



# 微流体与复杂流体

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天津大学化工学院

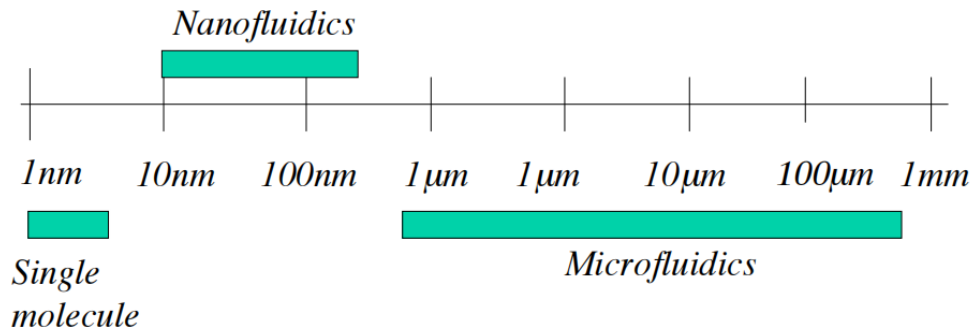
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化学工程联合国家重点实验室

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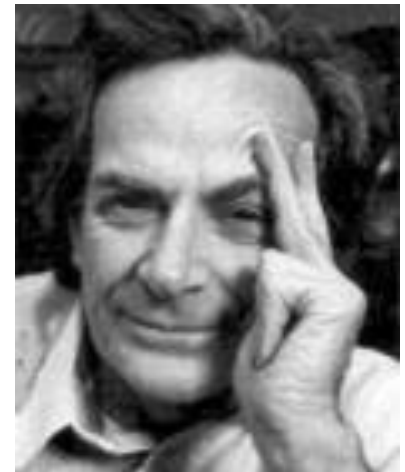
15222695879

There' s plenty of room at the bottom.



1959年，加州理工学院物理年会上的演讲

理查德·菲利普·费曼 (Richard Phillips Feynman) ， 1918年5月11日—1988年2月15日，美国著名理论物理学家，1965年，因在量子电动力学方面的成就而获得诺贝尔物理学奖。



# 微流体

微流体 (Microfluidics、微流控、微尺度流体流动)  
微系统中的流体流动与传递现象

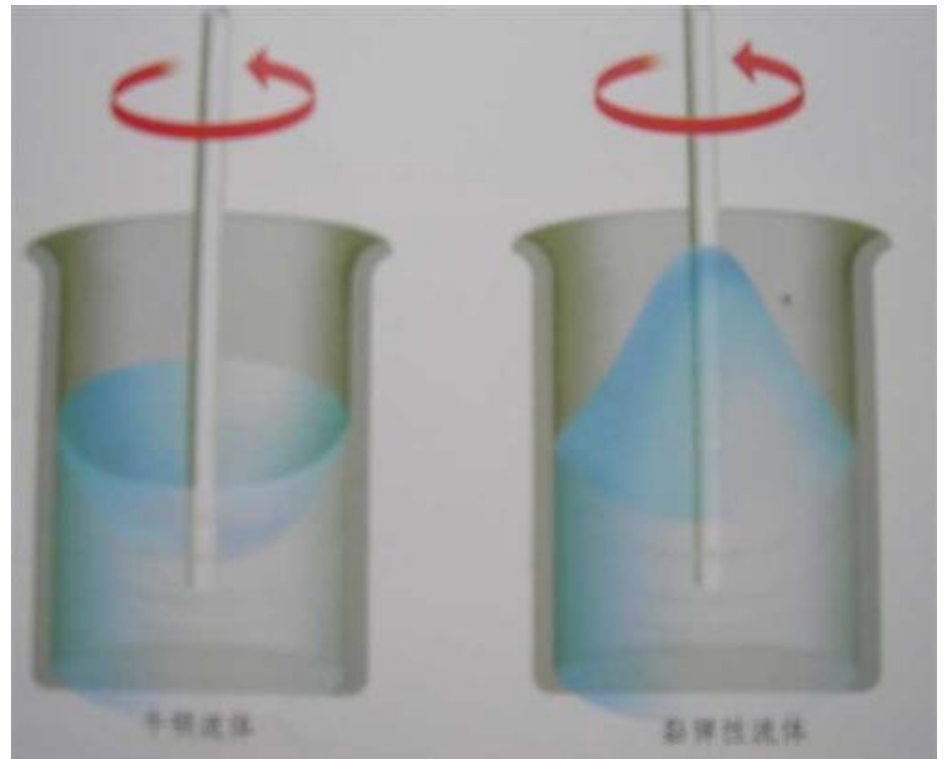
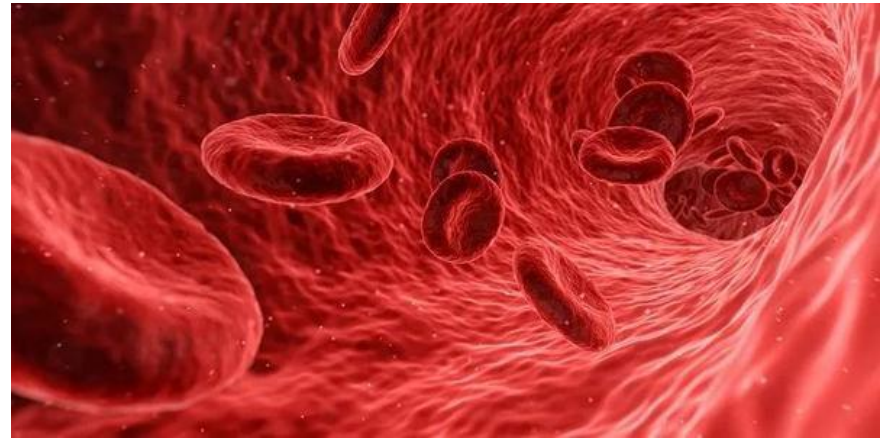


一根头发丝的直径是多少微米？60~90微米。60微米以下称为细发，60~90微米为普通发，90微米以上为粗发。

# 复杂流体



- **复杂流体**— (亦称**软物质**) 复杂流体具有复杂性和柔软性基本特性, 其力学性能处于常规流体和常规固体之间的中间地带, 且其形变与所受应力关系常表现为非线性的流变特征。
- 软物质(Soft matter), 由诺贝尔奖获得者、法国物理学家**德热纳**(P. G. de Gennes)于1991年提出来的。
- 广泛存在于高端产品如先进材料、高性能聚合物产品、精细化学品、生物医药产品、及能源与资源等相关的多相流、复杂乳液、生物流体等领域。



# Lab on a Chip

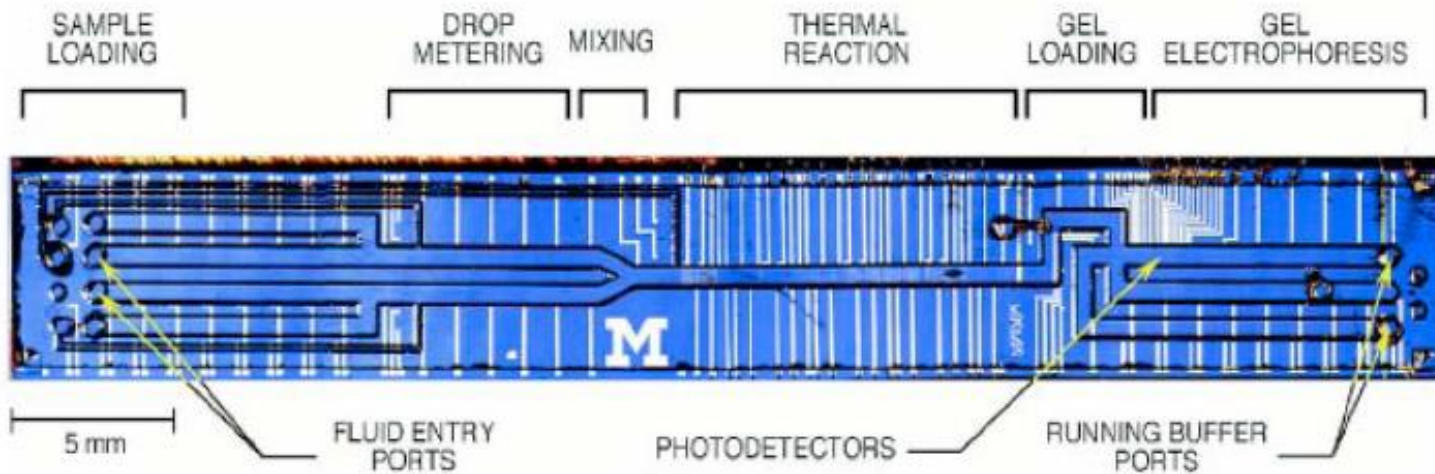
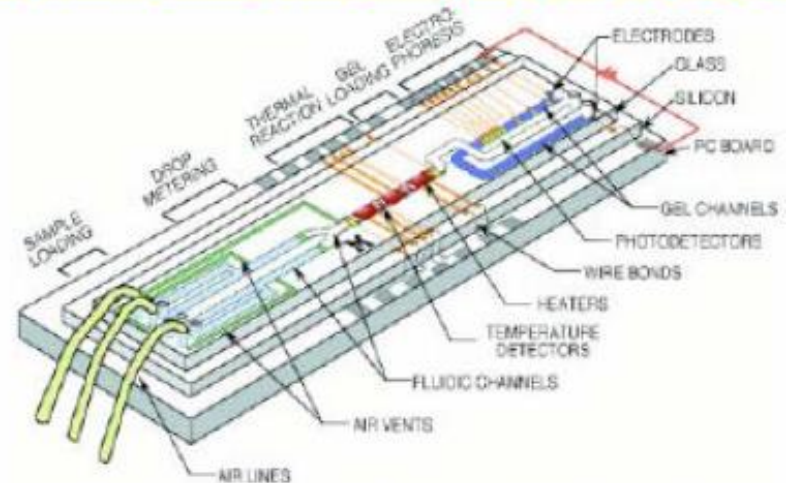
芯片实验室 (Lab-on-a-chip) 是指把生物和化学等领域中所涉及的样品制备、生物与化学反应、分离检测等基本操作单位集成或基本集成于一块几平方厘米的芯片上, 用以完成不同的生物或化学反应过程, 并对其产物进行分析的一种技术。实现化学分析检测即实现从试样处理到检测的整体微型化、自动化、集成化与便携化这一目标。

90年代初由Manz等人提出的以微电子加工技术为依托的芯片实验室的发展将会像四十年前微电子技术的信息科学的发展中引发一场革命一样, 预计芯片实验室将在未来的发展中对分析科学乃至整个科学技术以及相关的产业界产生相似的作用。计算机芯片使计算微型化, 而芯片实验室使实验室微型化, 因此, 在生物医学领域它可以使珍贵的生物样品和试剂消耗降低到微升甚至纳升级, 而且分析速度成倍提高, 成本成倍下降; 在化学领域它可以使以前需要在一个大实验室花大量样品、试剂和很多时间才能完成的分析和合成, 将在一块小的芯片上花很少量样品和试剂以很短的时间同时完成大量实验; 在分析化学领域, 它可以使以前大的分析仪器变成平方厘米尺寸规模的分析仪, 将大大节约资源和能源。

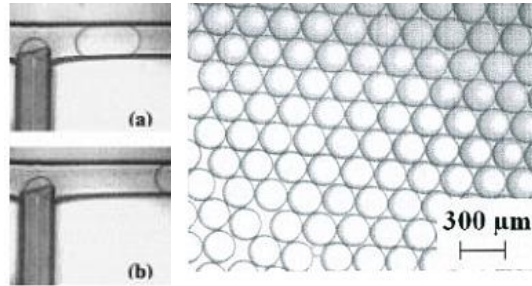
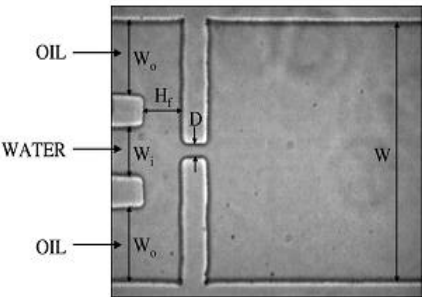


# Lab-on-a-Chip/Integrated Devices

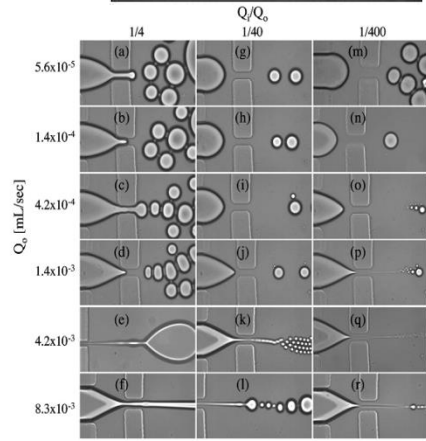
- Single chip device for DNA electrophoresis
- Sample loading and metering
- PCR on a chip (faster temperature cycling due to reduced thermal mass)
- Gel electrophoresis on chip



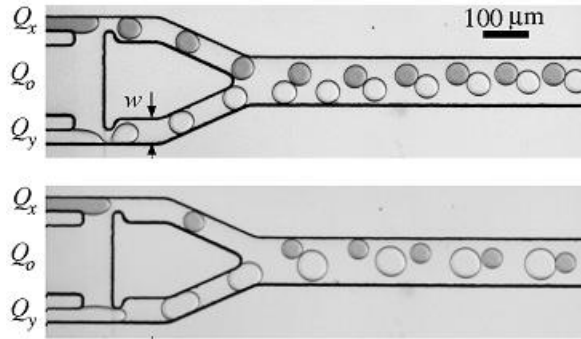
# 基于液滴的微流体技术



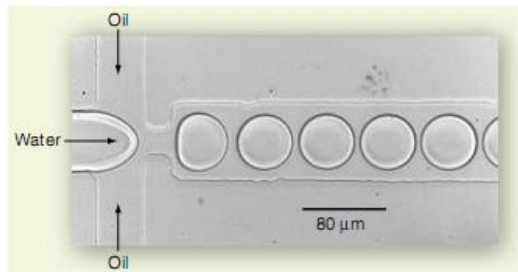
Droplet formation and size distribution. (Xu et al., *AIChE J.*, 2006)



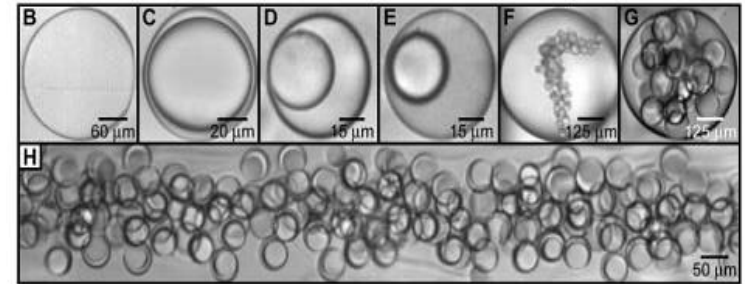
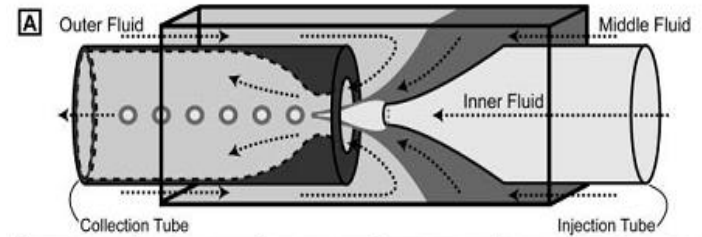
Droplet formation. (Anna et al., *APL.*, 2003)



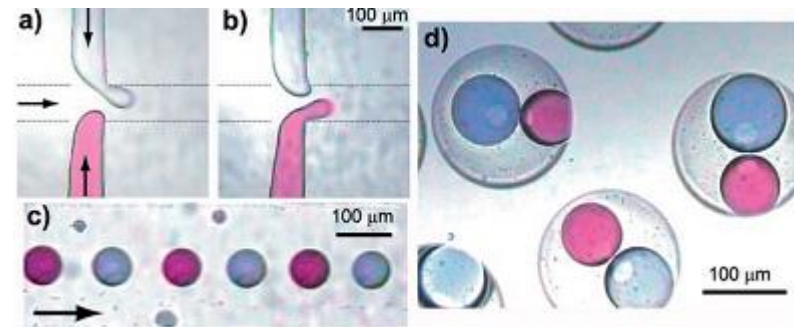
Pair droplets. (Frenz et al. *Langmuir*, 2008)



W/O droplets in a microdevice  
Joanicot et al., *Science*, 2005



Double emulsions from coaxial jets. (Utada et al., *Science*, 2005)

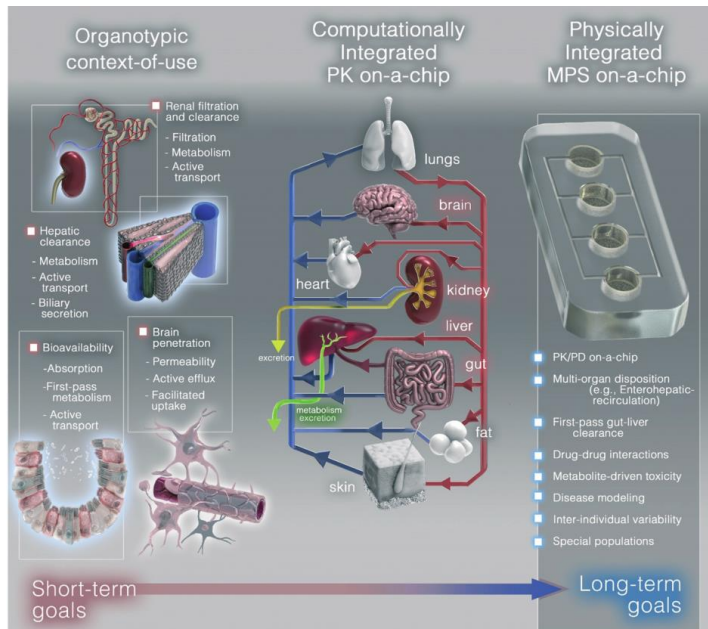
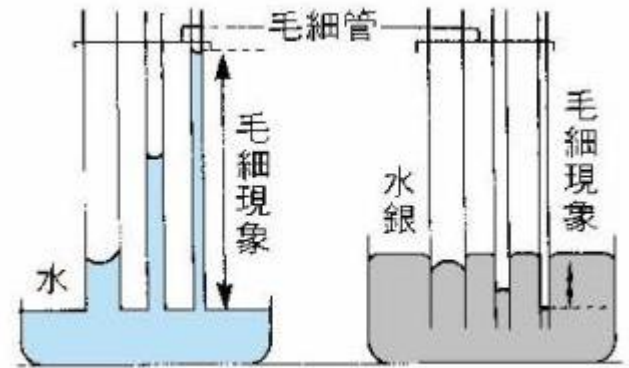


Double emulsions by encapsulation of alternating droplets (Okushima et al., *Langmuir*, 2004)



# 微流体相关自然及工程背景

- 毛细现象
- 芯片实验室
- 基于器官的芯片
- 仿生体系

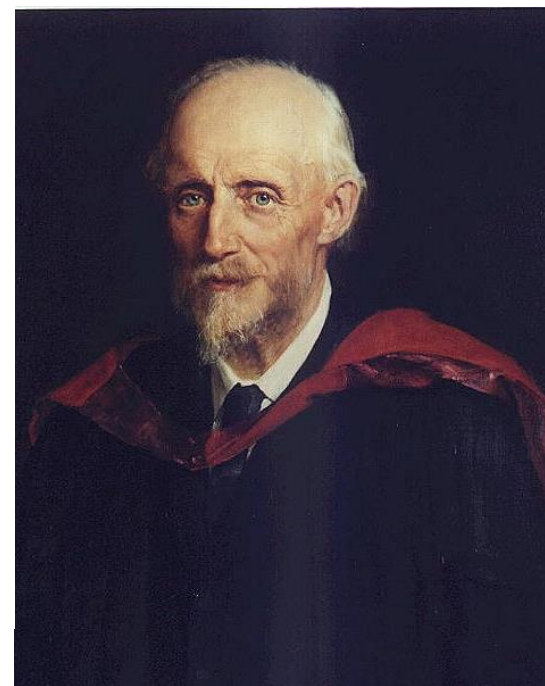
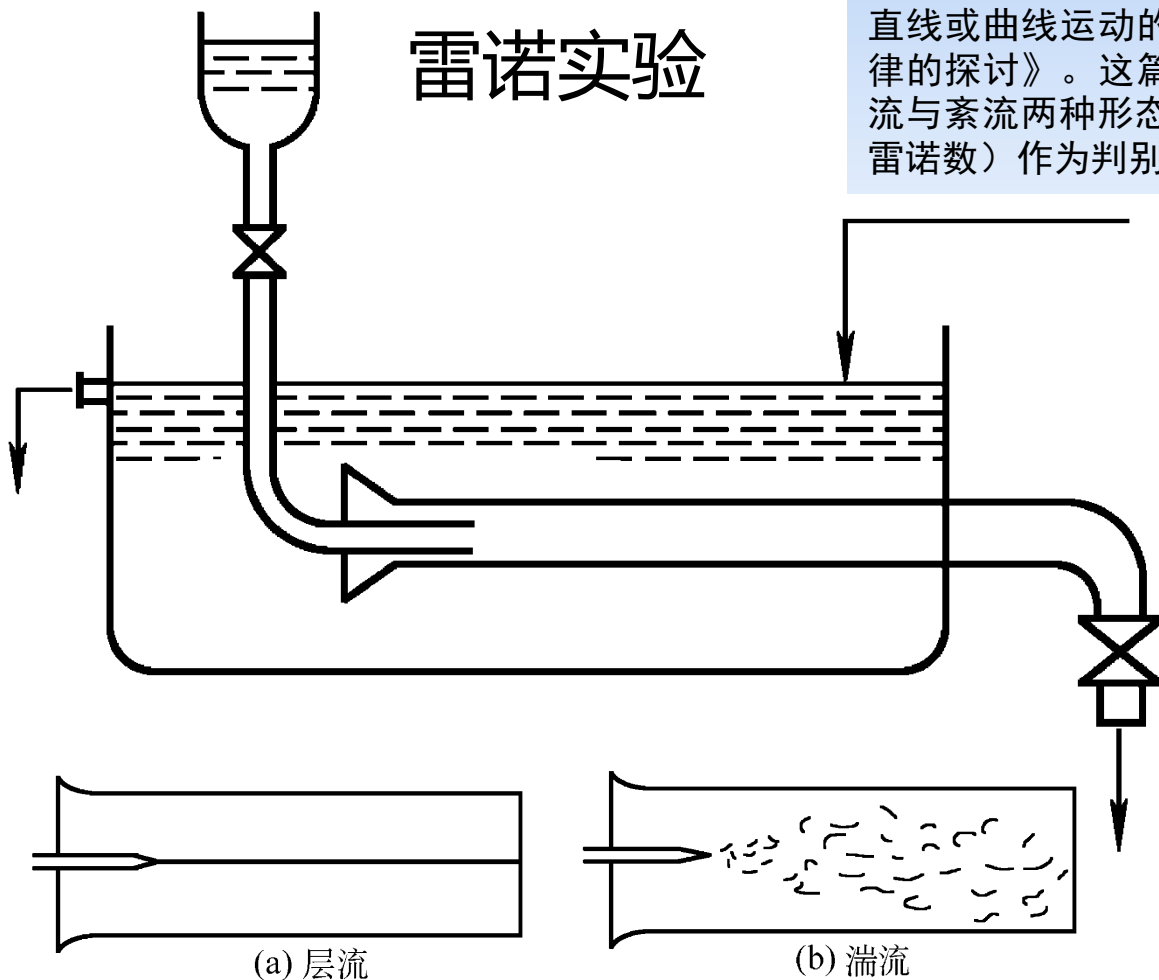


# 低雷诺数现象

雷诺 (O. Reynolds, 1842—1912, 爱尔兰)。英国力学家、物理学家和工程师。杰出的实验科学家。1842年8月23日生于北爱尔兰。1867年毕业于剑桥大学王后学院。1868年出任曼彻斯特欧文学院 (后改名为维多利亚大学) 的首席工程学教授。1877年当选为皇家学会会员。1888年获皇家勋章。

于1883年发表了一篇经典性论文——《决定水流为直线或曲线运动的条件以及在平行水槽中的阻力定律的探讨》。这篇文章以实验结果说明水流分为层流与紊流两种形态，并提出以无量纲数 $Re$  (后称为雷诺数) 作为判别两种流态的标准。

## 雷诺实验



# 时间可逆性与斯托克斯流



# 马兰戈尼效应

## 马兰戈尼效应

(Marangoni effect);  
由于两种表面张力不同的液体界面之间存在张力的梯度而使质量移动的现象，称为马兰戈尼效应。

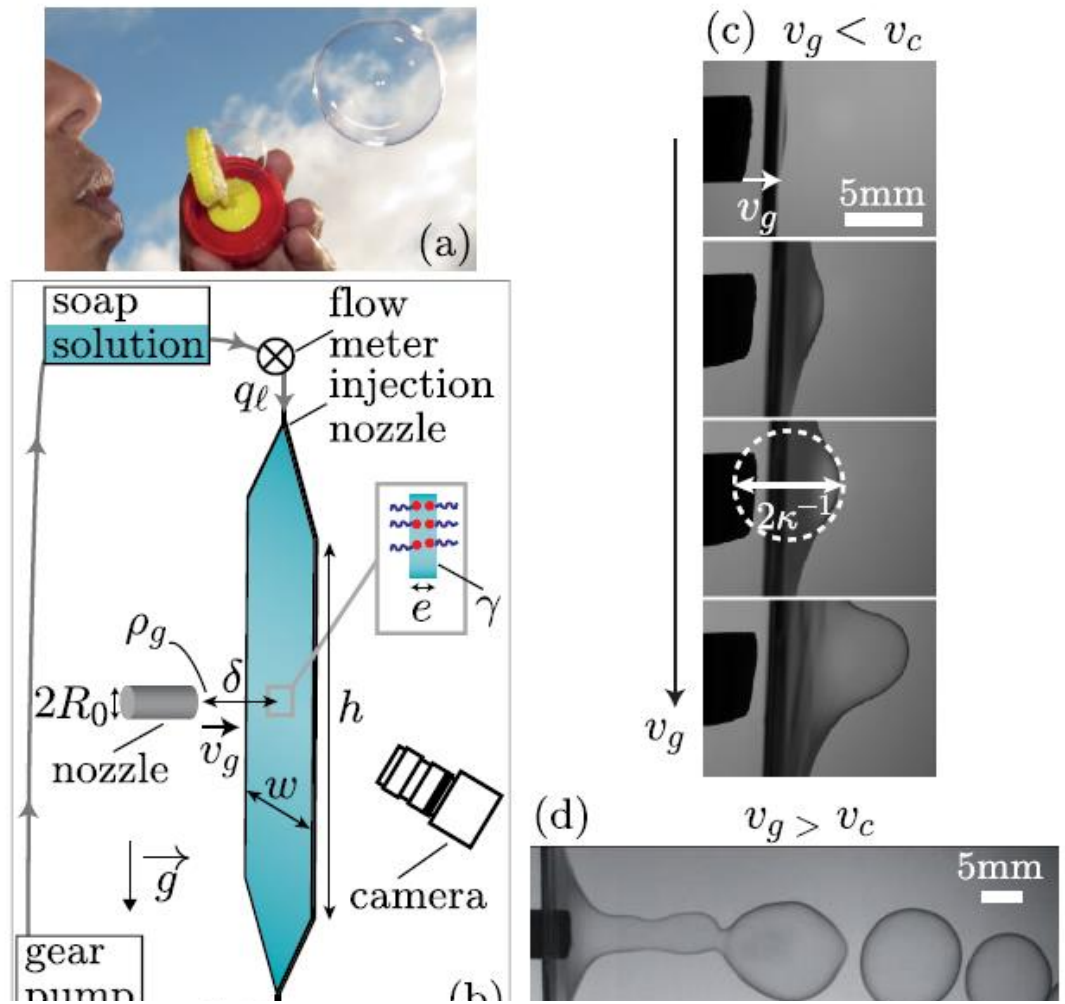


The Marangoni Effect





**稳定液膜**



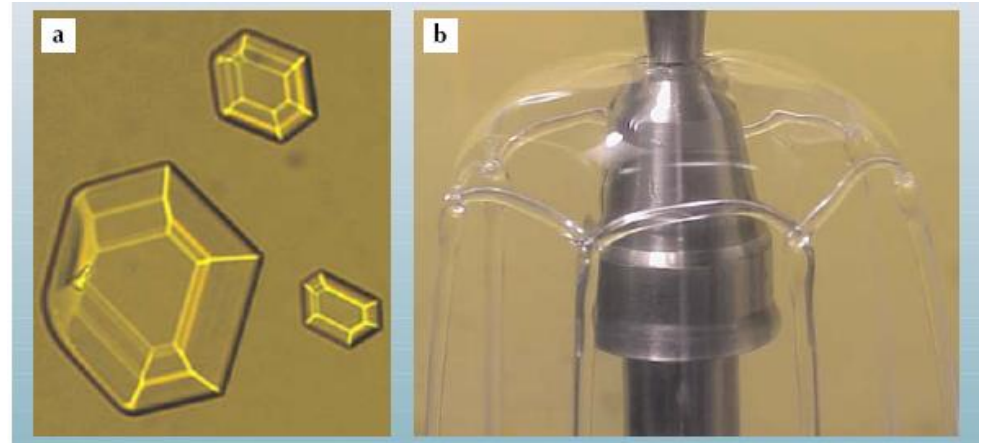
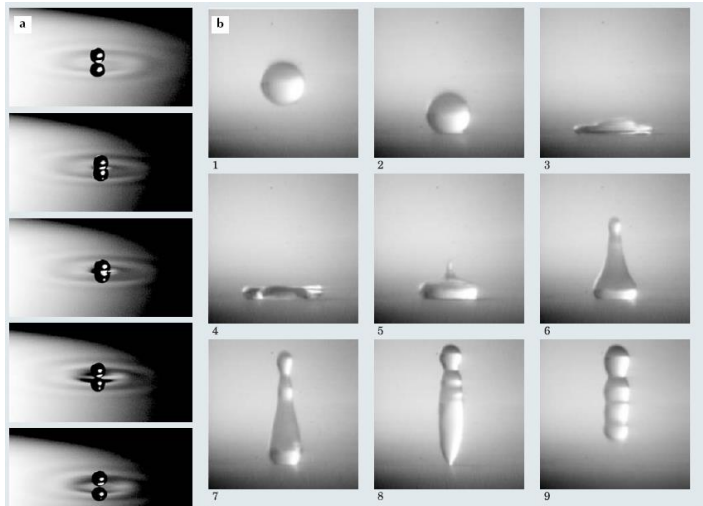
## Generating Soap Bubbles by Blowing on Soap Films

Louis Salkin, Alexandre Schmit, Pascal Panizza,<sup>\*</sup> and Laurent Courbin<sup>†</sup>

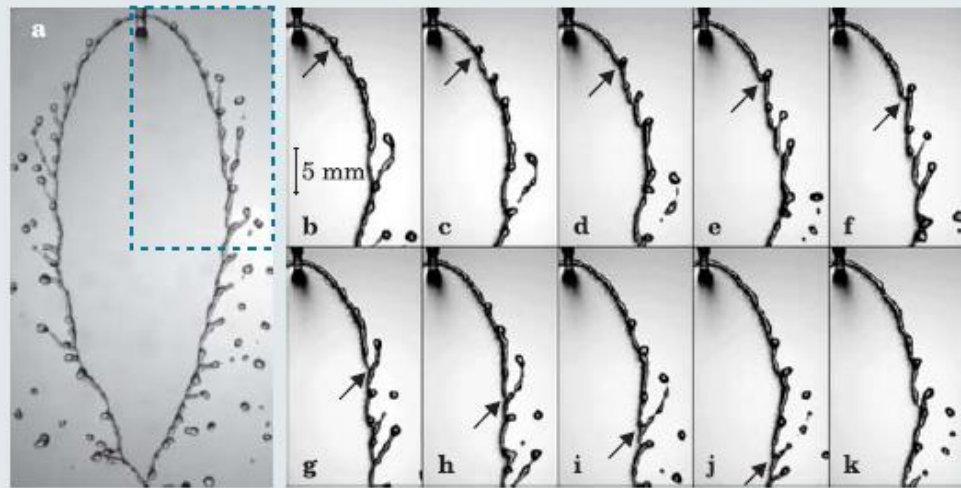
*IPR, UMR CNRS 6251, Campus Beaulieu, Université Rennes 1, 35042 Rennes, France*

(Received 26 August 2015; revised manuscript received 14 December 2015; published 19 February 2016)

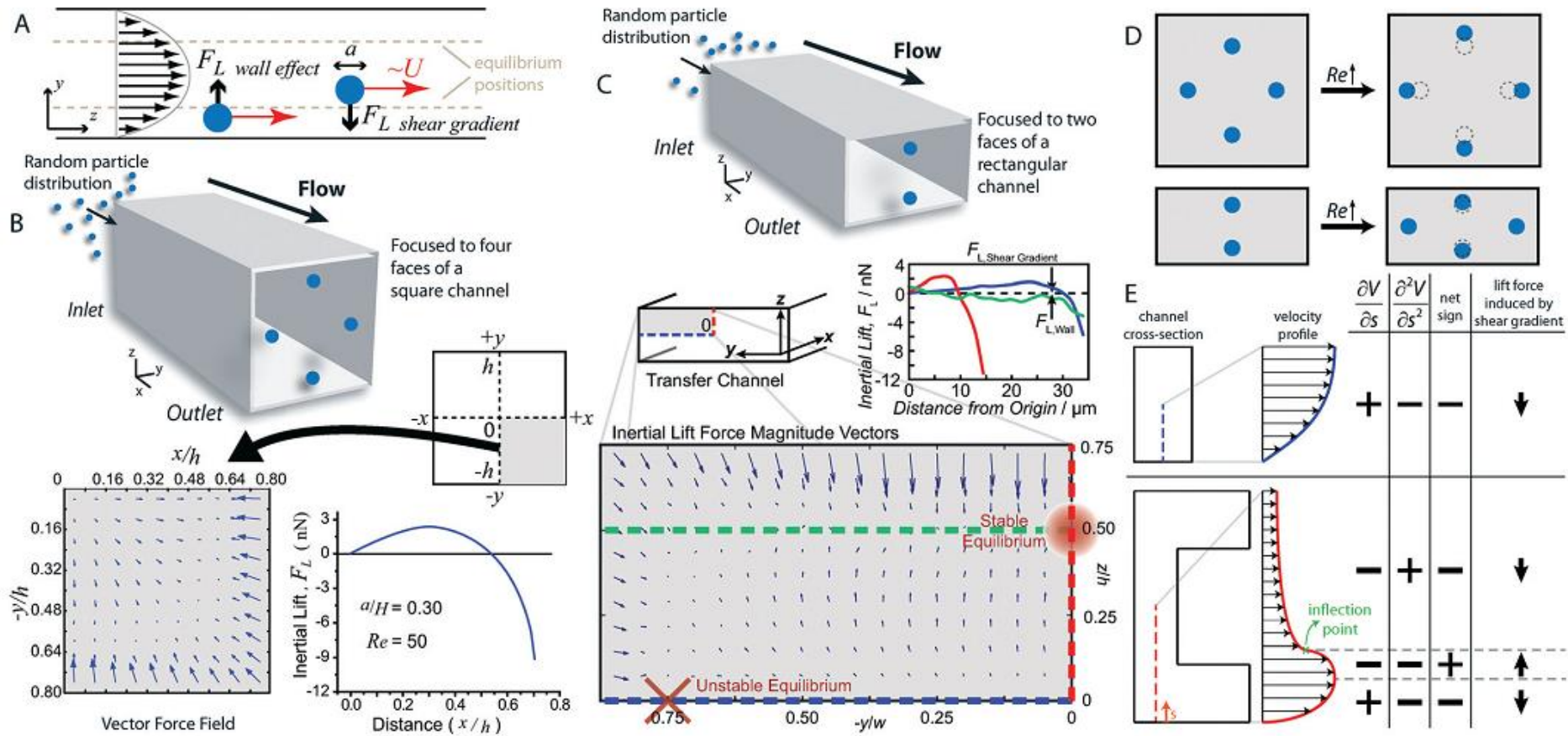
# 界面现象



**Figure 5. Drop formation** in ligaments. Two jets, normal to the page and meeting at a  $72^\circ$  angle, make a thin liquid sheet, the rim of which is visible here. The 10 panels on the right show the evolution of the fragmentation at the section of the rim indicated by the dashed blue line on the left; the arrows trace a ligament along the rim as it evolves. The time interval between the panels is 1 ms. The average shape of the sheet follows Laplace's law applied to its free edges.<sup>18</sup>

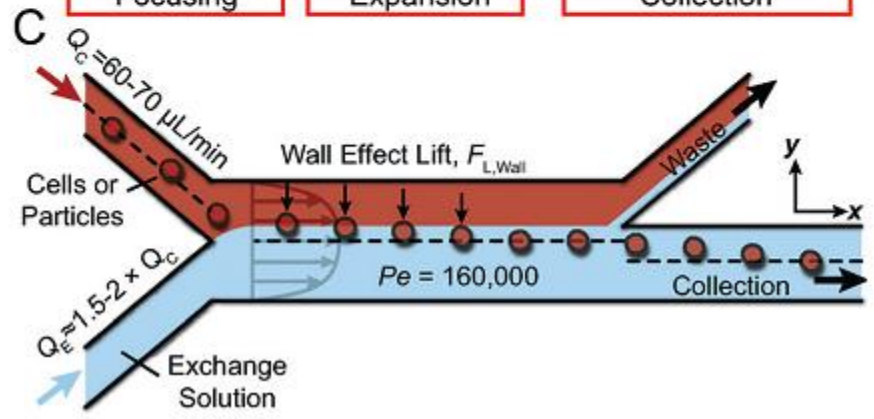
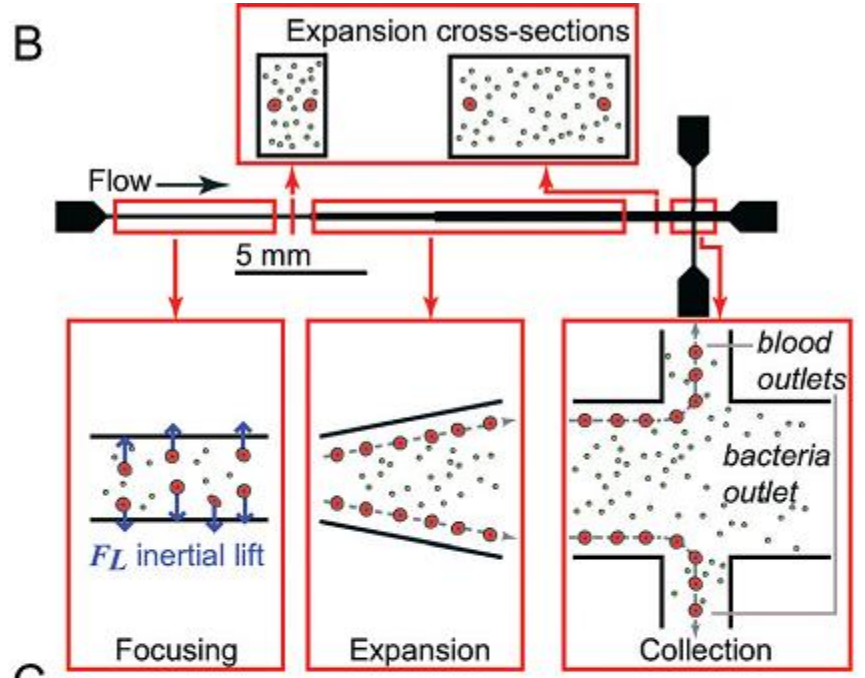
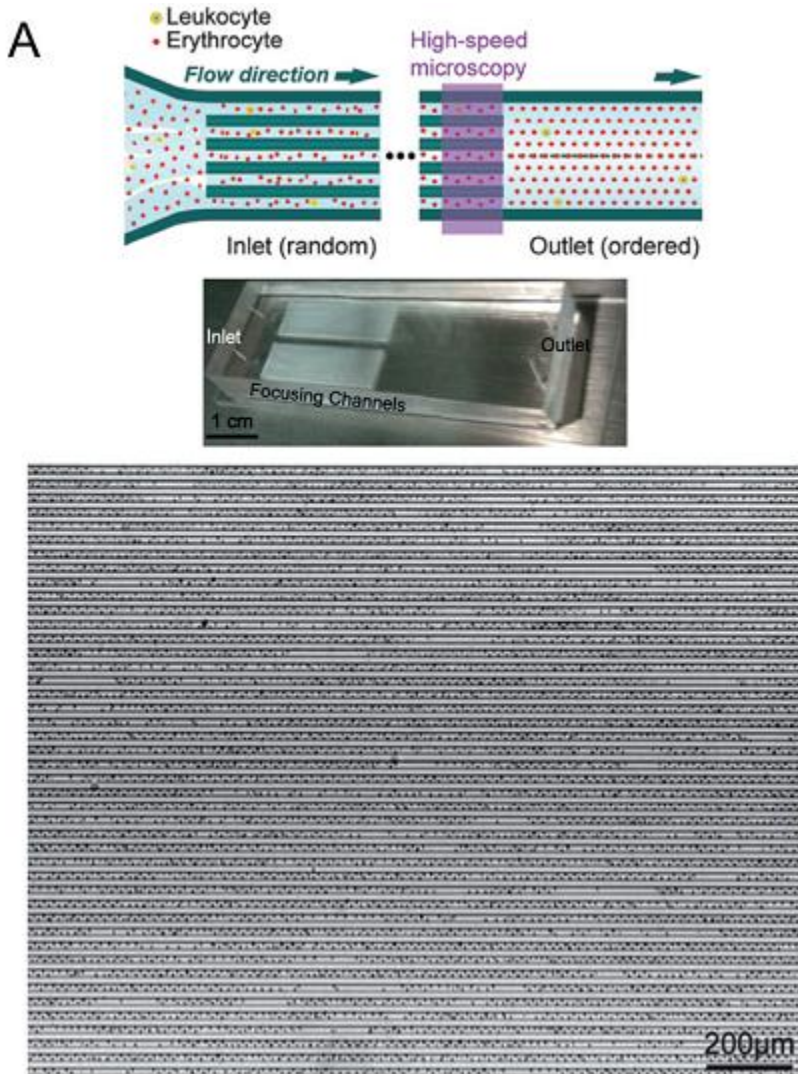


# Inertial microfluidics 惯性微流体





# 微流体与生物工程



# 微流体与材料化工

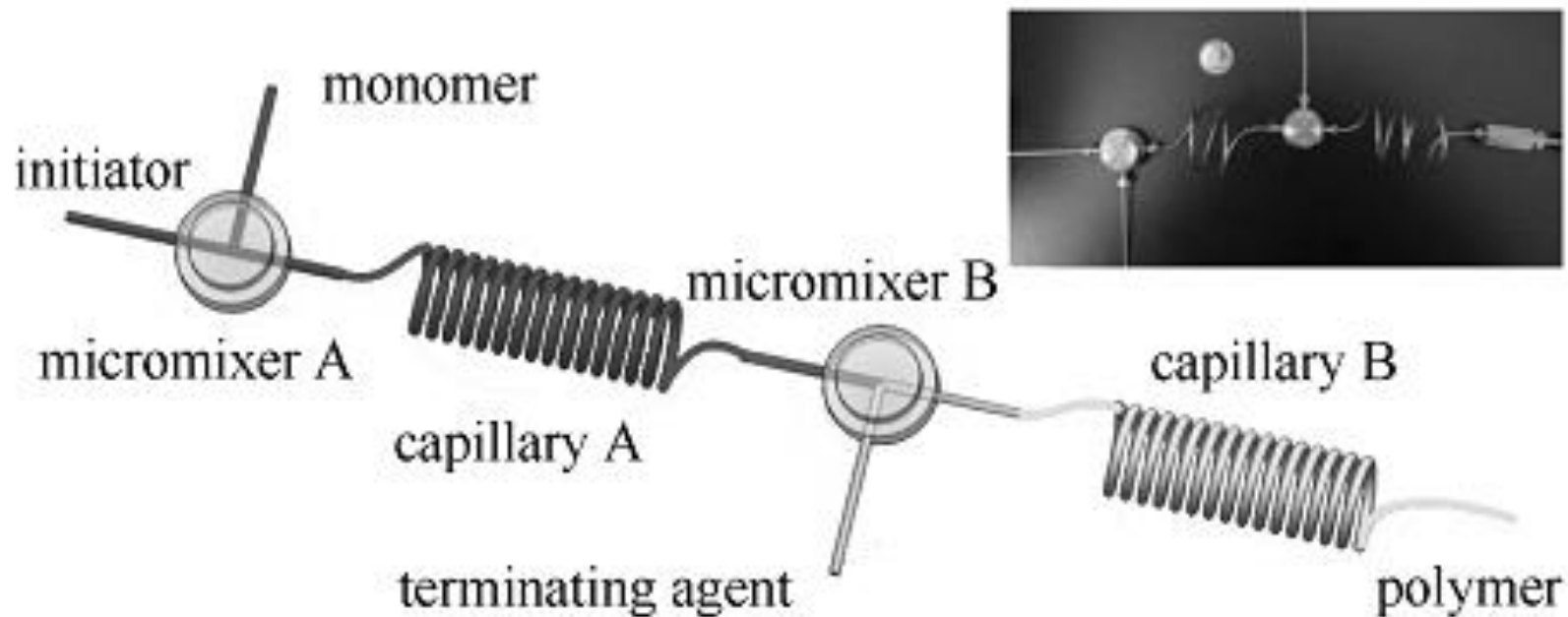


图 1 毛细管微反应器

Fig.1 Capillary microreactor

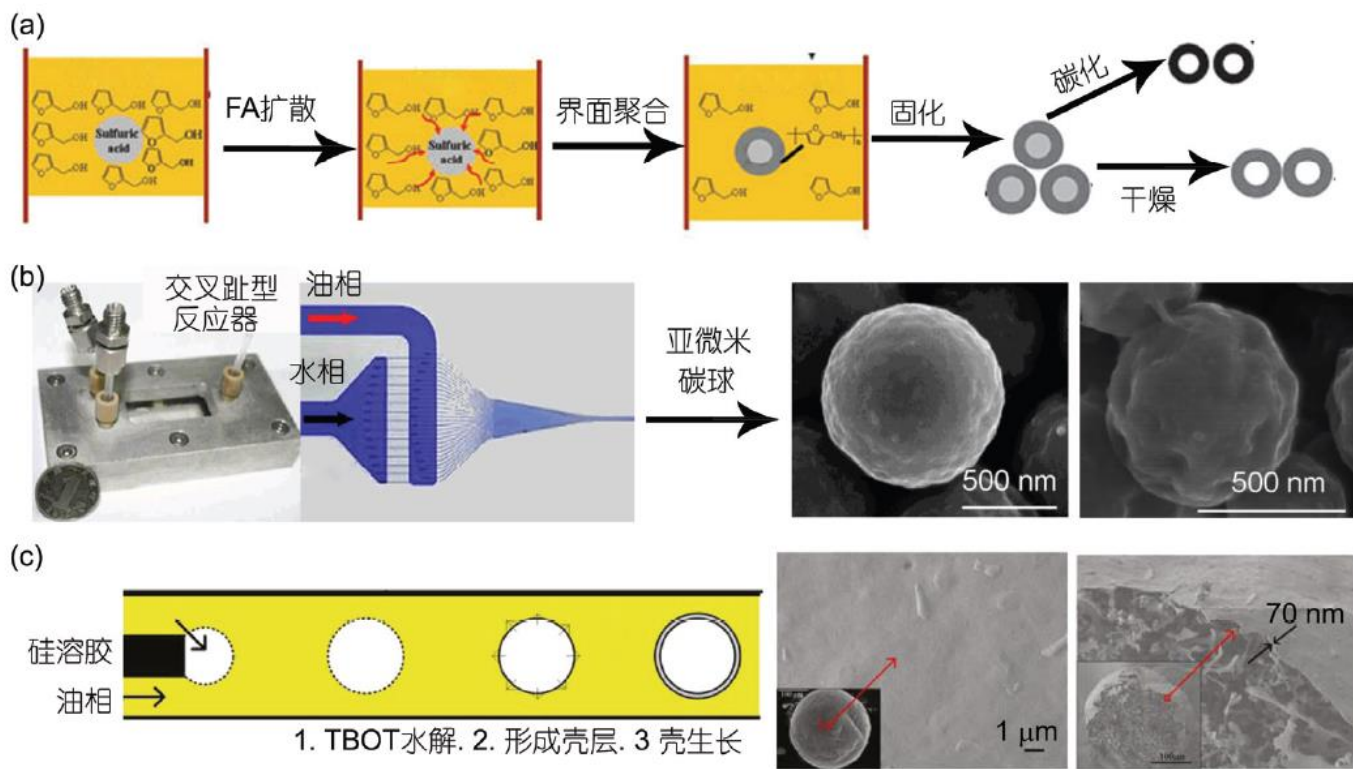


# 多级结构材料

- 多级结构材料指一类在微观尺度下结构或性质具有多样性的成型材料，如具有空心、核壳、Janus等结构的微球和微纤维、非球状的微囊泡、形貌独特的组装体、镶嵌结构 (structure-within-structure) 的复合体、复杂形貌和微结构的颗粒以及多级孔道结构的多孔材料等。
- 特点：结构复杂、形貌特殊、功能多样化

郭松, 尹苏娜, 潘宜昌, 陈苏, and 张利雄, *微流体技术制备多级结构材料的研究进展*, 中国科学化学 **45**, 24 (2015).





界面反应技术制备中空聚糠醇微球和炭微球<sup>[23]</sup>(a)、高尔夫型纳米碳球<sup>[24]</sup>(b)以及核壳结构 SiO<sub>2</sub>/TiO<sub>2</sub> 复合微球

郭松, 尹苏娜, 潘宜昌, 陈苏, and 张利雄, *微流体技术制备多级结构材料的研究进展*, 中国科学化学 **45**, 24 (2015).

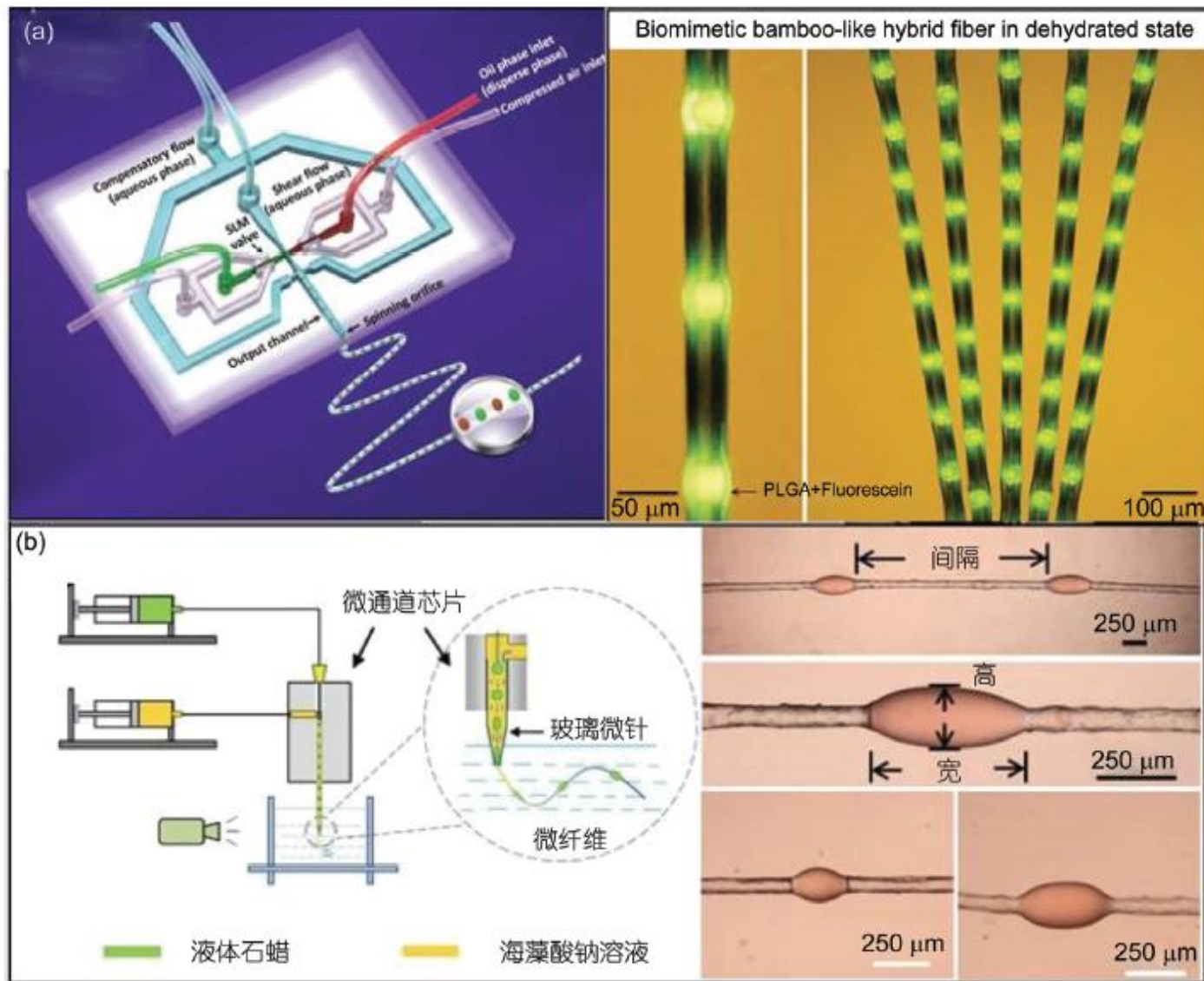
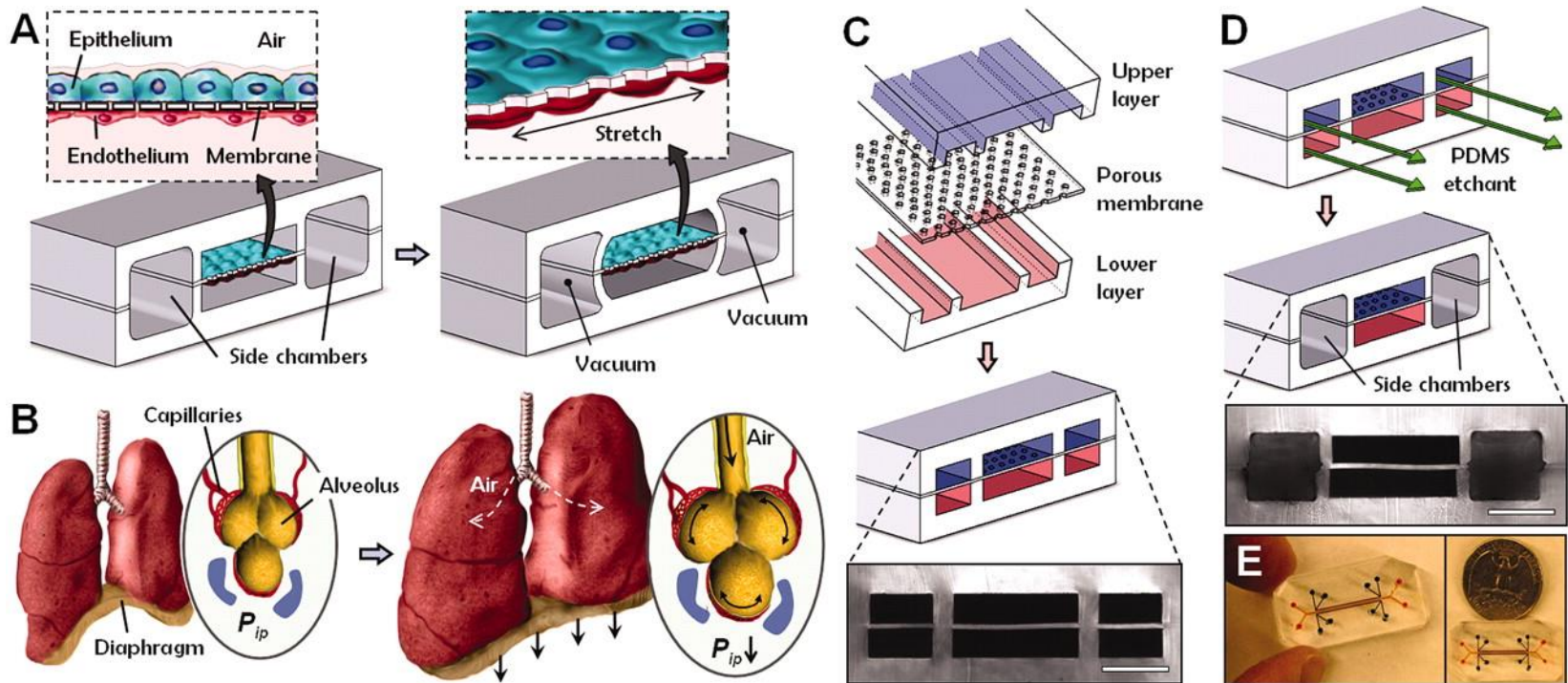


图 3 微流体纺丝与液滴技术相结合制备竹节状海藻酸钙纤维<sup>[31]</sup>(a)和珠串纤维

郭松, 尹苏娜, 潘宜昌, 陈苏, and 张利雄, 微流体技术制备多级结构材料的研究进展, 中国科学化学 45, 24 (2015).

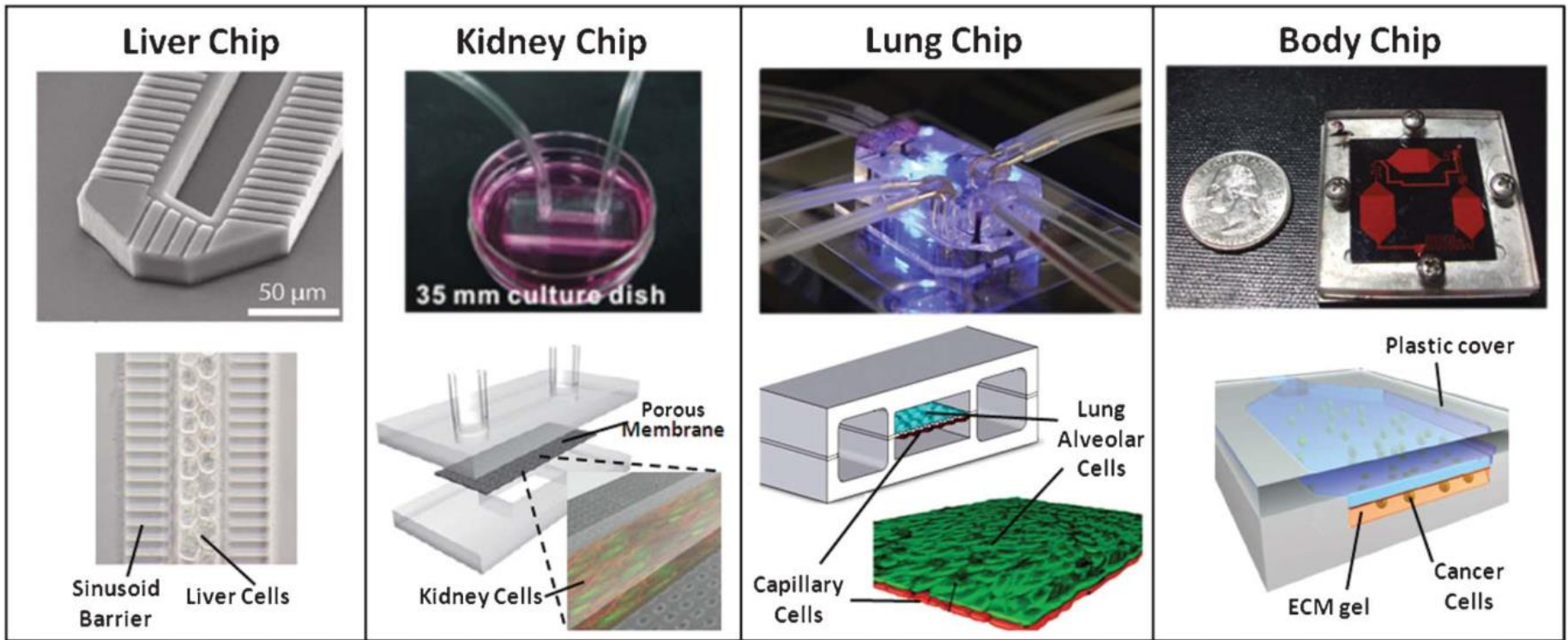
# 器官芯片-nature-inspired



**Fig. 1 Biologically inspired design of a human breathing lung-on-a-chip microdevice.**

Dongeun Huh et al. *Science* 2010;328:1662-1668





D. Huh, Y.-s. Torisawa, G. A. Hamilton, H. J. Kim, and D. E. Ingber, *Microengineered physiological biomimicry: Organs-on-Chips*, *Lab on a Chip* **12**, 2156 (2012).



# 合成生物学

## SYNTHETIC BIOLOGY

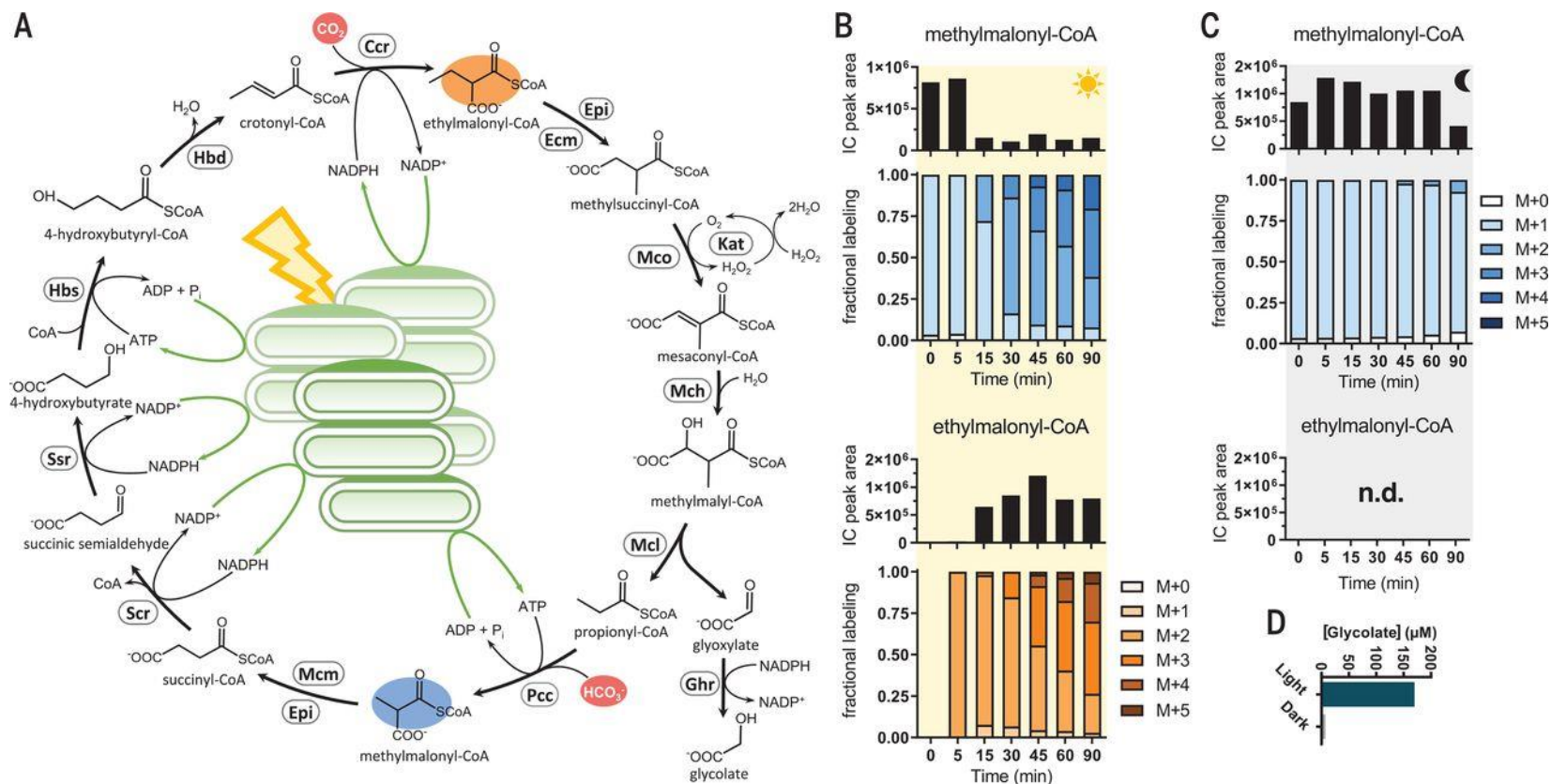
### Light-powered CO<sub>2</sub> fixation in a chloroplast mimic with natural and synthetic parts

Tarryn E. Miller<sup>1</sup>, Thomas Beneyton<sup>2</sup>, Thomas Schwander<sup>1</sup>, Christoph Diehl<sup>1</sup>, Mathias Girault<sup>3</sup>, Richard McLean<sup>1</sup>, Tanguy Chotel<sup>2</sup>, Peter Claus<sup>1</sup>, Niña Socorro Cortina<sup>1</sup>, Jean-Christophe Baret<sup>2,3\*</sup>, Tobias J. Erb<sup>1,4\*</sup>

Nature integrates complex biosynthetic and energy-converting tasks within compartments such as chloroplasts and mitochondria. Chloroplasts convert light into chemical energy, driving carbon dioxide fixation. We used microfluidics to develop a chloroplast mimic by encapsulating and operating photosynthetic membranes in cell-sized droplets. These droplets can be energized by light to power enzymes or enzyme cascades and analyzed for their catalytic properties in multiplex and real time. We demonstrate how these microdroplets can be programmed and controlled by adjusting internal compositions and by using light as an external trigger. We showcase the capability of our platform by integrating the crotonyl-coenzyme A (CoA)/ethylmalonyl-CoA/hydroxybutyryl-CoA (CETCH) cycle, a synthetic network for carbon dioxide conversion, to create an artificial photosynthetic system that interfaces the natural and the synthetic biological worlds.

T. E. Miller, et al., *Light-powered CO<sub>2</sub> fixation in a chloroplast mimic with natural and synthetic parts*, *Science* **368**, 649 (2020).

**Fig. 2 Light-driven, continuous fixation of CO<sub>2</sub> into organic acids.**



Tarryn E. Miller et al. *Science* 2020;368:649-654

# 化工前沿

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- Adamo, A., Beingessner, R.L., Behnam, M., Chen, J., Jamison, T.F., Jensen, K.F., Monbaliu, J.-C.M., Myerson, A.S., Revalor, E.M., Snead, D.R., Stelzer, T., Weeranoppanant, N., Wong, S.Y., Zhang, P., 2016. On-demand continuous-flow production of pharmaceuticals in a compact, reconfigurable system. *Science* 352, 61-67.

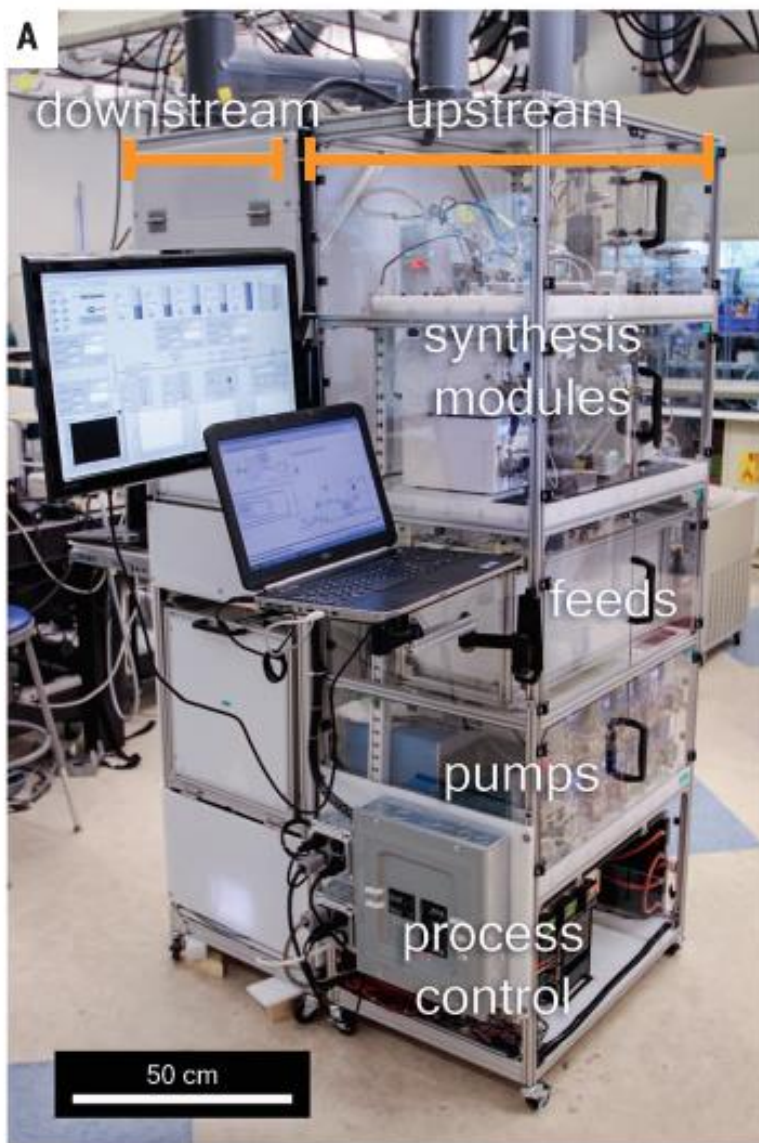


**Fig. 1. Reconfigurable system for continuous production and formulation of APIs.** (A)

Labeled photograph of the stack of upstream synthesis modules.

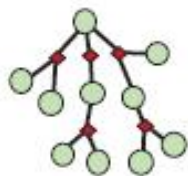
(B) Labeled photograph of the downstream purification and formulation modules. (C) Close-up examples of upstream units; PFA tube flow reactors in an aluminum shell for heating (left) and membrane surface tension-based separation units (right).

(D) Images of some of the main components in the downstream unit including the (a) buffer tank, (b) precipitation tank, (c) filtration unit, (d) crystallization unit, (e) filtration unit, (f) formulation tank, (g) solution holding tank, and (h) formulated API. Details are in the supplementary text.





# 智慧化工与智能化化工AI



## Route selection

- Retrosynthetic planning
- Condition recommendation
- Pathway evaluation



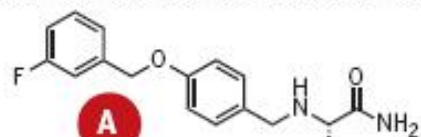
## Process development

- Specification of residence times, concentrations
- Module selection



## Reaction execution

- Recipe-driven synthesis
- Robotic reconfiguration
- Process monitoring



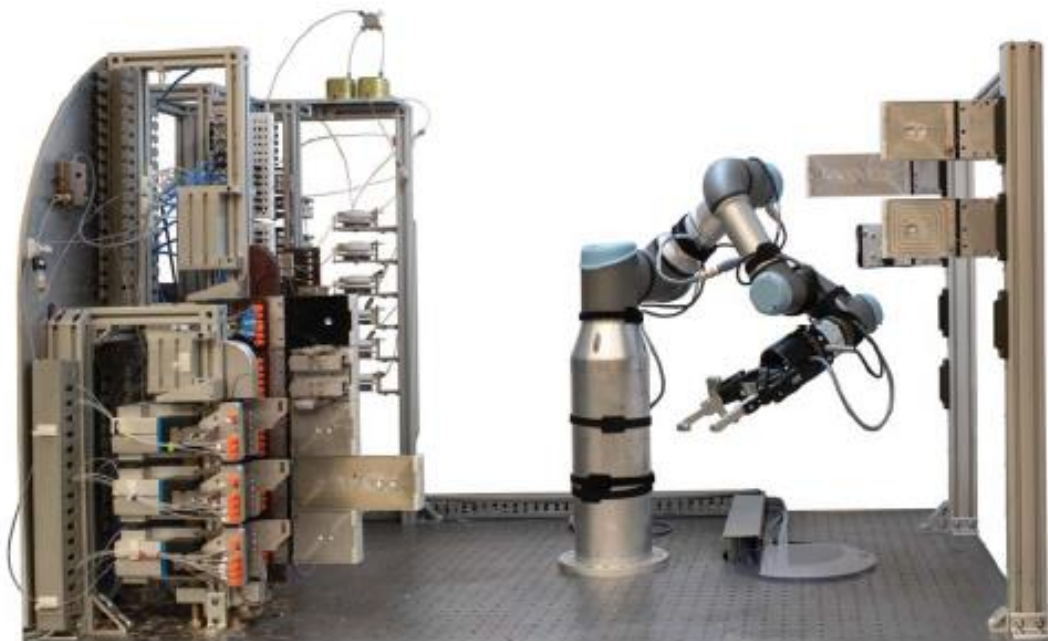
Target compound

Published reactions

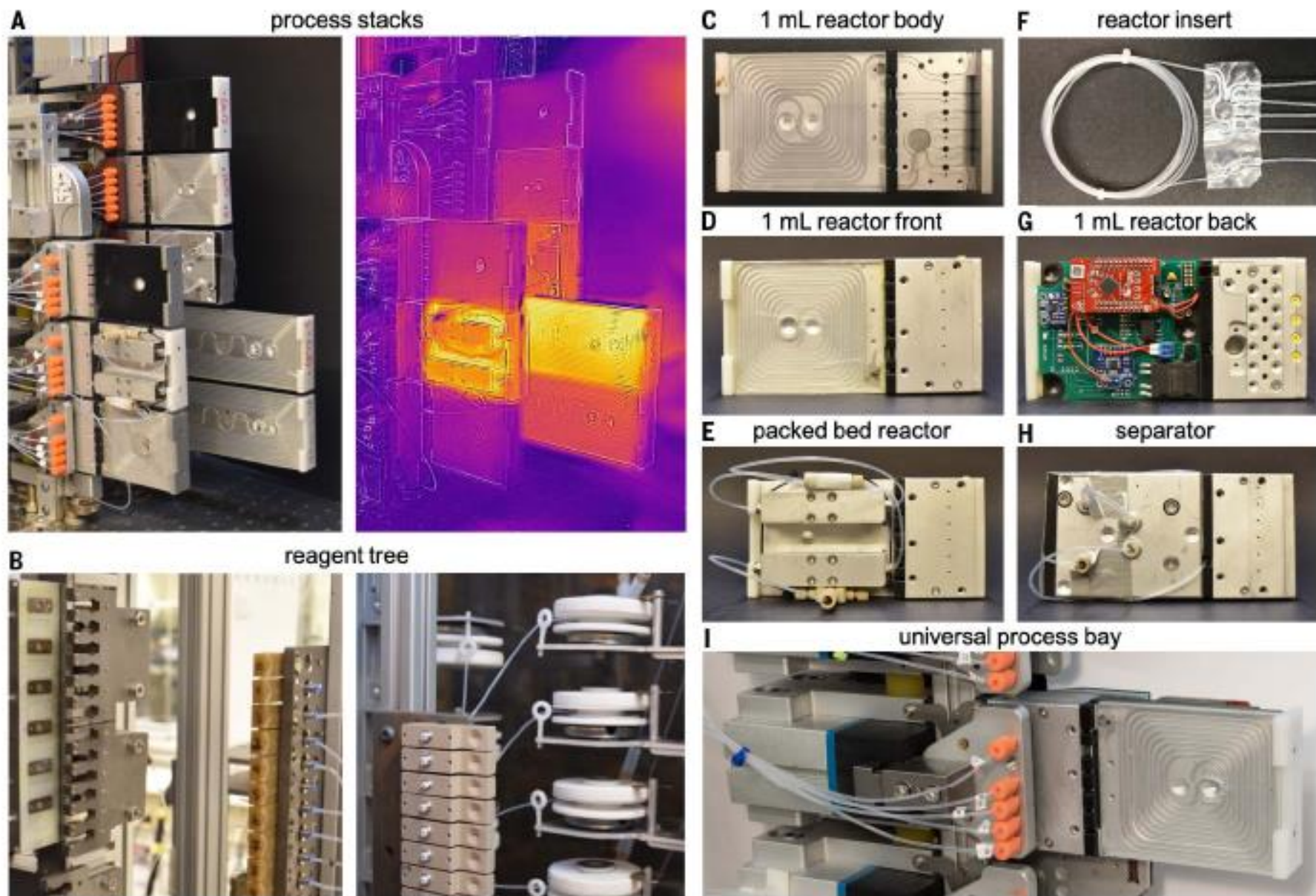


Commercially available compounds

Synthetic route



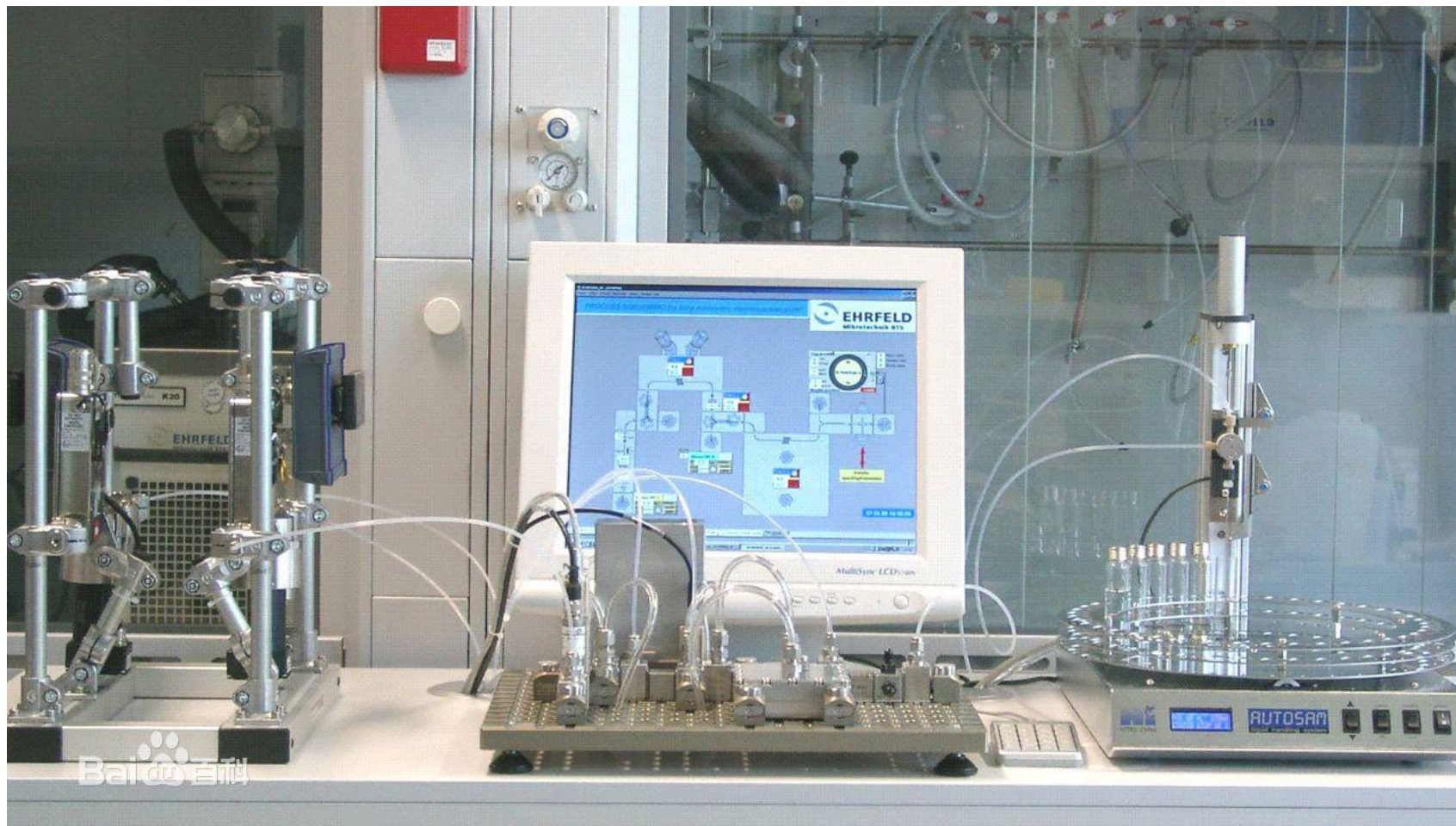
**Planning and execution.** A robotically reconfigurable flow chemistry platform performs multistep chemical syntheses planned in part by AI.



**Fig. 3. Process and submodules implemented on robotic flow chemistry platform.** (A) Process stack where modules interface with UPBs to form a continuous flow path (left) and thermal image showing heated reactors (right); (B) front view of the reagent tree and reagent manifold; (C) image of front view of reactor body; (D) 1.0-ml reactor process module; (E) two-column packed bed reactor process module; (F) disposable PFA reactor insert; (G) integrated electronics on back side of 1.0-ml reactor; (H) in-line membrane separator; (I) close-up of a UPB holding a 1.0-ml reactor.

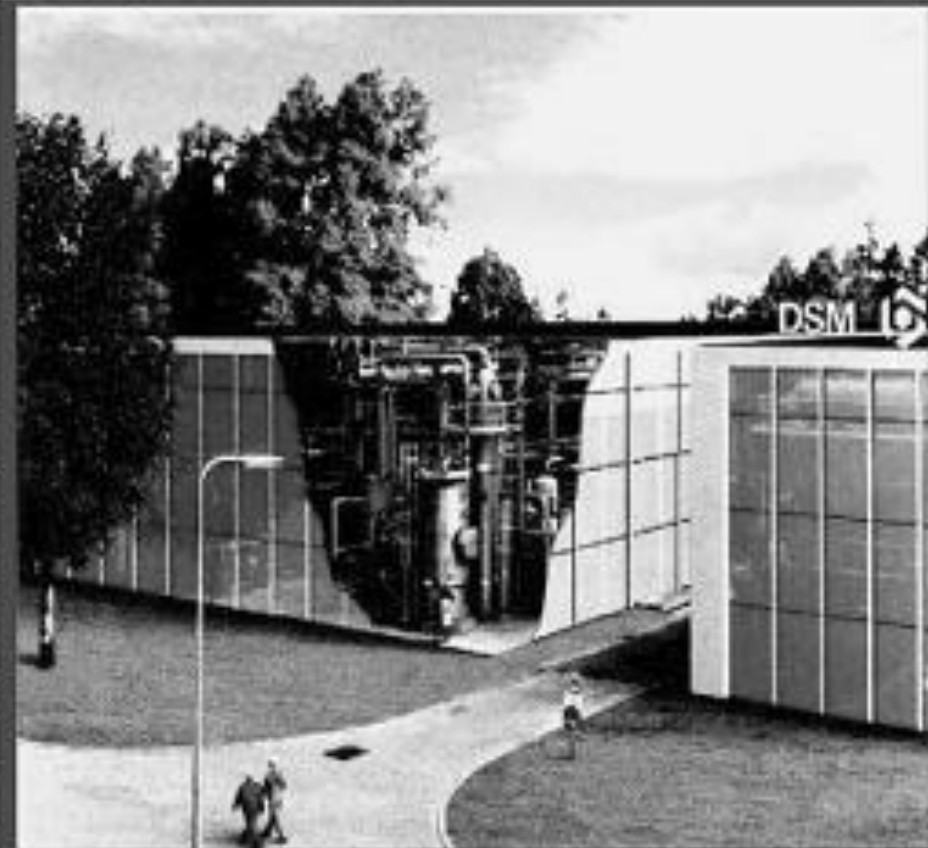


# 桌面工厂



拜耳-埃尔费尔德微技术公司  
模块化微反应系统

One vision of how a future plant (miniplant) employing process intensification may look (right) vs. a conventional plant (left) (Stankiewicz et al. *CEP*. 2000)



**OPERATING with NON POLLUTING PROCESSES involving  
PROCESS INTENSIFICATION**

**SAVINGS ABOUT 30% (RAW MATERIALS + ENERGY + OPERATING COSTS)**



# 本质安全



2021年5月11日上午，日本福岛县石城市一化工厂发生爆炸。



2021年5月6日，宁波科元精化股份有限公司生产装置发生爆燃。



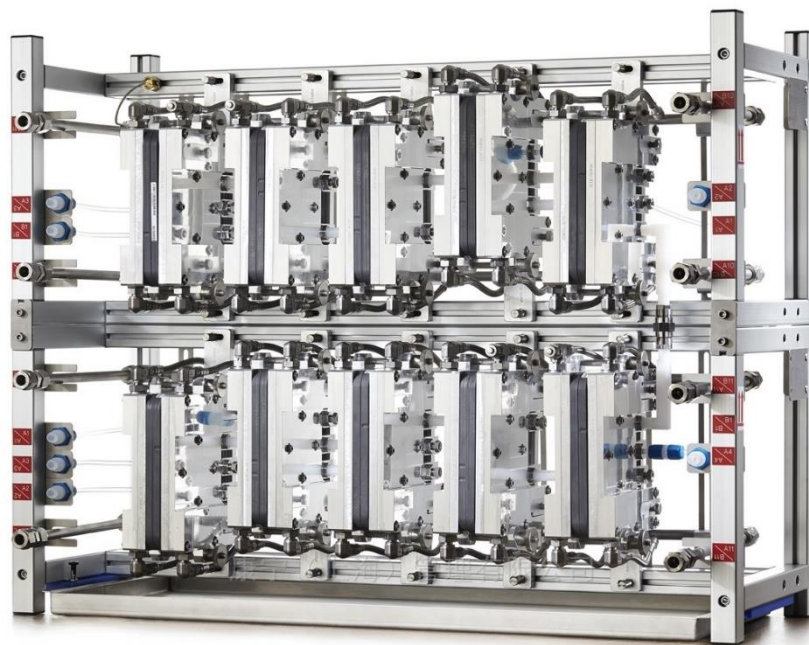
2020年11月17日，江西吉安井冈山经济技术开发区海州医药化工有限公司，废水蒸馏车间发生一起爆炸，致2人失联，6人受伤。

1974年，英国 Flixborough 大爆炸事故后，以 Trevor Kletz为代表的工程师开始认真思考怎么才能做到化工生产的本质安全。通常，本质安全包含四个方面的内容：

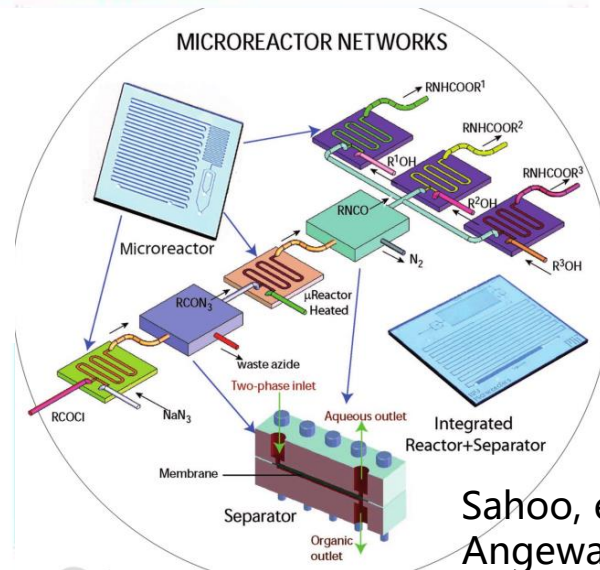
- 1、尽量消除各种危害和风险；
- 2、在不能完全消除的情况下，减小危险的程度；
- 3、同时降低危害发生的可能性；
- 4、在上述前提下，同时做好对人员的保护。

反应体系快速强放热，  
易引起安全问题。  
微化工技术能及时移除  
热量，并有效控制反应  
过程。

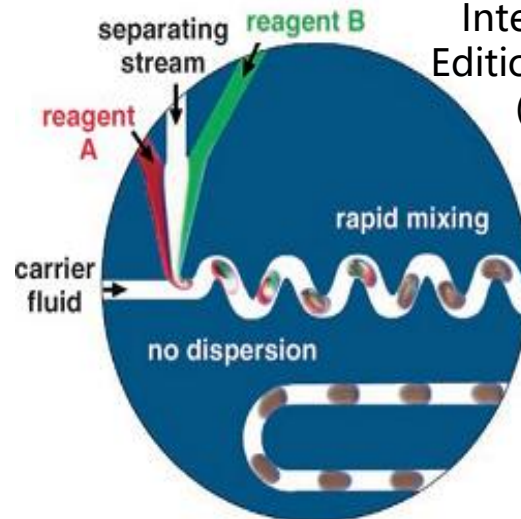
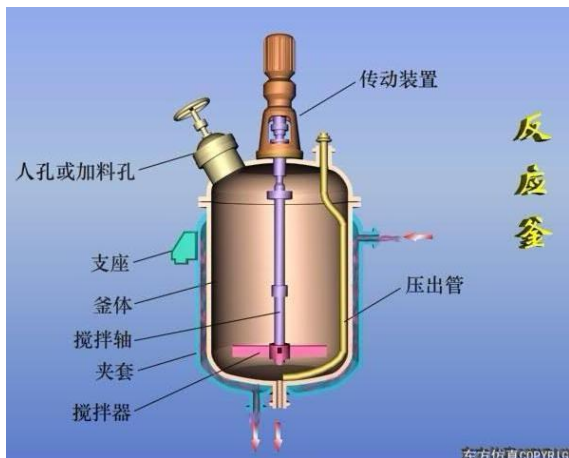
康宁-Advanced Flow Reactor



# 采用微反应器的连续流动式的优势



Sahoo, et al.,  
Angewandte  
Chemie  
International  
Edition **46**, 5704  
(2007).



Song et al., AC, 2003

# 碳达峰碳中和



**碳达峰**是指碳排放在由升转降过程中碳排放的最高点即峰值，**碳中和**指人为排放源与通过植树造林、碳捕集与封存技术等人为吸收碳汇达到平衡。目前中国能源强度是世界平均水平的1.3倍。对普通公众而言，碳达峰、碳中和是一个“新生事物”，而实现“30-60目标”更是涉及地方经济发展、传统行业转型、新兴领域前瞻性投资、个人消费观改变的系统工程。

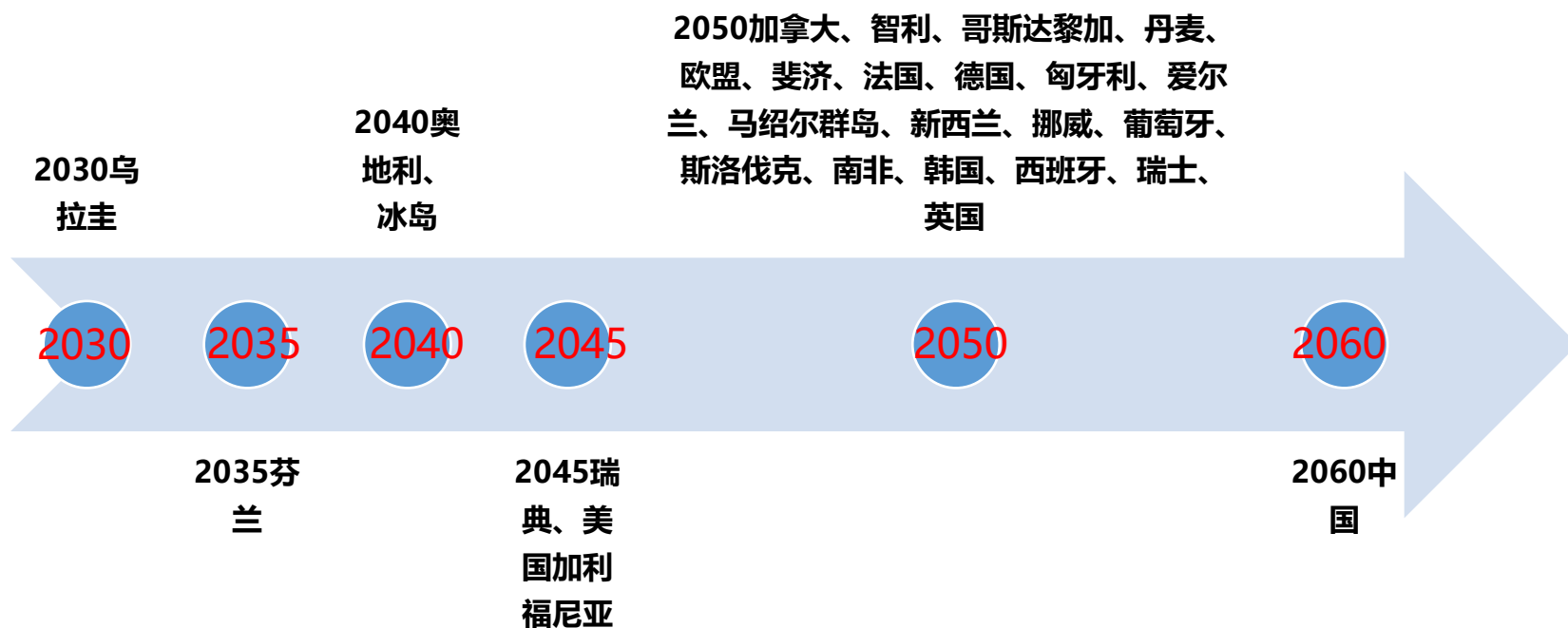
2020年9月，习近平主席在第七十五届联合国大会上郑重宣布：中国将提高国家自主贡献力度，二氧化碳排放力争于**2030年前达到峰值**，争取**2060年前实现碳中和**。

国家主席习近平22日晚在北京以视频方式出席领导人气候峰会并发表重要讲话。习近平指出，去年，我正式宣布中国将力争2030年前实现碳达峰、2060年前实现碳中和。这是中国基于推动构建人类命运共同体的责任担当和实现可持续发展的内在要求作出的重大战略决策。中国承诺实现从碳达峰到碳中和的时间，远远短于发达国家所用时间，需要中方付出艰苦努力。

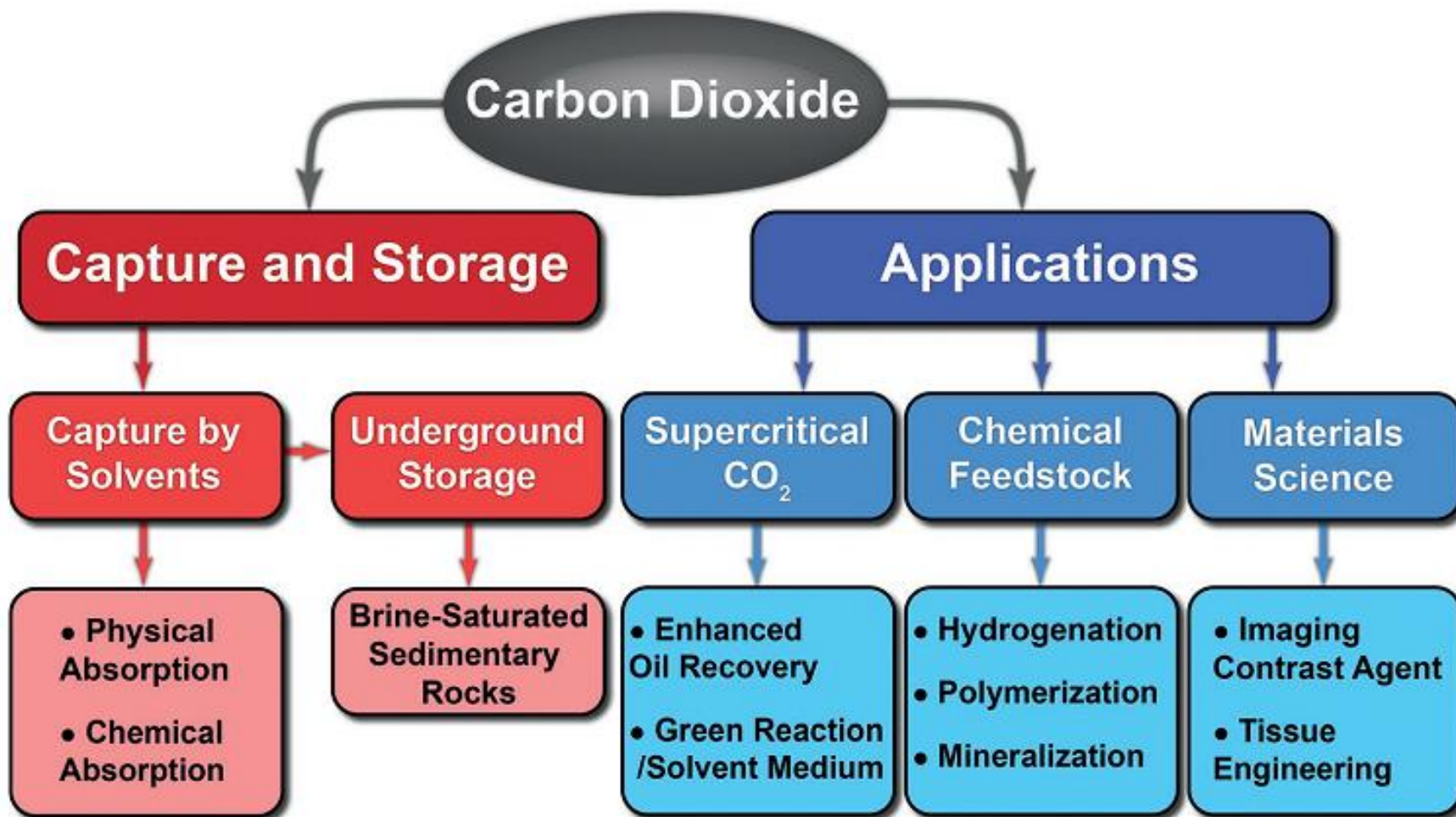


**碳中和 (carbon-neutral)** 定义如下：当一个组织在一年内的二氧化碳 (CO<sub>2</sub>) 排放通过二氧化碳去除技术应用达到平衡，就是碳中和或净零二氧化碳排放。

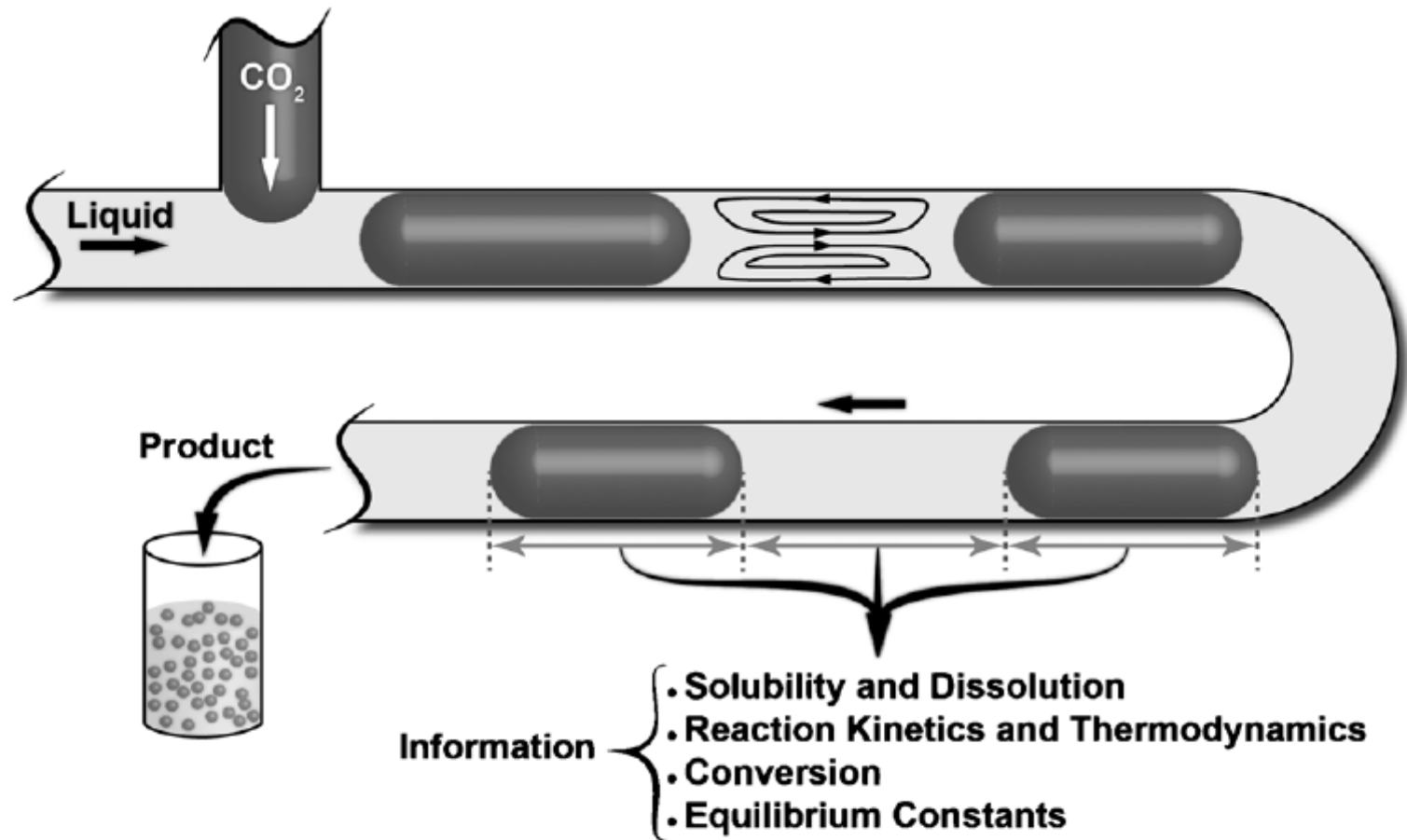
**净零排放 (net zero emission)** 的定义：当一个组织的一年内所有温室气体 (CO<sub>2</sub>-e, 以二氧化碳当量衡量) 排放量与温室气体清除量达到平衡时，就是净零温室气体排放。



# 二氧化碳捕集、封存与应用



Abolhasani, M., Günther, A., Kumacheva, E., 2014. Microfluidic studies of carbon dioxide. *Angewandte Chemie International Edition* 53, 7992-8002.

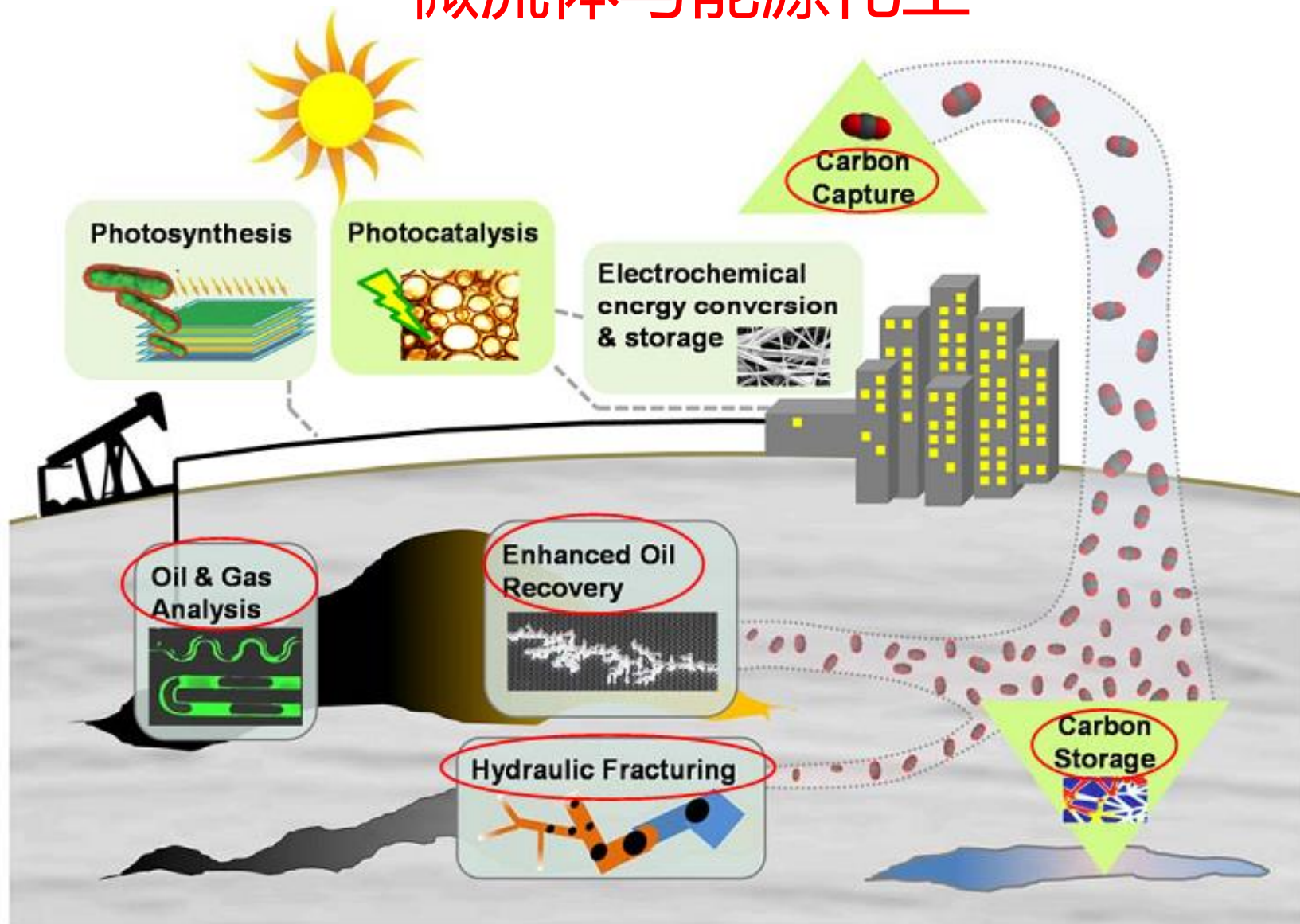


微流体系统强化二氧化碳捕集的传质过程，提高效率

快速测量传质与反应过程的参数

Abolhasani, M., Günther, A., Kumacheva, E., 2014. Microfluidic studies of carbon dioxide. *Angewandte Chemie International Edition* 53, 7992-8002.

# 微流体与能源化工



Sinton, D., 2014. Energy: the microfluidic frontier. Lab on a Chip 14, 3127-3134.



谢谢  
欢迎批评指正  
欢迎交流讨论