ETA-Graphics
An Interface to Endoreversible Thermodynamics

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Outline

1. Introduction
2. Endoreversible Thermodynamics
3. ETA-Graphics
4. Conclusion and Outlook

From Bond Graphs ...

- graphical representation of a physical system
- consists of a set of elements that are linked by bonds
- bonds are characterized by flow and effort variables
- relatively large number of elements, e.g. capacitive or resistive elements, 0-junctions, transformers, gyrators...

. . . to Endoreversible Thermodynamics

- simpler structure
- fewer components than Bond Graphs
- $\longrightarrow$ interface for endoreversible thermodynamics

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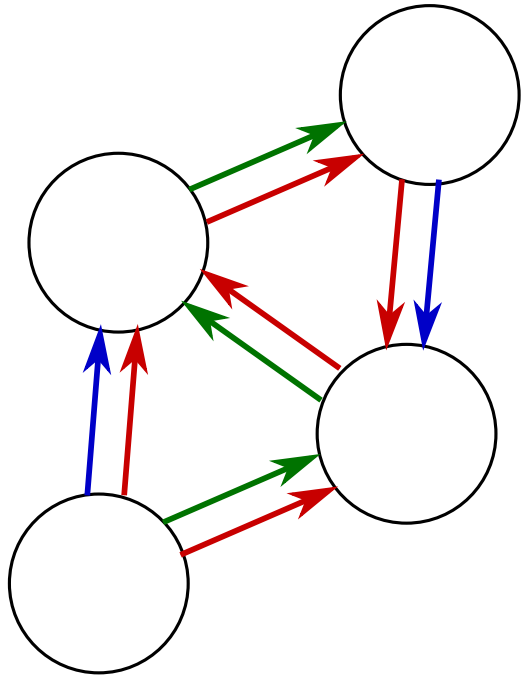
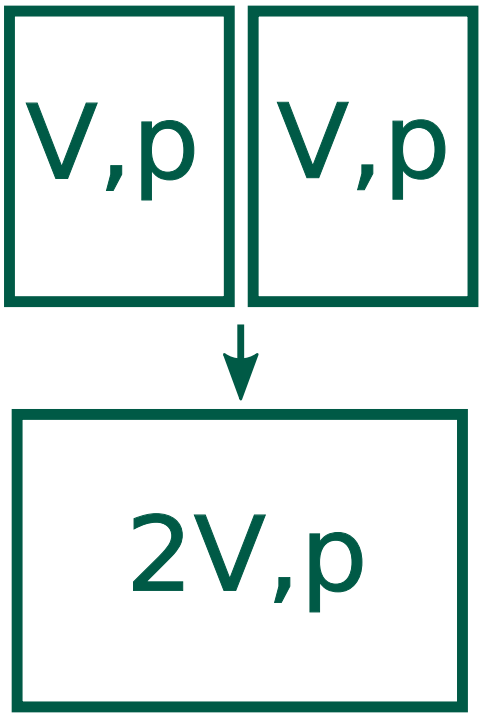
Endoreversible Thermodynamics

- partition of irreversible systems into reversible subsystems
- irreversibilities only at the interactions between the subsystems
- simplified calculations
- quantitatively measurable entropy production
- at first only investigation of heat engines
- later also chemical engines, electrical engines, etc.



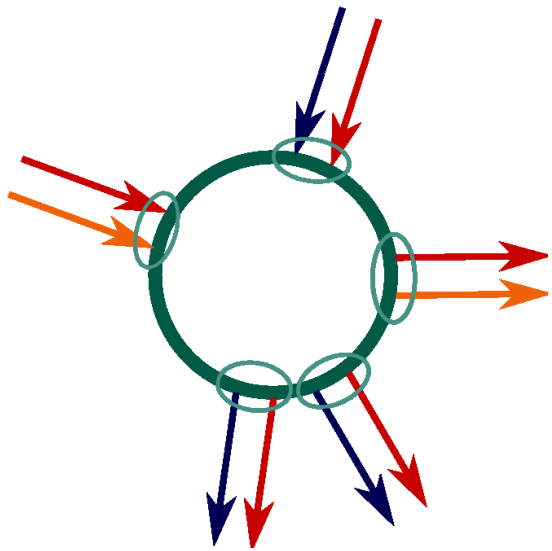
Extensities and intensities

extensive quantities	**intensive quantities**
volume	pressure
entropy	temperature
charge	electrical potential
momentum	velocity
angular momentum	angular velocity
particle number	chemical potential
...	...



Subsystems

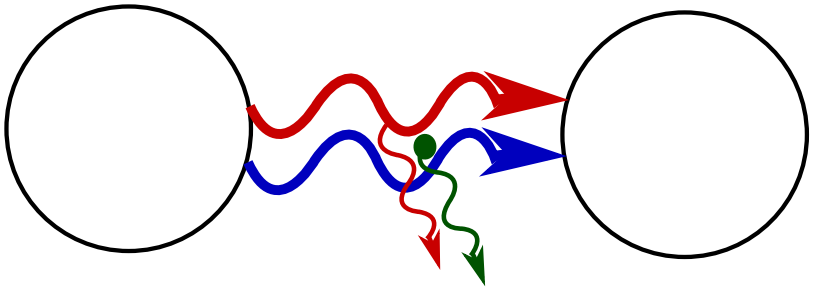
- reversible
- each subsystem is characterized by contact points through which energy and extensities are exchanged
- subsystems interact (irreversibly) with each other
- subdivision in reservoirs and engines



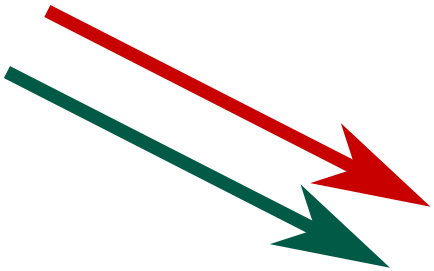
Interactions I

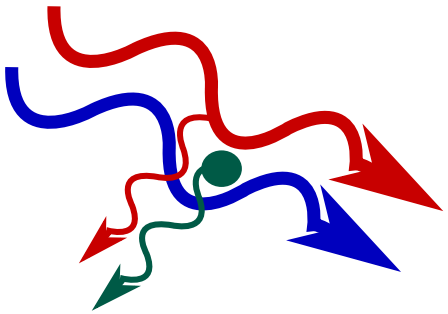
Interactions connect two subsystems.

- each interaction consists of two fluxes: energy and extensity
- subdivision into reversible and irreversible interactions



Interactions II





Reversible:

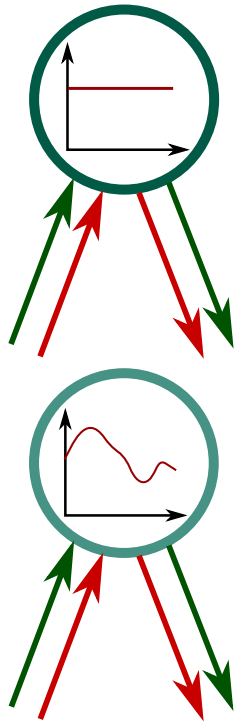
- intensities at both contact points are equal
- unlimited energy and extensity flux
- direct contact without losses

Irreversible:

- transport law for flux of energy or extensity
- production of entropy, which is deposited through an additional contact

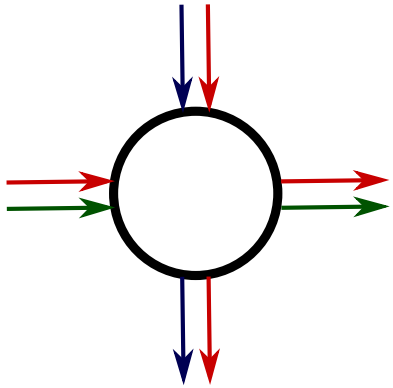
Reservoirs

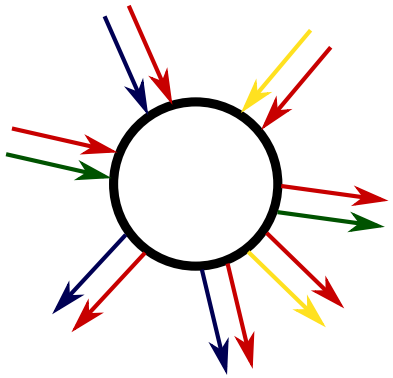
- thermodynamic system in equilibrium that acts as energy storage
- *infinite reservoirs:* characterized by constant intensities
- *finite reservoirs:* characterized by extensities and energy function; intensities are variable (e.g. the temperature of a heat bath decreases when energy is emitted)



Engines

- reversible subsystem that transferres energy from one extensity to another
- contact variables are linked via special balance equations
- the sum of the energy fluxes has to equal zero
- the sum of the extensity fluxes has to equal zero





Endoreversible systems . . .

. . . consist only of

- reservoirs
- engines
- interactions

With the help of endoreversible models various characteristics of a system can be investigated, e.g.:

- efficiency η
- power P
- entropy production

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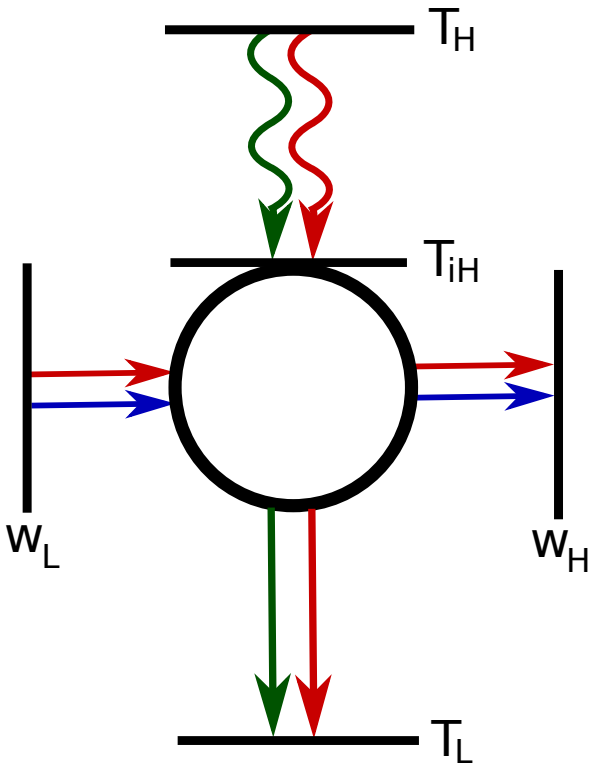
ETA-Graphics

- graphic-based interface to endoreversible thermodynamics
- construction and analysis of endoreversible systems
- simplified access to endoreversible thermodynamics
- supported input of transport laws
- automated construction and solution of the equation system using Mathematica (or Maxima)

The Novikov-engine

- continuously working reversible Carnot-engine
- internal working temperature of the engine: T_{iH} and T_{iL}
- infinite heat baths with constant temperatures T_L and T_H
- direct, reversible contact to the heat bath of temperature T_L, i.e. $T_L = T_{iL}$

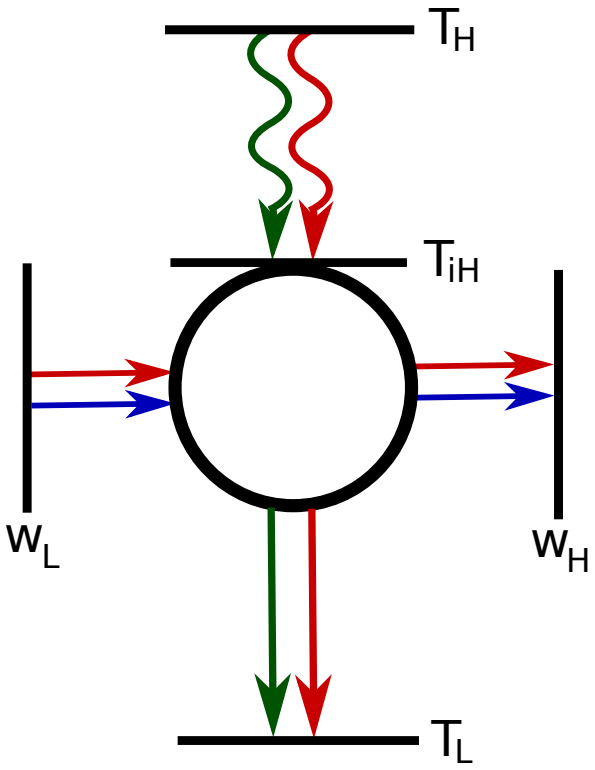


The Novikov-engine

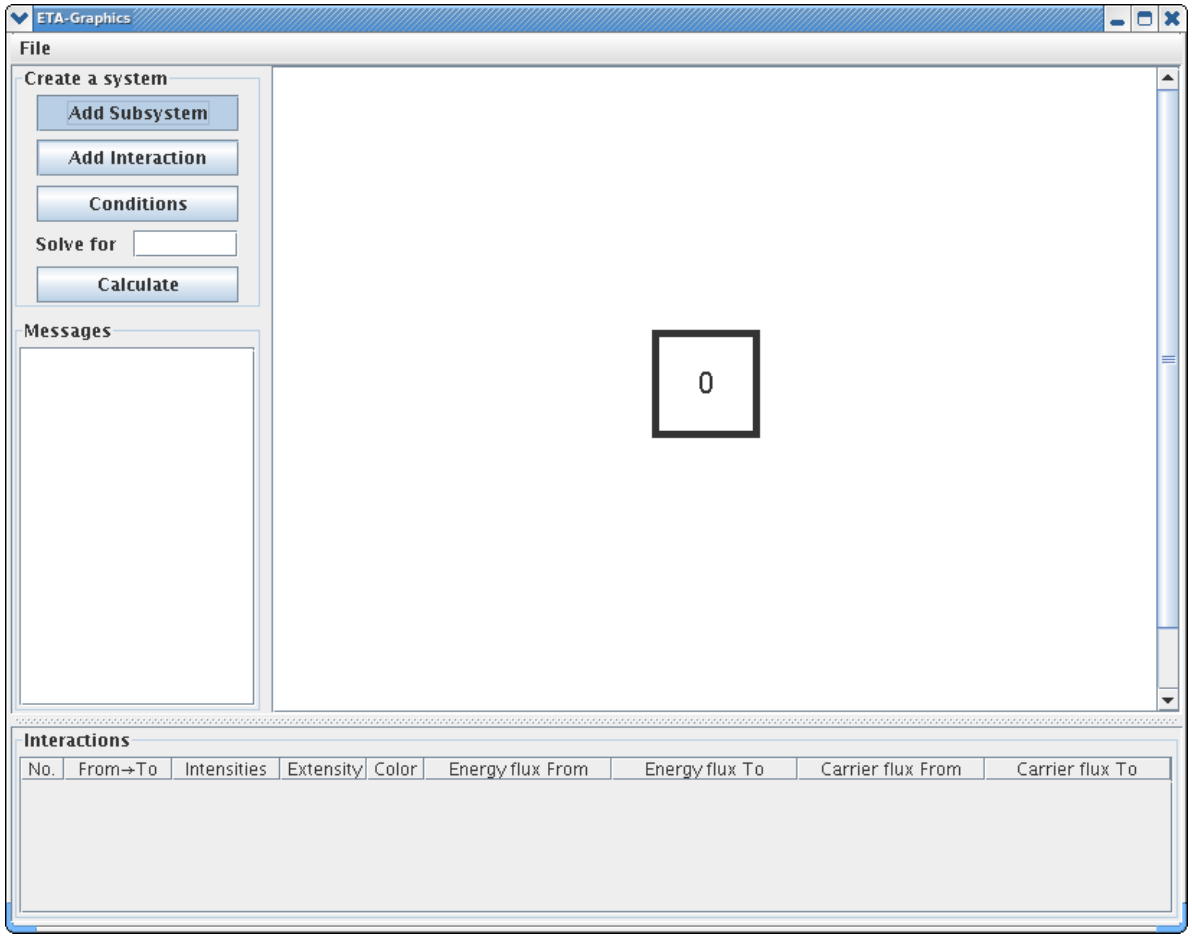
- heat transport between the reservoir of temperature T_H and the engine is proportional to the temperature difference:

$$q_H = K_H(T_H - T_{iH})$$

- finite rates, irreversible interaction



Creation of an endoreversible system



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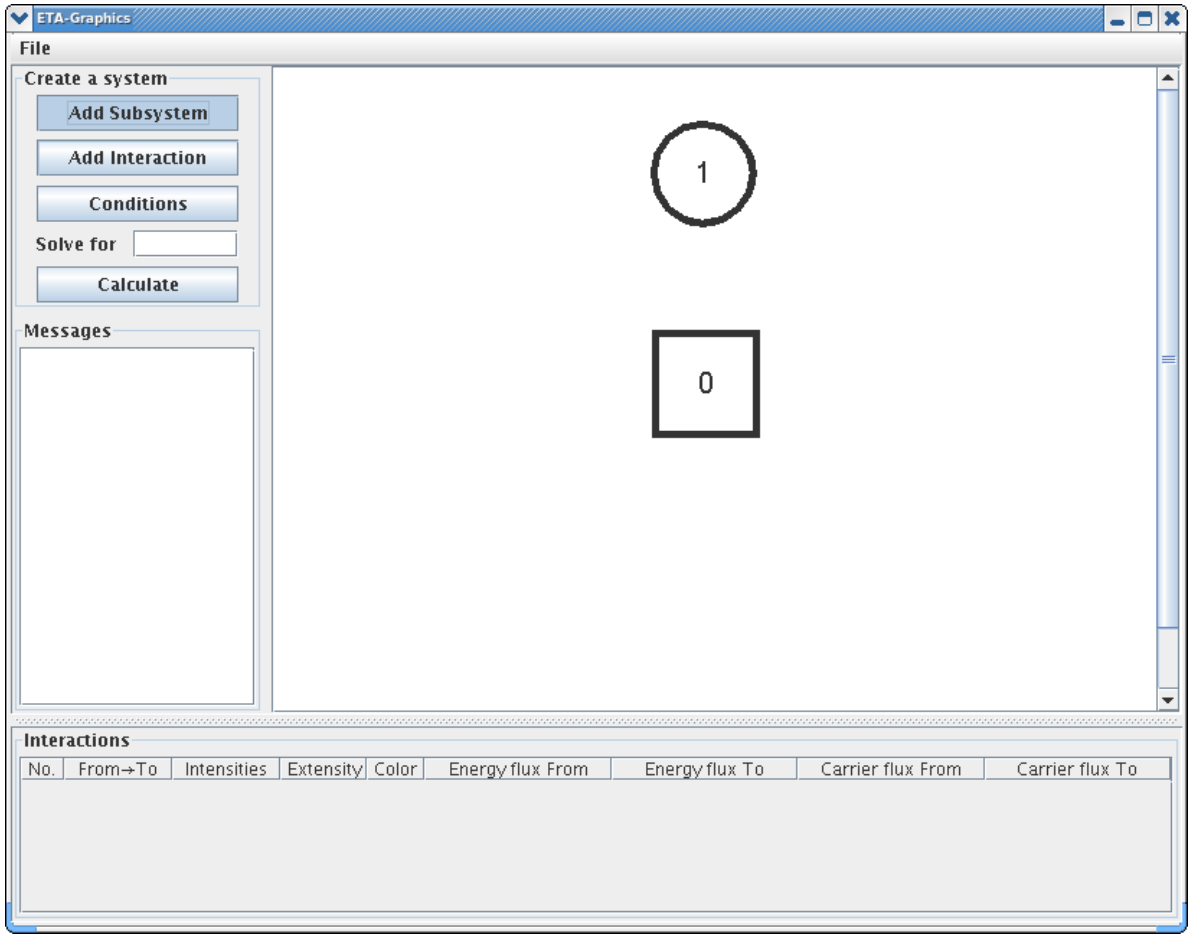

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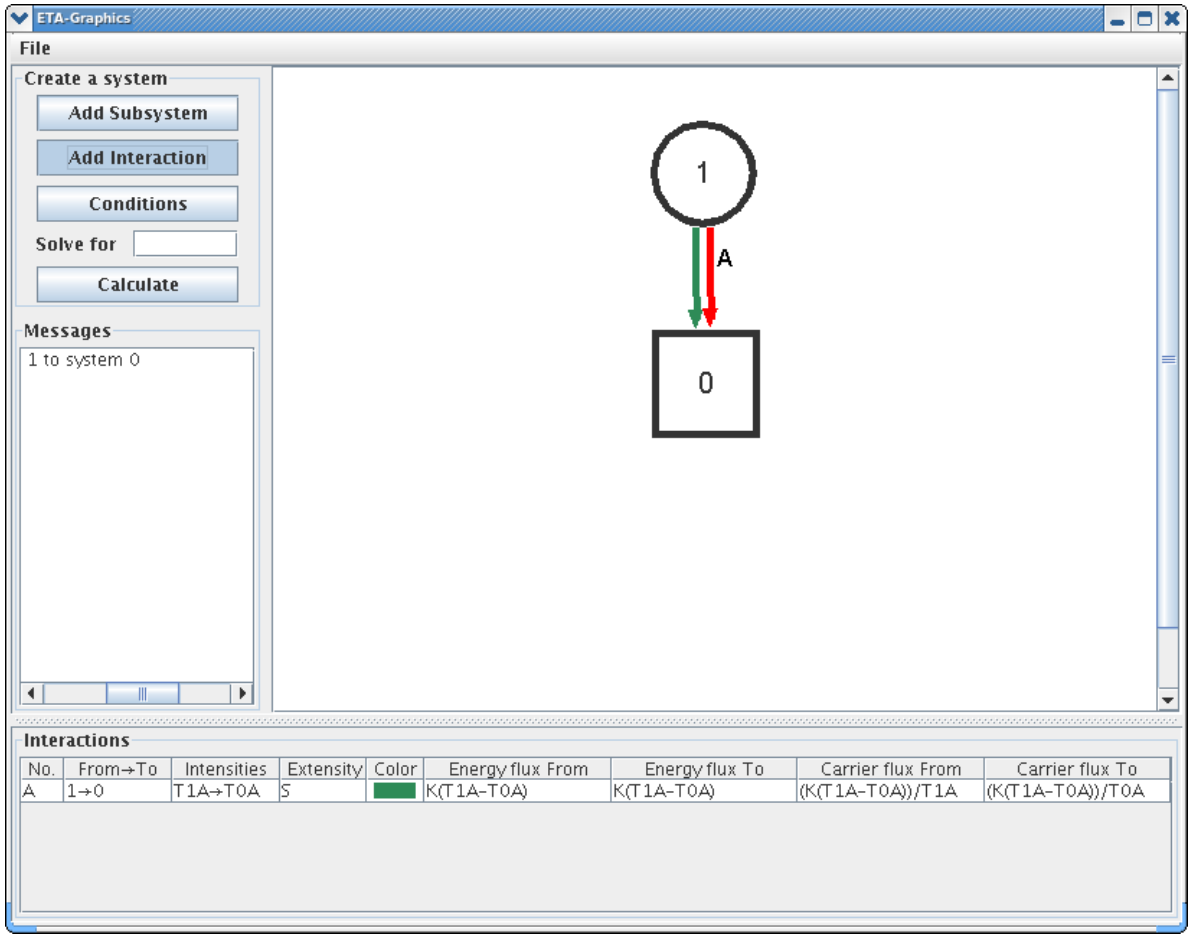
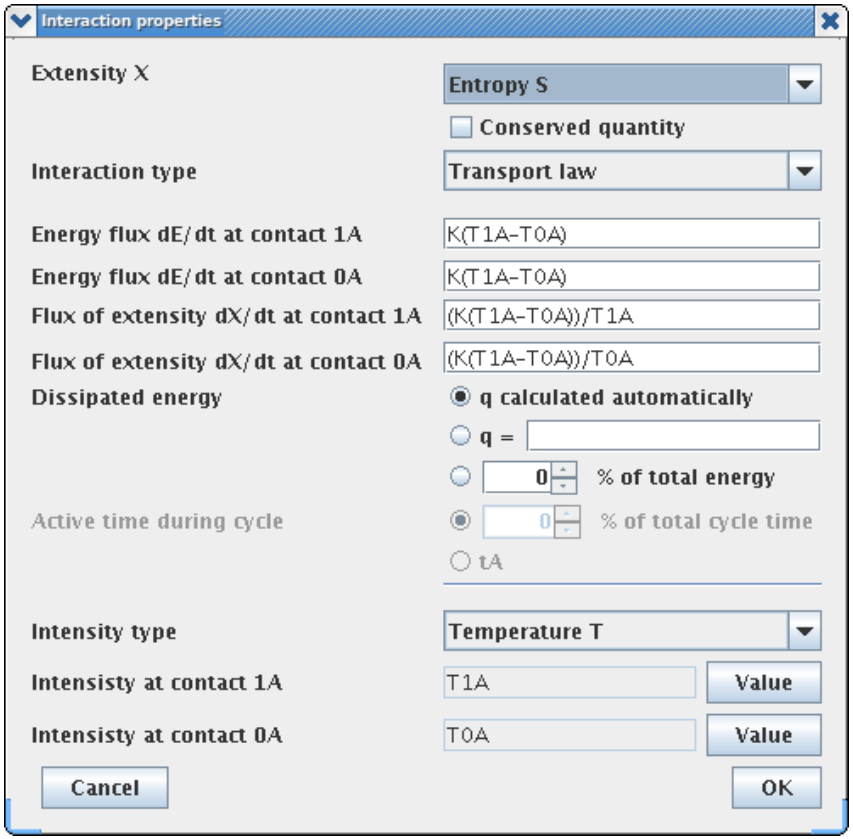
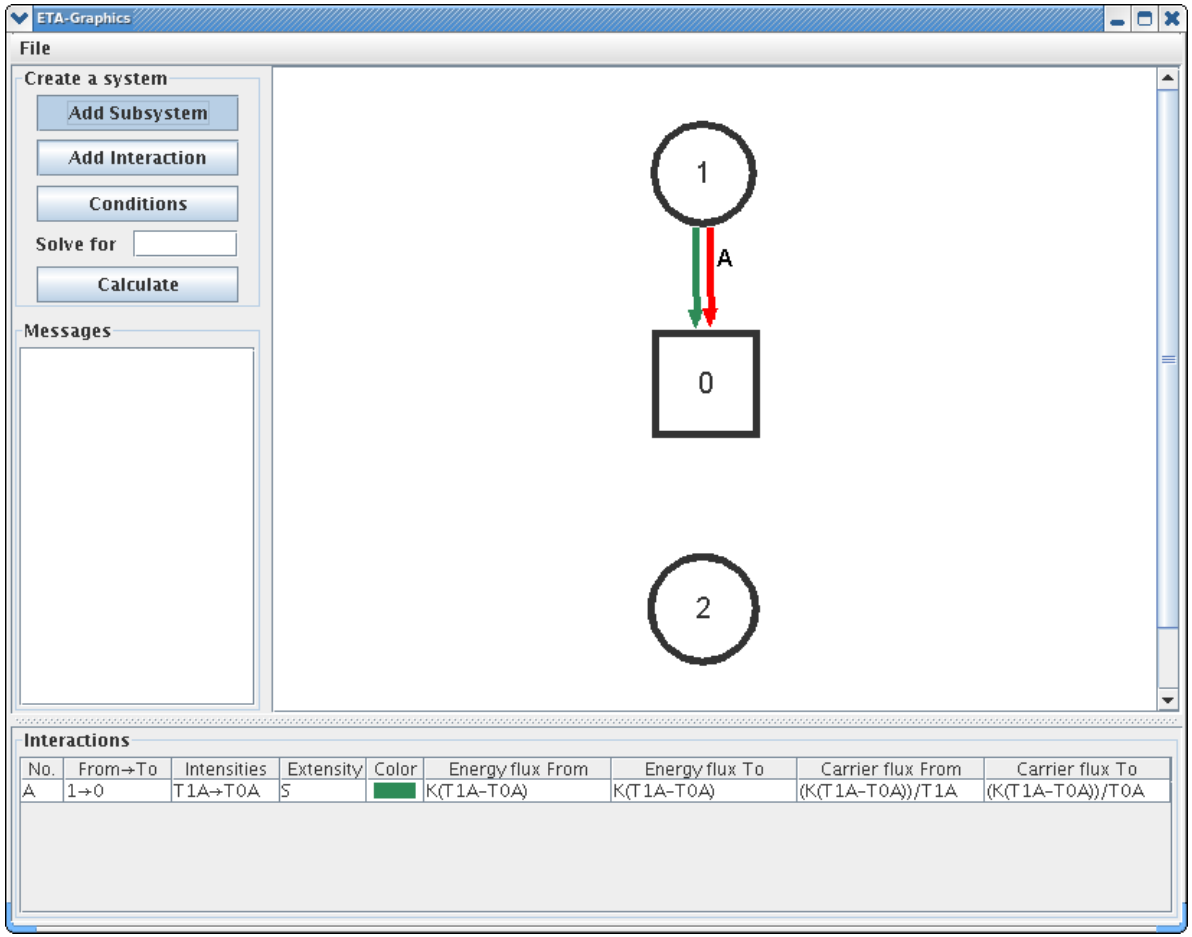


Input of interactions

- choice: extensity/intensity
- choice: reversible/irreversible
- input of transport laws for energy and extensity
- here:
  $\dot{E} = K(T1A - T0A)$
  with $T1A \equiv T_H$
  and $T0A \equiv T_{iH}$



Creation of an endoreversible system



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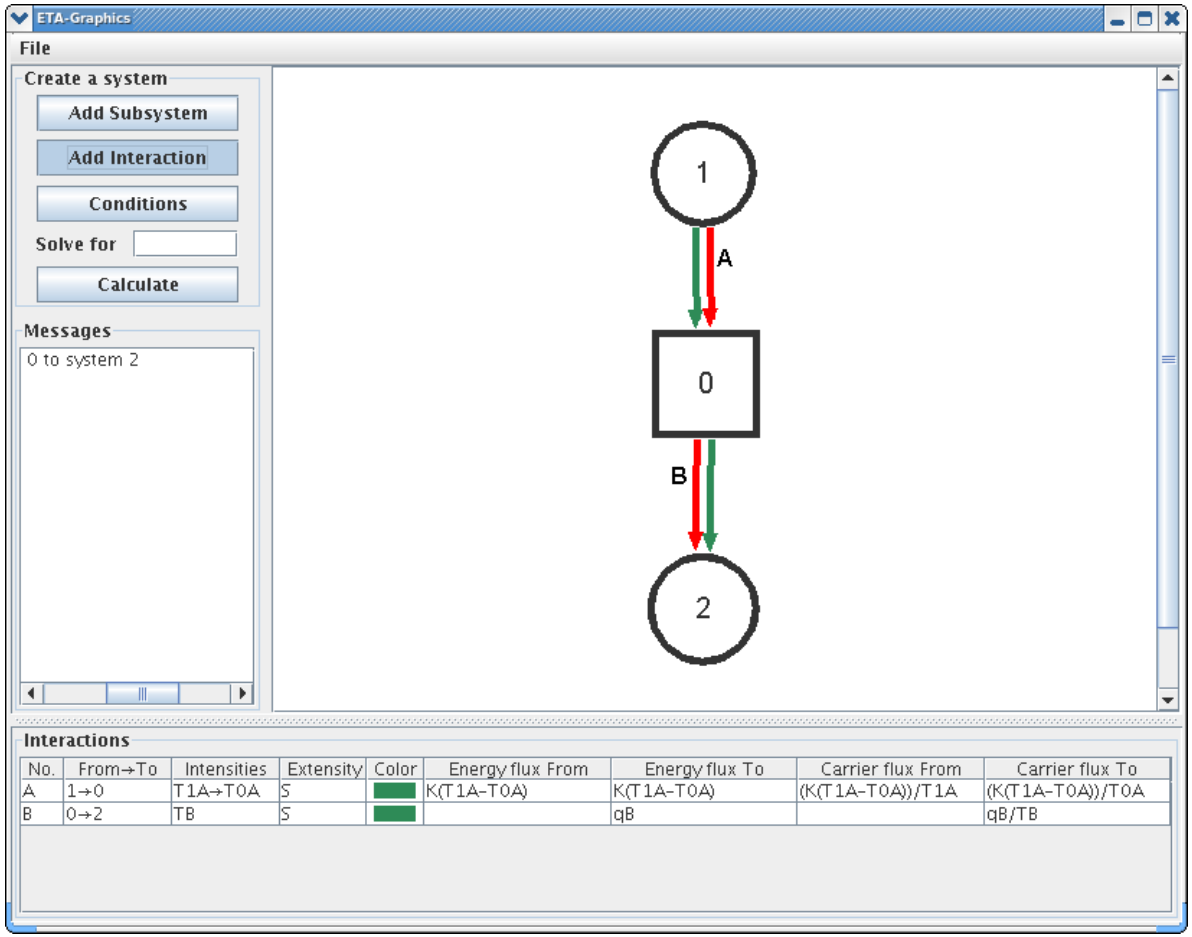
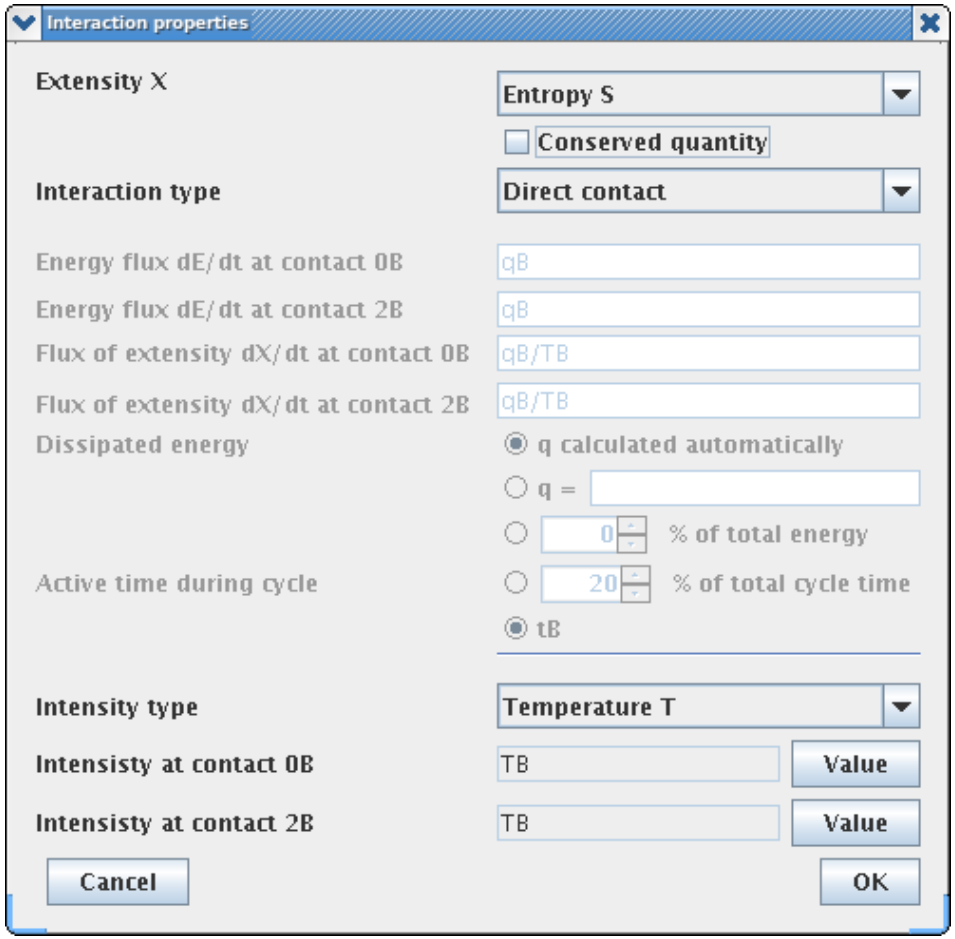
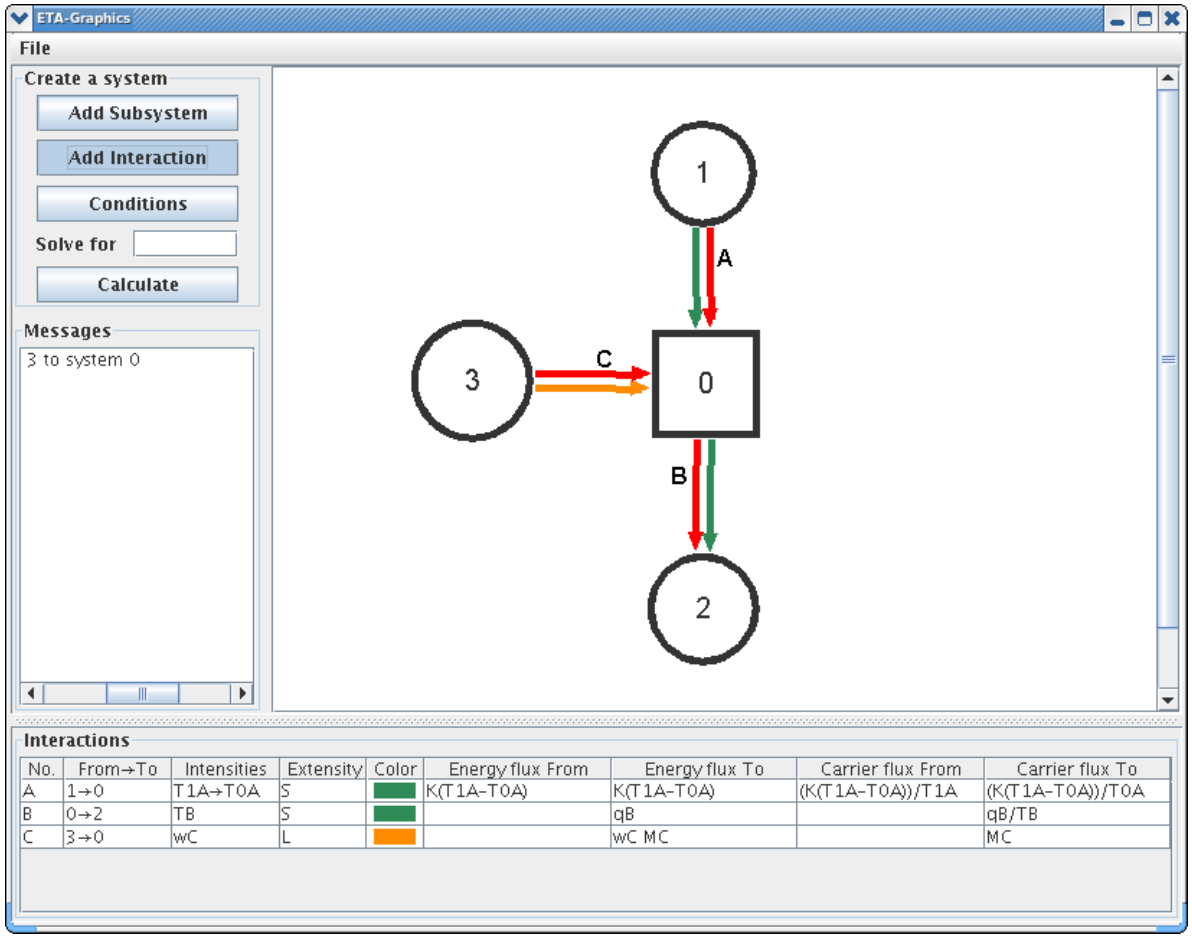


Input of interactions

- direct heat contact
- $TB \equiv T_L$

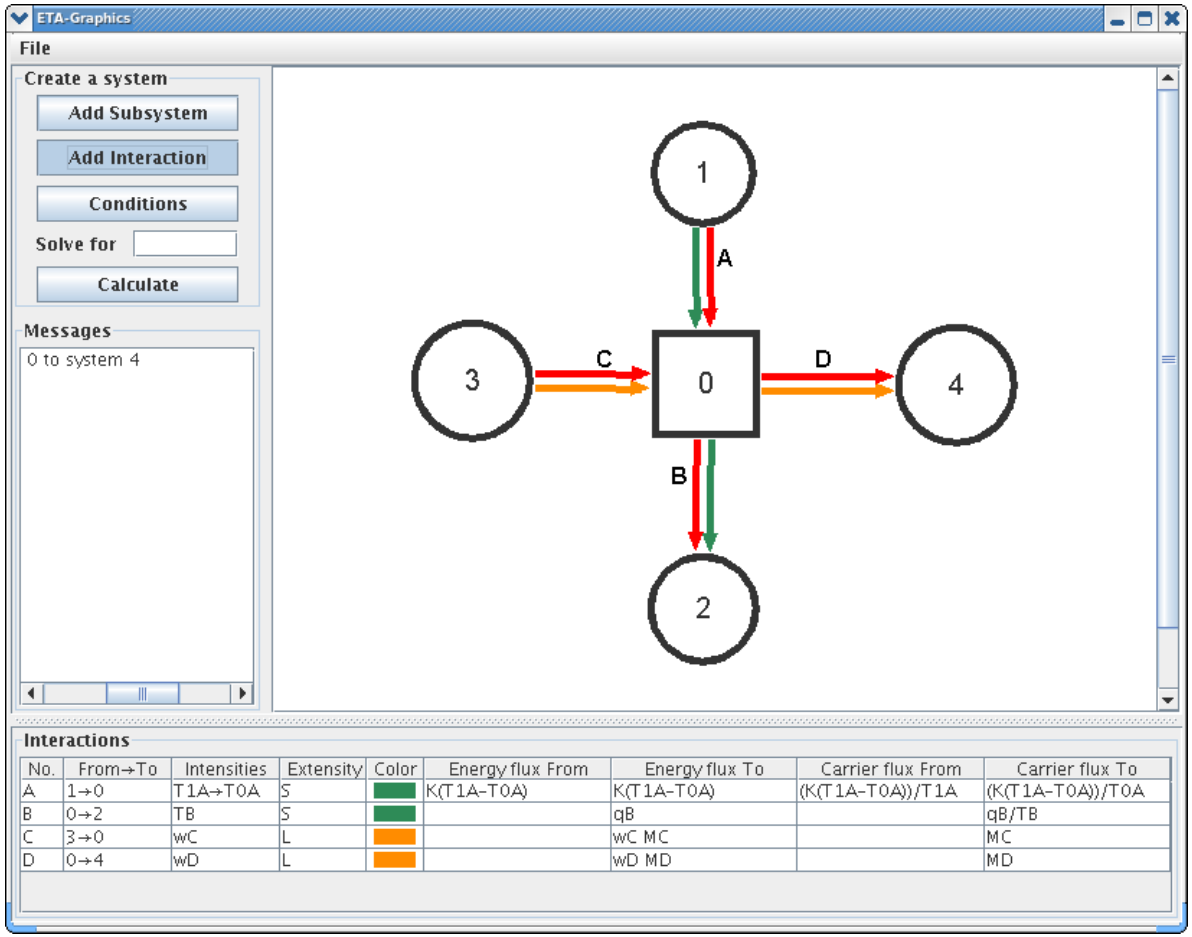


Creation of an endoreversible system

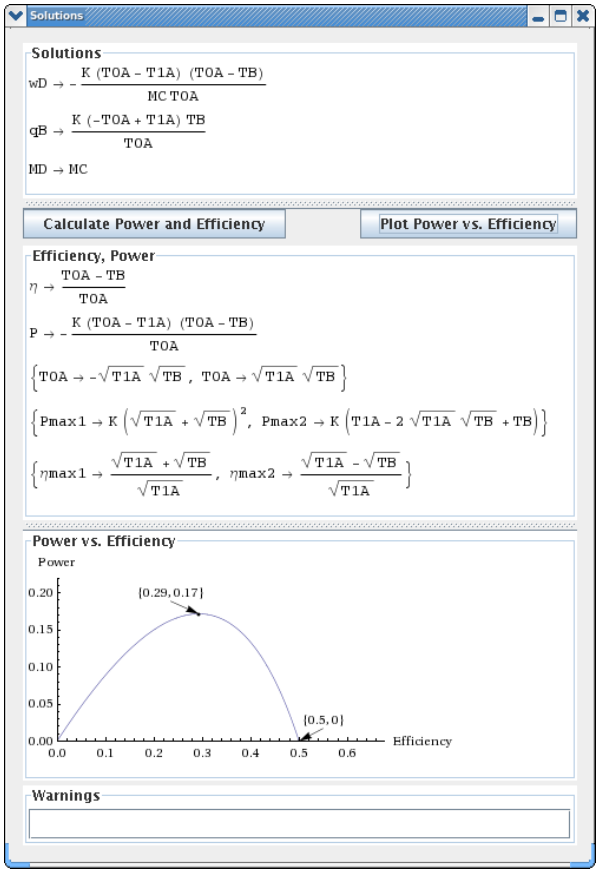


No.	From→To	Intensities	Extensity	Color	Energy flux From	Energy flux To	Carrier flux From	Carrier flux To
A	1→0	T1A→T0A	S		K(T1A-T0A)	K(T1A-T0A)	(K(T1A-T0A))/T1A	(K(T1A-T0A))/T0A
B	0→2	TB	S			qB		qB/TB
C	3→0	wC	L			wC MC		MC

Creation of an endoreversible system

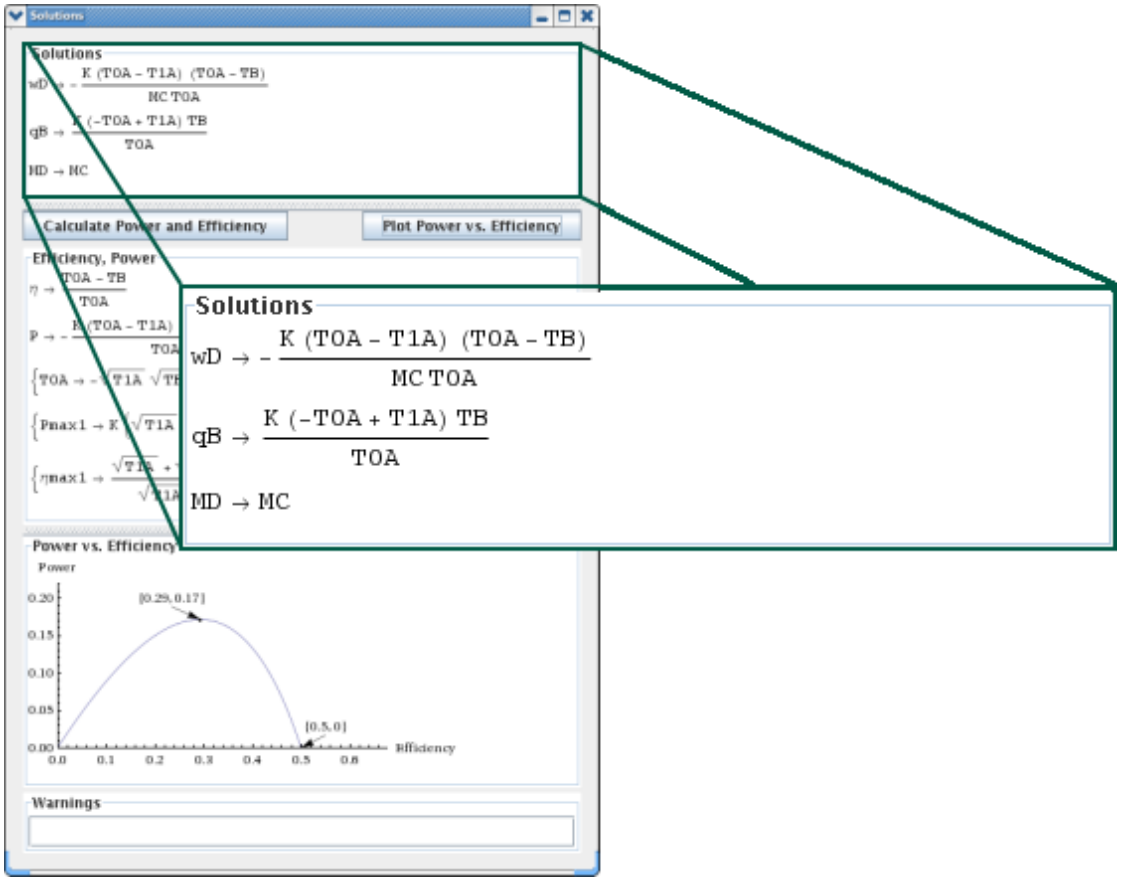


Results for the Novikov-engine



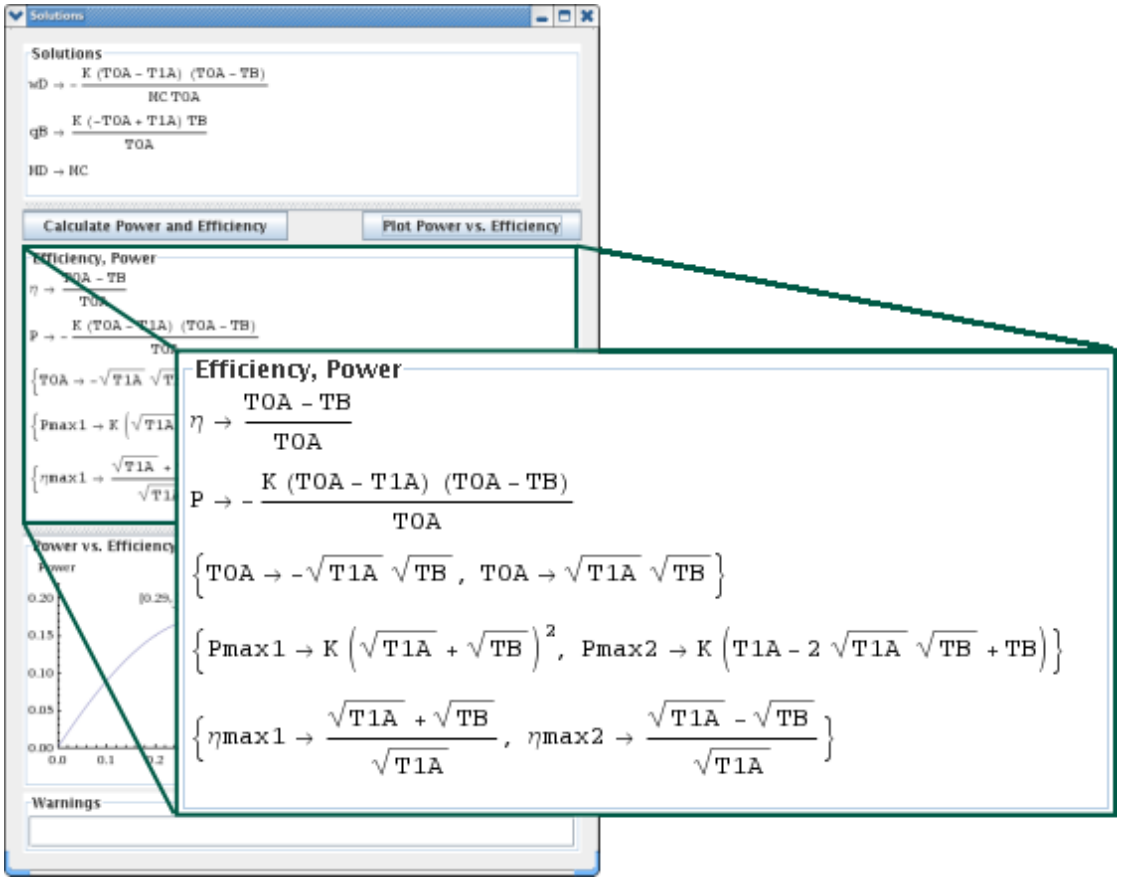
- equation system – consisting of the balance equations of the engine – is solved
- performance measures are calculated and plotted

Results for the Novikov-engine



- solutions of the equation system

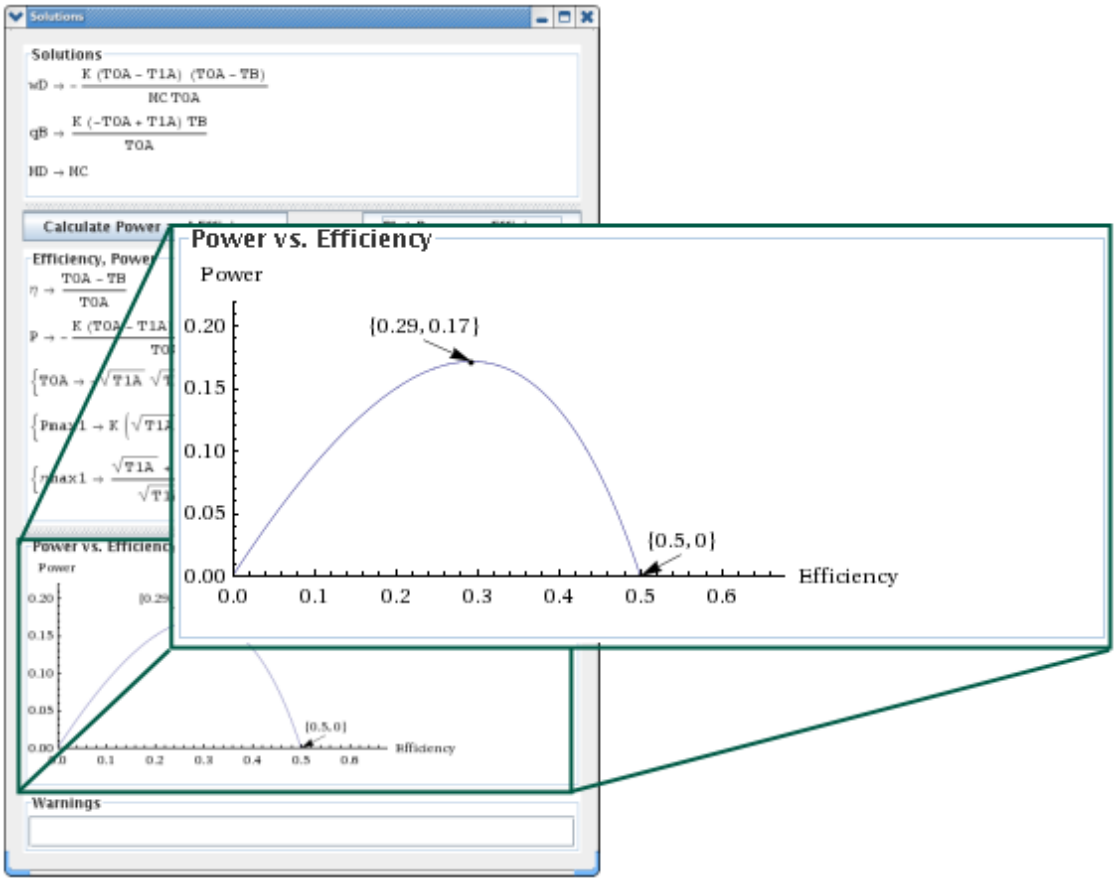
Results for the Novikov-engine



equations for:

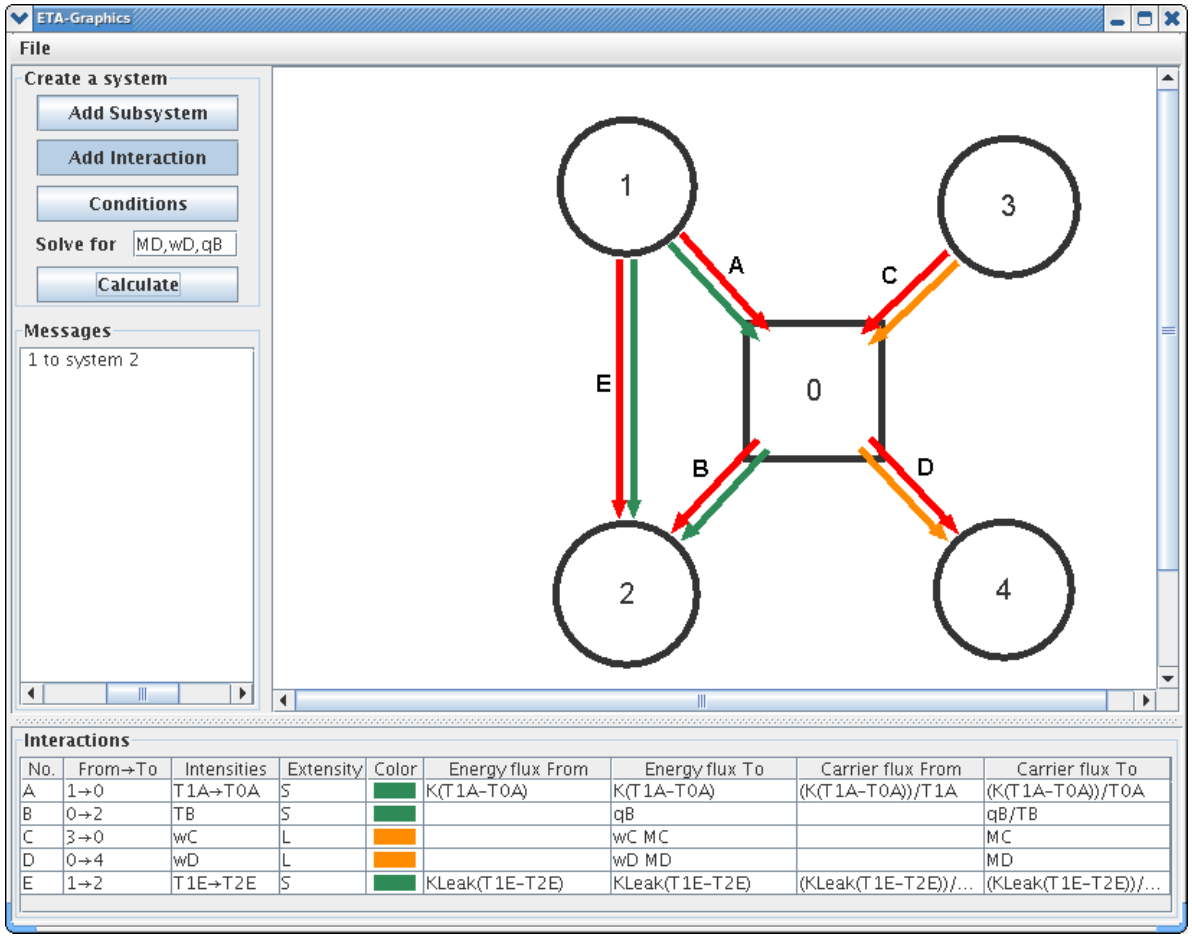
- efficiency and power
- maximum power
- efficiency at maximum power

Results for the Novikov-engine



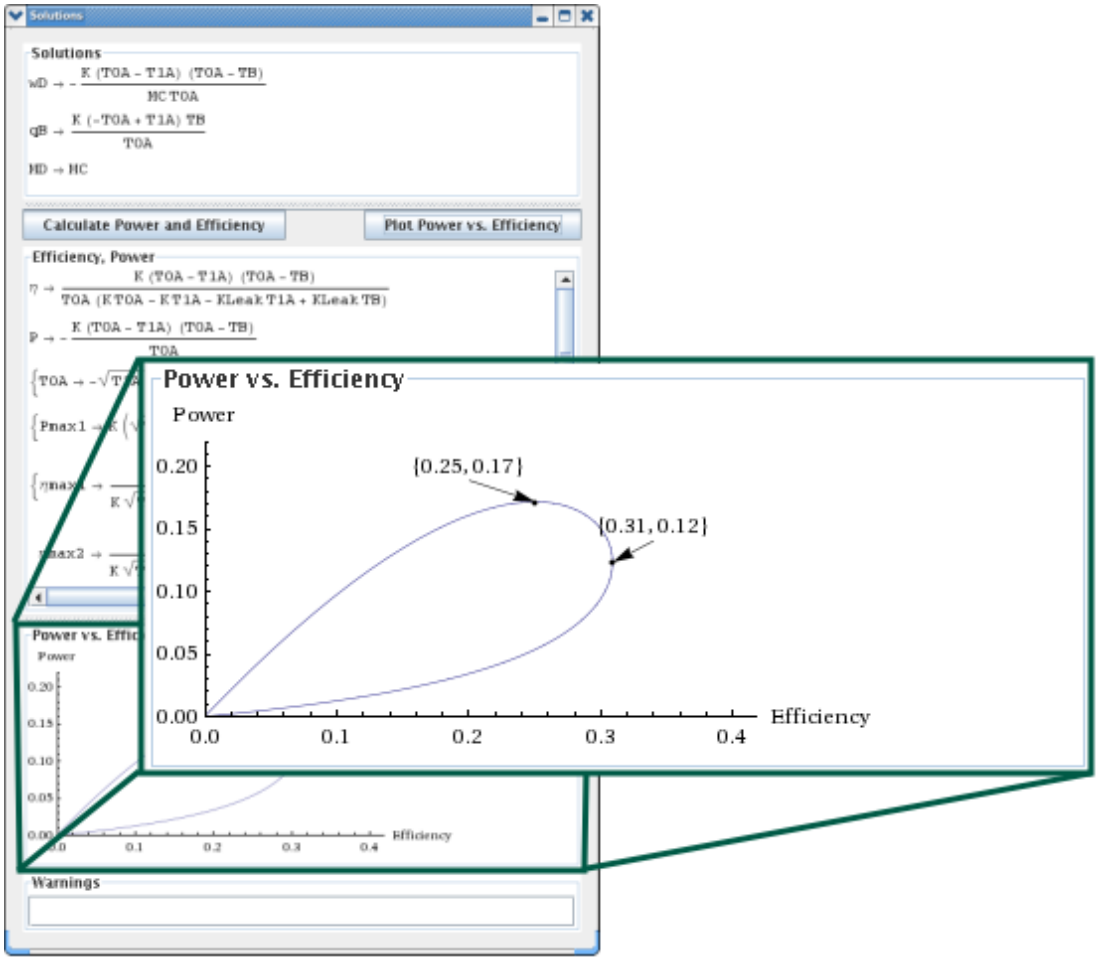
- power-efficiency-graph
- values for points of maximum power and efficiency

Novikov-engine with heat leak



No.	From→To	Intensities	Extensity	Color	Energy flux From	Energy flux To	Carrier flux From	Carrier flux To
A	1→0	T1A→T0A	S		K(T1A-T0A)	K(T1A-T0A)	(K(T1A-T0A))/T1A	(K(T1A-T0A))/T0A
B	0→2	TB	S			qB		qB/TB
C	3→0	wC	L			wC MC		MC
D	0→4	wD	L			wD MD		MD
E	1→2	T1E→T2E	S		KLeak(T1E-T2E)	KLeak(T1E-T2E)	(KLeak(T1E-T2E))/...	(KLeak(T1E-T2E))/...

Novikov-engine with heat leak



- same power as without leak
- different efficiency
- loop in the power-efficiency-graph

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Conclusion and Outlook

ETA-Graphics . . .

. . . is capable of supporting the user in easily creating and analyzing endoreversible systems.

Possible enhancements of ETA-Graphics:

- possibility to export the solutions to Mathematica to do further calculations
- extension to more dynamical systems