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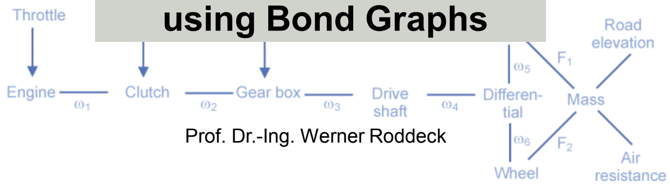
Object Oriented Modelling and Simulation of Mechatronic Systems using Bond Graphs



Prof. Dr.-Ing. Werner Roddeck

REM 2011, Kocaeli, Turkey

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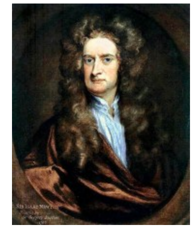

Sir Isaac Newton
1643 -1727

Gottfried Wilhelm Leibniz
1646 -1716

Newton developed point mechanics and the three laws of motion, with which movement of rigid bodys can be described on earth and in outer space. Electrical and magnetic phenomena weren't defined at that time and the concept of ***energy*** was indistinct.
At the same time Leibniz, one of the last polymath, developed the ***infinitesimal calculus*** and so did Newton simultaniously.

Creation of modern physics

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Newton defined the kinetic energy wrongly as

$$E_{kin} = c \cdot v^1$$

Leibniz made the statement: „ *The forces are of two kinds namely dead and live. The dead force depends on position and the live force is proportional to the square of velocity. The sum of these two forces in the universe remains constant.“*

Because the term ***energy*** was not yet defined Leibniz uses the term ***force.***
By replacing it one gets:

$$E_{kin} = c \cdot v^2$$ and $$E_{kin} + E_{pot} = const.$$

But the international reputation of Newton was stronger than that of Leibniz, so energy remained undistinct for another 100 years and Newtons three laws of motion became the crucical point in mechanics.

How it went wrong

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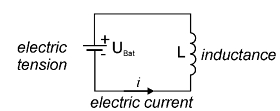
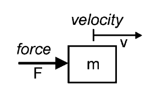
That domains of physics which evolved later like electrotechnology, used operands like electric tension and current, which have no counterparts in mechanics. Simular quantities there are force and velocity.

electro-technology



$$U = -L \cdot \frac{di}{dt}$$

mechanics



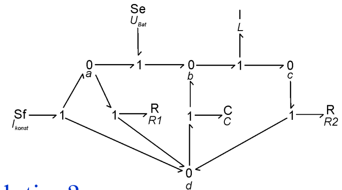
$$F = m \cdot \frac{dv}{dt}$$

Each physical discipline used their own set of formula, denotations and methods.

Confusion of formula, denotation and methods

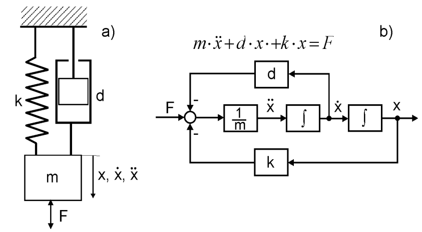
This confusion has made education of engineers much more complicated than it should be, longing for harmonised concepts in the course of the last 100 years.

In 1960 Prof. H.M. Paynter of MIT established a new graphical description formalism called ***bond graphs*** which was particularly suited for description of multidisciplinary systems.



Perhaps the solution?

Physical systems are modelled with differential equations which can be solved by integration.



To integrate modells block oriented editors like ***Simulink*** are used. But the modell in Simulink is not object oriented, the blocks do not represent objects of the system.

How modelling is done usually

- The method of ***bond graphs*** tries to describe physical systems consistently.
- The method is independant of a special area of expertise.
- A basic attribute of physical systems is the ***flow of energy (power)***.
- At each location of a system the ***theorem of conservation of power*** is valid.
- In each domain ***power*** can be represented by the product of two characteristic variables.

electrical → $P=U\cdot I$ mechanical → $P=F\cdot v$ (Translation)

mechanical → $P=M\cdot\omega$ (Rotation) hydraulic → $P=p\cdot\dot{V}$

thermodynamic → $P=T\cdot\dot{S}$

Power is always the product of two characteristic variables

Domain	Effort	Flow
electrical	electrical potential	current
mechanical	force	velocity
hydraulic	pressure	volume flow rate
chemical	chemical potential	molar flow rate
thermodynamic	temperature	entropy rate

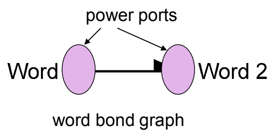
The two characteristic or „generalized variables“ for power are called ***effort (e)*** and ***flow (f)***. Power ist always the product of both:

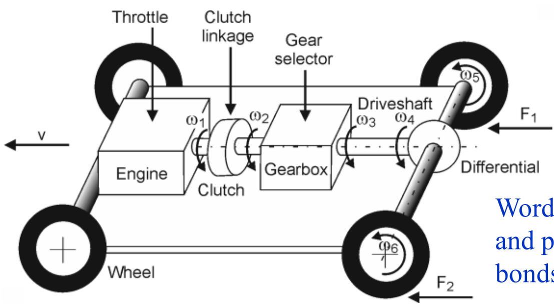
$P=e\cdot f$ respectively $P(t)=e(t)\cdot f(t)$

Two other generalized variables, so-called „energy variables“, are named ***momentum (p)*** and ***displacement (q)***:

$$p(t)=\int^{t} e(t)dt \quad \text{or} \quad \frac{dp(t)}{dt}=e(t)$$
$$q(t)=\int^{t} f(t)dt \quad \text{or} \quad \frac{dq(t)}{dt}=f(t)$$

Generalized variables





Word objects and power bonds

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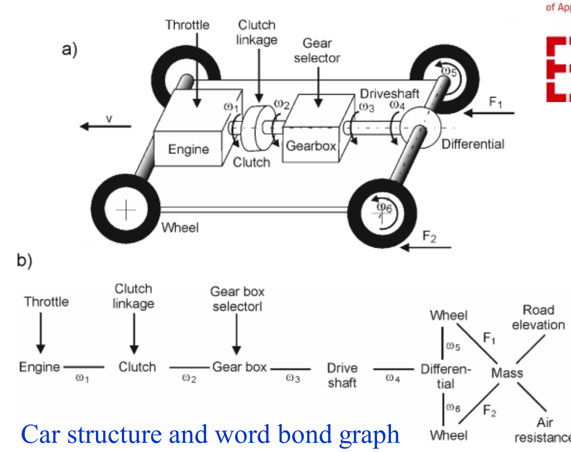

Car structure and word bond graph

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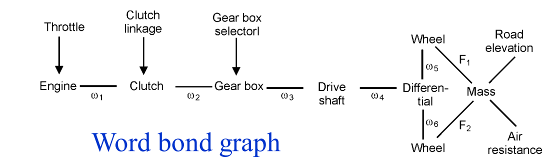
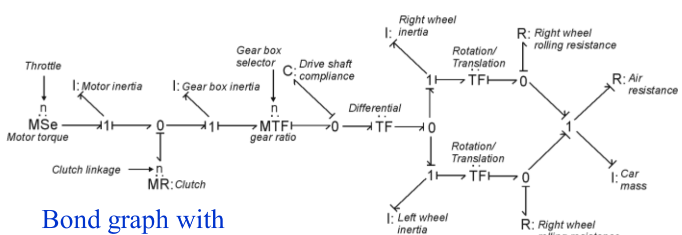


Word bond graph



Bond graph with standardized basic elements

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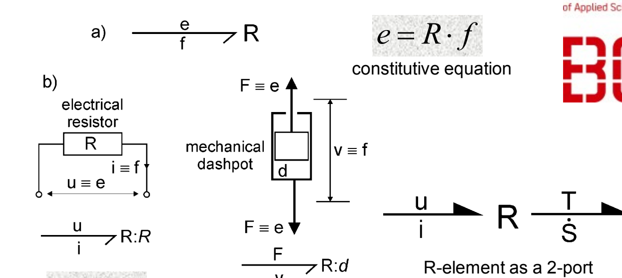

$e = R \cdot f$

constitutive equation

$u = R \cdot i$

R: electrical resistance

Ohm's law

$F = d \cdot v$

d: viscous resistance

Stokes' law

Basic 1-port R-element (dissipative element)

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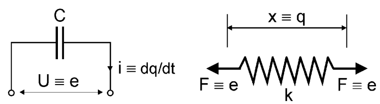
a) $\overset{e}{\underset{f = dq/dt}{\rightharpoonup}} C$ $\quad e = \frac{q}{C}$ or $f = C \cdot \frac{de}{dt}$

constitutive equation

b)



electrical capacitor

mechanical spring

$\overset{u}{\underset{i}{\rightharpoonup}} C{:}C$ $\qquad \overset{F}{\underset{v=\dot{x}}{\rightharpoonup}} C{:}\frac{1}{k}$

$$u = \frac{1}{C}\int^{t} i \cdot dt \qquad F = k \cdot x$$

C: electrical capacity

k = 1/C: stiffness

Current-voltage relation

Hooke's law

Basic 1-port C-element (storage element)

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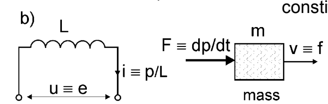
a) $\overset{e = dp/dt}{\underset{f}{\rightharpoonup}} I$ $\quad p = I \cdot f$ or $e = I \cdot \frac{df}{dt}$

constitutive equation

b)



inductor

mass

$\overset{u}{\underset{i}{\rightharpoonup}} I{:}L$ $\qquad \overset{F}{\underset{v}{\rightharpoonup}} I{:}m$

$$u = L \cdot \frac{di}{dt} \qquad F = m \cdot a = m \cdot \dot{v} = m \cdot \ddot{x}$$

m: mass

L: electrical inductance

Newton's 2. law

Current-voltage relation

Basic 1-port I-element (storage element)

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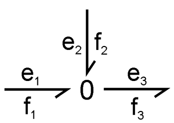
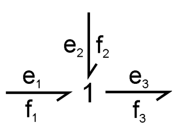


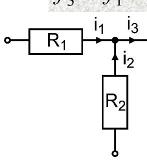


0-junction
flow-junction

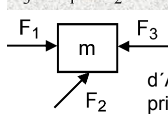
1-junction
effort-junction

$$e_1 = e_2 = e_3$$
$$f_3 = f_1 + f_2 \quad \text{or}$$
$$f_3 - f_1 - f_2 = 0$$

$$f_1 = f_2 = f_3$$
$$e_3 = e_1 + e_2 \quad \text{or}$$
$$e_3 - e_1 - e_2 = 0$$



Kirchhoff´s law



d´Alembert´s principle

Basic junction-elements (branching element)

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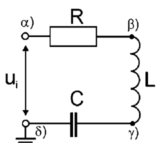

1.) For each location with a distinct potential, assign a 0-junction
2.) Insert basic 1-port elements between potentials by a 1-junction
3.) Remove 0-junction of ground potential and all attached power bonds
4.) Simplify bond graph by rules of simplification

Formal method of drawing bond graphs for electrical circuits

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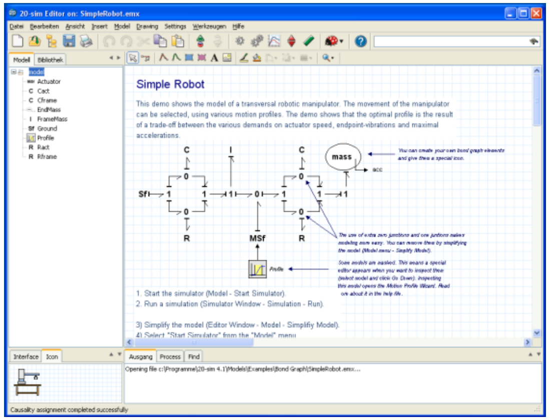

Screen of simulation program ***20-sim*** with bond graph

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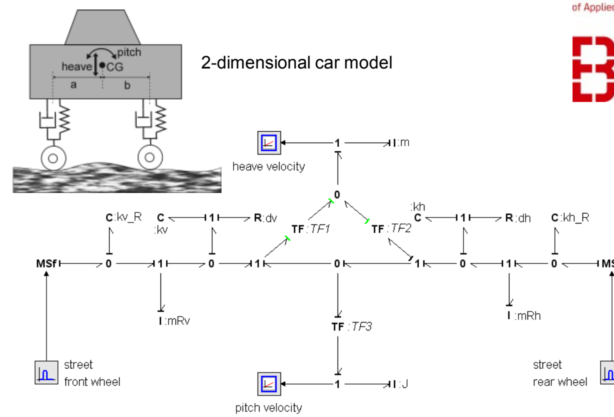

20-sim bond graph model of a street excited half car

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Simulation results of a half-car model with 20-sim