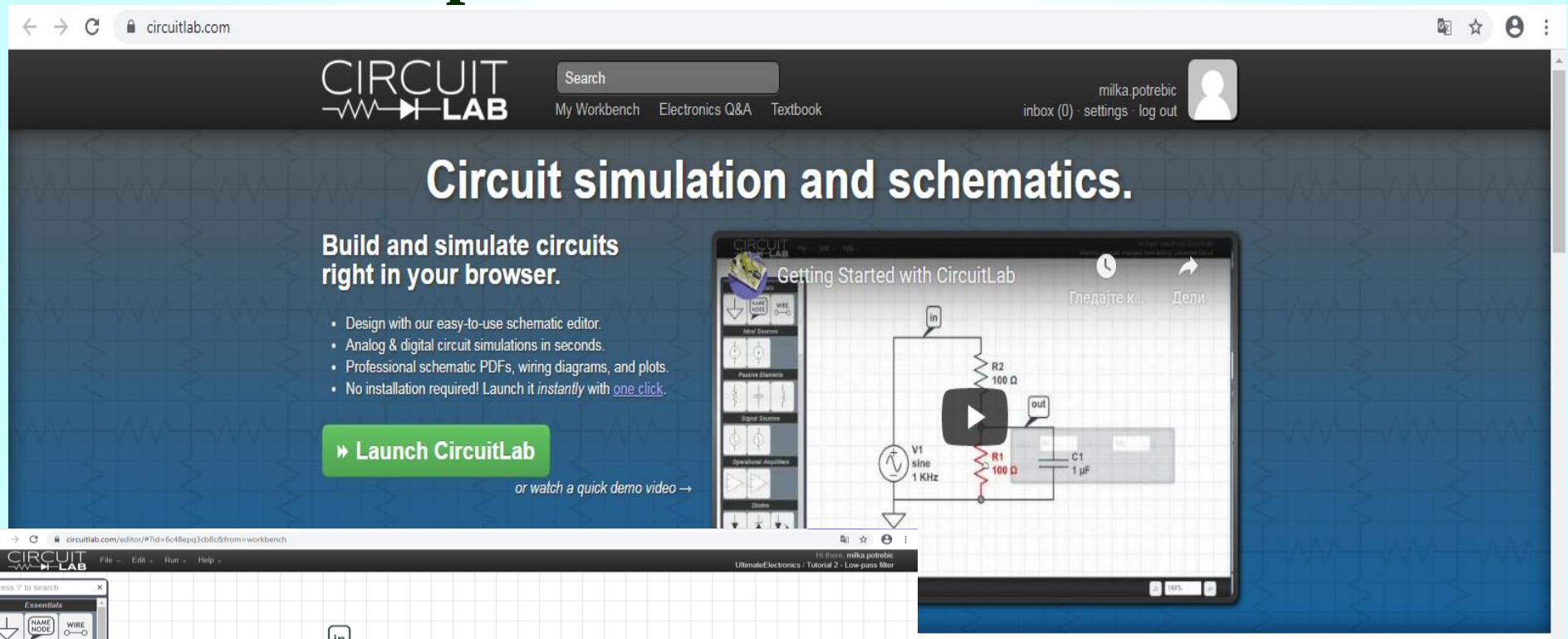
GNU Octave

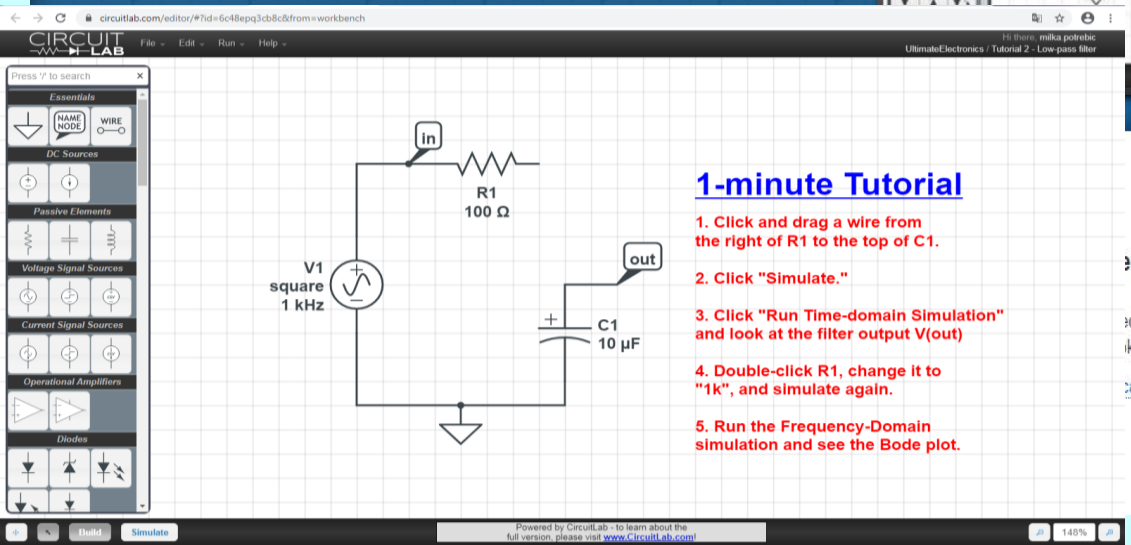
https://www.gnu.org/software/octave/



CircuitLab

https://www.circuitlab.com/





DoCircuits Circuit Simulator

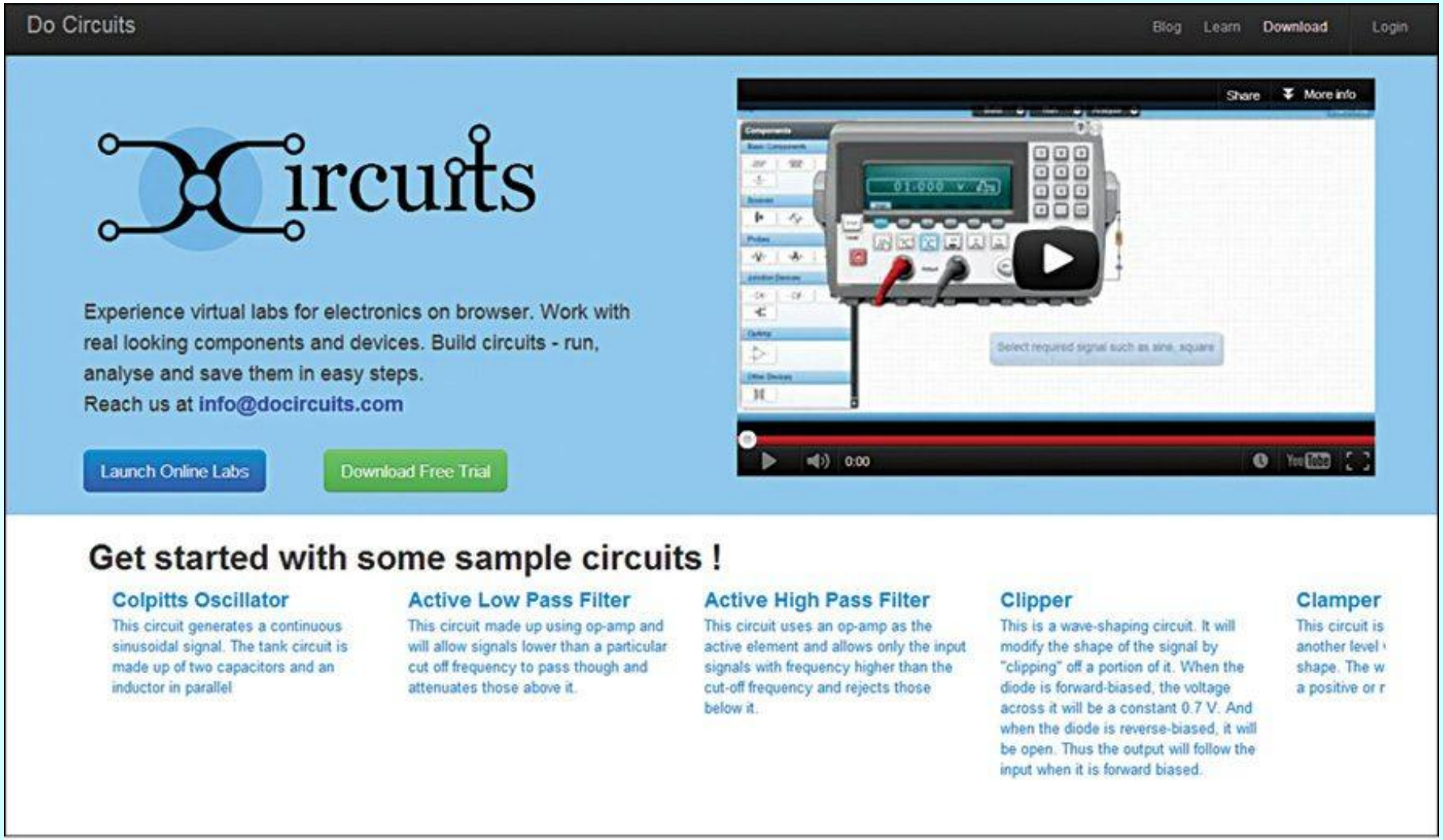
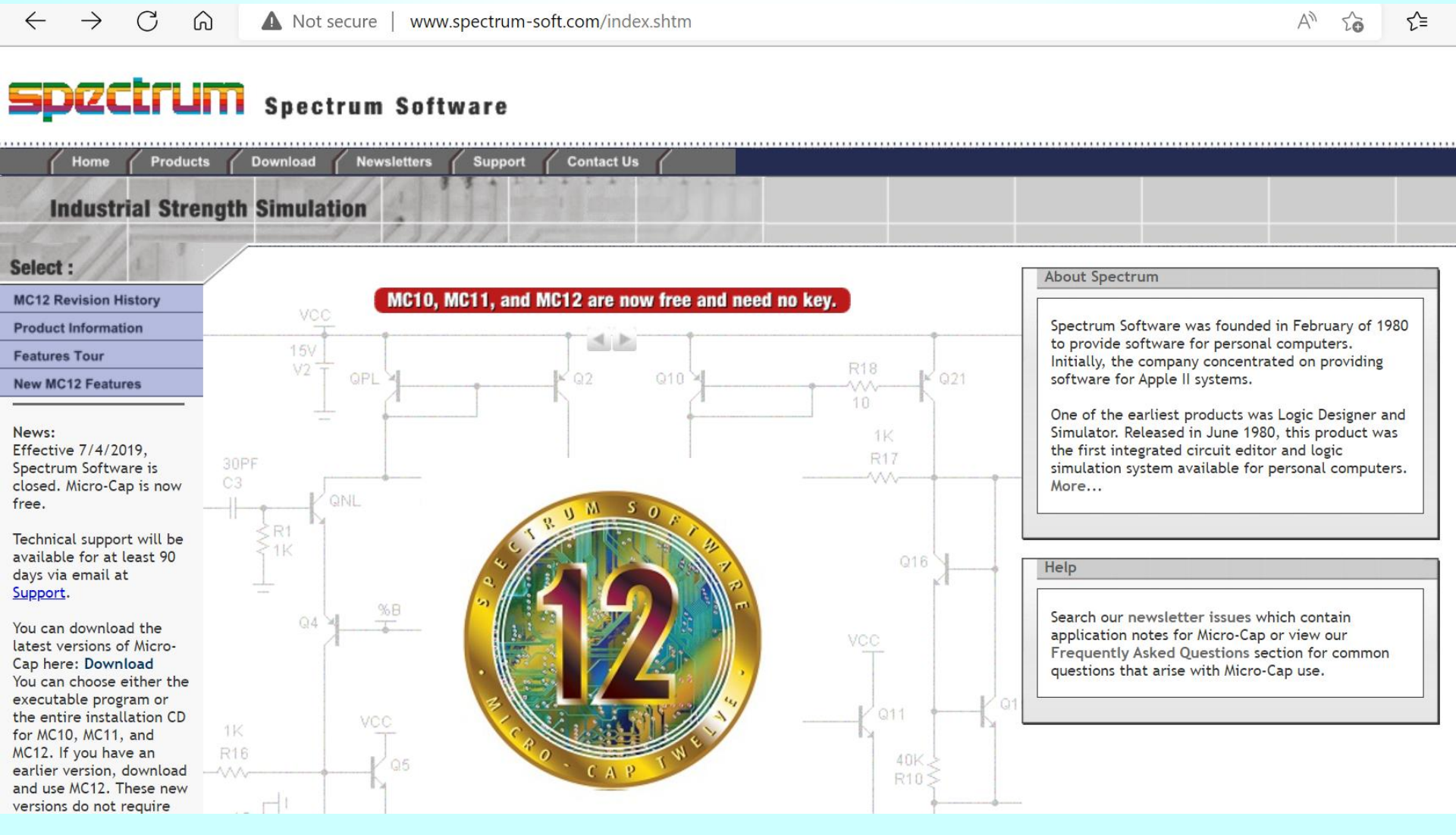


Fig. 1: DoCircuits - Home

Micro-Cap

http://www.spectrum-soft.com/index.shtm



ngSpice

http://ngspice.sourceforge.net/

Not secure | ngspice.sourceforge.net

NGSPICE

MIXED MODE - MIXED LEVEL CIRCUIT SIMULATOR

BASED ON BERKELEY'S SPICE3F5

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Sourceforge Developer Pages

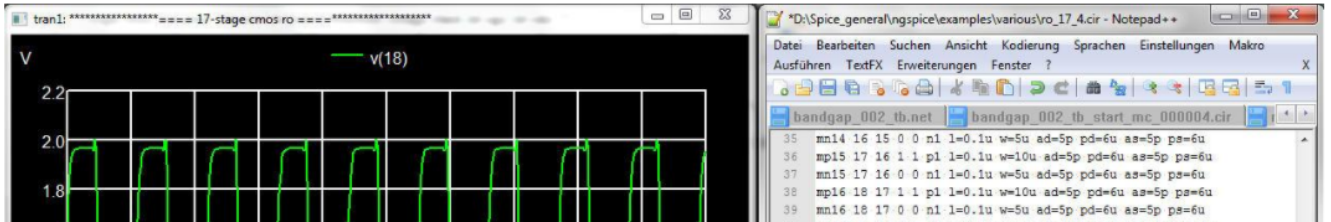
ngspice - open source spice simulator

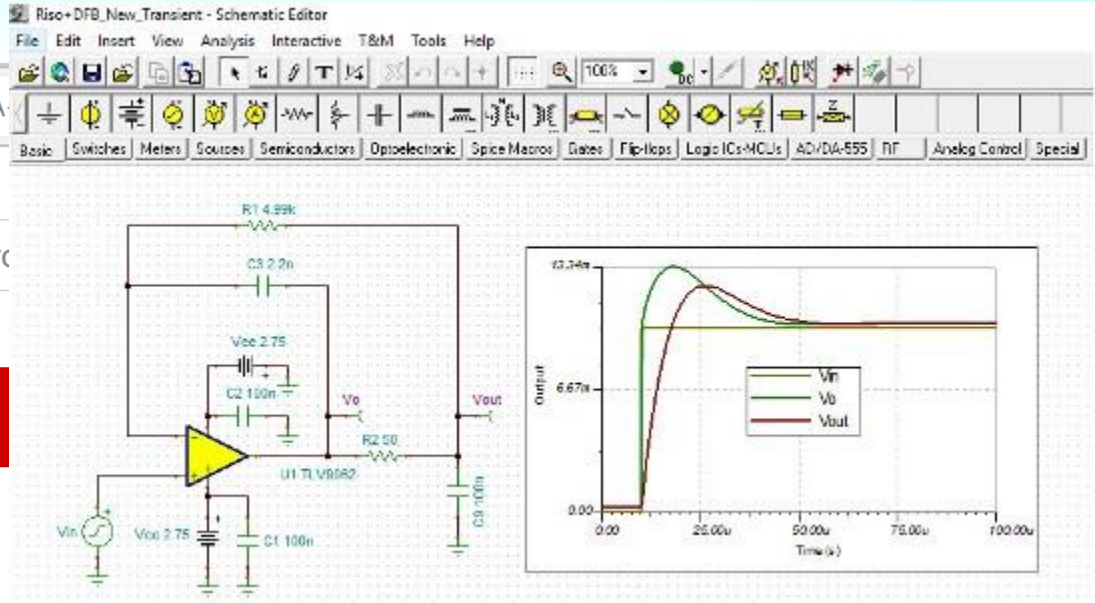
ngspice is the open source spice simulator for electric and electronic circuits.

Such a circuit may comprise of JFETs, bipolar and MOS transistors, passive elements like R, L, or C, diodes, transmission lines and other devices, all interconnected in a netlist. Digital circuits are simulated as well, event driven and fast, from single gates to complex circuits. And you may enter the combination of both analog and digital as a mixed-signal circuit.

ngspice offers a wealth of device models for active, passive, analog, and digital elements. Model parameters are provided by our collections, by the semiconductor device manufacturers, or from semiconductor foundries. The user adds her circuits as a netlist, and the output is one or more graphs of currents, voltages and other electrical quantities or is saved in a data file.

ngspice does not provide schematic entry. Its input is command line or file based. There are however third party interfaces available.





https://www.ti.com/tool/TINA-

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SPICE-based analog simulation program

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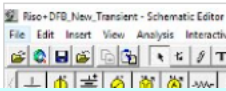
TINA-TI

https://www.ti.com/tool/TINA-TI

Overview

TINA-TI provides all the conventional DC, transient and frequency domain analysis of SPICE and much more. TINA has extensive post-processing capability that allows you to format results the way you want them. Virtual instruments allow you to



Electric Circuit Studio

https://play.google.com/store/apps/details?id=com.ecstudiosystems.electriccircuitstudio&hl=en_US&gl=US

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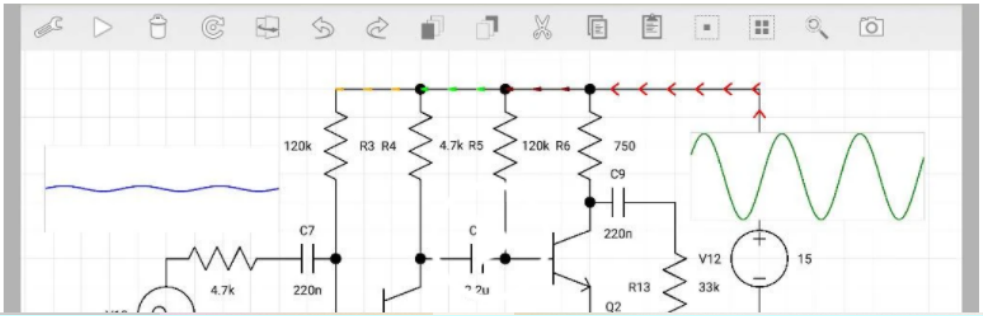

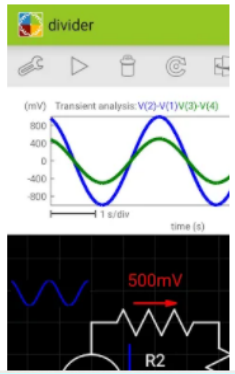

CircuitSafari SPICE Simulator

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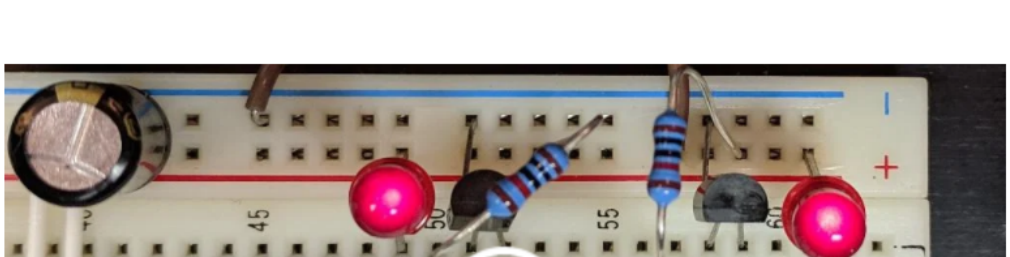
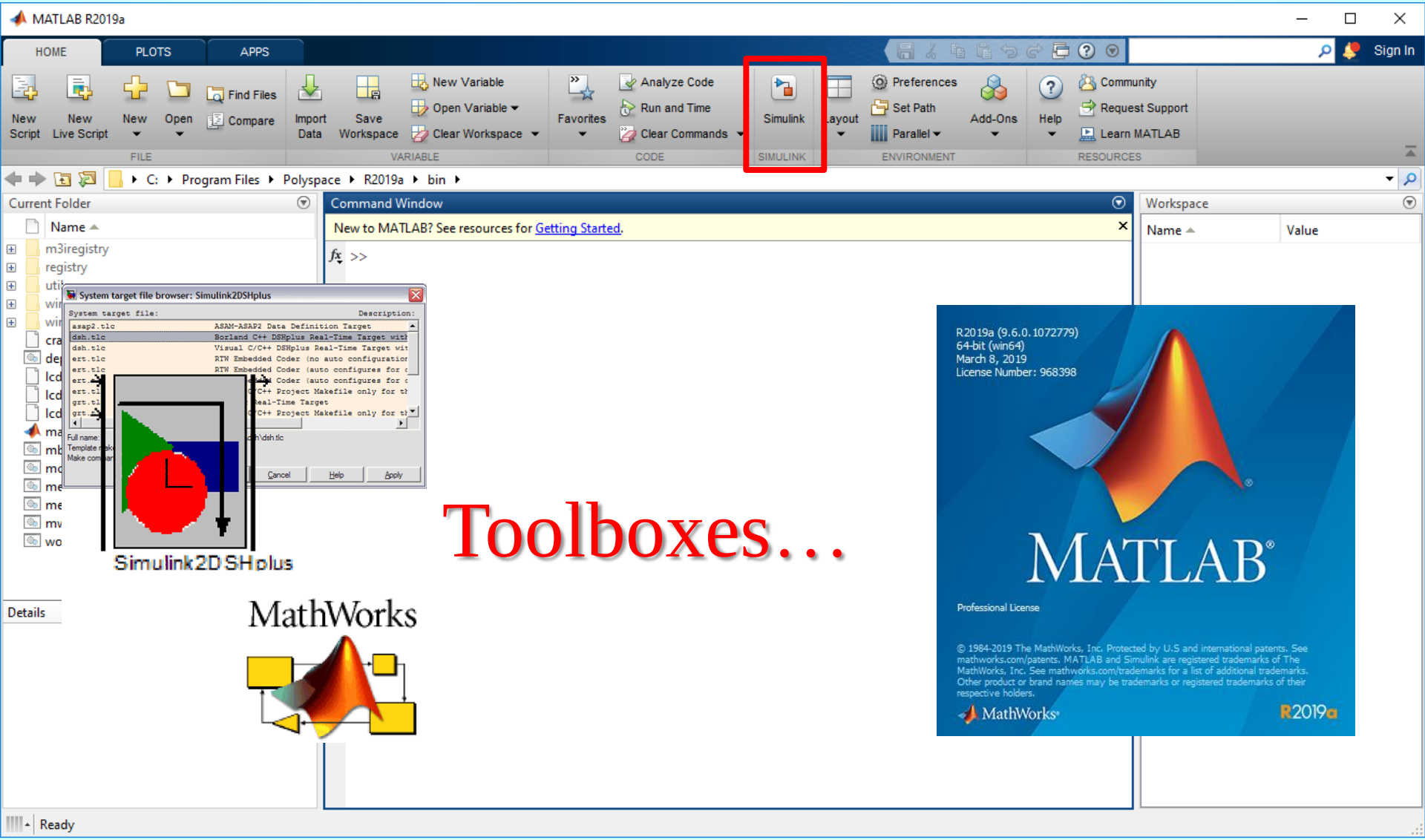


MATLAB

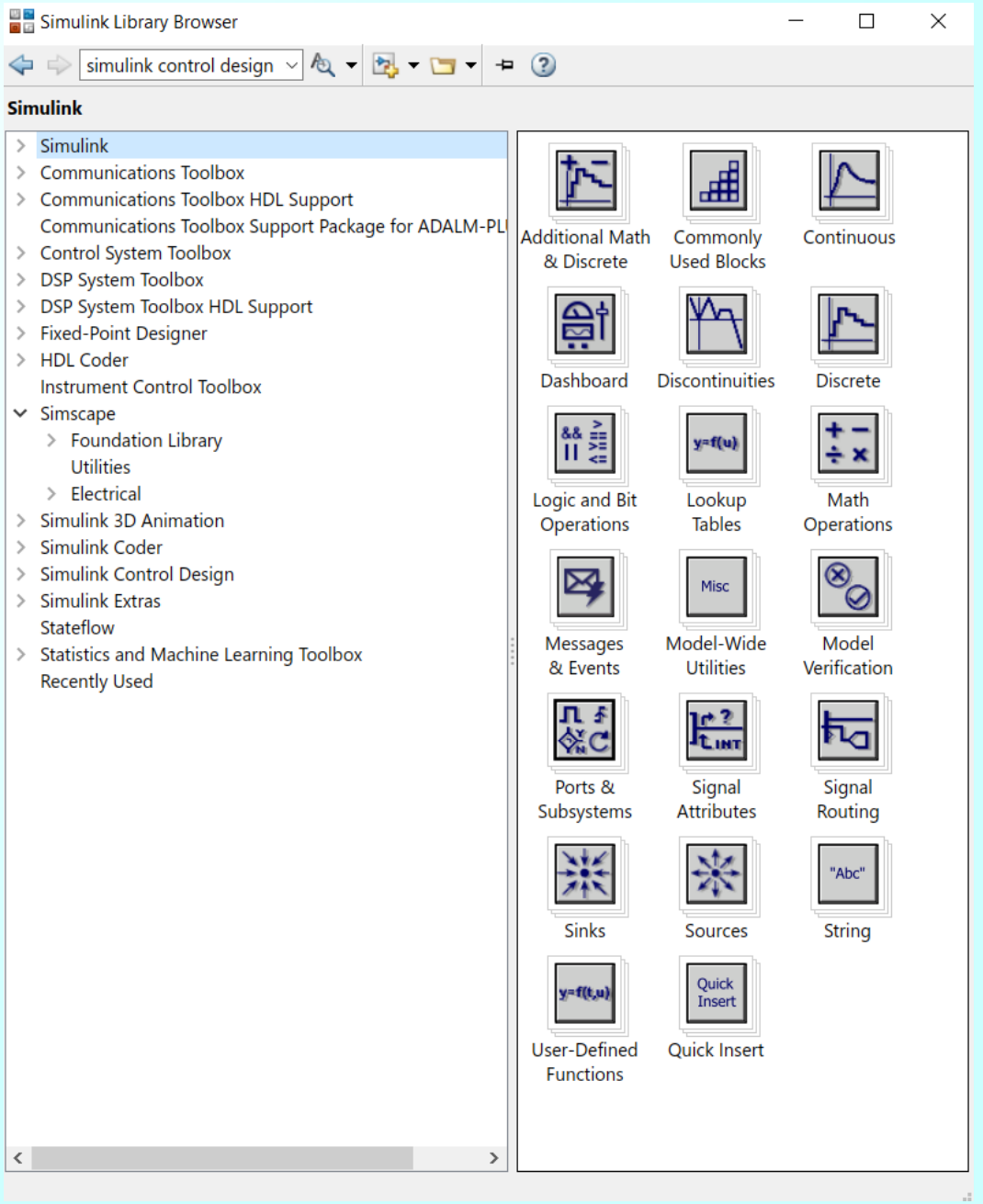
http://www.mathworks.com/



Toolboxes…

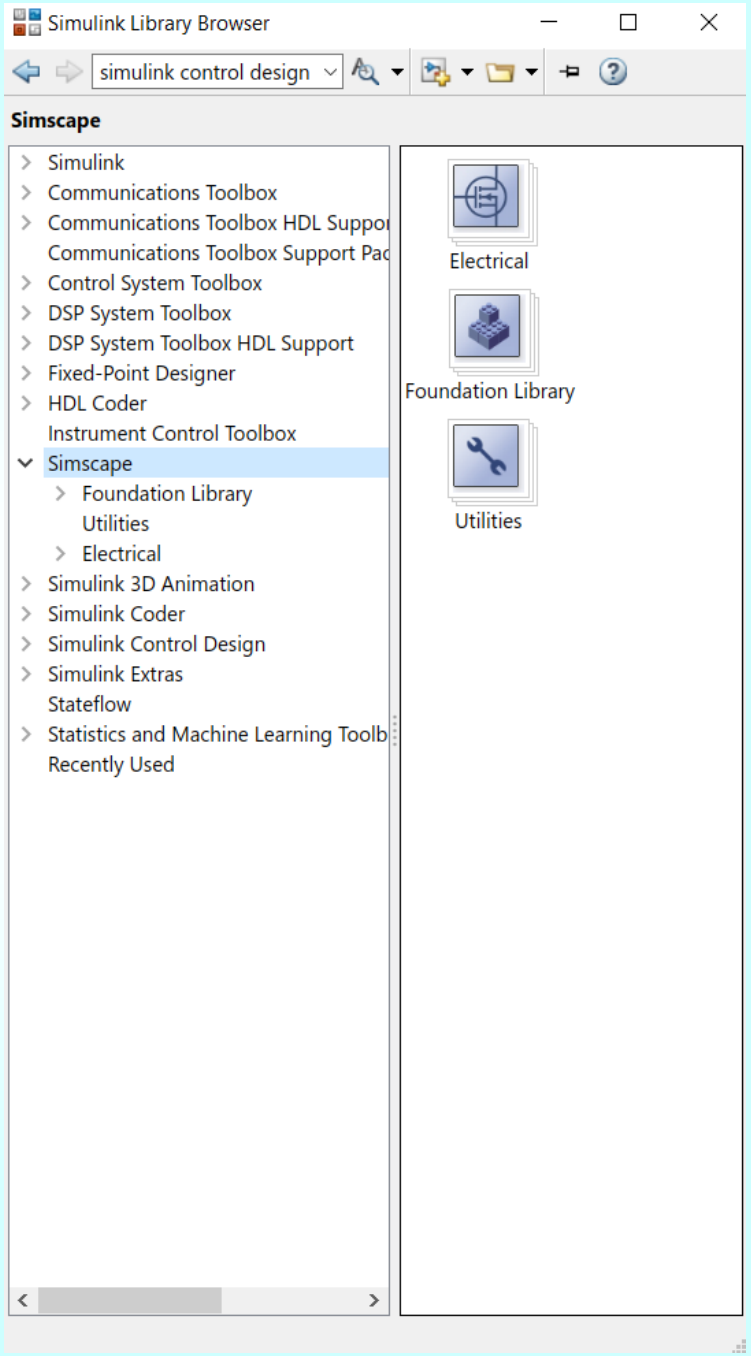
MATLAB Simulink

- Алатка за нумеричку анализу математичких модела
- Систем се дефинише графички, уметањем блокова и њиховим повезивањем у мрежу



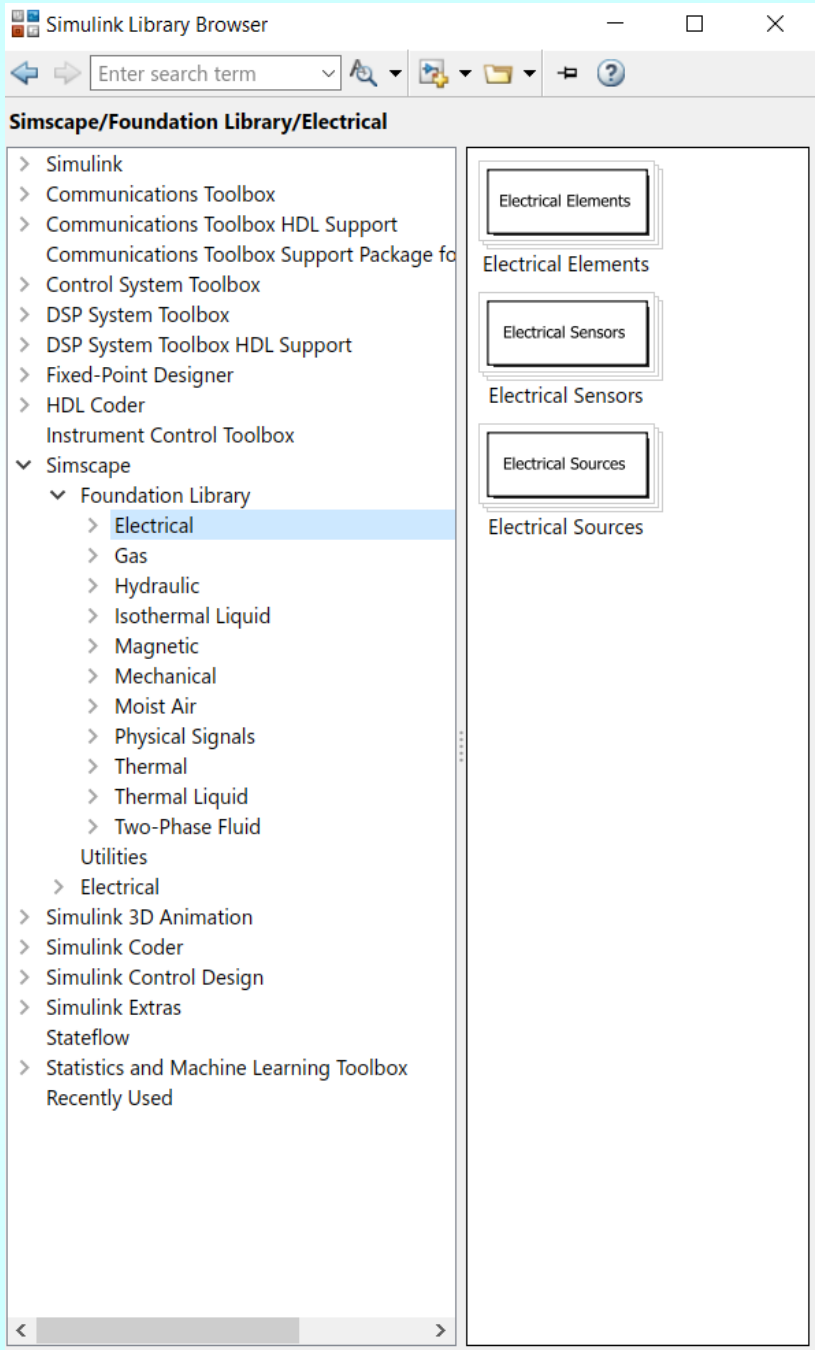
Simulink > Simscape

- Библиотека за симулацију и нумеричку анализу мултидоменских проблема (механика, електродинамика, оптика)



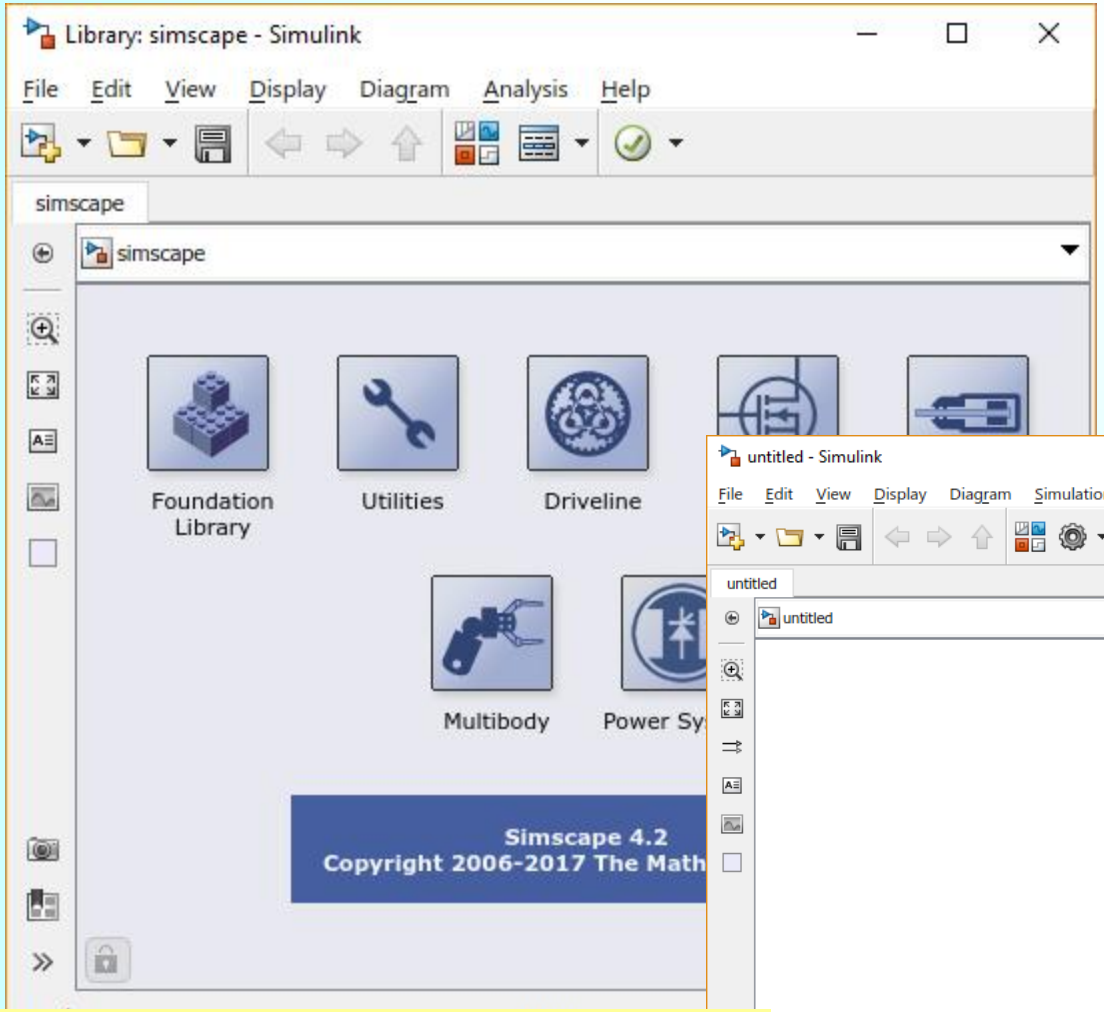
Simulink > Simscape > Foundation Library > Electrical

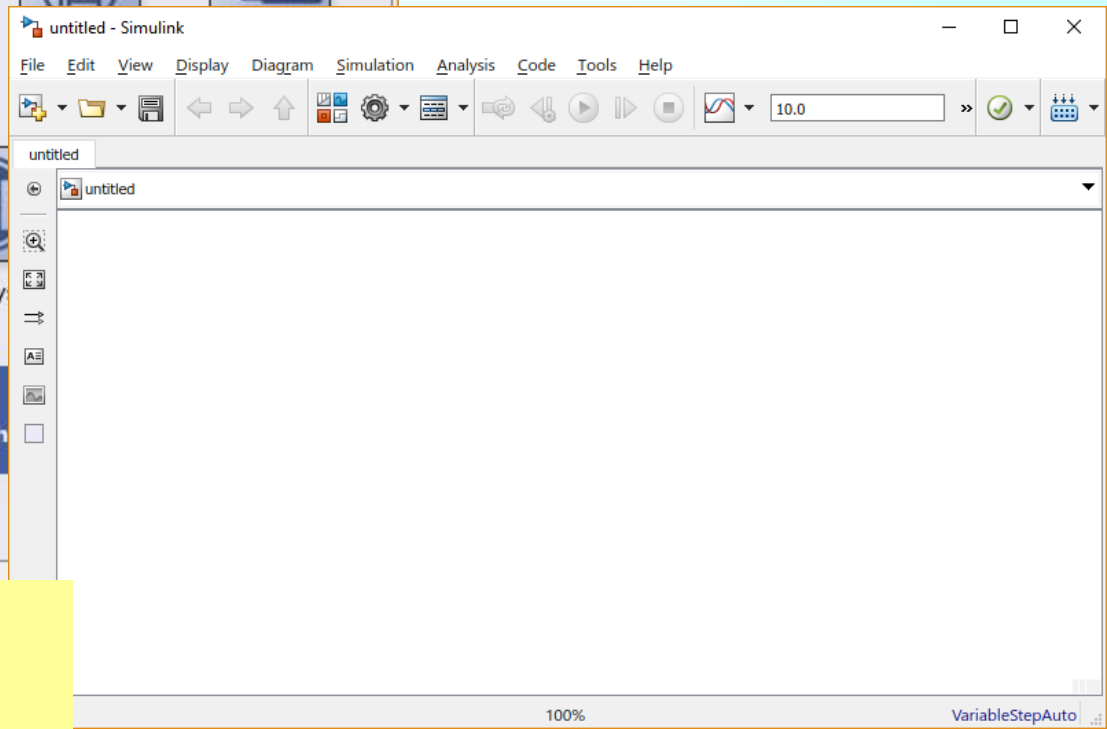
- Симулација линеарних и нелинеатних електричних кола



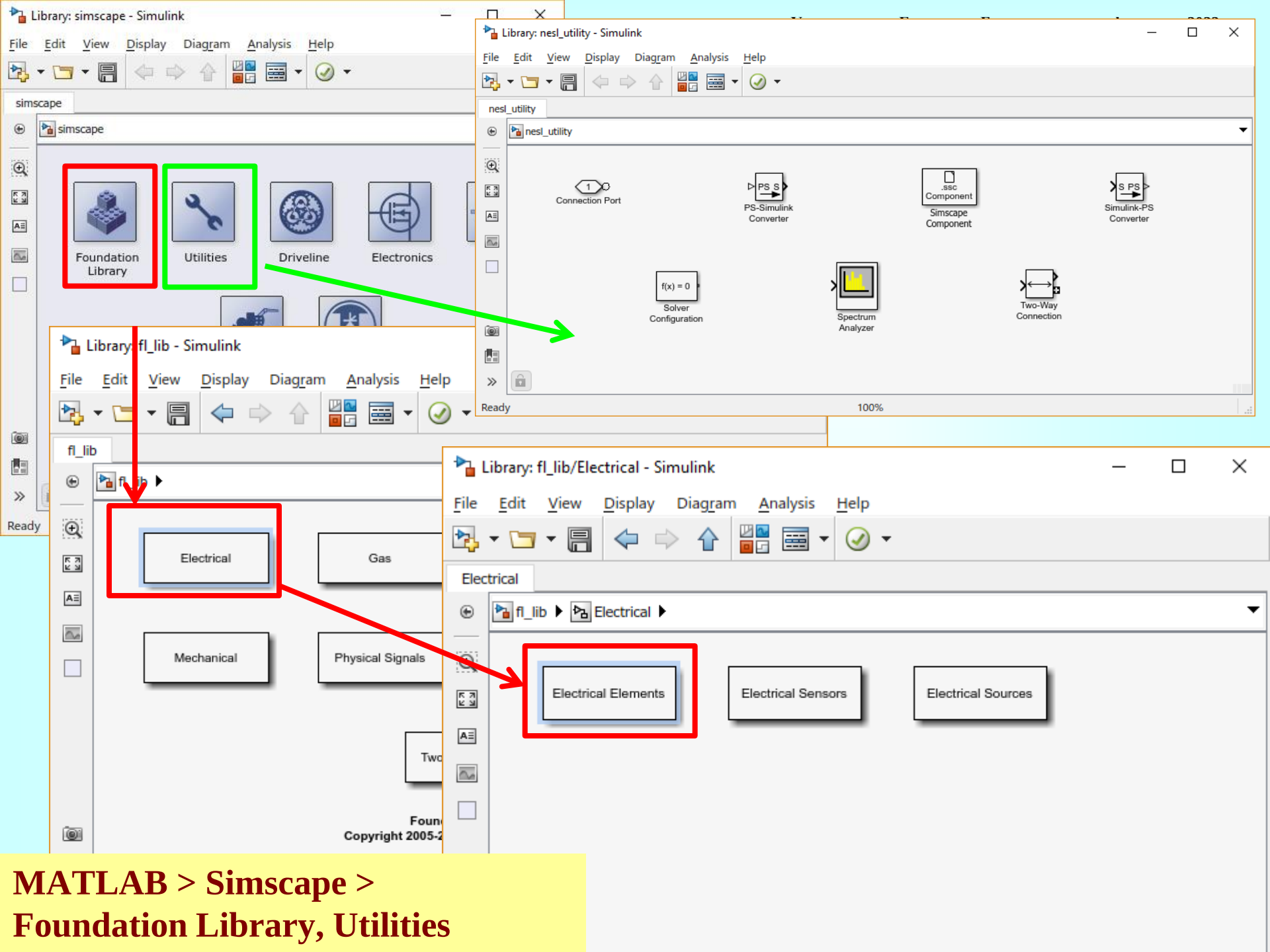
MATLAB > Simscape > Foundation Library, Utilities

Симулација електричног кола коришћењем **Simscape > Foundation Library** библиотеке

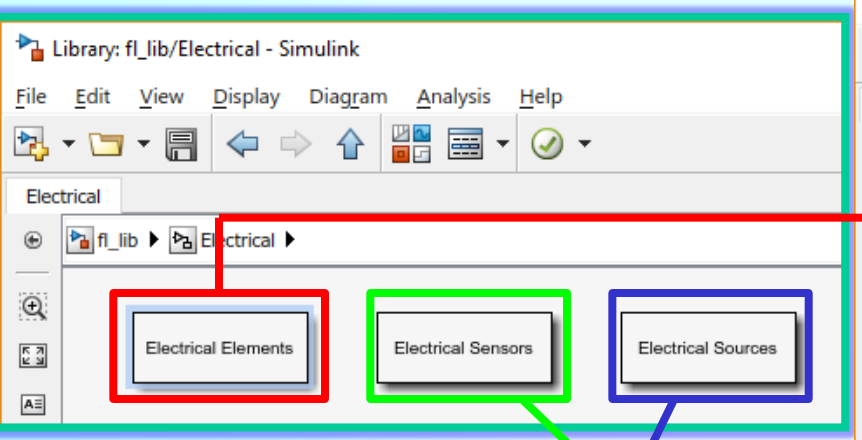




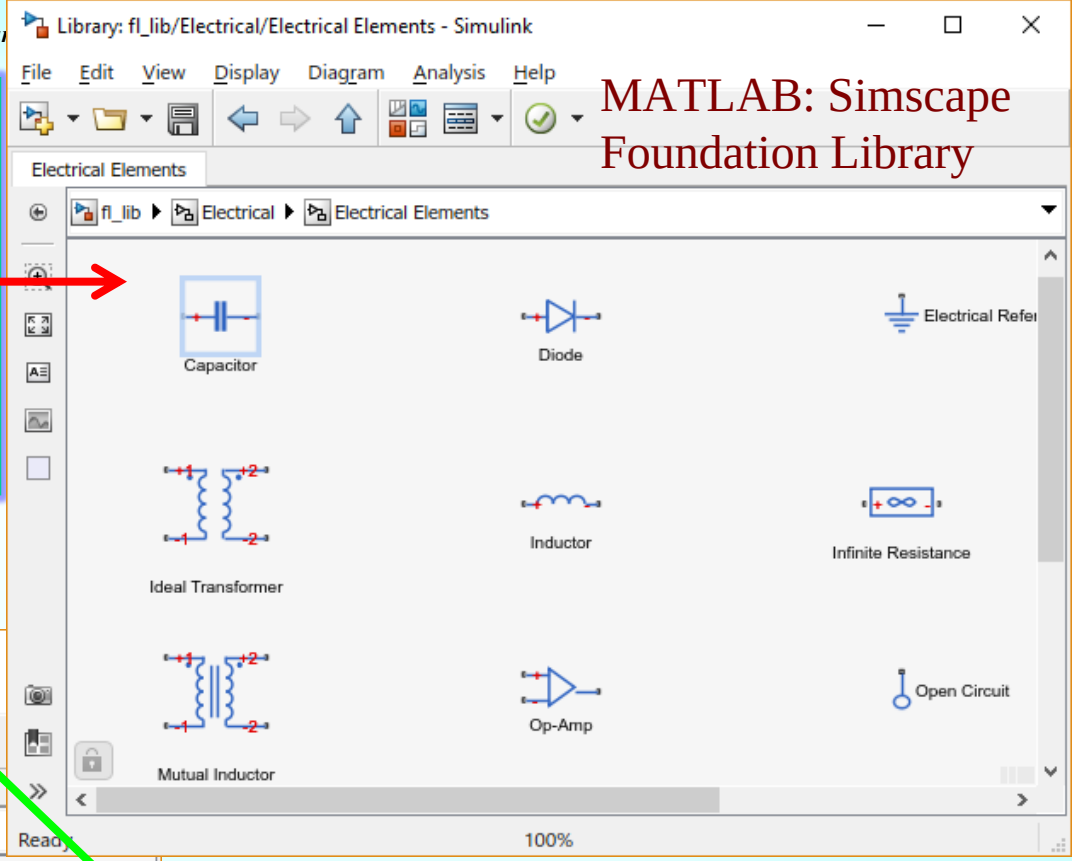
MATLAB > Simscape > Foundation Library, Utilities

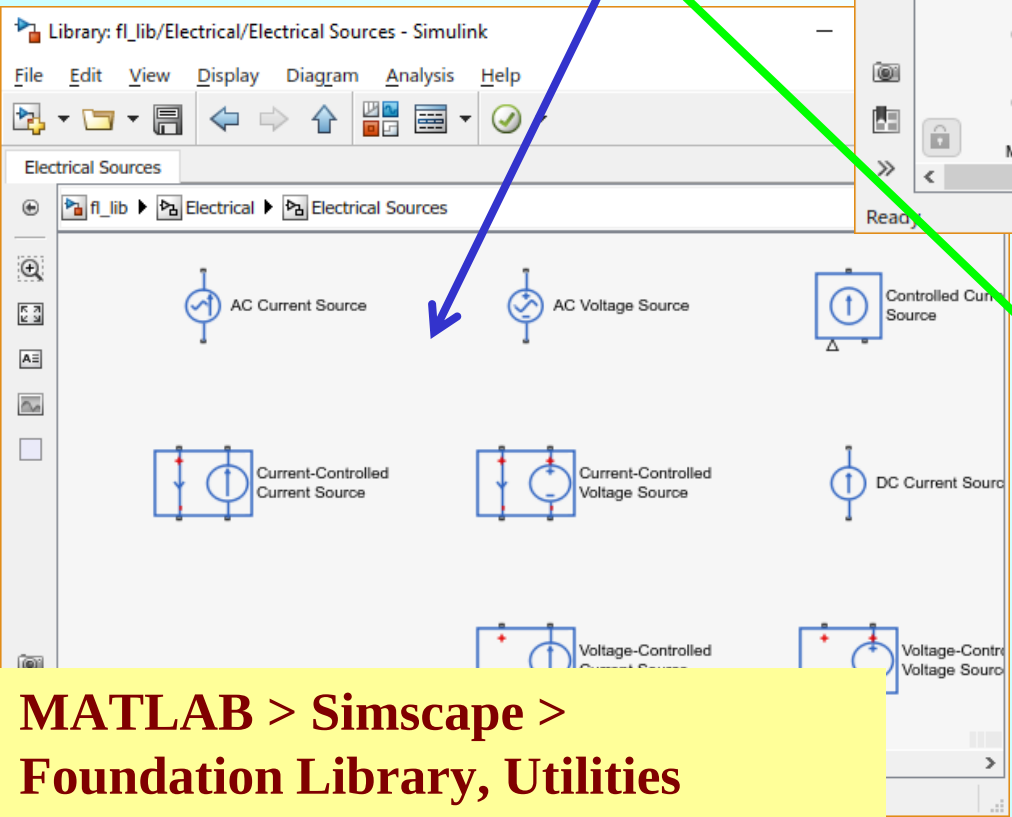


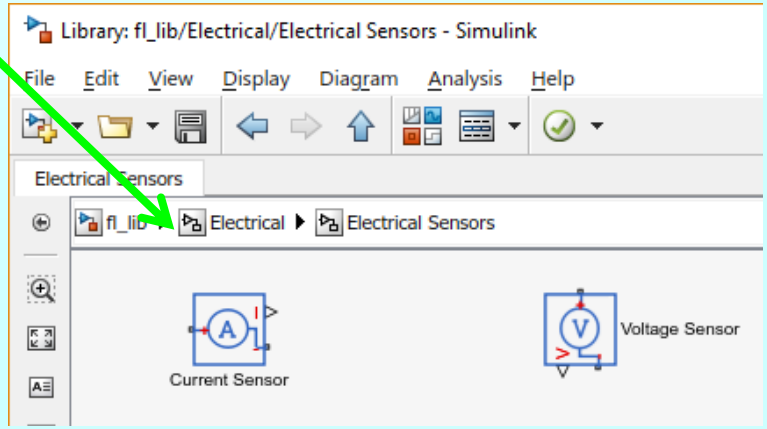
MATLAB > Simscape > Foundation Library, Utilities



MATLAB: Simscape Foundation Library

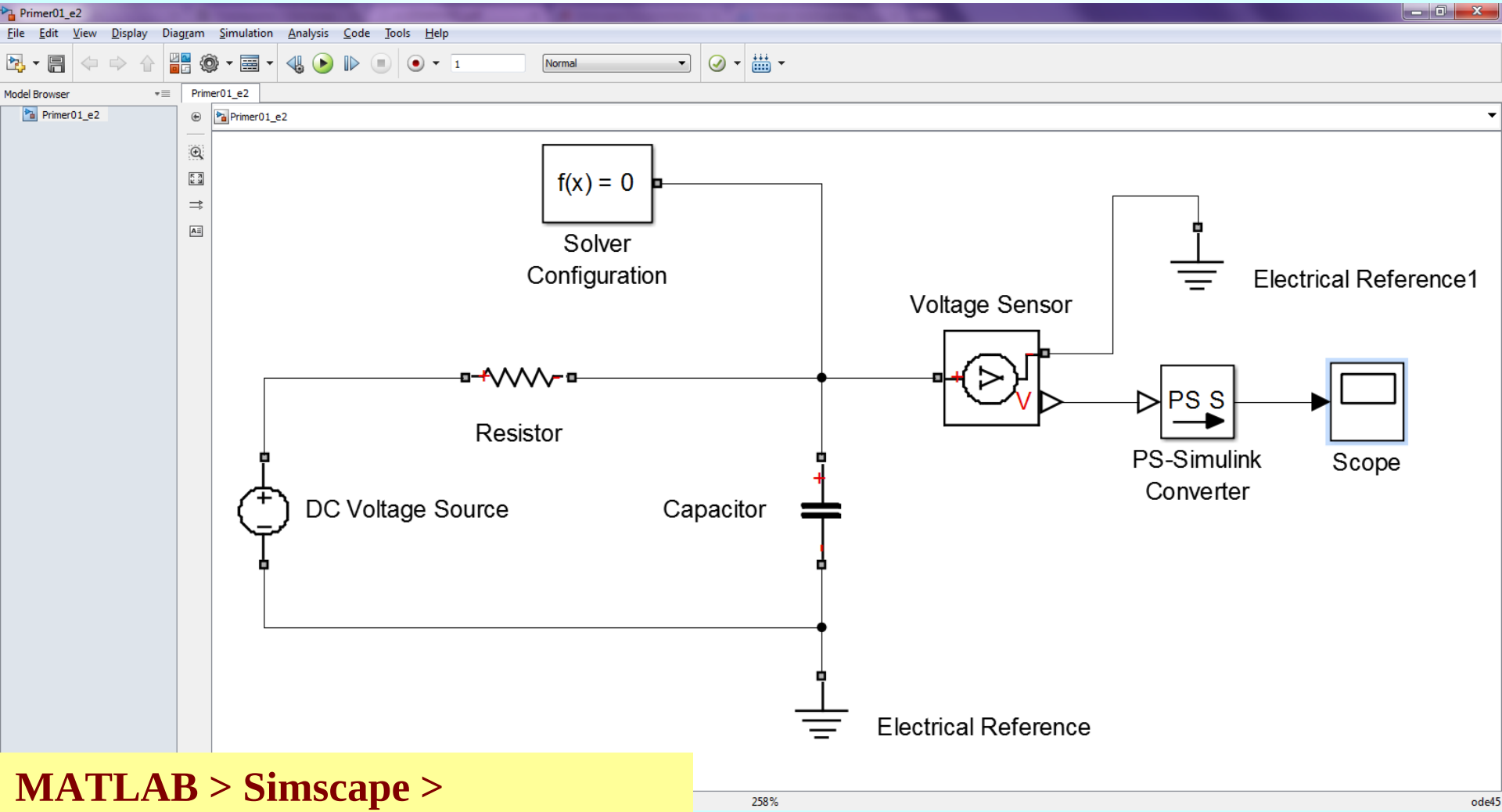




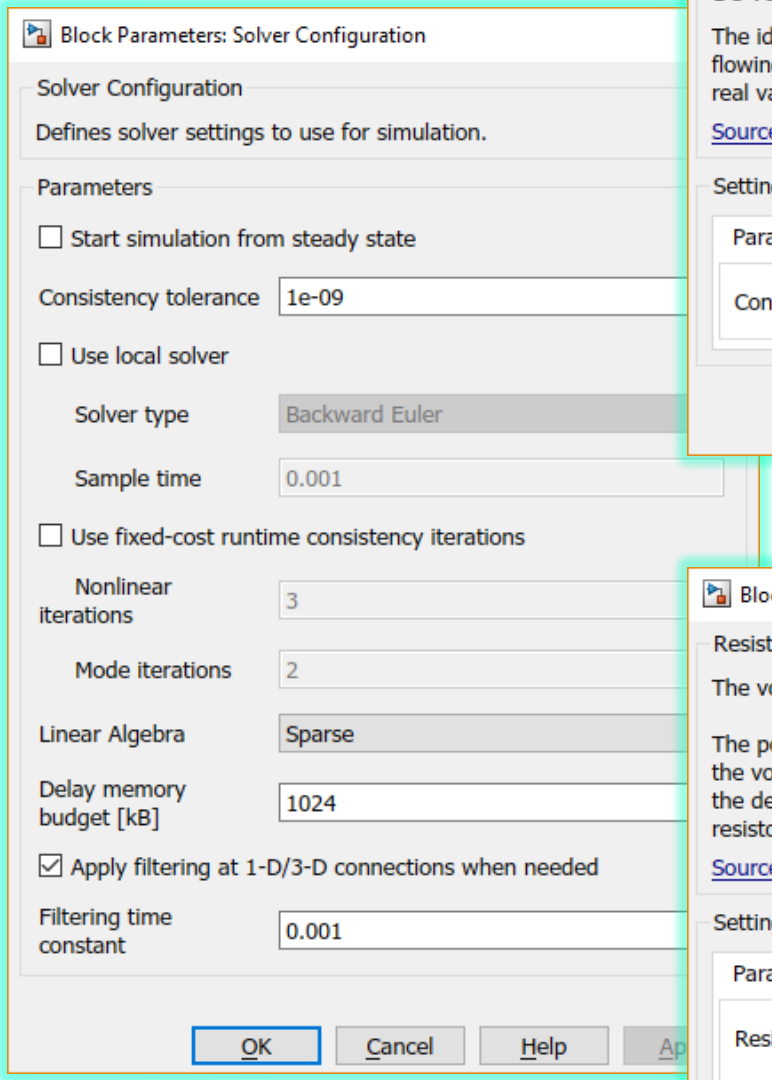


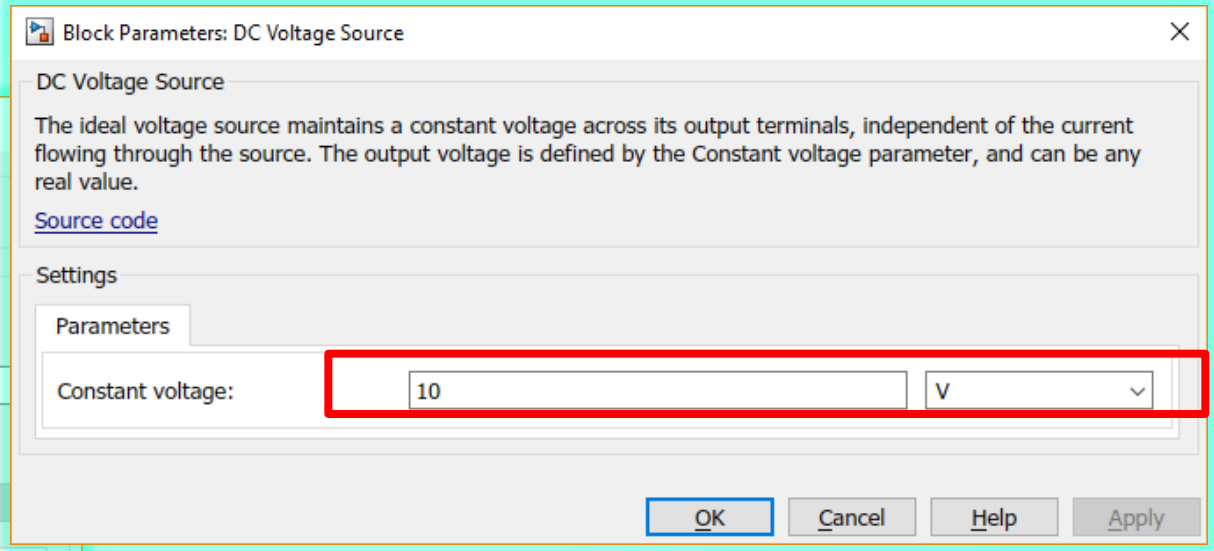
MATLAB > Simscape > Foundation Library, Utilities

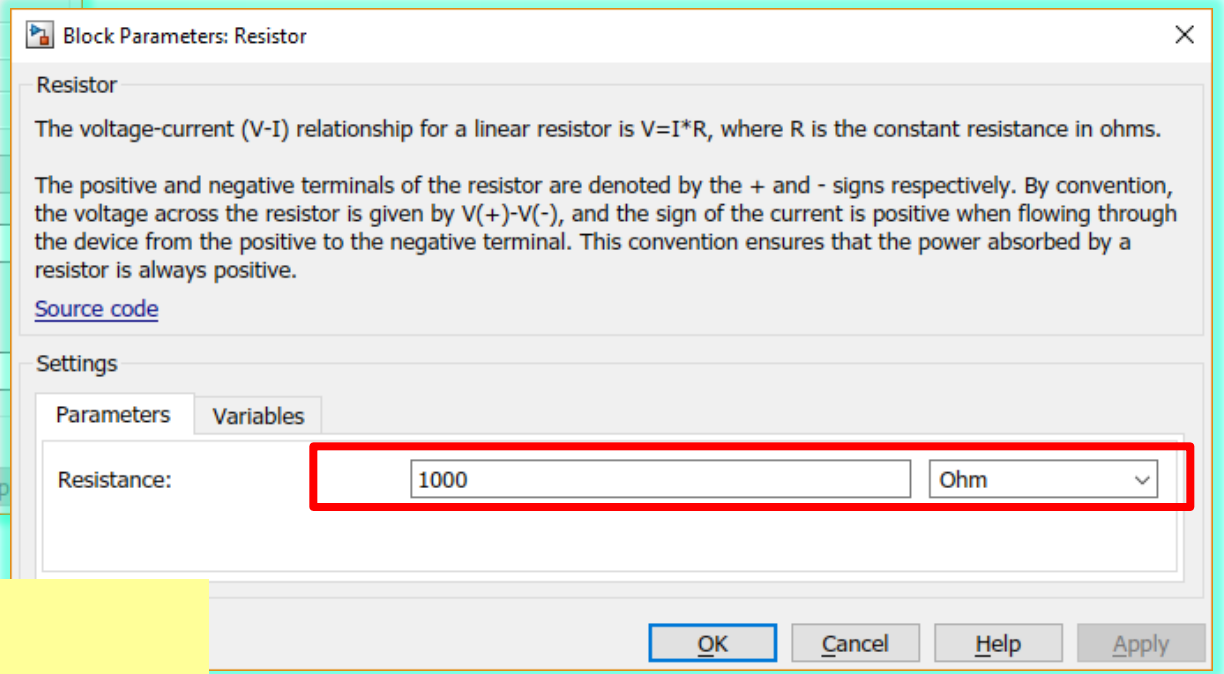
Симулација електричног кола коришћењем **Simscape > Foundation Library** библиотеке



MATLAB > Simscape > Foundation Library, Utilities

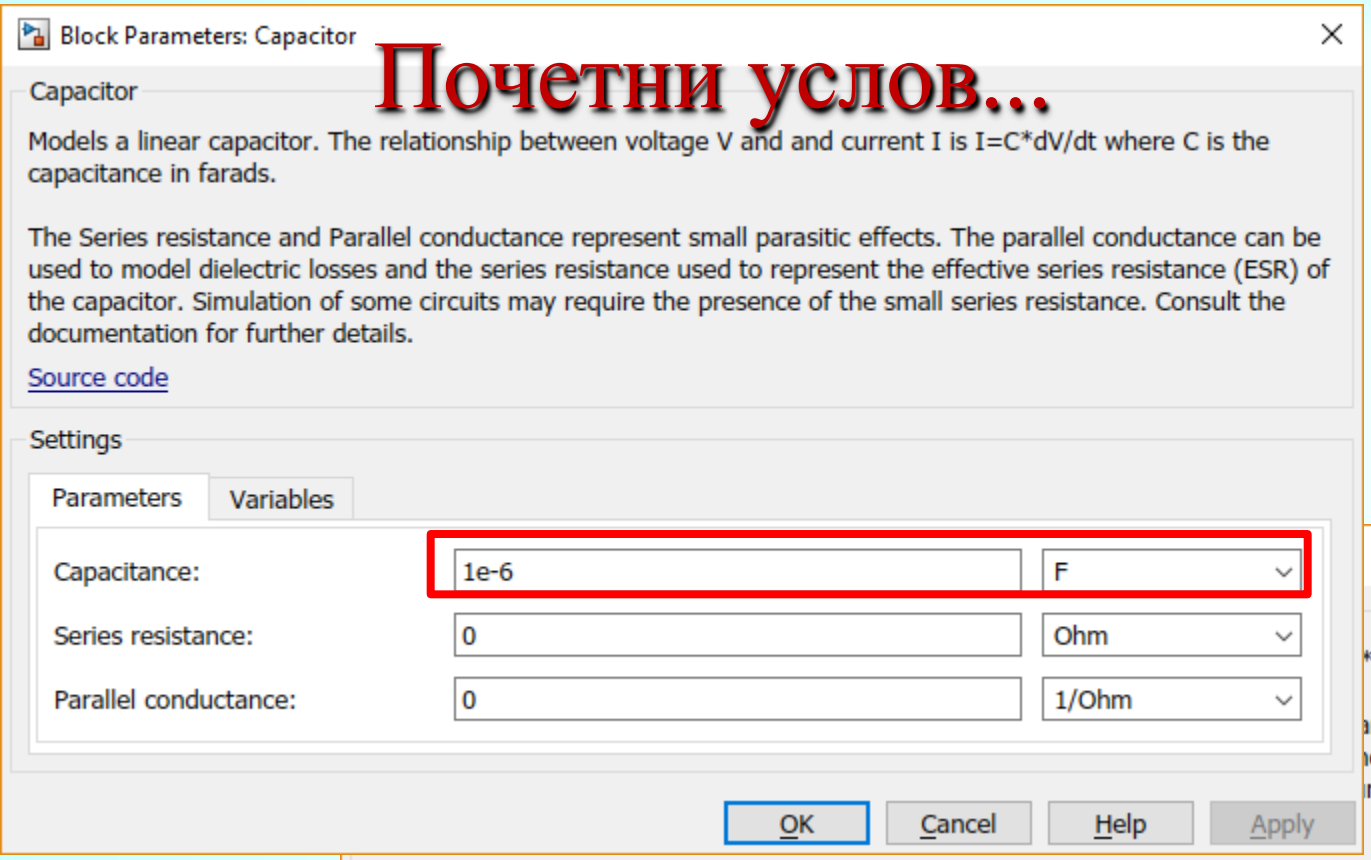


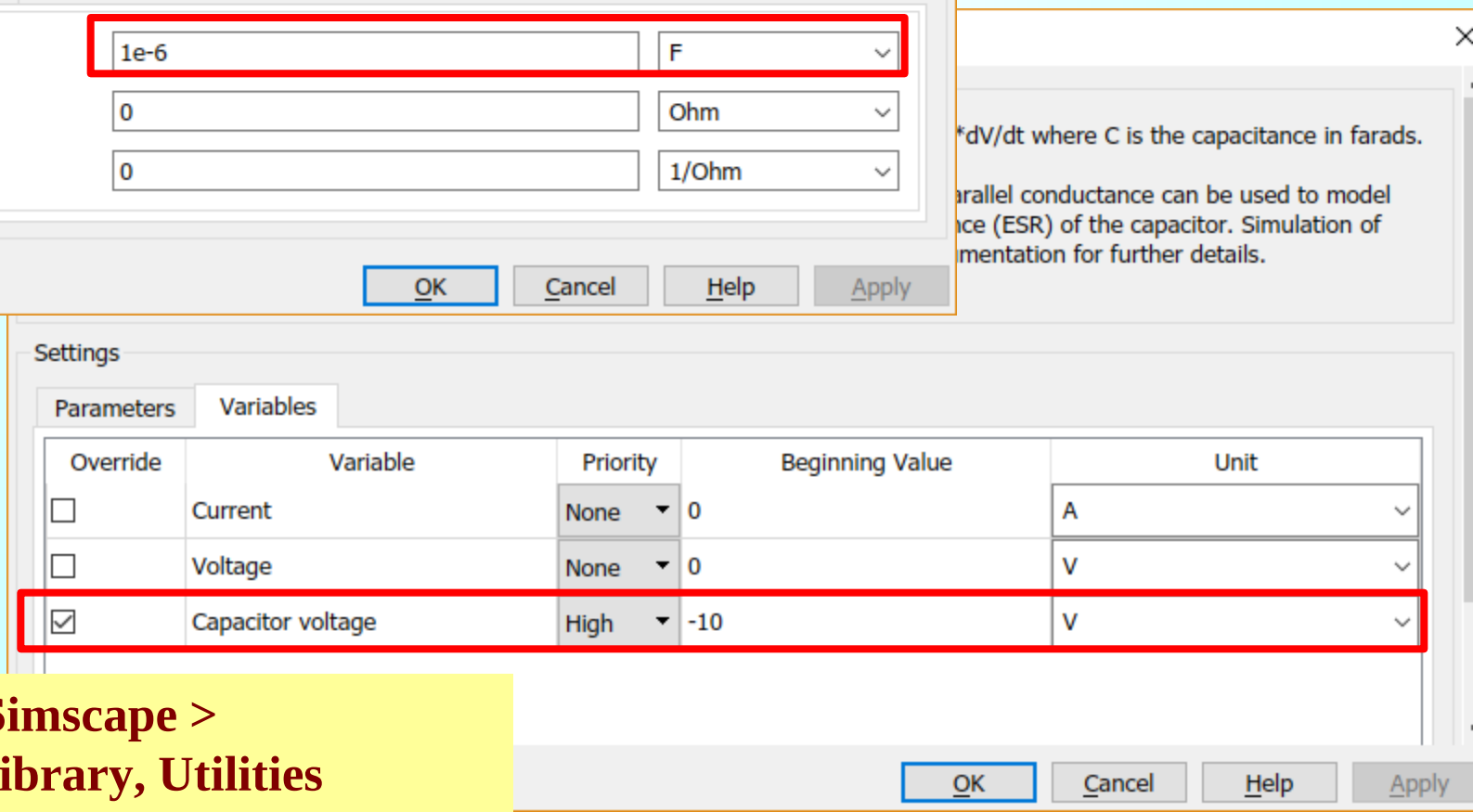




MATLAB > Simscape > Foundation Library, Utilities

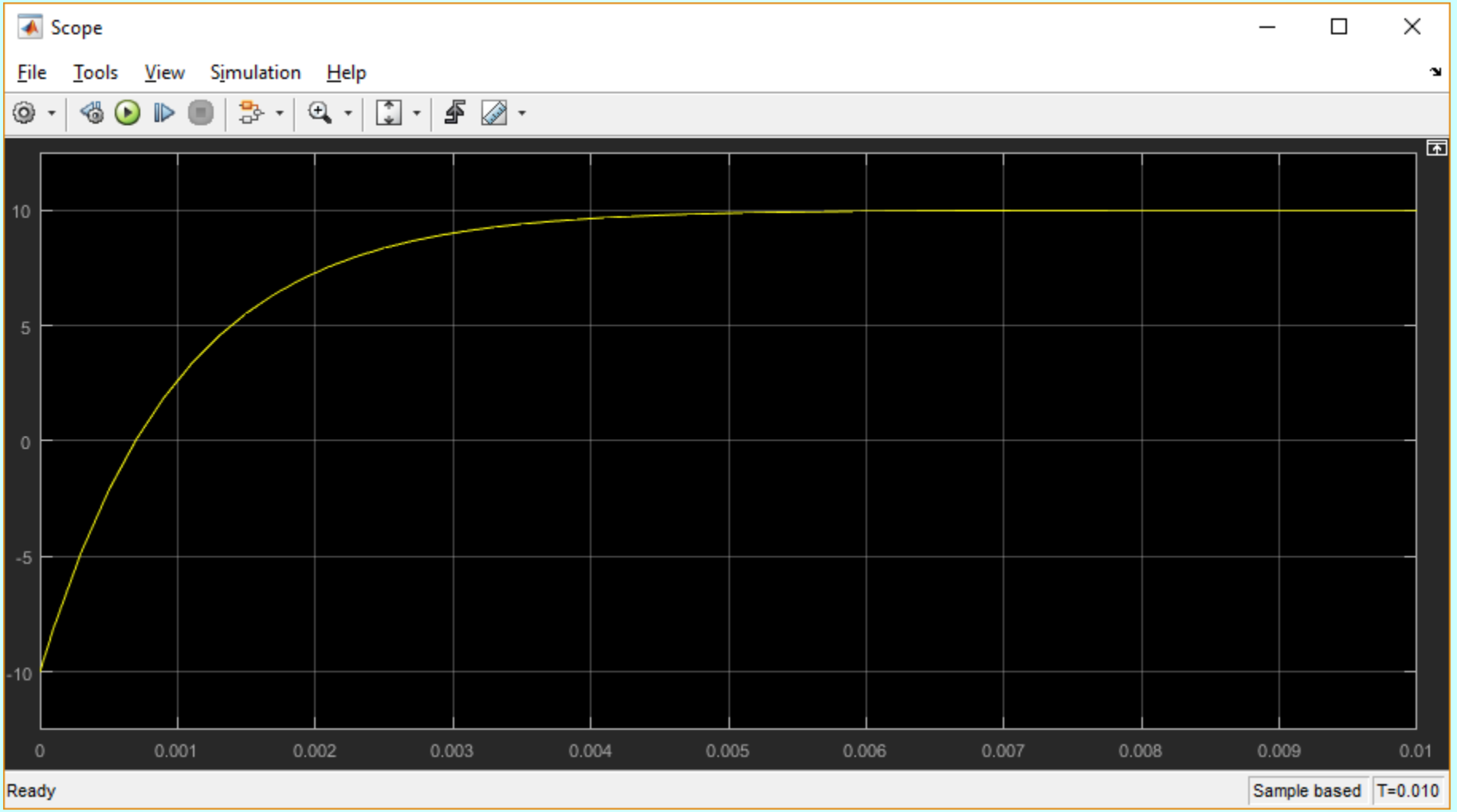
Почетни услов...





MATLAB > Simscape > Foundation Library, Utilities

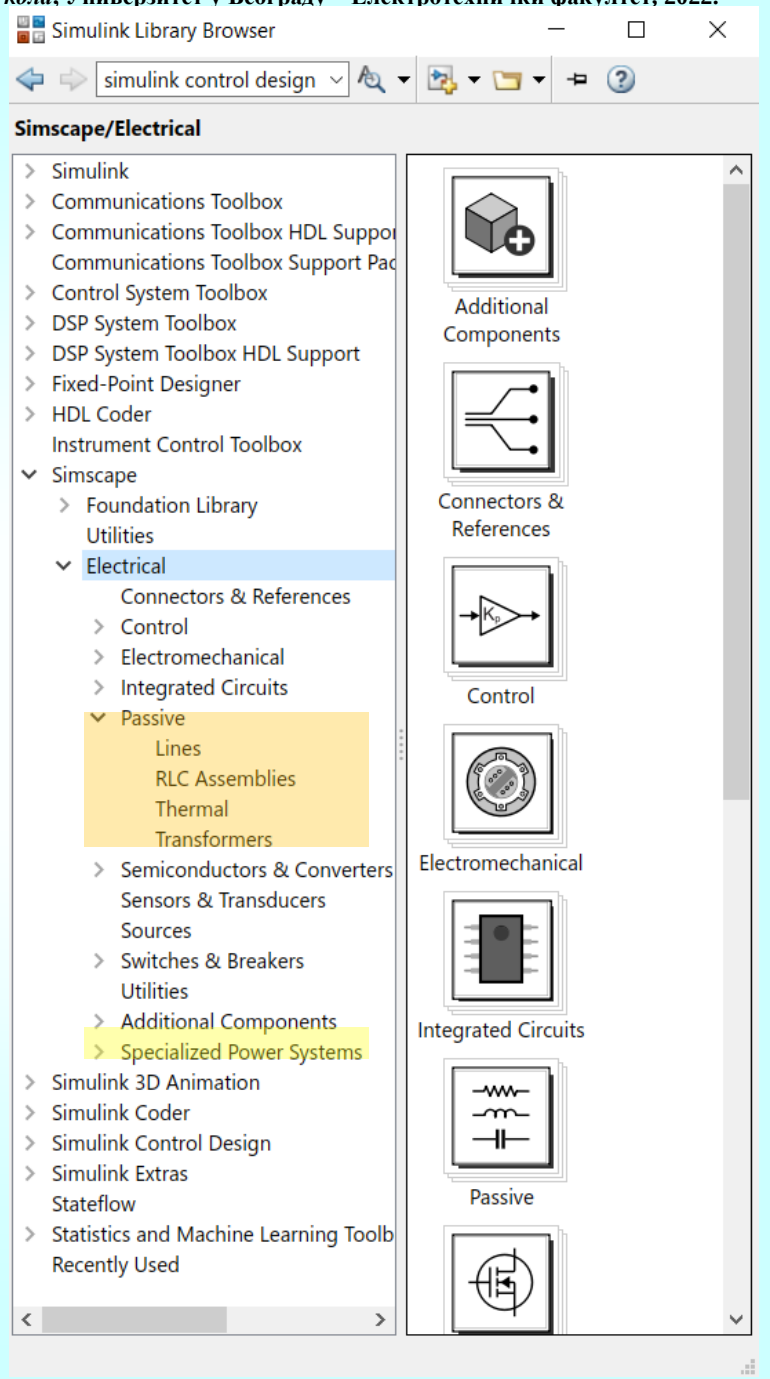
Налажење одзива...



MATLAB > Simscape > Foundation Library, Utilities

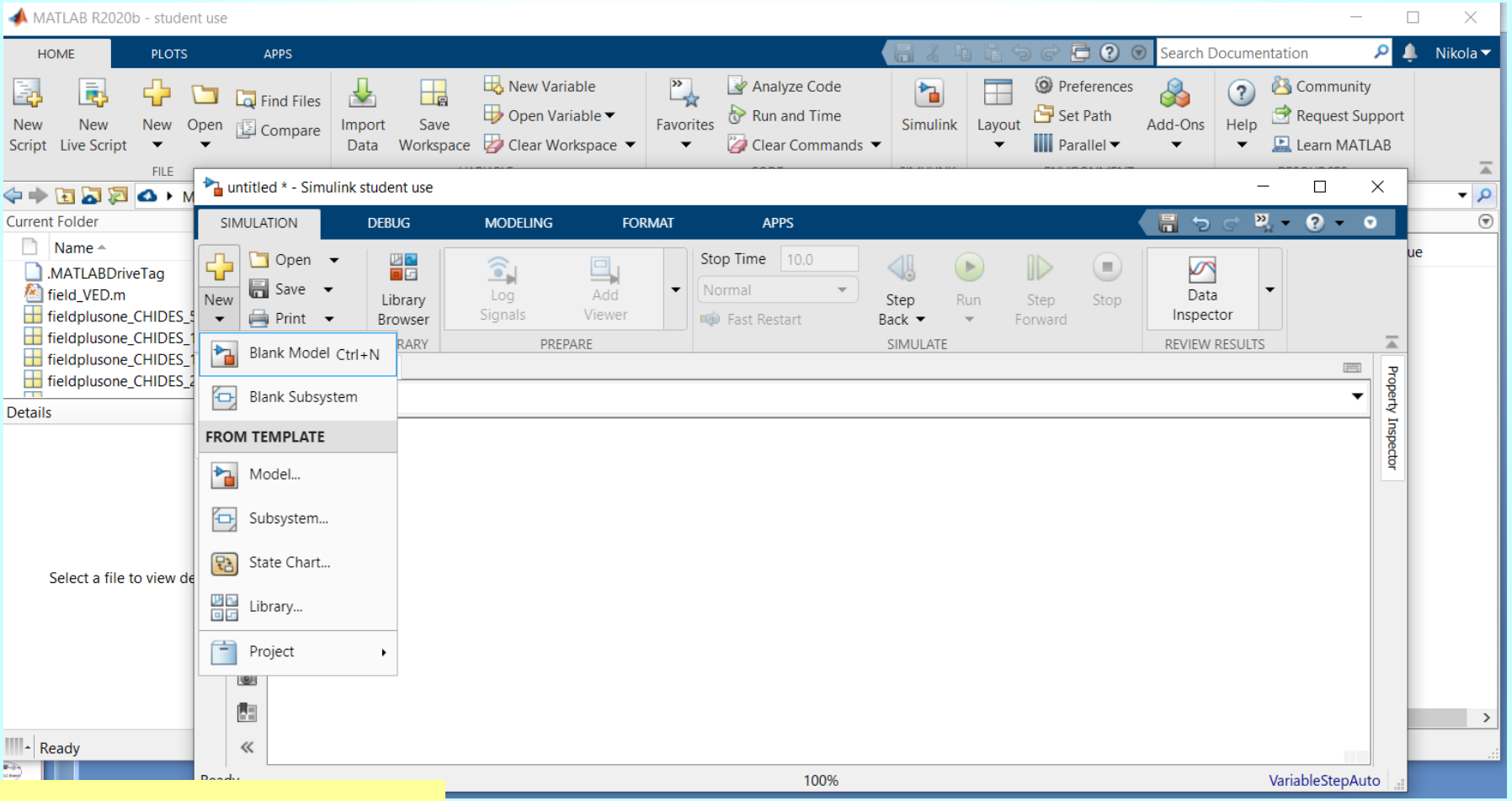
Simulink > Simscape > Electrical

- Библиотека за симулацију и нумеричку анализу електроенергетских система
- Трофазни извори, водови, трансформатори, потрошачи
- Термална анализа



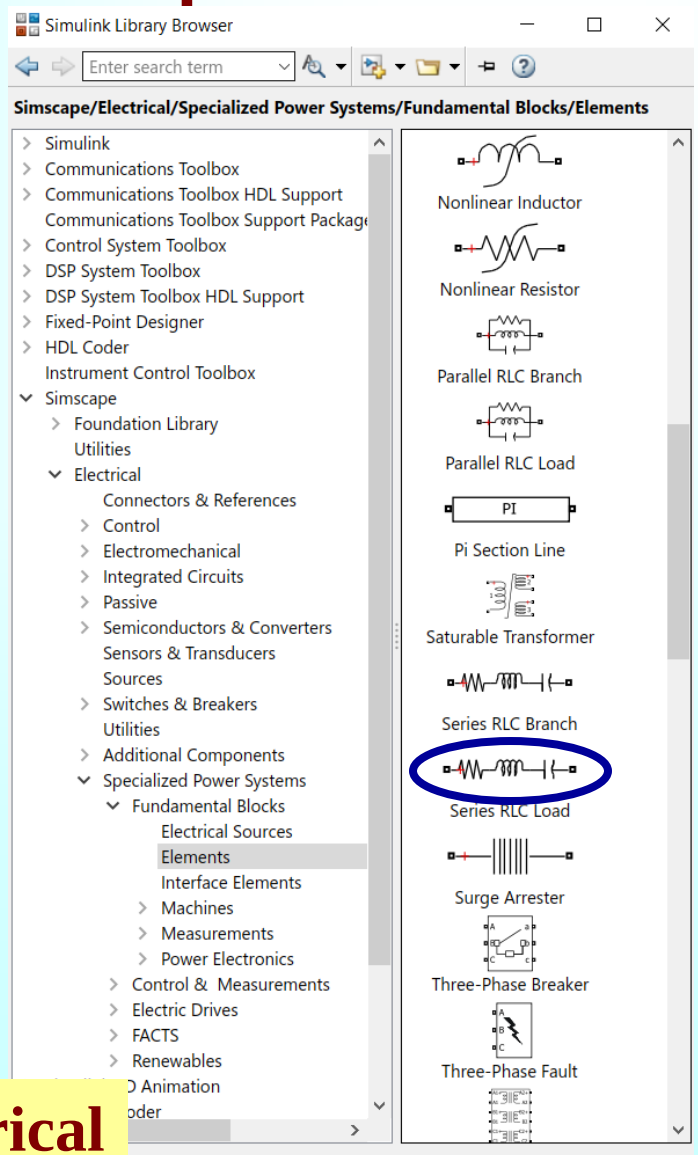
Simscape > Electrical

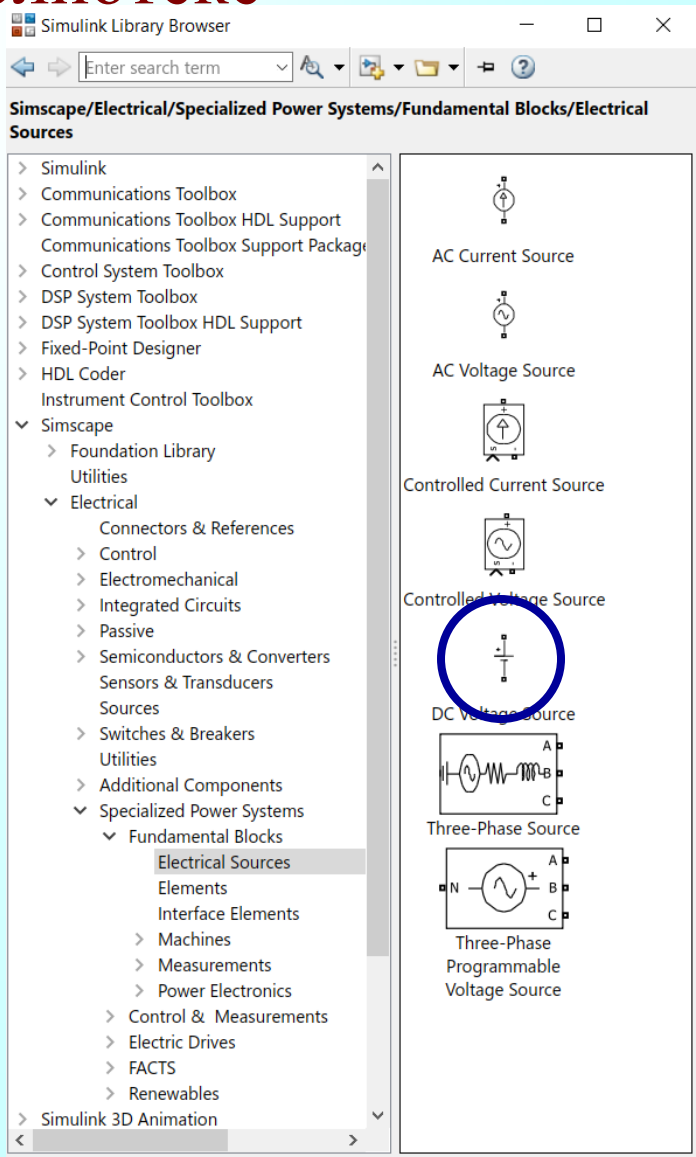
Симулација електричног кола коришћењем **Simscape>Electrical** библиотеке



Simscape > Electrical

Симулација електричног кола коришћењем **Simscape>Electrical** библиотеке

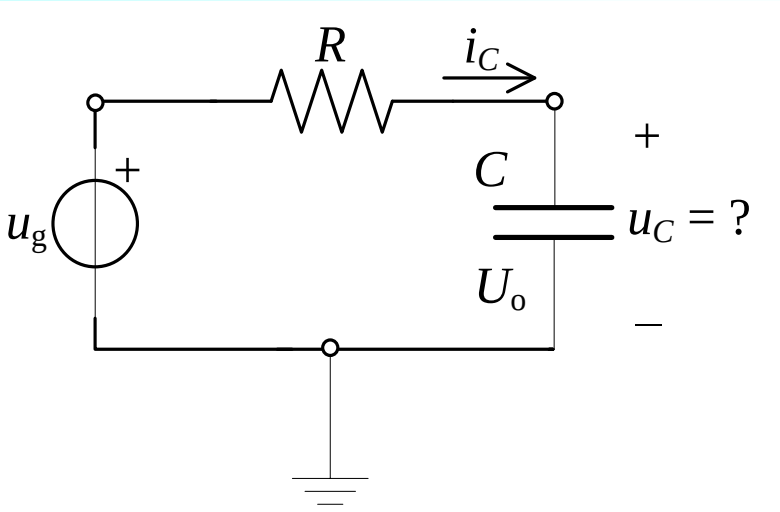


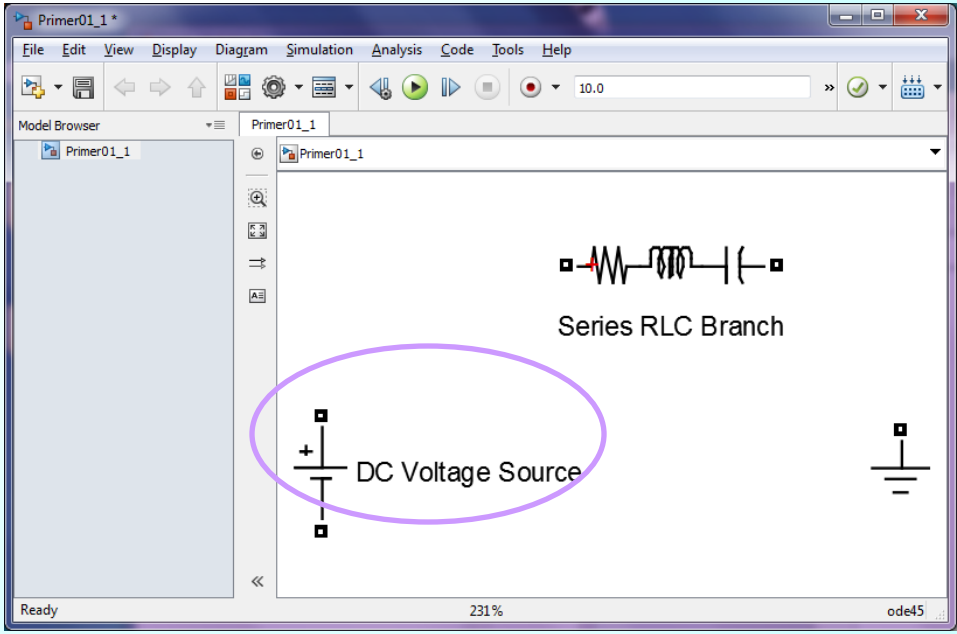


Simscape > Electrical

Симулација електричног кола коришћењем **Simscape>Electrical** библиотеке

коло је образовано у тренутку $t_0 = 0$



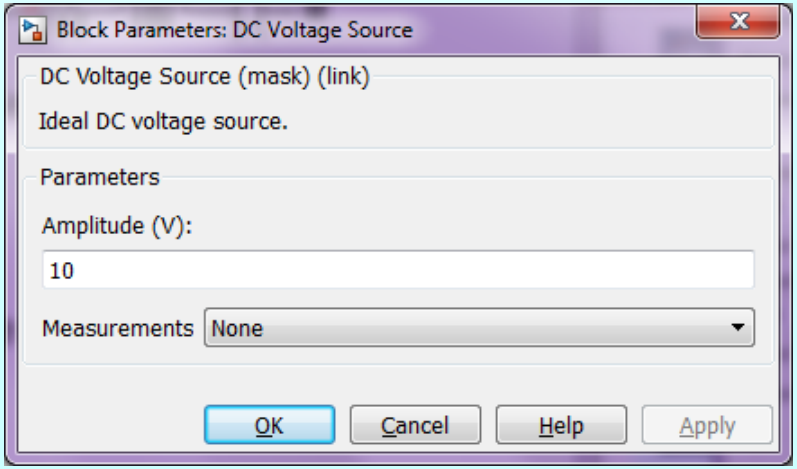


$R = 1\,\mathrm{k\Omega}$

$C = 1\,\mu\mathrm{F}$

$u_g(t) = U\,h(t), U = 10\,\mathrm{V}$

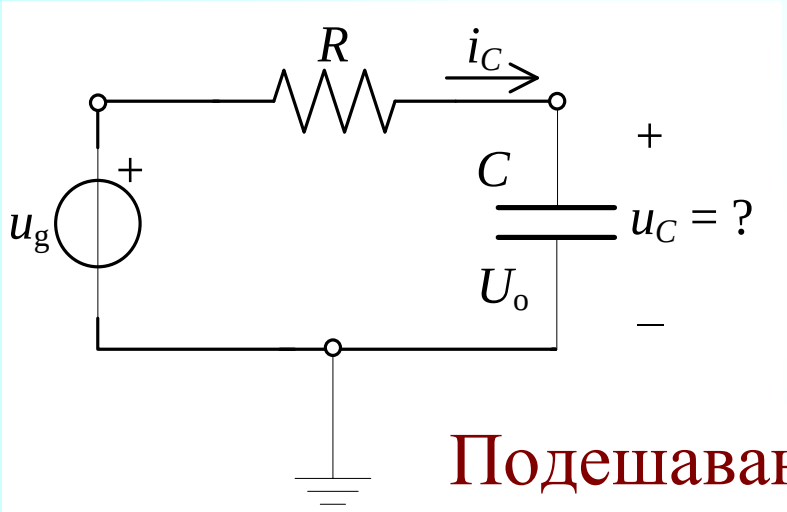
$u(t_0^-) = U_0 = -10\,\mathrm{V}$



Simscape > Electrical

Симулација електричног кола коришћењем **Simscape>Electrical** библиотеке

коло је образовано у тренутку $t_0 = 0$



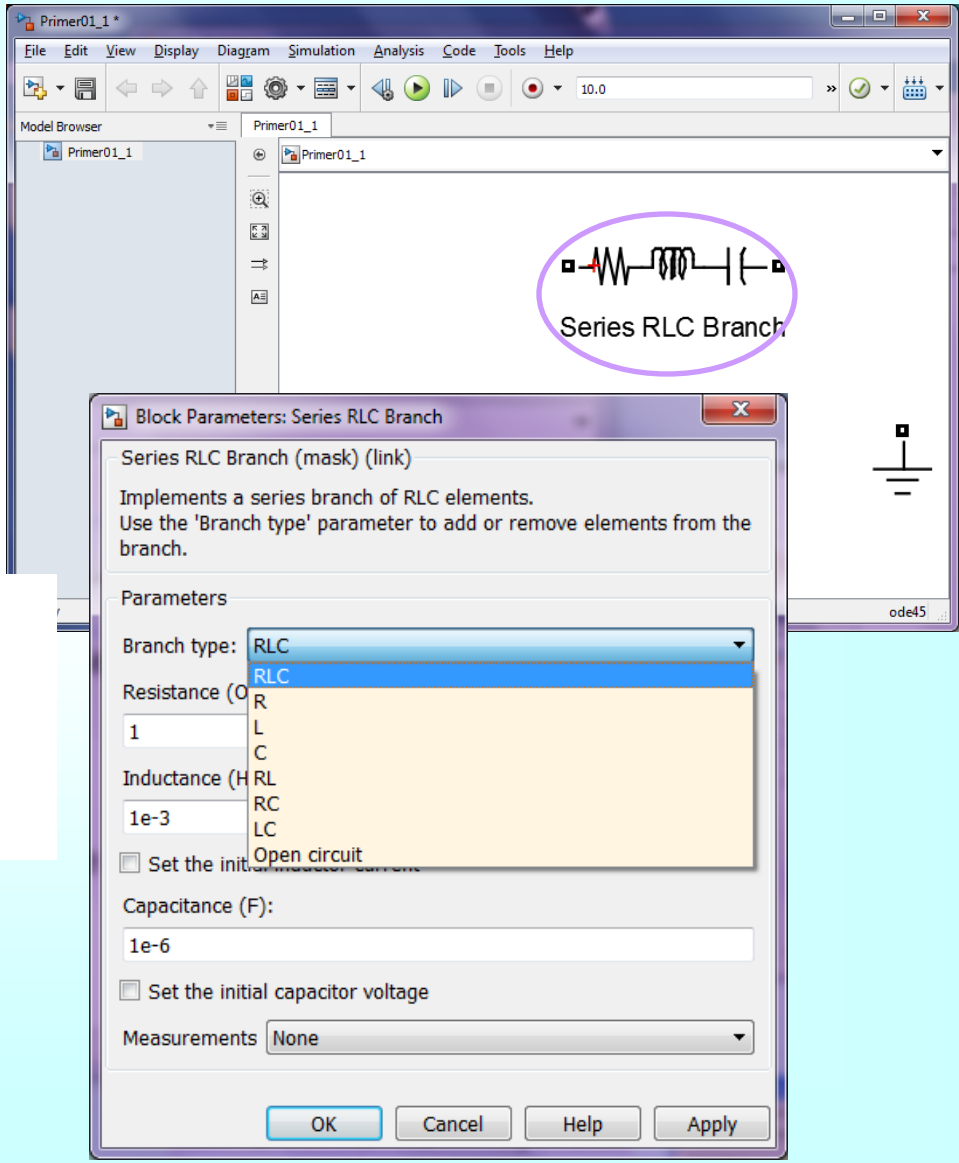
$R = 1\,\mathrm{k\Omega}$

$C = 1\,\mu\mathrm{F}$

$u_g(t) = U\,h(t), U = 10\,\mathrm{V}$

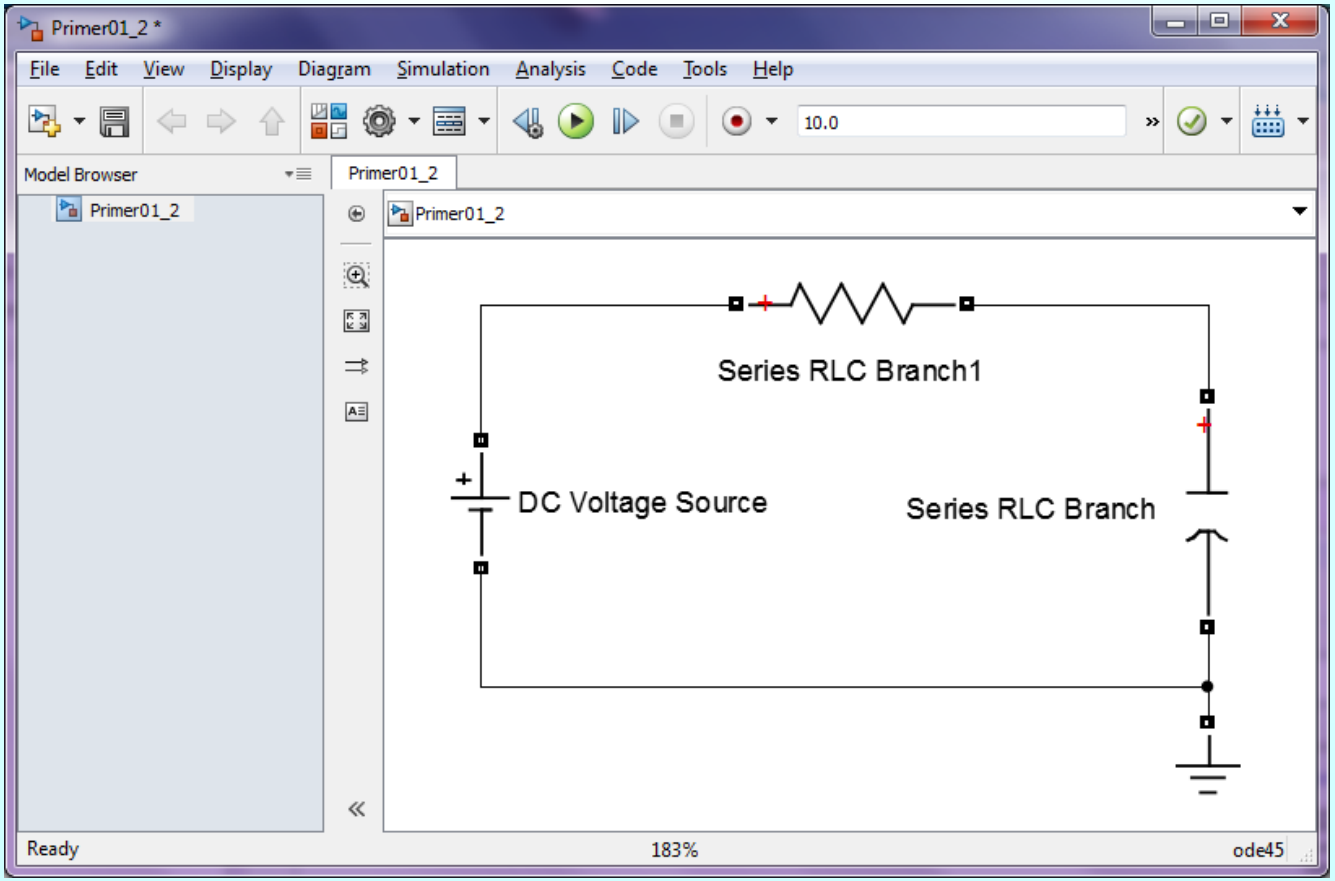
$u(t_0^-) = U_0 = -10\,\mathrm{V}$

Подешавање параметара симулације



Simscape > Electrical

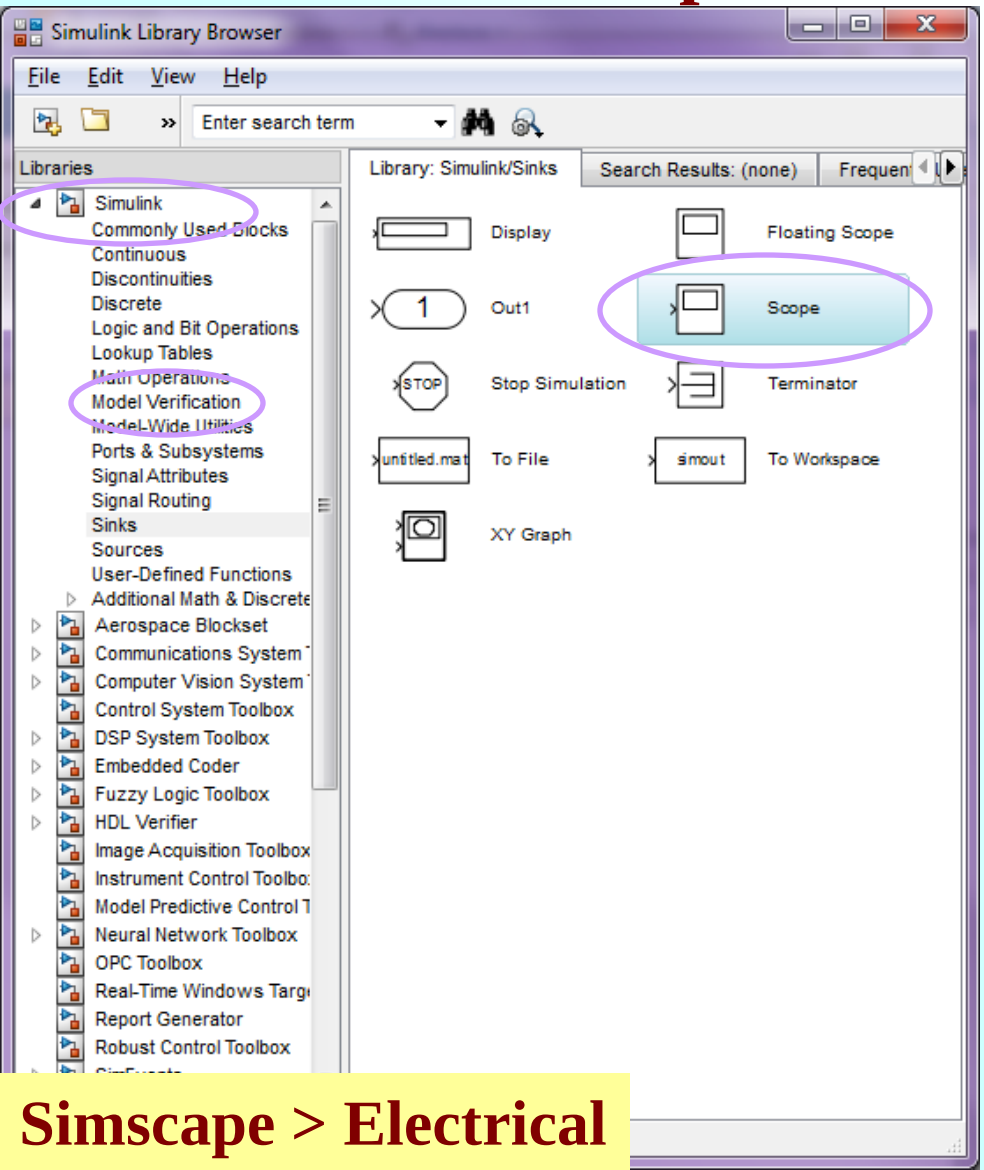
Симулација електричног кола коришћењем **Simscape>Electrical** библиотеке

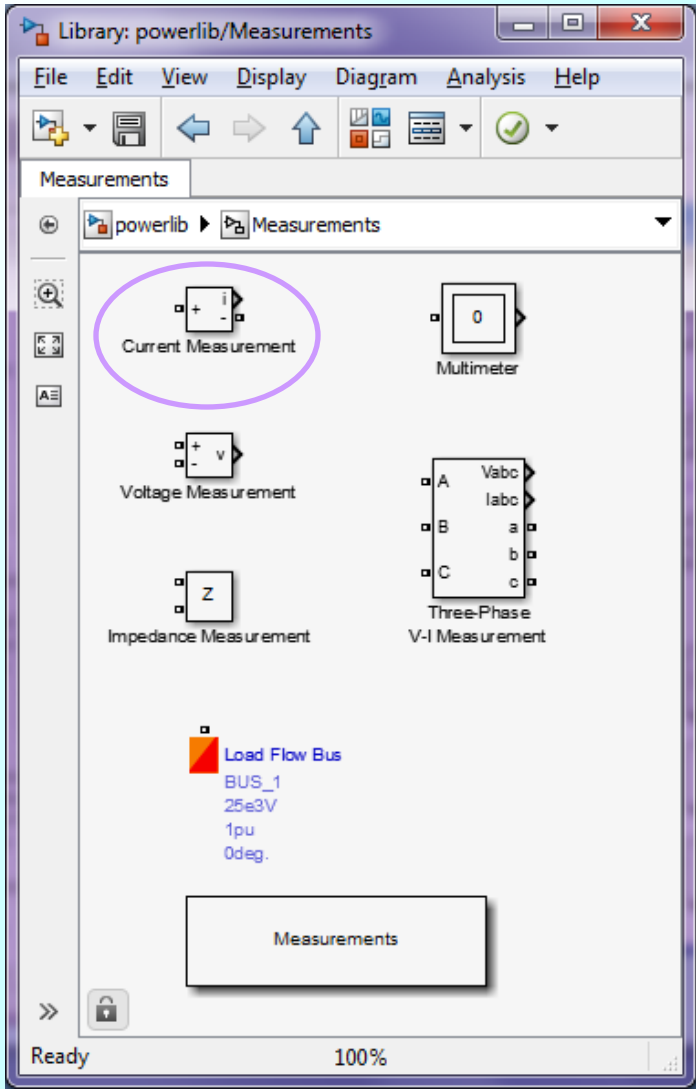


Како се мери напон???

Simscape > Electrical

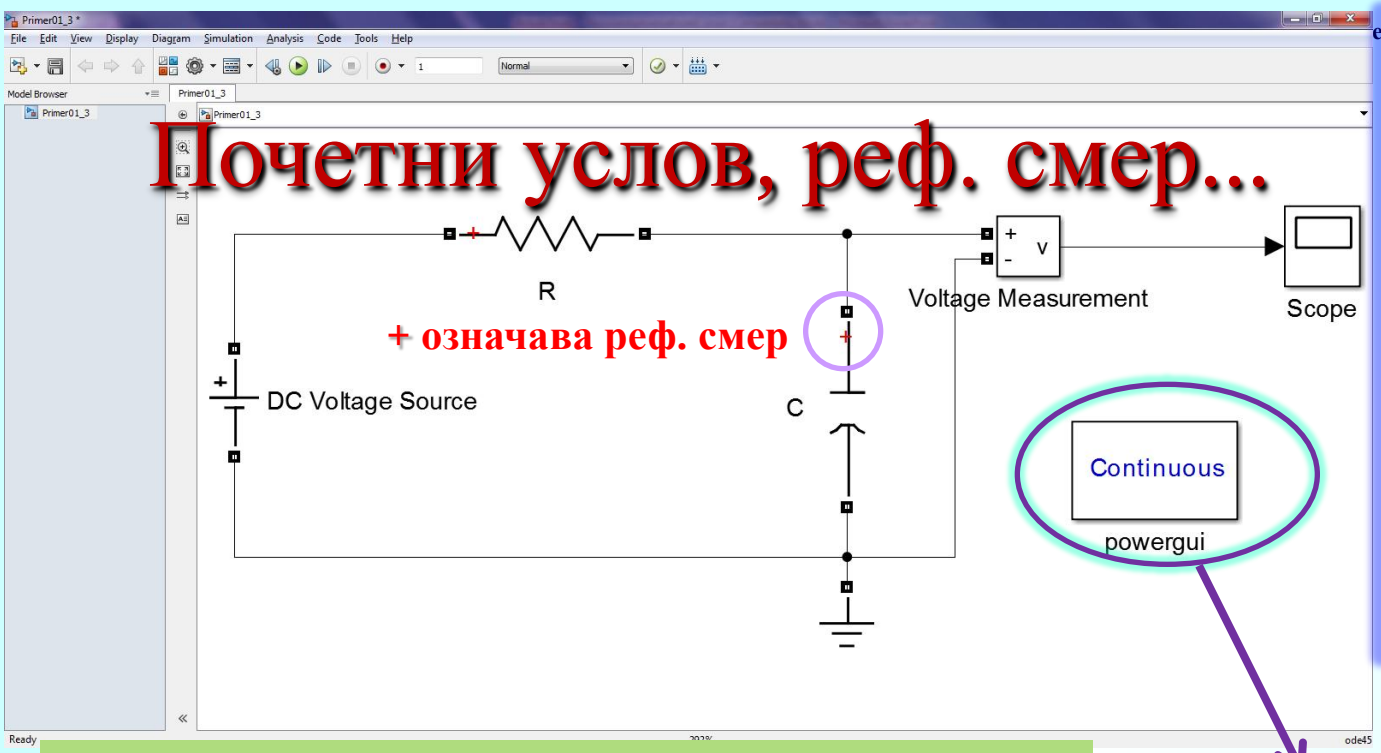
Симулација електричног кола коришћењем **Simscape>Electrical** библиотеке





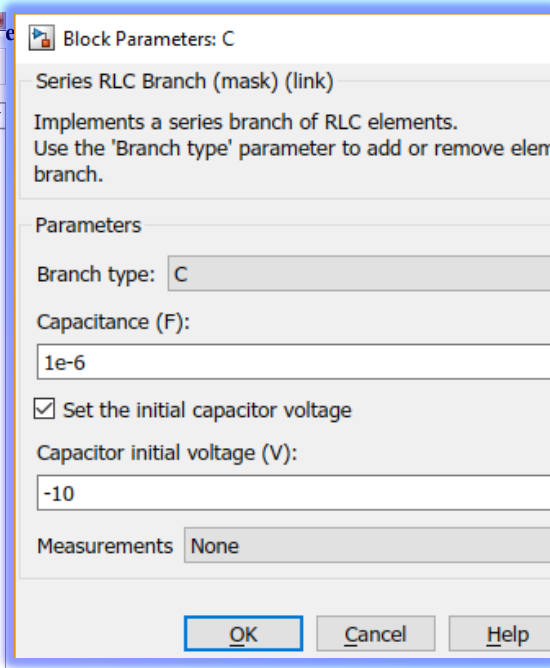
Simscape > Electrical

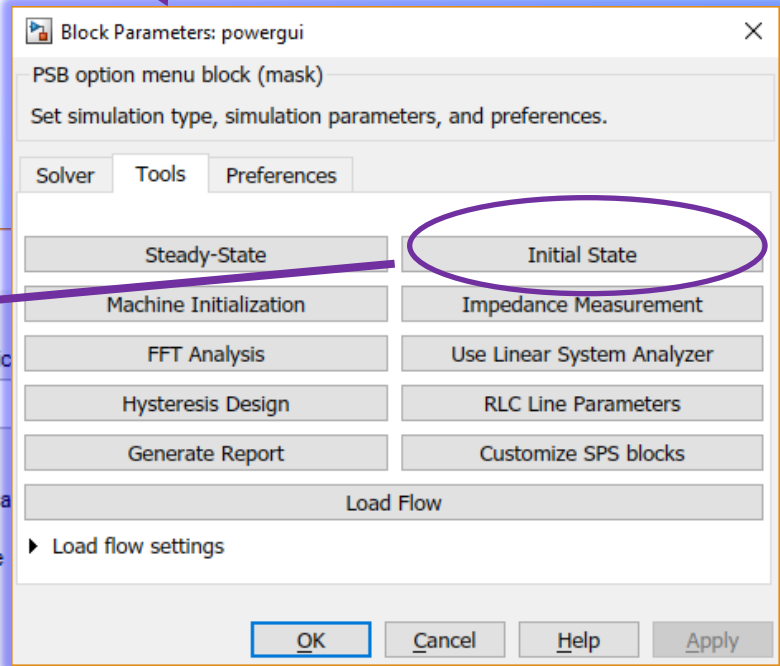
Почетни услов, реф. смер...

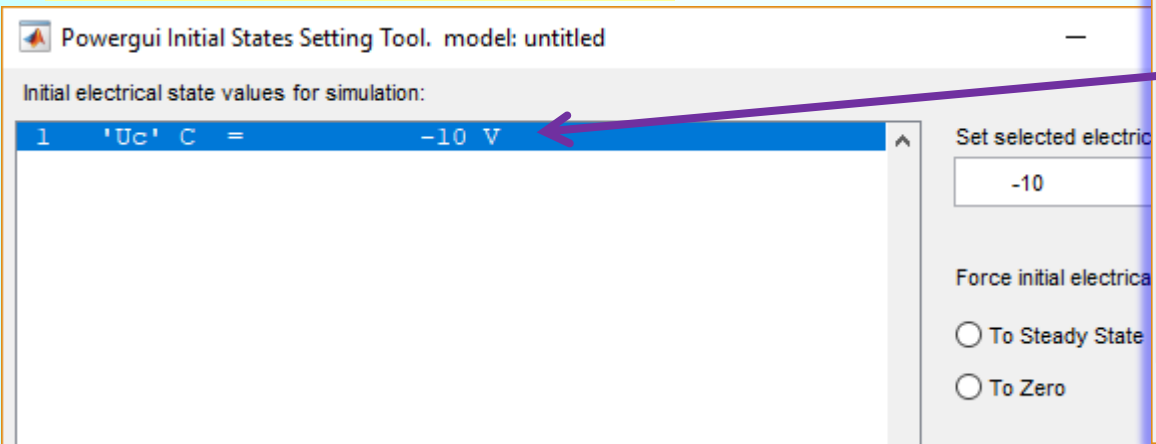


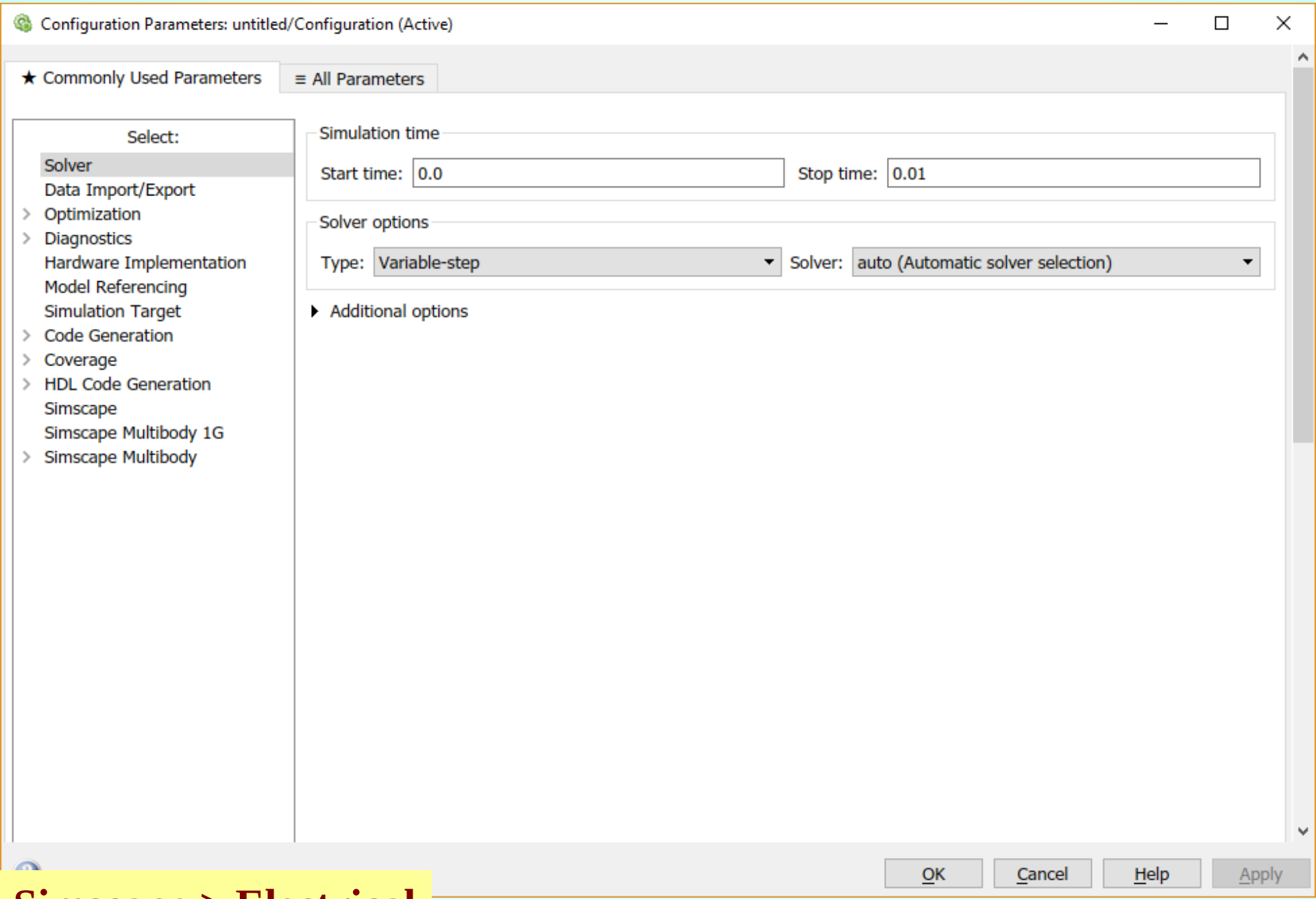
Плоче кондезатора се разликују!!!

Simscape > Electrical

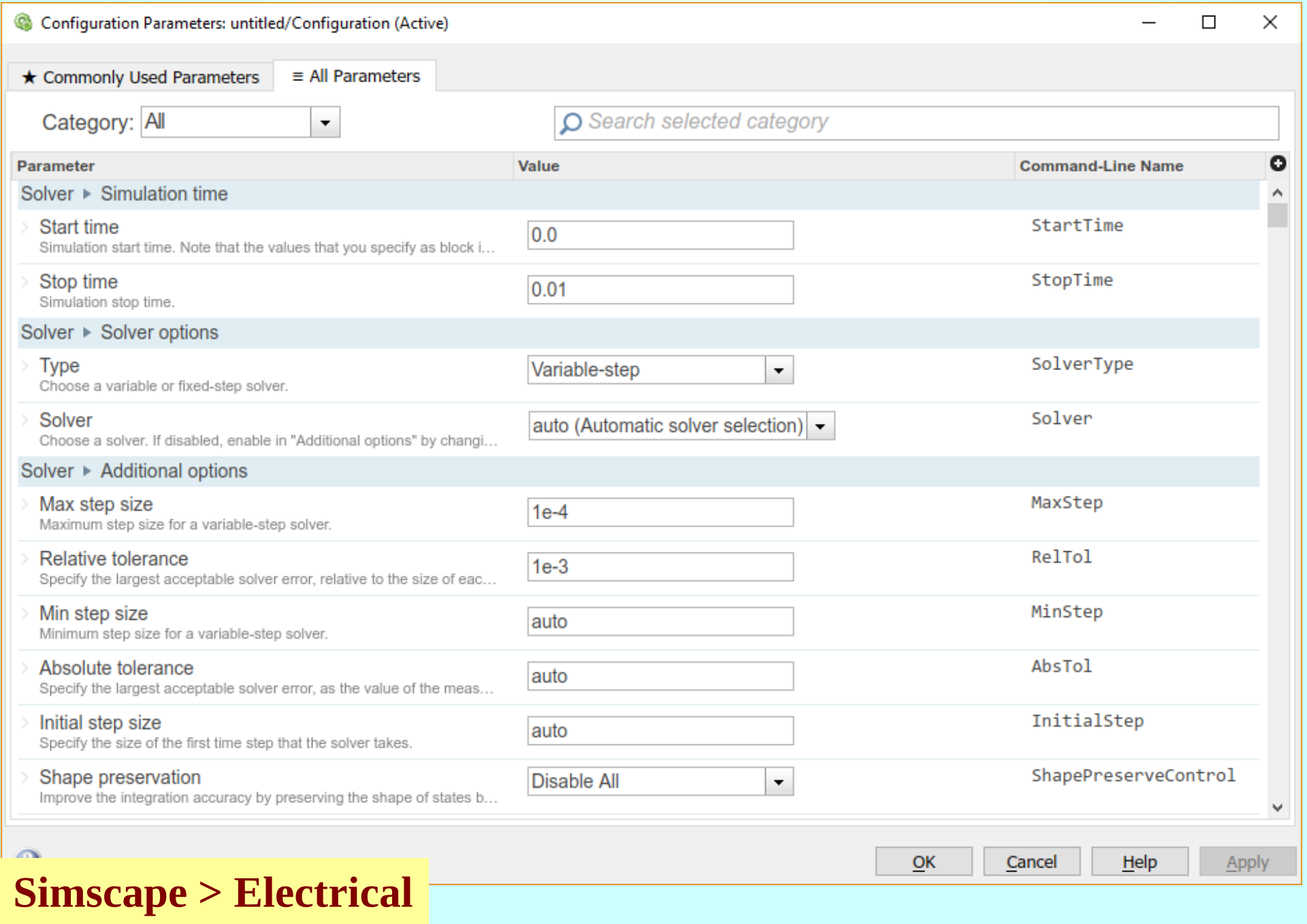






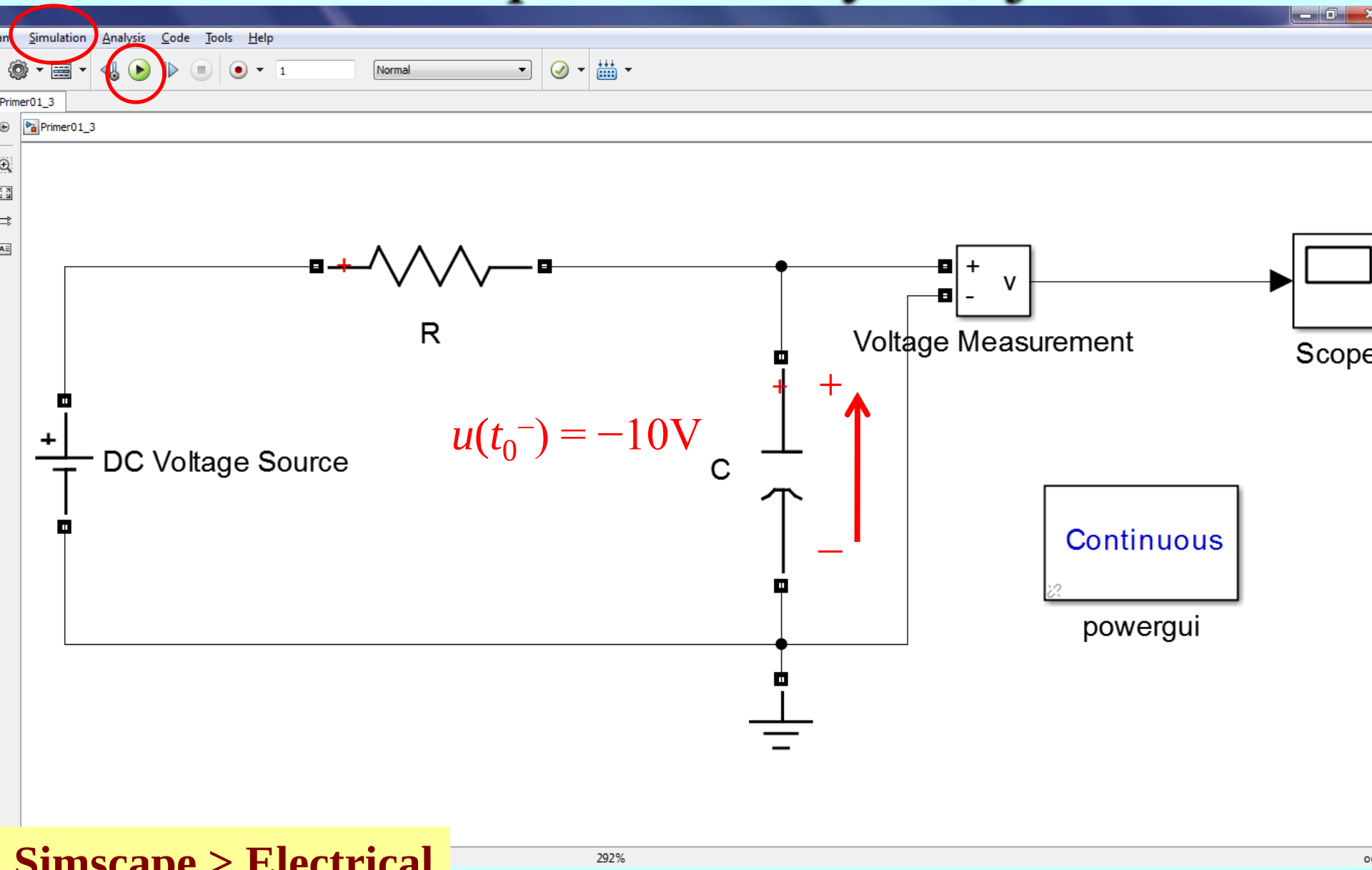


Simscape > Electrical



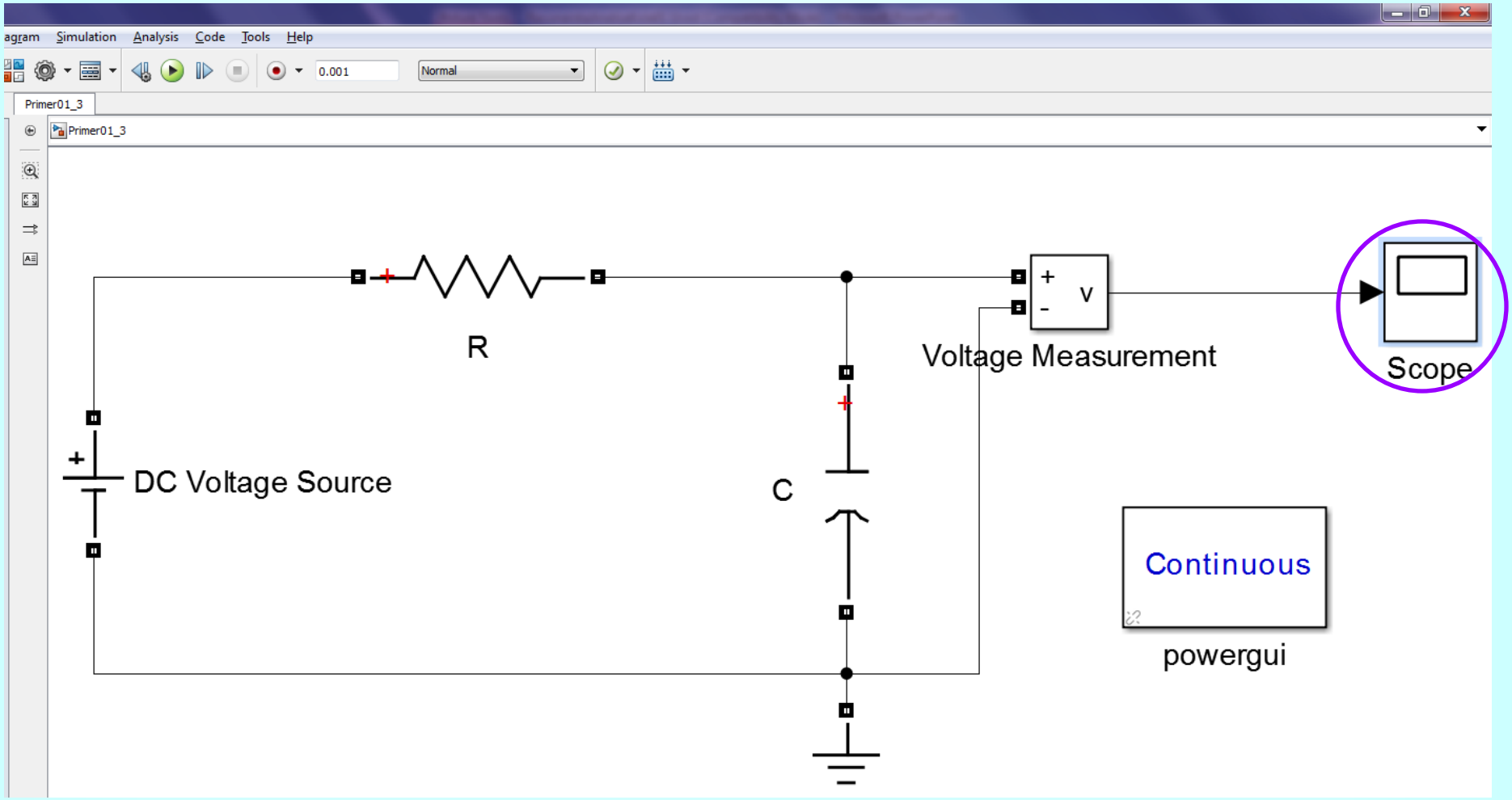
Simscape > Electrical

Покретање симулације...

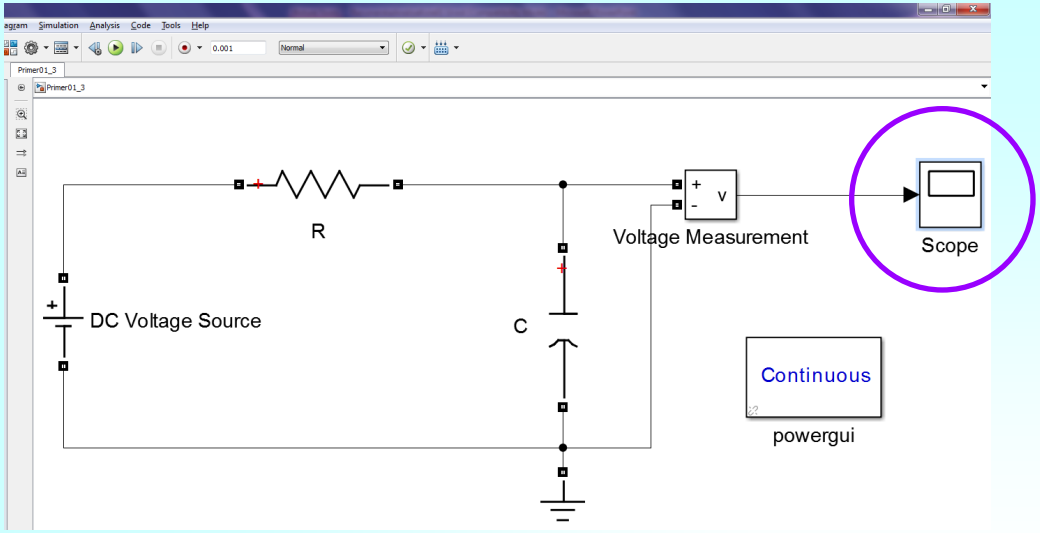


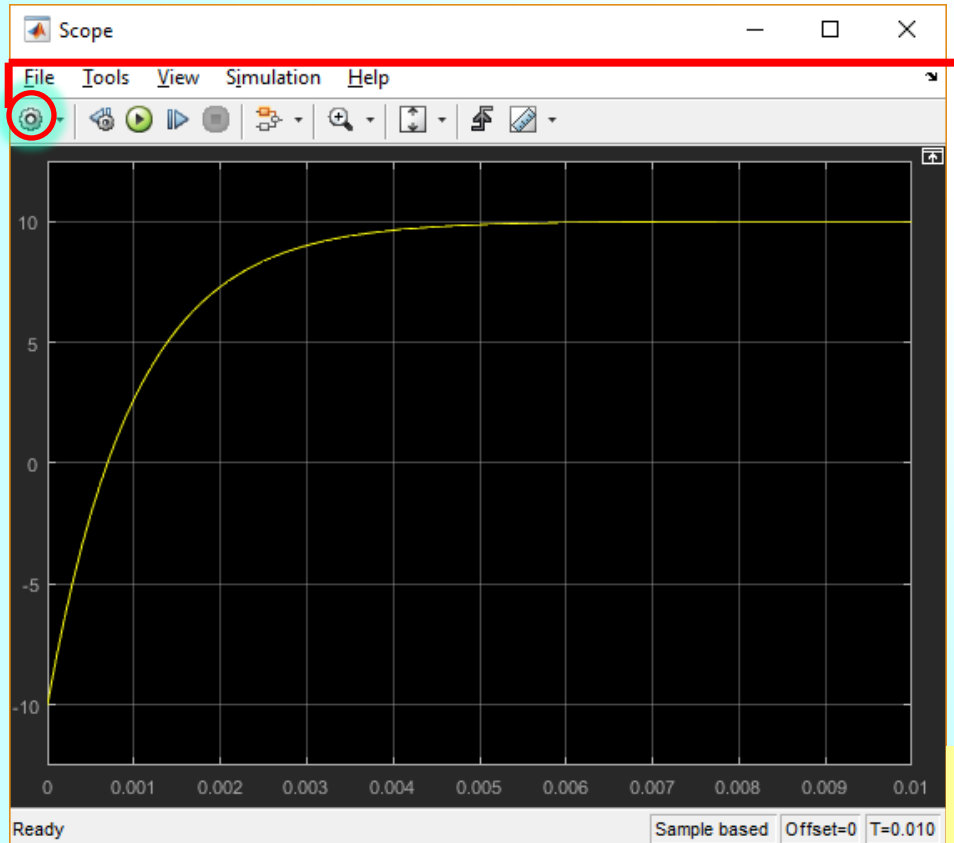
Simscape > Electrical

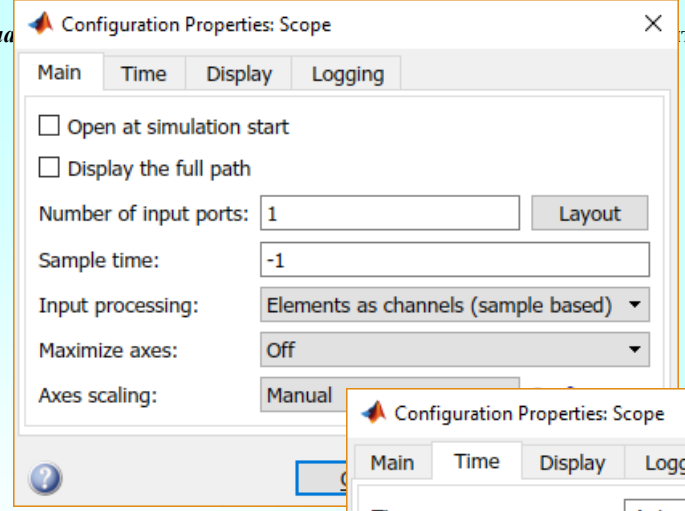
Налажење одзива... Осцилоскоп

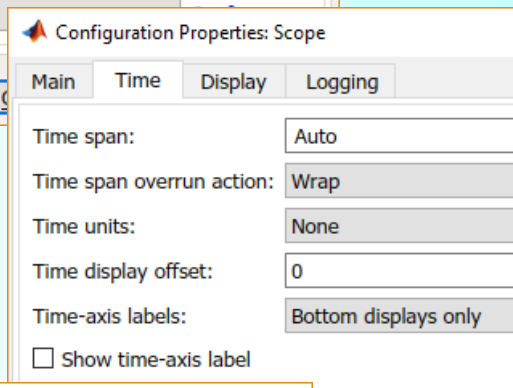


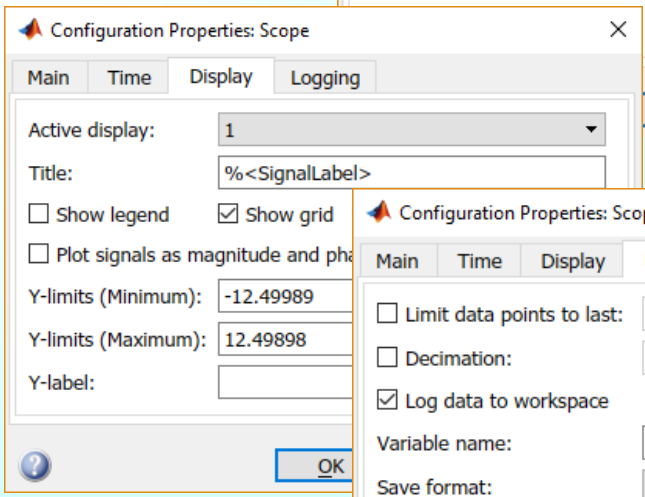
Simscape > Electrical

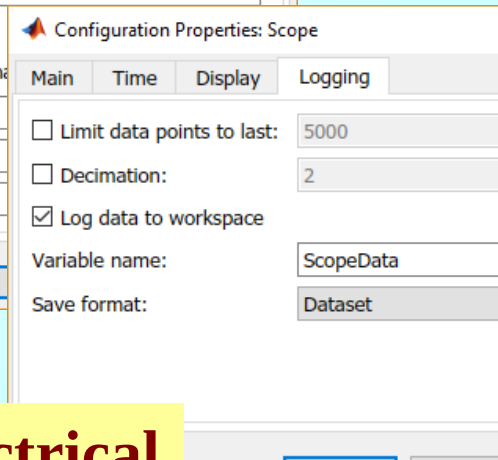












Simscape > Electrical

Configuration Parameters: untitled/Configuration (Active)

★ Commonly Used Parameters | ≡ All Parameters

Category: All

Search selected category

Parameter	Value	Command-Line Name
Solver ▸ Simulation time		
Start time Simulation start time. Note that the values that you specify as block i…	0.0	StartTime
Stop time Simulation stop time.	0.01	StopTime
Solver ▸ Solver options		
Type Choose a variable or fixed-step solver.	Variable-step	SolverType
Solver Choose a solver. If disabled, enable in "Additional options" by changi…	auto (Automatic solver selection)	Solver
Solver ▸ Additional options		
Max step size Maximum step size for a variable-step solver.	1e-4	MaxStep
Relative tolerance Specify the largest acceptable solver error, relative to the size of eac…	1e-3	RelTol
Min step size Minimum step size for a variable-step solver.	auto	MinStep
Absolute tolerance Specify the largest acceptable solver error, as the value of the meas…	auto	AbsTol
Initial step size Specify the size of the first time step that the solver takes.	auto	InitialStep
Shape preservation Improve the integration accuracy by preserving the shape of states b…	Disable All	ShapePreserveControl

$\tau = RC = 1\text{ms}$

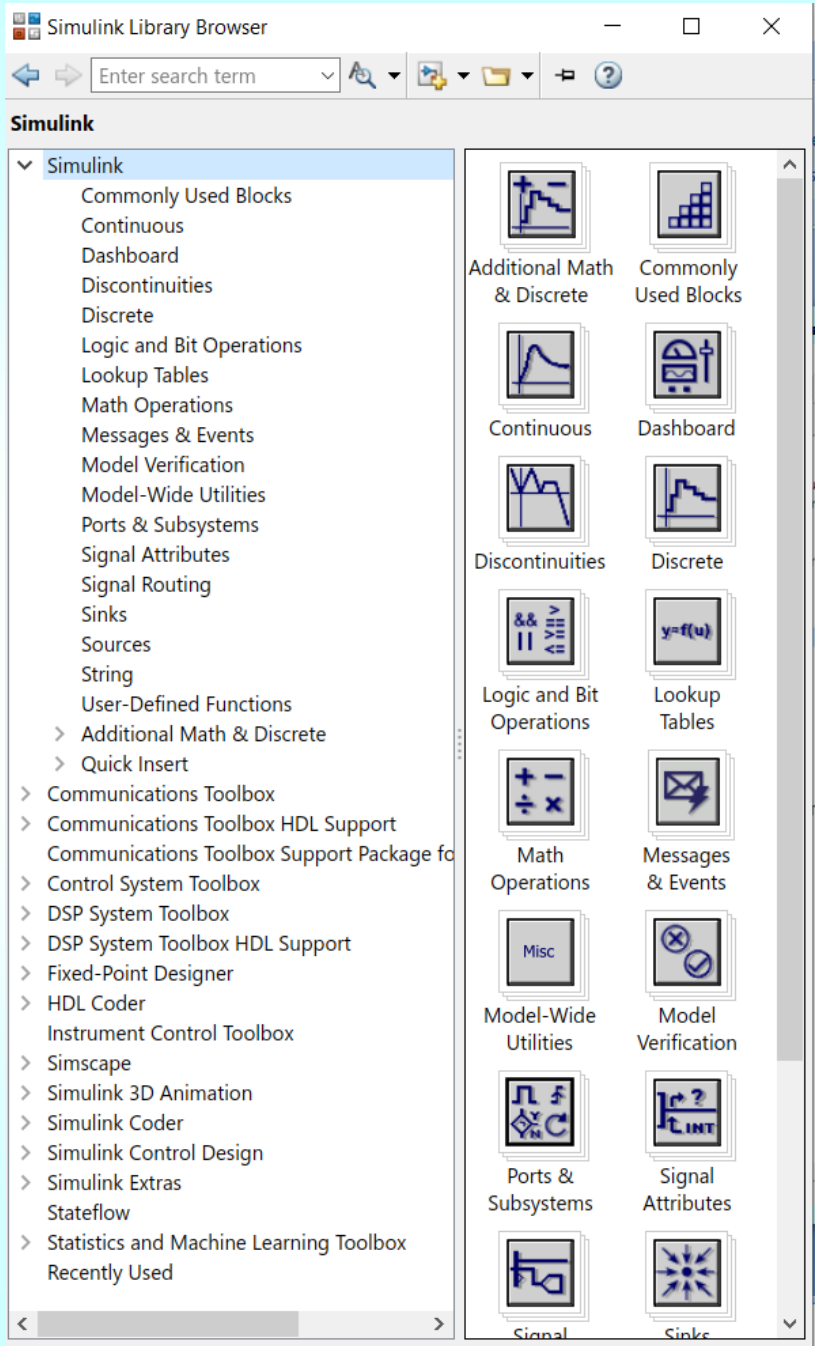
$\tau/10 = 0.1\text{ms}$

OK | Cancel | Help | Apply

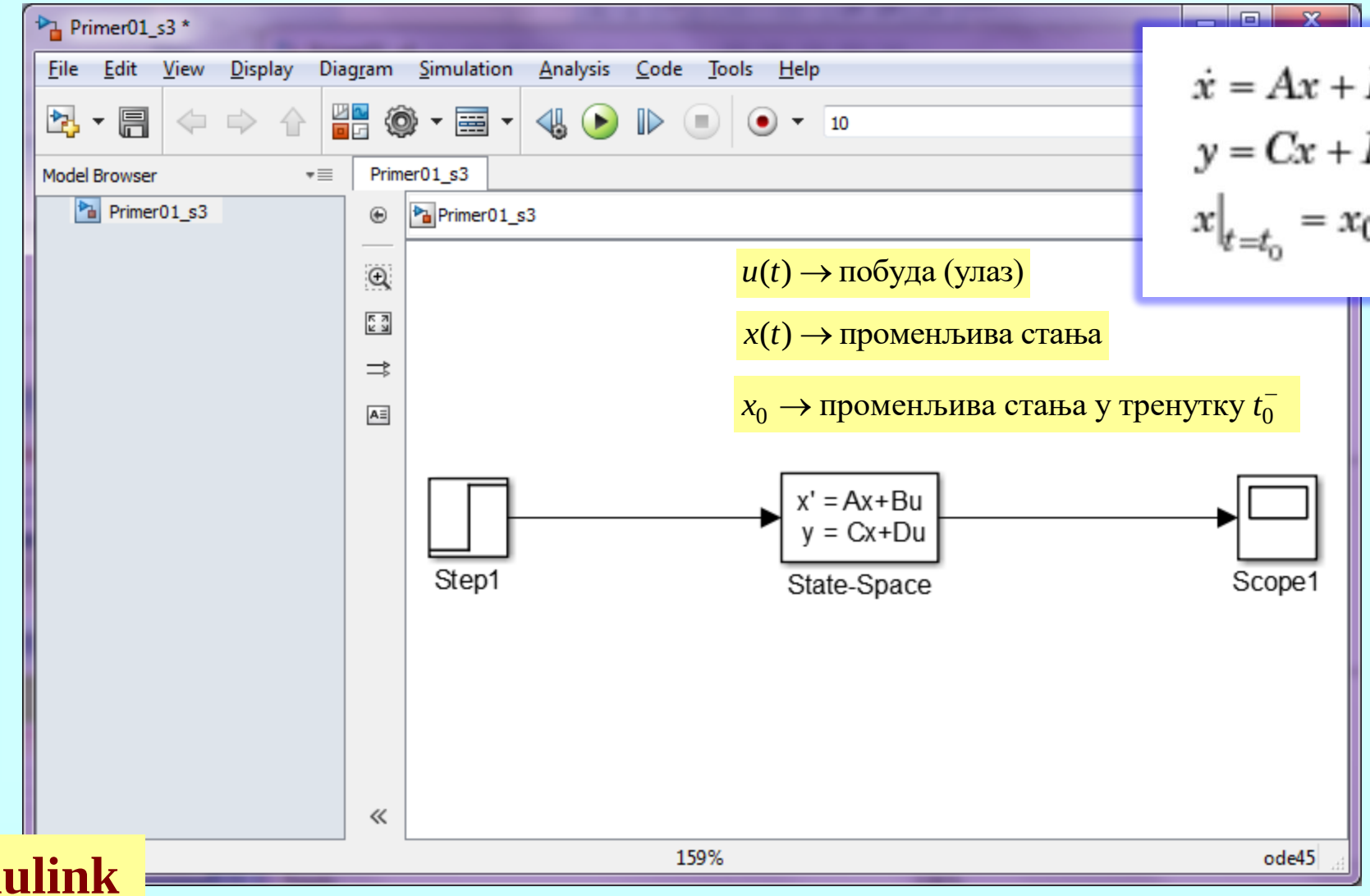
Simscape > Electrical

Simulink

- Решавање кола може се извршити његовим свођењем на систем линеарних диференцијалних једначина
- Дати систем може се представити једноставним блоком са више улаза и излаза

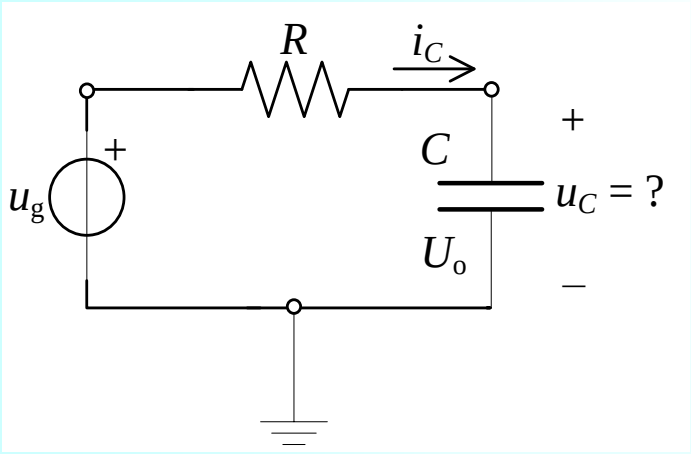


Симулација електричног кола као уопштеног система коришћењем **Simulink**-а



Simulink

Симулација електричног кола као уопштеног система коришћењем **Simulink**-а



$u = u_g(t) \rightarrow$ побуда (улаз)

$x = u_C(t) \rightarrow$ напон кондензатора (промењљива стања и одзив - излаз)

$x(t_0^-) = U_0 \rightarrow$ напон кондензатора у тренутку t_0^-

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$
$$x\big|_{t=t_0} = x_0,$$

коло је образовано у тренутку $t_0 = 0$

$$u_g(t) = Ri_C + u_C(t)$$
$$i_C = C\frac{du_C}{dt}$$
$$u_C(t_0^-) = U_0 = -10\,\mathrm{V}$$

$$R = 1\,\mathrm{k\Omega}$$
$$C = 1\,\mu\mathrm{F}$$
$$u_g(t) = U\,h(t), U = 10\,\mathrm{V}$$
$$u_C(t_0^-) = U_0 = -10\,\mathrm{V}$$

$$\frac{du_C(t)}{dt} = \frac{i_C}{C} = \frac{u_g(t) - u_C(t)}{RC} = -\frac{u_C(t)}{RC} + \frac{u_g(t)}{RC}$$
$$u_C(t_0^-) = U_0 = -10\,\mathrm{V}$$

$$\frac{du_C(t)}{dt} = Au_C(t) + Bu_g(t) \Rightarrow A = -\frac{1}{RC} = -1000, B = 1000$$
$$u_C(t) = Cu_C(t) \Rightarrow C = 1, D = 0$$
$$u_C(t_0^-) = U_0 = -10\,\mathrm{V}$$

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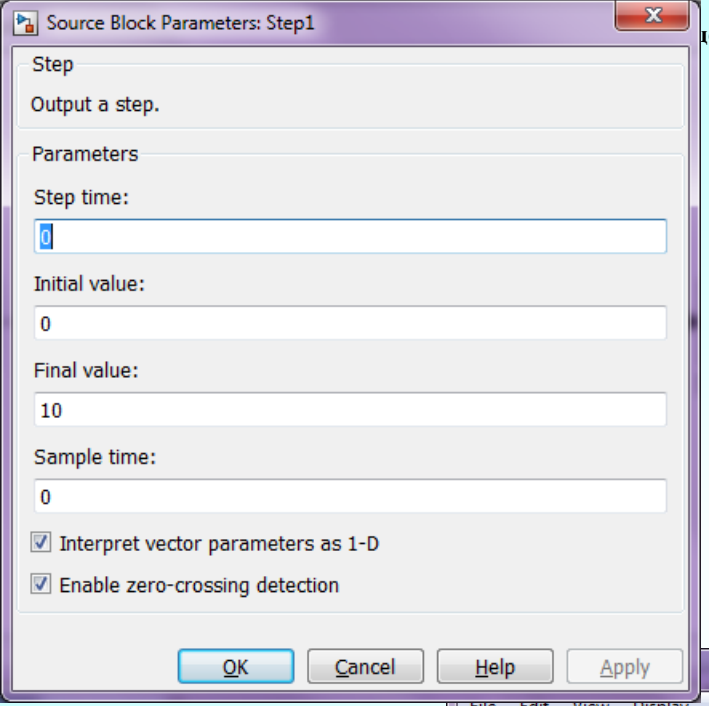
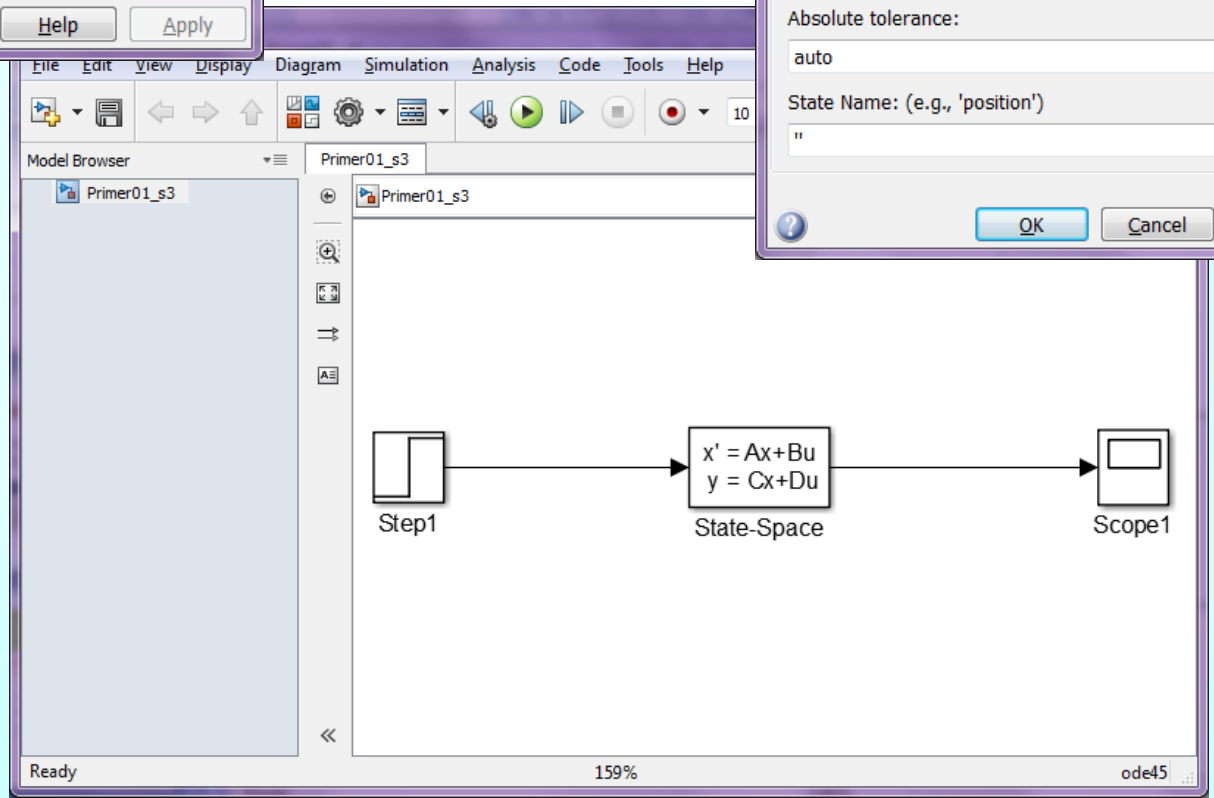
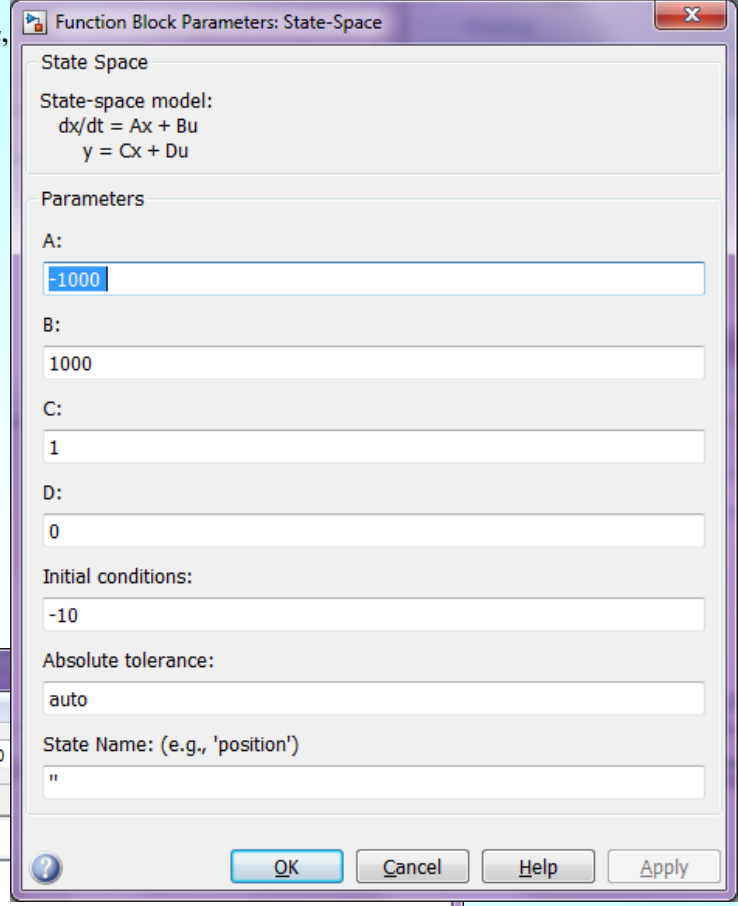
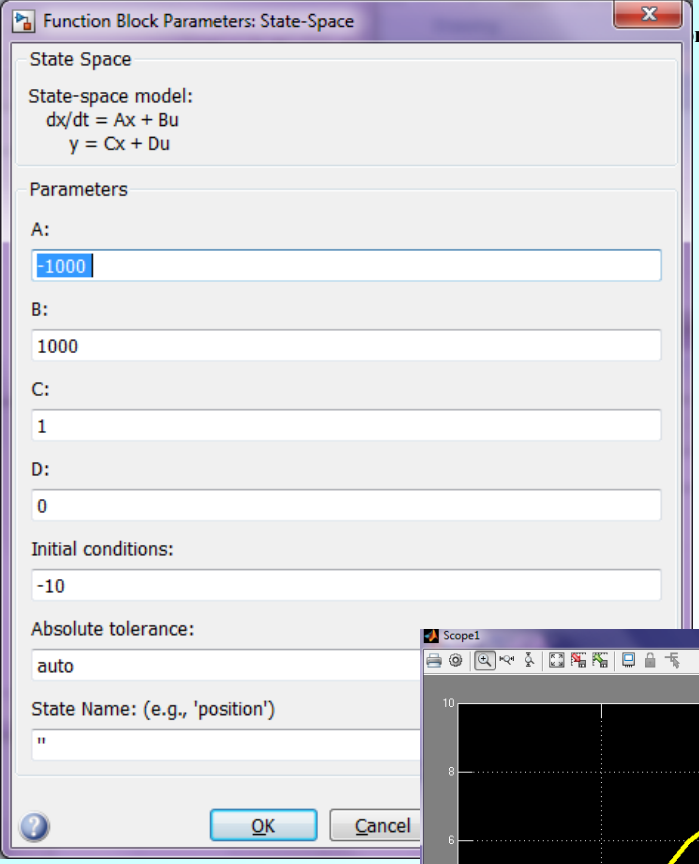


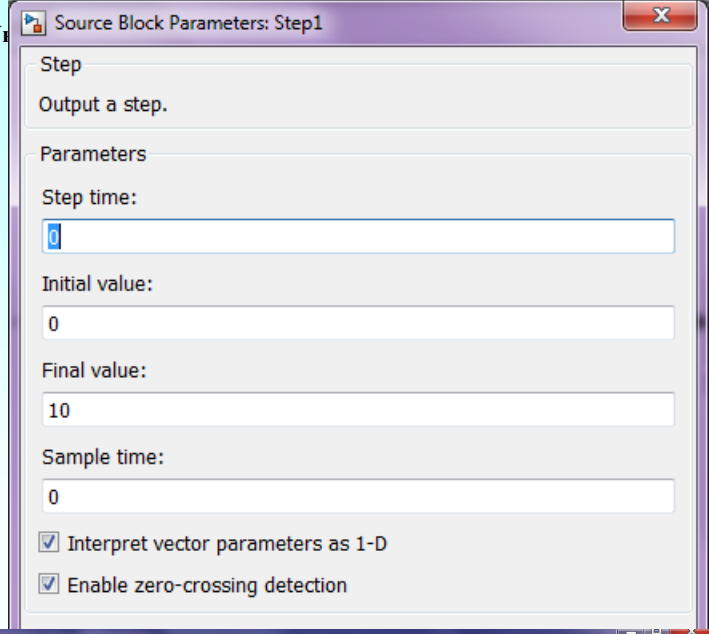


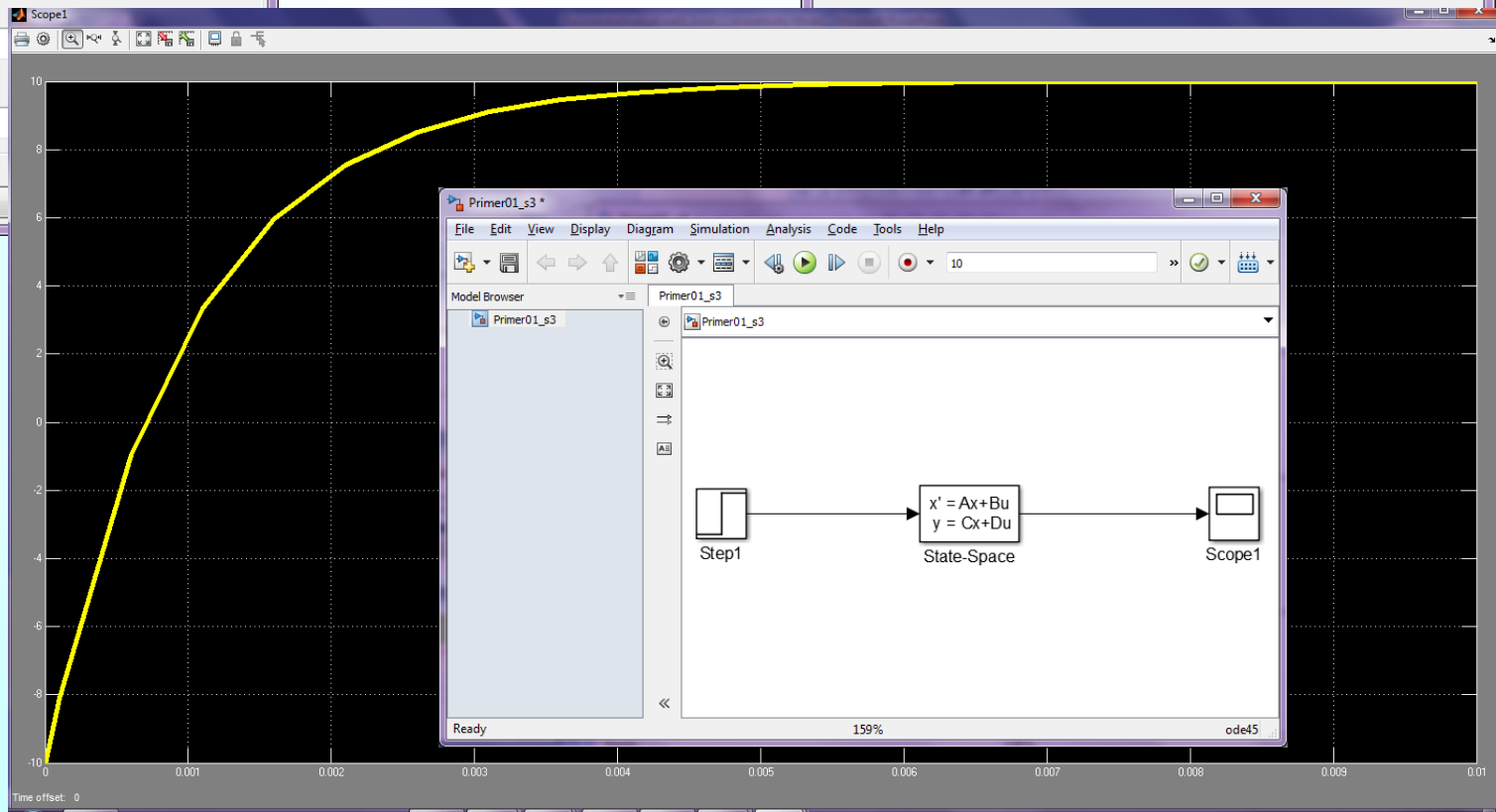


Simulink

Симулација електричног кола као уопштеног система коришћењем **Simulink**-а

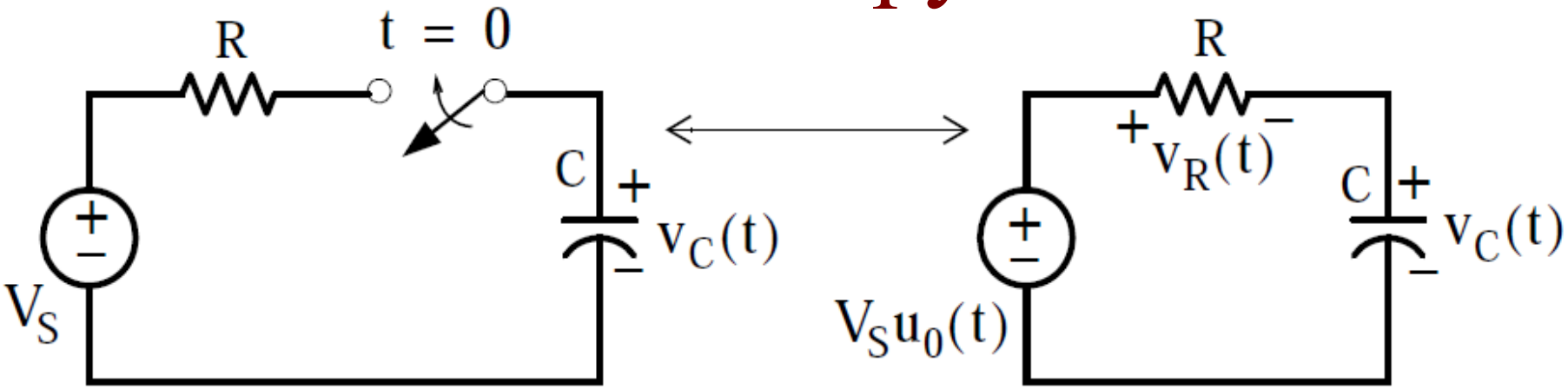






Simulink

Решимо “ручно”



$$v_R + v_C = V_S u_0(t)$$

$$i = i_C = C\frac{dv_C}{dt}$$

$$v_R = Ri = RC\frac{dv_C}{dt}$$

$$RC\frac{dv_C}{dt} + v_C = V_S u_0(t)$$

$t > 0$

$$RC\frac{dv_C}{dt} + v_C = V_S$$

$$v_C(t) = (V_S - V_S\, e^{-(1/RC)t})u_0(t)$$

MATLAB
Symbolic Math Toolbox (Live Script)

- Библиотека за симболички рачун (алгебарске и диференцијалне једначине)
- Омогућава нумеричку анализу резултата прорачуна

Live Editor - D:\Engineering_Work\ETF\Teaching\PRK\RCKolo_v0.mlx

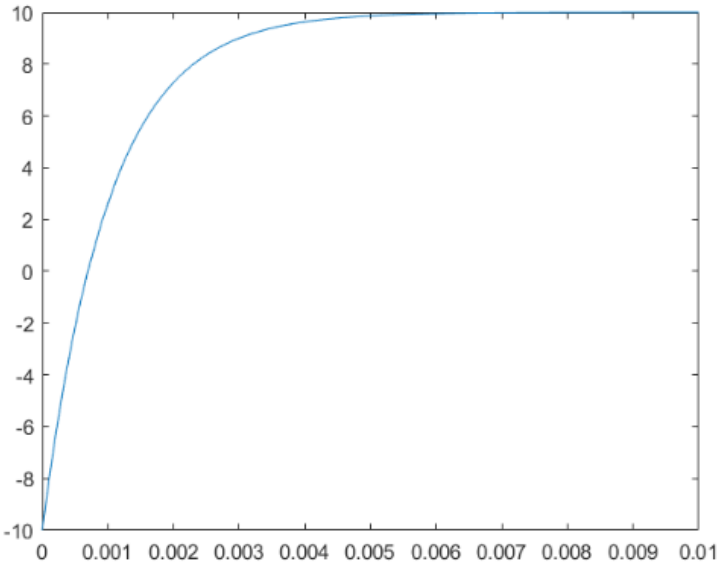
pluto1.m | template1.m | RCKolo_v0.mlx

```
1  syms v_c(t)
2  ode = diff(v_c,t) ==-1000*v_c+10000
3  cond = v_c(0)==-10
4  v_csol = dsolve(ode,cond)
5
6  fplot(v_csol, [0 0.01])
```

$$\frac{\partial}{\partial t} v_c(t) = 10000 - 1000\, v_c(t)$$

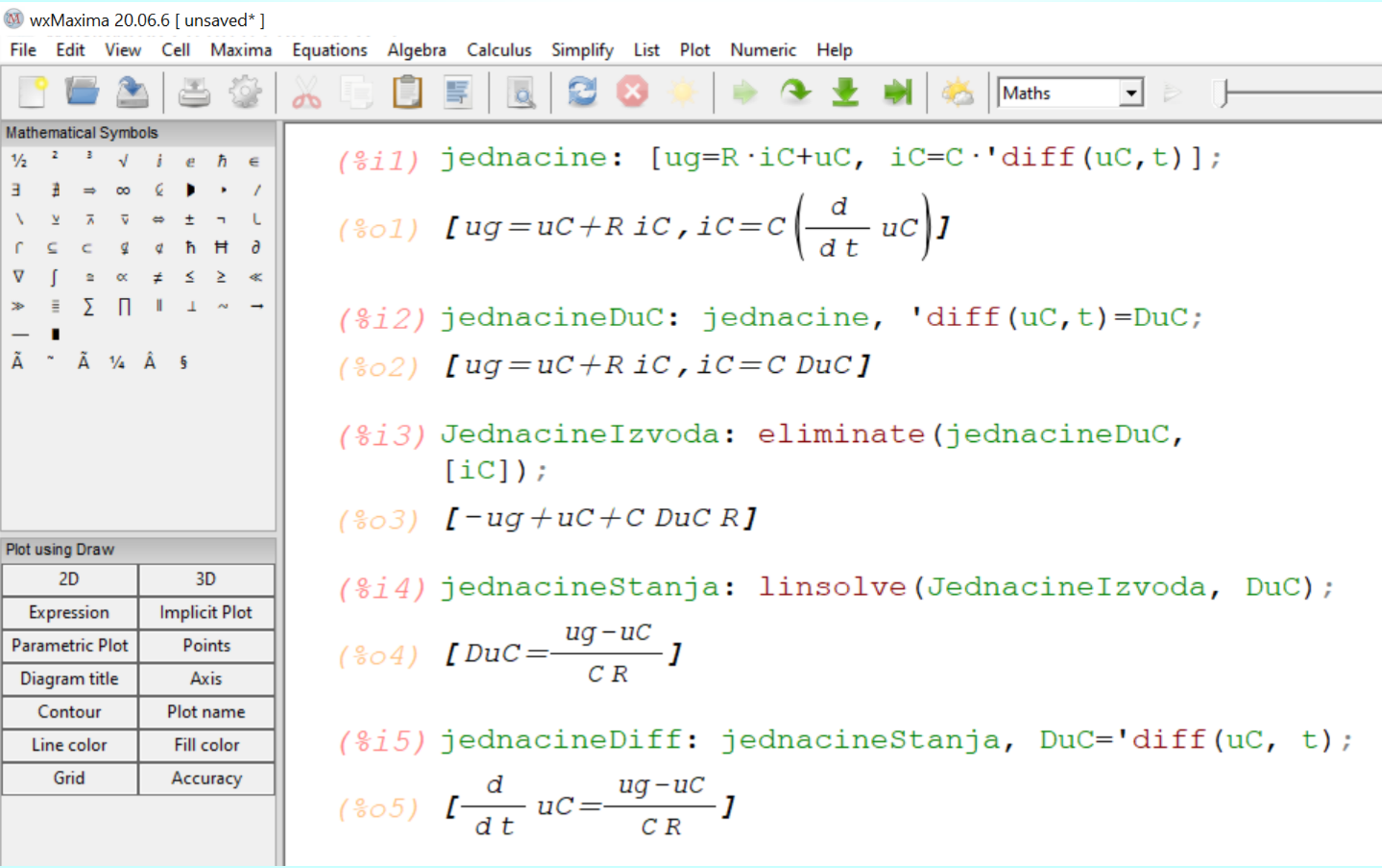
cond = $v_c(0) = -10$

v_csol = $10 - 20\, e^{-1000\, t}$



Simbolic Math Toolbox

wxMaxima


wxMaxima 20.06.6 [unsaved*]
File Edit View Cell Maxima Equations Algebra Calculus Simplify List Plot Numeric Help
Maths
Mathematical Symbols
Plot using Draw
2D
3D
Expression
Implicit Plot
Parametric Plot
Points
Diagram title
Axis
Contour
Plot name
Line color
Fill color
Grid
Accuracy
(%i1) jednacine: [ug=R·iC+uC, iC=C·'diff(uC,t)];
(%o1) [ug=uC+R iC, iC=C (d/dt uC)]
(%i2) jednacineDuC: jednacine, 'diff(uC,t)=DuC;
(%o2) [ug=uC+R iC, iC=C DuC]
(%i3) JednacineIzvoda: eliminate(jednacineDuC, [iC]);
(%o3) [-ug+uC+C DuC R]
(%i4) jednacineStanja: linsolve(JednacineIzvoda, DuC);
(%o4) [DuC=(ug-uC)/(C R)]
(%i5) jednacineDiff: jednacineStanja, DuC='diff(uC, t);
(%o5) [d/dt uC=(ug-uC)/(C R)]

```
(%i6) zamene: [ug=U];
```

$$(\%o6)\quad [ug=U]$$

```
(%i7) vrednosti: [R=1000, C=10^(-6), U=10, U0=-10];
```

$$(\%o7)\quad \left[R=1000,C=\frac{1}{1000000},U=10,U0=-10\right]$$

```
(%i8) JednacineDiffZamena: jednacineDiff, zamene;
```

$$(\%o8)\quad \left[\frac{d}{dt}\,uC=\frac{U-uC}{C\,R}\right]$$

```
(%i9) ode2(JednacineDiffZamena, uC, t);
```

$$(\%o9)\quad uC=\%e^{-\frac{t}{C\,R}}\left(U\,\%e^{\frac{t}{C\,R}}+\%c\right)$$

```
(%i10)ic1(%, t=0, uC=U0);
```

$$(\%o10)\quad uC=\%e^{-\frac{t}{C\,R}}\left(U\,\%e^{\frac{t}{C\,R}}+U0-U\right)$$

```
(%i11)uCt: ev(%, vrednosti);
```

$$(\%o11)\quad uC=\%e^{-1000\,t}\left(10\,\%e^{1000\,t}-20\right)$$

```
(%i17)wxplot2d(rhs(uCt), [t,0,0.01],
      [xlabel," t [s] "],
      [ylabel," uC [V] "],
      [xtics, 0, 0.002, 0.01],
      [legend, "Napon kondenzatora"], grid2d)$
```