Theorie der Bond-Graphen I

Modellierung kontinuierlicher dynamischer Systeme:

anschaulich, orientiert an E-Technik,

mit kontinuierlichem Leistungsfluss,

basierend auf Graphen

Einheitliche Sicht auf Energieerhaltungssätze mit

Effort * Flow als abstraktem Leistungsfluss

Begründer
Henry M. Paynter, MIT, 1959
D. C. Karnopp: System Dynamics, 1990

W. Bruns, 2006

Vorbild und Anregungen für Bond-Graphen

Elektrische Netzwerke (Schwingkreis) mit

Kirchhoff`‘s Strom-Gesetz

Summe Ströme i über einen Knoten = 0

Kirchhoff`‘s Spannungs-Gesetz

Summe Spannungen u über Kanten einer Masche = 0

Widerstandsgesetz $u = i * R$ R = Widerstand [Ohm]

Kapazitätsgesetz $du/dt = 1/C * i$ C = Kapazität [Farad]

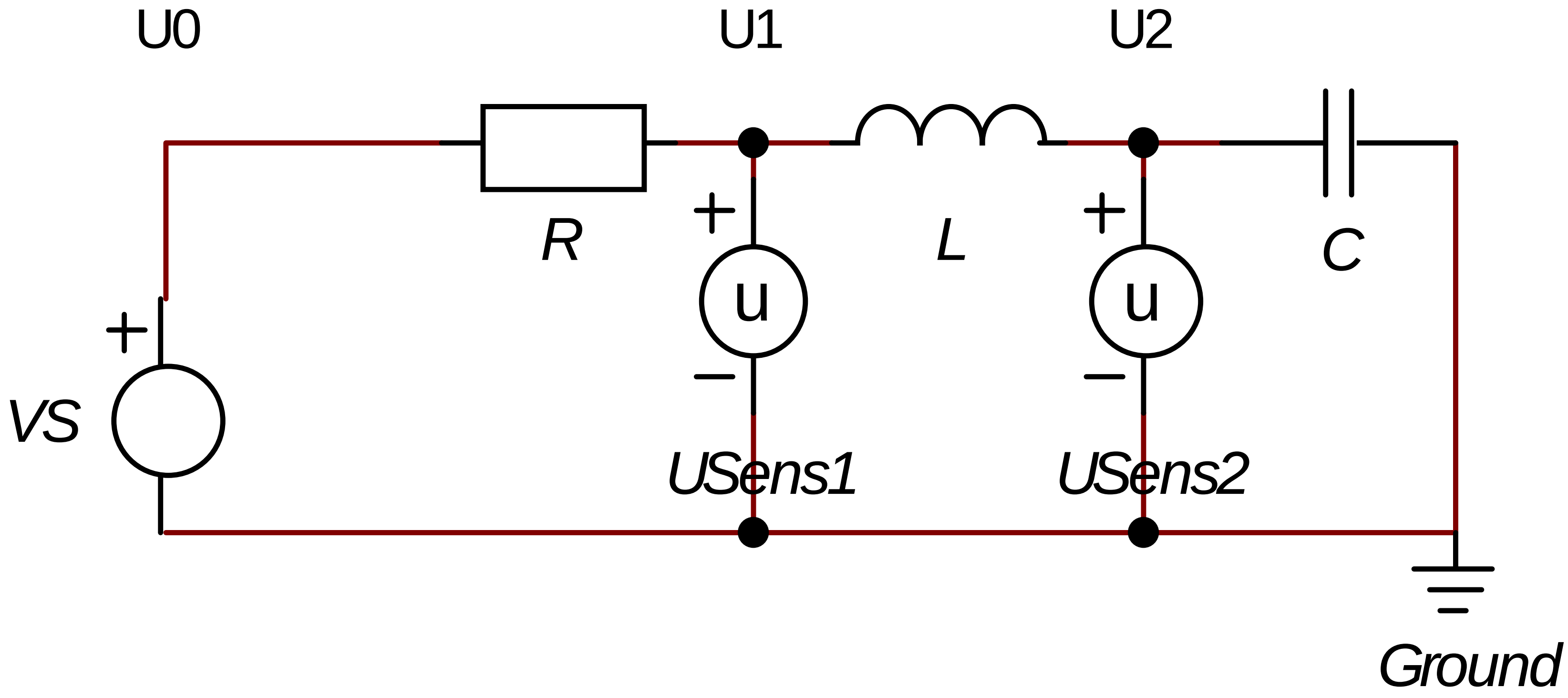
Induktionsgesetz $u = di/dt * L$ L = Induktivität [Henry]

W. Bruns, 2006

Elemente

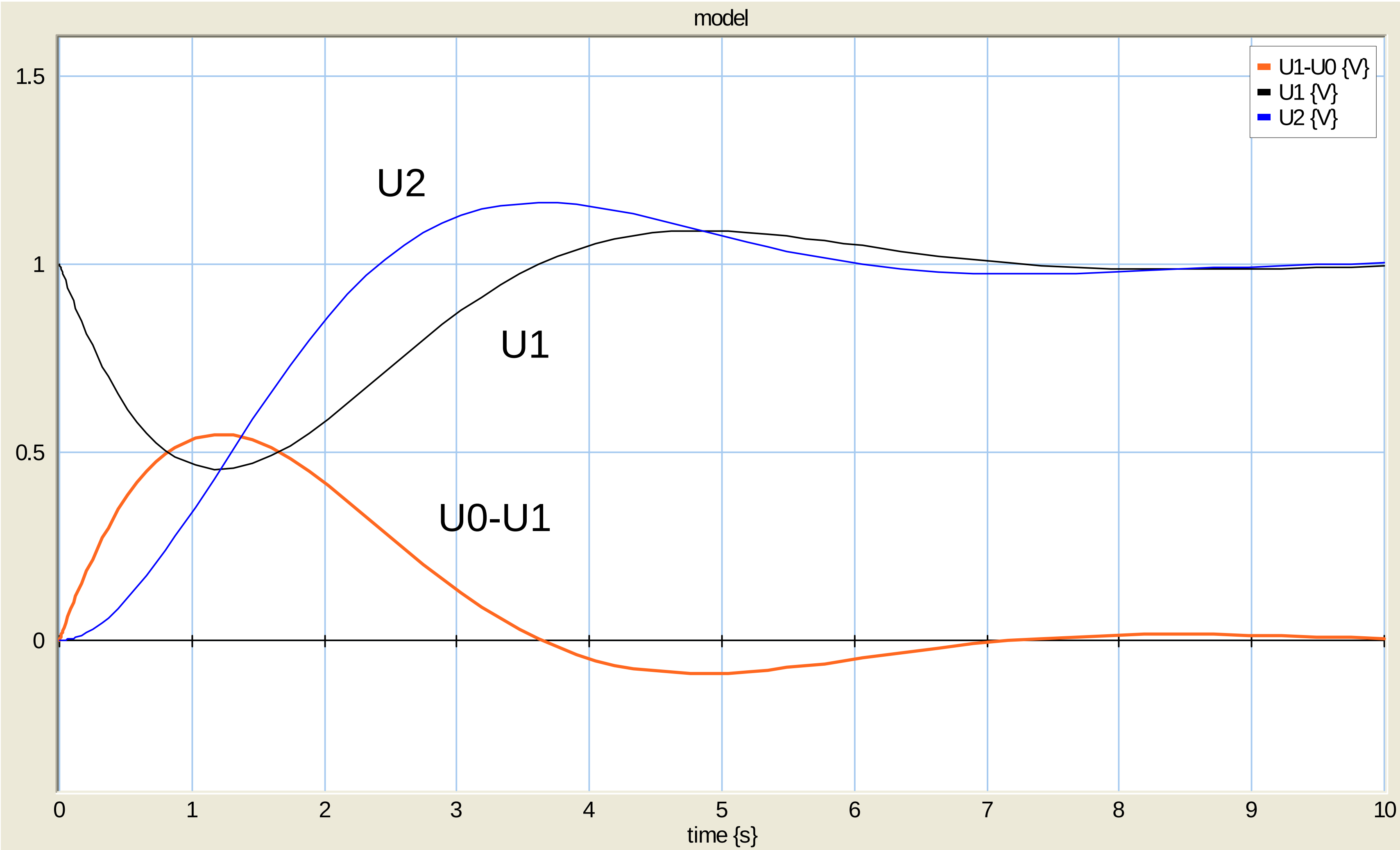
$\rightharpoondown$	Verbindungen, Energiefluss
0	Knoten mit gleichem *Effort (e)*
1	Knoten mit gleichem *Flow (f)*
R	Widerstand
C	Kapazität
I	Induktion
TF	Transformator $e1 = m * e2$
GY	Gyrator $m*f1 = f2$

Beispiel: Schwingkreis1



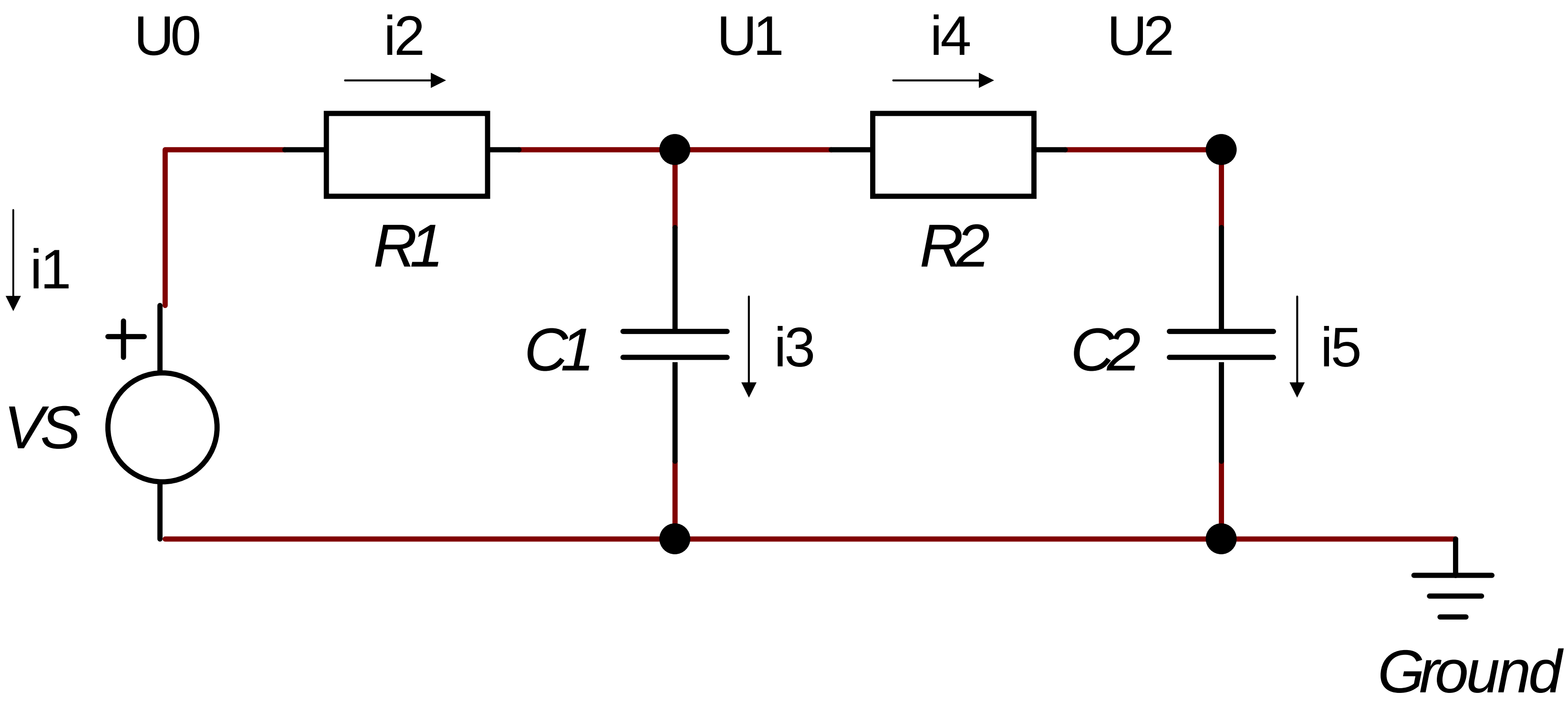
W. Bruns, 2006

Beispiel: Schwingkreis1



W. Bruns, 2006

Beispiel: Schwingkreis 2

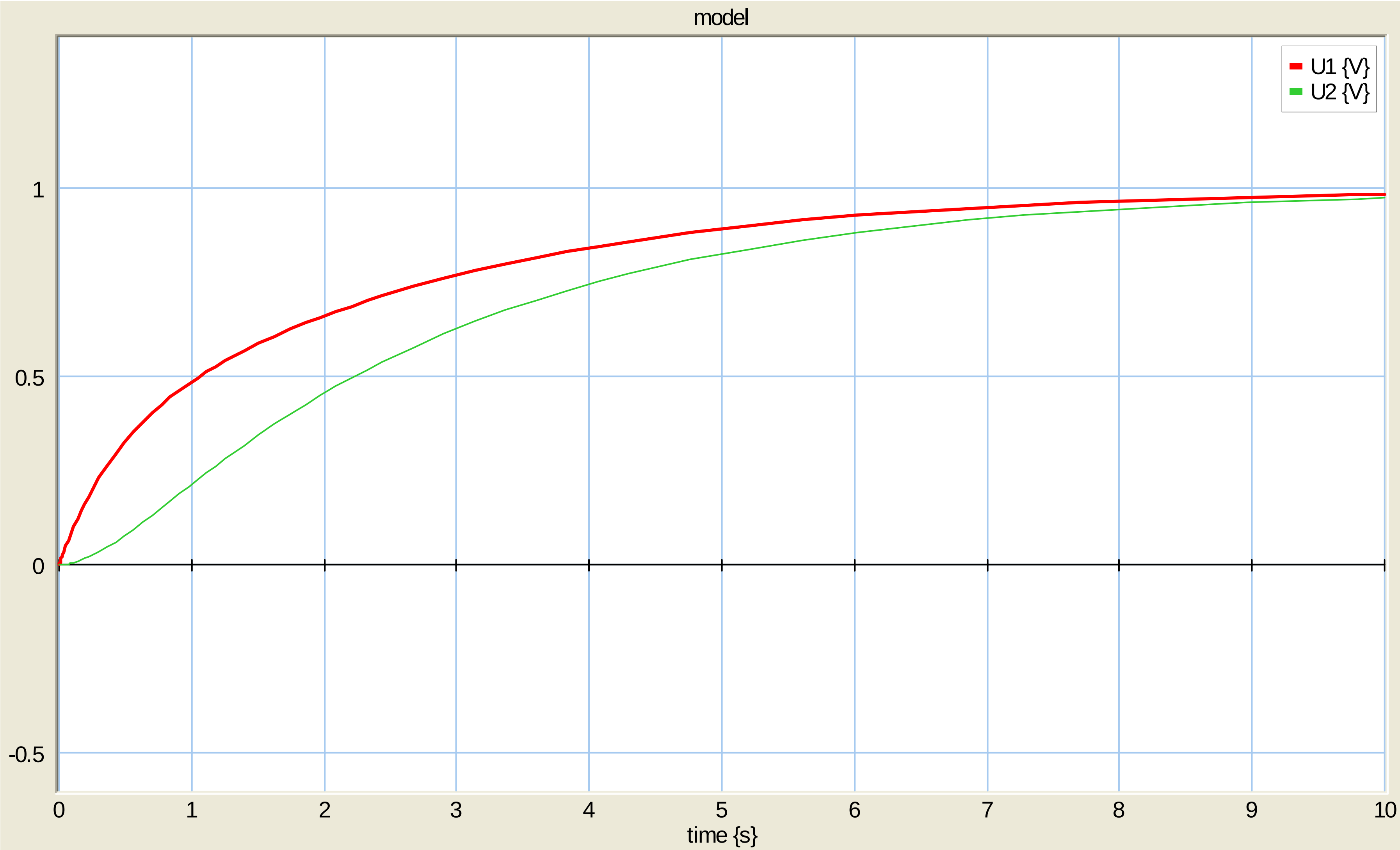


Spannungsabfälle

u1 = VS, u2 = U1-U0, u3 = U1, u4 = U2-U1, u5 = U2

W. Bruns, 2006

Beispiel: Schwingkreis 2



W. Bruns, 2006

Physikalische Zusammenhänge

Summe Ströme über Knoten = 0

$i1 + i3 + i5 = 0$

$i2 - i3 - i4 = 0$

$i4 - i5 = 0$ $\qquad$ $- i1 - i2 = 0$

Summe Spannungsabfälle über Maschen = 0

$-u1 + u2 + u3 = 0$

$-u1 + u2 + u4 + u5 = 0$

Widerstandsgesetz $u = i * R$

Kondensatorgesetz $du/dt = i / C$

Siehe auch P. Fishwick S.220

Mathematische Repräsentation

dU1/dt = 1/C1 ((E-U1)/R1 + (U2-U1)/R2)

dU2/dt = 1/C2 ((U1-U2)/R2

Allgemein: System linearer Differentialgleichungen

dX1/dt = a11* X1 + a12 * X2

dX2/dt = a21 * X1 + a22 * X2

Oder als Vektor DGL mit Koeffizienten-Matrix A

Lösungsansätze mit e-Funktion, analog der Problemstellung

X`(t) = a*X(t)   => Lösung $X(t) = be^{at}$

Lösungsmöglichkeiten

Wenn a zeitabhängig ist, dann ist eine analytische Lösung nicht immer möglich.

Dann erfolgt eine numerische Lösung:

Diskretisierung der DGL und Integration mit

Näherungsverfahren (Euler, Runge-Kutta ...)

Bond-Graphen Modellierung

Elektrischer Schwingkreis

1. Physikalisches Schema
2. Elemente und Referenzsystem
3. Objektmodell mit R, C, I und Knoten
4. 0, 1 Knoten
5. Verbinde Knoten
6. Verbinde Objekte
7. Vereinfache Graphen

Beispiel: Schwingkreis1

Elemente

R	**0**	**Se**
R1	*ZeroJunction1*	*Se1*
I	**1**	
I1	*OneJunction1*	
C		
C1		

Beispiel: Schwingkreis1

0-Knoten Struktur

R *R1*

I *I1*

C *C1*

0 *ZeroJunction1*

0 *ZeroJunction2*

0 *ZeroJunction3*

Se *Se1*

1 *OneJunction1*

Beispiel: Schwingkreis1

0-Knoten + 1-Knoten Struktur

R *R1*

I *I1*

C *C1*

0 *ZeroJunction1*

1 *OneJunction1*

0 *ZeroJunction2*

1 *OneJunction2*

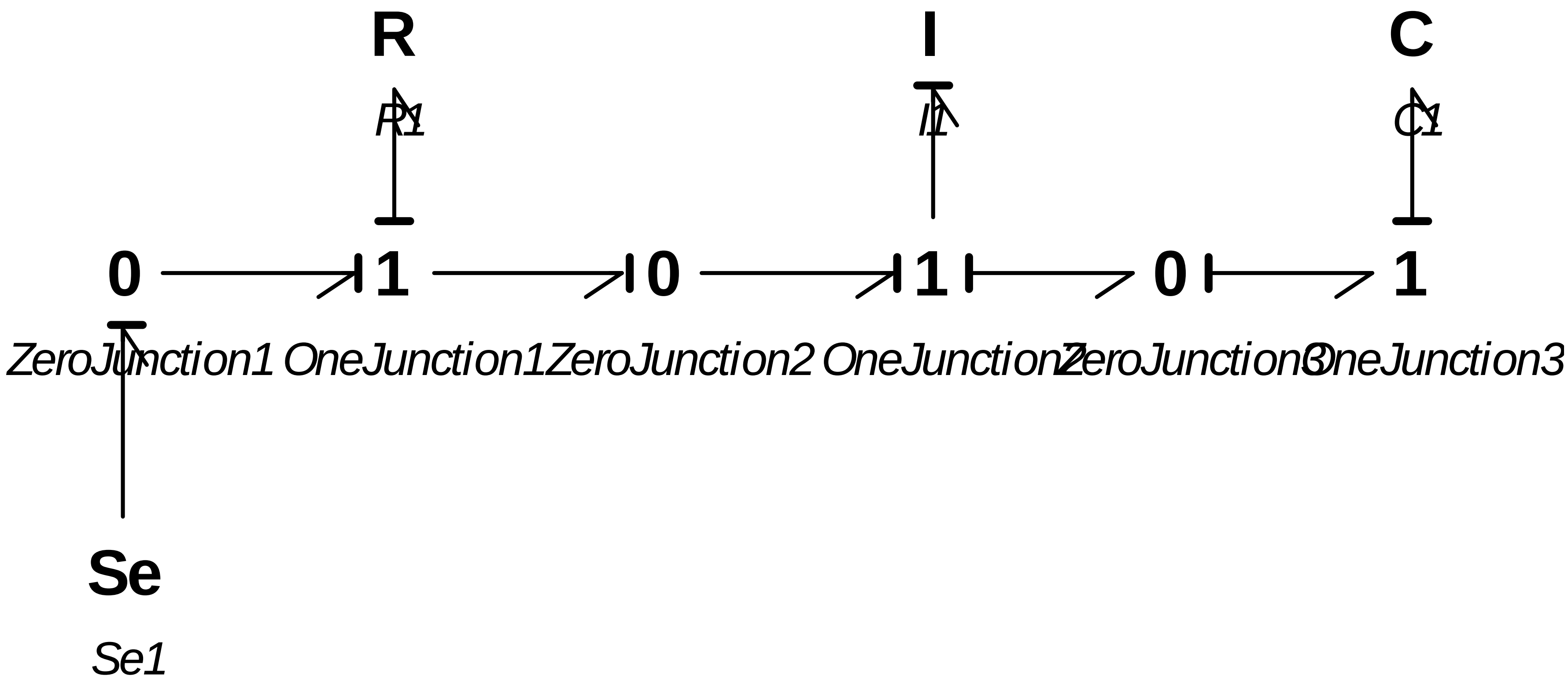
0 *ZeroJunction3*

1 *OneJunction3*

Se *Se1*

Beispiel: Schwingkreis1

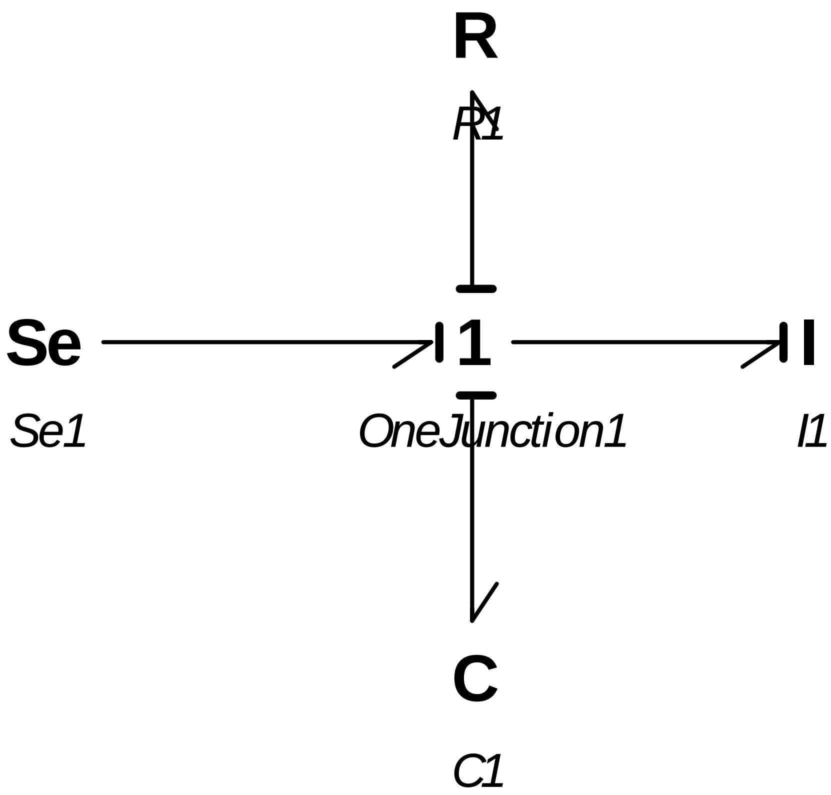
Bondgraph



W. Bruns, 2006

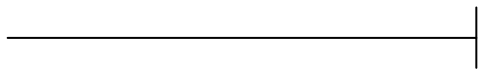
Beispiel: Schwingkreis1

Bondgraph Minimal



W. Bruns, 2006

Computational Causality



Richtung der Kausalität von *Effort*

Flow entgegengesetzt

W. Bruns, 2006

Siehe Folien und Literatur

Jose. J. Granada

Taehyun Shim – University of Michigan-Dearborn
Bond_graph_shim_w2.pdf

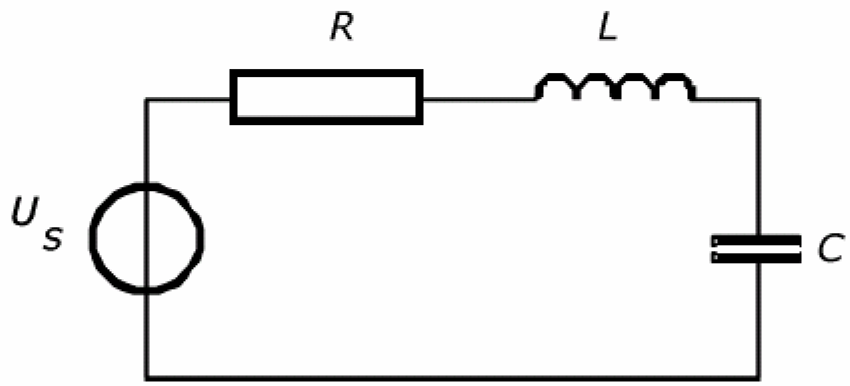
D. C. Karnopp (1990),
Slides_Bondgraph

Vorlesung Cellier
http://www2.inf.ethz.ch/~cellier/vorlesung/W1119_files/frame.htm

20-sim – University Twente

Introduction to Physical System Modeling Using Bond Graphs

Taehyun Shim, Assistant Professor
University of Michigan-Dearborn
Tel: (313)593-5127
Email: tshim@umich.edu



Electrical system

Power variables:

•Electrical voltage (U)

•Electrical current (*i*)

Power in the system: $P = u\,i$

Constitutive law

$$u_R = iR$$

$$u_c = \frac{1}{c}\int i dt$$

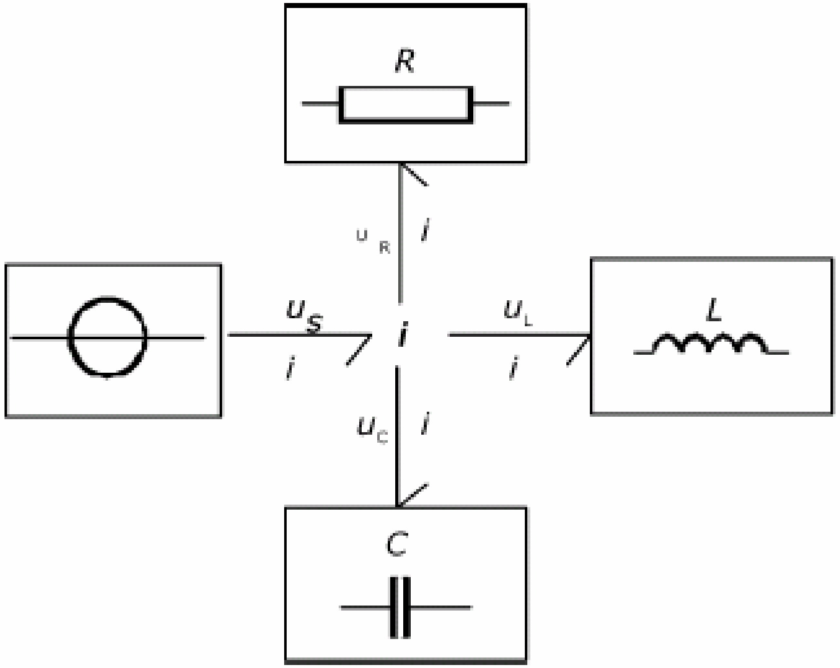
$$u_L = L\frac{di}{dt} or\ i_L = \frac{1}{L}\int u dt$$

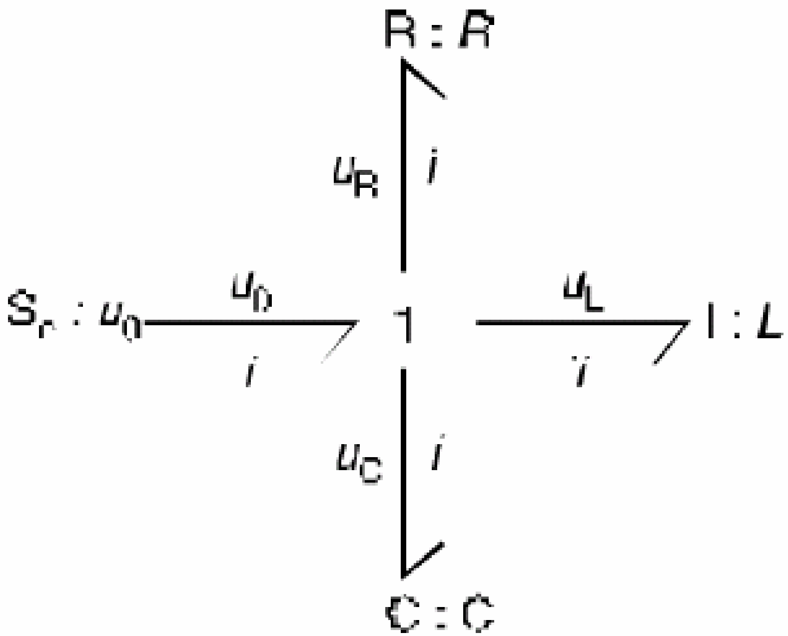
W. Bruns, 2006

Introductory example (RLC circuit-electrical)

The common current becomes a “1-junction” in the bond graphs.

(the current through all connected bonds is the same, the voltages sum is zero)

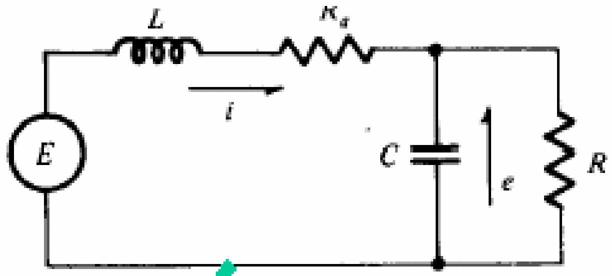




W. Bruns, 2006

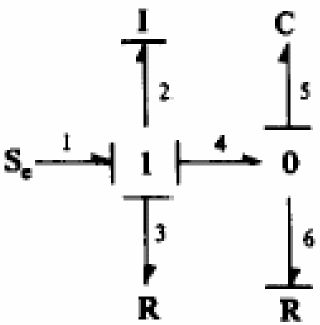
State-Space Equations

- Example:

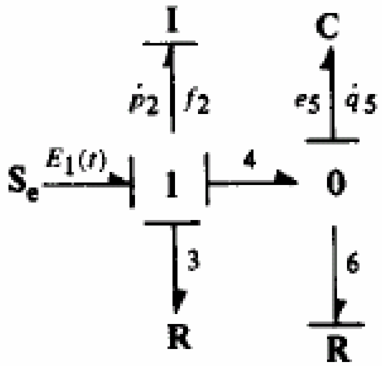


Draw bond graph

and assign causal stroke

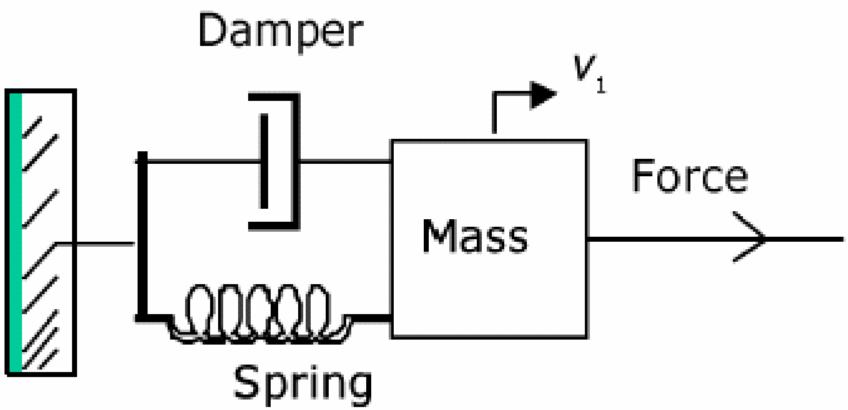


Identify key variables



W. Bruns, 2006

Introductory example (RLC circuit-mechanical)



Mechanical System

Power variables:

•Force (F)

•Linear velocity (v)

Power in the system: $P = F\,v$

$$F_d = cv$$

$$F_s = k_s \int v\,dt = \frac{1}{C_s} \int v\,dt$$

Constitutive law

$$F_m = m\frac{dv}{dt} \;\; or \;\; v = \frac{1}{m}\int F_m dt$$

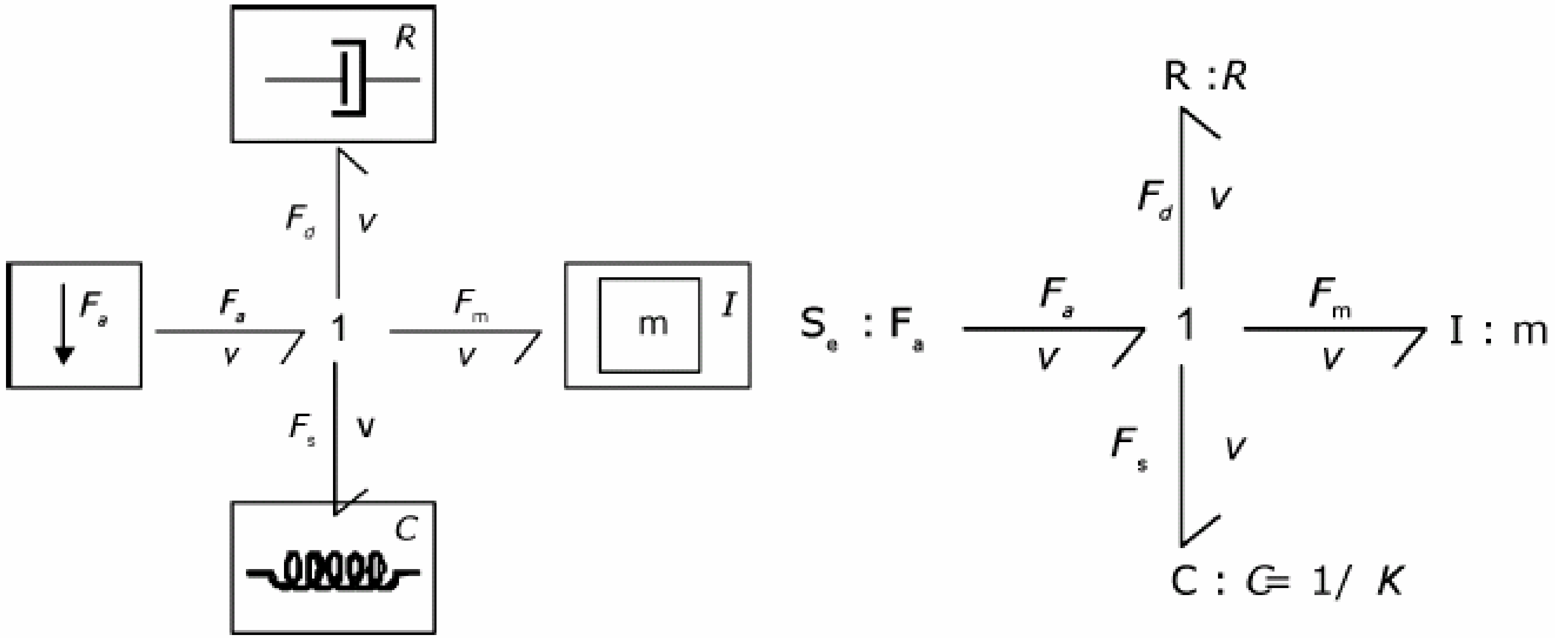
$$F_a = Force$$

W. Bruns, 2006

Introductory example (RLC circuit-mechanical)

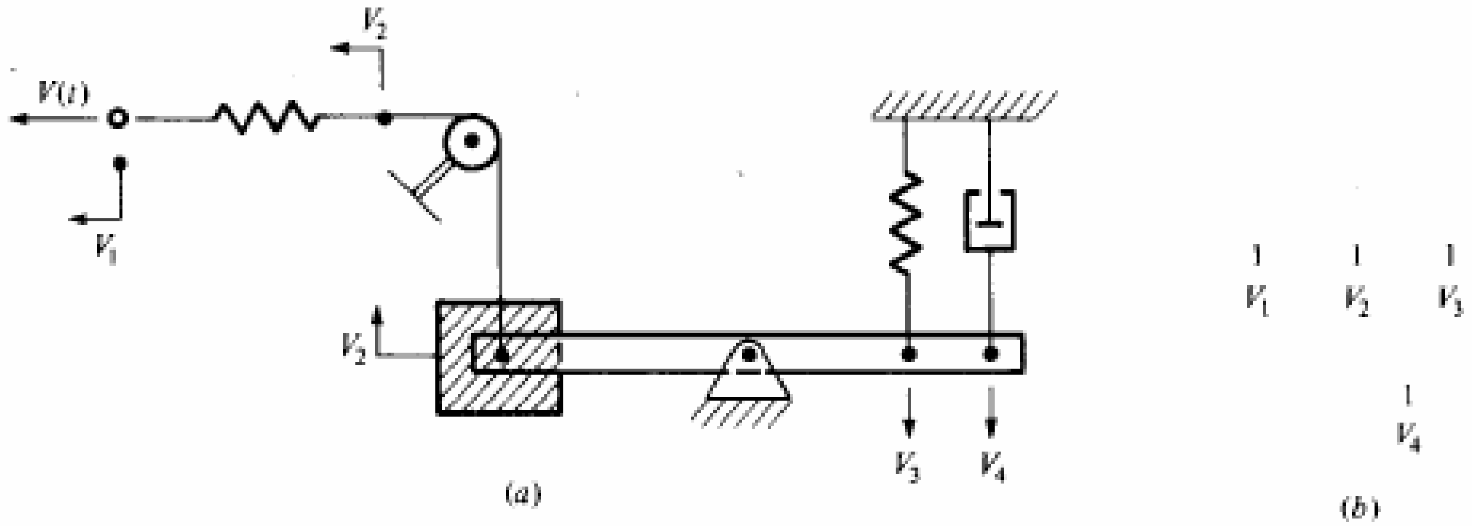
The common velocity becomes a "1-junction" in the bond graphs.

(the velocity all connected bonds is the same, the forces sum is zero)



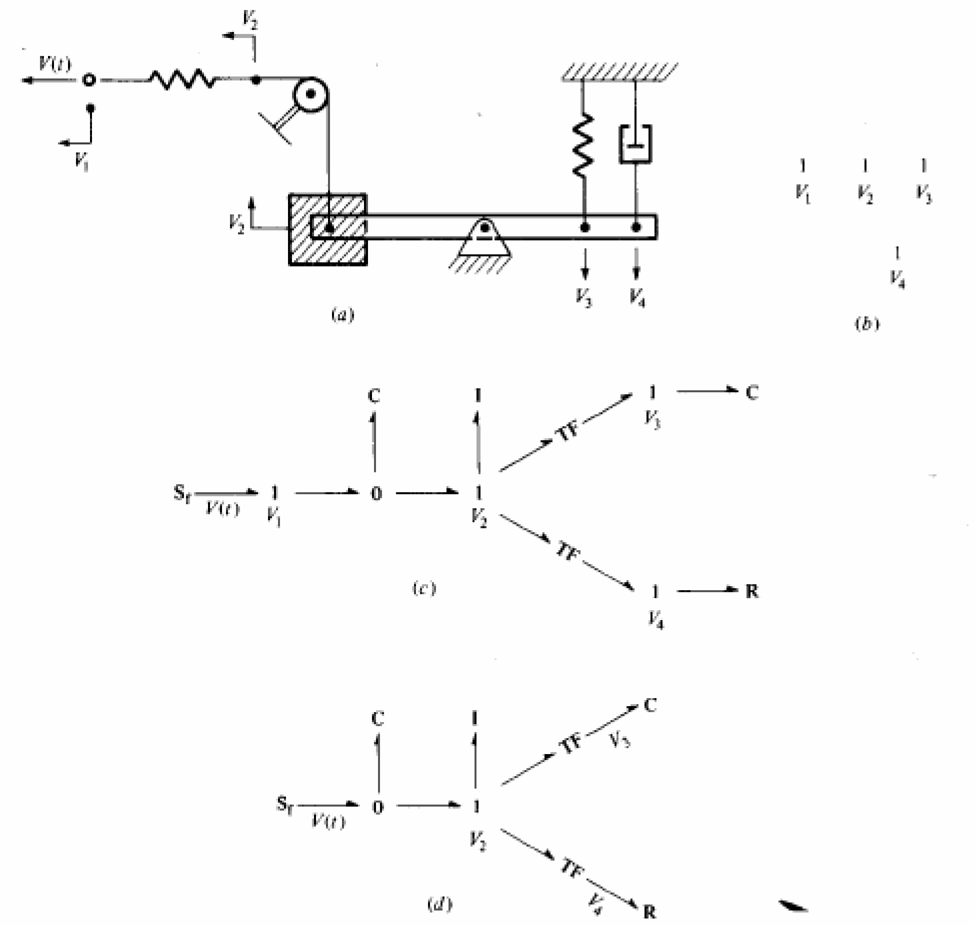
W. Bruns, 2006

Example :translation



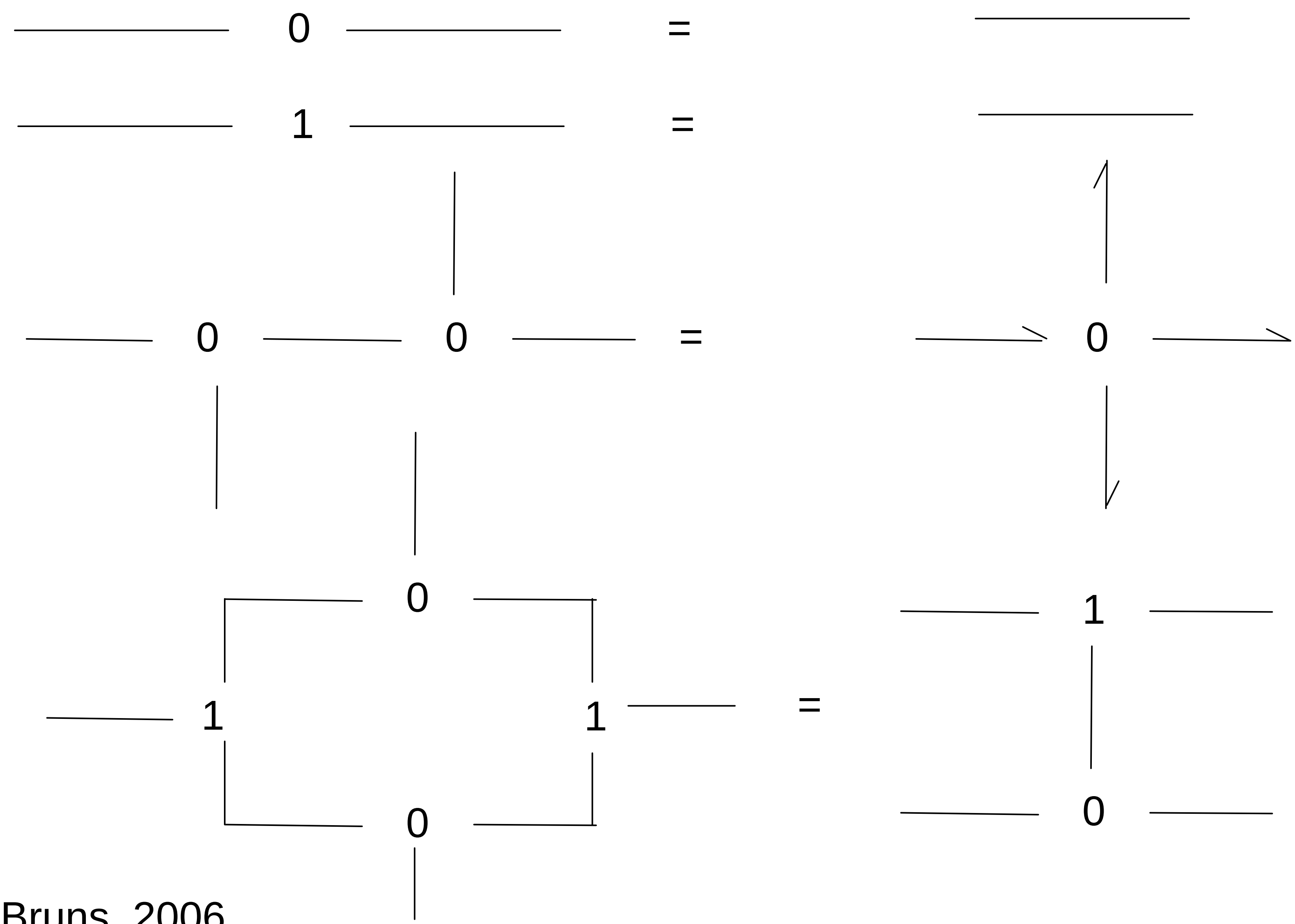
Übungsaufgabe 2
Entwickeln Sie einen minimalisierten Bondgraphen

Example :translation

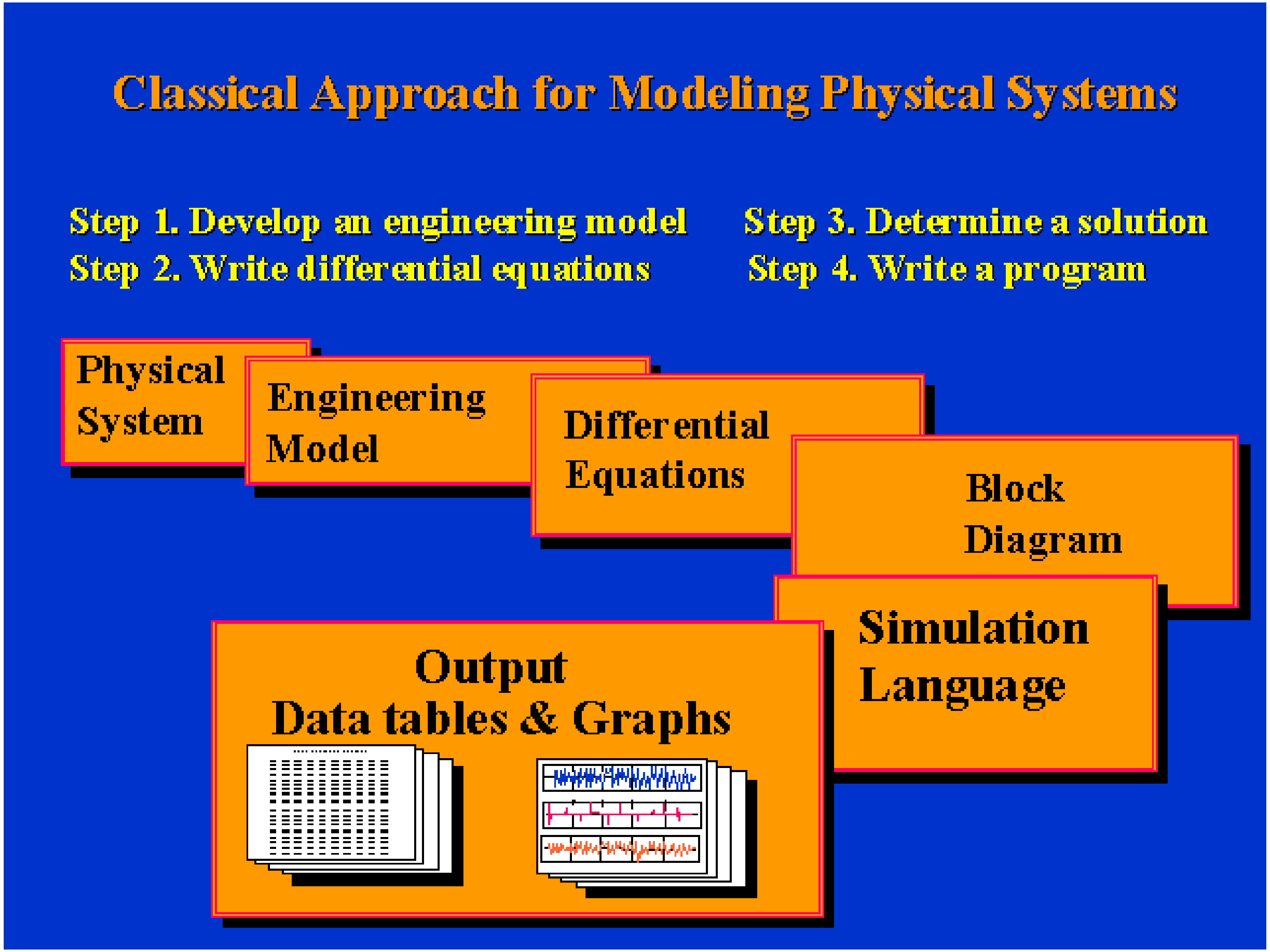


b
:M_c

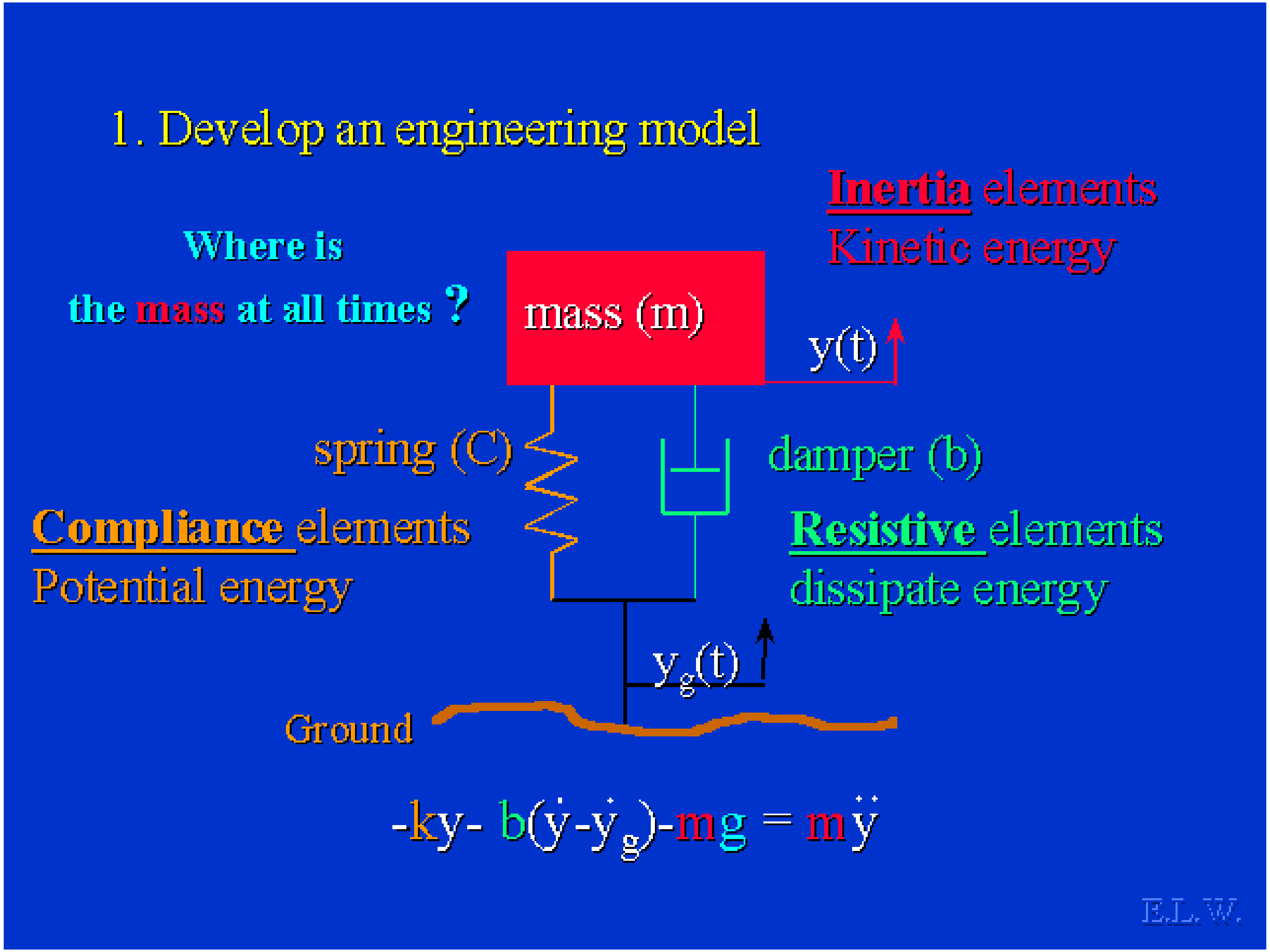
Vereinfachungsregeln



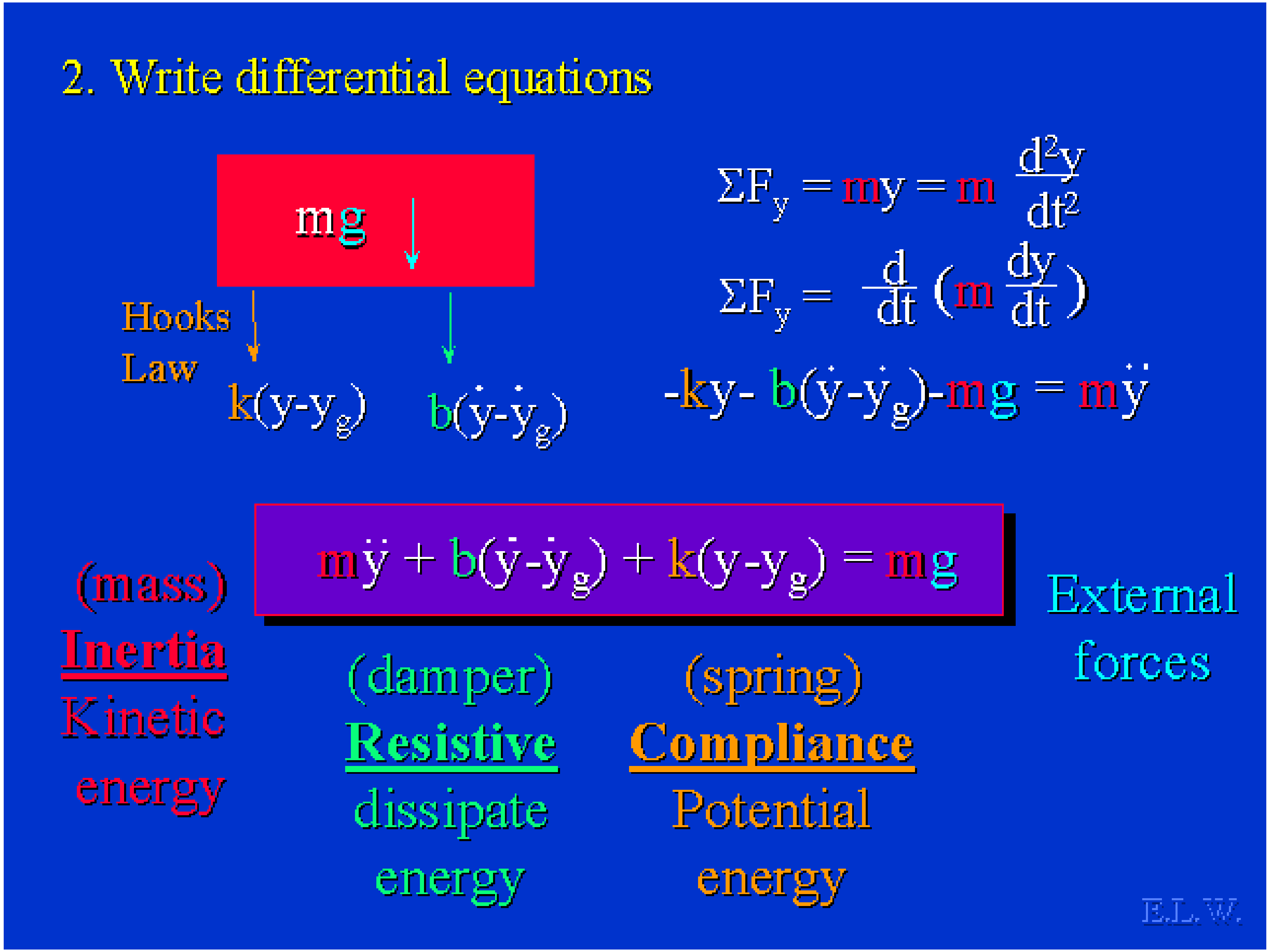
W. Bruns, 2006


Classical Approach for Modeling Physical Systems
Step 1. Develop an engineering model
Step 2. Write differential equations
Step 3. Determine a solution
Step 4. Write a program
Physical System
Engineering Model
Differential Equations
Block Diagram
Simulation Language
Output
Data tables & Graphs

W. Bruns, 2006


1. Develop an engineering model
Inertia elements
Kinetic energy
Where is
the mass at all times ?
mass (m)
y(t)
spring (C)
damper (b)
Compliance elements
Potential energy
Resistive elements
dissipate energy
$y_g(t)$
Ground
$-ky - b(\dot{y} - \dot{y}_g) - mg = m\ddot{y}$
E.L.W.

W. Bruns, 2006


2. Write differential equations
mg
Hooks
Law
$k(y-y_g)$
$b(\dot{y}-\dot{y}_g)$
$\Sigma F_y = m\ddot{y} = m\frac{d^2y}{dt^2}$
$\Sigma F_y = \frac{d}{dt}(m\frac{dy}{dt})$
$-ky-b(\dot{y}-\dot{y}_g)-mg = m\ddot{y}$
$m\ddot{y} + b(\dot{y}-\dot{y}_g) + k(y-y_g) = mg$
(mass)
Inertia
Kinetic
energy
(damper)
Resistive
dissipate
energy
(spring)
Compliance
Potential
energy
External
forces
E.L.W.

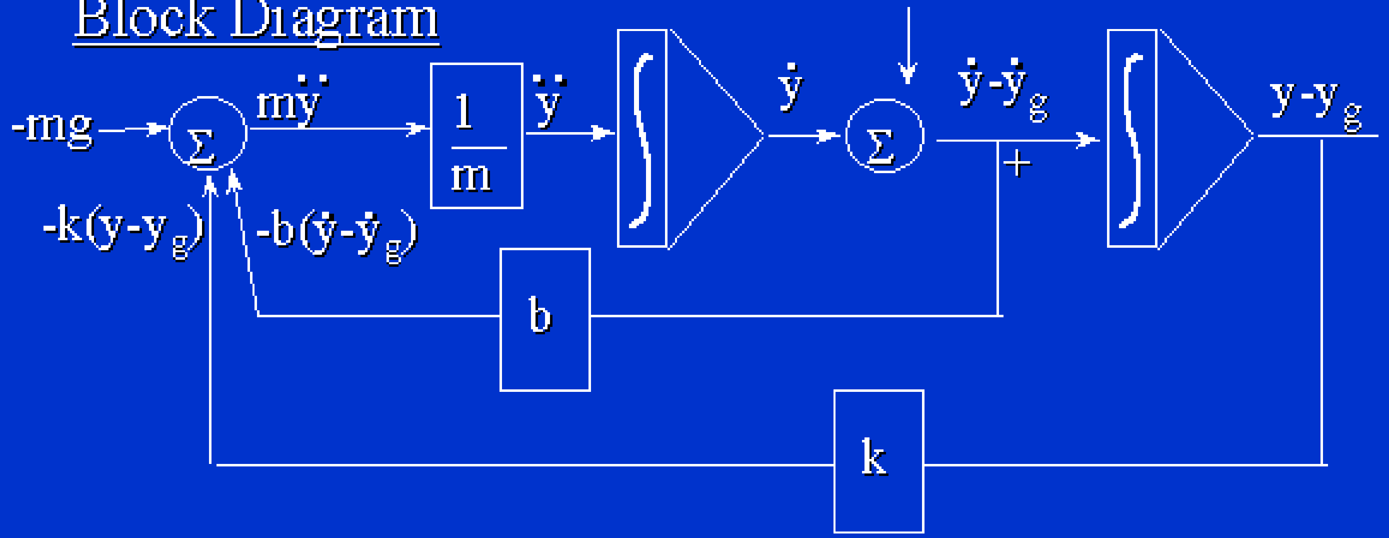
W. Bruns, 2006

3. Determine the solution

Options

- Analytical
- Block diagram
- Bond graph model
- Write a program
- Use simulation tools
- Frequency domain (Laplas Transforms)

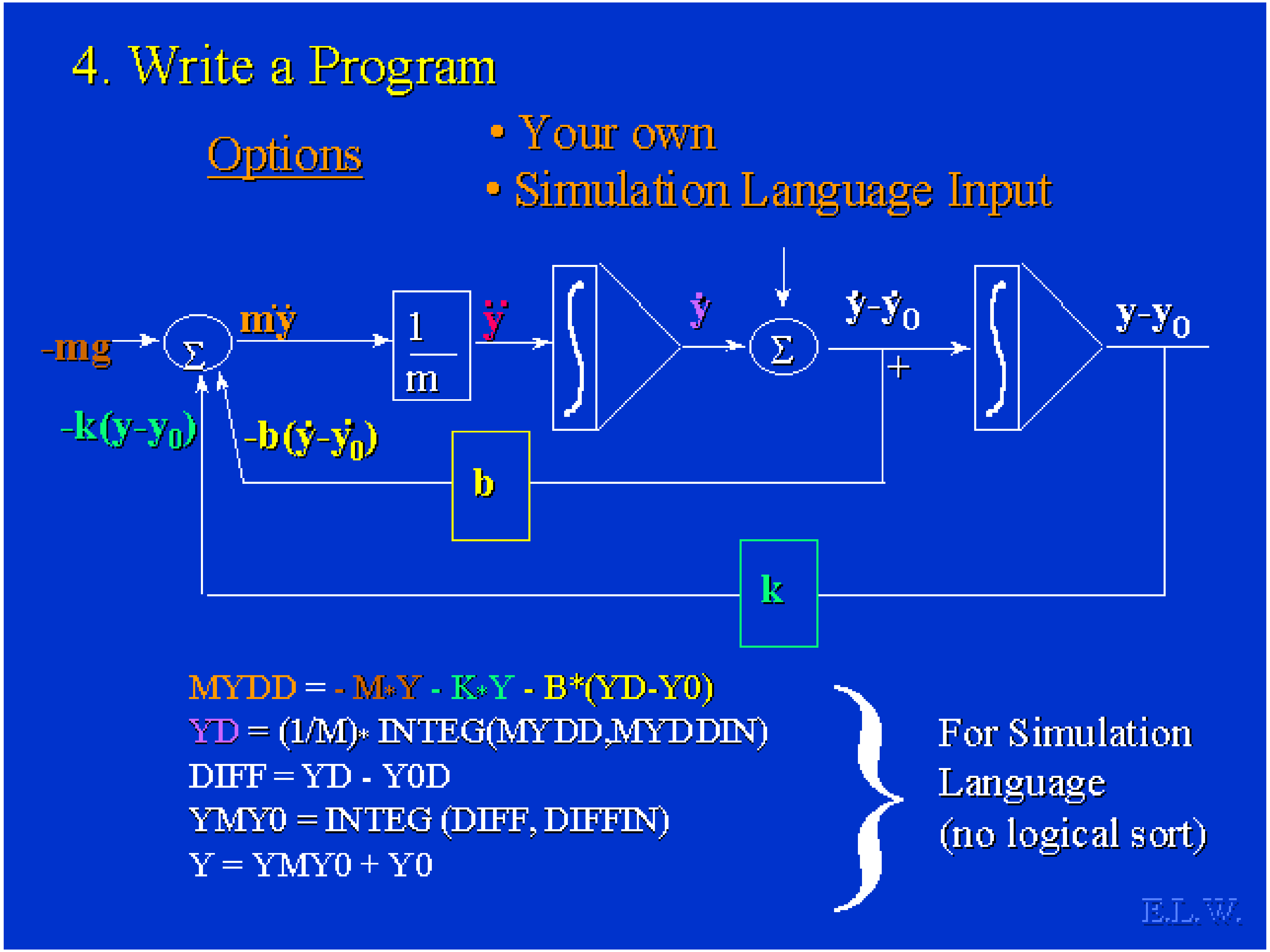
Block Diagram



A block diagram represents the dynamics of the system and describes program statements in single instructions.

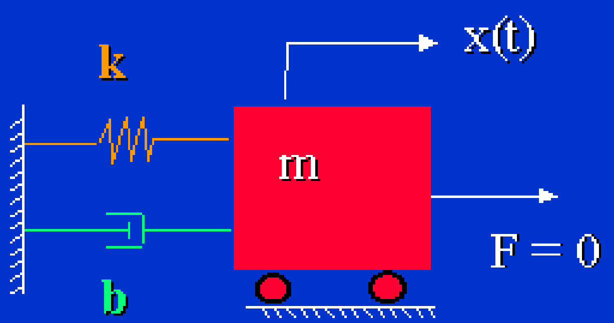
E.L.W.

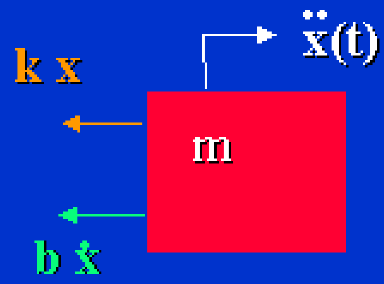
W. Bruns, 2006


4. Write a Program
Options
• Your own
• Simulation Language Input
-mg
Σ
mÿ
1/m
ÿ
ẏ
Σ
y-y0
+
y-y0
-k(y-y0)
-b(ẏ-ẏ0)
b
k
MYDD = - M*Y - K*Y - B*(YD-Y0)
YD = (1/M)* INTEG(MYDD,MYDDIN)
DIFF = YD - Y0D
YMY0 = INTEG (DIFF, DIFFIN)
Y = YMY0 + Y0
For Simulation
Language
(no logical sort)
E.L.W.

W. Bruns, 2006

PREPARING A BASIC ACSL MODEL





Single degree of freedom oscillator

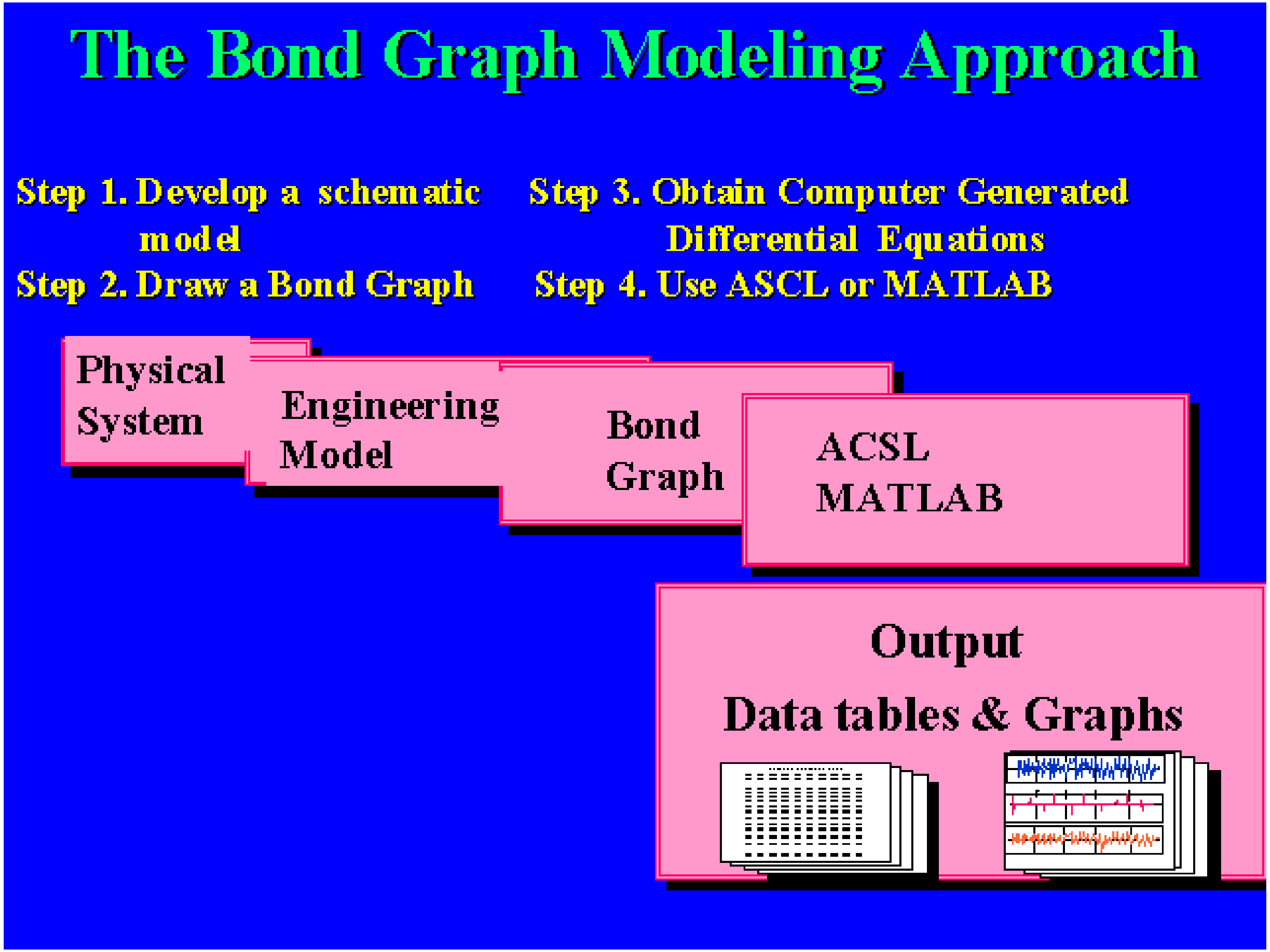
$$m\ddot{x} + b\dot{x} + kx = 0$$

Let the mass of 0.02 kg be initially displaced 0.04m at time zero, held, and then released with an initial velocity equal to zero. Let the spring constant be 1.96 N/m and the damper coefficient 0.05N-sec/m. It is desired to analyze the system response to an initial displacement or an external input.

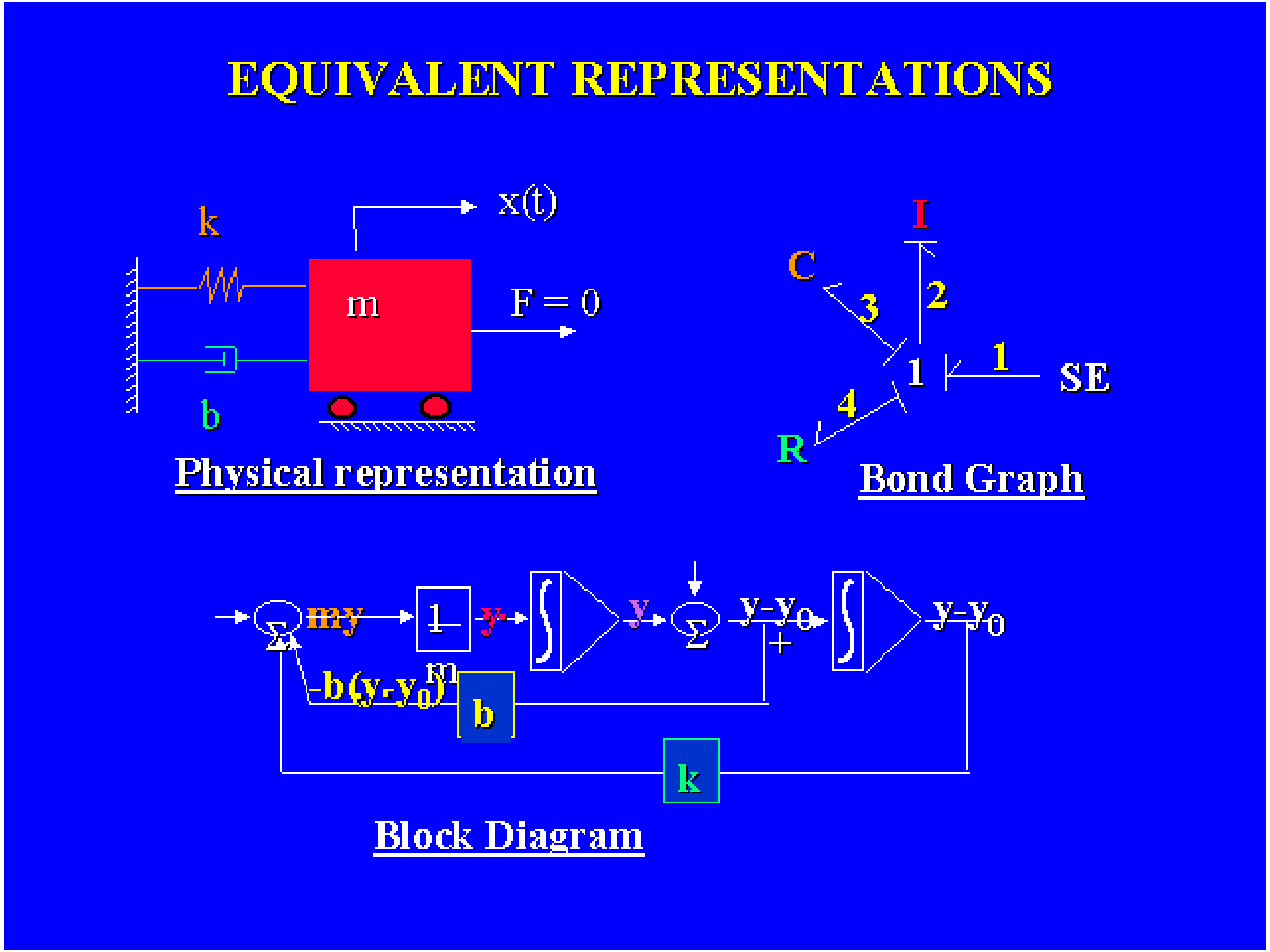
E.L.W.

PREPARING A BASIC ACSL MODEL

```
PROGRAM OSCILLATOR                          $"ACSL INPUT FILE…."
INITIAL
   CONSTANT M=0.02,K=1.96,B-0.05          $"<==Physical parameters"
   CONSTANT XDIN=0.0,XIN=0.04             $"<==Initial conditions"
   CONSTANT TSTP=5.0                      $"<==Final time"
   CINTERVAL CIN=0.05                     $"<==time step interval"
END $"OF INITIAL"
 DERIVATIVE                             $"<==start of derivative statements"
           F=0                          $"<==External Input"
"……SYSTEM EQUATIONS….."
   XDD=(B*XD-K*X+F)/M                     $"<==second order derivative,
acceleration"
   XD=INTEG(XDD,XDIN)                     $"<==first order derivative, Velocity"
   X=INTEG(XD,XIN)                        $"<==displacement"
   TERMT (T .GE. TSTP)                    $"<==end condition"
 END  $"OF DERIVATIVE"
END  $" OF PROGRAM"
```


The Bond Graph Modeling Approach
Step 1. Develop a schematic model
Step 2. Draw a Bond Graph
Step 3. Obtain Computer Generated Differential Equations
Step 4. Use ASCL or MATLAB
Physical System
Engineering Model
Bond Graph
ACSL
MATLAB
Output
Data tables & Graphs

W. Bruns, 2006

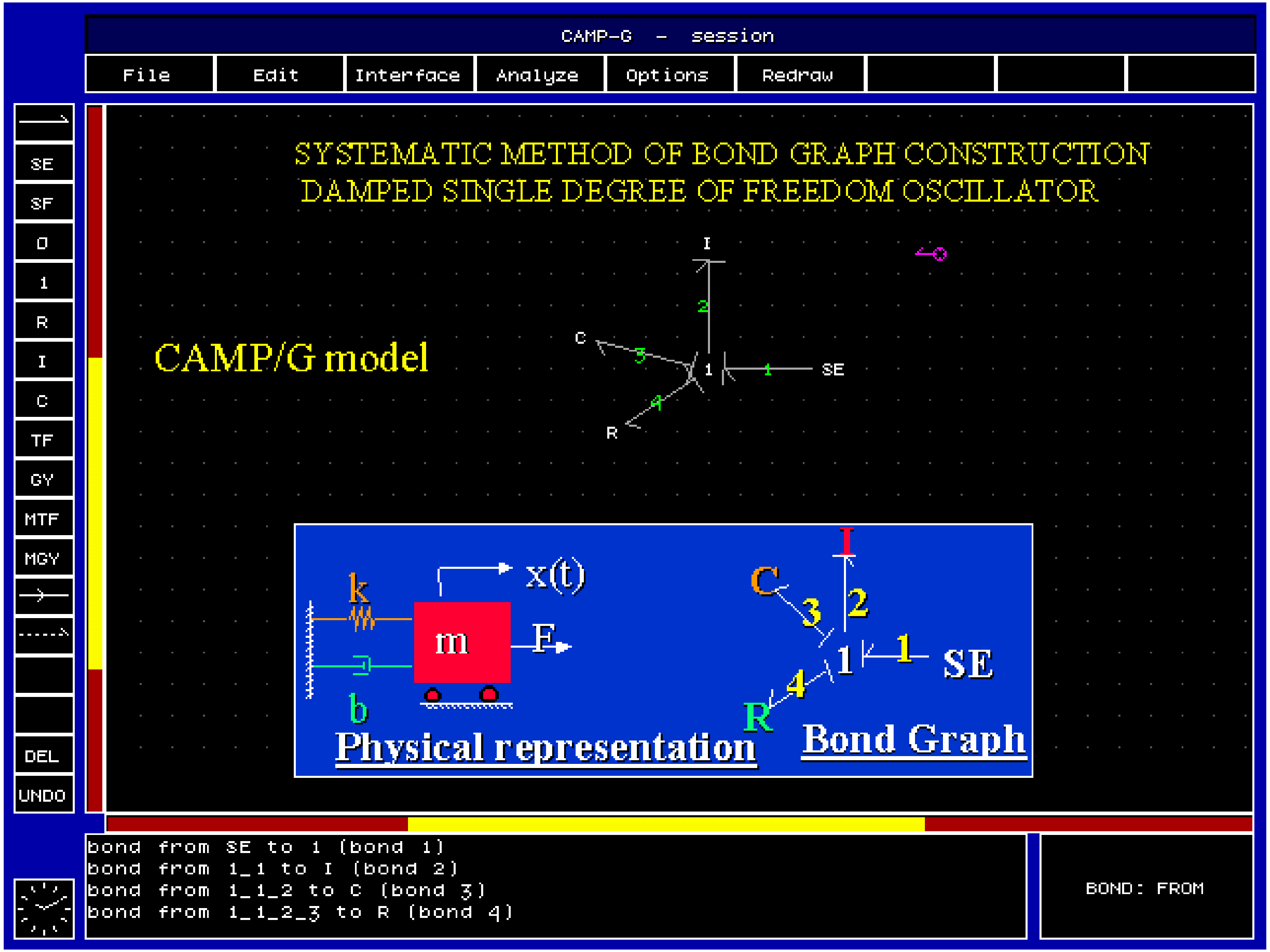

EQUIVALENT REPRESENTATIONS
x(t)
k
m
F = 0
b
Physical representation
I
C
3
2
1
1
SE
4
R
Bond Graph
my
1
m
y
y-y0
y-y0
b
k
Block Diagram

W. Bruns, 2006

The CAMP-G/ACSL System

- Generate Engineering Model of Reality
  Liner or Nonlinear
- Enter Bond Graph in Graphical Form
- CAMP-G Generates Source Code Model
- Add Physical Parameters. Block Diagrams. Tables, Non-linearities, ACSL libraries
- ACSL performs Simulation
- Graphical Results

W. Bruns, 2006


CAMP-G - session
File
Edit
Interface
Analyze
Options
Redraw
SE
SF
0
1
R
I
C
TF
GY
MTF
MGY
DEL
UNDO
SYSTEMATIC METHOD OF BOND GRAPH CONSTRUCTION
DAMPED SINGLE DEGREE OF FREEDOM OSCILLATOR
CAMP/G model
k
m
x(t)
F
b
Physical representation
Bond Graph
bond from SE to 1 (bond 1)
bond from 1_1 to I (bond 2)
bond from 1_1_2 to C (bond 3)
bond from 1_1_2_3 to R (bond 4)
BOND: FROM

W. Bruns, 2006

ACSL input file written with bond graph notation.

```
PROGRAM CAMPACSL                                    $"ACSL INPUT FILE...."
INITIAL
   CONSTANT P2IN=0.0 , Q3IN= 0.04                   $"<==Initial conditions "
   CONSTANT I2=0.02, C3=.510204, R4=0.05            $"<==Physical parameters"
   CONSTANT FINTIM=5.0                              $"<==Final time"
   CINTERVAL CIN=0.05                               $"<==Time control T=time"
END $"OF INITIAL"
 DERIVATIVE                              $"<==start of derivative statements"
            SE1 = 0                      $"<==External Input SE=F(T), SF=V(T)"
"......SYSTEM EQUATIONS....."
   e1=SE1          $  f1=f2
   e2=e1-e3-e4     $  f2=P2/I2
   e3=Q3/C3        $  f3=f2
   e4=f4*R4        $  f4=f2
   dP2=e2          $  dQ3=f3
"......STATE VARIABLES....."
   P2=INTEG(dP2,P2IN)                    $ "Displacement"
   Q3=INTEG(dQ3,Q3IN)                    $ "Momentum"
   TERMT (T.GE.FINTIM)                   $ "Terminate Condition"
 END  $"OF DERIVATIVE"
END  $" OF PROGRAM"
```

W. Bruns, 2006

Simulation results

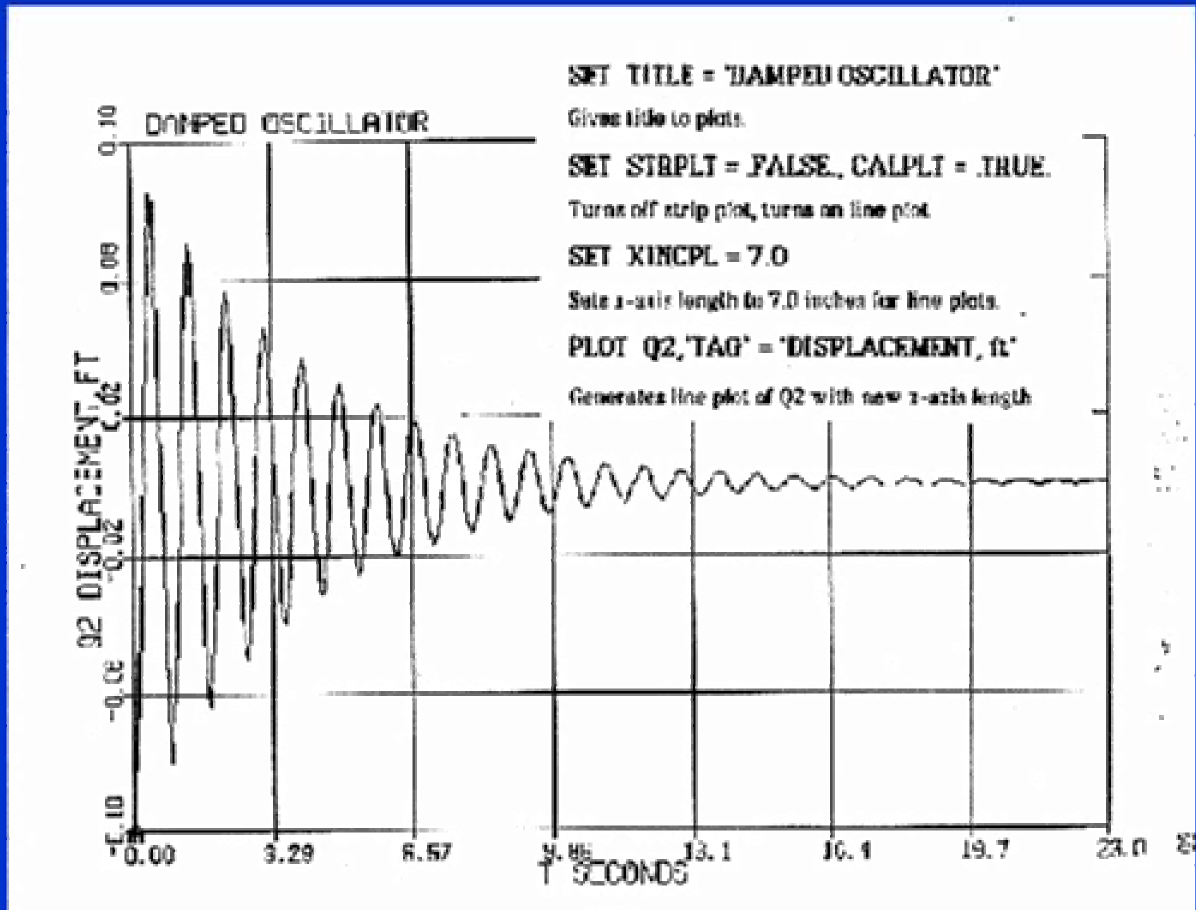
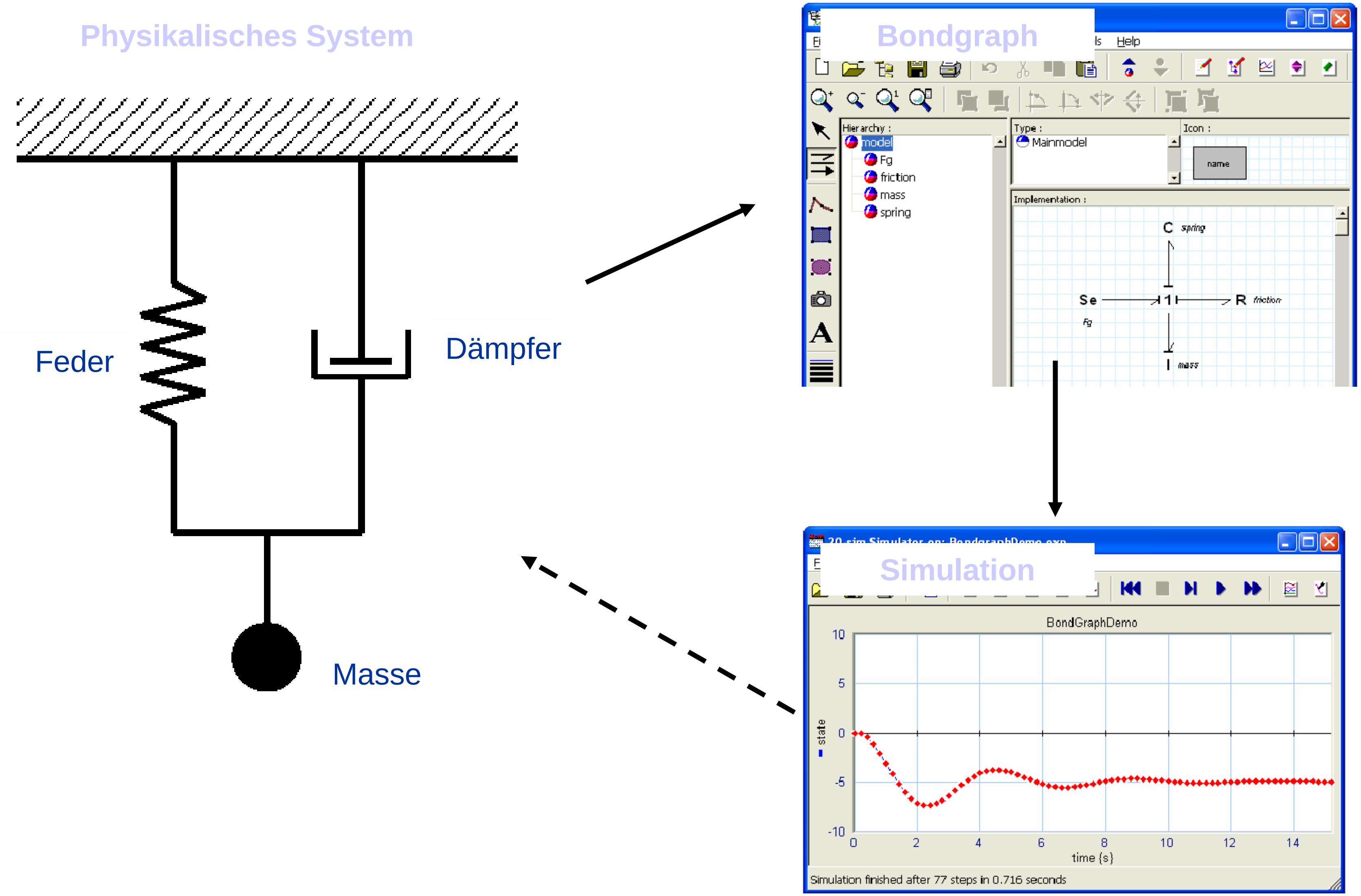


Fig 11

Plot of displacement of mass Vs time.

Masse-Feder-Dämpfer-System (I)



W. Bruns, 2006

Grundidee von Bondgraphen I

- Allen physikalischen Systemen gemeinsam sind die Erhaltungssätze für Energie und Masse
- Bondgraphen befassen sich mit der Erhaltung der Energie in einem physikalischen System
- Wenn die Energie in einem geschlossenen System erhalten wird, kann Energie eigentlich nur durch drei Mechanismen verändert werden:
  - Energie kann gespeichert werden.
  - Energie kann von einem Ort zu einem anderen transportiert werden.
  - Energie kann von einer Form in eine andere umgewandelt werden.