# Chemical integrated circuits

A. Richter
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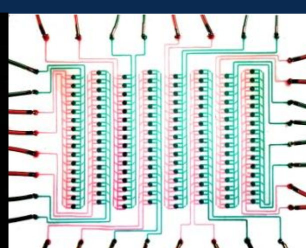
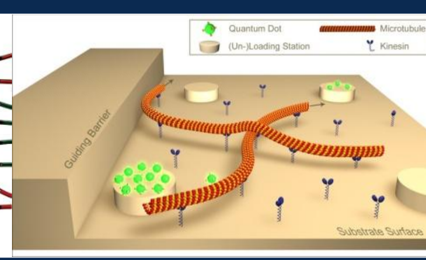
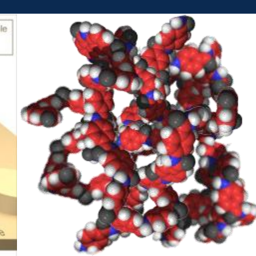
Polymeric Microsystems




## 7. Tagung „Feinwerktechnische Konstruktion“ Dresden

# Content

**Why chemical information processing ?**

**Research challenges**

**Diagnostic chemical ICs**

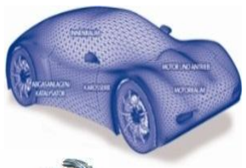
# Why chemical information processing



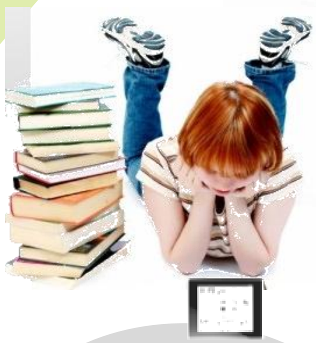
## Electronic IT and underlying semiconductor industry:

dominating our professional and private live

Services
World $ 6300B / Europe $ 1600B



Education, Science, Automotive, Industry, Energy, Medical, Aviation, IT



Electronics
World $ 1500B / Europe $ 315B

Devices
World $ 46B / Europe $ 2.9B

Semiconductors
World $ 256B / Europe $ 41B

Materials
World $ 42B / Europe $ 4B

Source DECISION, ESIA, Future Horizons, IMF, WSTS –2010

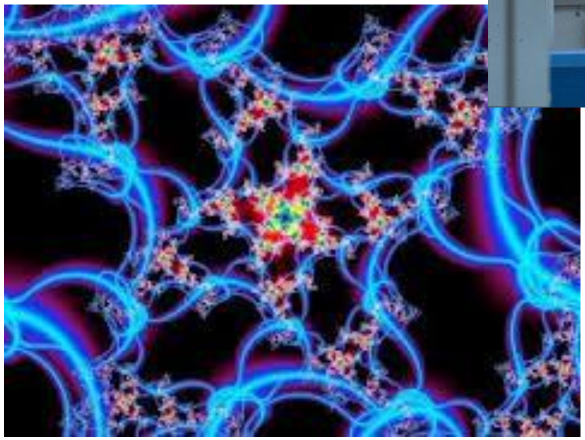
# Why chemical information processing

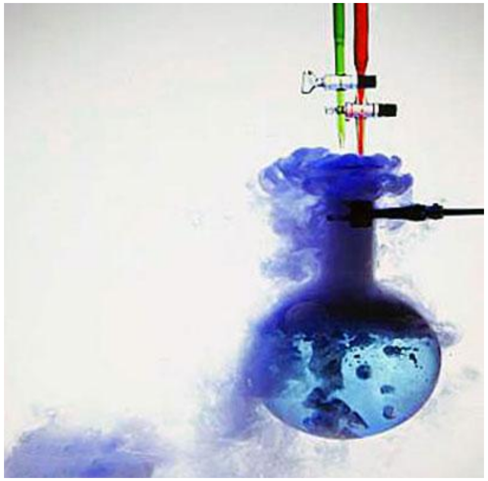


## Another important carrier of information

- cooking
- medicine
- chemical synthesis
- manufactoring industry
- . . .

⇒ **Matter**





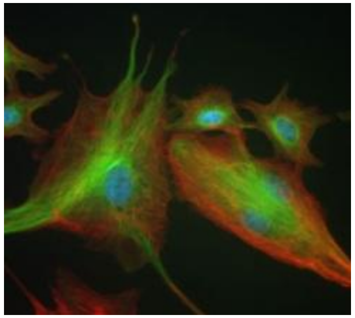
# Why chemical information processing



**Chemical information processing:**
**⇒ basic principle of living organisms**

**Unrivalled properties**
- performance
- resilience
- energy efficiency
- multi-functional
- self-learning
- . . .

**⇒ inspiration source**
rethink / optimize current information technology





Source duden.de, magicalnaturetour, TUD

# Why chemical information processing



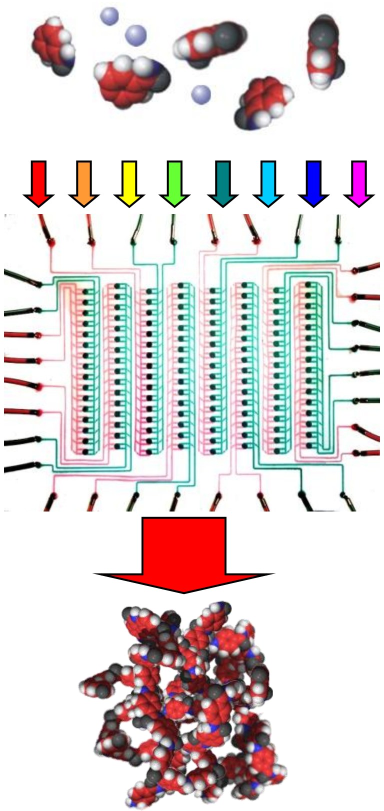
**CIP itself is most interesting as**
- beyond CMOS technology
- More than Moore approach

**Problem:**
- no suitable approaches to realize a hardware for chemical information technology

**Aim :**

Foundation of IC-based chemical information processing

Chemical Information processing

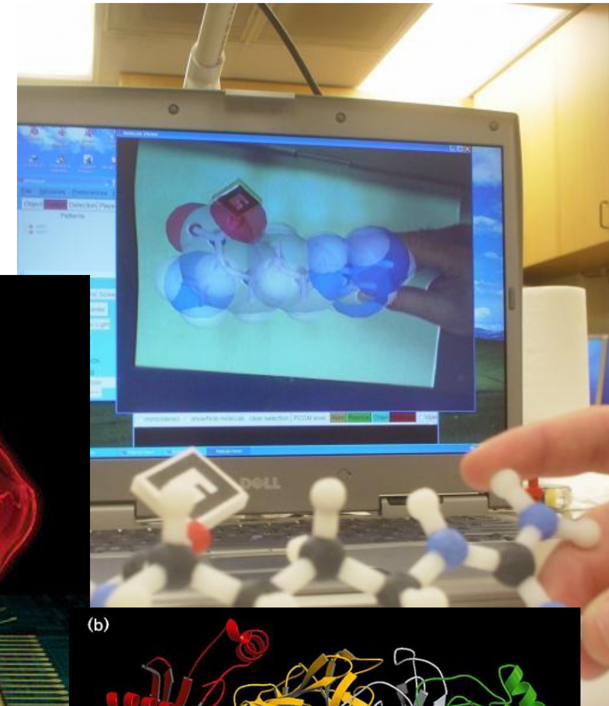


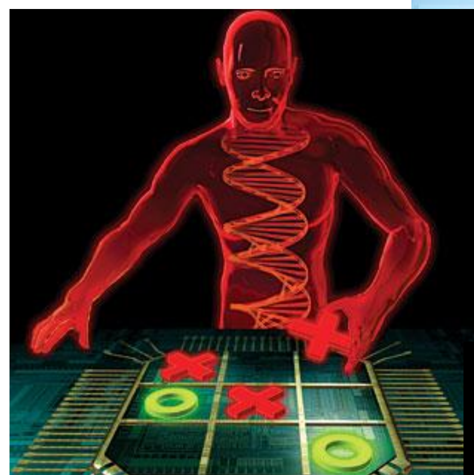
# Objectives



**IT systems**

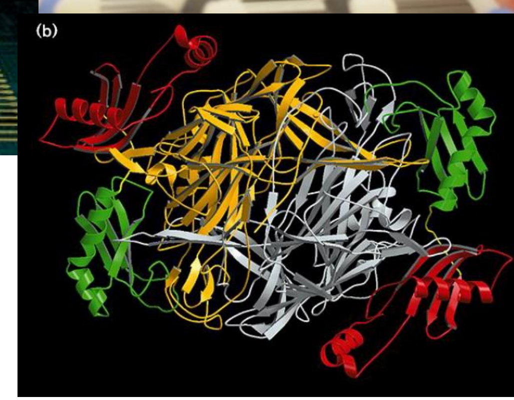
Solving chemical problems with chemicals as carrier of information





**Applications (examples)**

- computer-aided design of chemicals, catalysts, nanomaterials …

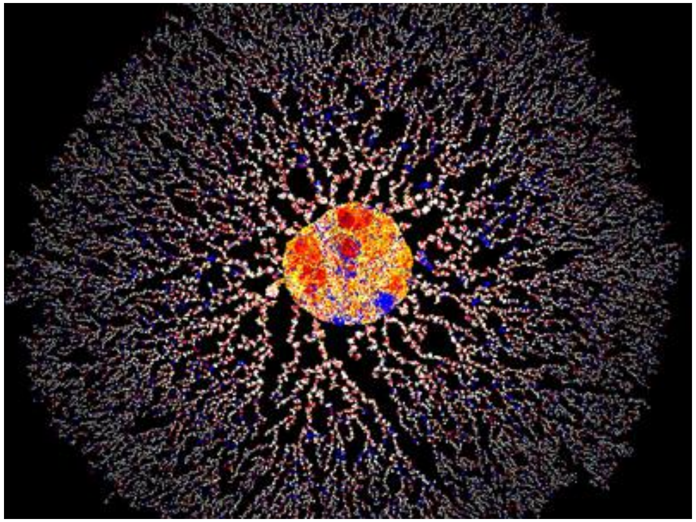



Source: biomedicalcomputationreview.org

# Objectives

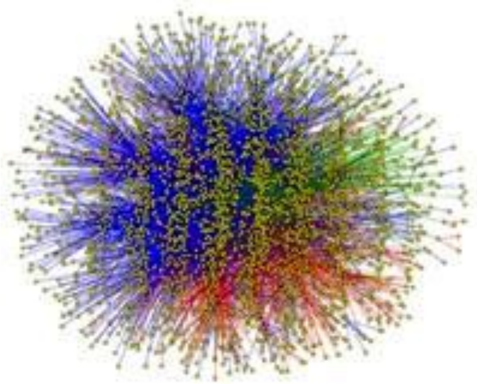
**IT systems**

Solving chemical problems with chemicals as carrier of information



**Applications (examples)**

- computer-aided design of chemicals, catalysts, nanomaterials …
- simulation / reconstitution of complex biological functions and systems



# Objectives

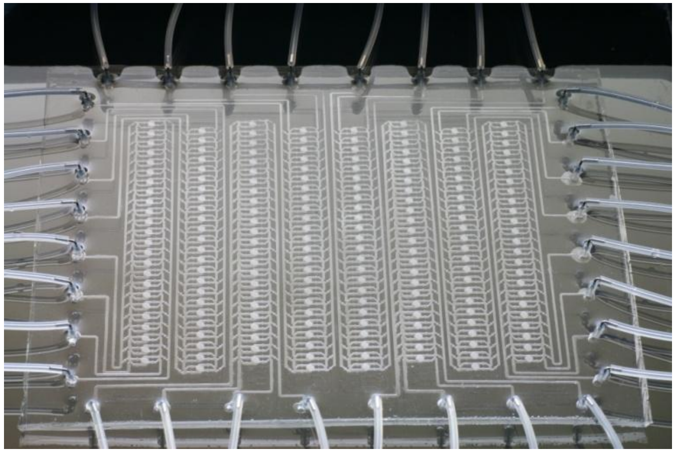


**IT systems**

Solving chemical problems with chemicals as carrier of information

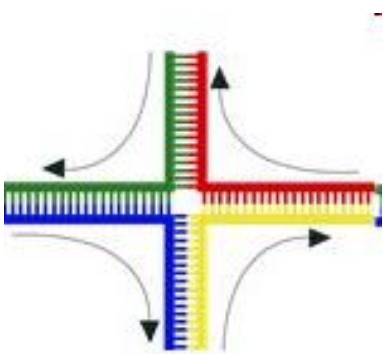
**Applications (examples)**

- computer-aided design of chemicals, catalysts, nanomaterials …
- simulation / reconstitution of complex biological functions and systems
- revolutionize analytics and medical diagnostics
  - ⇒ change of methodology towards processing of big data
    - ⇒ key for next generation methods of molecular medicine and gene technology



# Chemical design of nanomaterials

**DNA origami**
Controlled self-assembly of complex and well-defined nanostructures





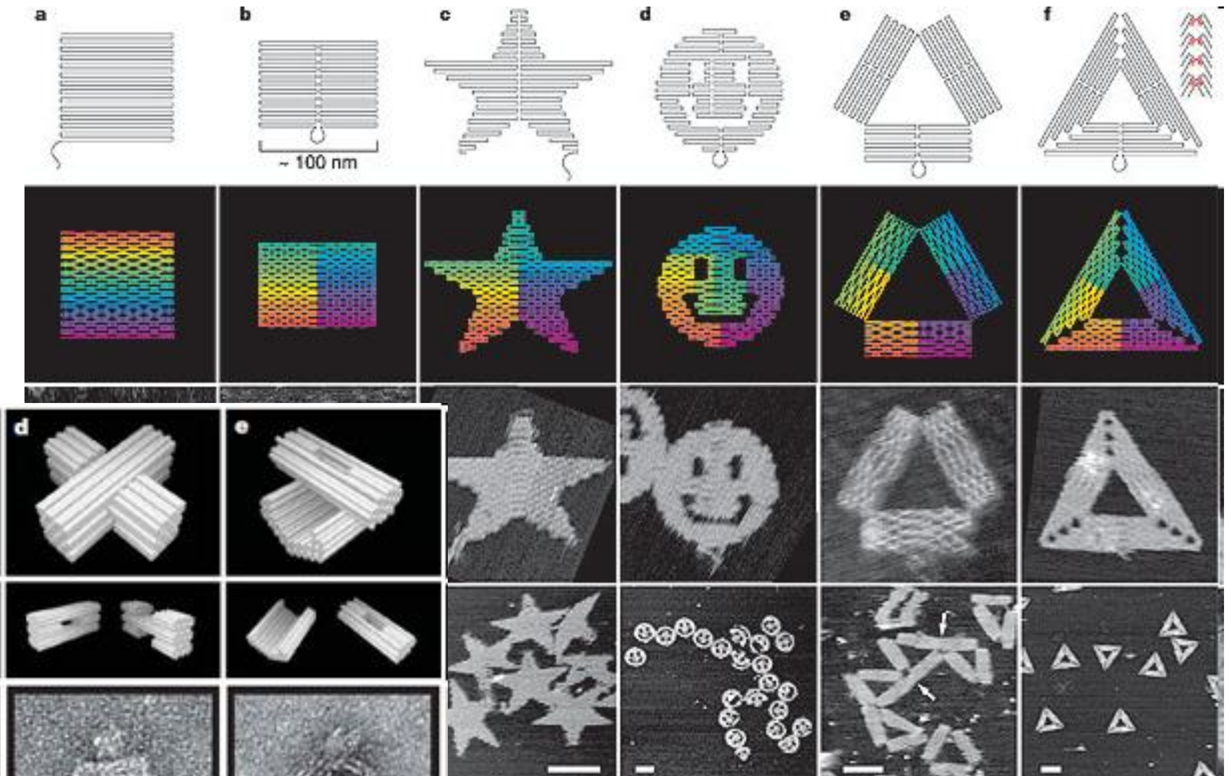
**Principle**
carry out a chemical program (reaction sequence)
*via* definition of Watson-Crick base pairs
⇒ desired nanostructure

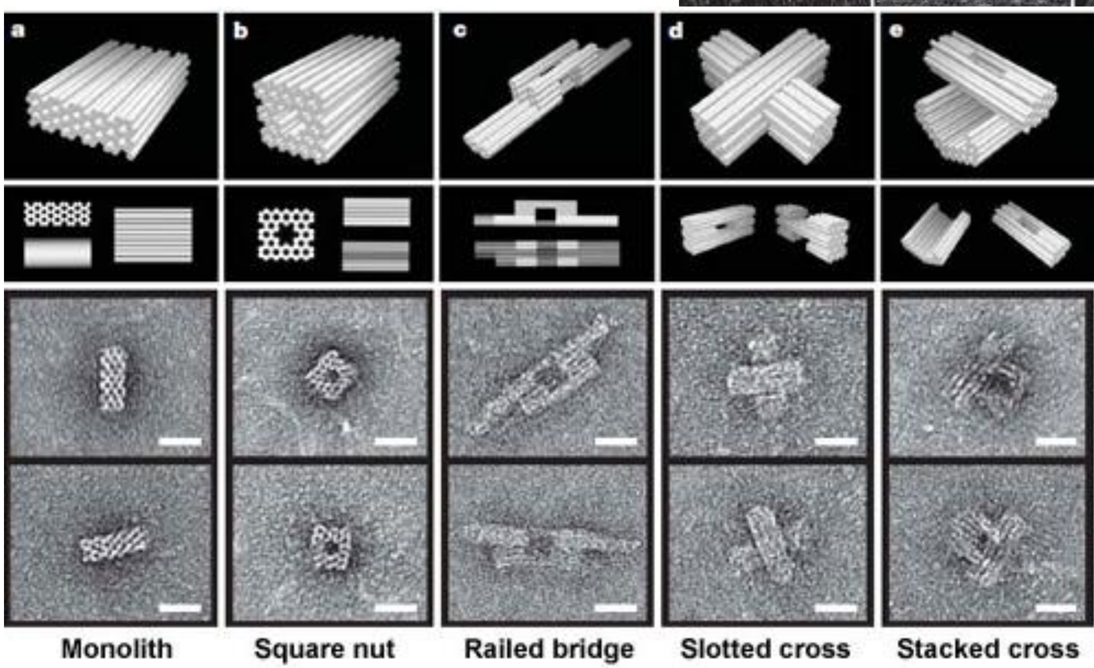
# Chemical design of nanomaterials



## Nanomaterials

→ 2D nanostructures
→ 3D nanostructures




*Nature* **440**, 297–302 (2006)

# Main topics

| | |
|---|---|
| **Materials** | *Responsible towards specific chemicals* |
| **Components** | *basic active components of CIP* |
| **Carriers of information** | *multiple types of information* |

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# Materials

**Necessary:**

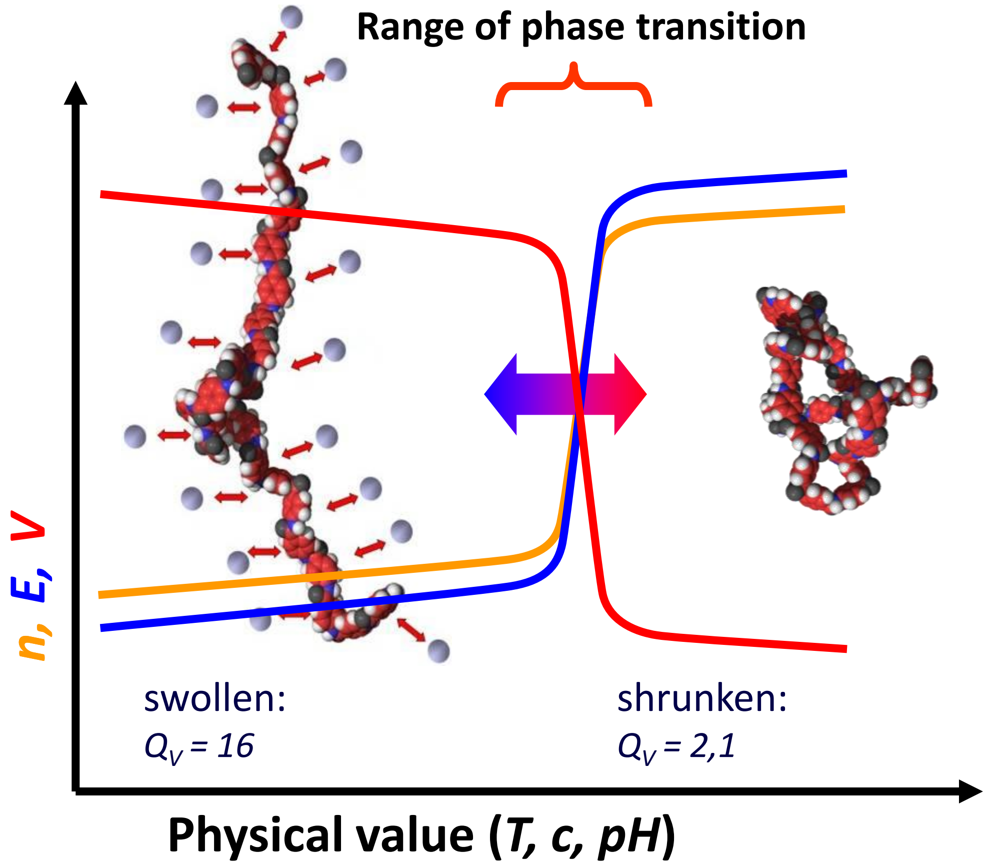
Large response towards chemical stimuli

⇒ **phase transition materials**

⇒ drastic changes in:

- optical properties
- mechanical properties
- volume, conformation

⇒ **stimuli-responsive polymers**



# Main topics

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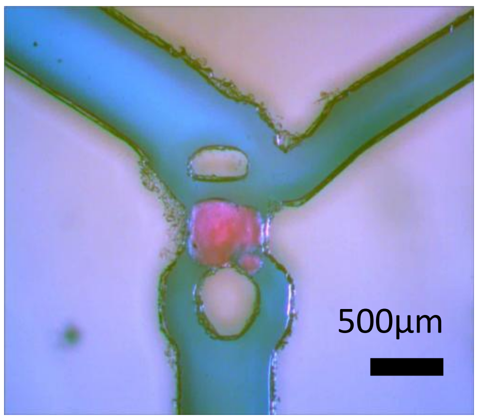
# Components

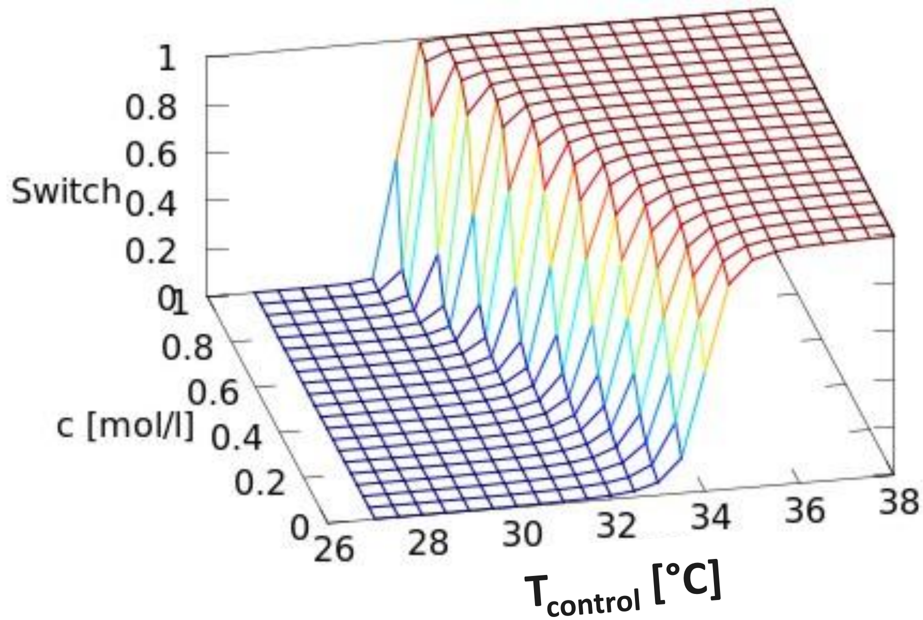
Phase transition motor proteins

Thermodynamic phase transition components

Chemical transistor




Propanol




- regulates a liquid flow depending on the threshold concentration of a certain chemical

- Other components: pressure sources, capacitors, memristors, switches . . .

⇒ foundations of design, technology, theory

# Components



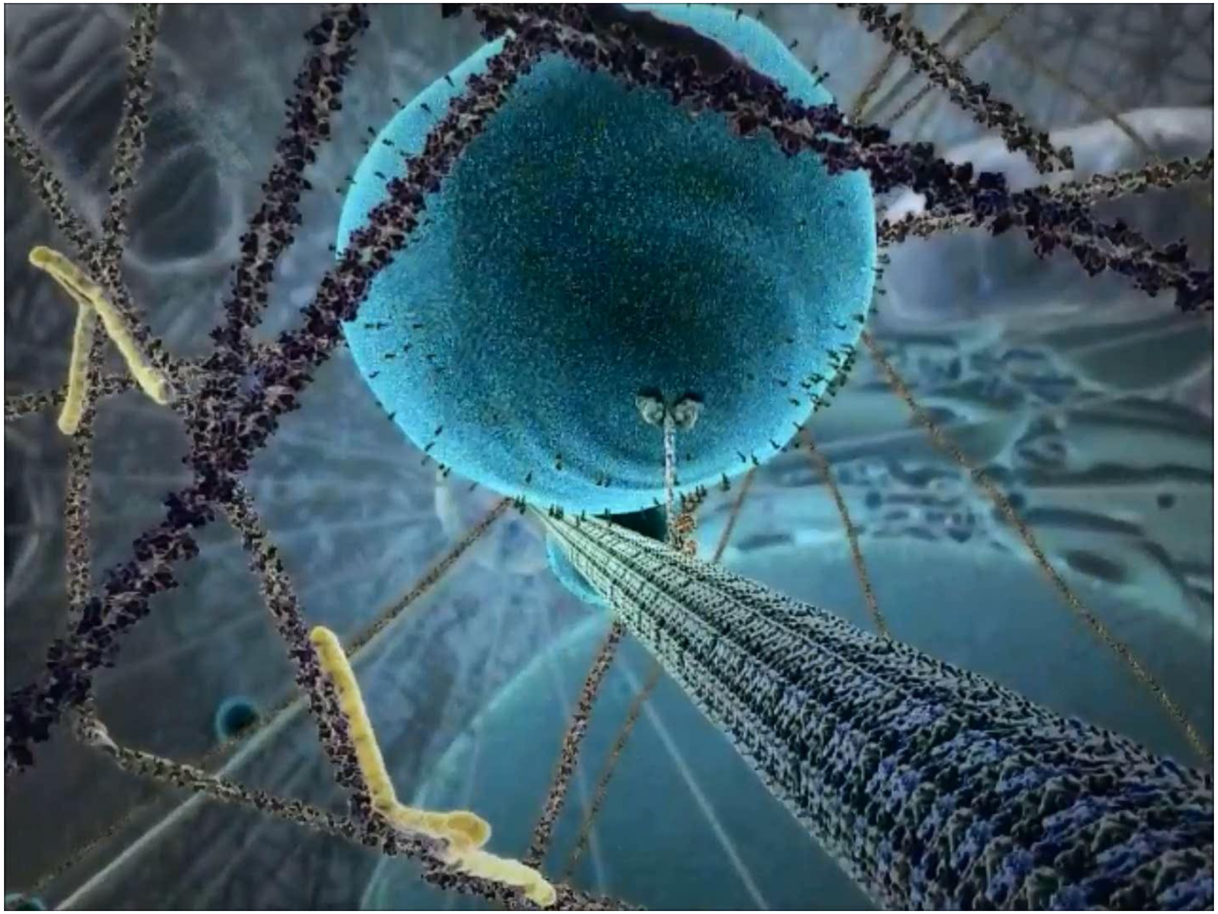


Phase transition motor proteins

Cargo systems on molecular level $\Rightarrow$ non-diffusive transport

- a basic moving system in living organisms
  - $\rightarrow$ muscles
  - $\rightarrow$ cell division

Motor protein walks on a microtubule
$\Rightarrow$ able to transport cargo vesicles



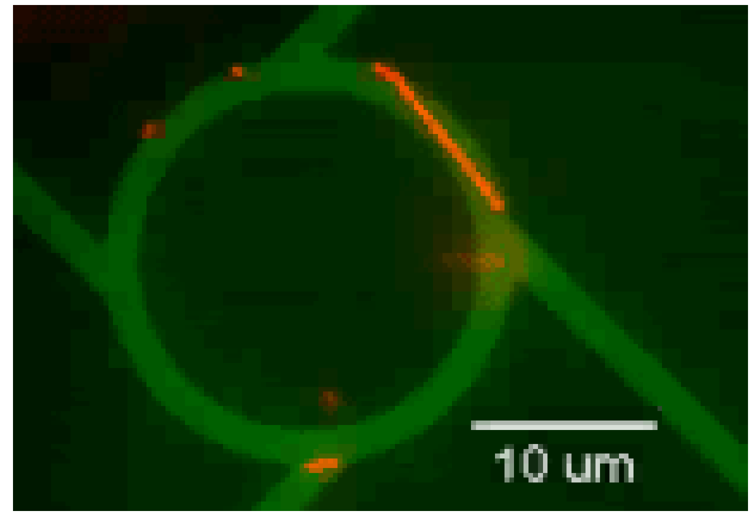
Source: youtube

# Components

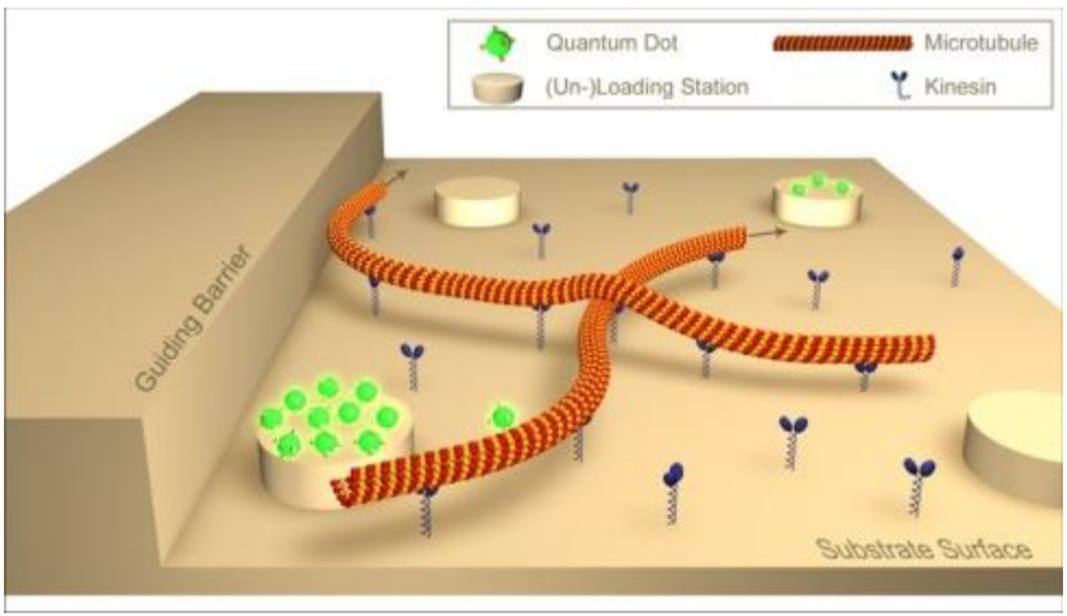
Phase transition motor proteins

Cargo systems on molecular level ⇒ non-diffusive transport at nanoscale

- a basic moving system in living organisms
  → muscles
  → cell division




© Diez Lab, TU Dresden




⇒ controlled transport in IC channels

# Main topics

| | |
|---|---|
| **Materials** | *Responsible towards specific chemicals* |
| **Components** | *basic active components of CIP* |
| **Carriers of information** | *multiple types of information* |

# Carriers of information

**State of the Art:**
Computing with
*single type of reaction*
in a chamber

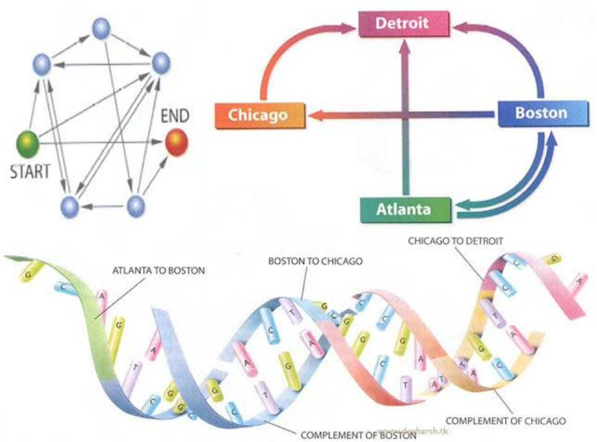
“aA + bB = cC + dD”

thought like electronic IP

**Our Approach :**
*Multiple types of information*
- “multi-dimensional”
- closer to nature

“aA + bB = cC + dD”
“eE + fF = gG + hH”
.
.
.
“wW + xX = yY + zZ”

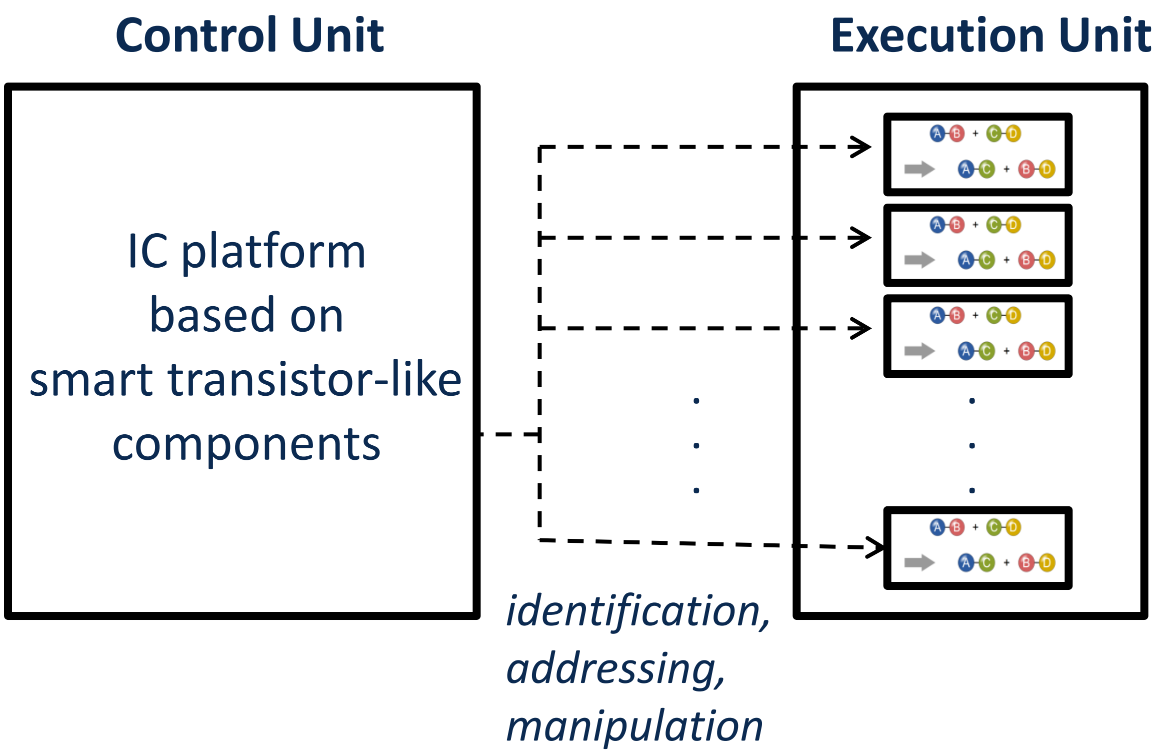
Kinds of chemical computing:
- reaction-diffusion
- conformational
- DNA computing
- …




Example: DNA computing

# Systemic approach

Distributed reactions; control via control unit
a) massive parallel, b) cascade, c) single molecule



# Diagnostic chemical ICs



**Medicine**

⇒ since 1990 scientists want to introduce the computational power of IC-based systems into **medical diagnostics**
→ Lab on a Chip approach

**Next Generation techniques in molecular diagnostics /gene technology:**

⇒ have to base on big data volumes

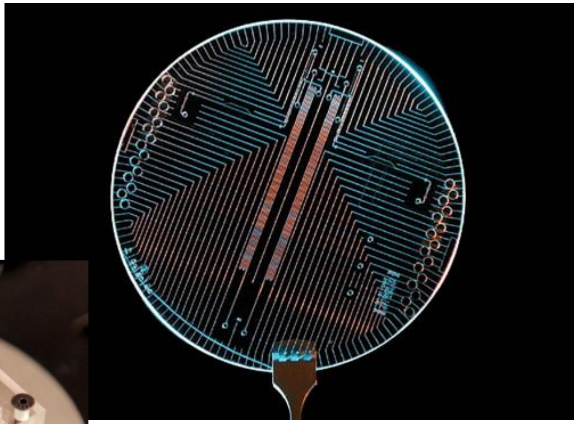
⇒ **key technology:** high-throughput LoC

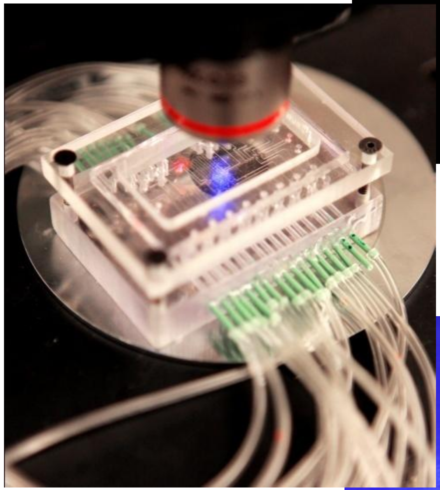
**Problem:**

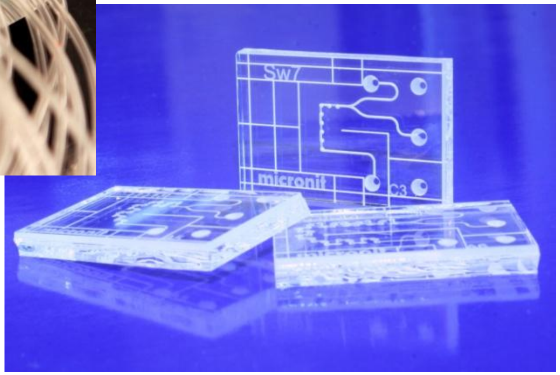
LoC technology of less efficiency

⇒ no suitable large-scale integration technologies

⇒ reasons discussed controversially







## Microprocessor-based

## Von Neumann Computer

**Central processing unit CPU (microprocessor) single integrated circuit**

**Control unit**

- Instruct. counter
- **Instruct. register**
- **Instruct. decoder**

**Execution unit**
ALU

**Bus system (Instructions, data, power)**

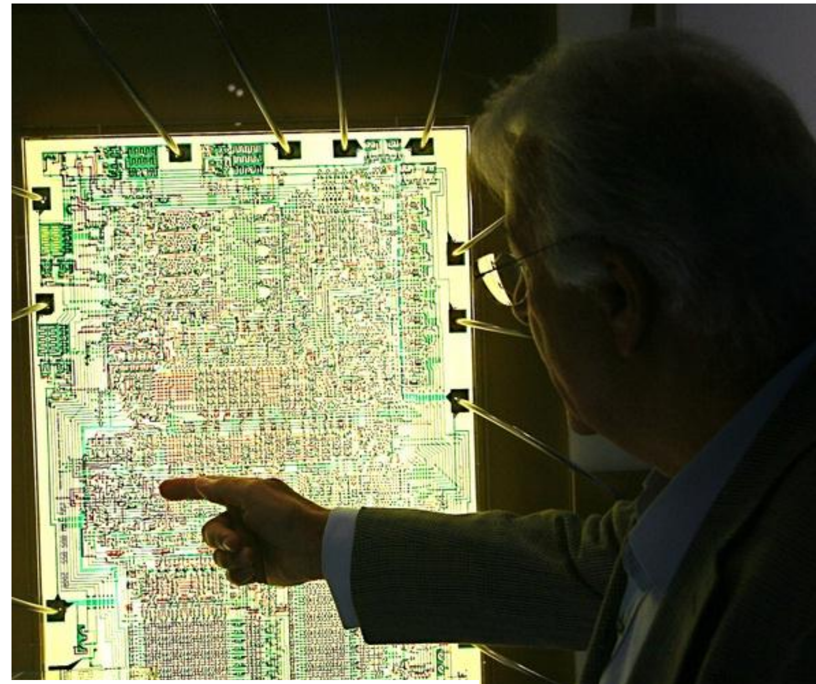
**Memory**
- **Instruc-tions**
- **Data**

**Input/output unit**

**External power supply**

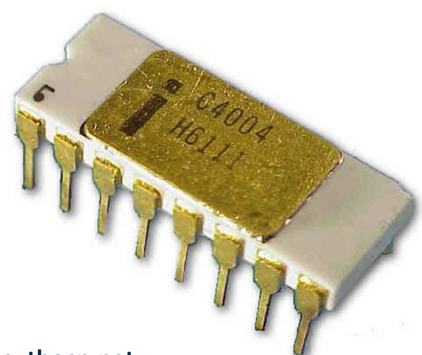
- CU & EU combined on a single IC, the CPU
- both process electronic information

$\Rightarrow$ same basic components (transistors)



F. Faggin, Designer of the Intel 4004

Source: flickr.com



Source: thocp.net

# System architecture



Today's LoC technology:

$\Rightarrow$ dominated by MEMS principle

To control the LoC

- Computer + control software
  $\Rightarrow$ electronic instructions
- transducer
  electronic $\rightarrow$ mechanical instructions

$\Rightarrow$different types of components necessary

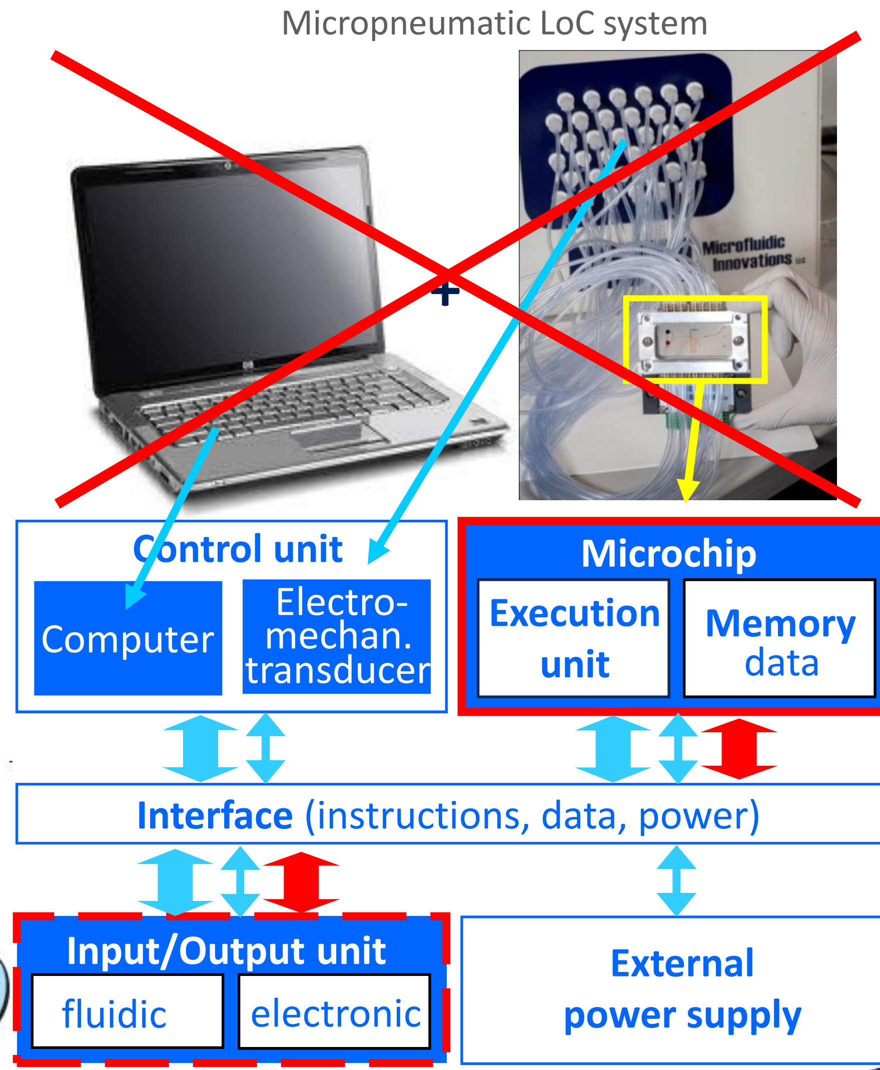
$\Rightarrow$ CU no part of IC

$\Rightarrow$ strong limitation of integration degree

$\rightarrow$ no scalability

**Idea:** using only one type of carrier of information

$\Rightarrow$ LoC as microprocessor




© Disney

# Idea – chemical integrated circuits

## Basic questions

**Which carrier of information?**
⇒ chemical information (concentrations)

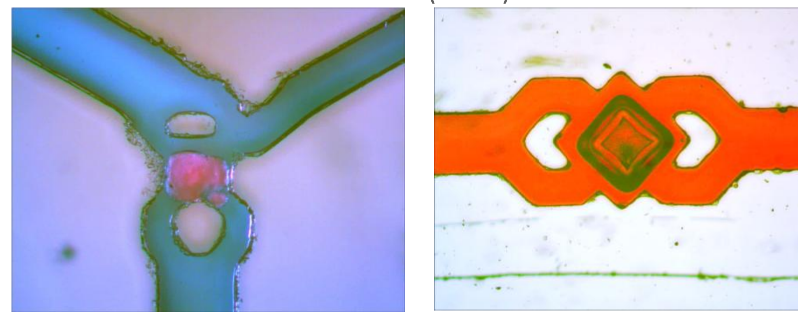
**Which components?**
⇒ chemical transistors and other chemically activated devices

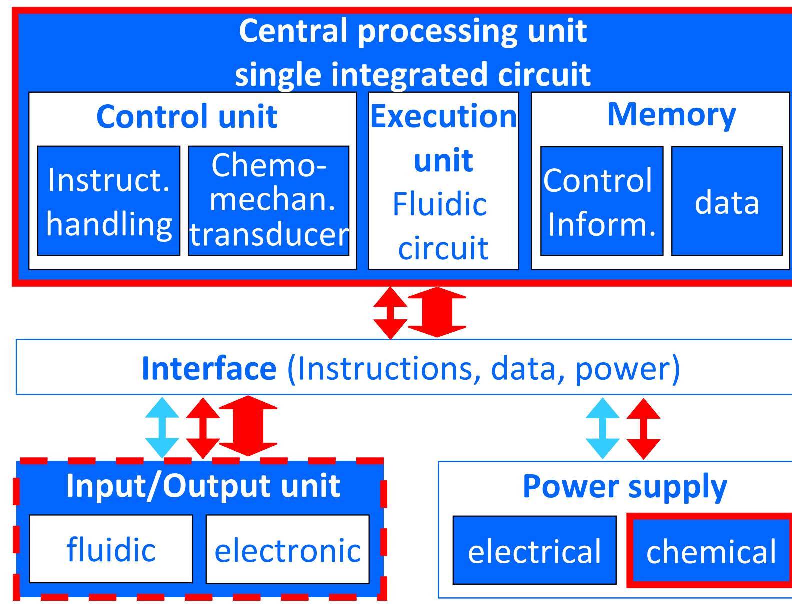
**Which monolithic fabrication technology?**

**⇒ Chemical microprocessors**

© Disney

Chemical Transistor
*Adv. Mater.* **21** (2009) 979






*Lab Chip* **12** (2012) 23, 5034

# IC fabrication

- Layer by layer: overlapping, micro-structured layers of different polymeric materials

**Substrate**

⇒ Hot embossing, Laserablation

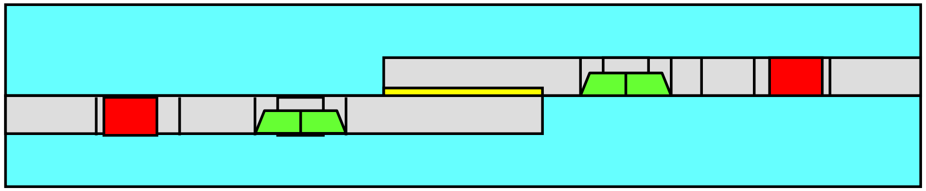
**cross-linked phase-changing polymers**

⇒ photo lithography

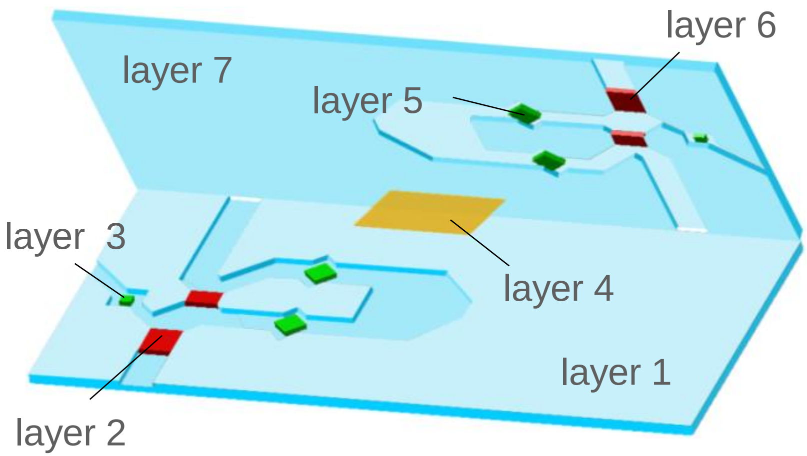
**uncross-linked phase-changing polymers**

⇒ printing technologies

⇒ Complex monolithic ICs with thousands of components

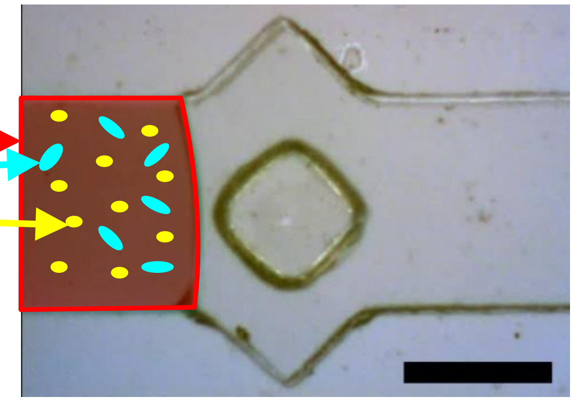


**Hot embossing**



# IC control and components





**IC processes two types of signals:**

- chemical control signals
- chemical data signals

**⇒ Parts of the aqueous process media**

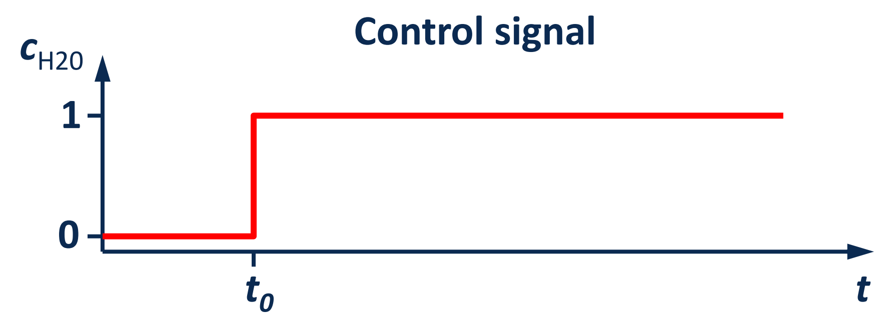
**Control signal:**

- binary chemical information

  ⇒ binary concentration of the water

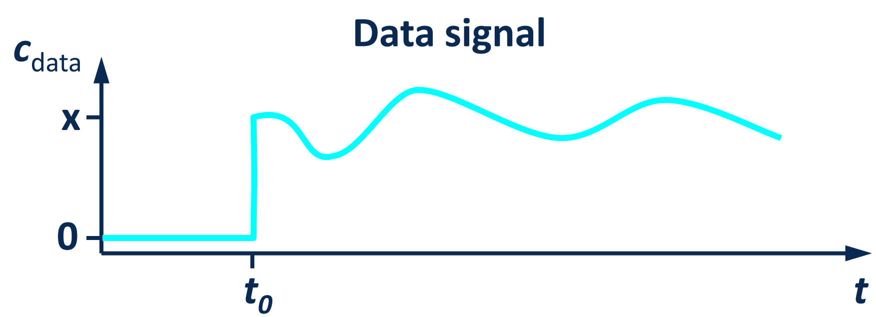
  $c_{H20}$ = 0: water is not applied

  $c_{H20}$ = 1: water is applied




**Data signal:**

- can be analogue signal, *e.g.* concentrations of sample, analyte
- processing: mixing reactions results , e.g. change of fluorescence intensity, observed with established optical methods

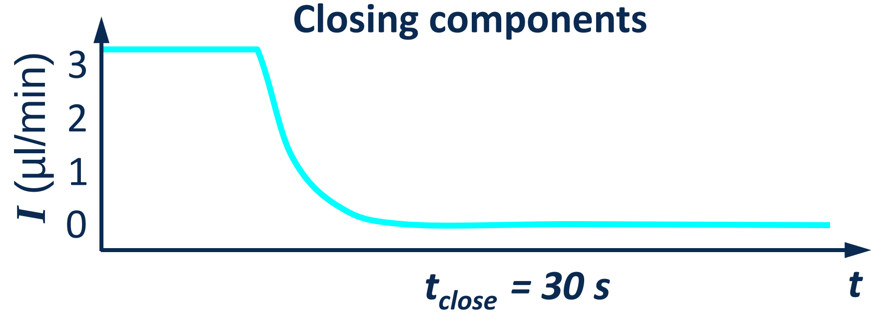


# IC control and components

**Transistor-like components (chemostat valves)**

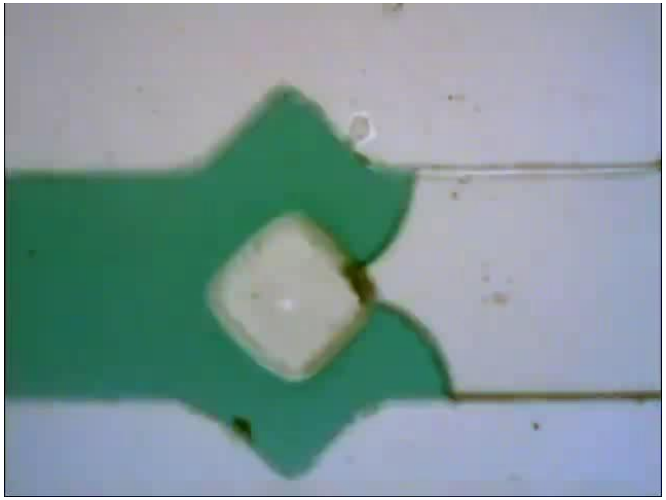
- **fluidic function:** regulate a liquid flow if the threshold concentration is reached

- **time defining function:** determine time schedule of IC program
  $\Rightarrow$ necessary: elements whose response time can be scaled over a big range

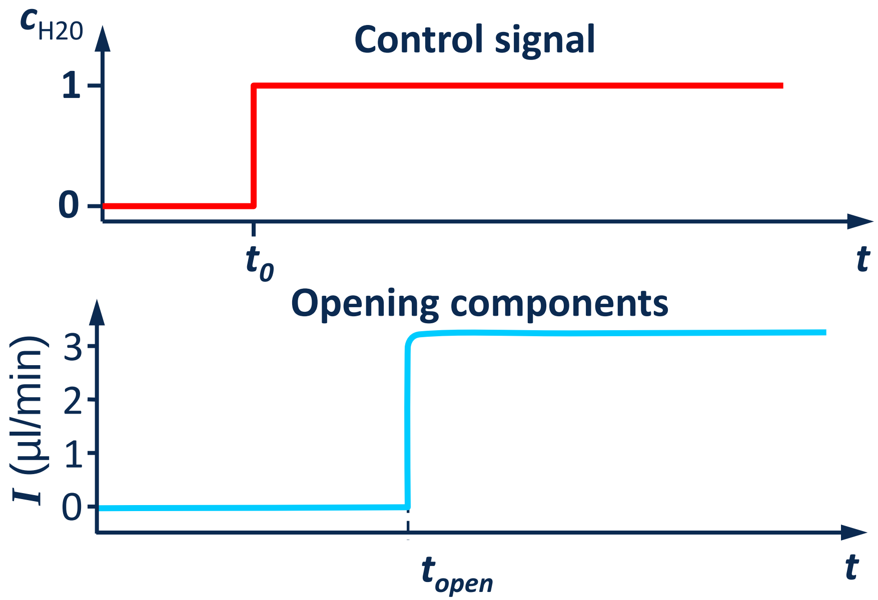

**Two types of transistor-like components**

**A) Closing components**



# IC control and components






**Transistor-like components (chemostat valves)**

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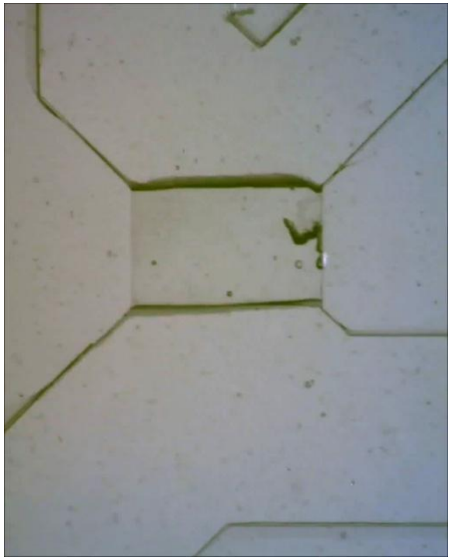
**Two types of transistor-like components**

**A) Closing components**

**B) Opening components**



# IC for high-throughput sampling



**Sampling**
most frequent task in medical diagnostics / life science
- single molecule detection
- immun response
- toxity
- …

**Standard laboratory**
Performed manually in large pipetting series

**Task:**
Investigation of 48 samples towards 48 properties:

- **manual** investigation time: **3 … 4 months**
- **IC-based** investigation time: **3 … 4 hours**
- IC reduces need for chemicals by **factor 1,000**

# IC for high-throughput sampling

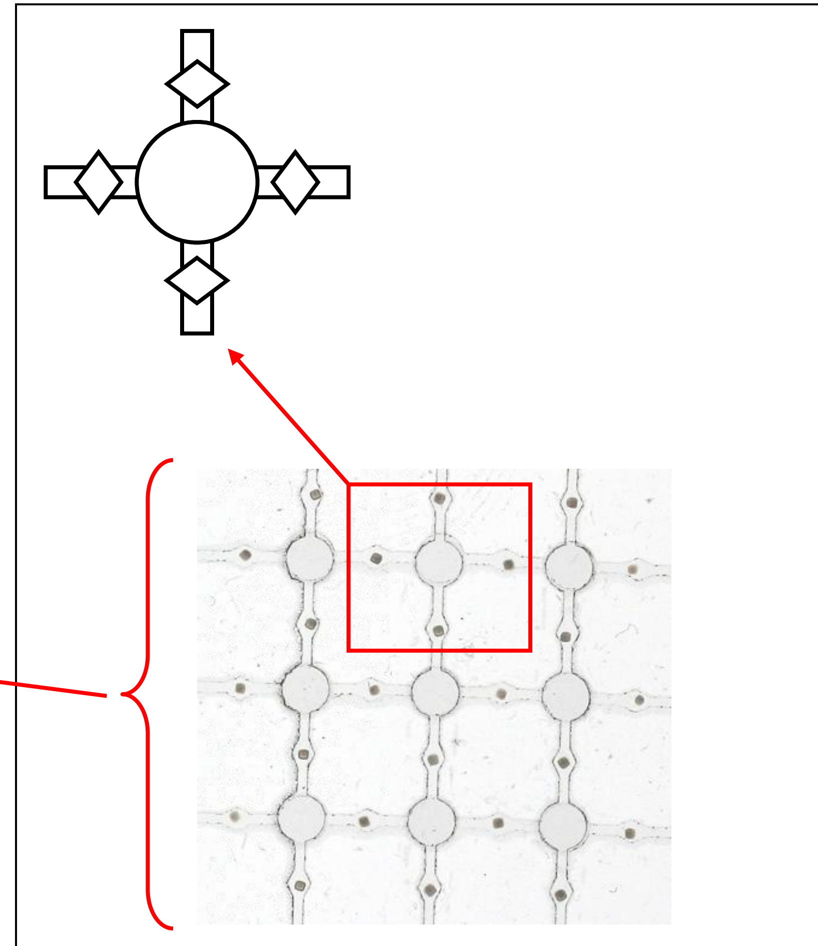


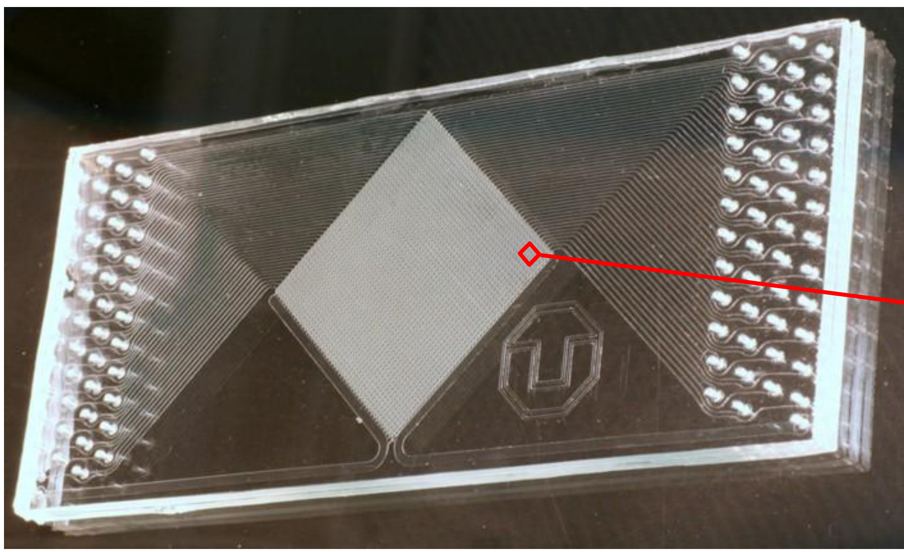
## Principle

after filling the IC with samples and chemicals

⇒ simultaneous execution of 2,304 test

⇒ parallelity is reason of reduction of test time





Chemical [48x48] sampling IC consisting of 7.012 chemical transistors, © Richter lab

# IC for high-throughput sampling

## Principle

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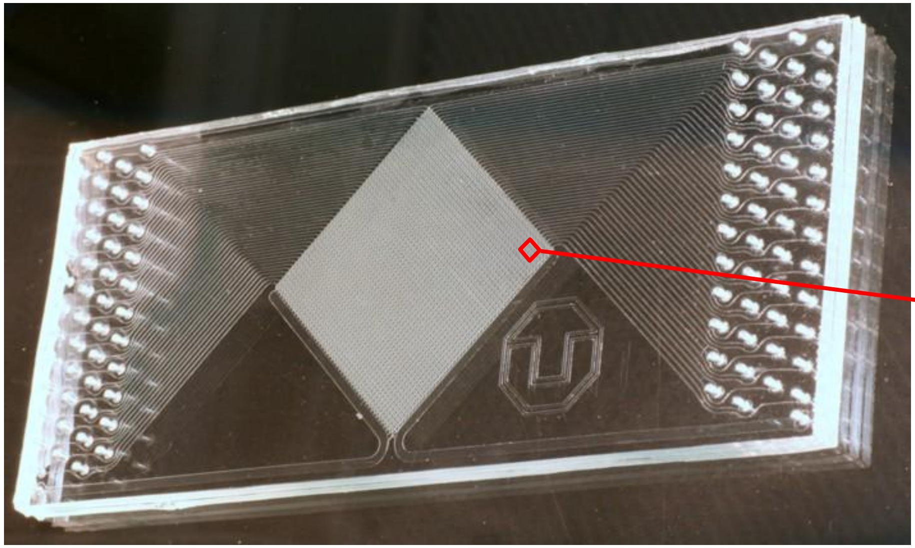
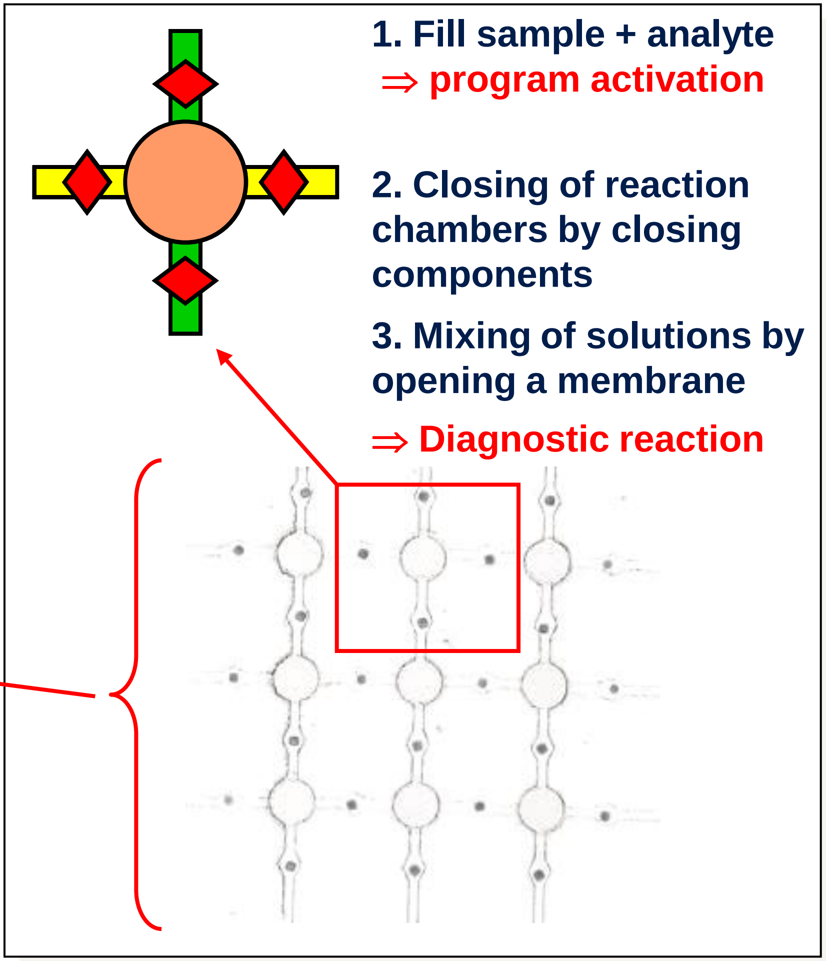


Chemical [48x48] sampling IC consisting of 7.012 chemical transistors, © Richter lab

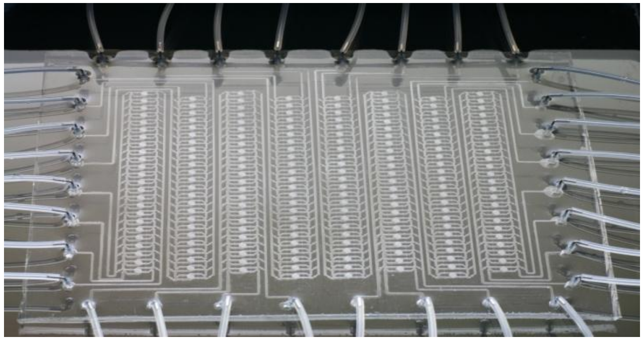


# Summary

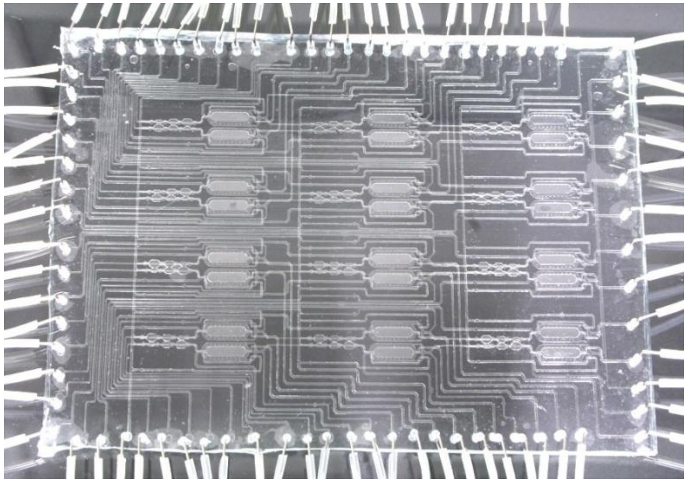
## Chemical ICs

- Introduce the concept of microprocessors into microfluidics
  ⇒ strong increase of system integration and functionality

- First LoC concept which is fully scalable
  ⇒ base of a microfluidic "Moore's law"
  ⇒ in microelectronics: most important factor of success



Chemical IC for long-term investigations
[*Lab Chip*, **12** (2012) 23, 5034]



Chemical IC with integrated pressure sources
[*Adv. Sci. Technol.*, 81 (2013), 84]

# Team

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European Union
European Social Fund
Investing in jobs and skills

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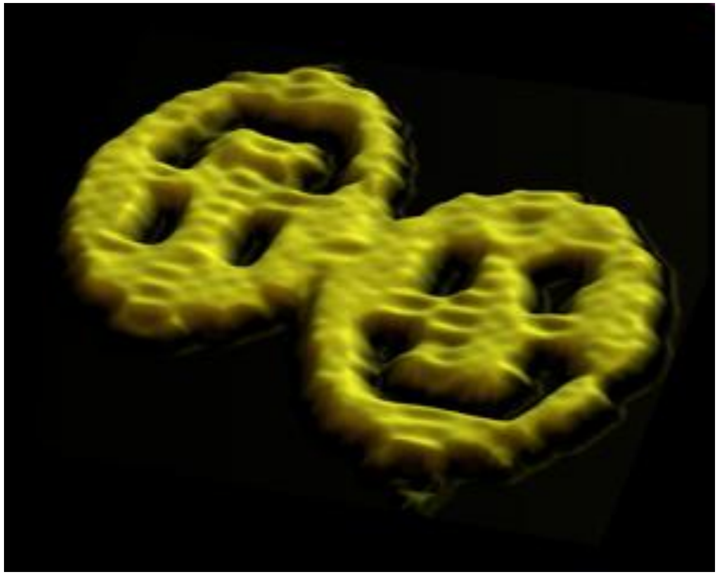
# Thank you !



Nano smileys made by DNA origami