Modelica History Session

with pictures from the event

1861-1999

Dr Hilding Elmqvist

CEO Mogram AB and Technical Fellow Modelon AB

1999-2019

Prof Martin Otter

DLR, Institute of System Dynamics and Control

Mogram

DLR

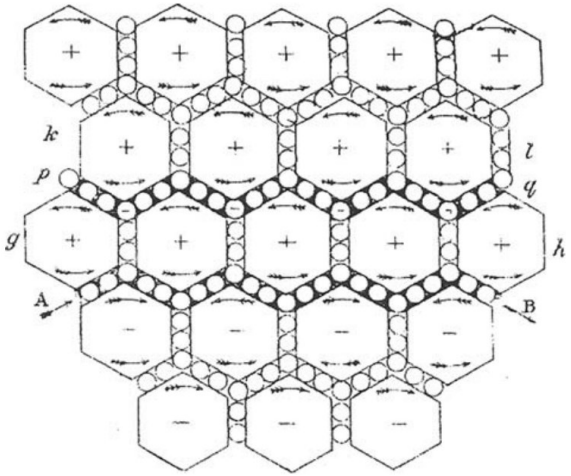
Hilding Elmqvist

Outline

- Maxwell – Mechanical Analogies
- Firestone – across and through variables
- Inspirations
- First Modelica Design Meeting
- Dymola (with demo)
- Modelica Evolution
- Modelica Association
- Modelica Tools

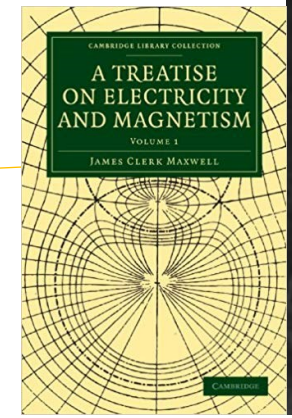
James Clerk Maxwell

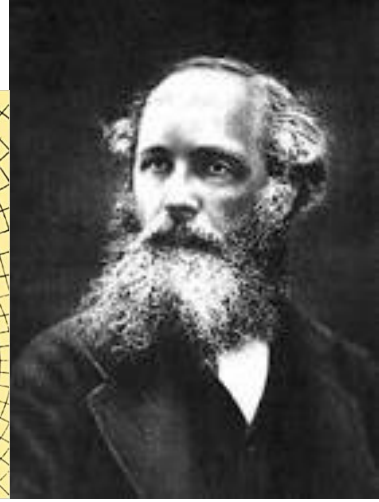
- Mechanical Analogies - Mental models
- 1861: Mechanical analogy for electromagnetism
- Lumped model – coupled elements
  - Hexagons – magnetic
  - Circular - electrical
- Graphical



$e+\frac{df}{dx}+\frac{dg}{dy}+\frac{dh}{dz}=0$	(1)	Gauss' Law
$\mu\alpha=\frac{d\mathrm{H}}{dy}-\frac{d\mathrm{G}}{dz}$ $\mu\beta=\frac{d\mathrm{F}}{dz}-\frac{d\mathrm{H}}{dx}$ $\mu\gamma=\frac{d\mathrm{G}}{dx}-\frac{d\mathrm{F}}{dy}$	(2)	Equivalent to Gauss' Law for magnetism
$\mathrm{P}=\mu\left(\gamma\frac{dy}{dt}-\beta\frac{dz}{dt}\right)-\frac{d\mathrm{F}}{dt}-\frac{d\Psi}{dx}$ $\mathrm{Q}=\mu\left(\alpha\frac{dz}{dt}-\gamma\frac{dx}{dt}\right)-\frac{d\mathrm{G}}{dt}-\frac{d\Psi}{dy}$ $\mathrm{R}=\mu\left(\beta\frac{dx}{dt}-\alpha\frac{dy}{dt}\right)-\frac{d\mathrm{H}}{dt}-\frac{d\Psi}{dz}$	(3)	Faraday's Law (with the Lorentz Force and Poisson's Law)
$\frac{d\gamma}{dy}-\frac{d\beta}{dz}=4\pi p'$ $\quad p'=p+\frac{df}{dt}$ $\frac{d\alpha}{dz}-\frac{d\gamma}{dx}=4\pi q'$ $\quad q'=q+\frac{dg}{dt}$ $\frac{d\beta}{dx}-\frac{d\alpha}{dy}=4\pi r'$ $\quad r'=r+\frac{dh}{dt}$	(4)	Ampère-Maxwell Law
$\mathrm{P}=-\xi p \quad \mathrm{Q}=-\xi q \quad \mathrm{R}=-\xi r$		Ohm's Law
$\mathrm{P}=kf \quad \mathrm{Q}=kg \quad \mathrm{R}=kh$		The electric elasticity equation (**E** = **D**/ε)
$\frac{de}{dt}+\frac{dp}{dx}+\frac{dq}{dy}+\frac{dr}{dz}=0$		Continuity of charge

Force-Voltage Analogy





- Maxwell (1873) introduced Force-Voltage Analogy
  - Effort and flow variables
  - Mass ≈ inductance
  - **Series** connection of electrical component **correspond** to **parallel** connection of mechanical components and vice versa
  - Paynter (1960): Bond graphs

Force-Current Analogy

- Floyd Firestone (1933) introduced Force-Current Analogy
  - Across (relative quantities) and Through variables
  - Mass ≈ Capacitor (Mass has reference to ground)
  - Kirchhoff's current law, etc – sum of through variables equal to zero
- Trent (1955): Isomorphism between Oriented Linear Graphs and Lumped Physical Systems

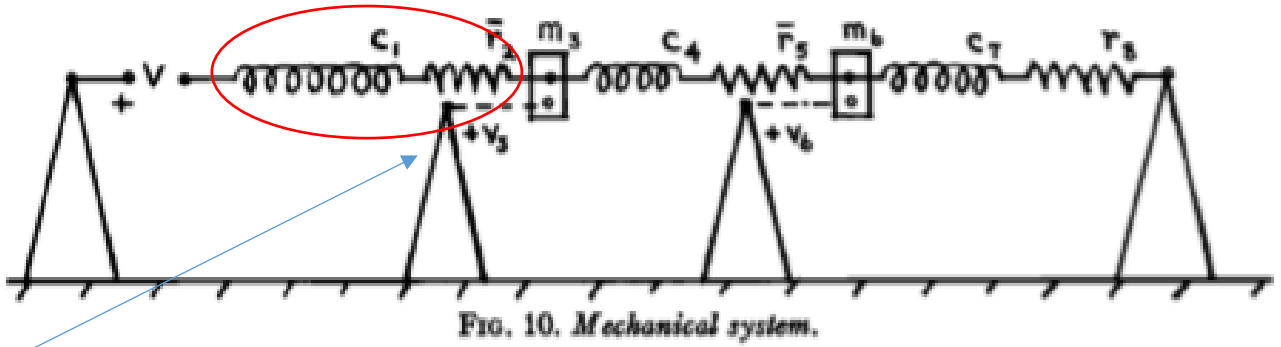


FIG. 10. *Mechanical system.*

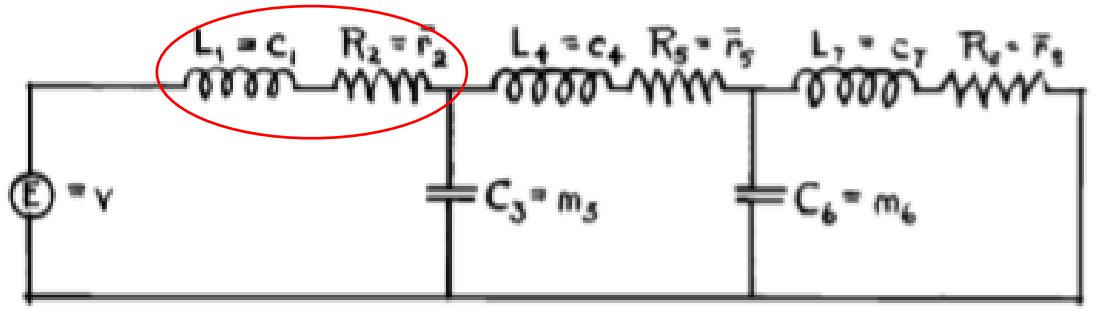


FIG. 11. *New analogue.*

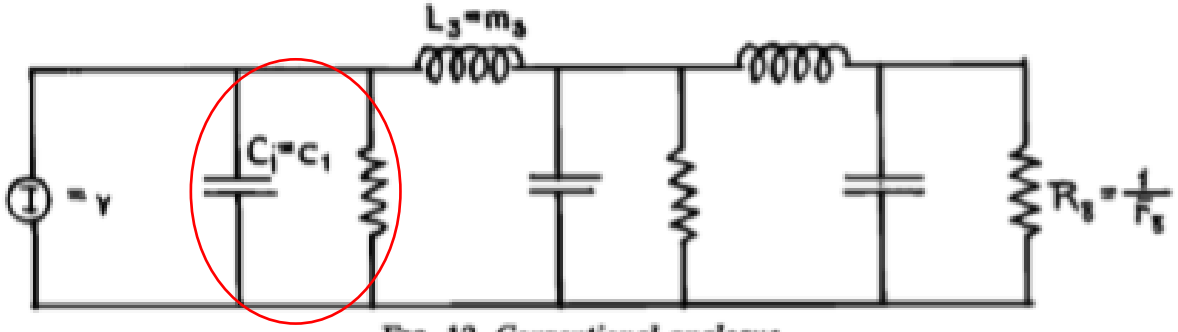


FIG. 12. *Conventional analogue.*

Inspiration

- Analysis of Discrete Physical Systems
  H. E. Koenig, H. K. Kesavan, and Y. Tokad, McGraw-Hill (1967)
- Describes across and through variable semantics (Force-Current Analogy)

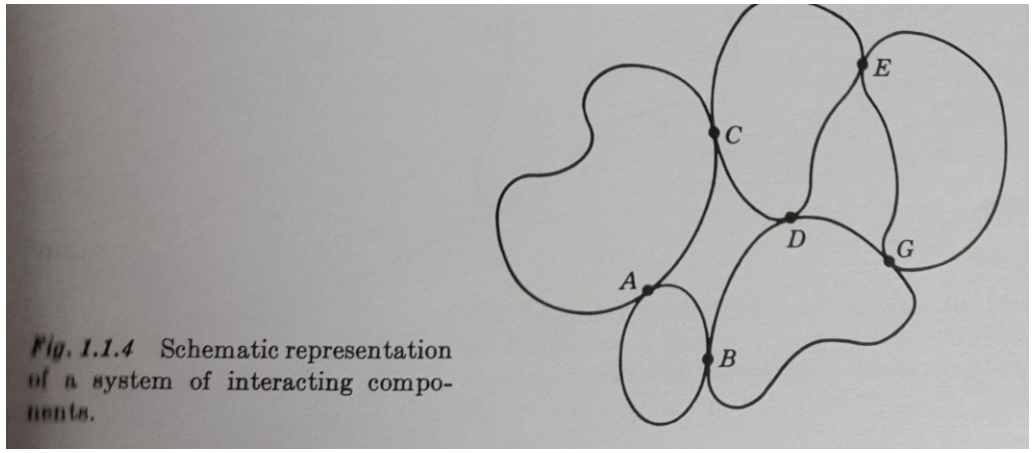
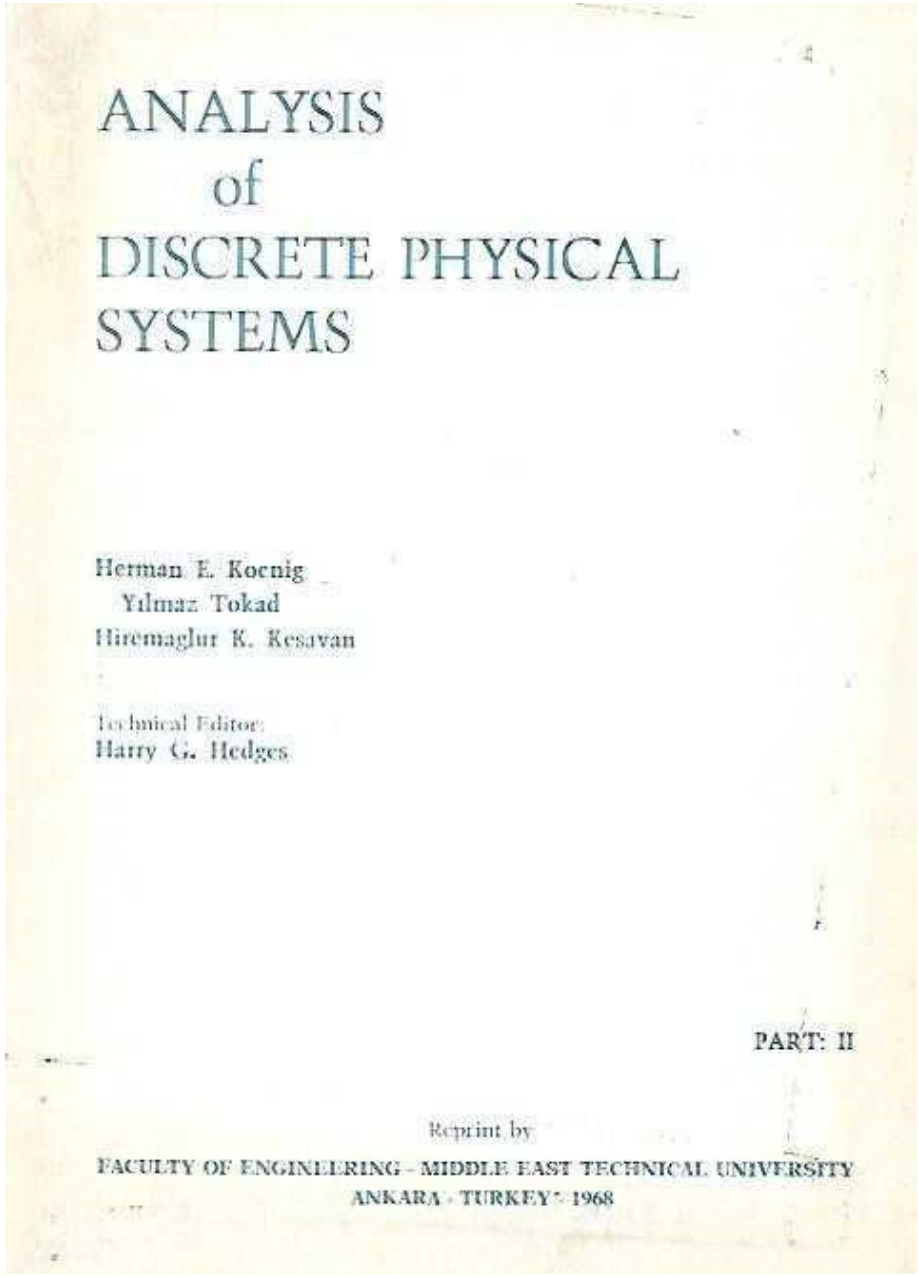
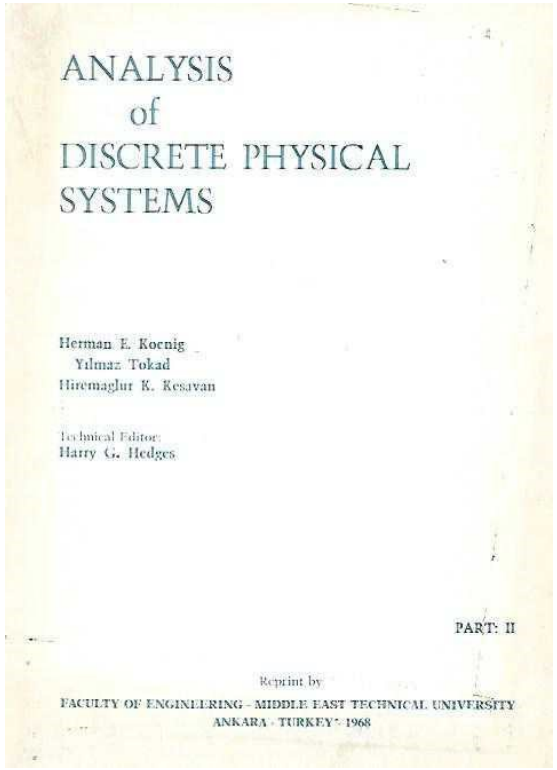


Fig. 1.1.4 Schematic representation of a system of interacting components.




ANALYSIS
of
DISCRETE PHYSICAL
SYSTEMS

Herman E. Koenig
Yilmaz Tokad
Hiremaglur K. Kesavan

Technical Editor:
Harry G. Hedges

PART: II

Reprint by
FACULTY OF ENGINEERING - MIDDLE EAST TECHNICAL UNIVERSITY
ANKARA - TURKEY - 1968

The first fundamental postulate of system theory is now stated as follows:

Postulate 1: The pertinent performance (behavioral) characteristics of each n-terminal component in an identified system structure are completely specified by a set of $n - 1$ equations in $n - 1$ pairs of oriented complementary variables $x_i(t)$ and $y_i(t)$ identified by an arbitrarily chosen terminal graph (the variables x_i and y_i may be vectors if necessary).

The identities of the complementary terminal variables $x(t)$ and $y(t)$ are shown in Table 1.2.1 for physical and socioeconomic processes. Following Firestone[2] and Trent[3], one variable, $x(t)$, is known as the *across variable* and the other, $y(t)$, the *through variable*. Although this terminology is used throughout this book, *propensity* and *flow rate* are also sometimes used, particularly in socioeconomic applications.

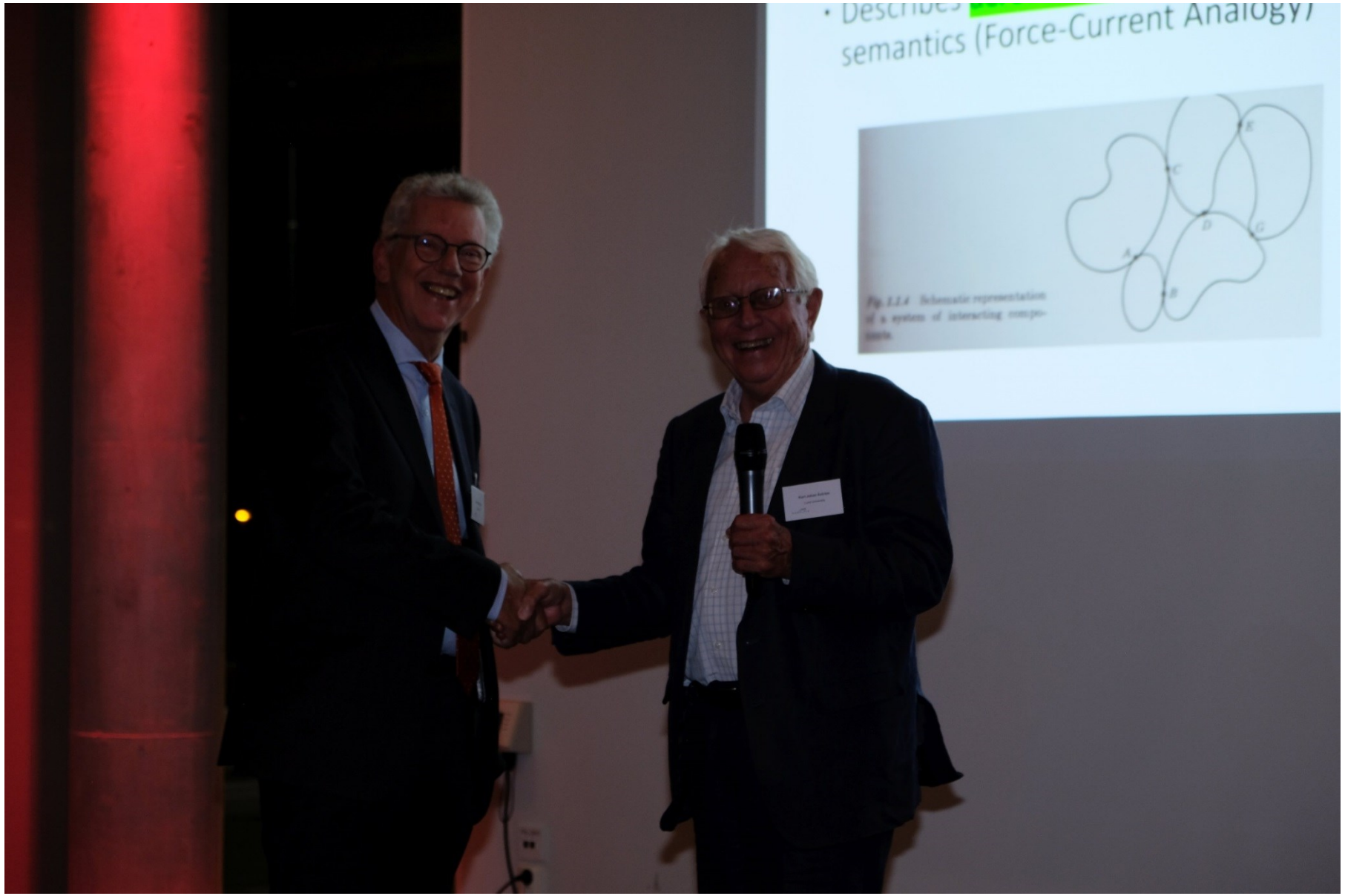
Conceptually, the pairs of complementary variables used to characterize each of the various processes are associated with a pair of component terminals and are oriented in one sense or another. In the physical sciences, each pair of complementary variables is also defined operationally; i.e., the variables are defined in terms of a specific set of operations (the instrumentation) for assigning a numerical value to the

Table 1.2.1 Complementary variables for typical processes

Process	*Mechanical*	*Hydraulic*	*Electrical*	*Traffic*	*Economic*	*General*
$x(t)$	Velocity	Pressure	Voltage	Density	Unit price	Across variable (propensity)
$y(t)$	Force	Flow rate	Current	Flow rate	Flow of goods	Through variable (flow)

Inspiration

- Prof Karl Johan Åström
- Department of Automatic Control
- CACE – Computer Aided Control Engineering project
- PDP-15 “personal computer”



Hilding Elmqvist and Karl Johan Åström

Inspiration - March 1976

- Sture Lindahl: A Nonlinear Drum, Boiler – Turbine Model

- Object oriented model structure
- *Manually* solving linear systems of equations
- *Manual* derivation of solutions of certain nonlinear equations
- *Manual* “index reduction”
- *Manual* unrolling Newton-Raphson algorithm

- **What if a tool could do all this**

$$\frac{d}{dt}\left[c_{dm8}m_{dm8}T_{dm8} + (V_{d\ell 8}-V_{ds8})\rho_{dw8}h_{dw8} + (V_{ds2}+V_{ds8})\rho_{ds2}h_{ds2}\right] =$$

$$= q_{dm8} + w_{d\ell 5}h_{d\ell 4} - w_{ps1}h_{ds2} - w_{dw8}h_{dw8} \qquad (9.1)$$

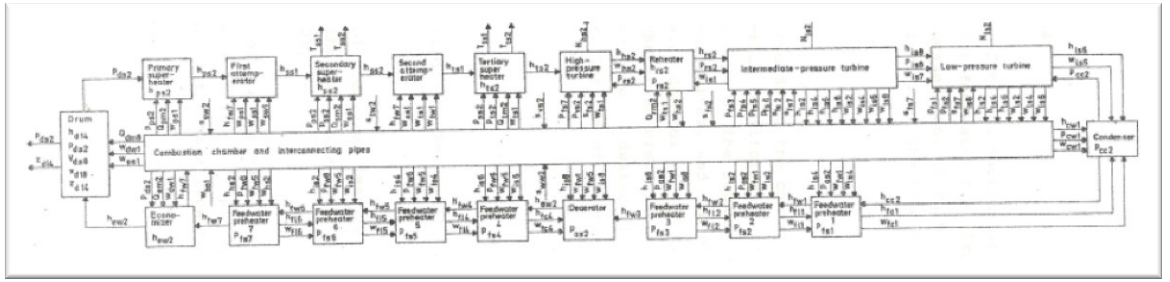
The mass balance the steam-water mixture in the risers and the steam in the drum becomes:

$$\frac{d}{dt}\left[(V_{d\ell 8}-V_{ds8})\rho_{dw8} + (V_{ds2}+V_{ds8})\rho_{ds2}\right] =$$

$$= w_{d\ell 5} - w_{ps1} - w_{dw8} \qquad (9.2)$$

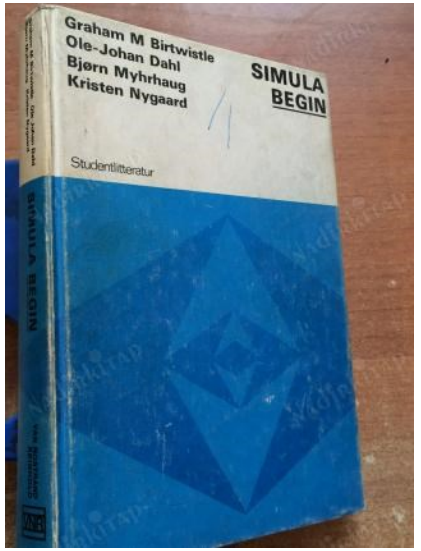
Multiplication of equation (9.2) by h_{dw8} and subtraction from equation (9.1) gives:

$$c_{dm8}m_{dm8}\frac{dT_{dm8}}{dt} + (V_{d\ell 8}-V_{ds8})\rho_{dw8}\frac{dh_{dw8}}{dt} +$$



Inspiration

- Simula language
  - First object-oriented language
- Graph theory
  - Matching in bipartite graphcs
  - Tarjan: Strongly connected components (BLT)

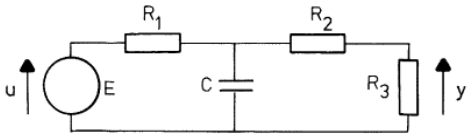


Dymola – Dynamic Modeling Language

- The Idea: Thursday, April 15 before Easter 1976
  - **Equations!**
- Leading to:
  - Object oriented – **inspired by Simula language**
  - Physically oriented coupling
  - Structural analysis by graph theory
  - Computer algebra
- PhD Dissertation in May 1978
- Boiler model coded in 8 pages
- 250 equations
- 11 systems of simultaneous equations

```
model type capacitor
  cut A (Va / I) B (Vb / -I)
  main cut C [A B]
  main path P <A - B>
  local V
  parameter C
  V = Va-Vb
  C*der(V) = I
end
```

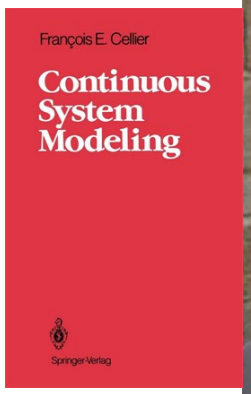
```
model Network
  submodel(resistor) R1 R2 R3
  submodel(capacitor) C
  submodel(voltage) E
  submodel Common
  input u
  output y
  connect Common to E to R1 to (C par (R2 to R3))to Common
  E.V = u
  y = R3.Va
end
```



Dynasim 1992-1996

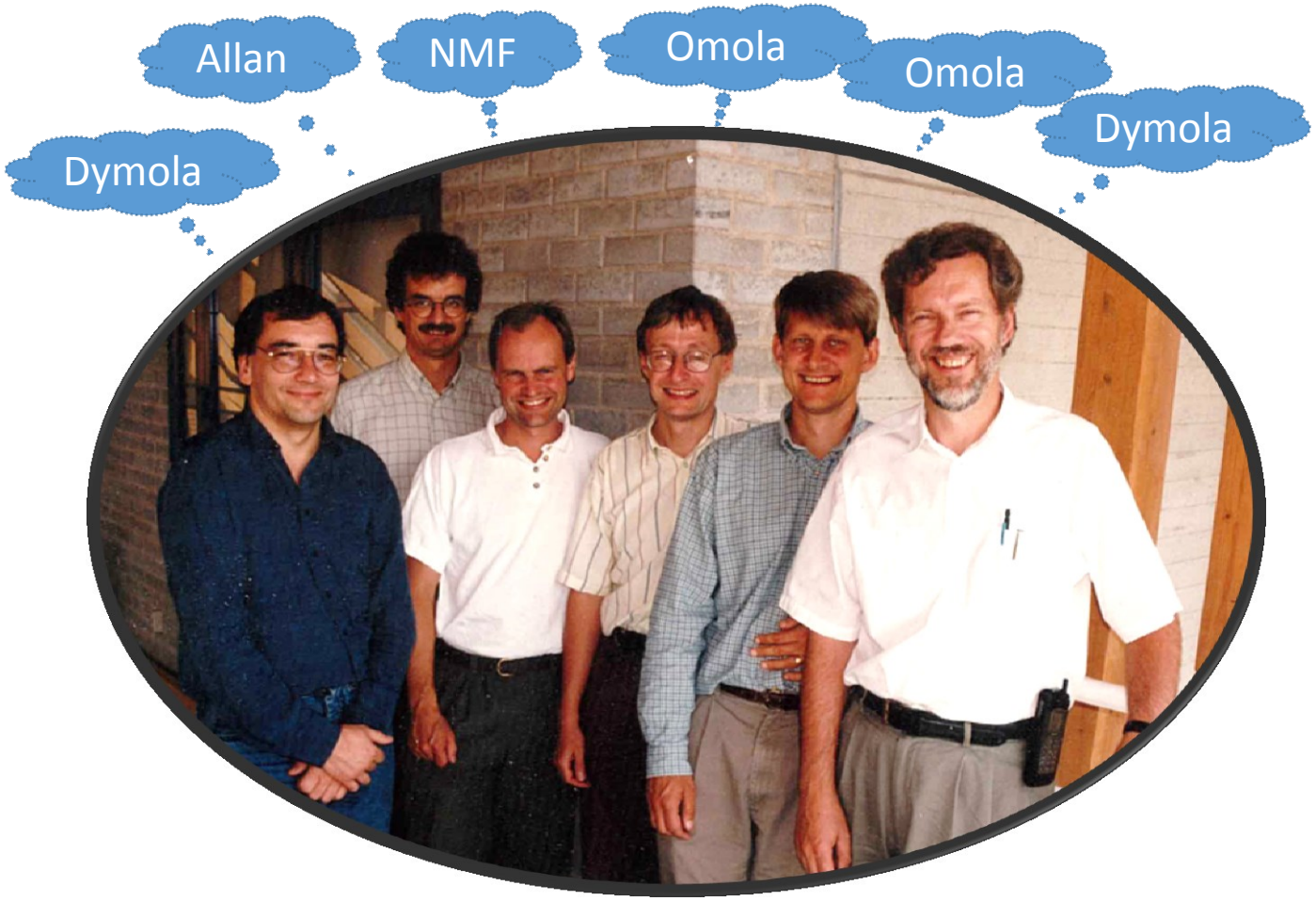
Dynasim

- Resumed Dymola work in 1991
  - François Cellier's book Continuous Systems Modeling dealing with Dymola
  - Started collaborating with François Cellier, University of Arizona, 1991
  - Windows 3.0 got linear address space (no 640 kByte barrier)
  - Founded Dynasim AB January 1992
  - Started collaborating with Martin Otter, DLR, summer 1992
- Collaboration with Martin Otter and François Cellier on:
  - Hybrid modeling features
  - Tearing
  - Multibody systems
  - Etc
- Use of Pantelides algorithm for index reduction
- Toyota started to use Dymola in 1996 for Prius development



Hilding Elmqvist, Martin Otter and Costas Pantelides

First MODELICA Design Meeting, Lund, September 1996



Martin Otter, DLR, **Alexandre Jeandel**, Gaz de France, **Per Sahlin**, Brisdata/Equa,
Sven Erik Mattsson, Lund University, **Bernt Nilsson**, Lund University,
Hilding Elmqvist, Dynasim, **Dag Brück**, Dynasim (behind camera)

… in 2019

Martin Otter, Per Sahlin, Dag Brück, Sven Erik Mattsson and Hilding Elmqvist

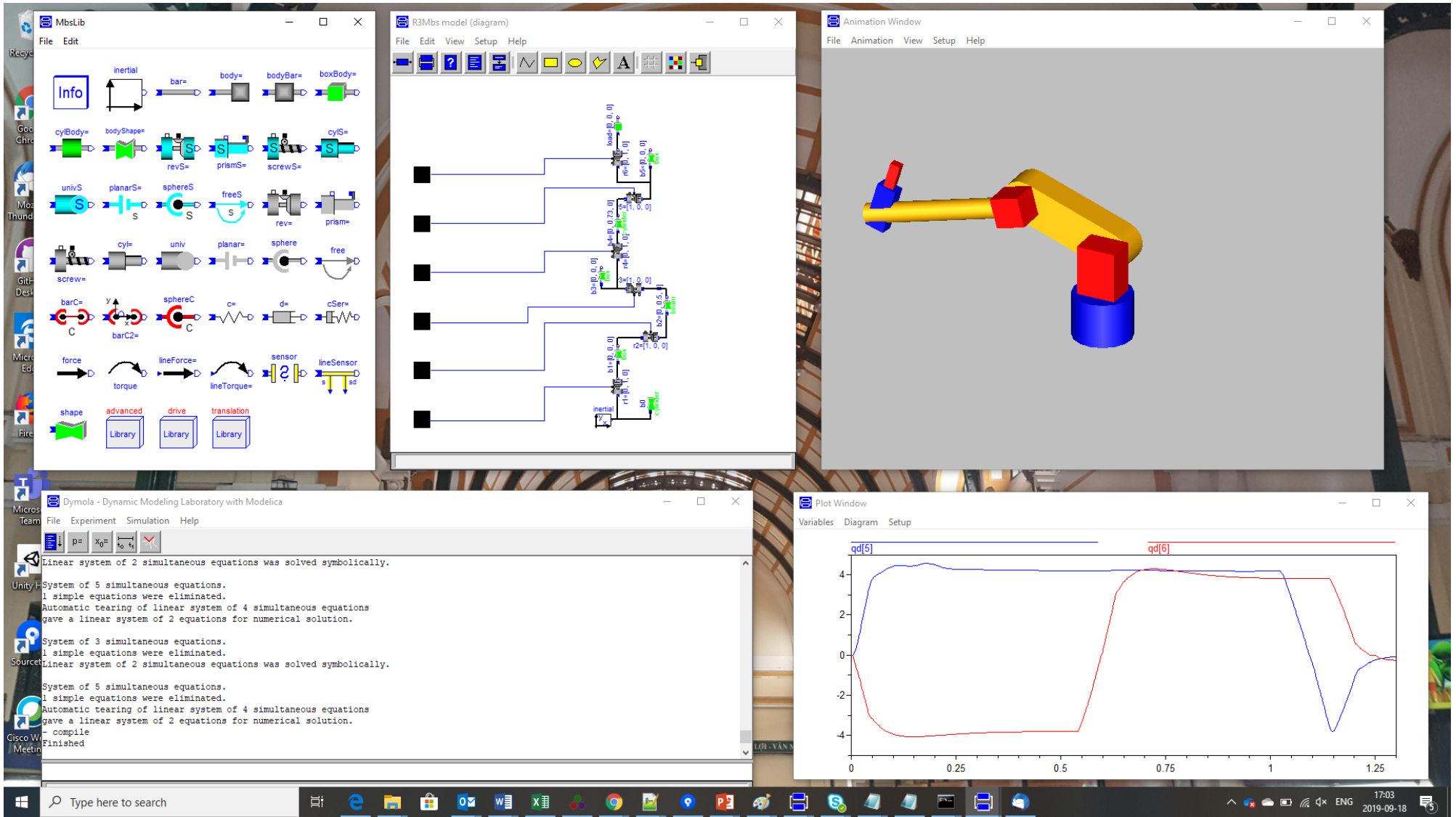
Modelica 1.0 – September 1997 at DLR

Dynasim team 1999

Sven Erik Mattsson, Dag Brück, Hilding Elmqvist, Hans Olsson

… in 2019

Dymola 4.0b - November 1999 - Demo



1997

2019

Evolution

Modelica Language

1.0-1.4	1997-2000	Continuous systems, hybrid systems, arrays, C-interface
2.0-2.2	2002-2005	Initialization, standardized graphics, overdetermined connectors
3.0	2007	Clean-up, new spec., balanced models
3.1	2009	Stream connectors
3.2	2010	Homotopy init., IP protection, ...
3.3	2012	Clocked equations/state machines, ...
3.4	2017	Many minor improvements, conversion

Modelica Libraries

1.3-1.6	1999-2004	Blocks, Electrical, Math, Rotational, Translational, HeatTransfer
2.1-2.2.2	2004-2007	MultiBody, Digital, Machines, Matrices, StateGraph, Utilities, Discrete, Tables
3.0-3.2.1	2008-2013	Modelica 3.0 Clean-up, Fluid, Magnetic, Spice3, QuasiStatic, Complex, ModelicaServices
3.2.2	2016	240 issues, PowerConverters, Noise, ...
3.2.3	2019	550 issues, 100 new models, BSD lic.
4.0.0	??	Clean-up, Clocked, ...

3.2.3: 1300 models, 1200 functions, 400 examples

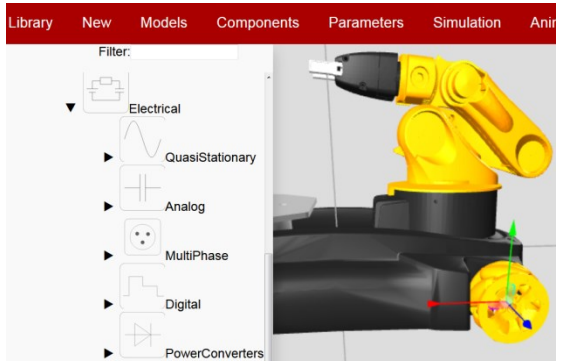
Attempts for Disruptive Innovation

ModelicaX (https://trac.modelica.org/ModelicaX, https://trac.modelica.org/ModelicaX/wiki/ListOfDocuments)

- 2010-2012 (67...76 design meeting)
- Hilding Elmqvist, Michael Tiller: Compiler prototype based on **Scala**
- Language proposals:
  - Hilding Elmqvist
  - Dirk Zimmer (Hornblower)
  - David Broman (Modeling Kernel Language)
  - Peter Fritzson (MetaModelica extension)
  - Various incomplete proposals (functional style, time and durations, connection semantics, improved class parameterization, ...)

Modia (https://github.com/ModiaSim)

- Since 2016, based on **Julia,** Julia packages, HTML, Javascript, three.js
- Hilding Elmqvist, Toivo Henningsson, Martin Otter, Andrea Neumayr, Oskar Åström, Chris Laughman



Modelica Association

2000 – 2019

Open, coordinated standards/software for system simulation

since 1997 — Modelica Language, Modelica Libraries

since 2010 — FMI Functional Mock-Up Interface

Most successful MA standard: Supported by > 130 tools

since 2019 — SSP System Structure & Parameterization

since 2019 — DCP Distributed Co-Simulation Protocol

since 2000 — Modelica Conferences

Board in 2019

Chairperson	Martin Otter (DLR)
Vice-Chairperson	Peter Fritzson (Linköping University)
Secretary	Michael Tiller (Xogeny)
Treasurer	Jonas Eborn (Modelon)
Marketing	Hubertus Tummescheit (Modelon)
Quality and Processes	Franceco Casella (Politecnico di Milano)
Technology	Torsten Blochwitz (ESI ITI)

Modelica Association Project Leaders and Deputies

Modelica Language	Hans Olsson (Dassault Systèmes)
Modelica Libraries	Thomas Beutlich, Dietmar Winkler (Uni. of South-Eastern Norway)
FMI	Andreas Junghanns (QTronic), Torsten Blochwitz (ESI ITI)
SSP	Jochen Köhler (ZF)
DCP	Martin Krammer (VIRTUAL VEHICLE), Klaus Schuch (AVL)

Members of the Modelica Association Board 2019:
Martin Otter, Klaus Schuch, Torsten Blochwitz, Martin Krammer, Hubertus Tummescheit, Peter Fritzson, Andreas Junghanns, Hans Olsson, Jonas Eborn, Francesco Casella

Tools

- 3DExperience Platform (Dassault Systèmes; powered by Dymola)
- Activate (Altair, powered by MapleSim, Maplesoft)
- CyModelica (originally deltatheta U.K., acquired 2012 by CyDesign USA, 2014 by ESI Group France)
- Dymola (originally Dynasim, Sweden, acquired 2006 by Dassault Systèmes).
- Ignite (Ricardo Software, powered by Optimica Compiler Toolkit, Modelon)
- MapleSim (Maplesoft, Canada, a division of Cybernet, Japan since 2009)
- MWorks (Suzhou Tongyuan, China)
- Optimica Compiler Toolkit (Modelon, Sweden)
- Simcenter Amesim (originally Imagine, France, acquired 2007 by LMS, acquired 2014 by Siemens)
- SimulationX (originally ITI GmbH, Germany, acquired 2016 by ESI Group France, now ESI ITI GmbH)
- SystemModeler (originally MathCore, Sweden, acquired 2011 by Wolfram Research, now Wolfram MathCore)
- Twin Builder, Simplorer (ANSYS, powered by Optimica Compiler Toolkit, Modelon)

Free Modelica Environments

- JModelica.org (Modelon, Sweden)
- OpenModelica (Open Source Modelica Consortium)

Representatives of Tool Vendors supporting the Modelica Language
Stefan Vorkoetter (Maplesoft), Johan Andreasson (Modelon), Dan Henriksson (Dassault Systèmes),
Gerd Kurzbach (ESI ITI), Otto Tronarp (Wolfram MathCore), Masoud Najafi (Altair), Peter Fritzson (Open Source Modelica Consortium)

Presenters from the Symposium

Karl Johan Åström
(Lund University)

Bengt Jacobson
(Chalmers University)

Mats Jonasson
(Chalmes University)

Peter Nilsson
(Volvo Trucks)

Erik Frisk
(Linköping University)

Costas Pantelides
(Process Systems Enterprise Ltd.)

Rüdiger Franke
(ABB)

Oliver Lenord
(Robert Bosch GmbH)

Miriam Mehl
(University of Stuttgart)

Chris Rackauckas
(MIT and University of Maryland)

Hilding Elmqvist
(Mogram)

Martin Otter
(DLR)

Presenters from the Symposium
Martin Otter, Miriam Mehl, Oliver Lenord, Rüdiger Franke, Costas Pantelides, Hilding Elmqvist, Chris Rackauckas, Karl Johan Åström