Efficiency and Sustainability of Processes

Ten pertinent propositions

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Delft University of Technology

Tsinghua University, Beijing (2003-2008)

Background

Challenge

Study the efficiency and sustainability of processes and arrive at a **quantitative** description based on sound scientific principles such as the laws of thermodynamics

Purpose of this lecture

SECOND EDITION

EFFICIENCY and SUSTAINABILITY in the ENERGY and CHEMICAL INDUSTRIES

Scientific Principles and Case Studies

Krishnan Sankaranarayanan
Hedzer J. van der Kooi
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CRC Press
Taylor & Francis Group

Energy in this Century

Of all factors that are important to our future, energy may well be the single-most critical problem that we have to face in this century

Octave Levenspiel

No sensible decision on energy and its physical and chemical transformations can be well-founded without understanding and applying the concepts of thermodynamics.

Proposition(1)

No sensible decision or claim on energy can be made without the approval of thermodynamiciens

Observation

“La Thermodynamique n’est pas tout,
mais elle est en tout”

On the second law, entropygeneration and lost work

Gouy-Stodola(~1900)

$$\dot{W}_{lost} = T_0 \dot{S}_{gen}$$

Identification

$$\dot{S}_{gen} = \sum_{i} (flowrate)_i * (force)_i$$

The magic triangle behind the second law

$\dot{S}_{gen} > 0$

Classical thermodynamics

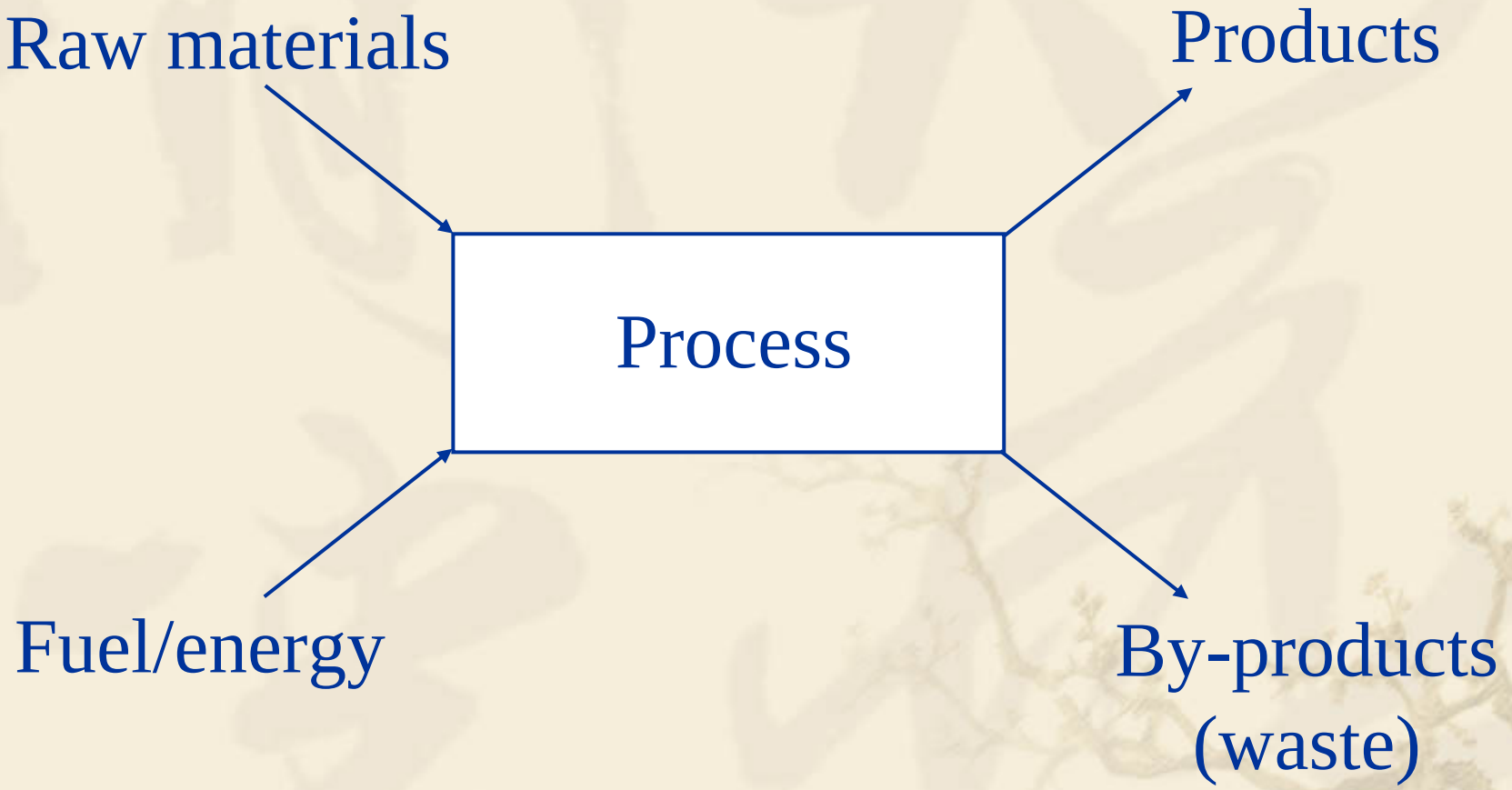
Engineering thermodynamics

Irreversible or non-equilibrium thermodynamics

$\dot{W}_{lost} = T_0 \dot{S}_{gen}$

$\dot{S}_{gen} = \sum_i J_i X_i$

Process model



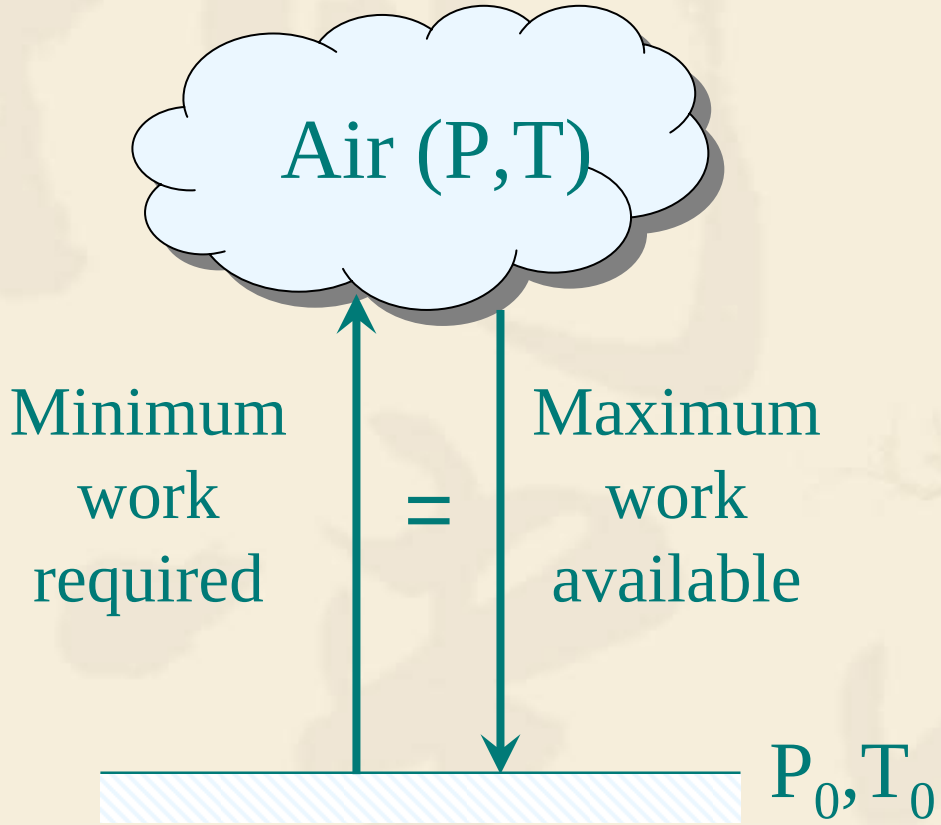
Proposition(2)

The fate of energy in a process can only be decided by the thoroughness of a thermodynamic analysis

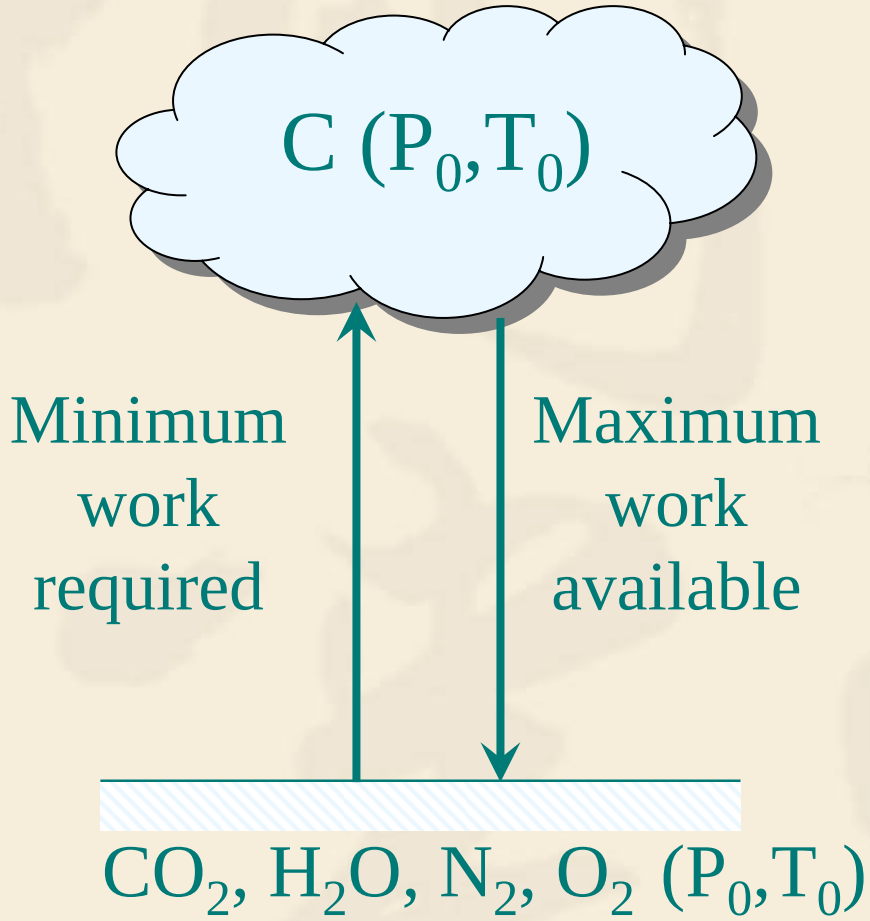
The remarkable role of exergy

$$Ex = (H - T_0 S)_{P,T} - (H - T_0 S)_{P_0,T_0}$$

Out of equilibrium with the environment (thermo-mechanical)



Out of equilibrium with the environment (chemical)



$$W_{available}^{\max} = 410\,kJ/mol$$

Exergy: fuels and foods (kJ/mole)

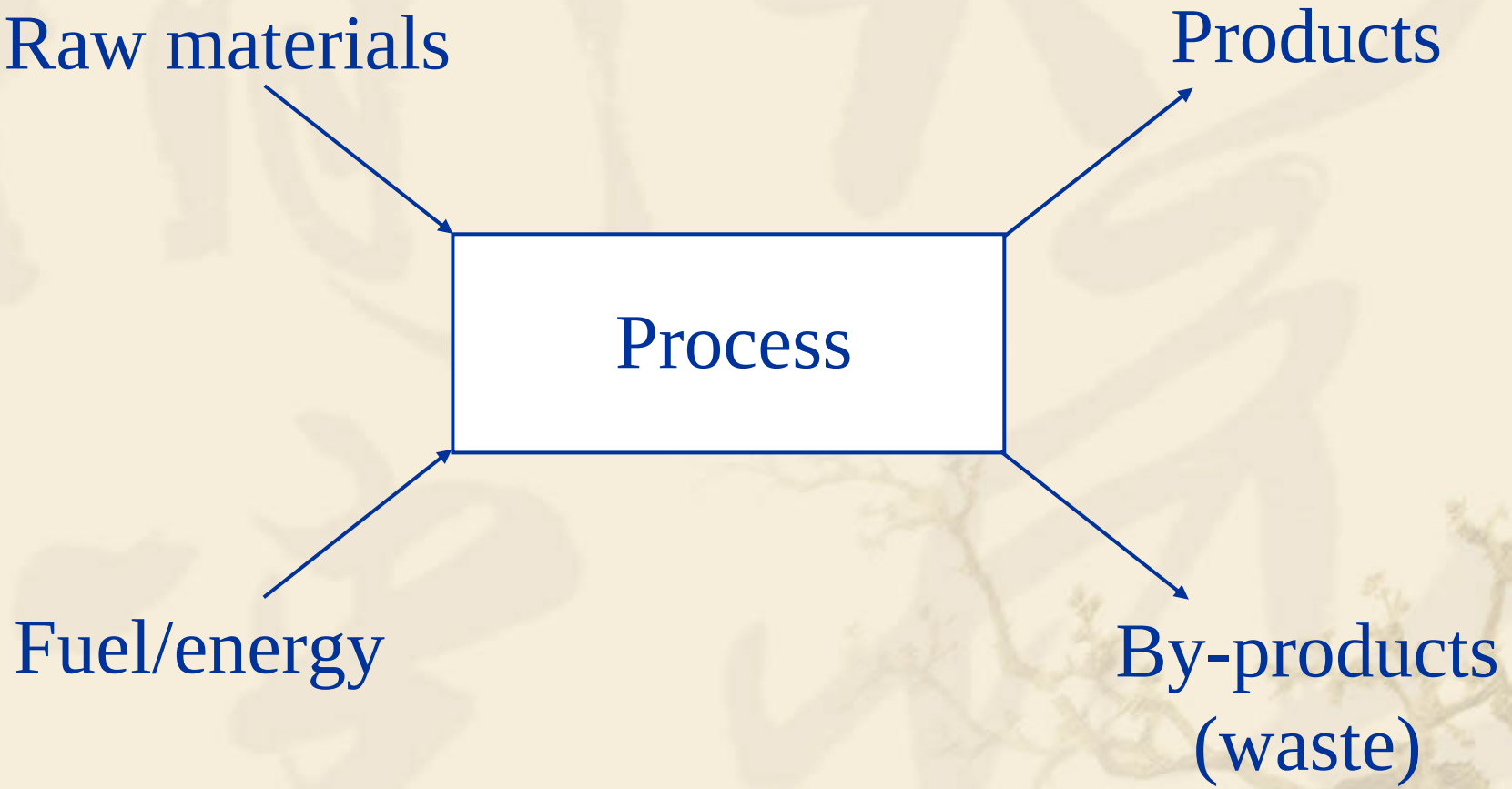
C (coal)	410
H_2 (fuel of the future?)	236
CH_4 (natural gas)	832
$-CH_2-$ (oil)	653
CH_3OH (methanol)	718
CH_xO_y (biomass)	490
CH_2O (carbohydrates)	504
$CH_2O_{0.1}$ (fat)	630

Proposition (3)

Exergy* is a unique, strictly thermodynamic and extremely practical concept that measures a system's distance from equilibrium with its environment

*Already identified by Gibbs as available work

Thermodynamic analysis



Objective: transfer of exergy with a minimum loss

Thermodynamic efficiency (%)

Electricity (coal/oil)	20-55
Separations	5-20
Chemical conversion	5-60
Biochemical conversion	
cycles	> 50
single steps	90-99

On Life Cycle Analysis

Life Cycle Analysis gains considerably in power when it is extended to include exergy

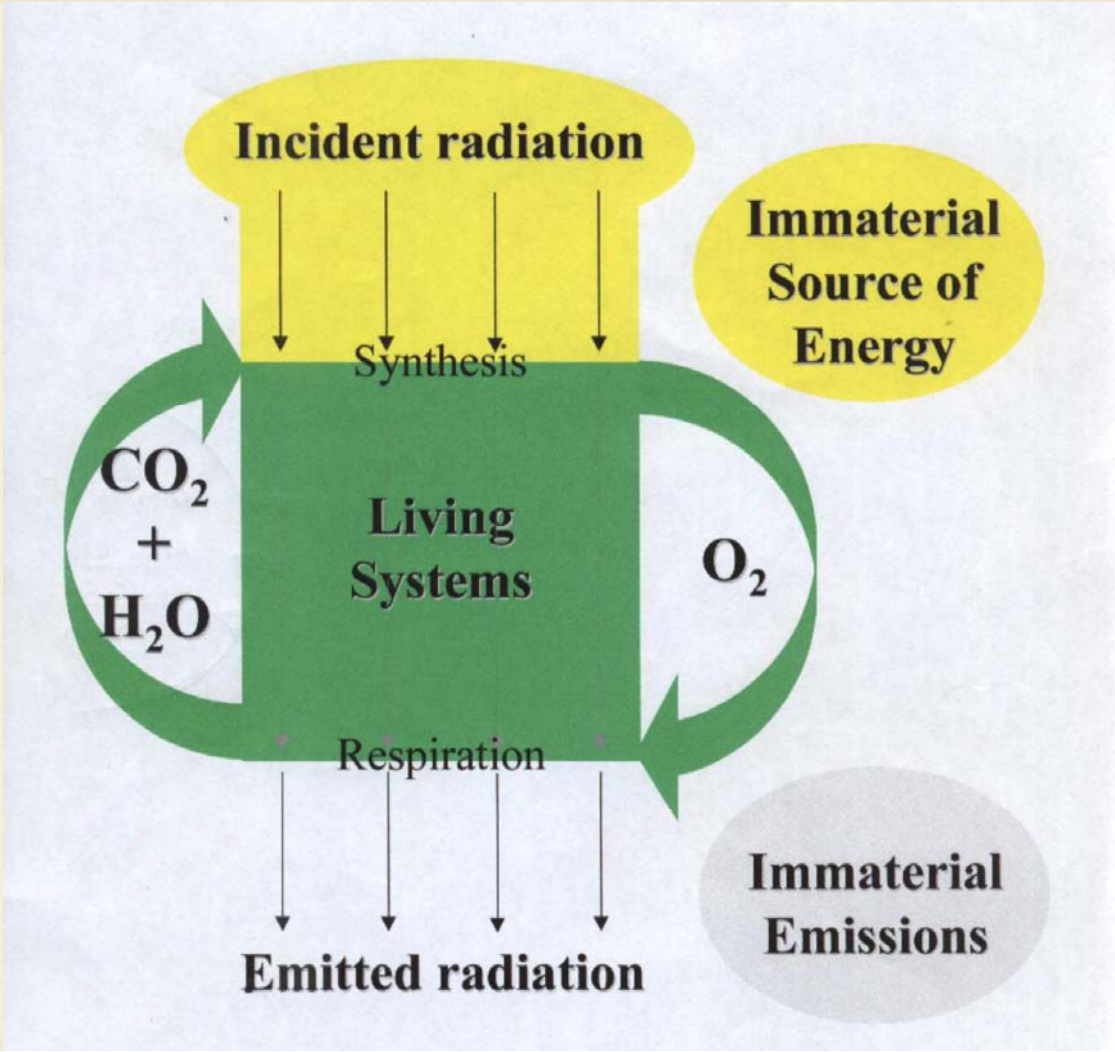
R.L.Cornelissen, Ph.D thesis
Twente University [1997]

On Sustainability

Sustainable development

…. using resources no faster than they can regenerate themselves and releasing pollutants to no greater extent than natural resources can assimilate them!

Angela Merkel, Ph.D
German Chancellor



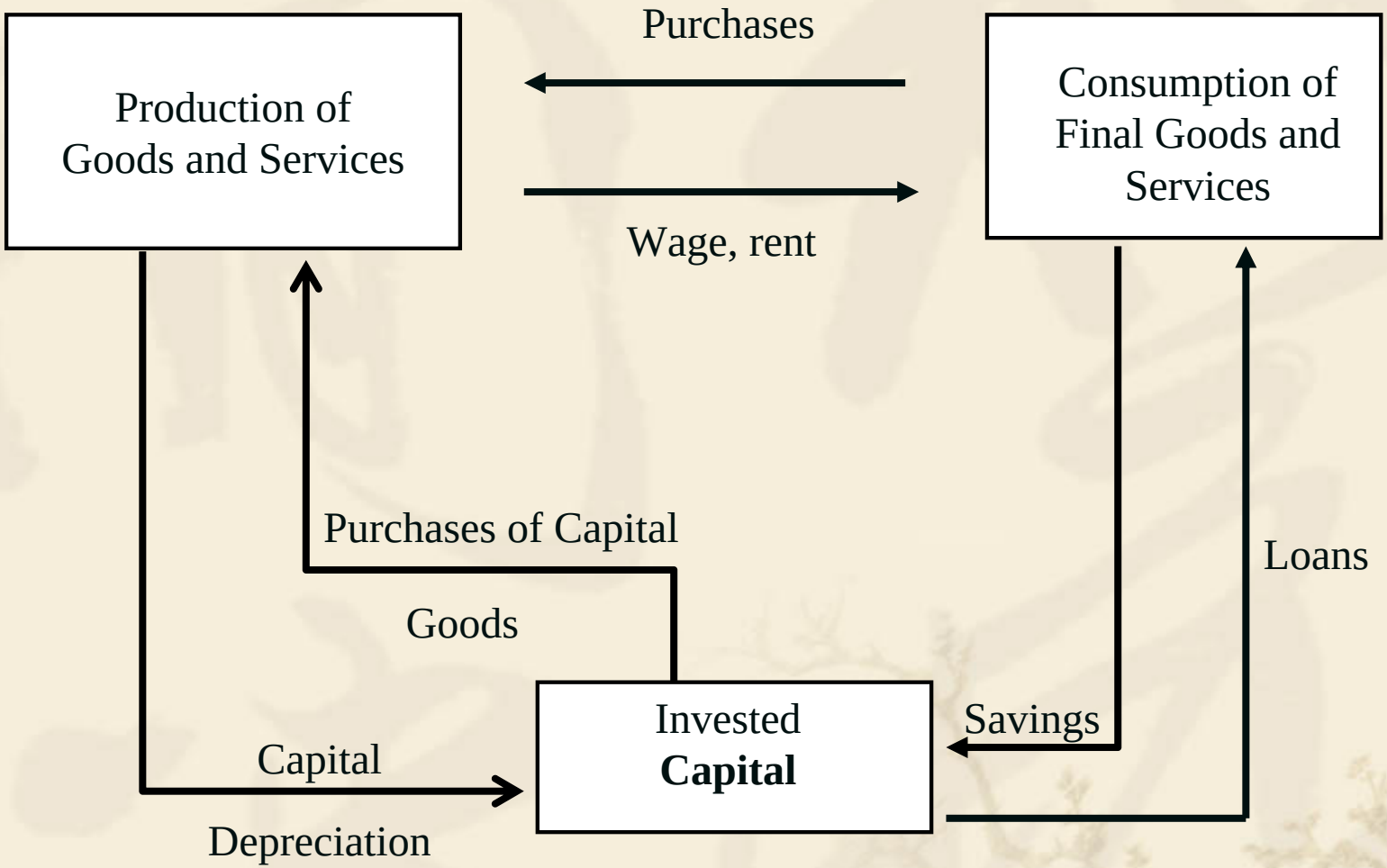
The Cycle of Life

Note

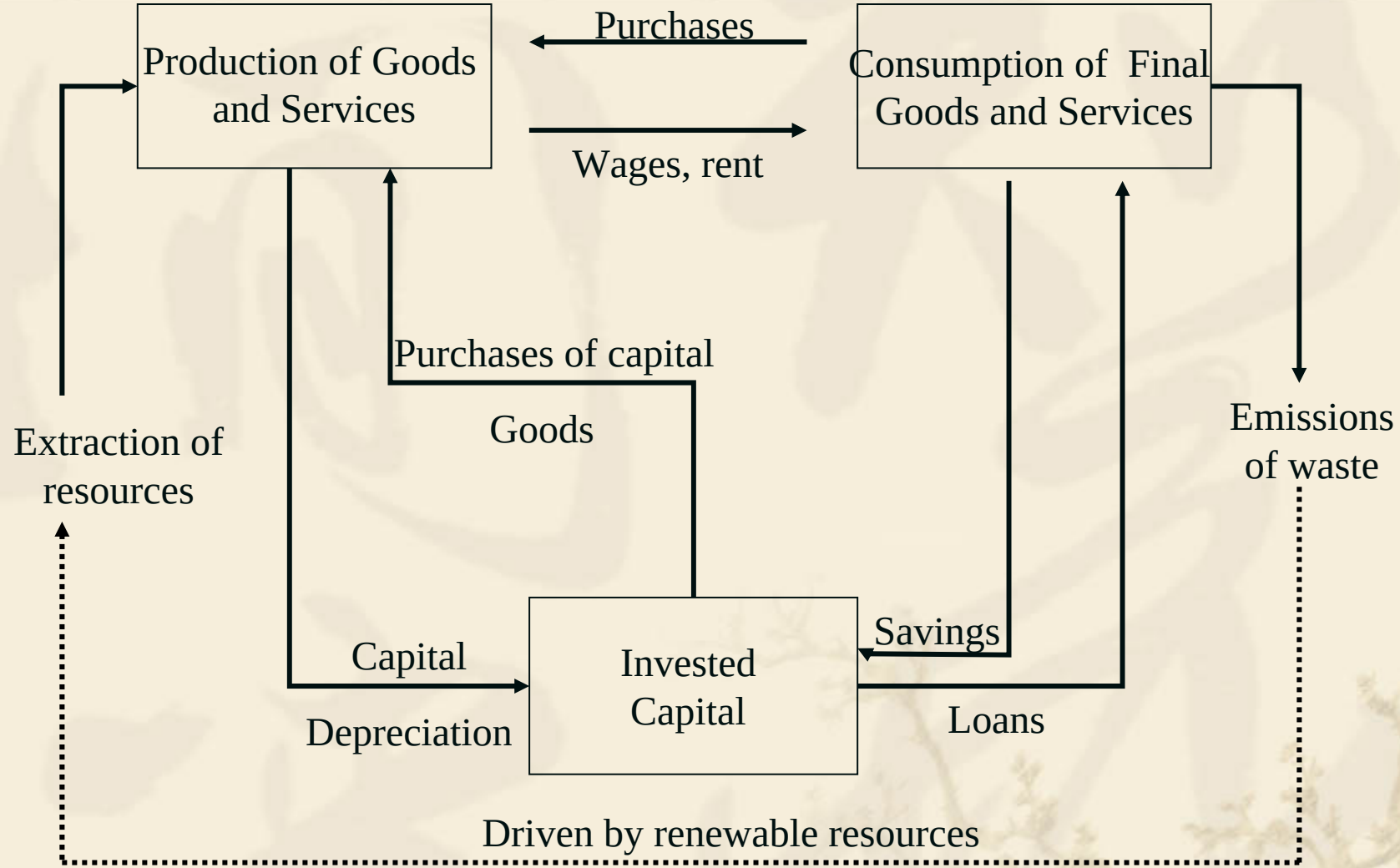
Looking more closely at the Cycle of Life it appears to be the prime example of sustainability in that it makes use of a renewable energy source, closes material cycles, and thus eliminates material emissions.

Proposition (4)

The characteristics of the Cycle of Life
make it the prime example of sustainability



Classical economics



Sustainable Economics

Economic systems

The second law is the arrow of time, also for spontaneous processes in economic systems. The basic driving force here originates in the creation and maintenance of asymmetries in information

J.A.Roels

Delft University Press [2010]

Proposition (5)

Non-equilibrium thermodynamics can be expected to make significant contributions to a better understanding of the behaviour of economic systems

Intermezzo

Ecological Footprint

Measures how much land and water area a human population requires to produce the resources it consumes and to absorb the wastes it generates, taking into account prevailing technology.

Wackernagel and Rees [1990]

www.footprintnetwork.org

Footprint, Biocapacity and Overshoot

The ratio of footprint against biocapacity was about 1 in 1980, is 1.5 now and will reach 2 in 2030 i.e. we will need two globes. The “overshoot” is maintained by liquidating the Earth’s resources. The carbon footprint is more than 80% of the footprint

Observation

1 billion people (the developed world) consume 32 times faster than the 5.5 billion people in the developing world i.e. 85% of the global consumption at any moment in time.

New York Times

2.01.2008

Jared Diamond

Professor of Geography

UCLA

Proposition (6)

This world provides sufficient for everybody's **need** but not enough for everybody's **greed**.

Mahatma Gandhi (1869-1948)

Behavioral adjustment

"The greatest challenge in the modern world is for people to give up the materialism that surrounds them”

Sher Khan in
"Man and the future
Environment”
European Review
Vol. 12, No. 3, 273-292 [2004]

Richer, fatter and not much happier

A survey in 65 countries has shown that life-satisfaction (happiness) grows with income up to a certain level then flattens off. A high quality of life is not so much obtained by "wealth", the accumulation of material goods, but by the experience of "well-being" in terms of freedom, health, security and so on.

(Worldwatch Institute)

On Biomass Conversion, Solar Energy and Hydrogen

Biomass conversion and the fossil load factor

The non-renewable work input (e.g. from fossil fuel) per unit of work available in the renewable product output.

Fossil load factor

- fertilizer
- fuel for agricultural machinery
- herbicides/insecticides
- separation
- waste water treatment
- depreciation

How green are green plastics?

Gerngross and Slater
Scientific American
Feature Article
August 2000

“Green" means

made from a renewable resource

biodegradable upon disposal

On "green" plastics

"We discovered that this (green) approach (to plastics) would consume even more fossil resources than most petrochemical manufacturing routes"

(JdSA)

Gerngross and Slater
Scientific American
August 2000

Bioethanol

A thorough thermodynamic analysis shows that for the production of ethanol from corn the amount of fossil, thus non-renewable, work required, most likely exceeds the work available in the, renewable, product.

Exergy Int. J.
1(4) 256-268 [2001]

A simple exergetic calculation

….shows that about 5.5 cc of wood produce at most 1 cc of biofuel, assuming a thermodynamic efficiency of 50%, and emit 2.6 times the amount of CO2 emitted by 1 cc of fossil fuel.

Note on efficiency

The thermodynamic efficiency of a process drops dramatically if the process is made compatible with the environment and makes use of renewable resources.

The price of sustainability

S. Lems, H.J. van der Kooi, J. de Swaan Arons

ISEE International Conference,

Montreal, 12-14 July 2004

Based on the work of Dr. FENG Wei, BUCT, Beijing

Padzek and Pimentel

Based on solid thermodynamics and plant science they compared the land areas required to power a car and concluded that the transportation fuel of the future is electricity from the Sun.

Presentation to OECD

Paris [2007]

Competition for land

A fierce competition for the acquisition of land is emerging between the producers of

food	1
feed for livestock	~10
raw material for biofuel	~100

Do we really want this?

- 2-3 km driving in an economical car (25 km/liter) requires the same “energy” as a healthy person requires in 1 day.

No free lunch

Thermodynamics and its main laws do not differentiate between physical, chemical or biochemical processes. Micro-organisms need food i.e. exergy too.

biomass→polysaccharides→glucose→fuel

Proposition (7)

Fuels from biomass is an illusion; the evidence is available but either unknown, ill-understood, or ignored altogether

The Solar Cyclist

Transforms light into work!

Alexis DeVos

Thermodynamics of Solar Energy Conversion

VCH/Wiley [2008]

Solar Power Station

light-heat-work-electricity

R.E.Smalley, Nobel laureate

Denounces biomass, hydrogen and new hydroelectricity and makes a strong plea for a nationwide electrical network, leaving no doubt on his strong belief in solar electricity that ultimately can easily fulfill USA's energy needs.

The Terawatt Challenge

MRS Bull. June[2004]

Nate Lewis, Caltech, USA

Six strategically chosen sites on our planet, each of 10000 square km, can provide a world population of 10 billion people with a power consumption of 2000 W

Steven Chu, Nobel laureate

The road to sustainable energy can be compared to the “Man on the Moon” project in terms of ambition and funding.

Co-chairman IAC-report

Lighting the way [2007]

Secretary of Energy USA

Idle capacity

The idle off-peak grid capacity in the USA would be sufficient to power 84% of all its vehicles if they were immediately replaced with electric vehicles. Unfortunately this same grid is not able yet to absorb electricity from renewable sources.

Proposition (8)

Solar energy is usually “waved aside” as being too costly, without rewarding it for its renewable characteristics. This is frustrating, unfair and non-productive

Labyrinth

Hydrogen as a fuel and the corresponding economy is a labyrinth where only thermodynamics can show the way out.

Stored exergy

Coal	50-60 kJ/cc
CH4	9.28 kJ/cc (250 bar)
H2	7.37 kJ/cc(700 bar)
H2(liq)	8.38 kJ/cc
Gasoline	38-45 kJ/cc

Remarkable

There is more hydrogen in a liter of gasoline (116g) than there is in a liter of pure liquid hydrogen(71g). Of course, liquid hydrogen is free of CO_2.

Unlikely

Solid thermodynamic arguments such as the overall well-to-grid and well-to-wheel thermodynamic efficiencies, and H2's low exergy content/cc, lead us to the proposition….

Proposition (9)

H2 as “the fuel of the future” is possible but unlikely

Proposition (10)

Thermodynamiciens should organize and position themselves in society in such a way that any decision, claim or statement on energy is only meaningful after their ratification with the

"Carnot seal" or Le Sceau de Carnot

Final remark