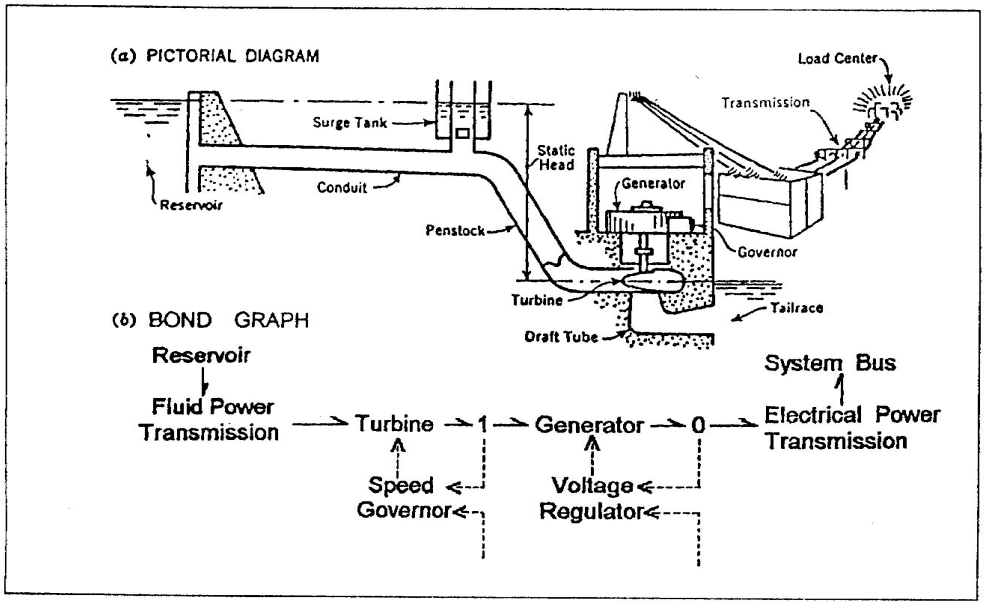
The Gestation and Birth of Bond Graphs

by Prof. H.M. Paytner (c. 2000)

Bond graphs were born in their present form on April 24, 1959. They were the direct outgrowth of my academic and professional experience during two previous decades.

My MIT undergraduate and graduate training was centered on hydroelectric engineering, as was my work at Puget Power and my 8 years teaching in the Civil Engineering Department at MIT. This involved all aspects of the typical power plant indicated below.



Hydroelectric plant.

This training and experience in hydroelectric power actually forced certain insights upon me, most particularly an awareness of the strong analogies existing between:

TRANSMISSION (fluid pipes & electric lines);
TRANSDUCTION (turbines & generators);
CONTROL (speed governors & voltage regulators).

When these analogous devices were reduced to equations for computer simulation, distinctions became completely blurred.

Even before 1957 it was obvious that the above hydro+electric plant necessarily involved two energy-converting transduction multiports: the hydraulic turbine converting fluid power to rotary shaft power and the electrical generator

converting this shaft power into polyphase AC power. Moreover, the strict analogy between these two devices holds right down to the local field-continuum level. Thus the fluid vorticity corresponds precisely to the current density and the fluid circulation to the magnetizing current, so that even the turbine blades correspond to the generator pole pieces! In dynamic consequence, both these highly-efficient components become 2-port gyrators, [-GY-],with parasitic losses. Common sense dictated that such compelling analogies implied some underlying common generalization from which other beneficial specializations might ensue.

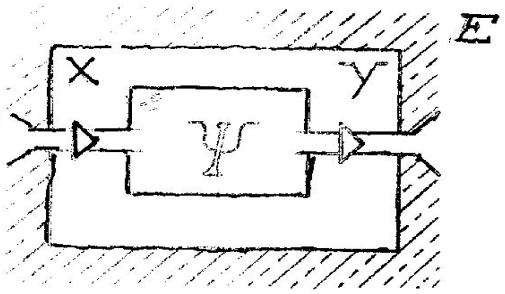
My efforts were also strongly motivated by a preoccupation with the logical philosophy underlying analogies in general. Such concerns were much earlier formalized by the mathematician, Eliakim Hastings Moore, in the following dictum:

> **"We lay down a fundamental principle of generalization by abstraction:**
>
> ***The existence of analogies between central features of various theories implies the existence of a general theory which underlies the particular theories and unifies them with respect to those central features...*** **"**

In 1954, I moved over to the MIT ME department to establish the first systems engineering subjects at MIT. It was this specific task which 5 years later produced bond graphs, drawing naturally upon all the attitudes and experience indicated above. So it was on April 24, 1959, when I was to deliver the lecture as posted below, I awoke that morning with the idea of the 0,1-junctions somehow planted in my head overnight ! Moreover the very symbols (0,1) for KCL and KVL, respectively, made direct the correspondence between circuit duality and logical duality. (The limited use of these 3-ports in the hydro plant BG above hardly does justice to their role in rendering BGs a complete and formal discipline.)

SYSTEMS ENGINEERING SEMINAR

"PORTS, ENERGY, SYSTEMS"



Professor Henry M. Paynter will present a seminar on the subject, "Ports, Energy and Thermodynamic Systems" on Friday, April 24 at 3:15 p.m. in Room B 103 of the Mechanical Engineering Building.

Dr. Paynter is Assistant Professor of Mechanical Engineering at M.I.T. and Director of the American Center for Analog Computing (a facility of Pi-Square Engineering Company). He is prominently recognized for his work in controls, dynamic systems, analog simulation and related fields. He is the author of very many authoritative papers covering a wide range of topics. He has also done extensive consulting work in industry and government.

Dr. Paynter is a very interesting and stimulating speaker. His viewpoints are novel and thought-provoking.

CASE INSTITUTE OF TECHNOLOGY

Cleveland, Ohio

The Birth of 0 & 1

As mentioned above, it was at this same Case lecture that the two ideal energy junctions were presented publicly for the first time. Shown below were 3 sketch sheets prepared on that morning of April 24, 1959, which were then dittoed and handed out to the audience as well as transcribed to the blackboard during the presentation.

Several things should be noted from these pages. First both noncausal and causal forms of the 0-junction and the 1-junction were given. While the concept is acausal, the causal forms are radical generalizations of KCL & KVL both within and without electrical circuitry. It is the causal stroke (invented even before 0 & 1) which yields the new view of state determinism and Hamiltonian dominance. Few EEs had ever made use of H(p,q).

I can't really remember why the curious word "chemergetics" was coined but remember that "bond graphs" would have been equally strange.

But also note the iconography used to express unfamiliar causality in terms of gender !

Chemergetics

IDEAL ENERGY JUNCTIONS

Noncausal Forms

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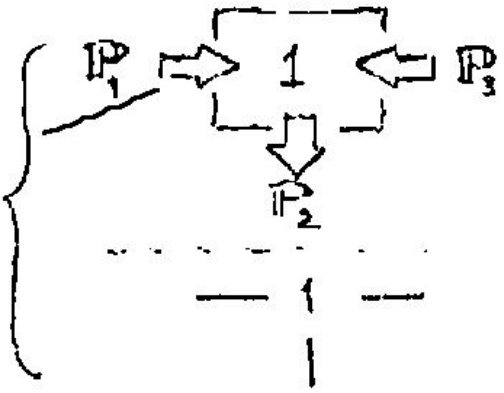
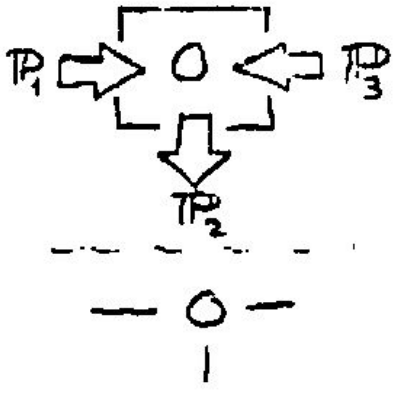
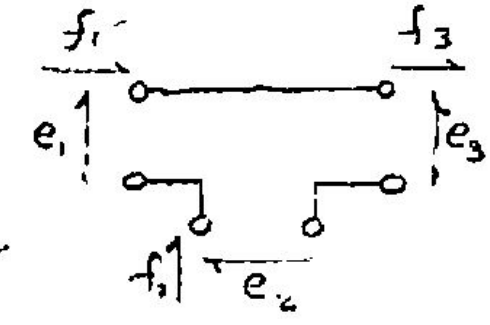
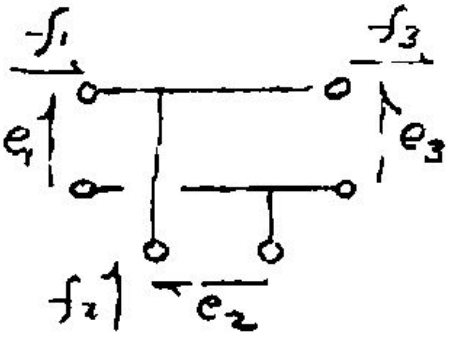
	EFFORT Junction	FLOW Junction
Relations	$\mathbb{P}_1 + \mathbb{P}_3 \equiv \mathbb{P}_2$ $e_1 + e_3 = e_2$ $f_1 \equiv f_3 \equiv f_2$	$\mathbb{P}_1 + \mathbb{P}_3 \equiv \mathbb{P}_2$ $e_1 \equiv e_3 \equiv e_2$ $f_1 + f_3 = f_2$
Symbols		
Example of Electrical Realization		

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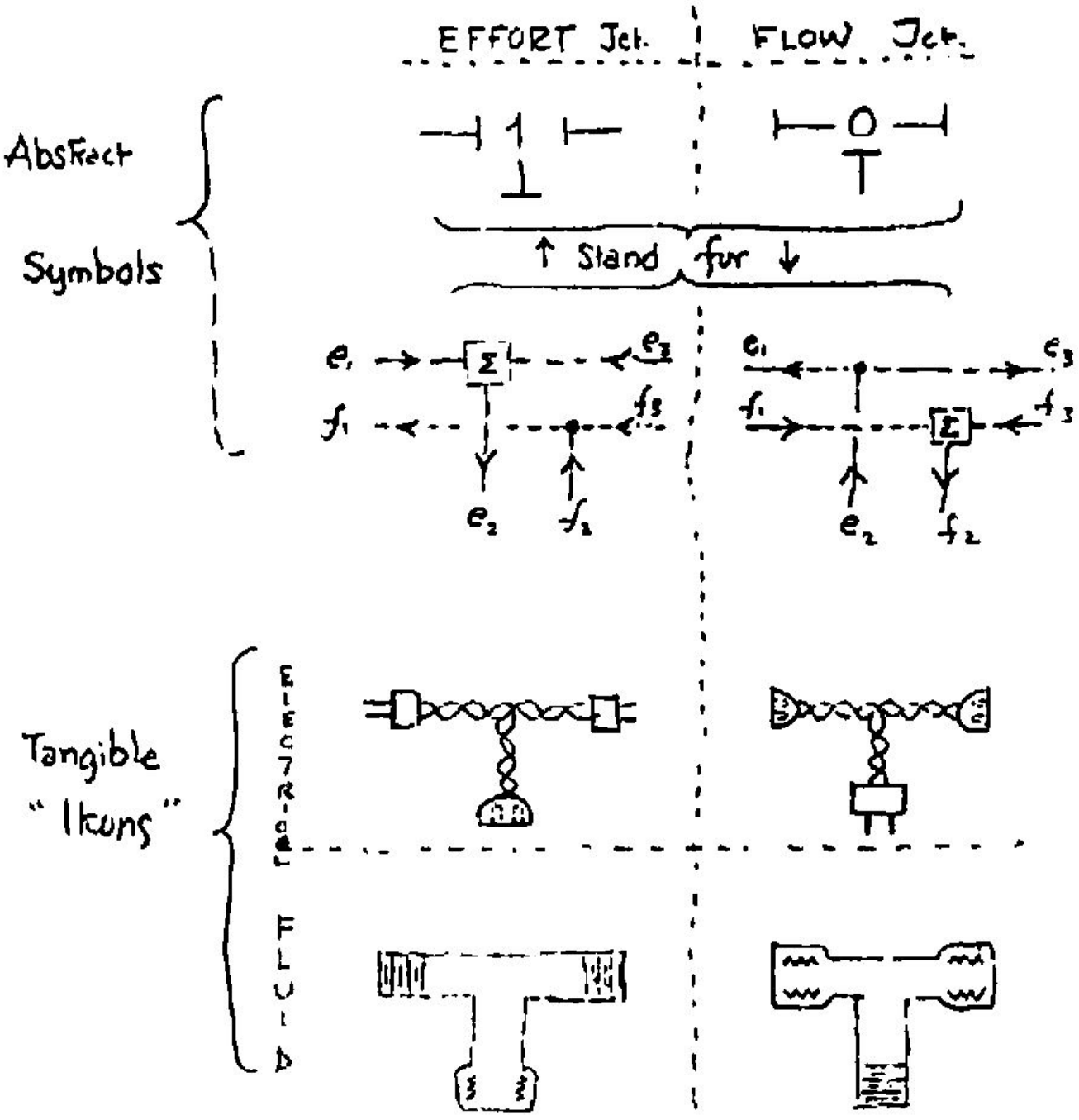
Chemergetics
IDEAL ENERGY JUNCTIONS
Causal Terms



Chemergetics

An ELECTRONIC MODEL of a PUMPING PLANT

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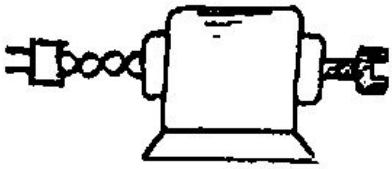
Practical IKons of System Components.

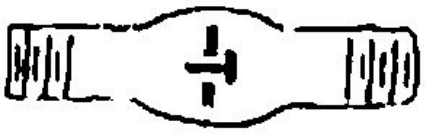
⊣ INDUCTION MOTOR ⊣



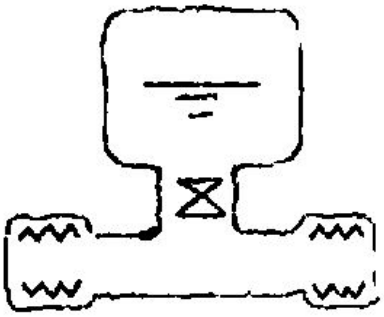
⊣ MECHANICAL INERTIA ⊢

⊢ CENTRIFUGAL PUMP ⊣

⊣ CHECK VALVE ⊢



⊢ AIR CHAMBER ⊣



⊣ FLUID PIPE ⊢

(⊣ INERTIA ⊢ RESISTANCE ⊢)

Besides promptly teaching this new system to my 2.751 and 2.752 students, it was first published in 1960 via an evolving series of folio signatures made

available to students and others. This material was then re-gathered into the 1961 MIT Press book *Analysis and Design of Engineering Systems*.

However, it took nearly 20 more years before BGs became widely known and employed. A few individuals were primarily responsible for this promotion, most notably among others, Dean Karnopp, Ronald Rosenberg, Jean Thoma and the late Jan van Dixhoorn. Jan made BGs familiar to all parts of Europe while Jean has carried the Gospel to all parts of the Globe.As a result of this effort many BG books and papers have been published and numerous groups are actively involved with BGs throughout the world. All these can be located via the links below.

- Bond Graph Researchers
- Bond Graph Prehistory