Quantity, Intensity, and Power of Heat

A Direct Approach to a Dynamical Theory of Heat

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GOAL…

In this talk, I wish to discuss how (**1**) a **dynamical theory of heat** can be constructed; for this I use the Second Edition of *The Dynamics of Heat* (Springer, New York 2010). At the same time I hope to clarify (**2**) its **conceptual roots** and show (**3**) **how it can be taught**.

Note: To make goals (2) and (3) clear, I will use a **form of language** throughout that reflects the **figurative** nature of **human thought**. This should give you a feeling for the **form of conceptualization** I use when teaching the physics of dynamical systems.

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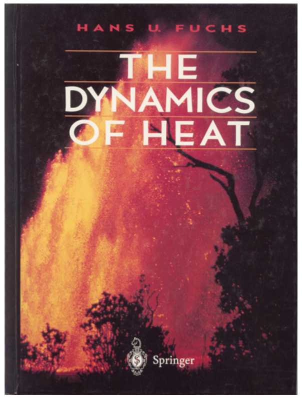

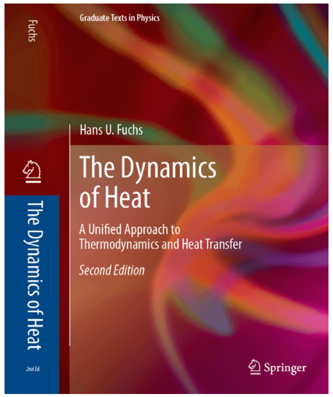

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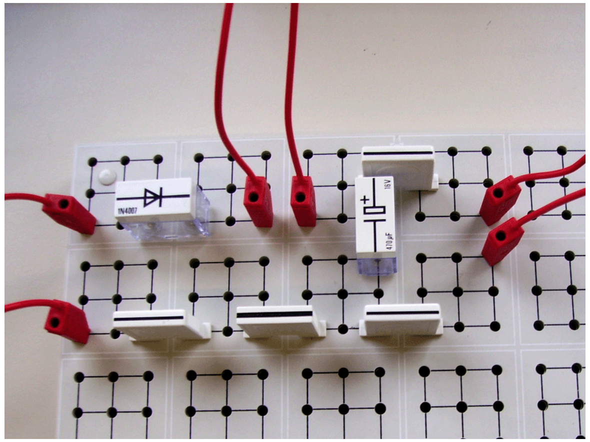
Part 1

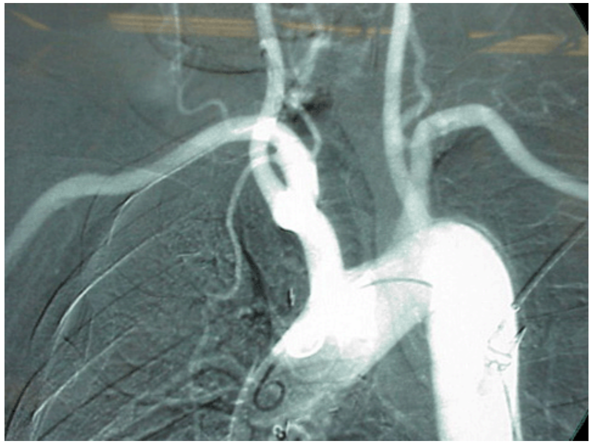
DYNAMICAL FLUID AND ELECTRIC PHENOMENA

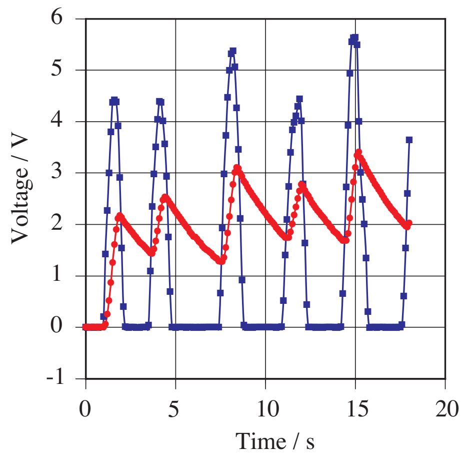
As an example, an exercise in modeling of electric windkessel circuits and the mammalian systemic blood flow system is presented.

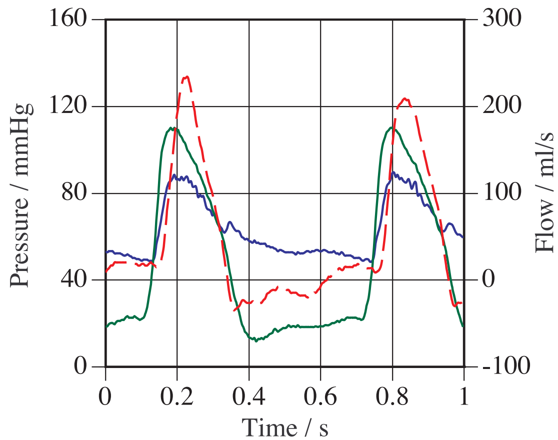
We will see that the models make use of **only a small handful of concepts** which have **analogous structures** in fluids and electricity.

ELECTRIC WINDKESSEL AND MAMMALIAN SYSTEMIC BLOOD FLOW: EXPERIMENTS

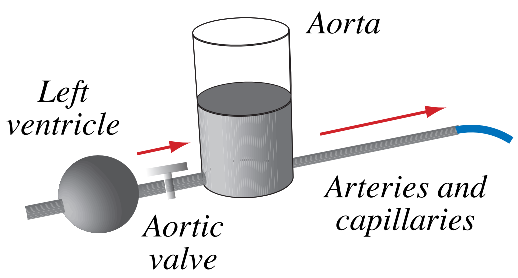


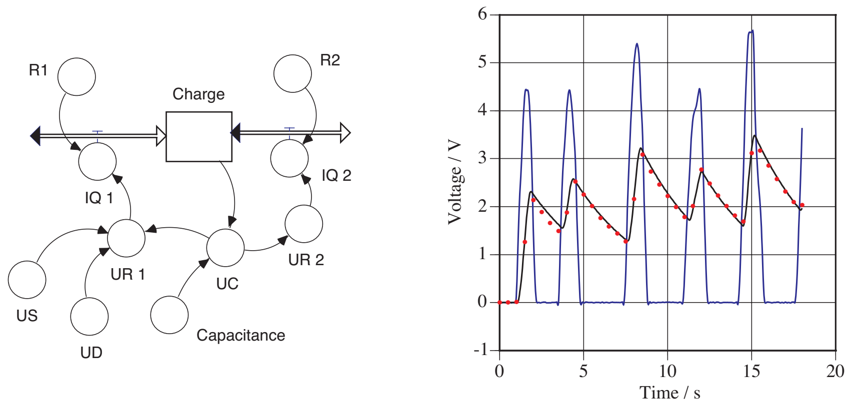


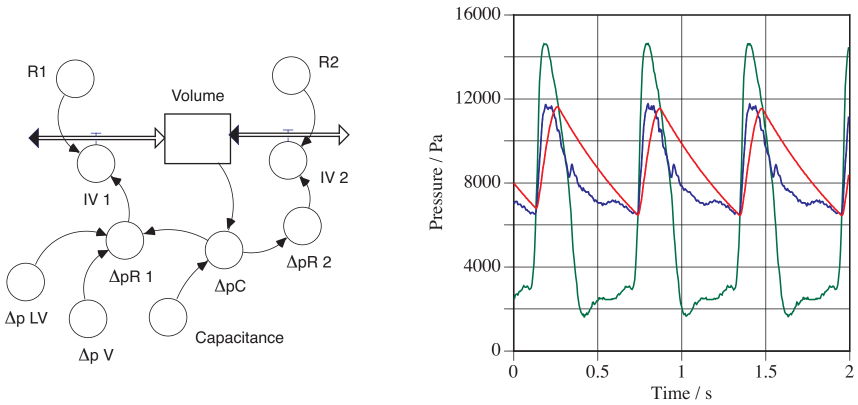




ELECTRIC WINDKESSEL AND MAMMALIAN SYSTEMIC BLOOD FLOW: MODELS







$$\frac{dV}{dt} = I_{V1} - I_{V2} \quad , \quad V(0) = V_0$$

$$\Delta p_{R1} = \Delta p_{LV} - \Delta p_C - \Delta p_V$$

$$\Delta p_{R2} = \Delta p_C$$

$$\Delta p_C = V/C$$

$$I_{V1} = \Delta p_{R1}/R_1 \ \left(\Delta p_{R1} > 0\right) \quad , \quad I_{V2} = \Delta p_{R2}/R_2$$

STRUCTURE OF DYNAMICAL MODELS

Law of balance

$$\frac{dV}{dt} = I_{V1} - I_{V2} \quad , \quad V(0) = V_0$$

Loop rule

$$\Delta p_{R1} = \Delta p_{LV} - \Delta p_C - \Delta p_V$$

$$\Delta p_{R2} = \Delta p_C$$

Constitutive relation 1: Capacitive law

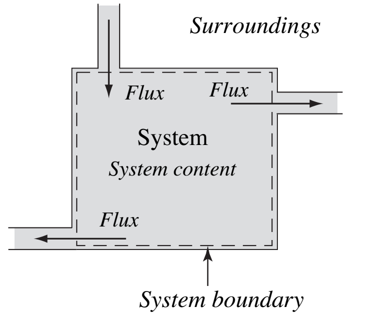
$$\Delta p_C = V/C$$

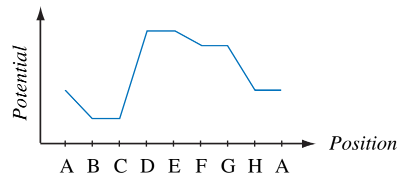
Constitutive relation 2: Flow law

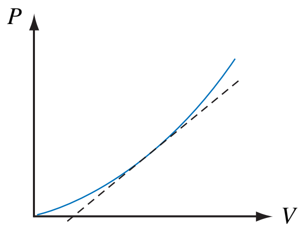
$$I_{V1} = \Delta p_{R1}/R_1 \;\; (\Delta p_{R1} > 0) \quad , \quad I_{V2} = \Delta p_{R2}/R_2$$

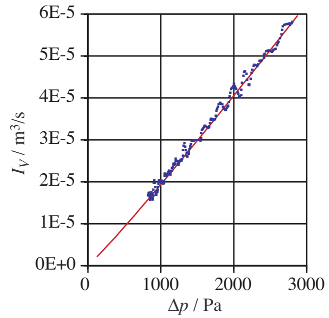
Basic quantities to build hydraulic models with:

Volume, volume current, pressure and pressure difference









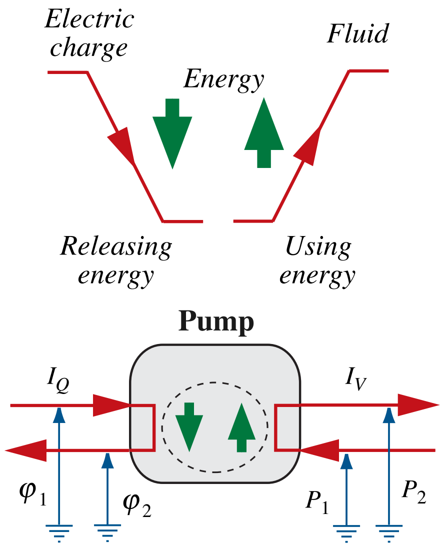
Part 2

A GENERALIZED APPROACH TO ENERGY IN PHYSICAL PROCESSES

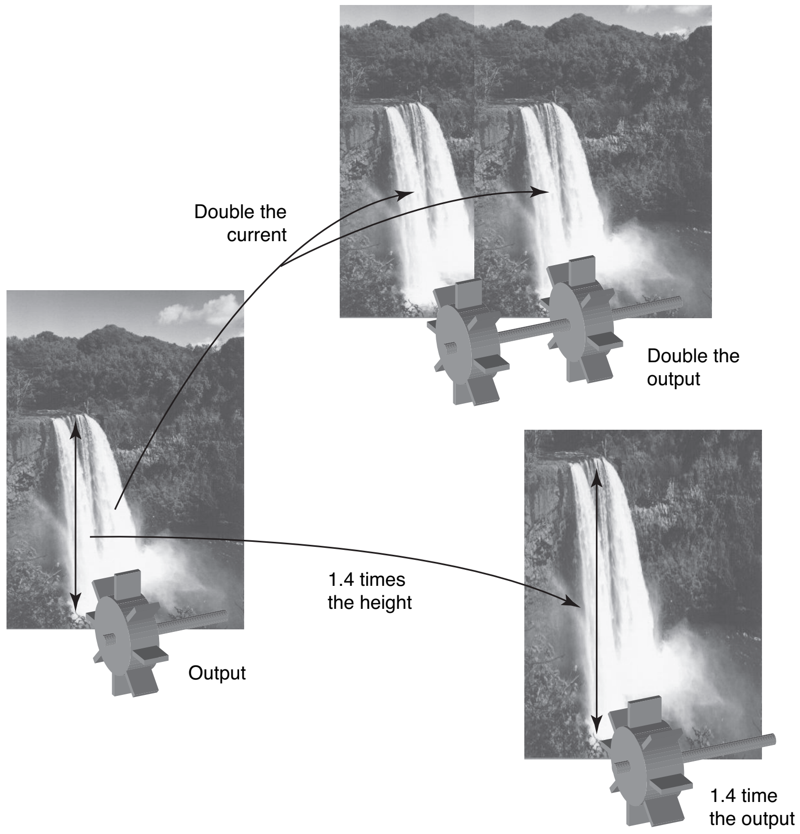
Here is a generalized approach to energy that owes much to Sadi Carnot's and J. W. Gibb's thermodynamics. Energy is conceived as the same quantity in all physical processes—there are no "forms of energy."

Carnot's image of **waterfalls** used as an analogy for heat engines can be generalized to all processes. It suggests that we should think of **energy** being **released** (or used) in physical processes…

WATERFALLS AND THE POWER OF PROCESSES

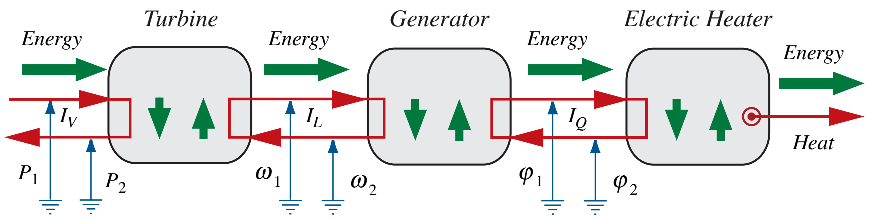


Power = Level Difference · Flow



Energy Transport and Energy Storage

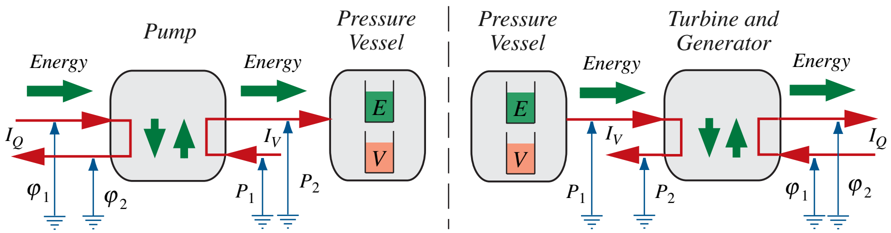
Transport



Energy current =
Level · Flow

This relation holds only for ***conductive transports*** (not for radiation or convection).

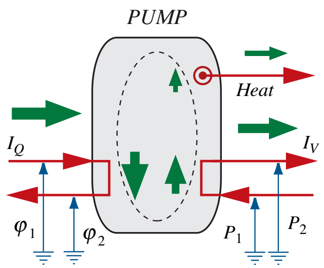
Storage



Balance of energy:

$$\frac{dE}{dt} = I_{E1} + I_{E2} + \ldots$$

Efficiency



Part 3

FIGURATIVE STRUCTURES OF MACROSCOPIC PHYSICS

The human mind is **embodied**, it functions by creating **schemas**.

Our thinking is **figurative**. Literal Language and thought are the exception (if they exist at all)…

The most important structures of the human mind are image schemas, gestalts of rich phenomena, metaphors, and larger narrative units (such as stories).

The concepts of macroscopic physics can be understood in terms of the **Force Dynamic Gestalt** structured with the help of metaphoric projection of a few simple schemas.

FROM PERCEPTUAL GESTALTS TO REASONING

Gestalts: The act of perception is one of abstraction, products of **perception** are **abstractions** (gestalts, patterns, configurations) where the whole is simpler than the sum of its parts.

The power of the human mind is in part due to our ability to **differentiate the gestalts** of rich phenomena, i.e., to elaborate on the **aspects** of gestalts by using schemas (which are themselves gestalts) and their metaphoric projections.

In this way we fill the phenomena with embodied meaning. The schemas applied are simple yet they have internal structure and this structure can be made use of in **reasoning**.

A particular gestalt or schema to understand rich phenomena is what I call the **Force Dynamic Gestalt**. (Fuchs, 2010b)

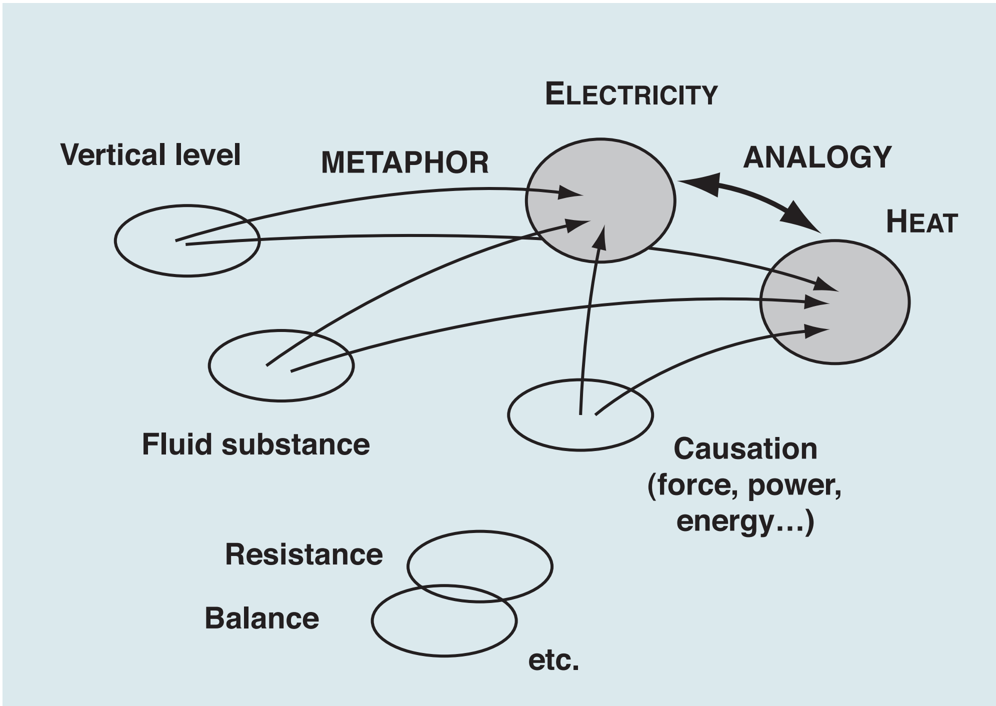
RICH EXPERIENTIAL GESTALTS IN PHYSICS: FDG OF ELECTRICITY

Schemas	**Linguistic expressions**
Quantity (amount) *Container, Path*	The capacitor stores a lot of electricity Electricity (charge) flows through this connector
Polarity *Intensity, Level of…* *Level difference*	This body is strongly charged (weakly charged) The capacitor has been charged to a high level The difference of potentials is called voltage
Force or power *Agent and patient, causation*	Electricity drives this pump Electricity is used to…
Tension	The difference of intensities creates an electric tension
Balance	Voltages of the capacitors have finally equilibrated
Letting, hindering	The resistor obstructs the flow of charge

The basic perceptual function of **Figure-Ground Reversal** applies to physical phenomena as well. Example: a. Charge is draining from this element; b. This body is on a higher electric level. This may well be the root of the concept of quantity of electricity (if we take the notion of polarity as given).

FDG: Schemas, Metaphoric Projections, and Analogical Reasoning

If we use the same **schemas** and **metaphoric projections** to understand different phenomena, these phenomena attain a degree of similarity in our mind. This can be used in a form of **analogical reasoning** (analogy as structure mapping, Gentner, 1983).



Part 4

QUANTITY, INTENSITY, AND POWER OF HEAT — FROM THE ACCADEMIA DEL CIMENTO TO SADI CARNOT AND BEYOND

Early scientific accounts of the phenomenon of heat (and cold) clearly demonstrate that we employ the **Force Dynamic Gestalt of heat** to understand thermal processes.

Sadi Carnot achieved a clear differentiation of the three main aspects of the FDG of heat: **quantity**, **intensity**, and **power**.

The accounts assume that we can create a **dynamical theory of heat**, not just one of the statics of heat.

EVIDENCE FOR THE GESTALT OF THERMAL PROCESSES

The concept of heat in the Accademia del Cimento

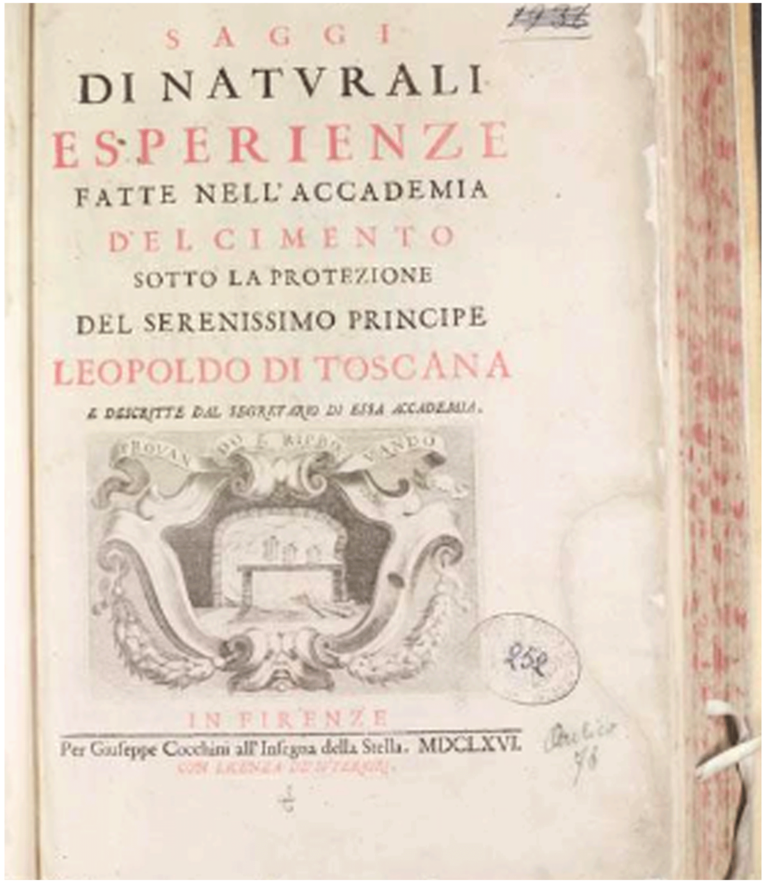
The concept of heat of the members of the Accademia del Cimento: Saggi di naturali esperienze… (1667)

M. Wiser and S. Carey (1983): When Heat and Temperature were one.

"The Experimenters' concept of heat had three aspects: **substance** (particles), **quality** (hotness), and **force**."

A weakly differentiated gestalt

It seems that the Experimenters did not really distinguish between these aspects of the gestalt of heat.

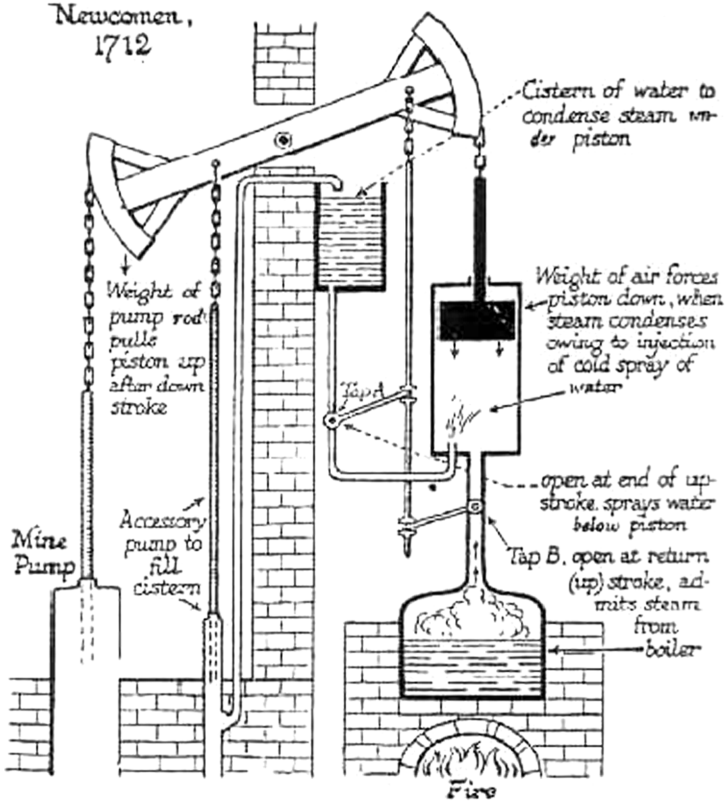


THE FORCE DYNAMIC GESTALT OF HEAT

Sadi Carnot (1796-1832)

Réflexions sur la puissance motrice du feu (1824)

D'après les notions établies jusqu'à présent, on peut comparer avec assez de justesse la *puissance motrice de la chaleur* à celle d'une *chute d'eau* […]. La puissance motrice d'une chute d'eau dépend de sa hauteur et de la quantité du liquide; la puissance motrice de la chaleur dépend aussi de *la quantité de calorique* employé, et de ce qu'on pourrait nommer, de ce que nous appellerons en effet *la hauteur de sa chute*, c'est-à-dire de *la différence de température* des corps entre lesquels se fait l'échange du calorique.



DIAGRAMMATIC VIEW OF NEWCOMEN'S ATMOSPHERIC OR FIRE ENGINE (1712)

Part 5

INTRODUCING A THEORY OF DYNAMICAL THERMAL PROCESSES

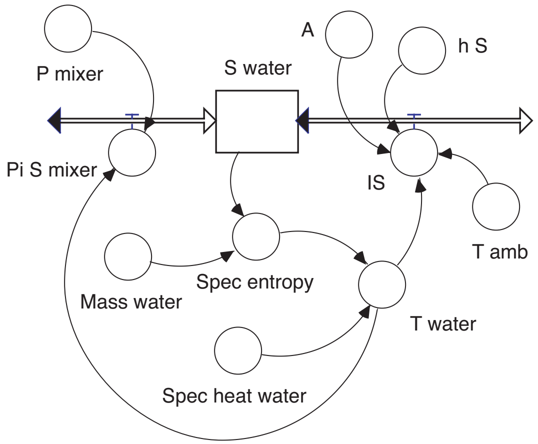
The following points, taken from Sadi Carnot and from a direct analogy with fluid and electric processes, lead to a dynamical theory of heat (Fuchs, 2010a):

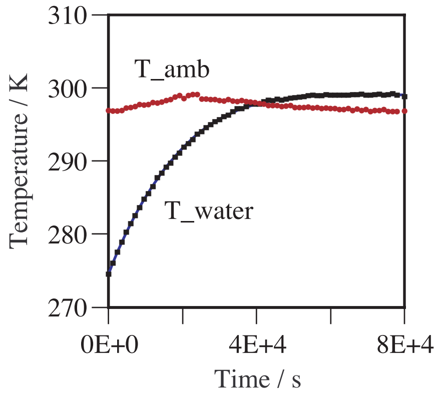
Properties of a quantity of heat (entropy): storage, flow, and production, balance of entropy

Temperature as the thermal level and temperature differences as thermal driving force

The power of heat (entropy) in analogy to the power of a waterfall

HEATING COLD WATER IN A WARM ROOM (DOH, CHAPTER 4.6)





Law of balance of entropy:

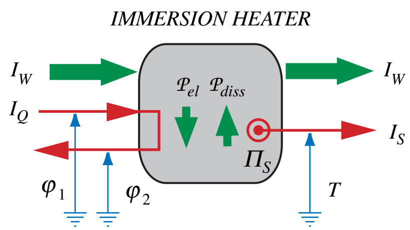
$$\frac{dS_w}{dt} = I_S + \Pi_S$$

Constitutive relations:

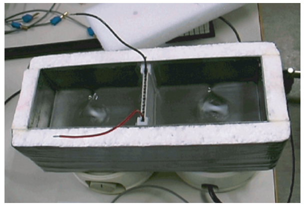
$$T = T_{ref} \exp(s/c)$$

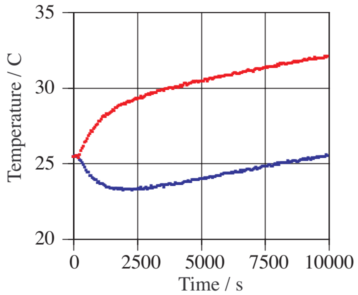
$$I_S = -A h_S (T - T_a)$$

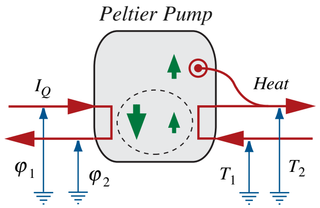
$$\Pi_S = \mathcal{P}_{diss}/T$$



PELTIER DEVICE (DOH, CHAPTER 4.7)



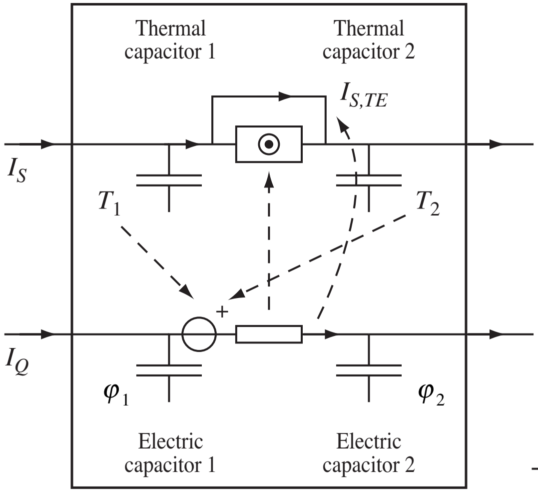


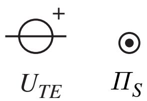


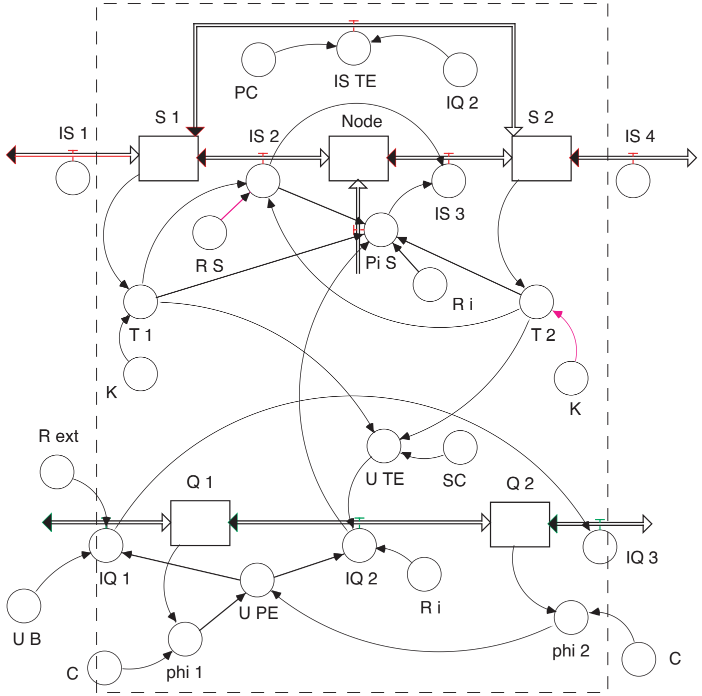
$$I_S = \alpha I_Q - G_S \left(T_2 - T_1 \right)$$

$$U = \varepsilon \left(T_2 - T_1 \right) + R_i I_Q$$

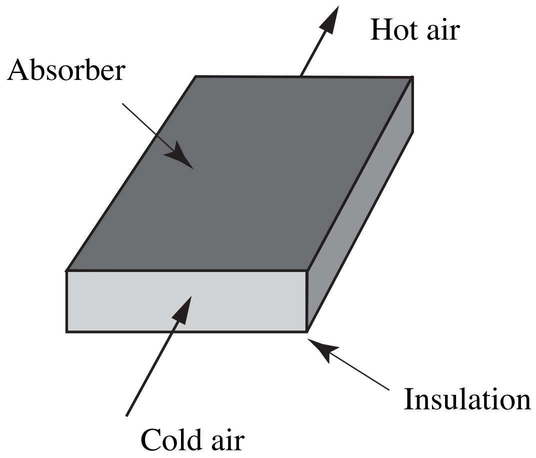
$$\alpha = \varepsilon$$

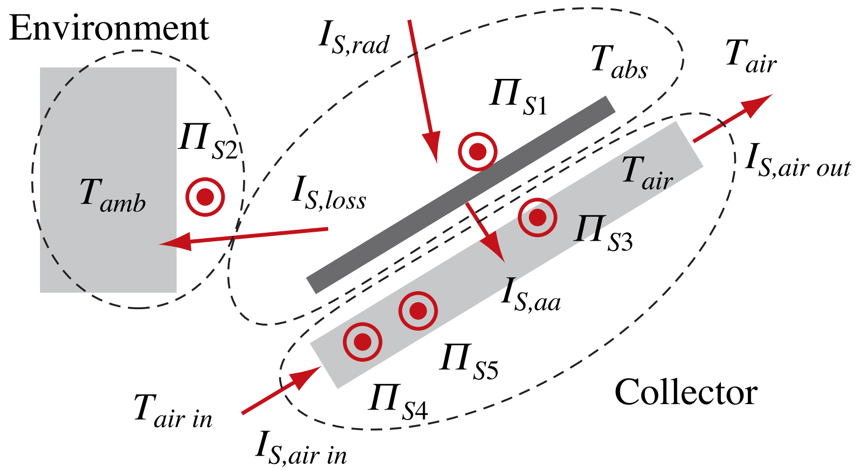


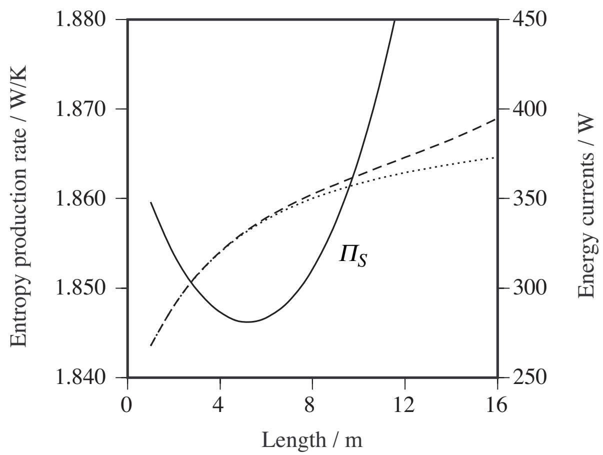




OPTIMIZING THERMAL SOLAR COLLECTORS (DOH, CHAPTER 9.4)







$$0 = I_{S,rad} - I_{S.aa} - I_{S,loss} + \Pi_{S1}$$

$$0 = I_{S,aa} - I_{S,conv} + \Pi_{S3} + \Pi_{S4} + \Pi_{S5}$$

$$I_{S,rad} = \frac{4}{3}\frac{(\tau\alpha)A\mathcal{G}}{T_{sun}}$$

$$\Pi_{S1} = \left(\frac{1}{T_{abs}} - \frac{4}{3}\frac{1}{T_{sun}}\right) I_{E,abs}$$

$$\Pi_{S5} = \frac{I_{E,pump}}{T_{air}}$$

...

$$\Pi_S = \Pi_{S1} + \Pi_{S2} + \Pi_{S3} + \Pi_{S4} + \Pi_{S5}$$

Part 6

UNIFORM MODELS OF VISCOUS FLUIDS

Here, a **spatially uniform model** of the thermo-fluidics of a viscous fluid is presented. It follows the model of viscous, heat-conducting fluids in **continuum physics** (Müller, 1985).

It shows how time appears explicitly in our evolution equations: we get **initial value problems** for the processes undergone by a fluid.

THERMODYNAMICS OF A SINGLE VISCOUS FLUID (DOH, CHAPTER 10.1)

ASSUMPTIONS

$$\dot{S} = I_S + \Pi_S$$

$$\dot{E} = I_{E,comp} + I_{E,th}$$

$$P\left(V,T,\dot{V}\right) = P\big|_E\left(V,T\right) + a\dot{V}$$

$$S = S\left(V,T,\dot{V}\right) \quad , \quad E = E\left(V,T,\dot{V}\right) \quad , \quad P = P\left(V,T,\dot{V}\right) \quad , \quad \ldots$$

$$I_{E,th} \propto I_S$$

$$I_{E,comp} = -P\dot{V}$$

CONSEQUENCES

$$I_{E,th} = T\,I_S$$

$$\Pi_S = -\frac{a}{T}\dot{V}^2$$

$$I_S = \Lambda_V\dot{V} + K_V\dot{T} + \frac{a}{T}\dot{V}^2$$

$$\dot{E} = T\,\dot{S} - P\big|_E\dot{V}$$

Application of these results to particular examples leads to **initial value problems** (evolution equations for temperature and volume).

A Final Word…

ON THE FIGURATIVE CONCEPTUALIZATION IN TRADITIONAL THERMODYNAMICS

Fundamentally, Clausius and Kelvin use the same imaginative figures to conceptualize of thermal processes: quantity of heat, temperature, and power of heat.

The theory of the Force Dynamic Gestalt shows that traditional thermodynamics uses a messed up version of the FDG of thermal processes: **quantity and power of heat are mixed up**.

Naturally, the concept of **quantity of heat** as different from its power comes back to haunt us in the form of **entropy**… (Fuchs, 1986)

LITERATURE

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