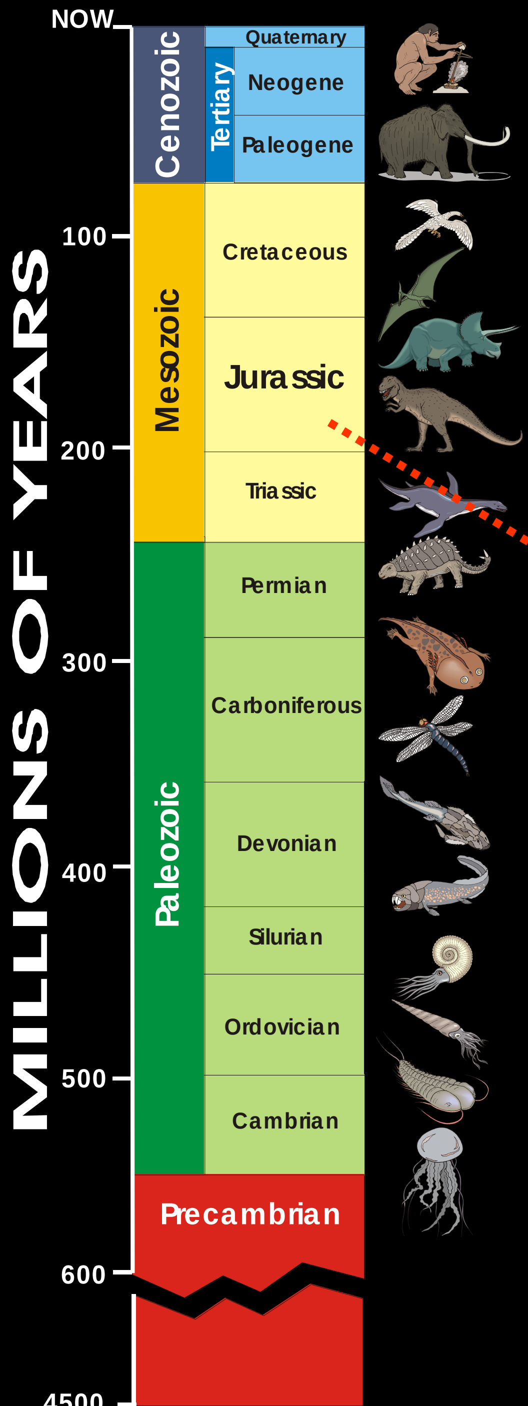
# INTRODUCTION TO PROCESS INTENSIFICATION:

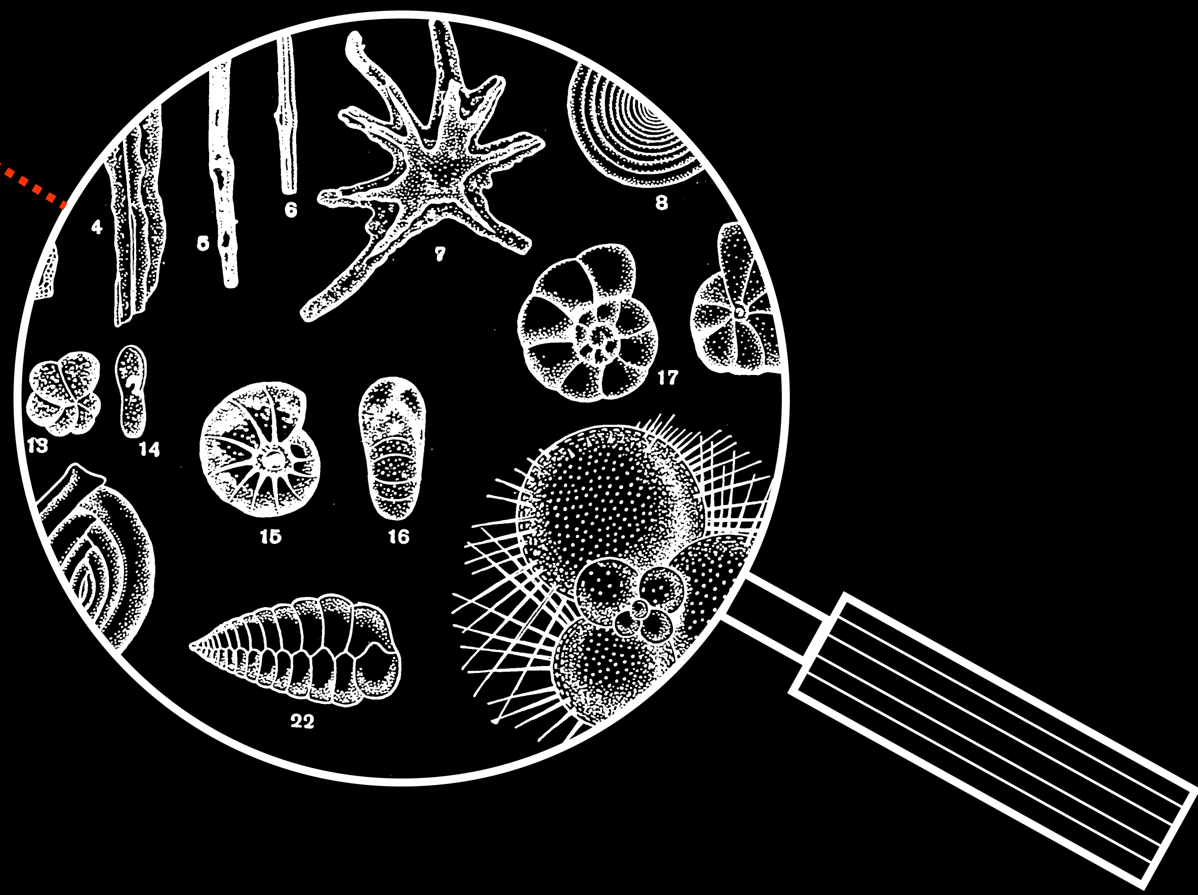
# PHILOSOPHY AND BASIC PRINCIPLES

Giorgos Stefanidis / Andrzej Stankiewicz

## SOURCES OF OIL:

# FORAMINIFERA



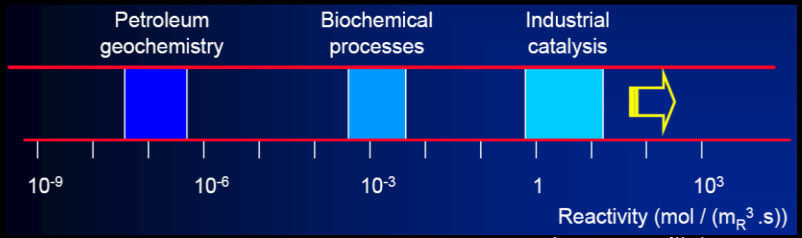
# THE OMNIPRESENT CHEMISTRY:
# FROM THE CRADLE TO THE GRAVE …AND BEYOND!

# Consumption of chemical products is rapidly increasing

- **new types of chemical and biochemical products brought to the market**
- **new markets open in different parts of the world for already existing products**

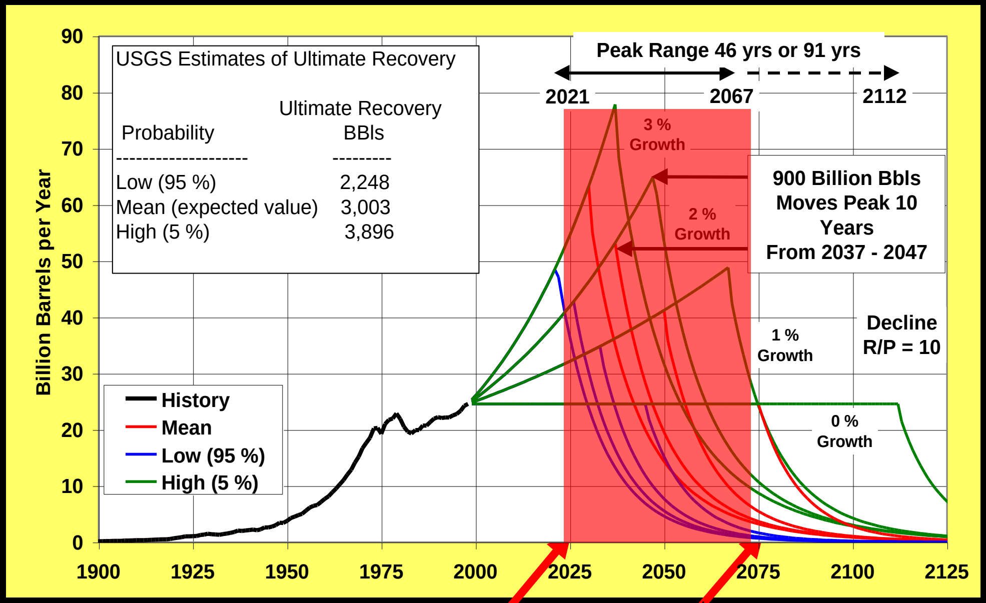
# Main reasons

- **rapid growth in world's population**
- **growth in consumers' wealth**
- **growth in consumers' needs**




(J. A. Moulijn)


GENERATION << CONSUMPTION




1 generation ahead

3 generations ahead

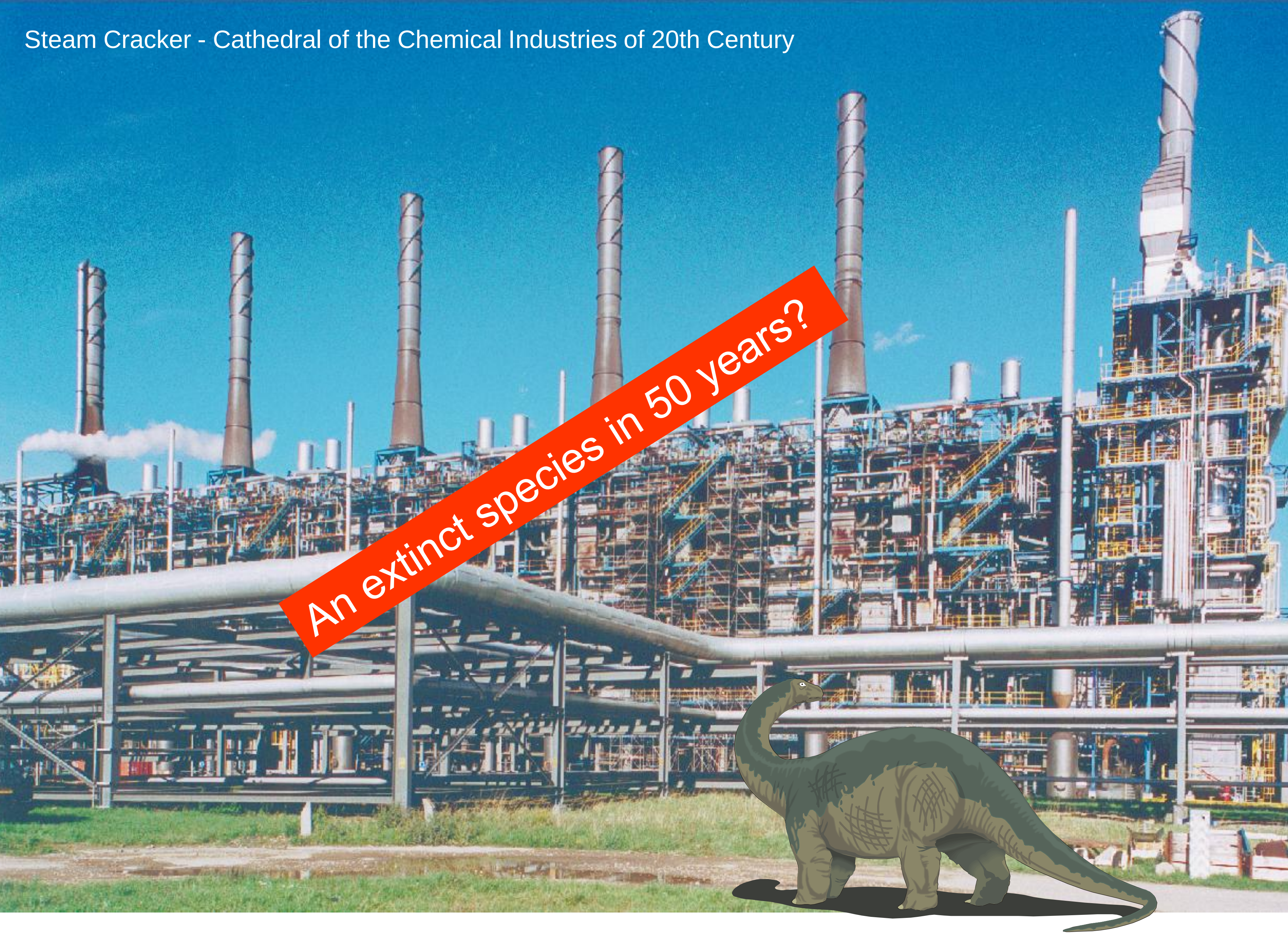
# OIL PRODUCTION FORECAST

(U.S. Energy Information Administration)

# THE NON-SUSTAINABLE MANKIND

## SOME FORECASTS:

- **WE WILL ESSENTIALLY USE UP ALL THE WORLD'S OIL RESOURCES BY 2050** (S. A. Nelson)
- **WE WILL ESSENTIALLY USE UP ALL THE WORLD'S GAS RESOURCES BY 2070** (P.-R. Baquis)
- **WE WILL ESSENTIALLY USE UP ALL THE WORLD'S COAL RESOURCES BY 2500** (S. A. Nelson)


Steam Cracker - Cathedral of the Chemical Industries of 20th Century
An extinct species in 50 years?

# How to solve the resources problem?

## OPTION 1:

- **start exploitation of extraterrestrial resources**

  - still in the S-F stage and may remain so

## OPTION 2:

- **develop technically and economically feasible processes based on the renewable feedstocks ("green", biomass-based processes)**

# How to solve the resources problem?

## Some open questions to OPTION 2:

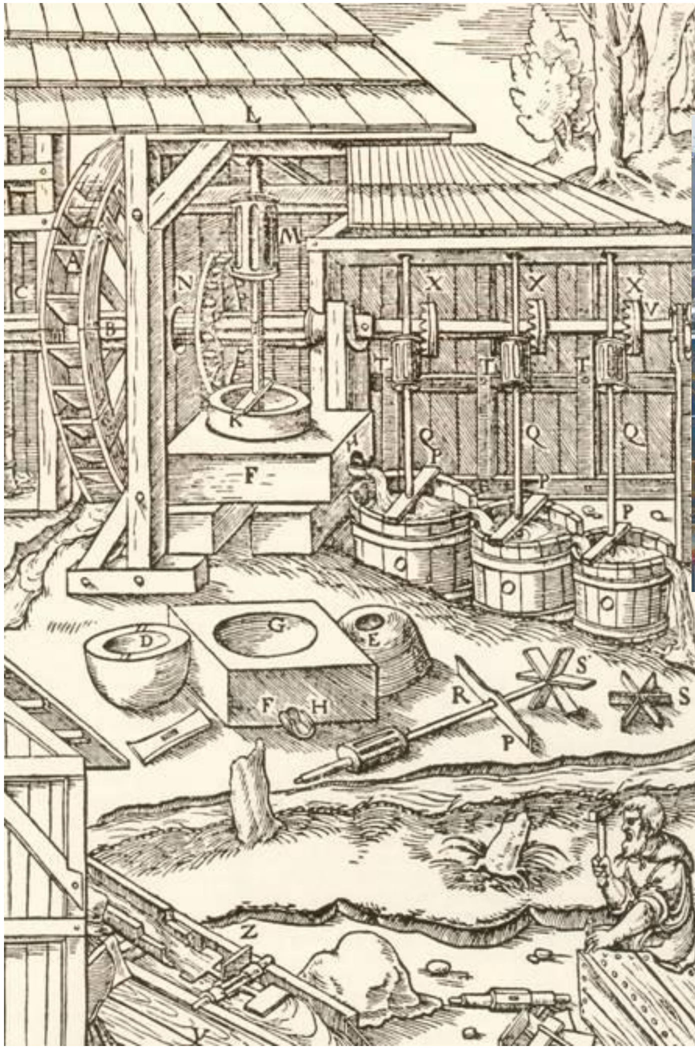
- do we have enough arable land to feed mankind AND to provide energy AND to supply raw materials simultaneously?
- what will we do with by-products, such as $CO_2$?
- how will this “new farming” influence environment?
- what will be repercussions of genetic manipulations?
- what about inorganic chemical products?
- when will this all be feasible?

# How to solve the resources problem?

## OPTION 3:

- develop innovative methods and technologies that would DRASTICALLY increase the EFFICIENCY of chemical and biochemical processes

  - FACTOR 4 (Von Weizsacker, 1998)
  - FACTOR 10 (Schmidt-Bleek, 1993)
  - FACTOR 20? (AllChemE – Alliance for Chemical Sciences and Technologies in Europe, 2001)



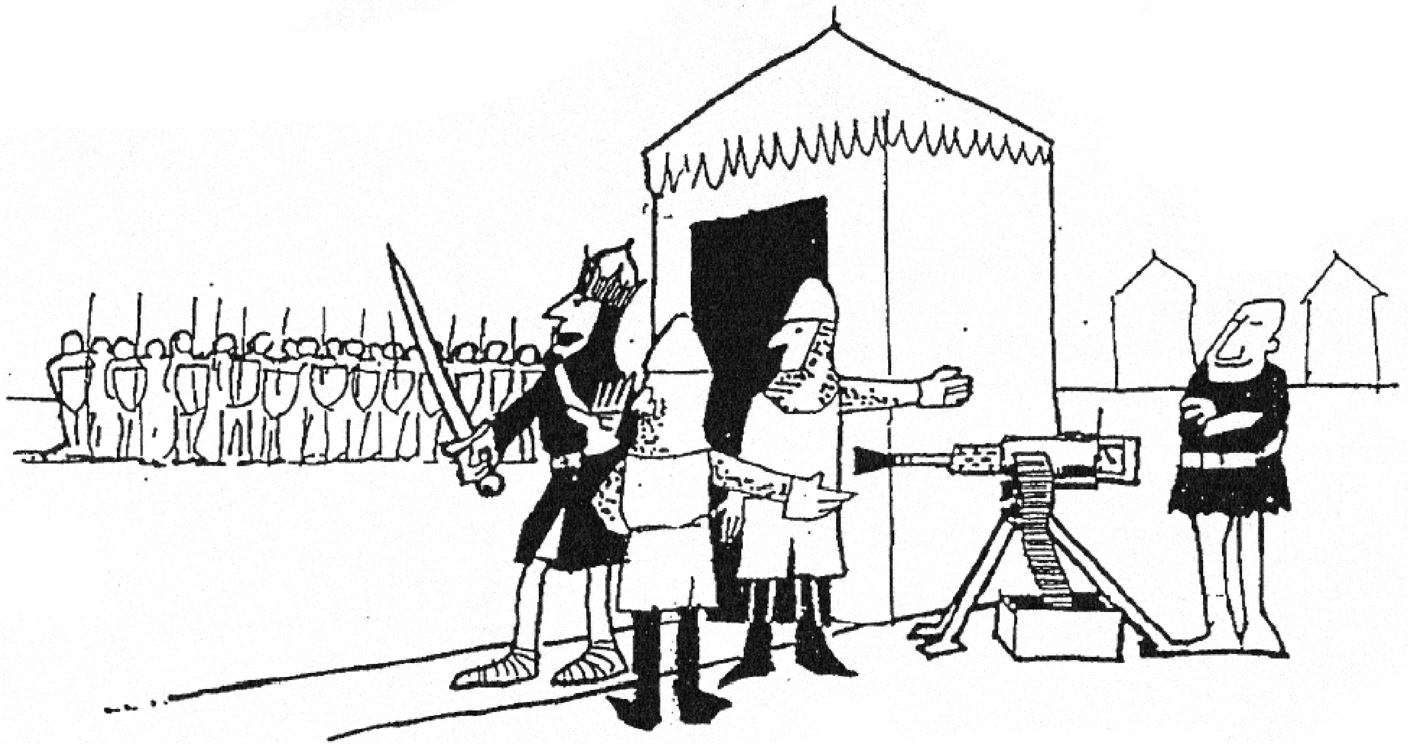
G. Agricola, *De Re Metallica*, 1556

Chemical Process Industry, 2012

- **THIS IS NOT THE WAY TO BOOST EFFICIENCY**
- **PROCESS INNOVATION IS CLEARLY NEEDED**

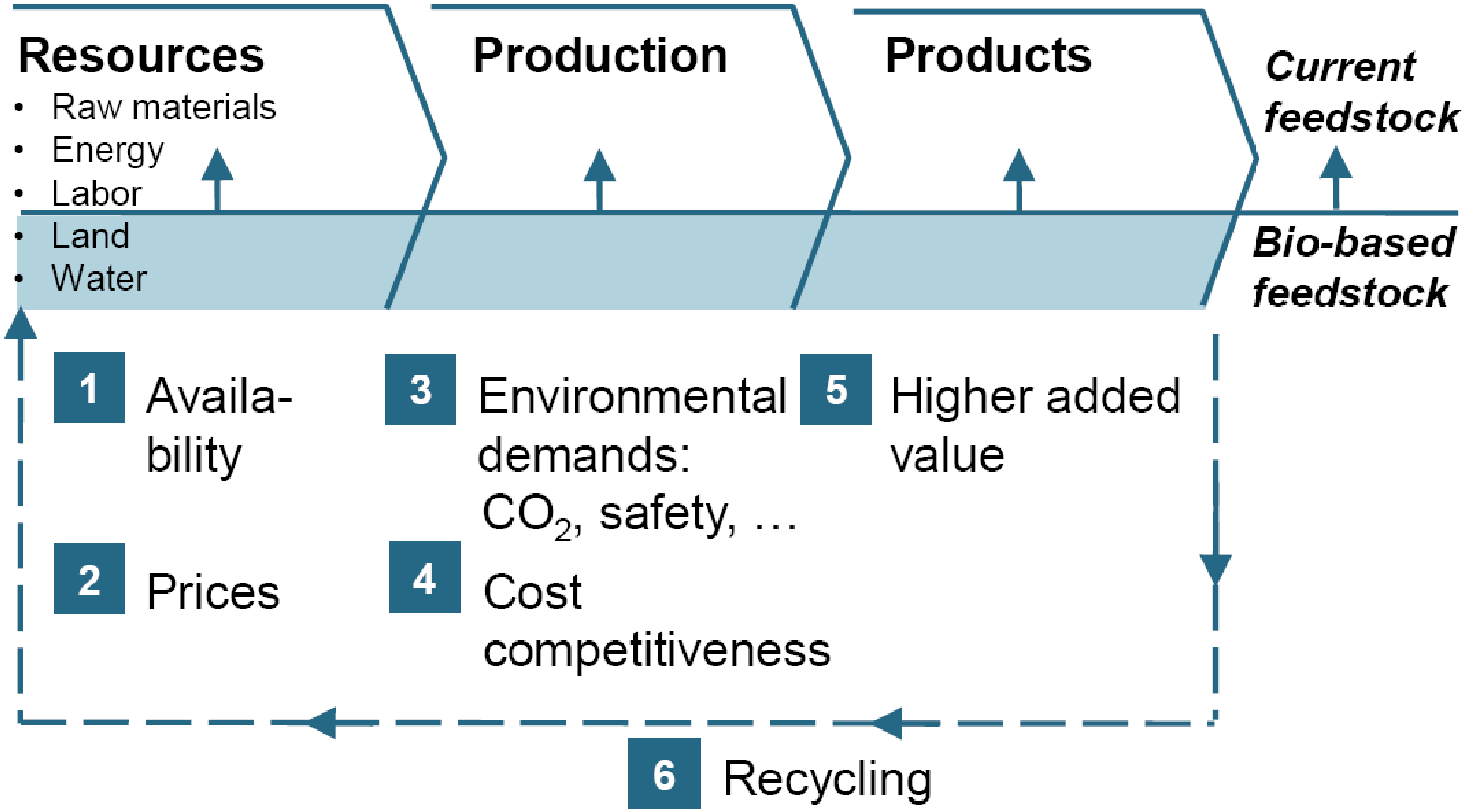
# Innovation = Unproven Solutions

## *("Plant manager never wants to be the first")*



*"Don't bother me with new ideas, i've got a battle to fight!"*

# Process industry is facing numerous challenges

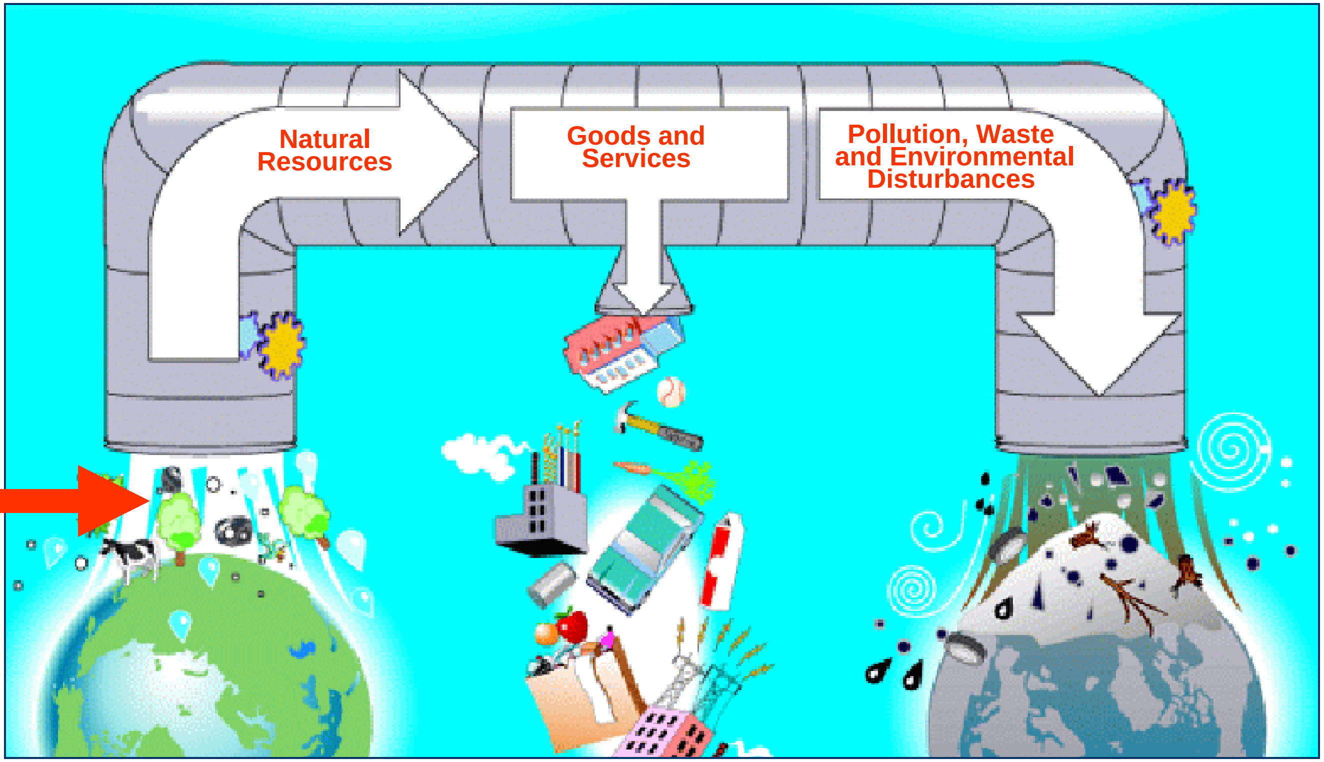



Source: Roland Berger

# MATERIAL EFFICIENCY OF MANUFACTURING

**Only 25 wt% of what goes into the pipe comes out as goods and services**

(Source: World Resource Institute)



# ISSUES OF CONCERN FOR CHEMICAL INDUSTRY: ENVIRONMENT

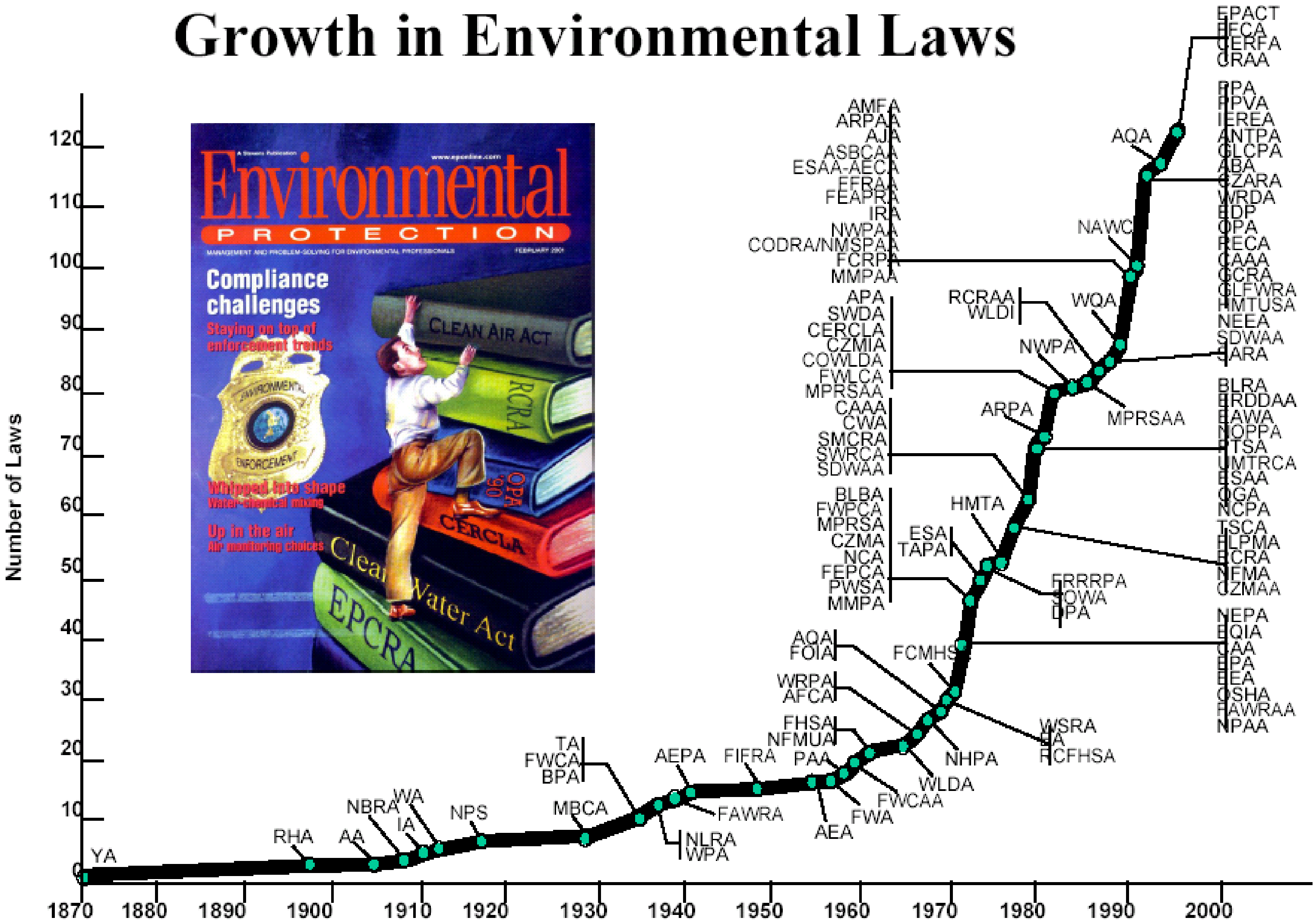
| Industry Sector | Product tonnage | Tons by-product/ton product |
|---|---|---|
| Oil refining | $10^6 – 10^8$ | < 0.1 |
| Bulk chemicals | $10^4 – 10^6$ | 1 - 5 |
| Fine chemicals | $10^2 – 10^4$ | 5 – 50+ |
| Pharmaceuticals | $10 – 10^3$ | 25 – 100+ |



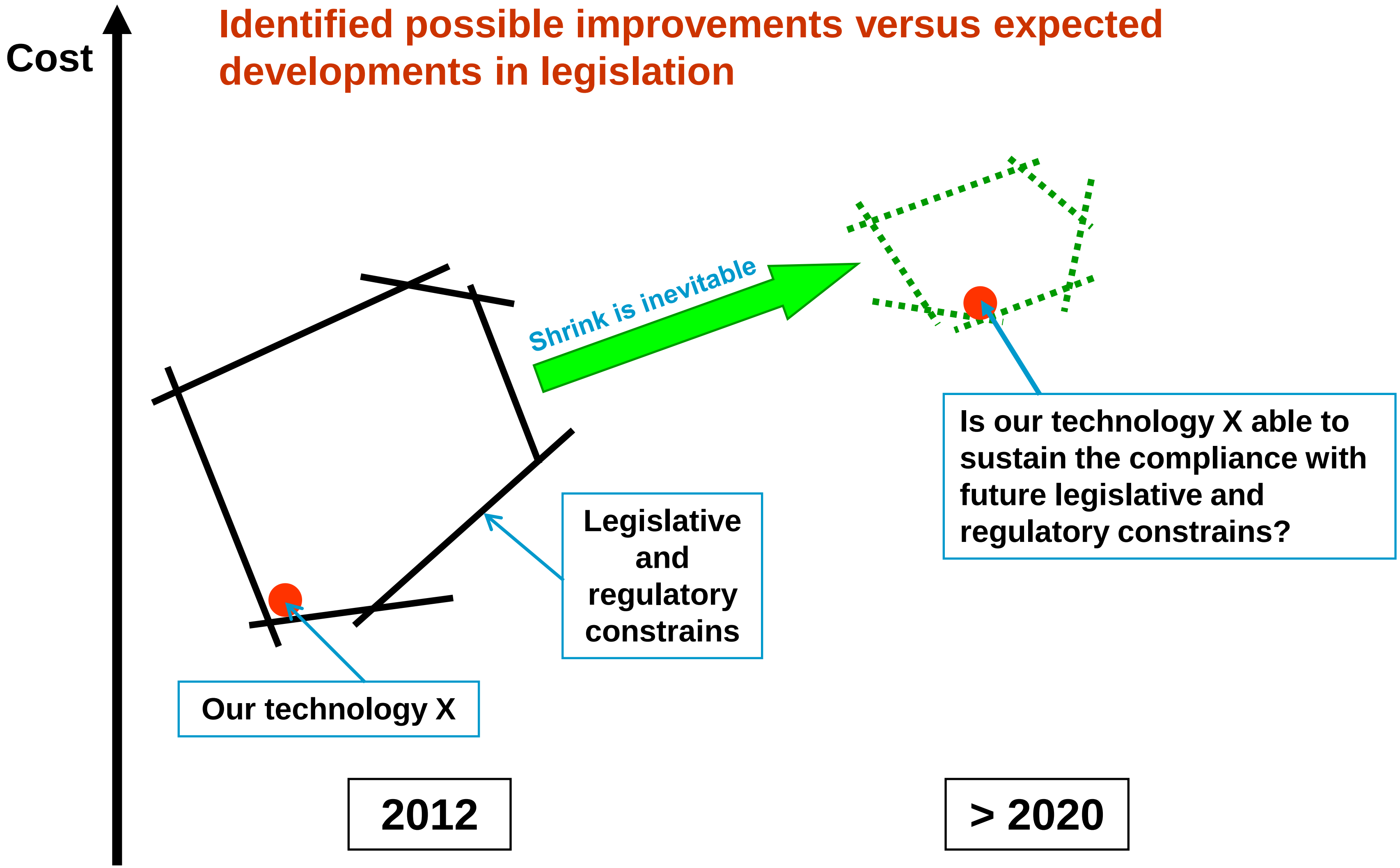




# Laws and Regulations

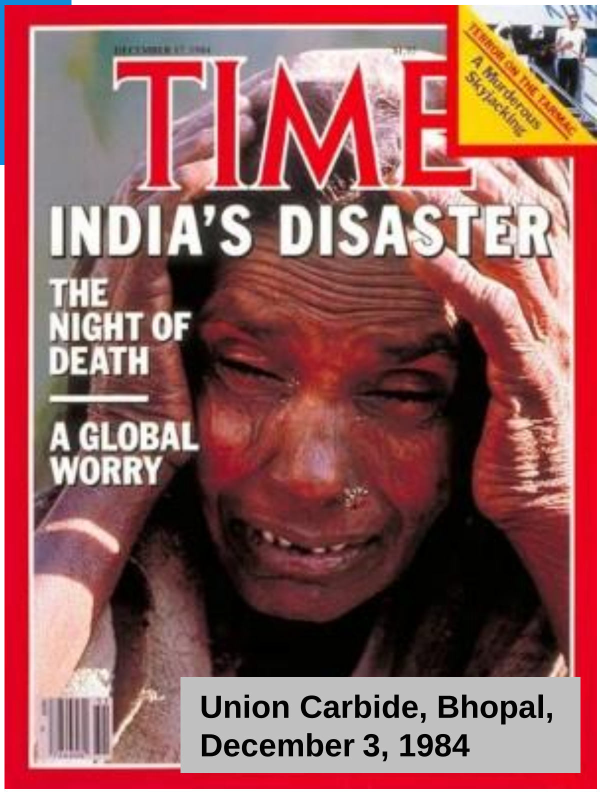


# Laws and regulations

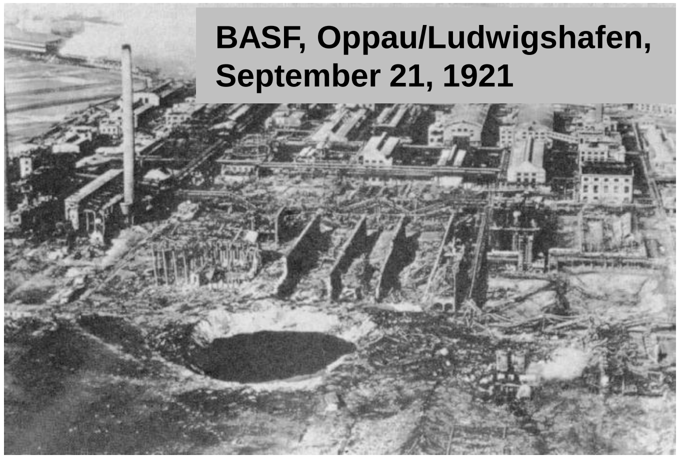


# SAFETY




Union Carbide, Bhopal, December 3, 1984



BASF, Oppau/Ludwigshafen, September 21, 1921

AZF, Toulouse, September 21, 2001

**TERRORISM – THE PLAGUE OF THE 21ST CENTURY:**

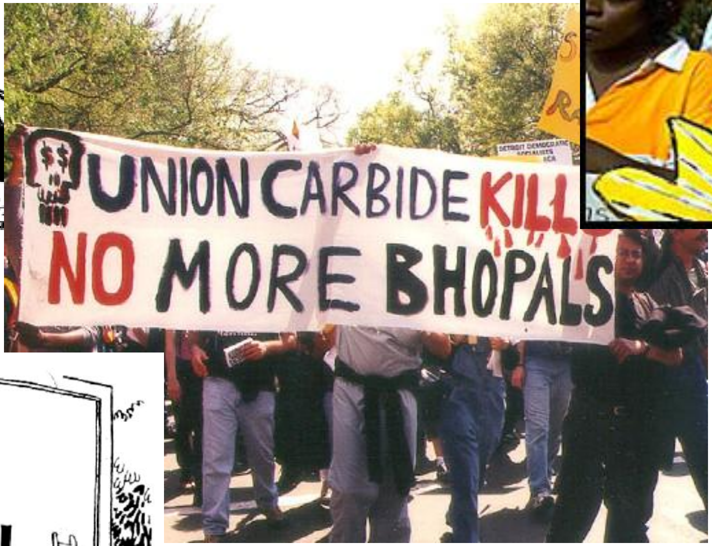
**IS CHEMICAL INDUSTRY SAFE ENOUGH?**

# License to Operate

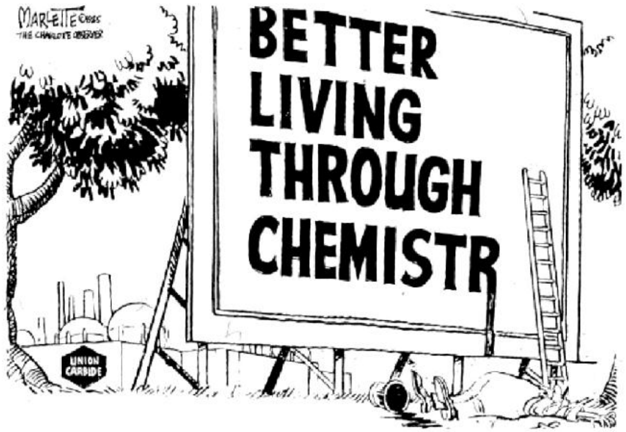
**Within 8 days from the accident ban on ALL chemical activities in the Toulouse area, Licence to Operate withdrawn permanently**

**AZF, Toulouse, September 21, 2001**

# ISSUES OF CONCERN FOR CHEMICAL INDUSTRY: PUBLIC IMAGE

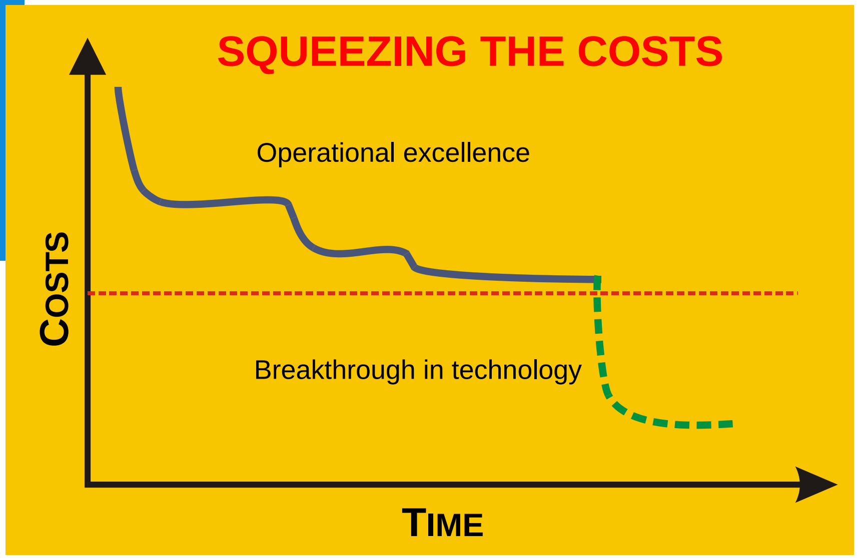







**ONLY TOBACCO AND NUCLEAR SECTORS HAVE WORSE PUBLIC IMAGE**

## ISSUES OF CONCERN FOR EUROPEAN CHEMICAL INDUSTRY: COST





- **sooner or later a critical limit will be reached**
- **competitors will follow**
- **the only way to go beyond that limit and gain significant long-term advantage over the competitors is via innovative technological development**

# Process Intensification

## One of PI definitions

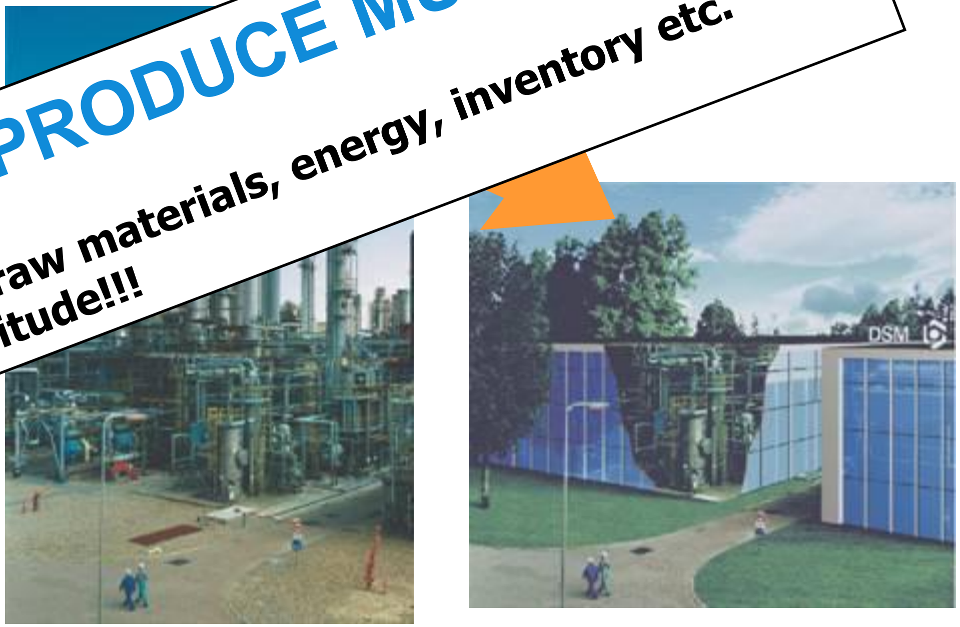
*A set of often radically **innovative** principles (“paradigm shift”) in process and equipment design, which ca*

***significant*** *(more than f*

*in terms of pro*

*capital*

*07)*

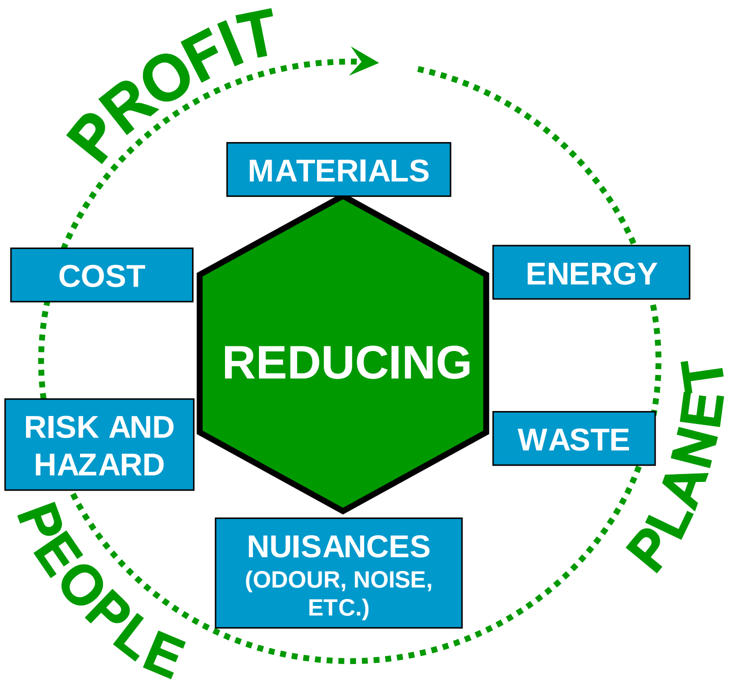



**USING MUCH LESS TO PRODUCE MUCH MORE**

**LESS = investment, space, time, raw materials, energy, inventory etc.**

**MUCH = factors, orders of magnitude!!!**

# PI - fundamental benefits



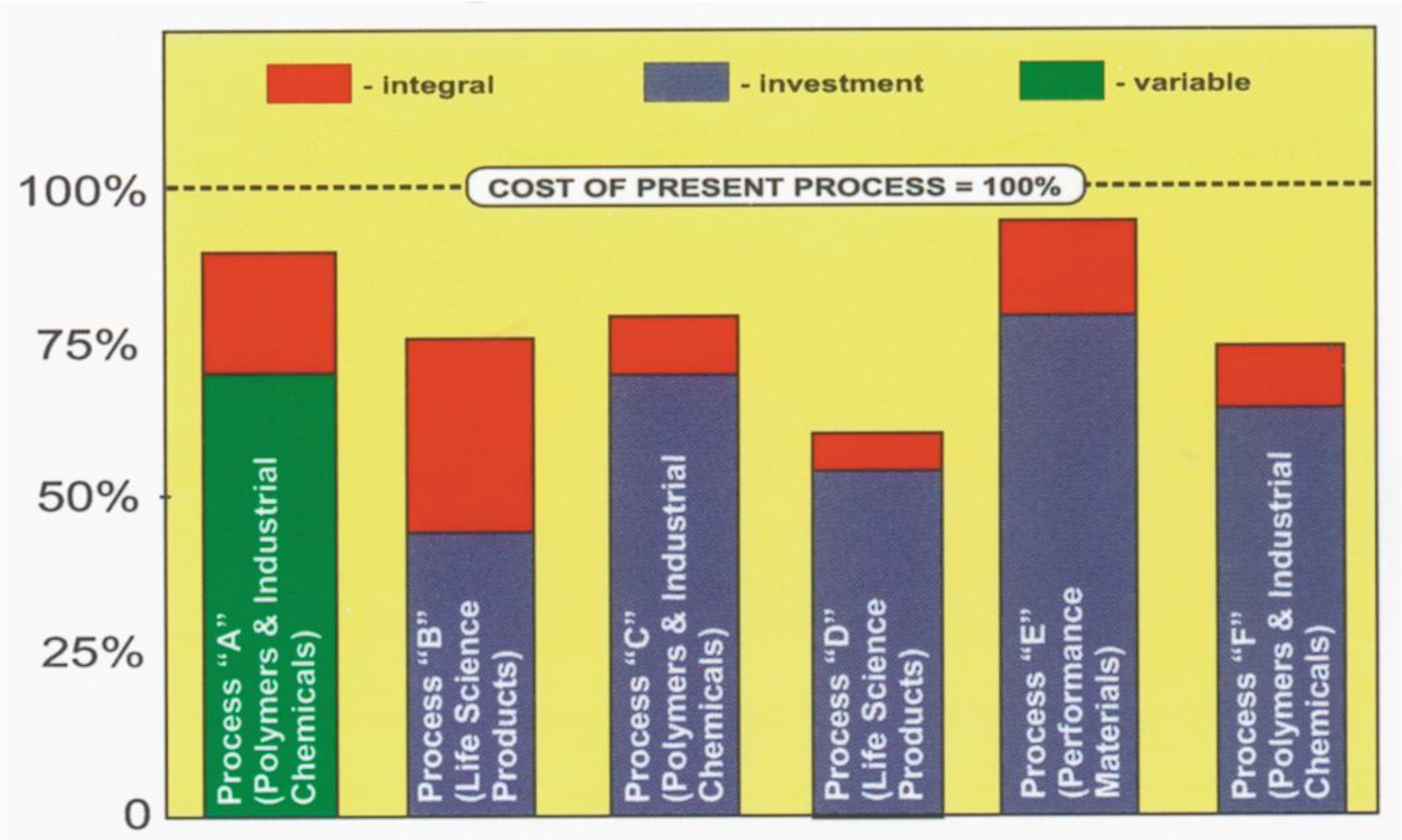

- **Energy savings (20 – 80%)**
- **CapEx and OpEx savings (20 – 80%)**
- **Selectivity and yield increase (up to >10 times)**
- **Significant process safety increase (reactor volume & inventory of chemicals decreased 10-1000 times + better reaction control)**

(2006 study by SenterNovem, Dutch Energy and Environmental Agency)

# Lower costs due to PI

- **land costs** (much higher production capacity and/or number of products (plants) per unit of manufacturing area);
- **other investment costs** (cheaper, compact equipment, reduced piping etc.);
- **costs of raw materials** (higher yields/selectivities);
- **costs of utilities** (energy in particular);
- **costs of waste-stream processing** (less waste in general).

# Lower costs due to PI



# Shorter time to the market = lower cost

**Example: How to shorten time to the market in pharmaceutical technologies?**

## Possible solution: a continuous lab-scale plant as a commercial-scale production unit

**Advantages:**

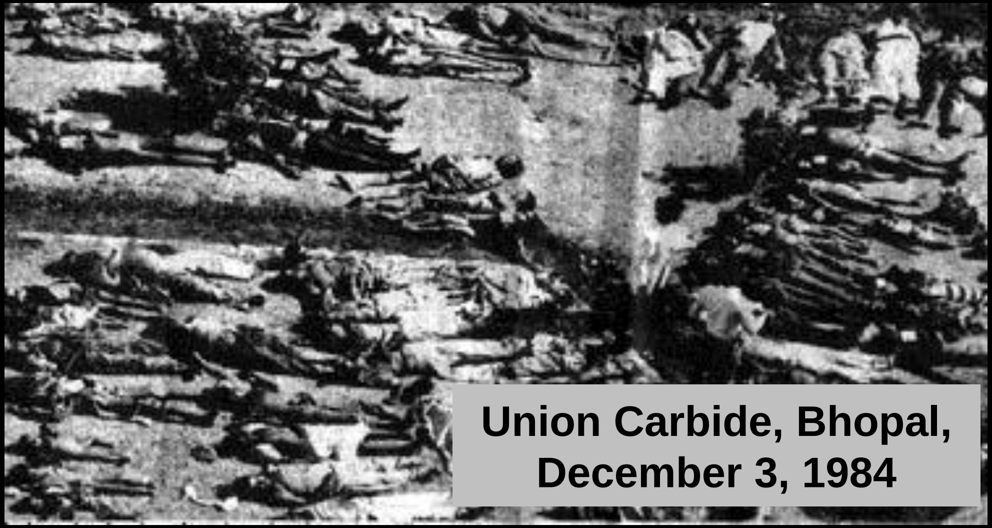
- FDA approval procedures of drug technology take place only once: the lab-scale is the commercial-scale.
- Process development takes place only once, with no scale-up via a pilot plant to the industrial scale.

**Result:**

- Start of the commercial production speeded up, in some cases even by several years.
- Time to the market shortened - patent time better utilized.

**Do not forget: in continuous operation 1 ml/s = 30 t/year!**

# PI AND SAFETY



Union Carbide, Bhopal, December 3, 1984

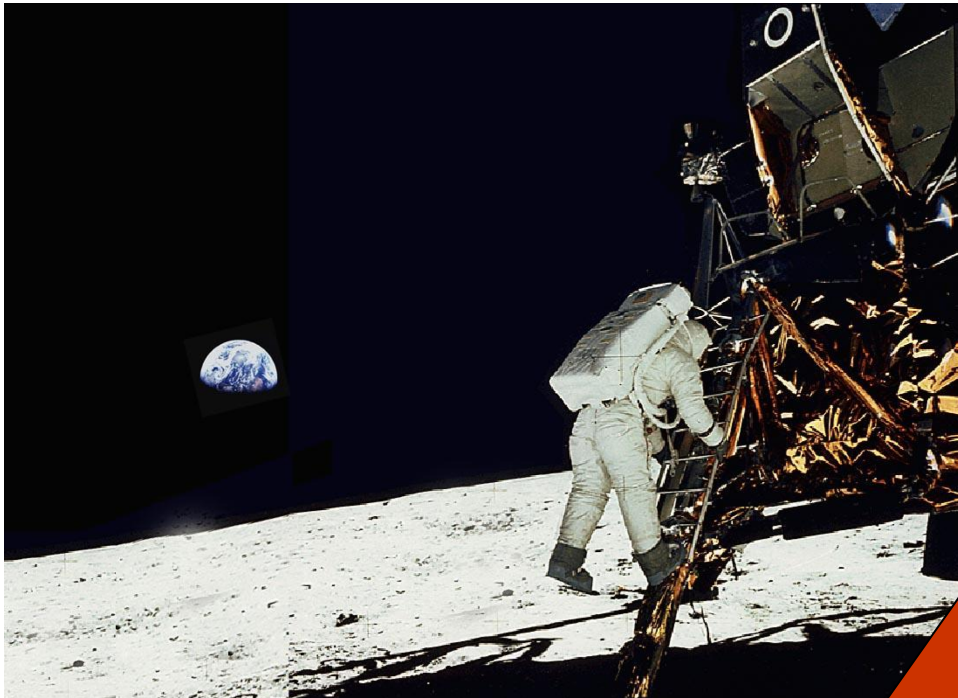
**LESSON LEARNED:**

**Process could have been intensified to contain a total inventory of less than 10 kg of MIC, instead of 41 tons!**

**Intensified *means:* SAFER!**

# SHORT HISTORY OF PI

# Origins of Process Intensification



**FROM NASA's SPACE PROGRAM TO INNOVATIVE CHEMICAL PLANTS**

# History of process intensification

- **Term “Process Intensification” appeared in early 1960’s**
  - Mostly East-European publications on METALLURGY
  - “Process Intensification” = “Process Improvement”

- **Comes to chemical engineering literature in 1970’s**
  (Leszczynski, 1973, Romankov, 1977, Kleemann and Hartmann, 1978)
  - still East-European domain
  - still “Process Intensification” = “Process Improvement”

# History of process intensification

- **1983 - Colin Ramshaw from ICI New Science Group describes studies on application of centrifugal fields (so-called "HiGee") in distillation processes**
  - PI = "devising exceedingly compact plant which reduces both the "main plant item" and the installations costs"

- **1983 - Annual Research Meeting of IChemE entitled Process Intensification held at UMIST, Manchester**
  - first paper presented at that meeting concerned PROCESSING OF GOLD ORE using intensive methods
  - PI = "order-of-magnitude reductions in process plant and equipment" (Heggs)

# History of process intensification

- **1980's and early 1990's – mainly British discipline**
  - primarily focused on four areas: the use of centrifugal forces, compact heat transfer, intensive mixing and combined technologies
  - 1995 - 1st Conference on Process Intensification
  - Process Intensification Network – PIN-UK

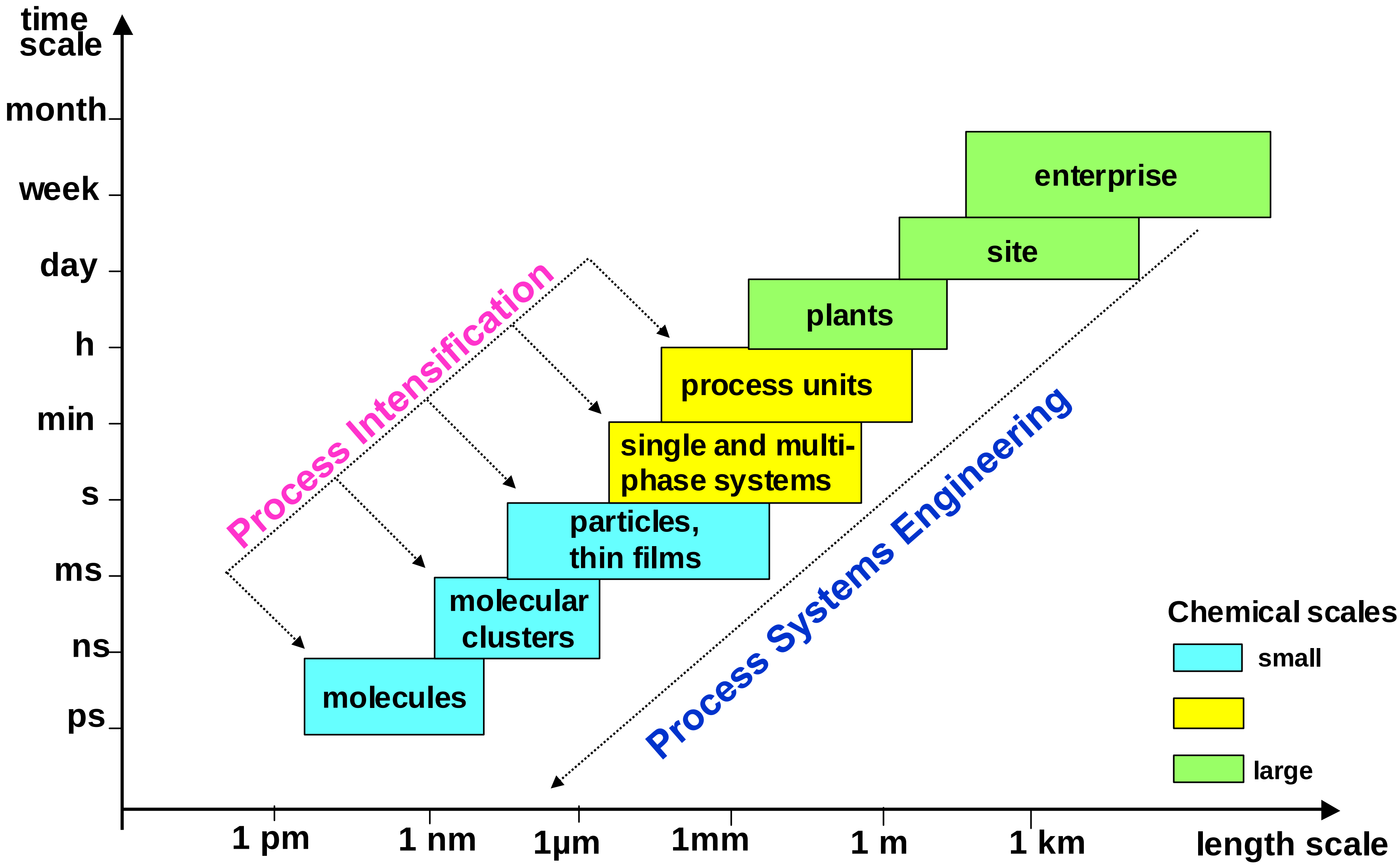
- **late 1990's – growing interest and activities in different parts of the world**
  - research centers in US (PNNL, MIT), France (Greth CEN), Germany (IMM), UK (BHR), China (HighGravitec) and many more…
  - industry enters the scene – first applications at Eastman, Dow, DSM, Sulzer and many more…

# Awareness of the importance of PI has grown strongly in last 10 years

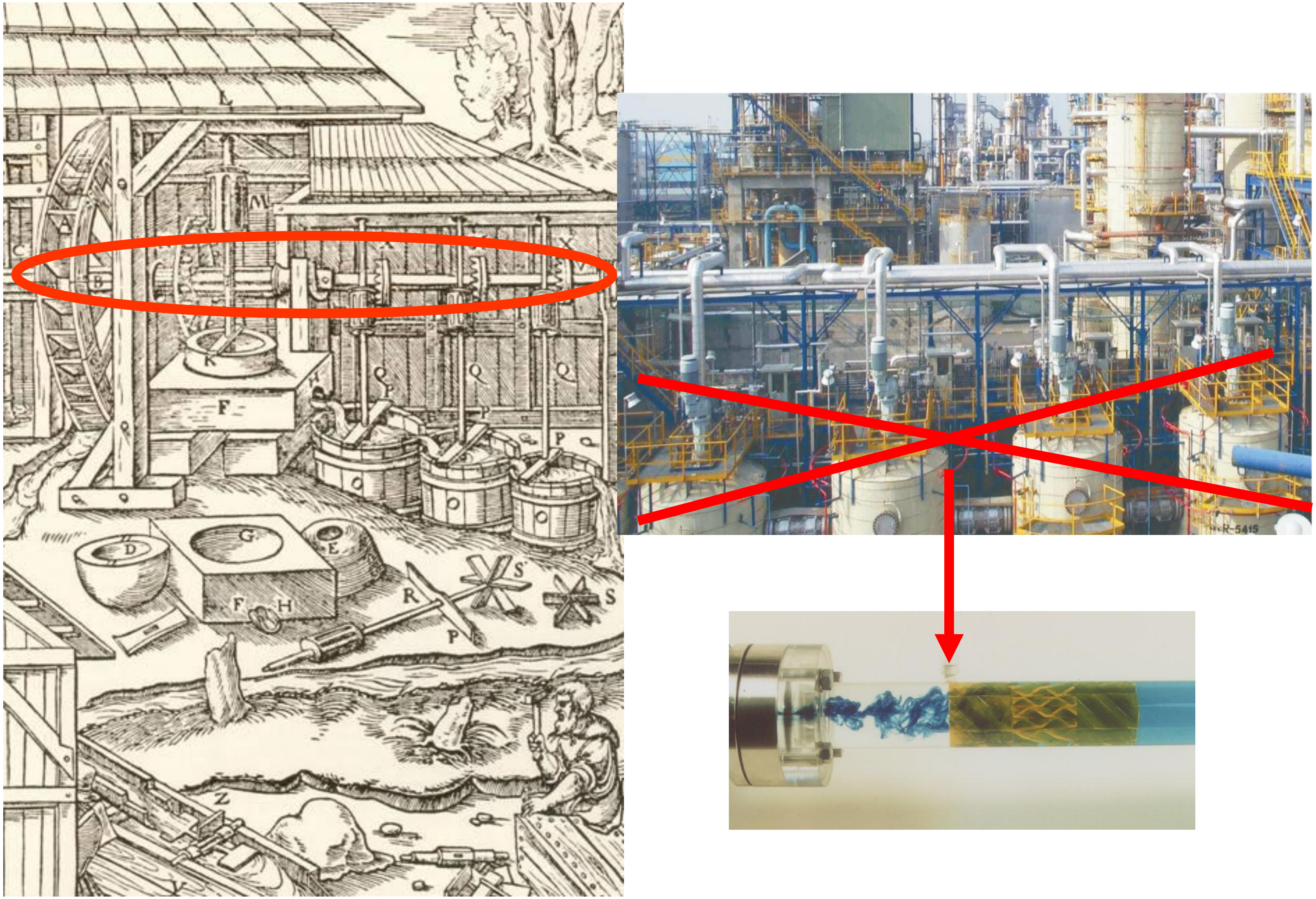
- PI placed clearly in sustainability context
- First university courses, books, international conferences, journal
- National networks in UK, NL and DE
- Numerous industrial initiatives
- EFCE establishes of the Working Party on Process Intensification
- PI in FP7
- European Roadmap for PI

# POSITION OF PI

# PI versus Process Systems Engineering



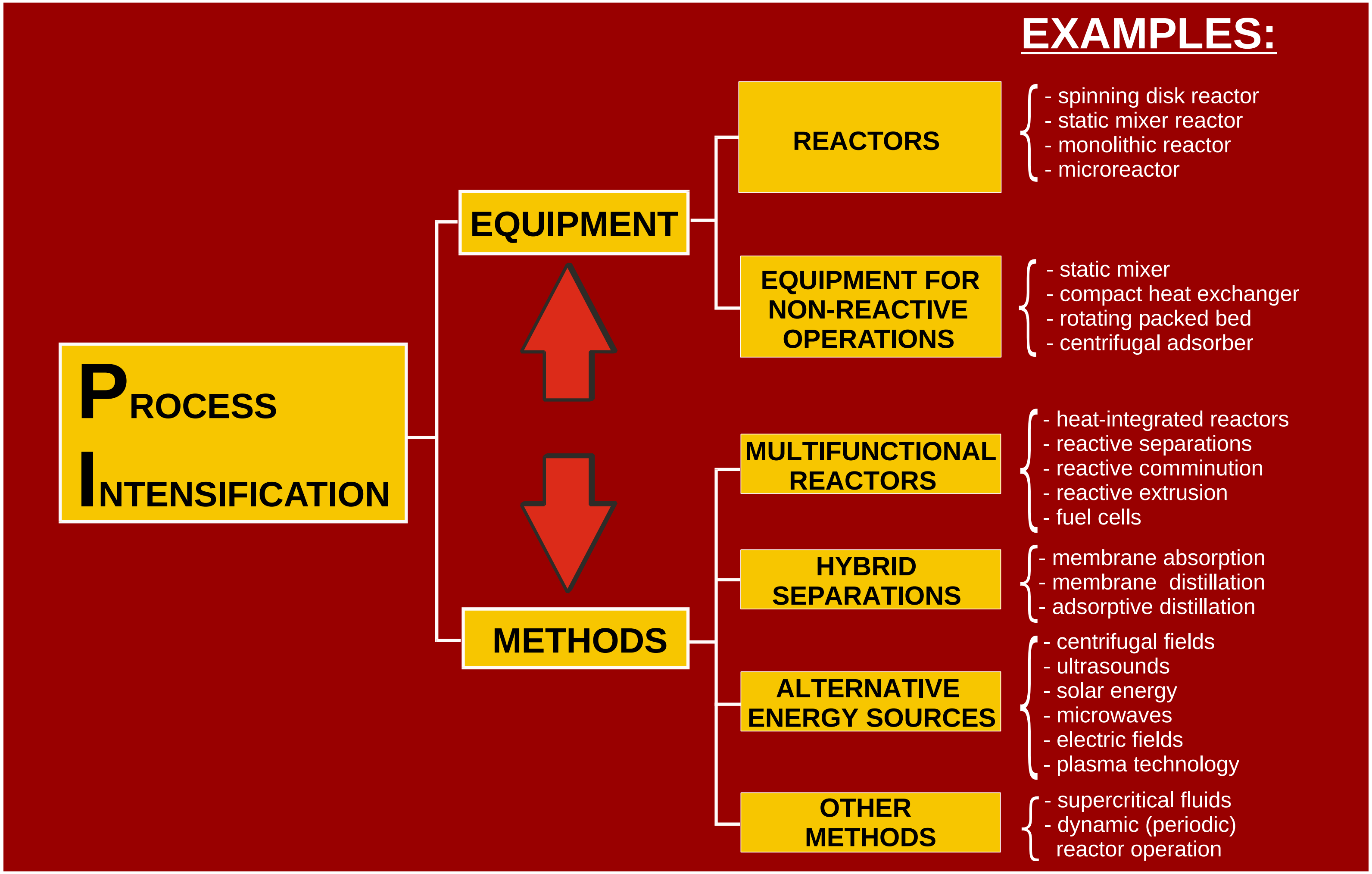

After W. Marquardt (2000)



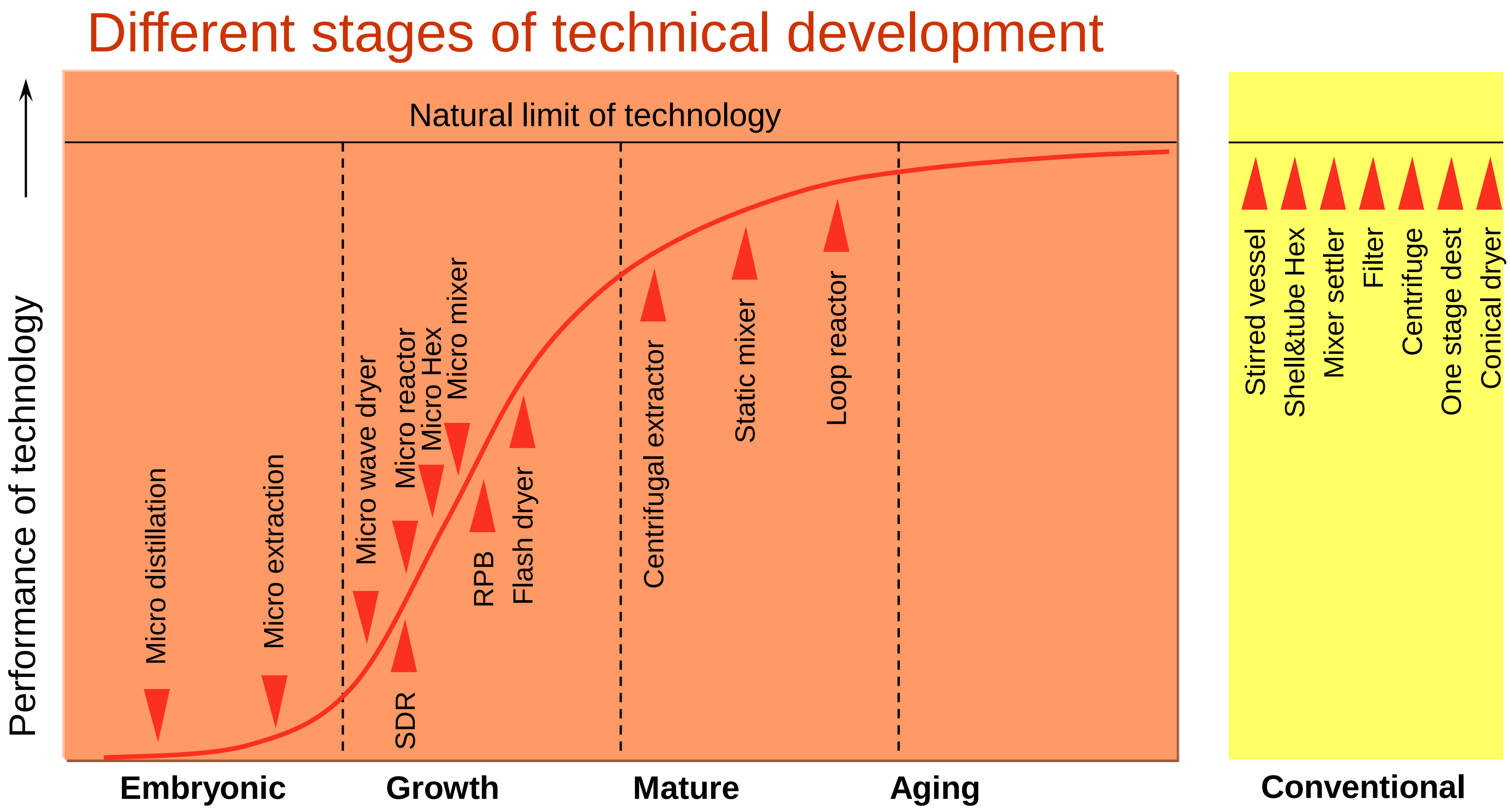
# Process Intensification versus Process Systems Engineering and Process Optimization

| | Process Optimization | Process Systems Engineering | Process Intensification |
|---|---|---|---|
| **Aim** | Performance improvement of existing concepts | Multi-scale integration of existing and new concepts | Development of new concepts of process steps and equipment |
| **Focus** | Model, numerical method | Model, software | Experiment, phenomenon, interphase |
| **Interdisciplinarity** | Weak (interface with applied mathematics) | Modest (mostly applied mathematics and informatics, chemistry) | Strong (chemistry & catalysis, applied physics, mechanical engineering, materials science, electronics, etc.) |

# PI as a technology toolbox



# PI technologies on maturity S-curve




(R. Reintjens)

# FUNDAMENTALS OF PROCESS INTENSIFICATION

*Ind. Eng. Chem. Res.* **2009**, *48*, 2465–2474 **2465**

100TH ANNIVERSARY
REVIEW

**Structure, Energy, Synergy, Time—The Fundamentals of Process Intensification**

**Tom Van Gerven[†] and Andrzej Stankiewicz***

*Process & Energy Department, Delft University of Technology, Leeghwaterstraat 44, 2628 CA Delft, The Netherlands*

# Fundamentals of Process Intensification

PRINCIPLES (GOALS)

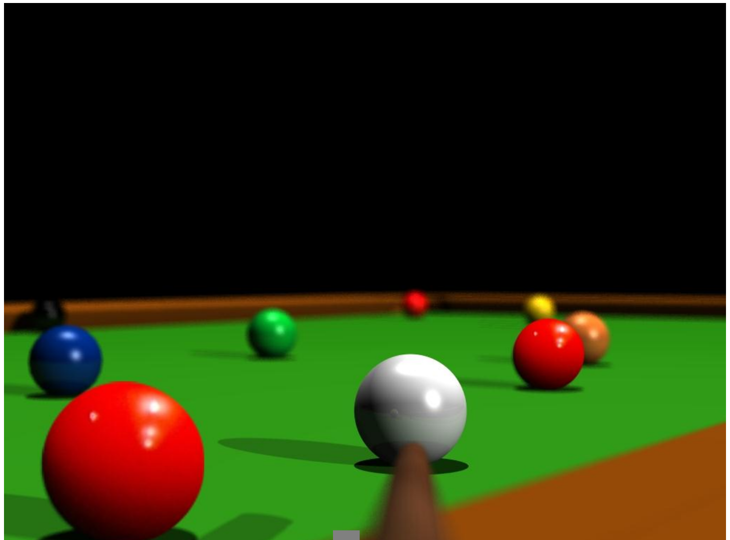
**maximizing the effectiveness of intra- and intermolecular events**

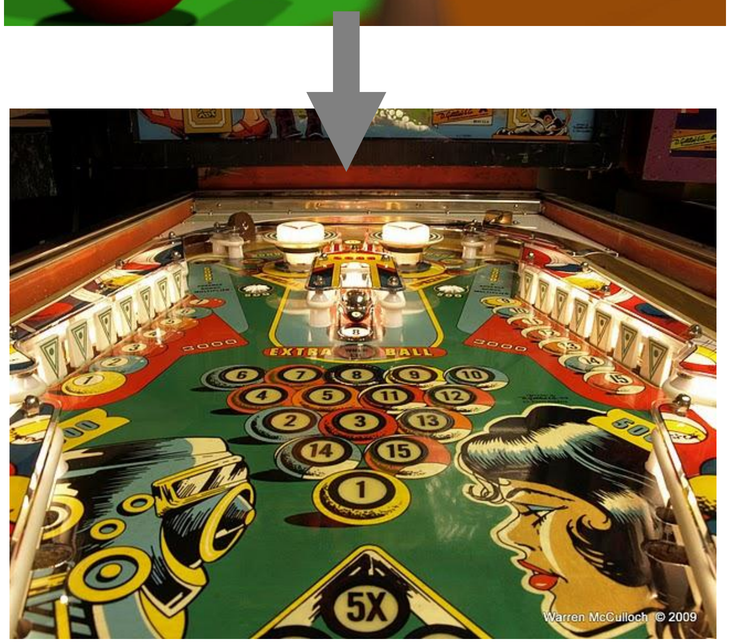
**ch molecule processing erience**

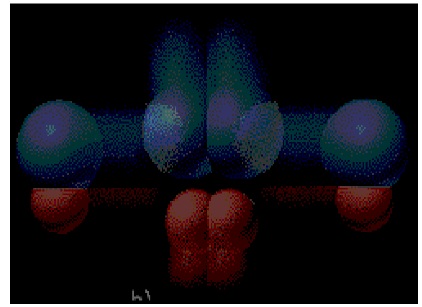
**optimizing the driving forces and maximizing the specific surface areas to which these forces apply**

**maximizing synergistic effects from partial processes**

# What’s wrong with current reactors?
## - Limited control upon molecules



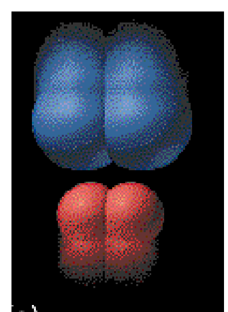


**effective collision**

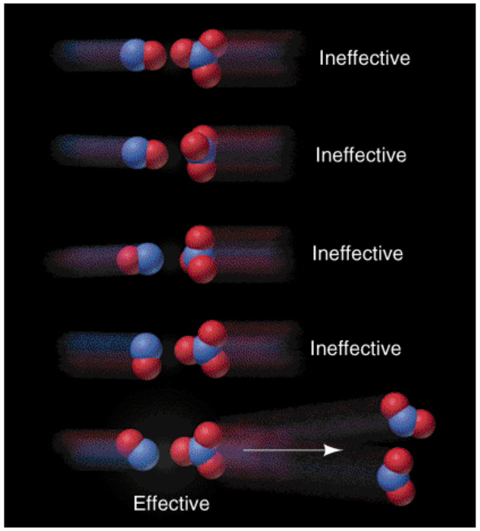
### Energizing molecules via conductive heating, or turning snooker into pinball

- non-selective
- amplifies random motions and collisions
- produces temperature gradients

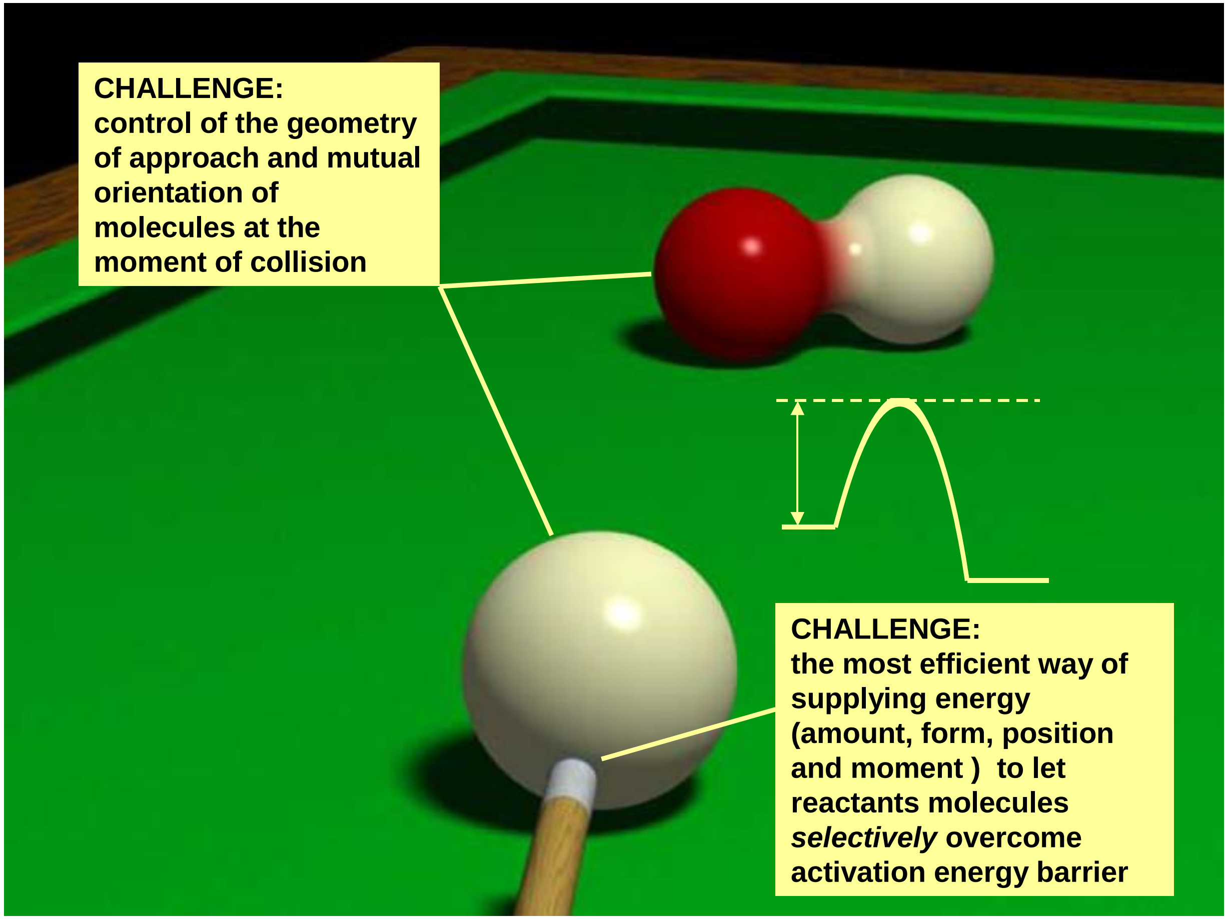


**ineffective collision**

# A snooker game with molecules: how to hit the right one, with right energy, at right orientation?




(www.drmackay.org)



# Where are the limits of reaction rate?

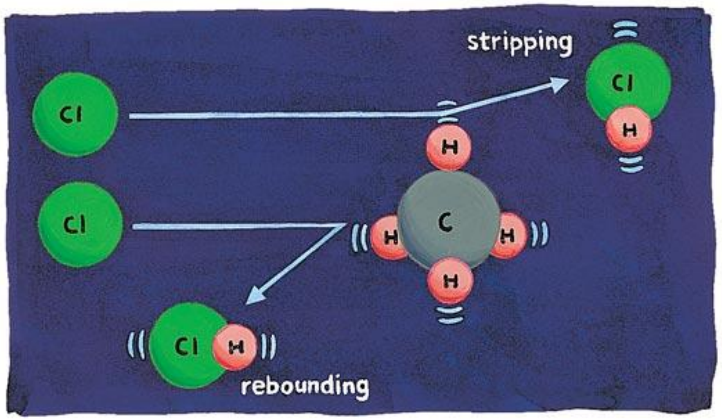
**…or is our thinking about reactions and reactors not limited by the traditional, macroscopic temperature-based approach to reaction kinetics?**

$$k = k_0 e^{-\frac{E_a}{R \cdot T}}$$

CATALYST

HEATING

?




Laser-induced vibration: C-H bond stretching, making the target molecule “bigger” for collisions + introducing stripping collisions: **reaction rate increase >100x**

(Simpson et al. 1996; Kandel & Zare, 1998; Hoffman, 2000)

# Control of spatial orientation of molecules and geometry of collisions

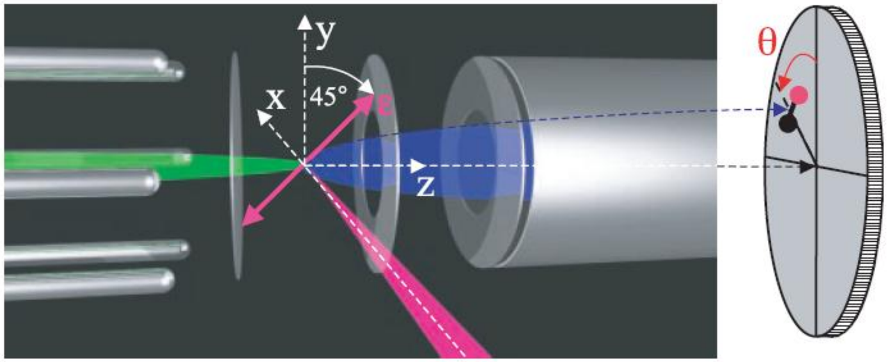
**Methods for controlling molecular alignment and orientation**

- **Orientation control via nano-structural confinement**
  - Shape-selective catalysts
  - Imprinted catalysts
  - Molecular reactors (cyclodextrins)
  - Liquid crystals
- **Alignment and orientation control via external fields**
  - Molecular beam
  - Stark's effect methods (electric field)
  - *Brute force* methods
    - Magnetic
    - Electric
  - Non-resonant laser
    - Adiabatic
    - Femtosecond

- Molecules get immobilized
- Structures confining the access
- "Take it or leave it"

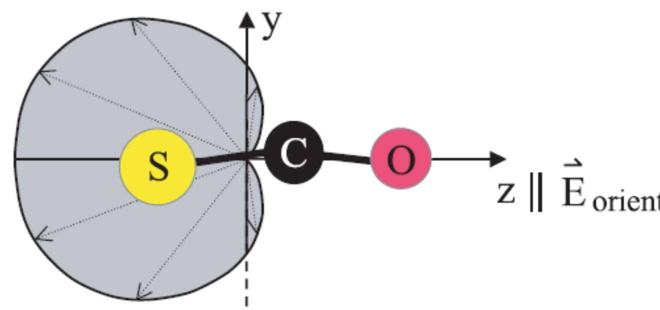
- Molecules move

# Control of spatial orientation of molecules and geometry of collisions



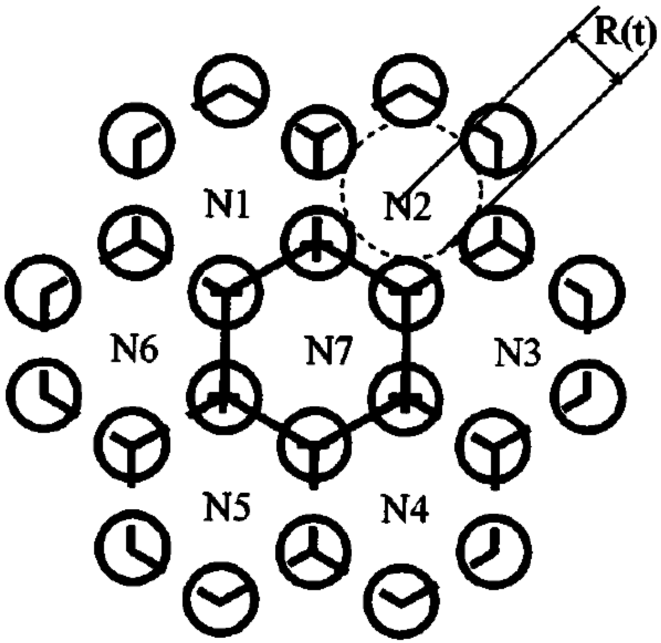

(A)

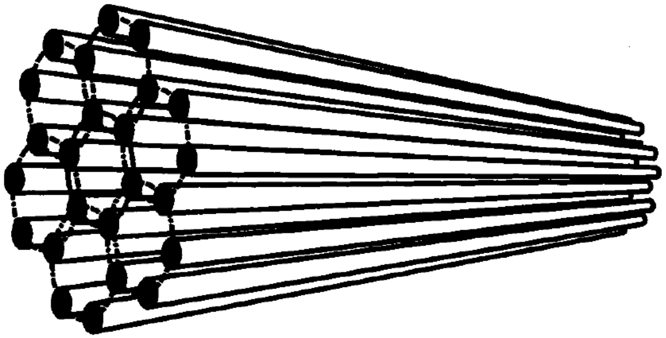
(B)




*(A)- Orientation of a molecular beam of carbonyl sulphide molecules moving along the z-axis by a hexapole electric field (left) followed by their dissociation by a laser beam acting along the x-axis (from Rakitzis, et al, 2004); (B) - Probability plot of the molecular orientation of the OCS molecule; dotted arrows are proportional to the orientation probability of the OCS dipole moment along each direction*.

## A “multitubular reactor” of the future?



Multi-beam hexapole honeycomb device for orienting molecules in static electric field

(Shimizu, 2003)

# Fundamentals of Process Intensification

PRINCIPLES (GOALS)

maximizing the effectiveness o[f] intra- and intermolecular events

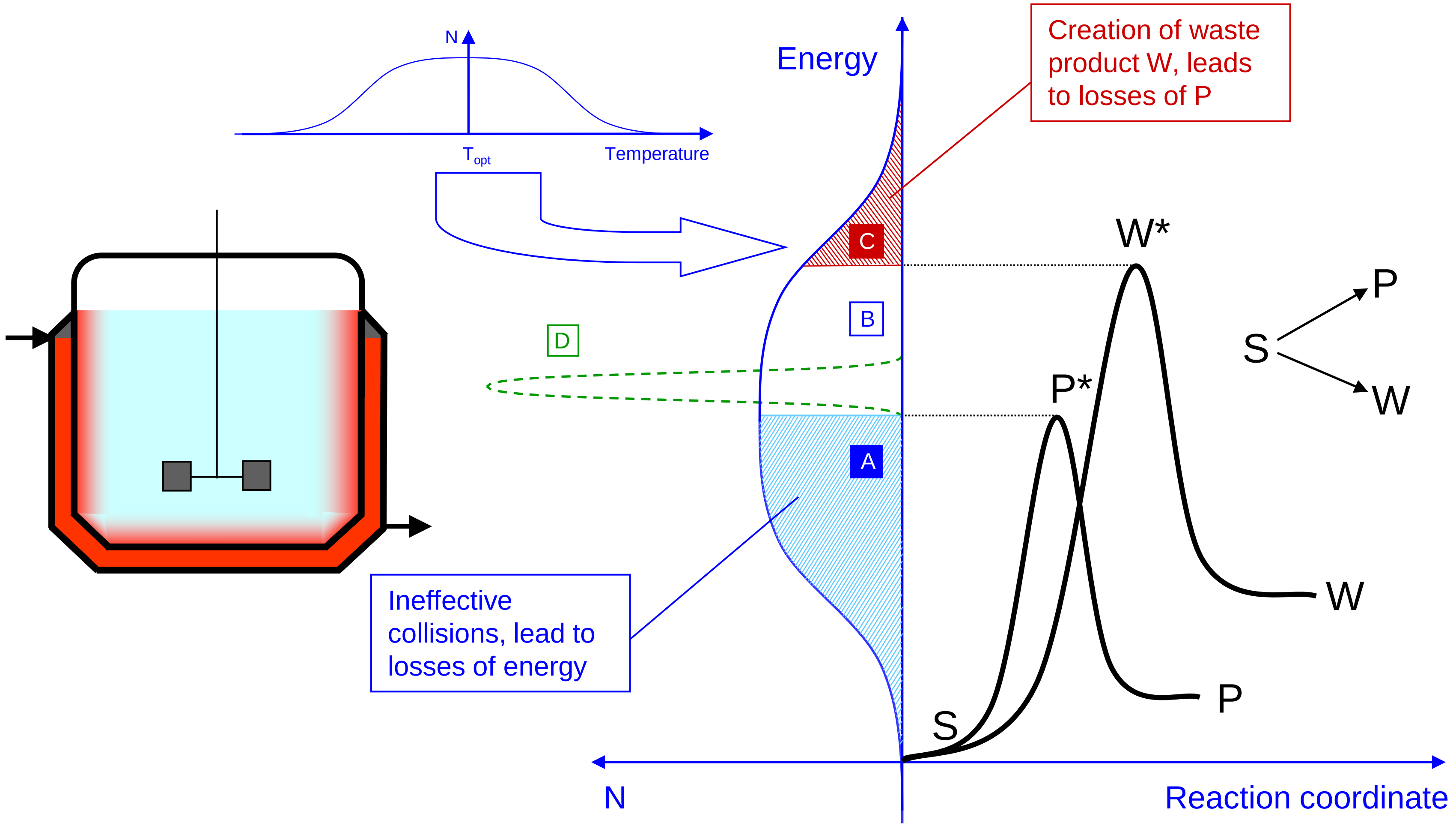
**giving each molecule the same processing experience**

[...]izing the driving [...] and maximizing [...]specific surface [...] to which these [...]orces apply

maximizing synergistic effects from partial processes

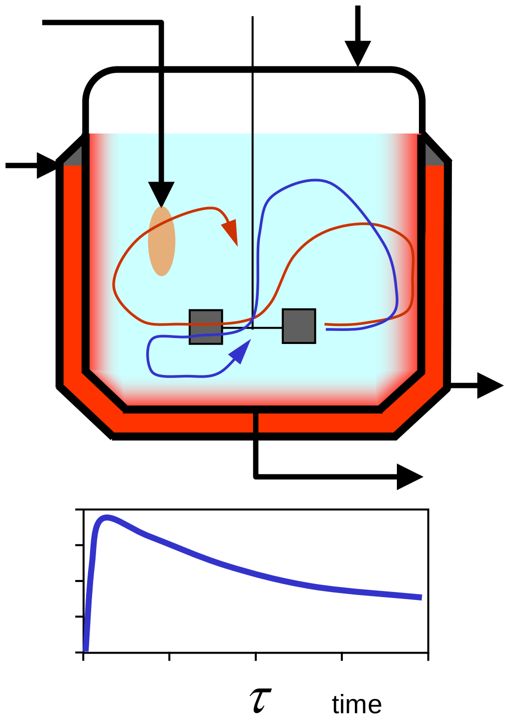
# What's wrong with current reactors?

# - Limited control upon molecules

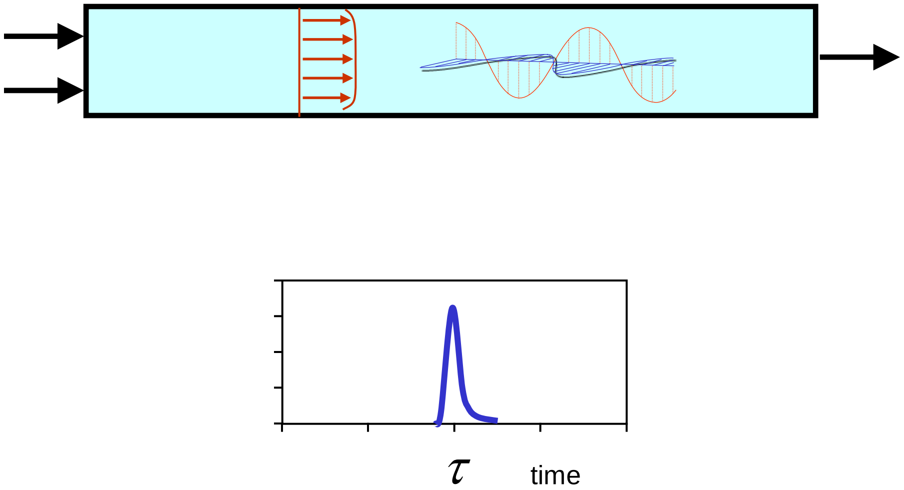



*. Illustration of the energy distribution problem in molecules, in relation to the yield of simple parallel reactions. A stirred-tank reactor with conductive heating generates energy distribution due to temperature gradients, which translate to both material and energy losses.*

# Giving each molecule the same processing history




(a)




(b)

Stirred-tank reactor with a heating jacket (a) contradicts the 2$^{nd}$ principle of Process Intensification. The residence time of molecules is widely distributed and both concentration and temperature non-uniformities are present. On the other hand, a plug-flow reactor with a gradientless, volumetric (e.g. microwave) heating (b) enables a close realization of that principle.

# Fundamentals of Process Intensification

PRINCIPLES (GOALS)

maximizing the effectiveness of intra- and intermolecular events

giving each mole
the same proces
experience

**optimizing the driving forces and maximizing the specific surface areas to which these forces apply**

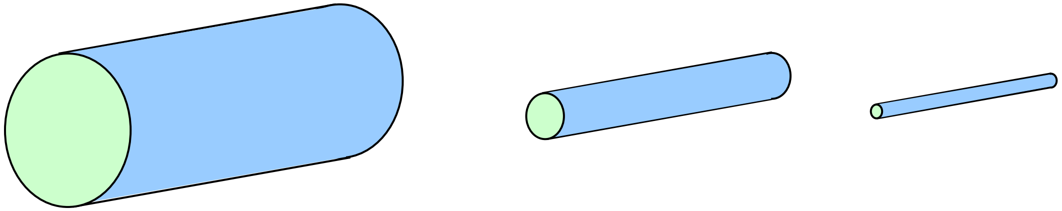
maximizing
nergistic effects
from partial
processes

# Optimizing the driving forces and maximizing the specific surface areas to which those force apply

**Surface to volume ratio depends on diameter**

$$\frac{A}{V} = \frac{\pi \cdot D \cdot L}{\left(\frac{\pi \cdot D^2 \cdot L}{4}\right)} = \frac{4}{D}$$

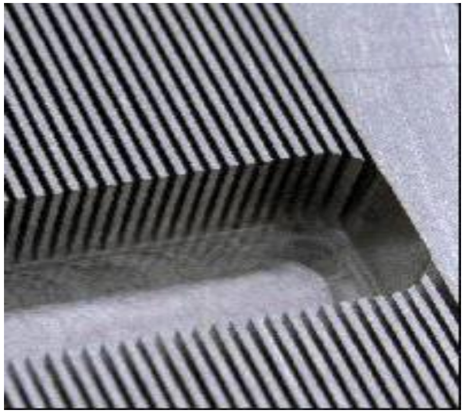
**Enhance mass and heat transfer by increasing the transfer area**



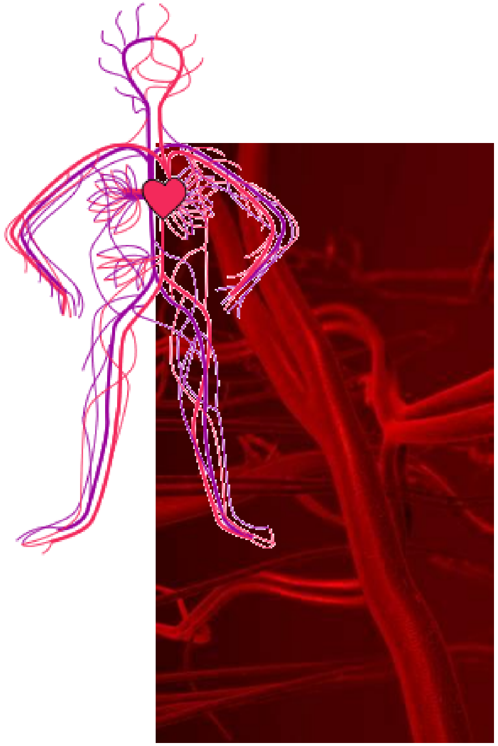
| | | | |
|---|---|---|---|
| D (m) | 1 | 0,1 | 0,001 |
| A / V ($m^2/m^3$) | 4 | 40 | 4000 |

# Optimizing the driving forces and maximizing the specific surface areas to which those force apply

**How to catch up with the Nature and generate ultra-high-interface systems?**



| | |
|---|---|
| D (m) | 0,0001 |
| A / V ($m^2/m^3$) | 40000 |



***Capillary blood vessels***

| | |
|---|---|
| D (m) | 0.00001 |
| A/V ($m^2/m^3$) | 400,000 |

# Fundamentals of Process Intensification

**PRINCIPLES (GOALS)**

- maximizing the effectiveness of intra- and intermolecular events
- giving each molecule the same processing experience
- optimizing t
  forces and m
  the specific
  areas to wh
  forces a
- **maximizing synergistic effects from partial processes**

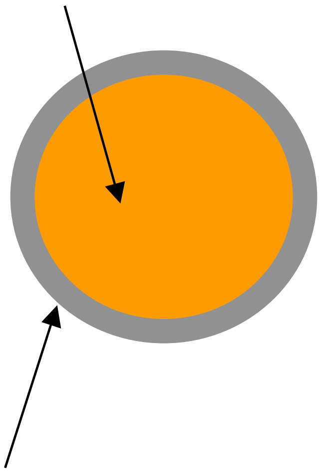
# Maximizing synergistic effects from partial processes

## Example: catalytic function + separation function

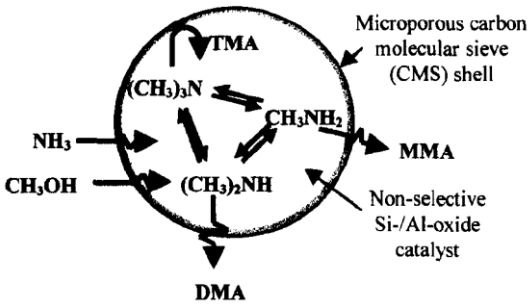
**methanol + ammonia → monomethylamine + dimethylamine + trimethylamine**

**(MMA) (DMA) (TMA)**

ordinary Si-Al catalyst



Carbon molecular sieve layer (~ 0.5 nm pores)



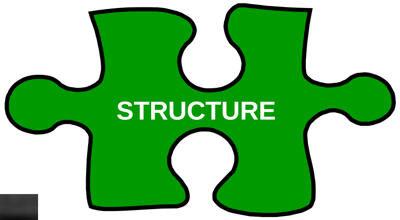

| | Selectivity (MMA+DMA)/TMA |
|---|---|
| catalyst | 2 |
| catalyst + membrane | 5 |

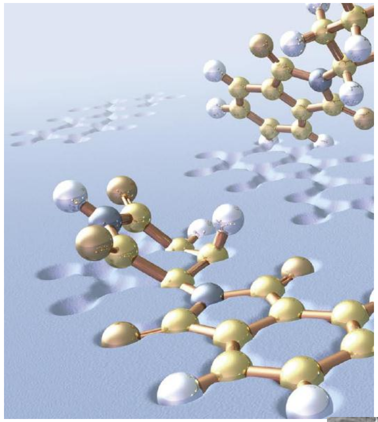
Agar, 1999

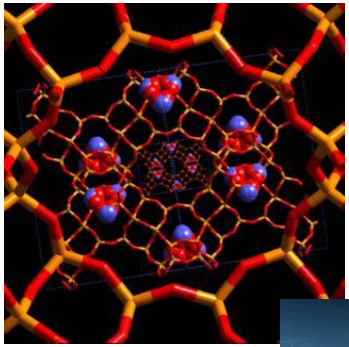
# Fundamentals of Process Intensification

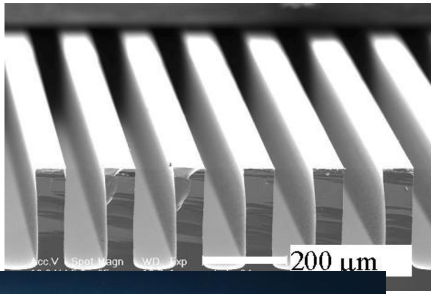
| | | | | |
|---|---|---|---|---|
| **PRINCIPLES (GOALS)** | **maximizing the effectiveness of intra- and intermolecular events** | **giving each molecule the same processing experience** | **optimizing the driving forces and maximizing the specific surface areas to which these forces apply** | **maximizing synergistic effects from partial processes** |
| **APPROACHES** | STRUCTURE (spatial domain) | ENERGY (thermodynamic domain) | SYNERGY (functional domain) | TIME (temporal domain) |

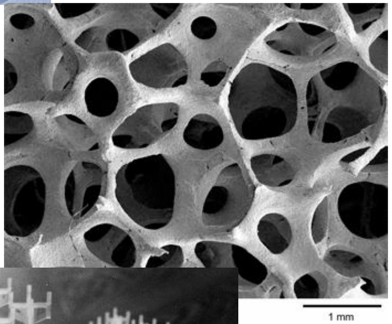
# STRUCTURE: examples

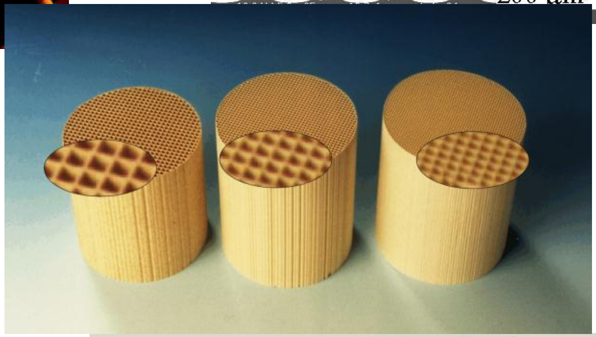


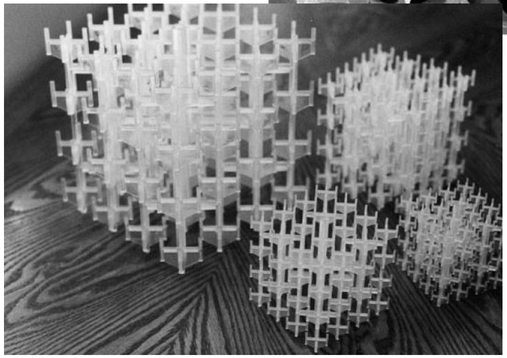



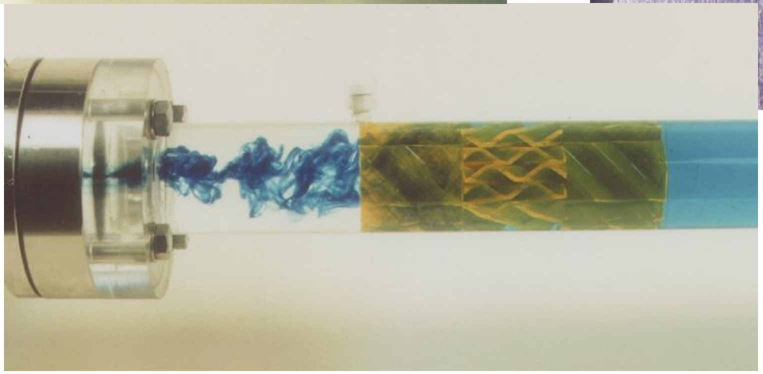








# Example: Microreactor for manufacturing of a specialty product (DSM)

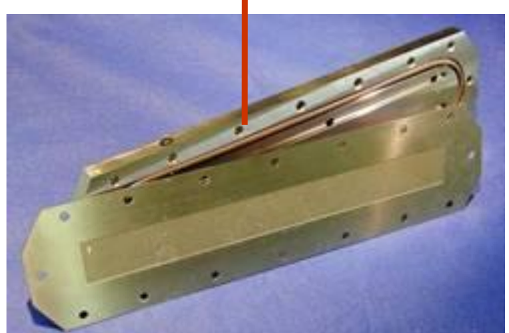
STRUCTURE

**Traditional technology**

**Stirred Tank Reactor:** the reactants are mixed in a large vessel, and the heat is removed through the jacket or a heat transfer coil.


**PI technology**

**Microreactor:** the reactants are mixed, and the heat is removed through thousands of micro channels, fabricated by micromachining or lithography



**Benefits**

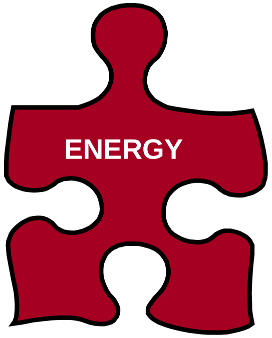
- Equipment content 3 litres vs 10 $m^3$
- 20% higher selectivity → 20% higher material yield
- Process more reliable because continuous instead of batch
- Same capacity (1700 kg/h)

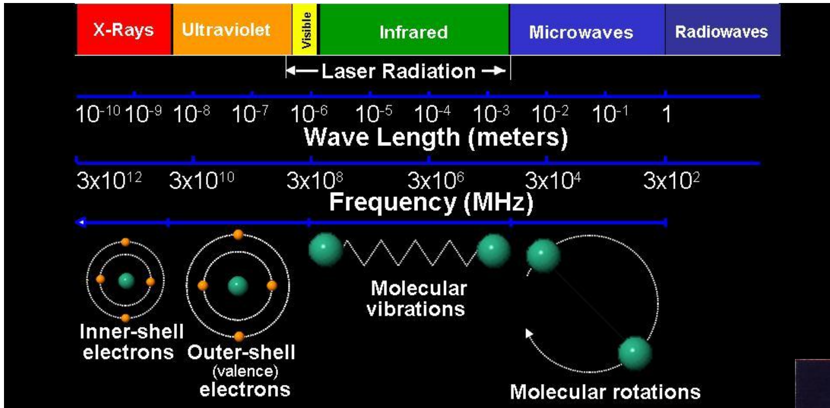
Photos courtesy of DSM and Forschungszentrum Karlsruhe

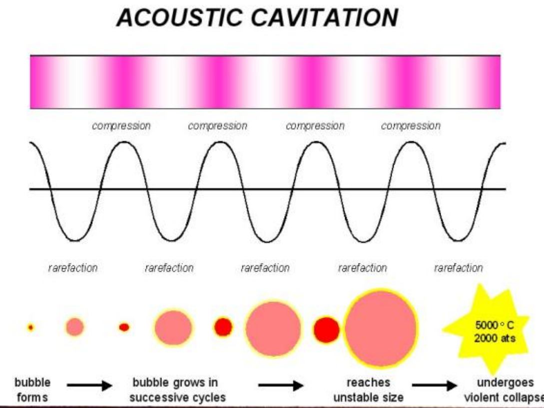
# Fundamentals of Process Intensification

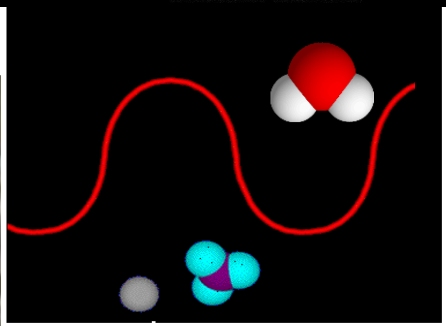
| | | | | |
|---|---|---|---|---|
| **PRINCIPLES (GOALS)** | **maximizing the effectiveness of intra- and intermolecular events** | **giving each molecule the same processing experience** | **optimizing the driving forces and maximizing the specific surface areas to which these forces apply** | **maximizing synergistic effects from partial processes** |
| **APPROACHES** | STRUCTURE (spatial domain) | ENERGY (thermodynamic domain) | SYNERGY (functional domain) | TIME (temporal domain) |

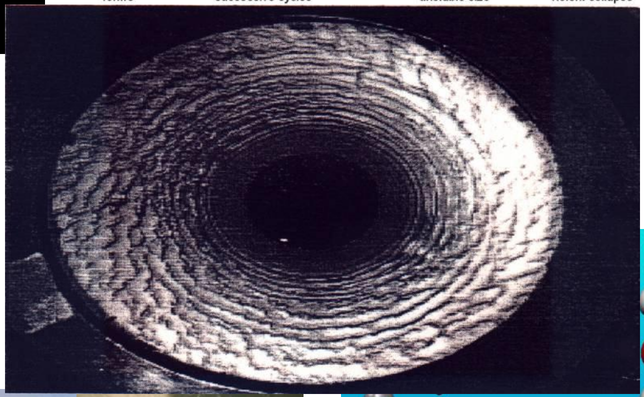
# ENERGY: examples

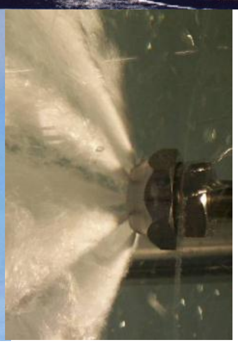


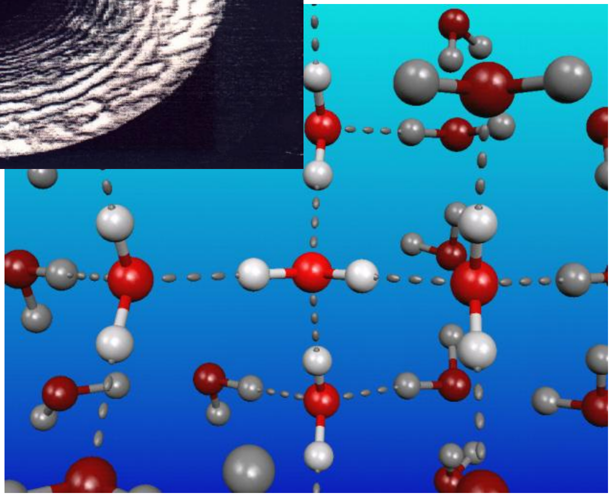









# Example: High-Gravity Rotating Packed Bed for the production of hypochlorous acid (Dow Chemical)

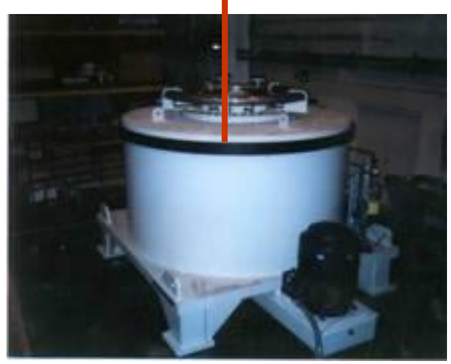
ENERGY

**Traditional technology**

**A system of absorption-stripping columns:** the main product (HClO) has to be removed as quickly as possible from the reaction environment to prevent its decomposition.

**PI technology**

**Reactive stripping in High-Gravity (HiGee) Rotating Packed Beds:** the reactants are subjected to intensive contact and the product is immediately removed via stripping using high-gravity forces in a rotating apparatus with a specially designed packing



Photos courtesy of Dow Chemical Company;

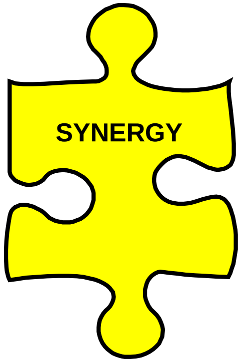
**Benefits**

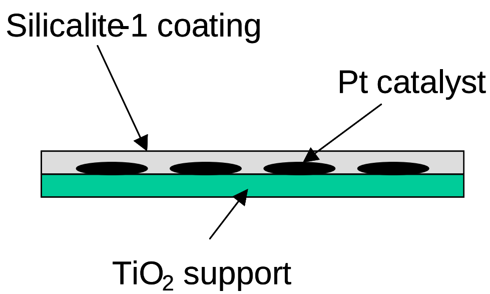
- Equipment size decreased by a factor of ca. 40
- Ca. 15% higher product yield
- 50% reduction of the stripping gas
- 1/3 reduction in waste water & chlorinated byproducts
- Same processing capacity

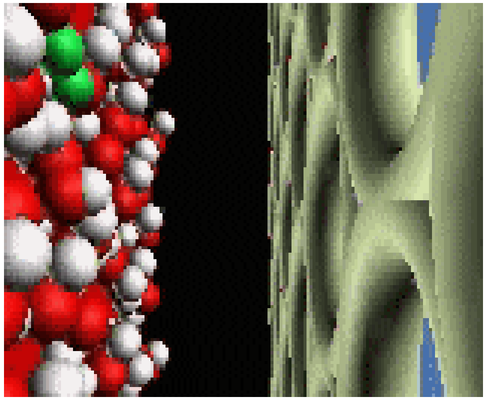
# Fundamentals of Process Intensification

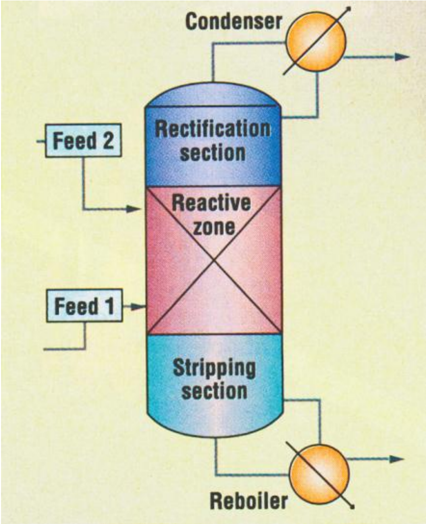
| | | | | |
|---|---|---|---|---|
| **PRINCIPLES (GOALS)** | **maximizing the effectiveness of intra- and intermolecular events** | **giving each molecule the same processing experience** | **optimizing the driving forces and maximizing the specific surface areas to which these forces apply** | **maximizing synergistic effects from partial processes** |
| **APPROACHES** | STRUCTURE (spatial domain) | ENERGY (thermodynamic domain) | SYNERGY (functional domain) | TIME (temporal domain) |

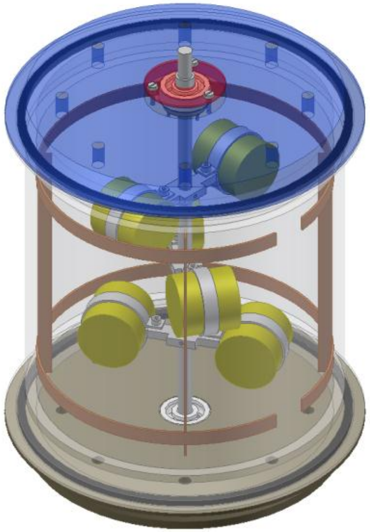
# SYNERGY: examples

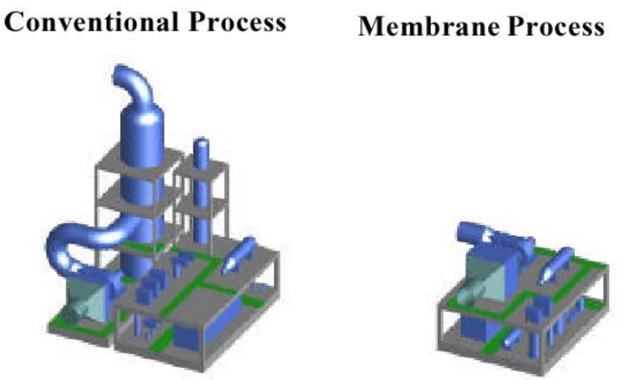


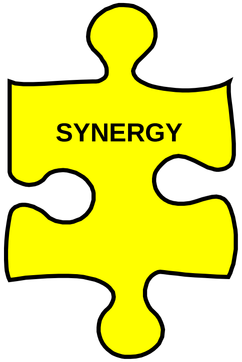





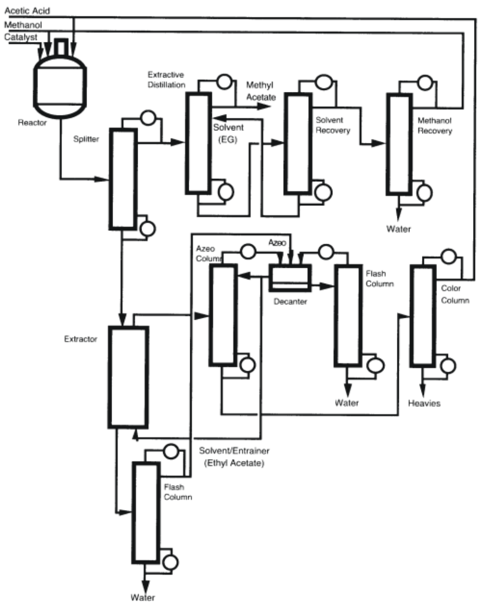


# Example: Methyl acetate in multifunctional reactor (Eastman Chemical)



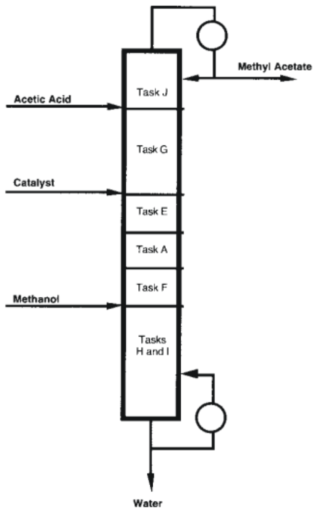

## Traditional technology

**28 pieces of equipment:** separation problem - two azeotropes




## PI technology

Multifunctional reactor column including reactive and extractive distillation steps




## Benefits

- Equipment from 28 reduced to 3
- reduced energy consumption by ca. 85%
- reduced investment by ca. 80%

# Fundamentals of Process Intensification

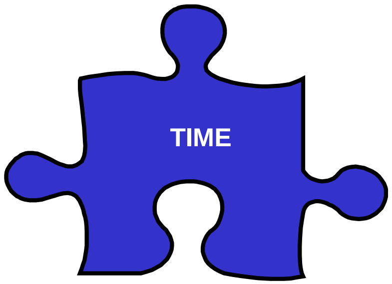
**PRINCIPLES (GOALS)**

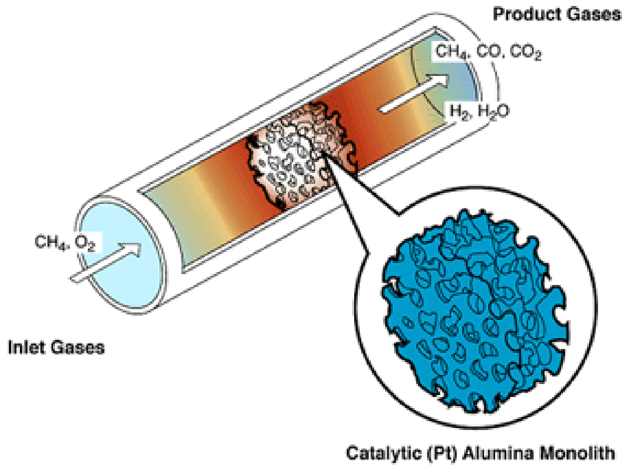
| maximizing the effectiveness of intra- and intermolecular events | giving each molecule the same processing experience | optimizing the driving forces and maximizing the specific surface areas to which these forces apply | maximizing synergistic effects from partial processes |
|---|---|---|---|

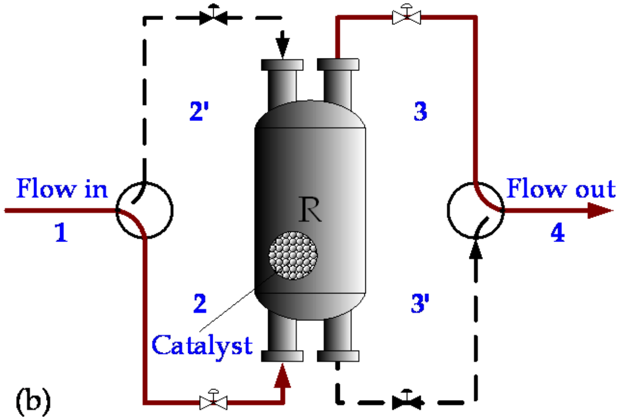
**APPROACHES**

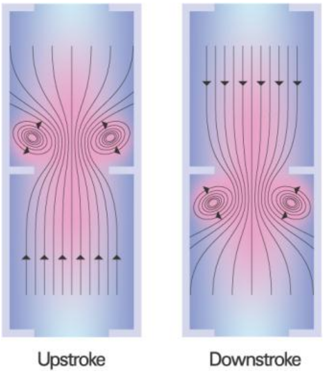
| STRUCTURE (spatial domain) | ENERGY (thermodynamic domain) | SYNERGY (functional domain) | TIME (temporal domain) |
|---|---|---|---|

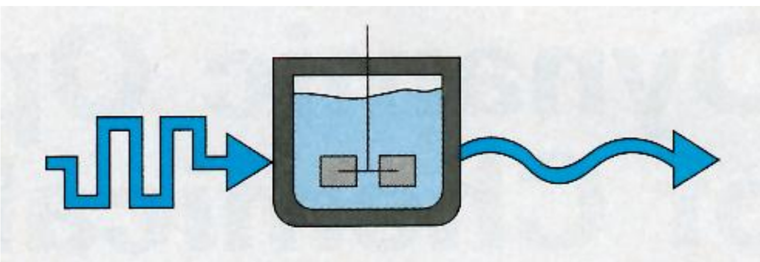
# TIME: examples

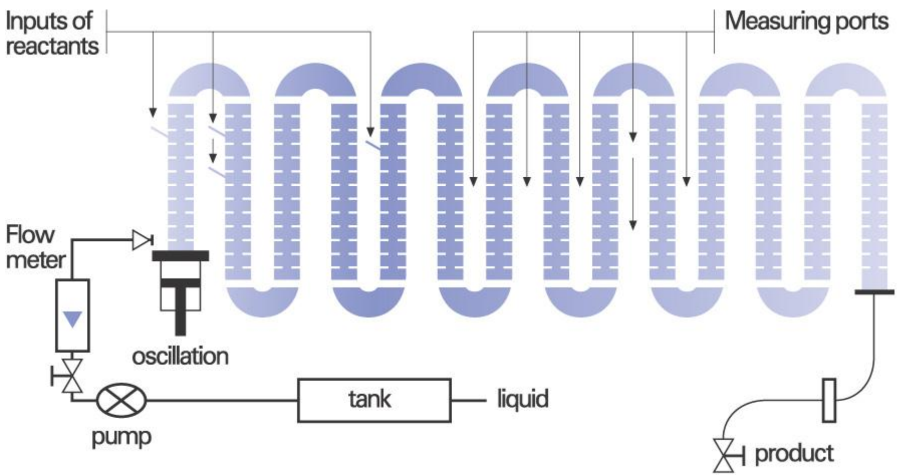


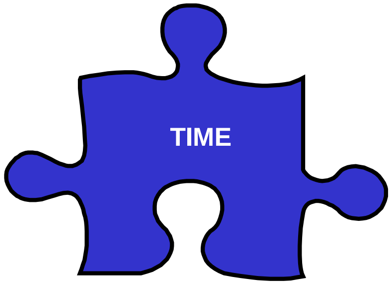



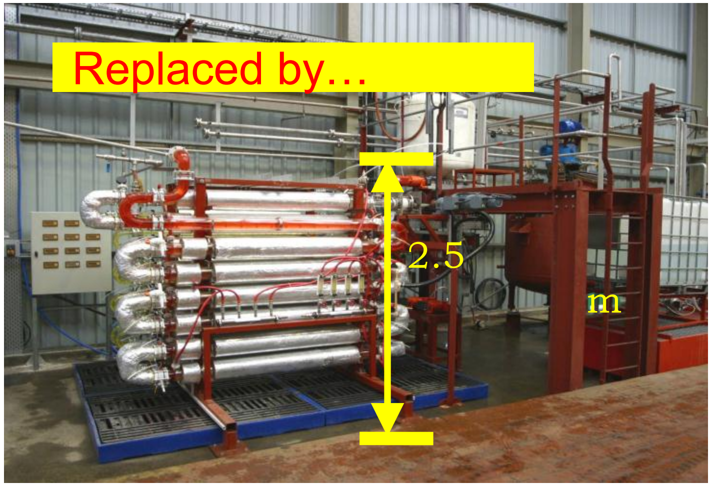


# Example: Oscillatory Baffle Flow Reactor




27 m

James Bond at James Robinson, or
SHAKEN, NOT STIRRED…




Reduction in:
Space (20x)
Process time (20x)
Capital cost (2x)
Energy and waste (many times)
Quality defects

# Fundamentals of Process Intensification

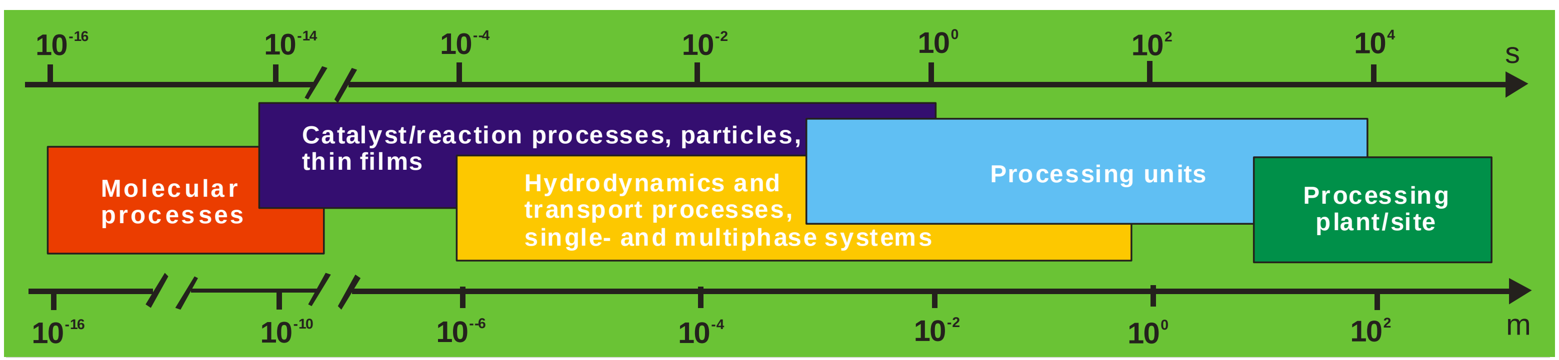
**PRINCIPLES (GOALS)**

- maximizing the effectiveness of intra- and intermolecular events
- giving each molecule the same processing experience
- optimizing the driving forces and maximizing the specific surface areas to which these forces apply
- maximizing synergistic effects from partial processes

**APPROACHES**

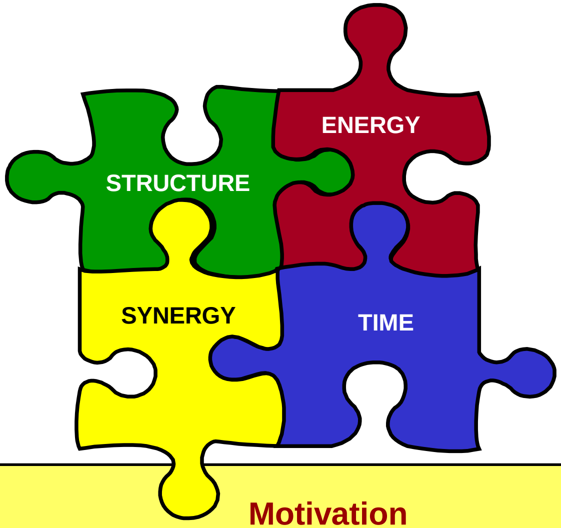
- STRUCTURE (spatial domain)
- ENERGY (thermodynamic domain)
- SYNERGY (functional domain)
- TIME (temporal domain)

**SCALES**



# SUMMARIZING…

**Fundamental principles and approaches of Process Intensification are applicable to any chemical process or operation. Intensification needs simultaneous addressing the four domains, as given below:**




| Domain | Main focus | Process Intensification concepts applied | Motivation |
|---|---|---|---|
| Spatial | Structured environment | Milli- and microchannels; structured (catalyst) surfaces | • well-defined geometry<br>• creating maximum specific surface area at minimum energy expenses<br>• creating high mass and heat transfer rates<br>• precise mathematical description<br>• easy understanding, simple scale-up |
| Thermodynamic | Alternative forms and transfer mechanisms of energy | Electric and electromagnetic fields | • manipulation of molecular orientation<br>• excitation of targeted molecules<br>• selective, gradientless and local energy supply |
| Functional | Integration of functions/steps | Combination of alternative energy forms (e.g. electric and laser fields), combination of catalyst and energy source or energy-absorbing material. | • synergistic effects<br>• better heat management<br>• increase of overall efficiency<br>• more compact equipment |
| Temporal | Timing of the events, introducing dynamics | Dynamic (pulsed) energy supply, millisecond contacting | • controlled energy input<br>• utilizing resonance<br>• increased energy efficiency<br>• side reactions minimized |

# SUMMARIZING: about multidisciplinarity

**Multidisciplinarity of R&D approach is essential to Process Intensification. Collaboration between chemical engineering and other disciplines such as chemistry & catalysis, material science, applied physics or electronics is of crucial importance.**

(O. Levenspiel: Chemical Reactor Omnibook)

# Course program

| Date | Block | Subject | Lecturer |
|---|---|---|---|
| Mon 5 Nov 13.45–15.45 | Fundamentals | Genesis of Process Intensification. Issues of concern for Chemical Process Industry. Definitions of Process Intensification. Position of PI in Chemical Engineering science, its boundaries and interrelations with other ChemEng disciplines. Generic principles of Process Intensification, its scales and fundamental approaches (TIME-STRUCTURE-ENERGY-SYNERGY). | Stefanidis/ Stankiewicz |
| Thurs 8 Nov 08.45 -10.45 | | Designing a Sustainable Chemical Plant (including elements of Inherently Safer Process Design) – presentation of PI project assignments | Stefanidis/ Sturm |
| Mon 12 Nov 13.45–15.45 | PI in Temporal Domain | TIME | Stefanidis |
| Thurs 15 Nov 08.45-10.45 | PI in Spatial Domain | STRUCTURE | Stankiewicz |
| Mon 19 Nov 13.45–15.45 | PI in Thermodynamic Domain | ENERGY – Part 1 | Stefanidis |
| Thurs 22 Nov 08.45 -10.45 | | ENERGY – Part 2 | Stefanidis |
| Mon 26 Nov 13.45–15.45 | PI in Functional Domain | SYNERGY – Part 1 | Stankiewicz |
| Thurs 29 Nov 08.45 -10.45 | | SYNERGY – Part 2 | Stankiewicz |
| Mon 3 Dec 13.45–15.45 | “FOCUS ON” lectures by guest experts: | Reactive Distillation and Heat Integrated Distillation | Kiss (Akzo Nobel) |
| Thurs 6 Dec 08.45 -10.45 | | Photocatalytic and Ultrasonic Reactors | Van Gerven (Katholieke Universiteit Leuven) |
| Mon 10 Dec 13.45–15.45 | | Rotating Fluidized Beds | De Wilde (Université Catholique de Leuven) |
| Thurs 13 Dec 08.45 -10.45 | | PI project assignments – mid-term reporting/discussion | Students |
| Mon 17 Dec 13.45–15.45 | | PI project assignments – mid-term reporting/discussion | Students |
| Wed 23 Jan 14.00-17.00 | | EXAMINATION | |
| | | EXTRA EXAMINATION | |

# Present course

- **22 hours of lectures**
- **case study project (inc. 4 hrs mid-term review)**
- **6 credit points:**
  - **written examination (50%)**
  - **case study project (50%)**

**Required minimum: grade 6 on written examination AND grade 6 in total**

- **Daily help-desk/project supervision:**

  **Guido Sturm, George Krintiras, Maryam Khodadadian**

# Present course - materials

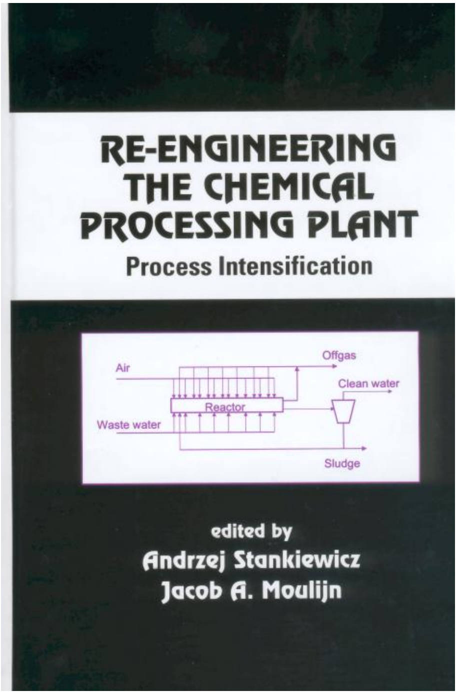
## Lecture notes

**(Auxiliary)**
**Re-Engineering the Chemical Processing Plant**
Process Intensification

**Edited by:** Andrzej Stankiewicz
Jacob A. Moulijn

**Book**
Hard Cover | Illustrated
**Print ISBN:** 0-8247-4302-4
www.dekker.com

**Free on-line reading via TUD Library**




**(Auxiliary)**
**Process Intensification Info Sheets (aid for the case study project)**

# QUESTIONS?