Ce que peut la matière : quelques éléments de réflexion à l'échelle du nanomètre

Xavier Bouju

Groupe Nanosciences - CEMES-CNRS, Toulouse

Christine Browaeys Bernard Monnier

13 juin 2019

« Personne n'a jusqu'à présent déterminé ce que peut le corps. »

« L'expérience n'a jusqu'ici enseigné à personne ce que, grâce aux seules lois de la Nature, le corps peut ou ne peut pas faire, à moins d'être déterminé par l'esprit. Car personne jusqu'ici n'a connu la structure du corps assez exactement pour en expliquer toutes les fonctions. »

L'Éthique, Spinoza

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corps → matière

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L'Éthique, Spinoza

corps → matière

Ce que peut la **matière** ?

Car personne jusqu'ici n'a connu la **structure** de la matière assez exactement pour en expliquer les **fonctions**.

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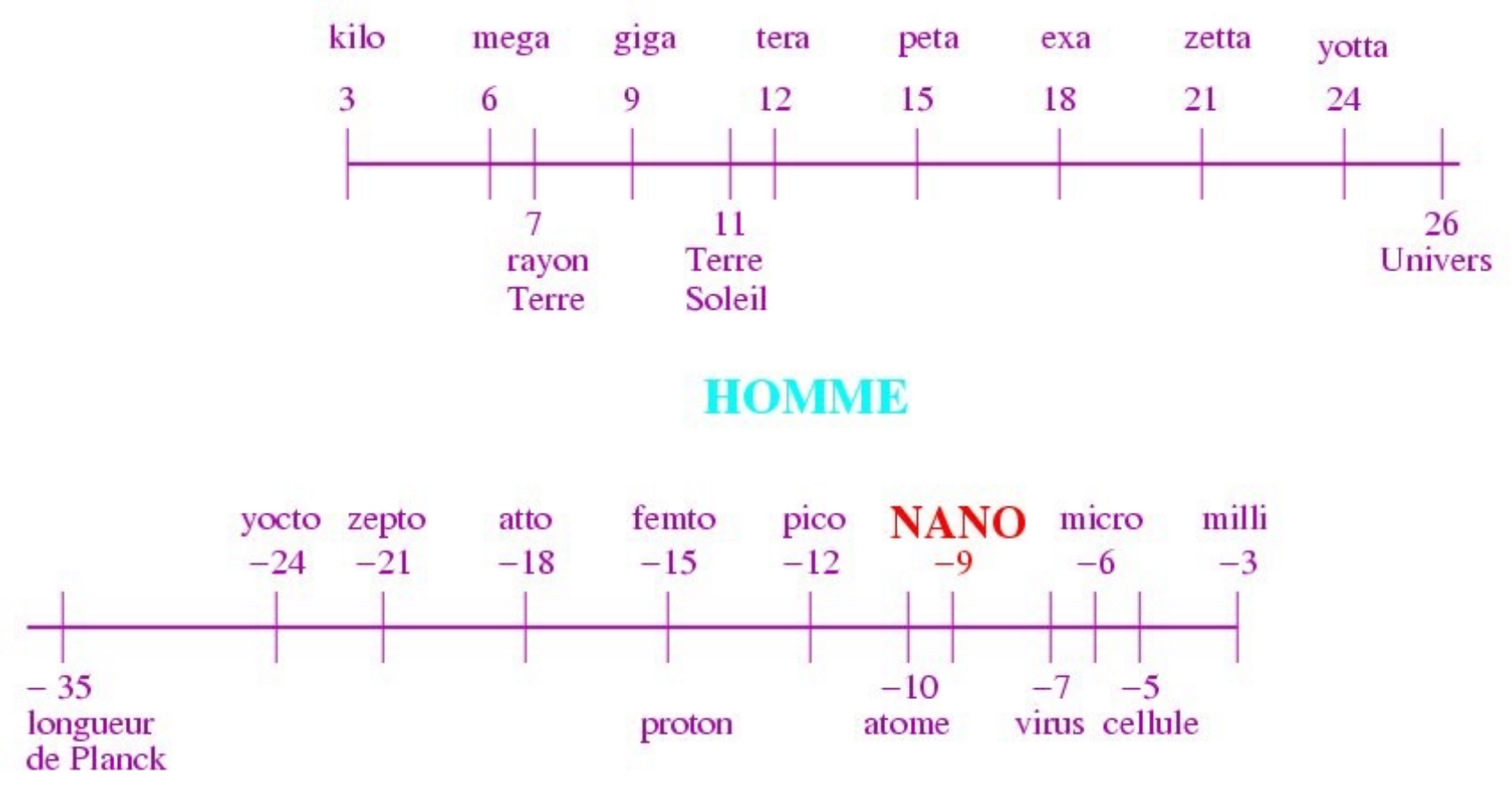
Nanomètre ?



Échelle logarithmique

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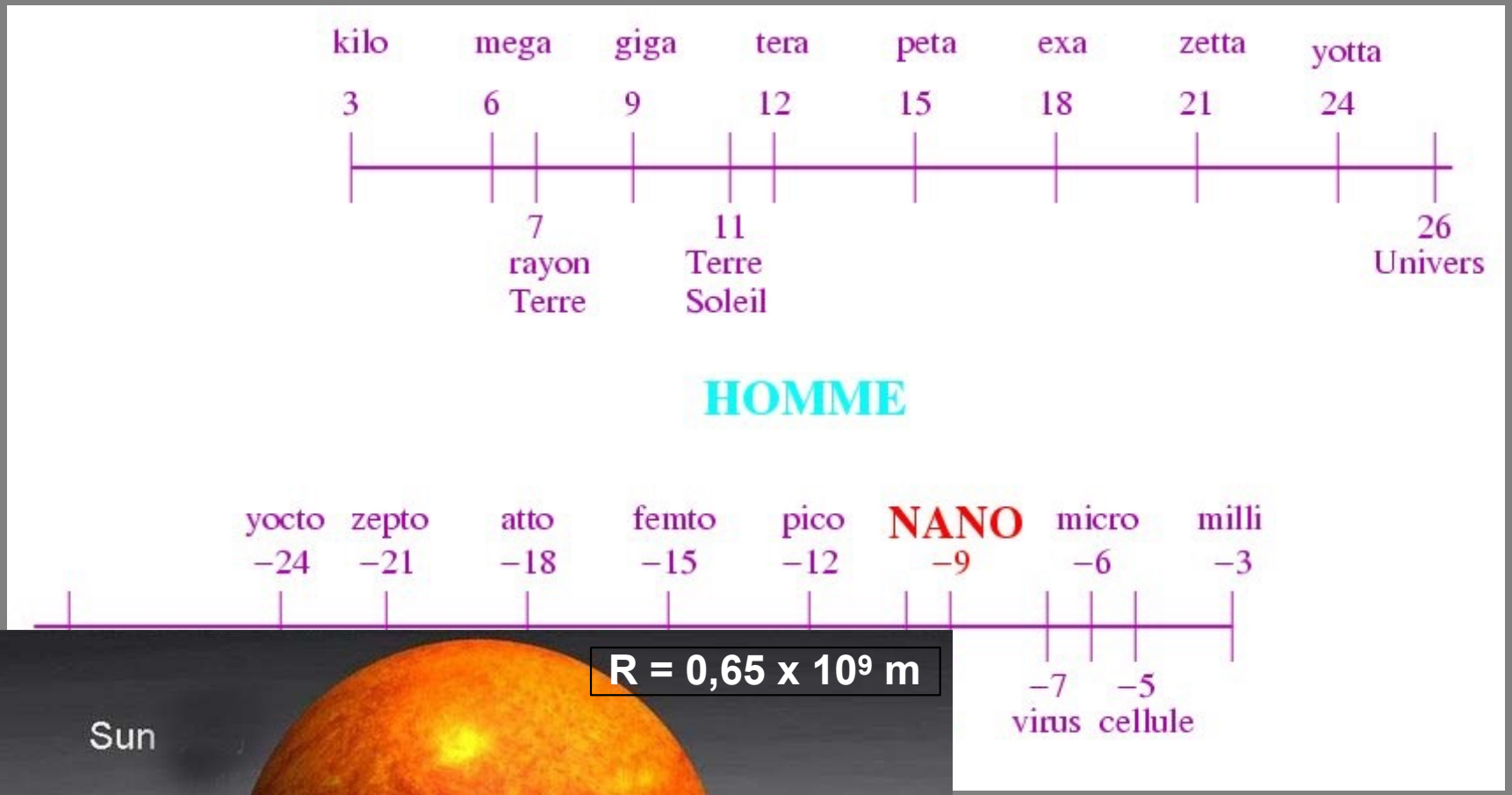
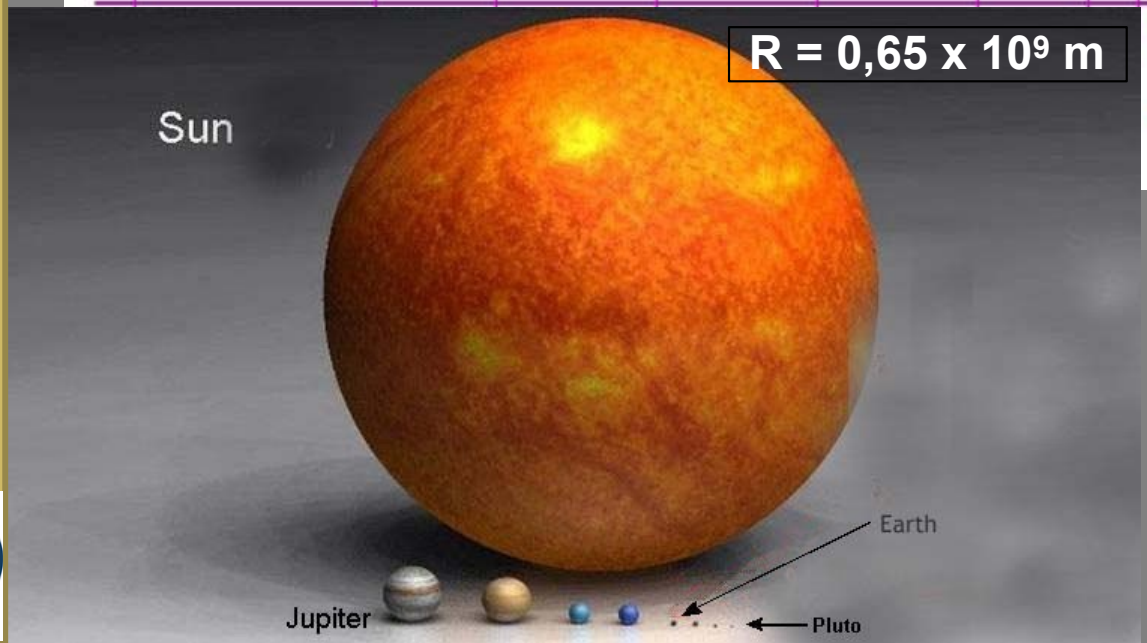
Nanomètre ?





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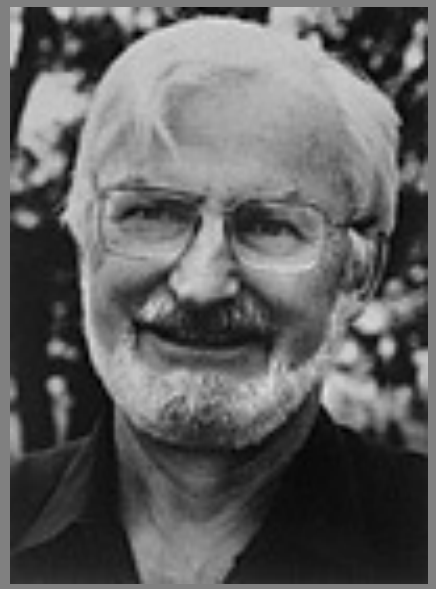
Fabriquer une image
Les sondes locales

STM : microscope à effet tunnel électronique

Gerd Binnig



Heinrich Rohrer

IBM Zürich

Prix Nobel 1986

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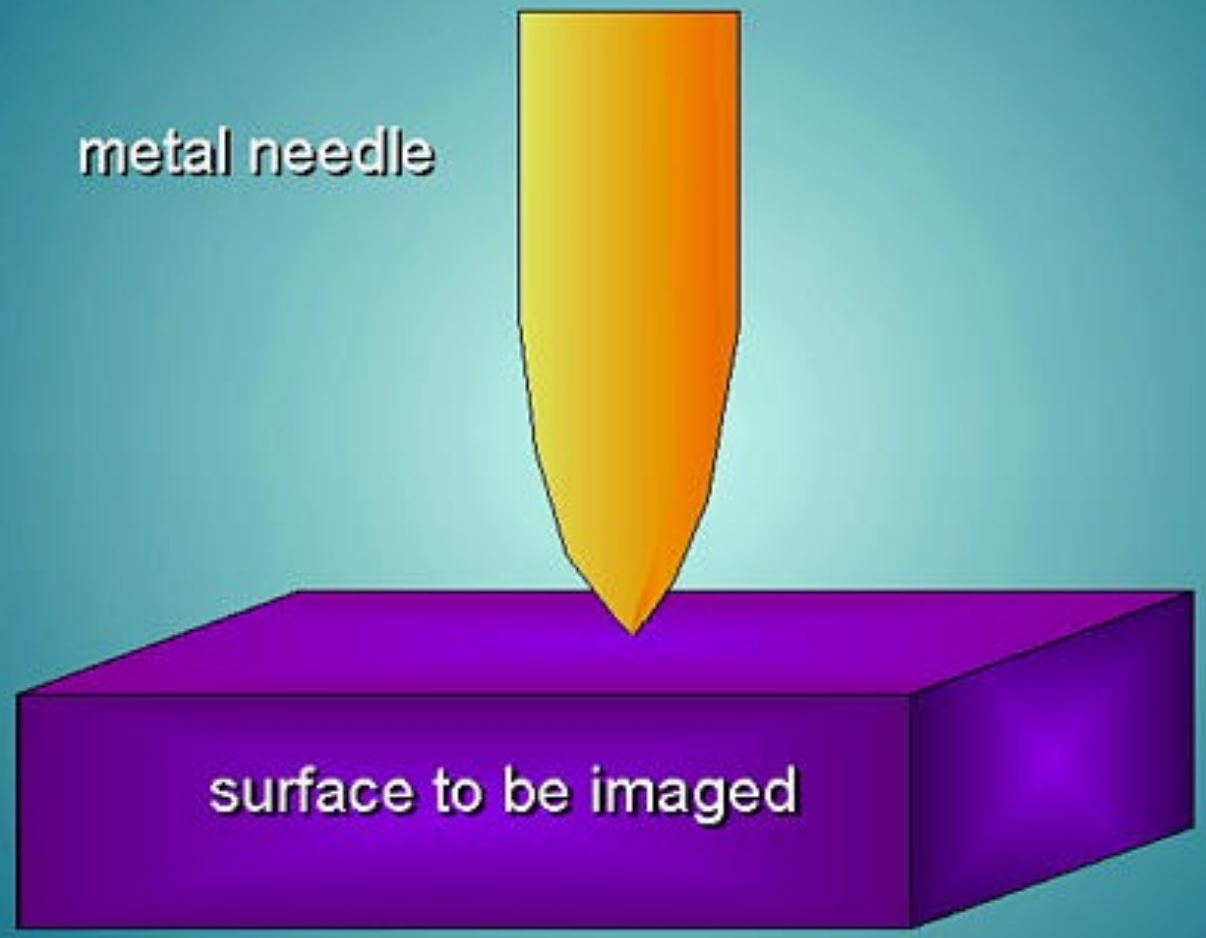

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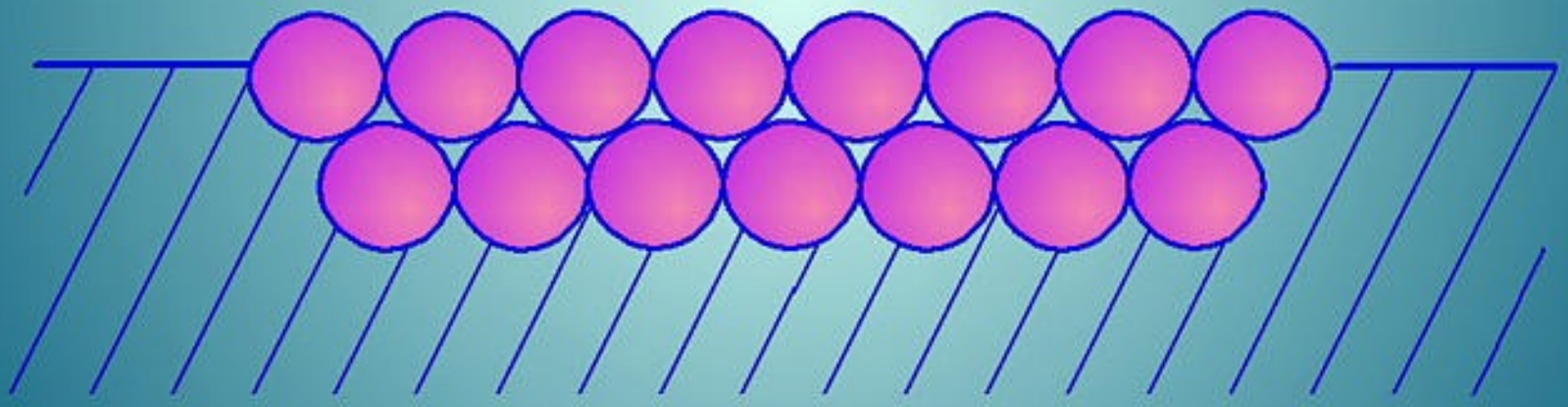

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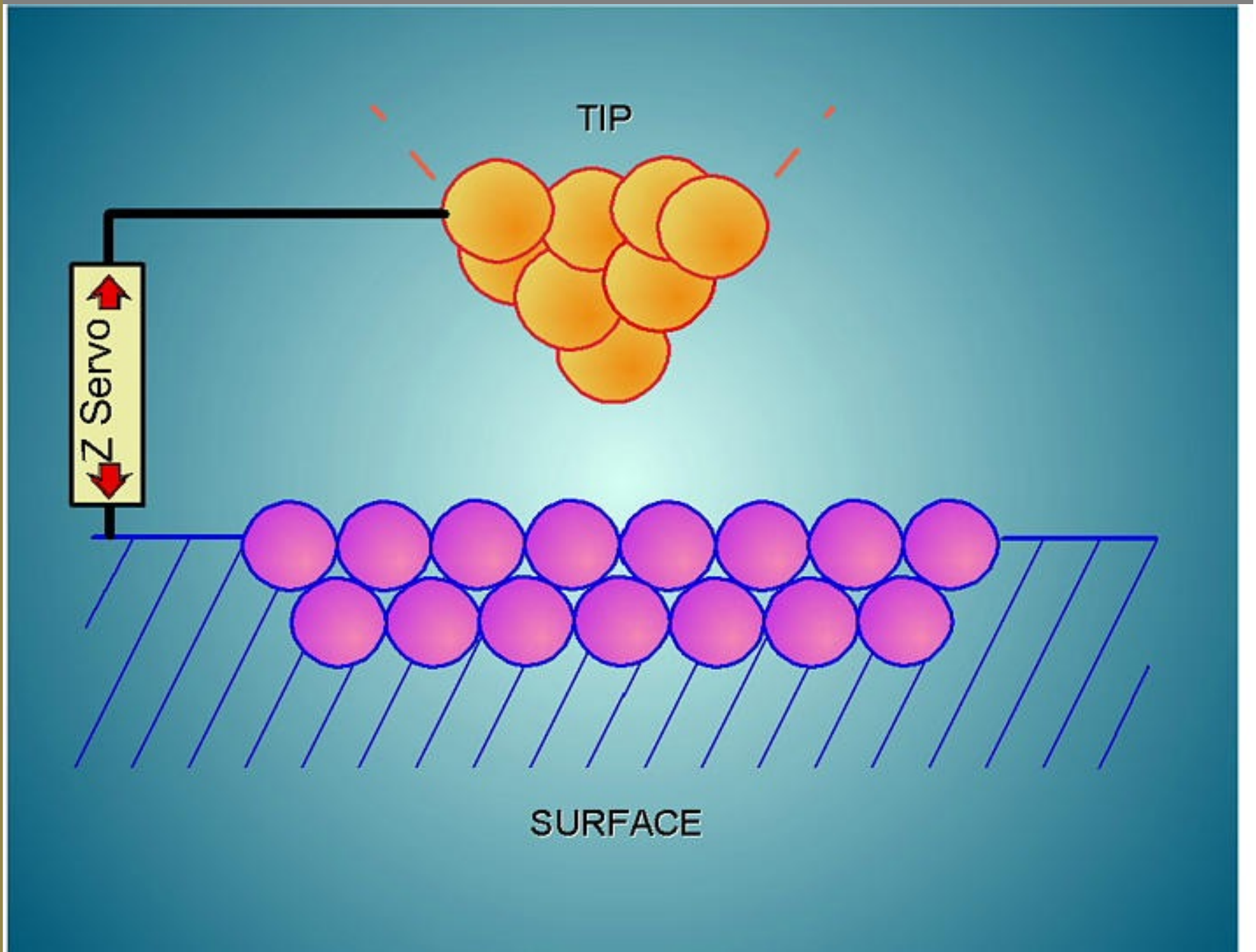

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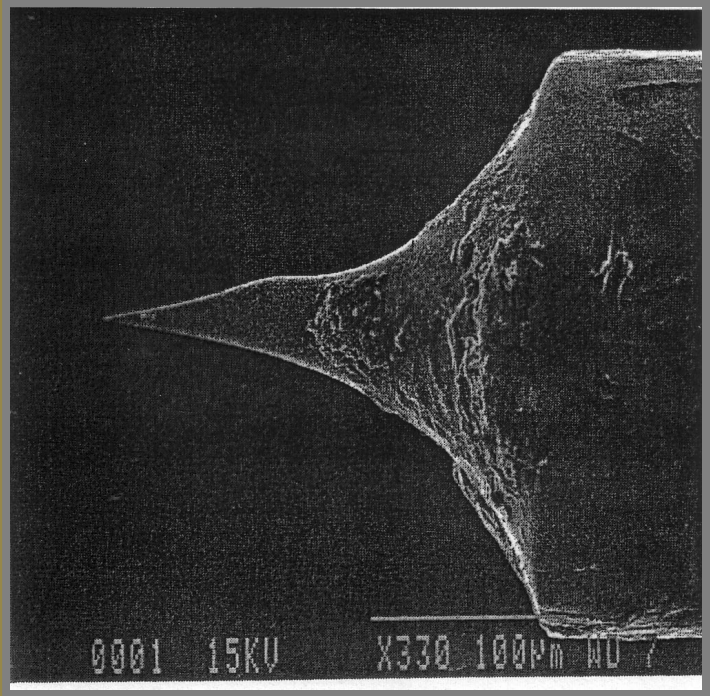
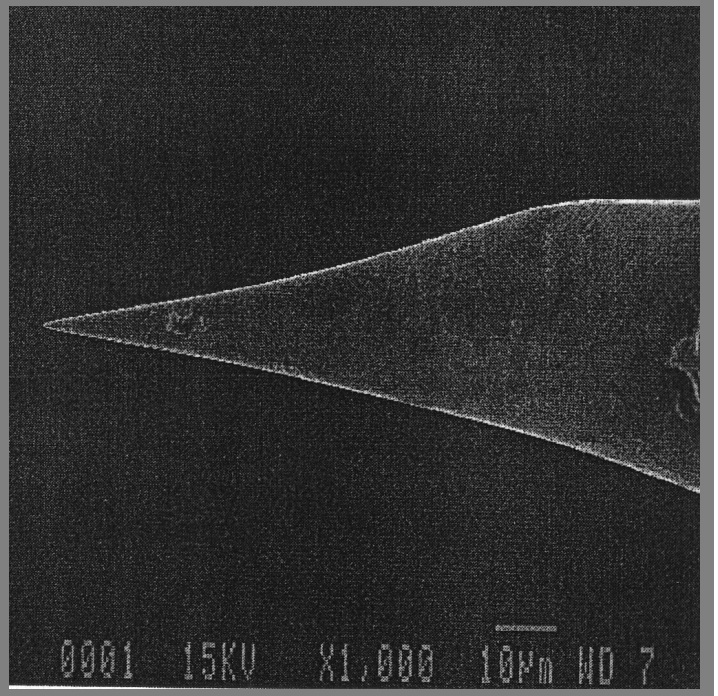
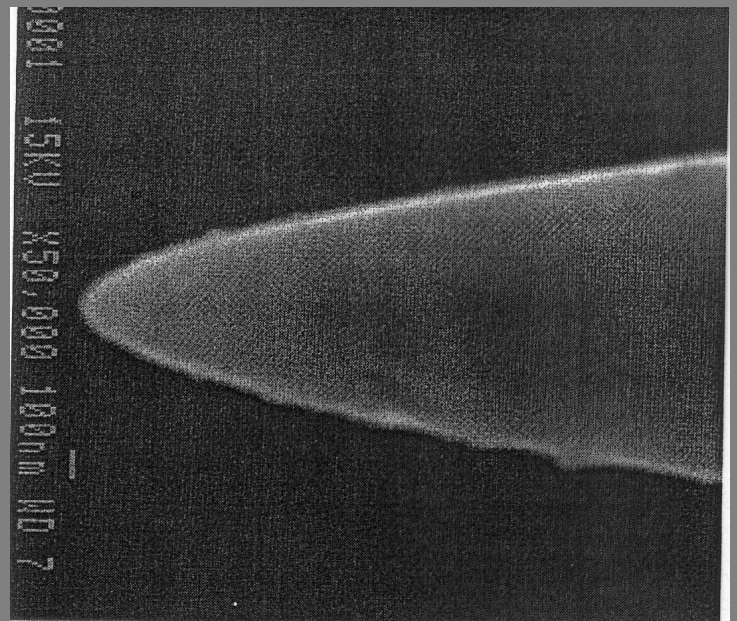
Pointes



Rayon de courbure : ~ 50 nm





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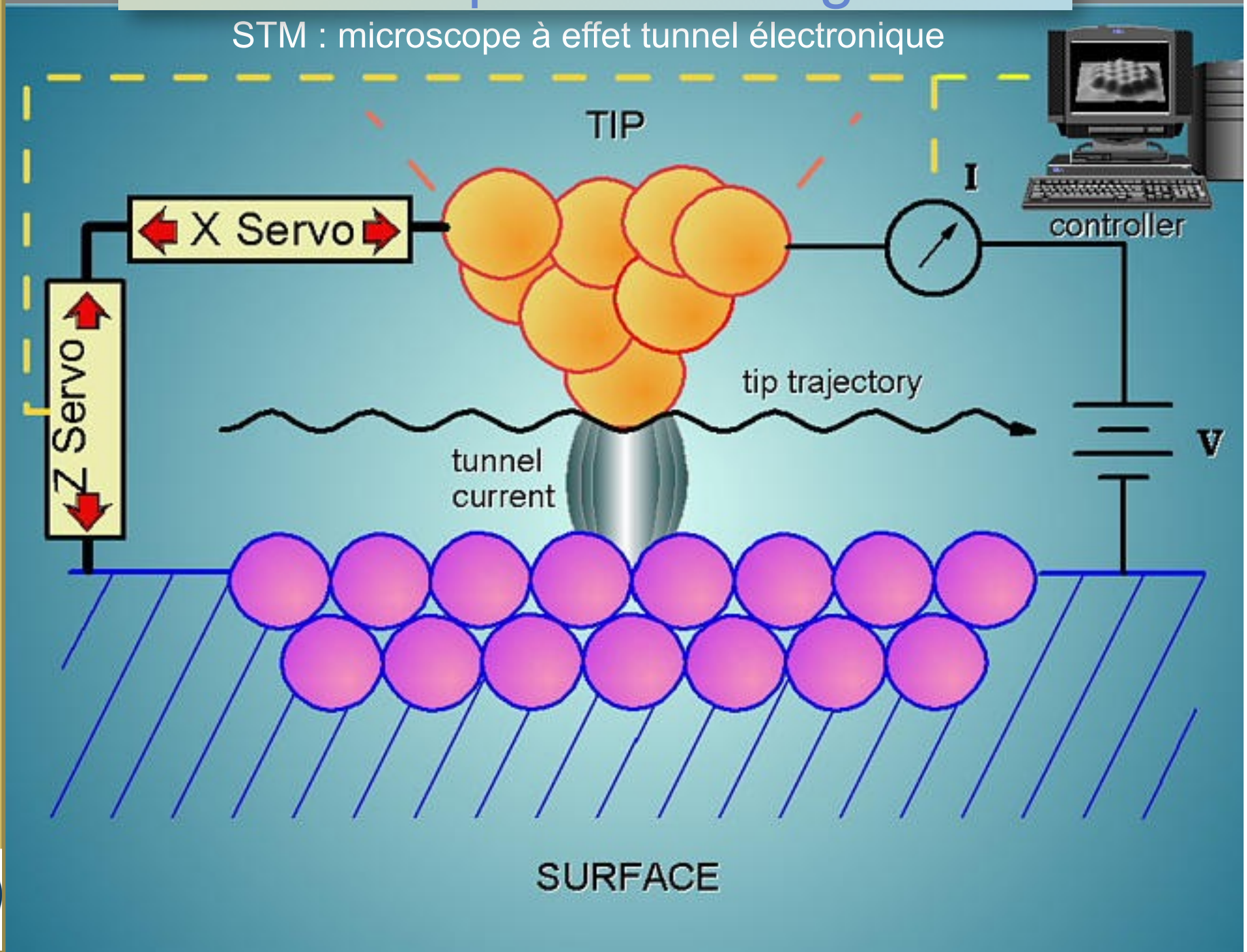
STM : microscope à effet tunnel électronique



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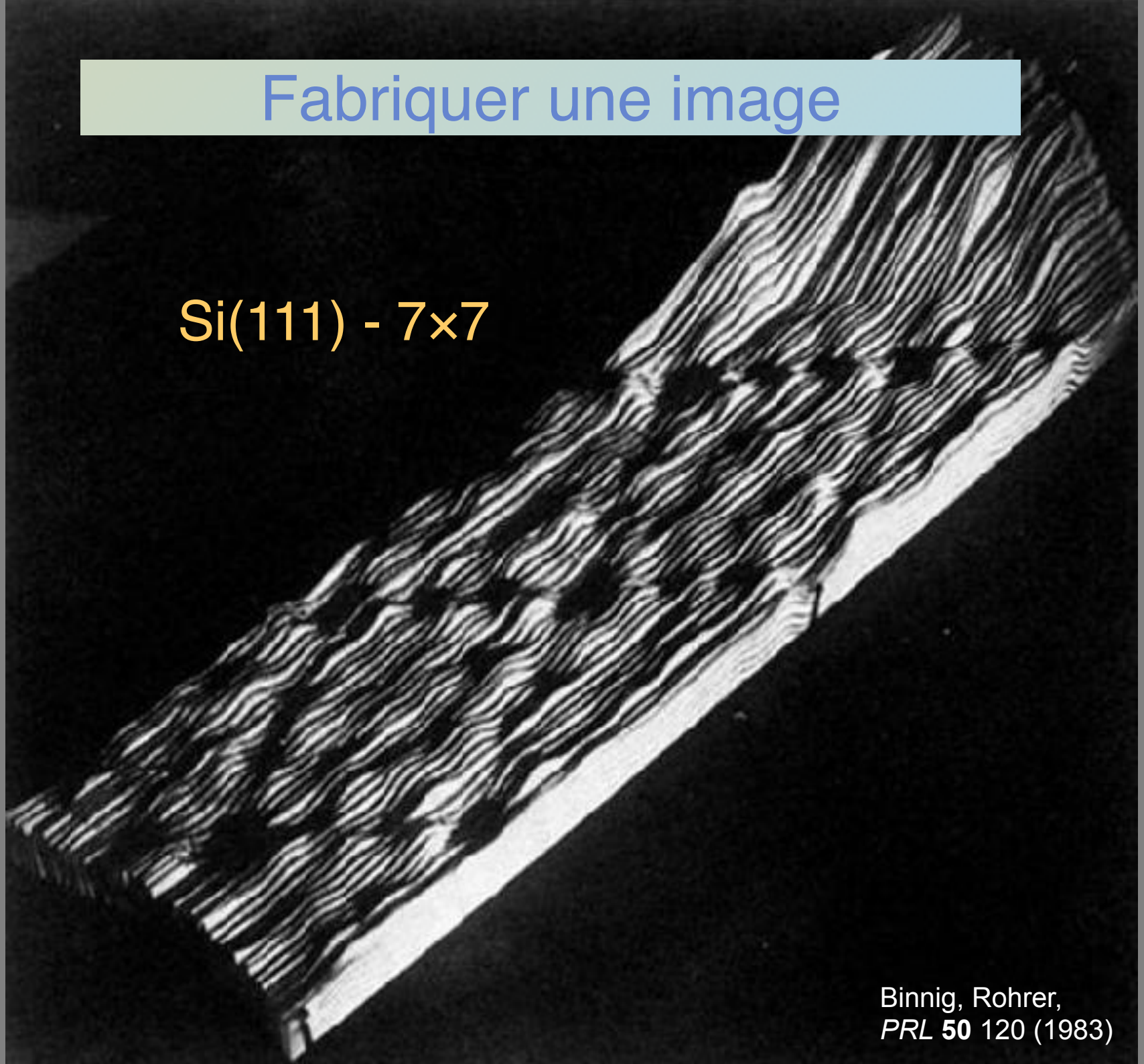

Binnig, Rohrer,
PRL **50** 120 (1983)

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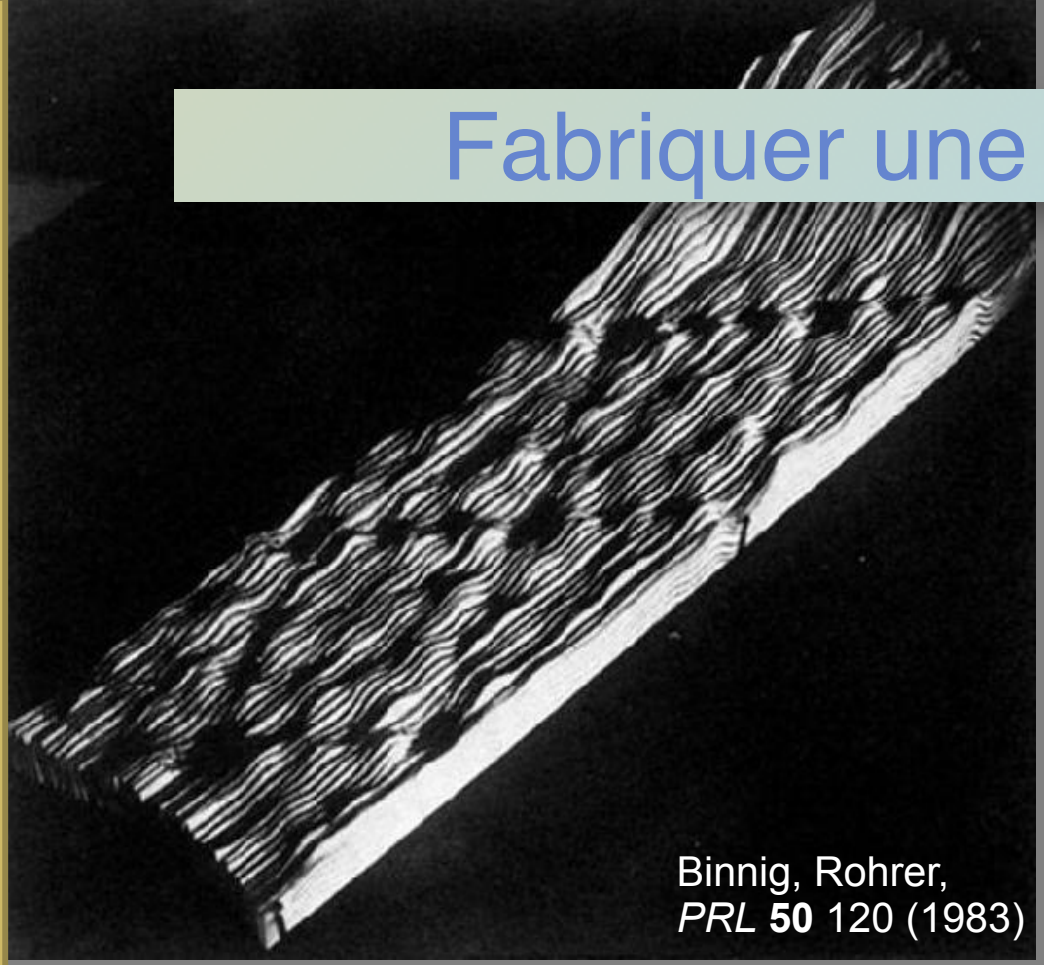

Binnig, Rohrer,
PRL **50** 120 (1983)

Si(111) - 7×7

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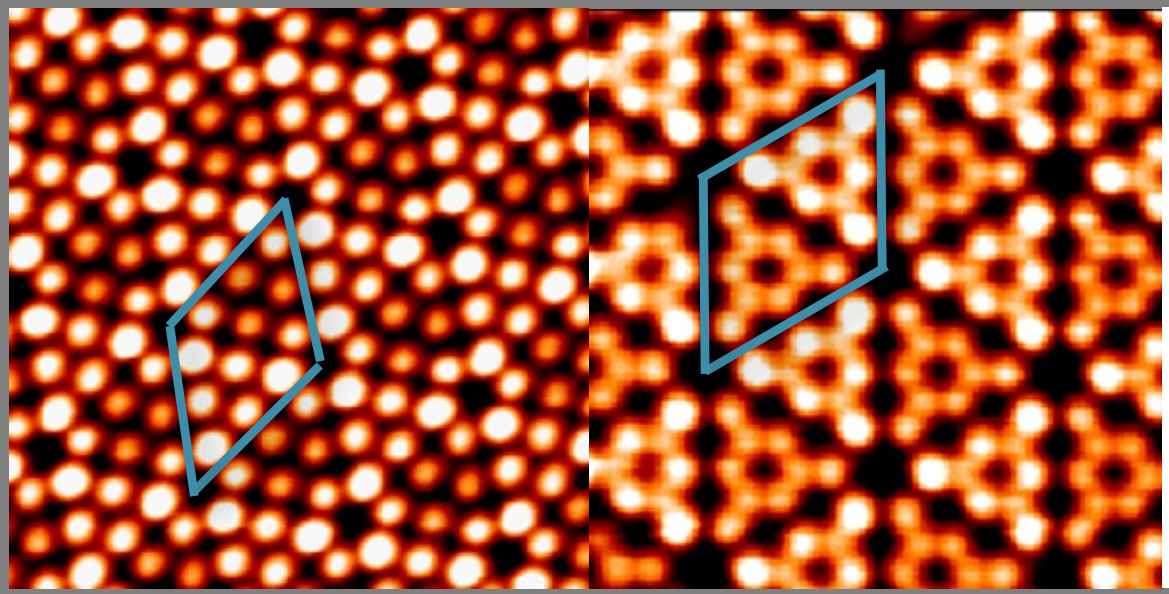
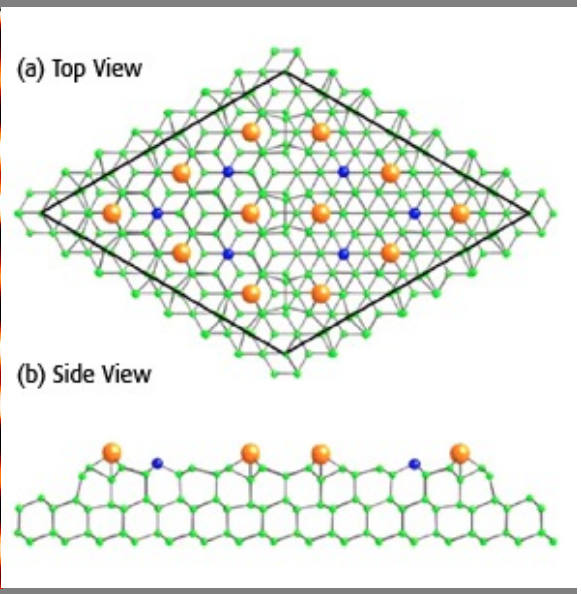
H.-J. Gao, PRB **70**, 073312 (2004)





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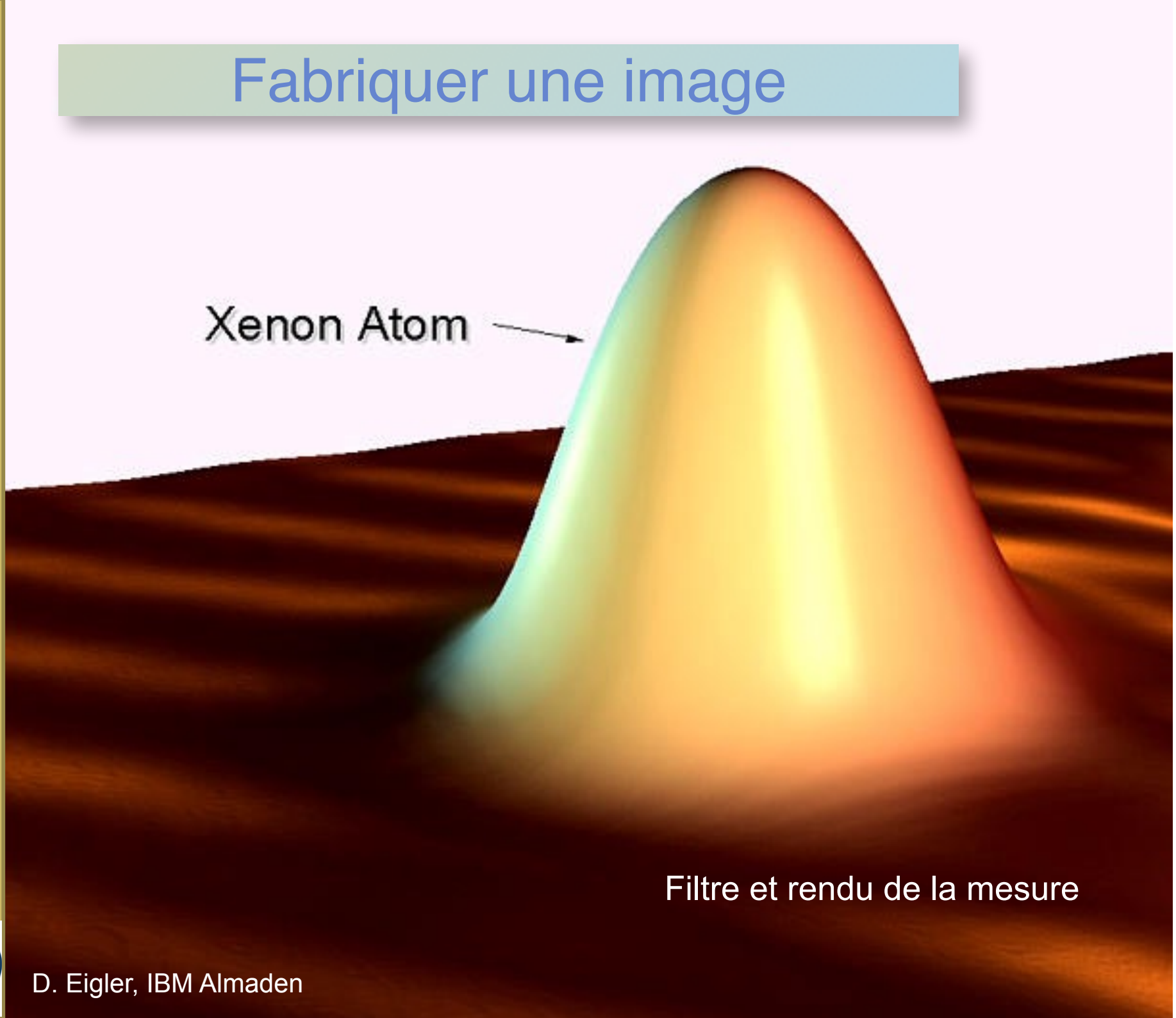

Filtre et rendu de la mesure

D. Eigler, IBM Almaden

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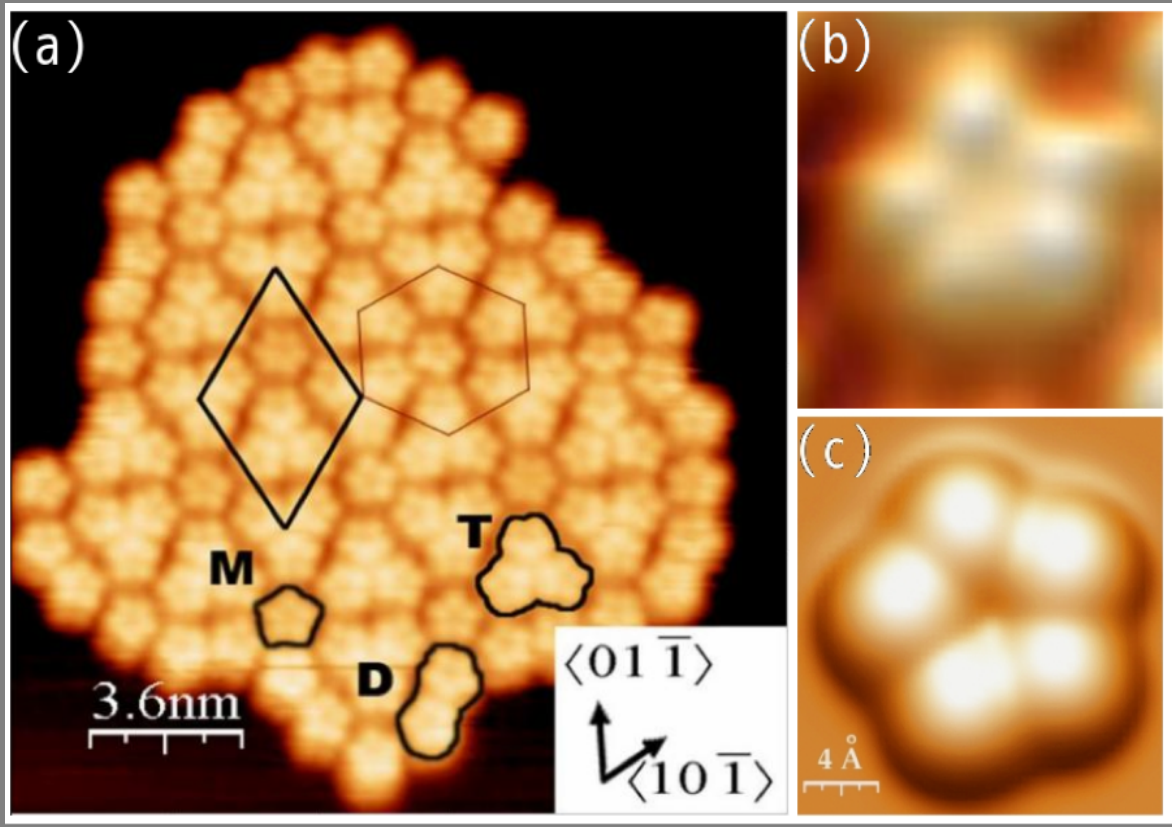
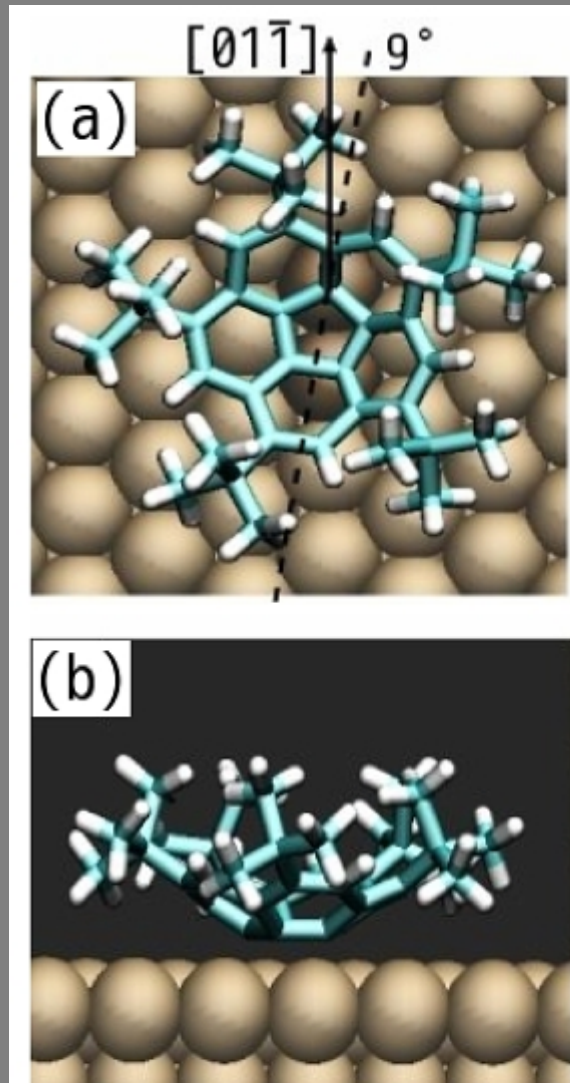
Expérience



Calcul



Guillermet, Niemi, Gauthier, Bouju
ACIE (2008)

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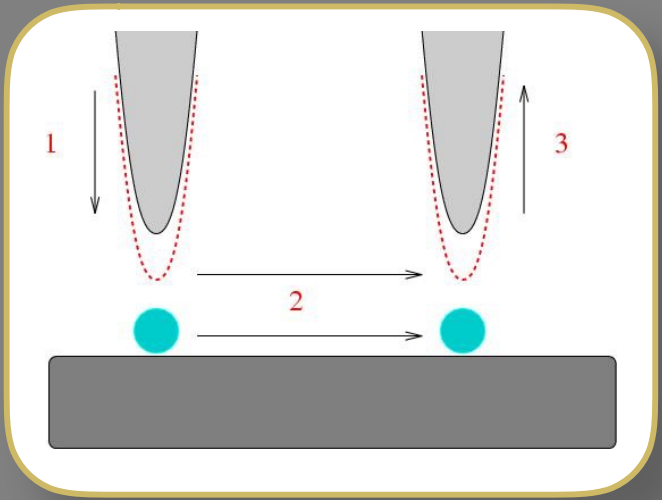
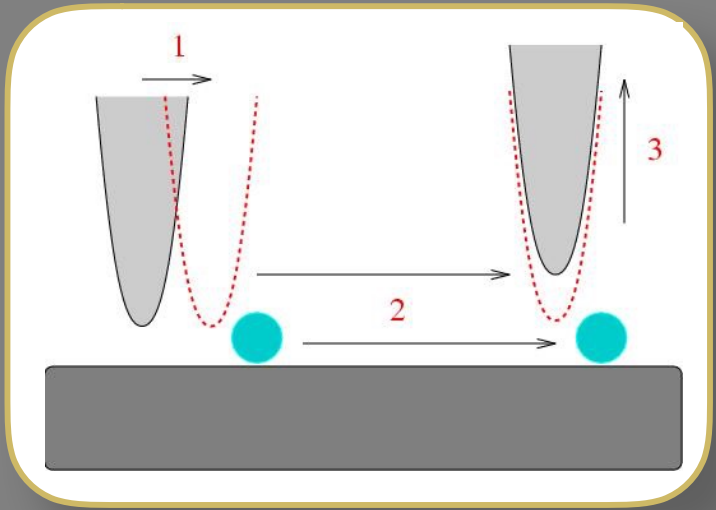
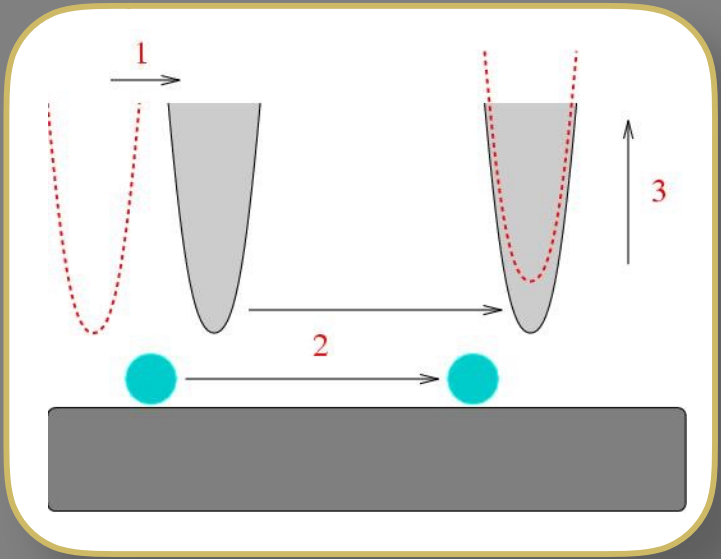
Manipulation latérale contrôlée



Mode de glissement



Mode de poussée



Mode de tirage

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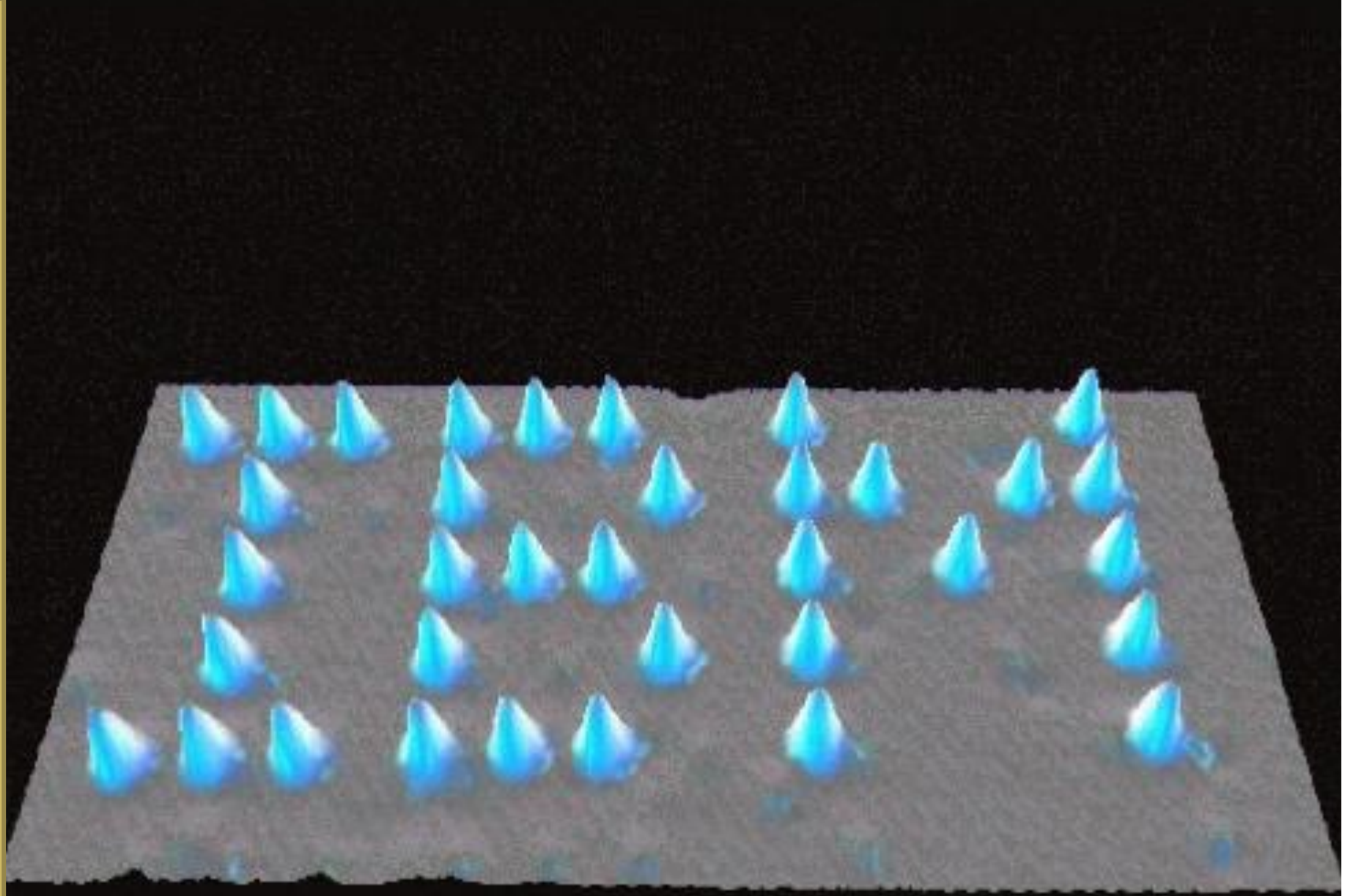

Xe/Ni(110)

Eigler, Schweizer, *Nature* **344** 524 (1990)

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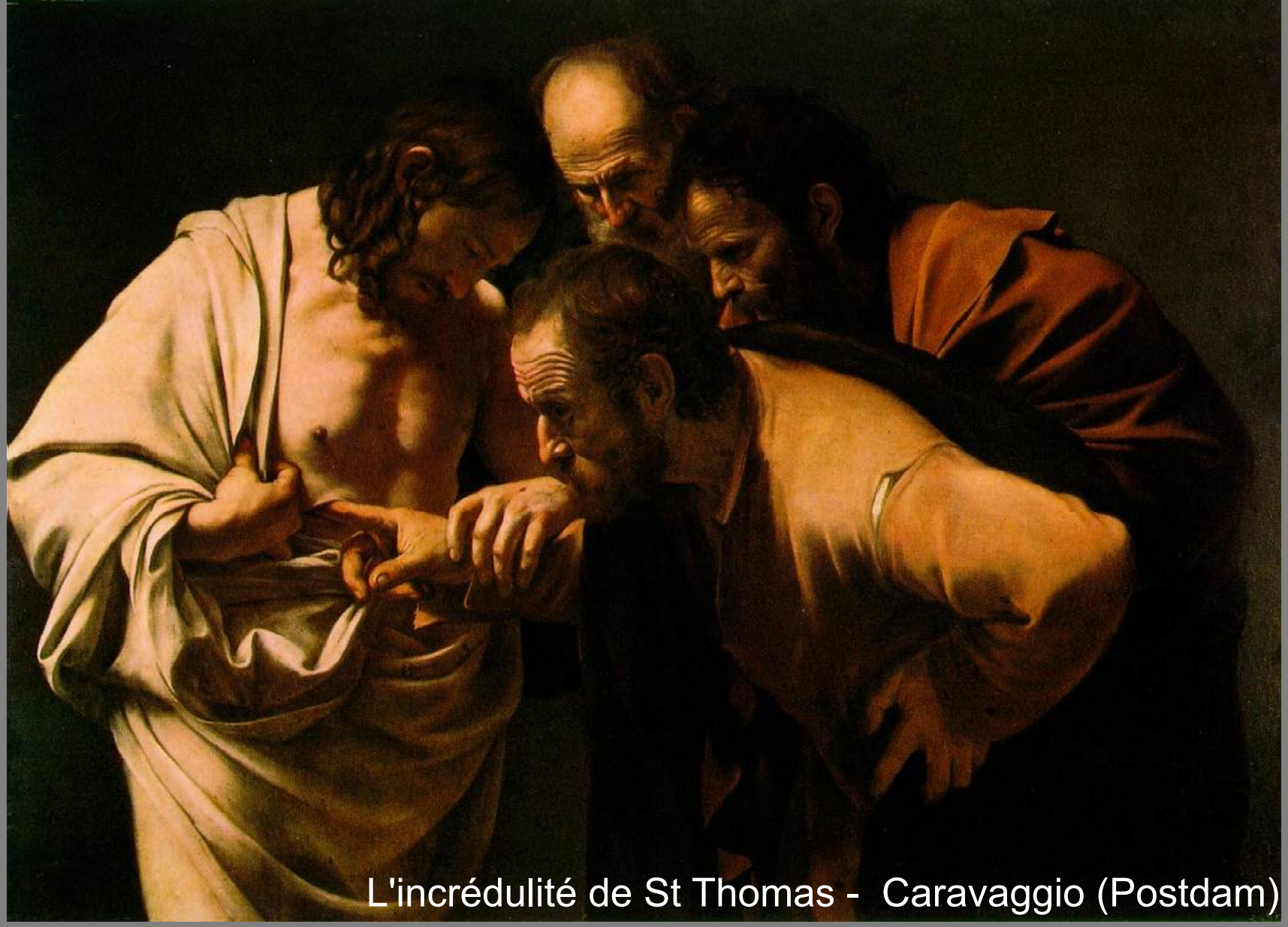
Séminaire
X-Aristote
13 juin 2019



L'incrédulité de St Thomas - Caravaggio (Postdam)

Image ne suffit pas : on veut toucher, on veut *rentrer* en interaction

Microscope à sonde locale : de l'optique à l'haptique

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Explorer de nouveaux concepts
Approche bottom-up

Techno-mimétisme

imitation du monde macroscopique vers le monde nanoscopique

Vers les machines moléculaires

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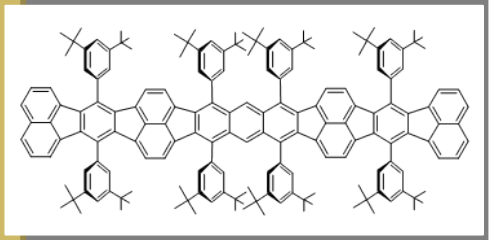
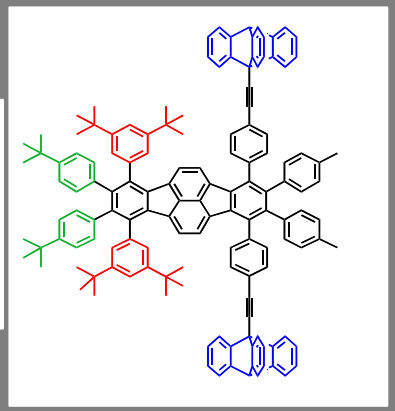
Explorer de nouveaux concepts
Approche bottom-up

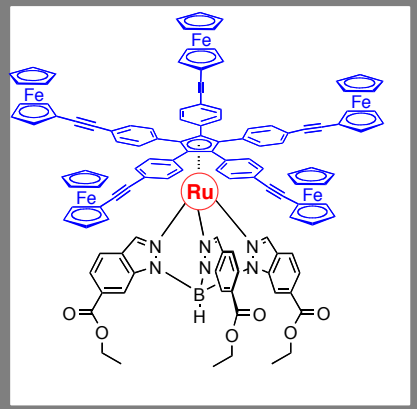
« Landers »



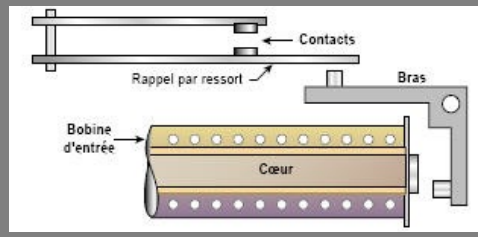
Brouette

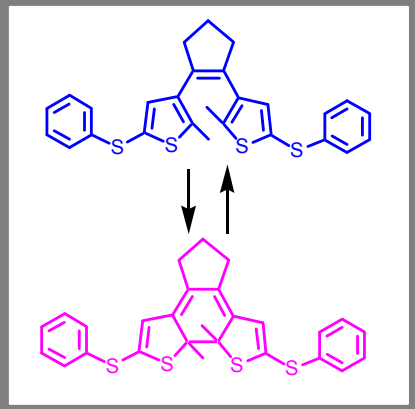


Moteur rotatif

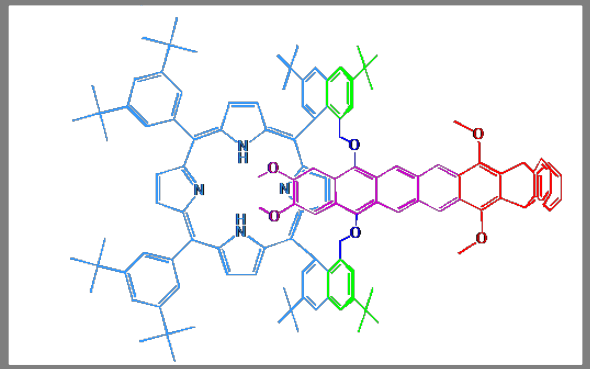


Interrupteur





Manipulateur Morse



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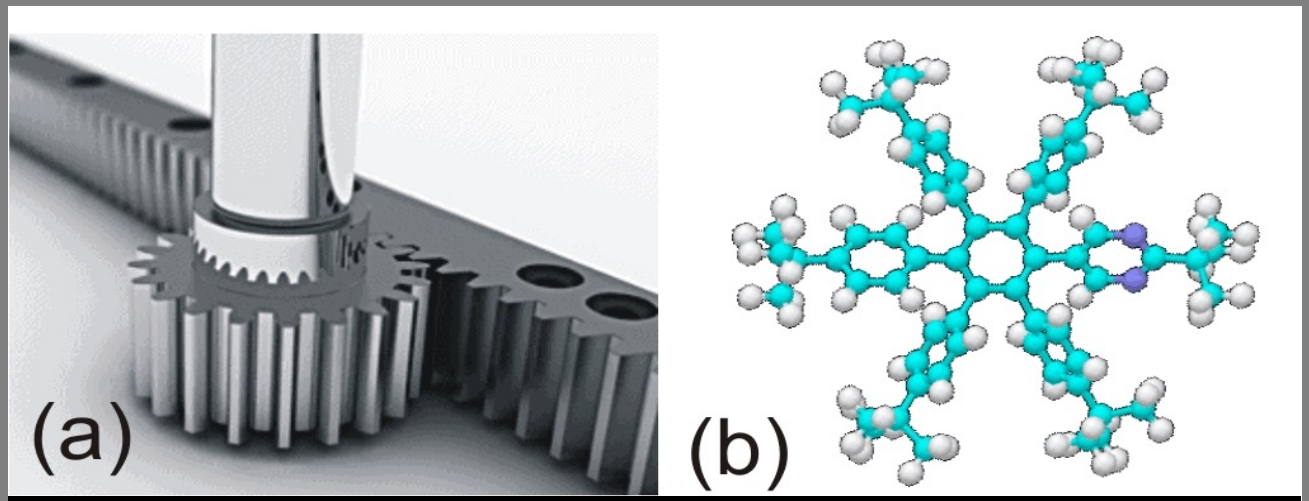
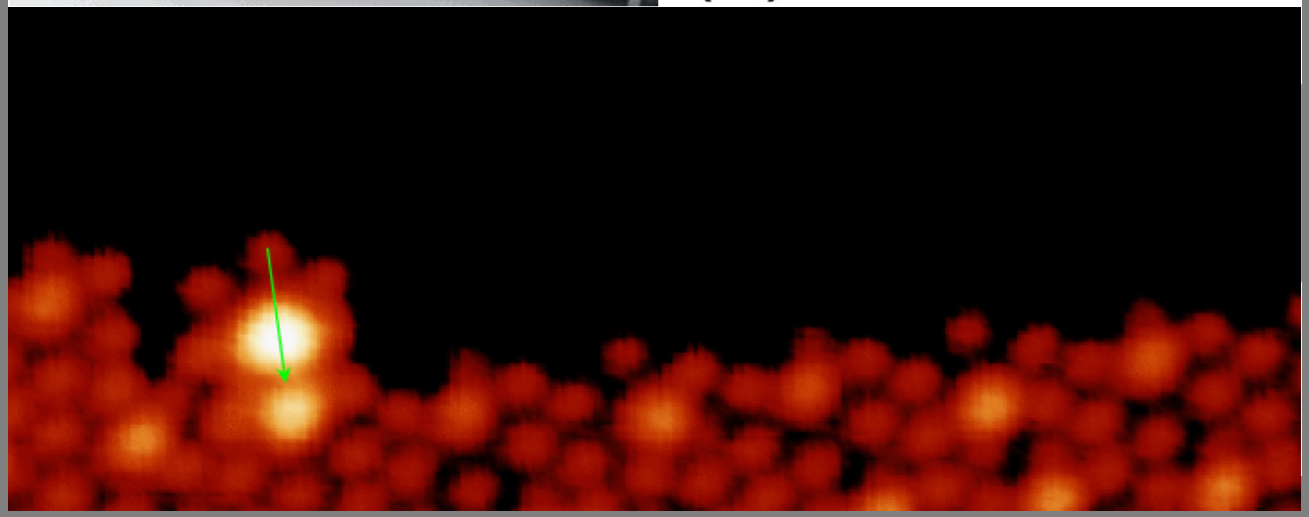
Molécule-machine

Image et représentation

A MOLECULAR RACK-AND-PINION





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Chiaravalloti *et al*. Nature Materials **6**, 30 (2007)

Explorer de nouveaux concepts

Transformer un mouvement de translation en un mouvement de rotation

Techno-mimétisme

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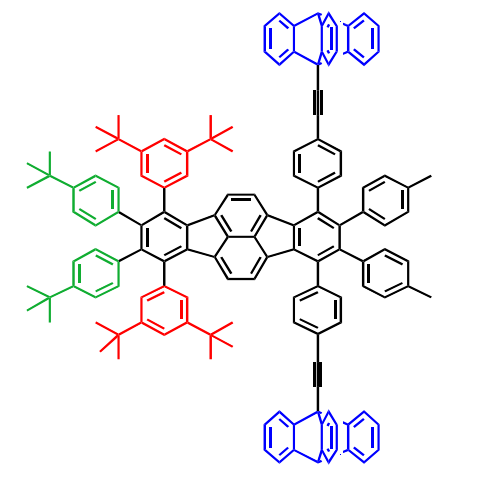
Explorer de nouveaux concepts

Une brouette moléculaire



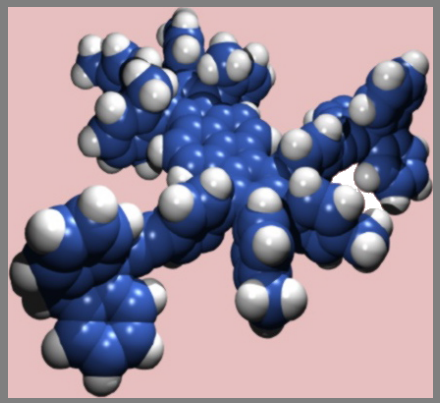
Gwénaël Rapenne

. Un chassis (plateau poly-aromatique central)
. Deux axes indépendants reliés à :

→ **deux roues indépendantes** pour mouvement sur la surface

→ **deux pieds** pour isoler le plateau de la surface

→ **deux poignées** pour manipulation avec un pointe STM



Nanotechnology **13**, 330 (2002)

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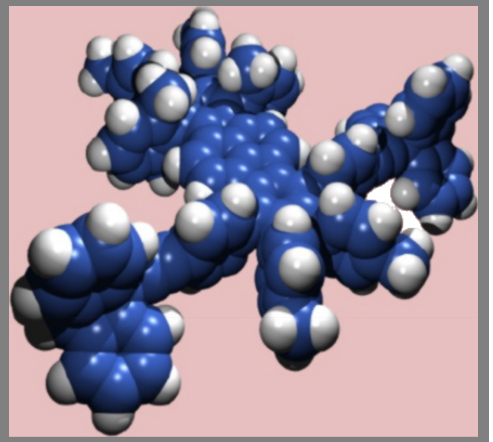
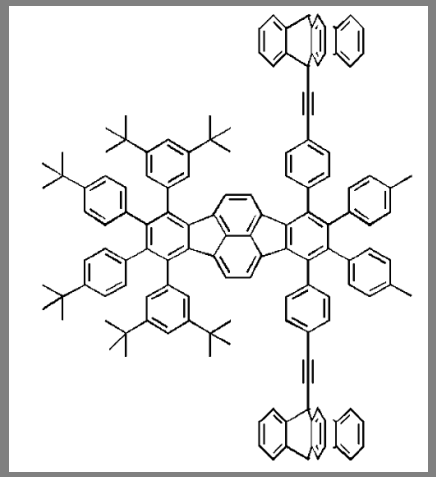
Molécule-machine

Image et représentation mentale
imitation du monde macroscopique vers le monde nanoscopique





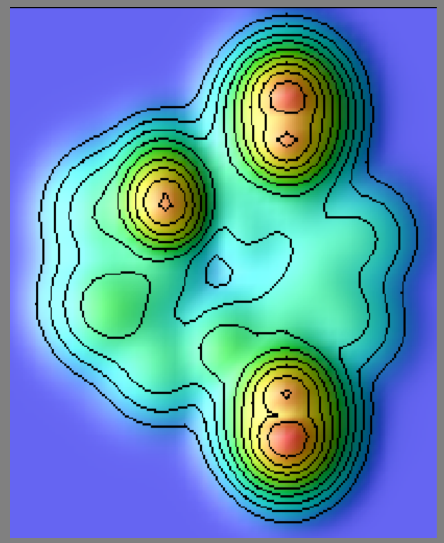


Image STM calculée (ESQC)

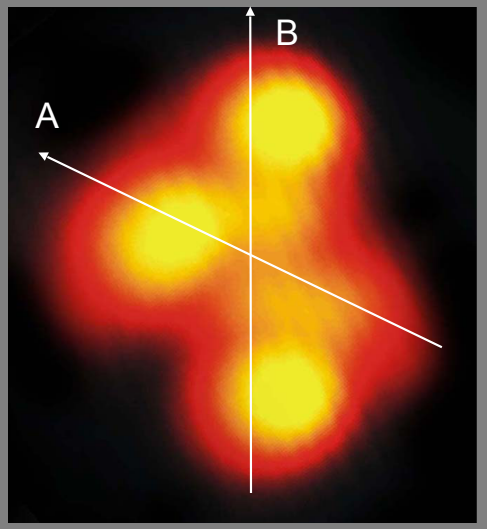


Image expérimentale

L. Grill *et al.*, *Surf. Science* (2005).

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Molécule-machine

Image et représentation mentale
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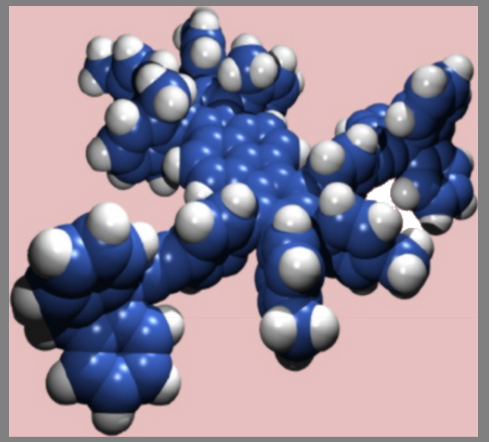

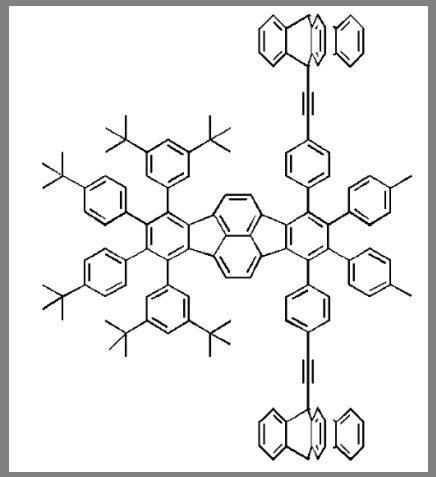

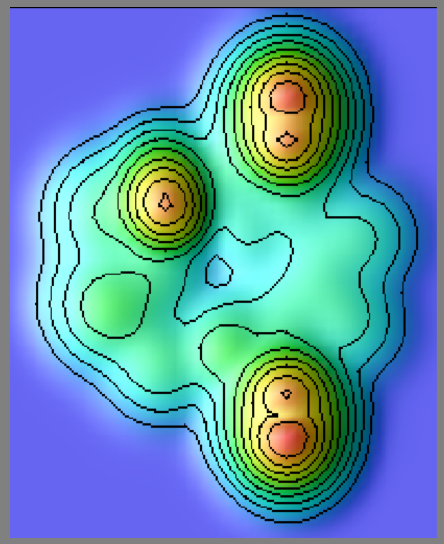

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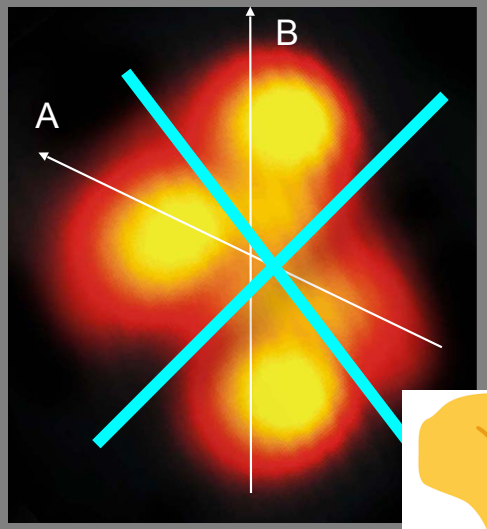

Image expérimentale

Est-on sur la bonne voie ?

Autres champs de forces

L. Grill *et al.*, *Surf. Science* (2005).

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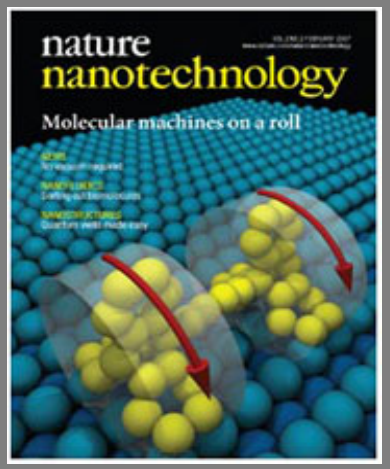
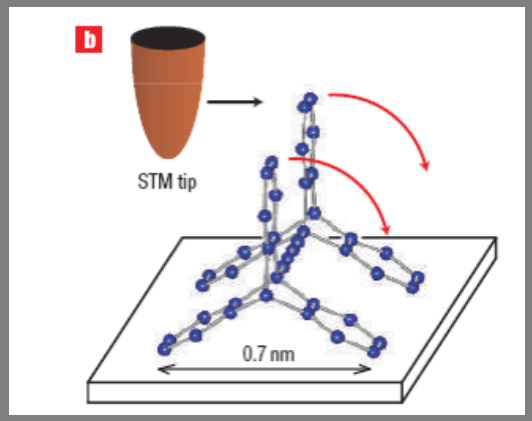
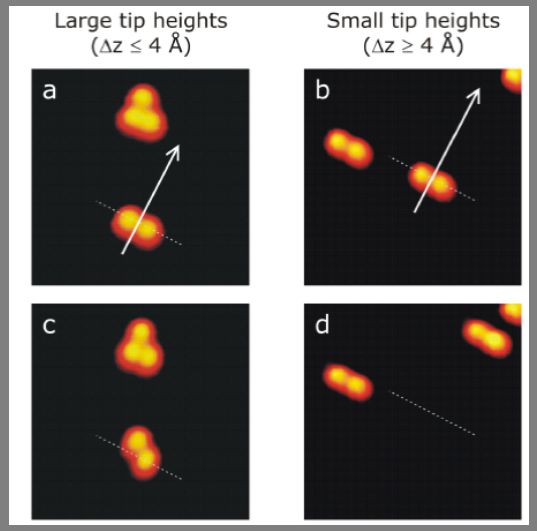
Explorer de nouveaux concepts

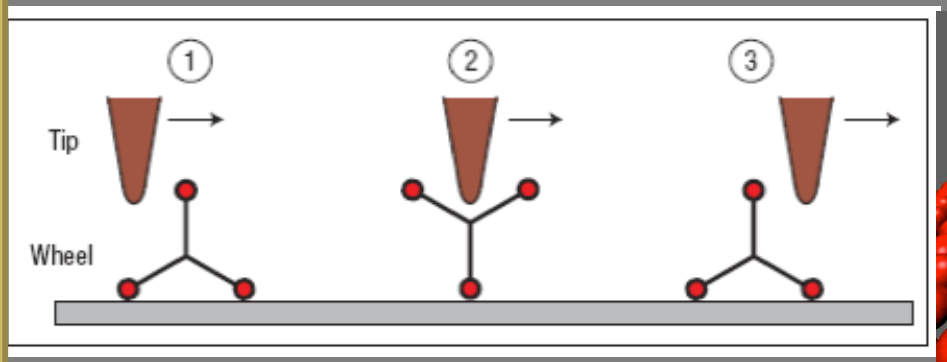
Molécule-machine artificielle

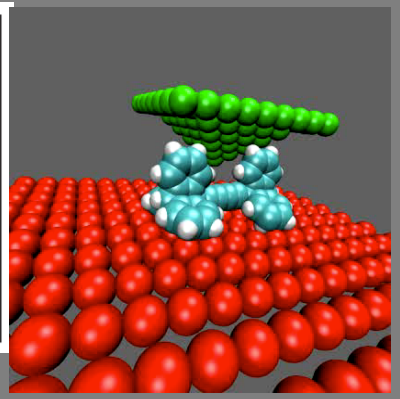
Démonstration de la rotation d'une roue moléculaire

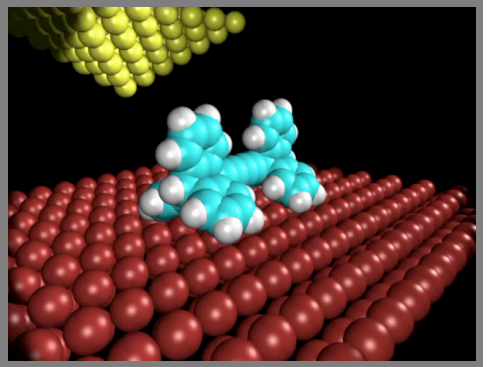












Grill *et al*,
Nature Nanotechnology 2007

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CNRS

The nanocar race

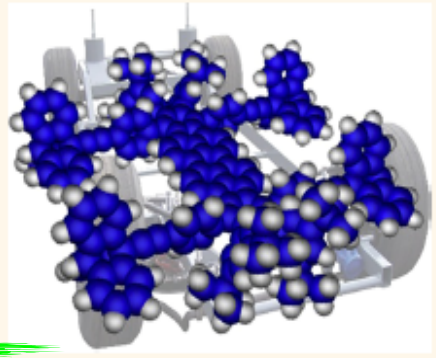
PERSPECTIVE

Molecule Concept Nanocars: Chassis, Wheels, and Motors?

Christian Joachim[†,‡,*] and Gwénael Rapenne[†,§]

[†]CEMES-CNRS, NanoSciences Group & MANA Satellite, 29 rue Jeanne Marvig, BP 94347, F-31055 Toulouse cedex 4, France, [‡]IMRE, A*STAR (Agency for Science, Technology and Research), 3 Research Link, 117602, Singapore, and [§]Université de Toulouse, UPS, 118 route de Narbonne, F-31062 Toulouse cedex 9, France

ABSTRACT The design, synthesis, and running of a molecular nanovehicle on a surface assisted by proper nanocommunication channels for feeding and guiding the vehicle now constitute an active field of research and are no longer a nano-joke. In this Perspective, we describe how this field began, its growth, and problems to be solved. Better molecular wheels, a molecular motor with its own gears assembling for torque transmission must be mounted on (*i.e.*, chemically bonded to) a good molecular chassis for the resulting covalently constructed molecular nanovehicle to run on a surface in a controlled manner at the atomic scale. We propose a yearly molecule concept nanocar contest to boost molecular nanovehicle research.



ACS Nano, 7, 11 (2013).

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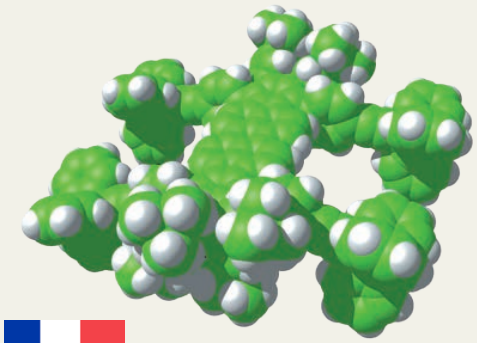
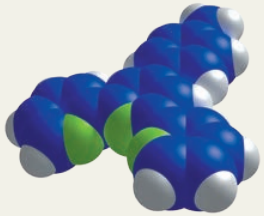
6 équipes

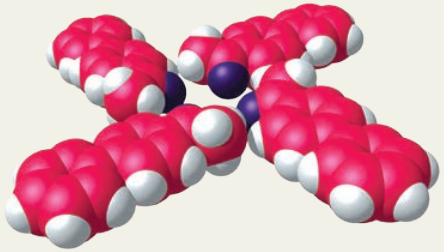


THE GREEN BUGGY
Chassis curved to minimize interaction with surface.

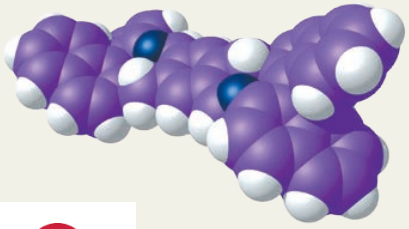


SWISS NANO DRAGSTER
Simple structure so that molecule won't fall apart during race.

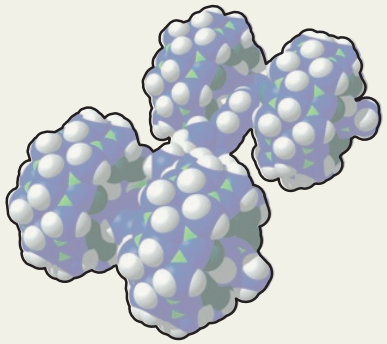
DIPOLAR RACER*
Has wheels, axles and a chassis.



WINDMILL
Four blades allow steering in four directions.



NIMS—MANA CAR
Flaps flutter like a butterfly's wings.



OHIO BOBCAT NANO-WAGON*
Pumpkin-shaped wheels may roll or slide on surface.

*Prototype model: final design not revealed

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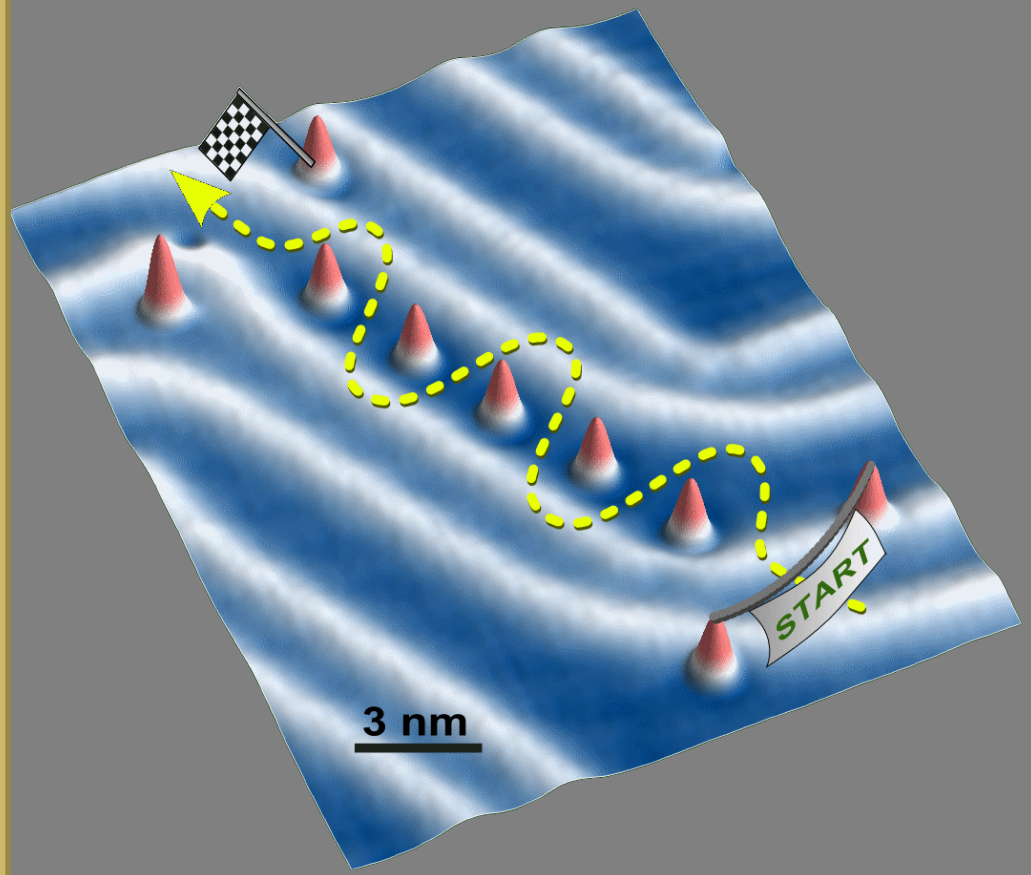
La nano-course de voiture

Règles



Au(111) image @ 4.7 K
W.H. Soe & C. Manzano (IMRE, 2013)

Piste : Au(111)

Manipuler une molécule individuelle entre les lignes de départ et d'arrivée

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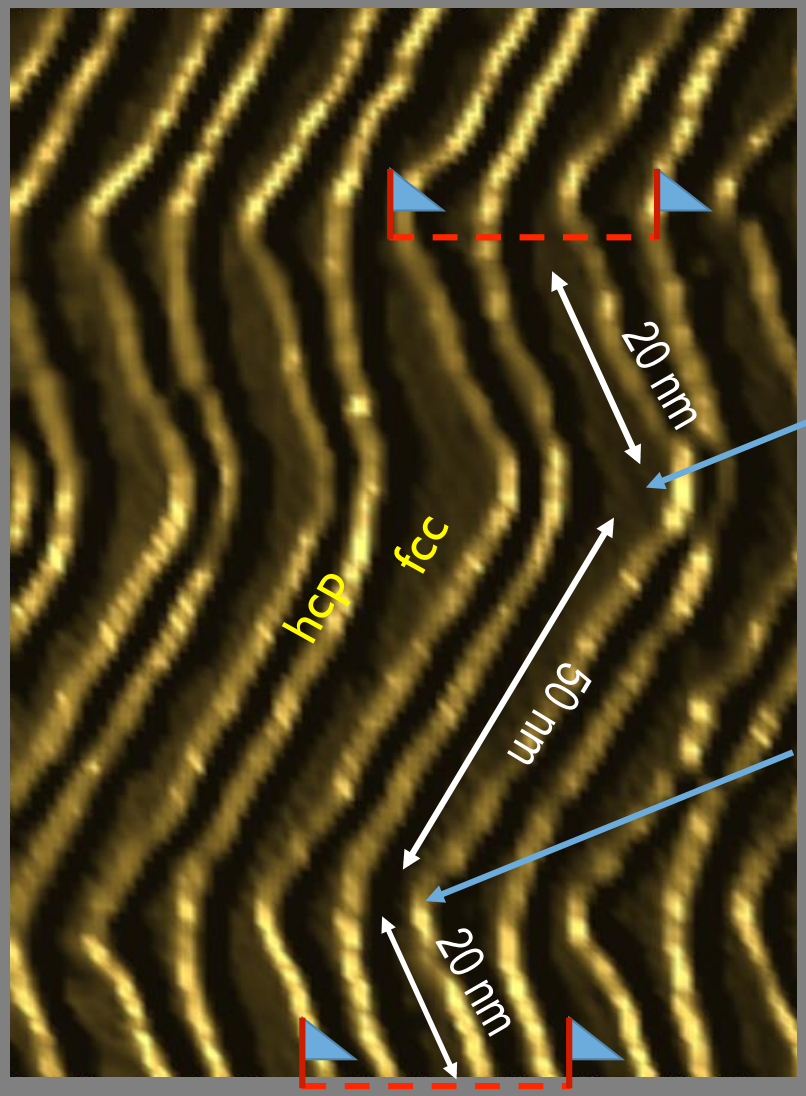
La nano-course de voiture

Règles



Virage 2

Virage 1

Piste : Au(111)

Manipuler une molécule individuelle entre les lignes de départ et d'arrivée

Image 36.5 nm × 48.6 nm de la reconstruction de surface.
Largeur de la piste : 4-6 nm
Hauteur du rail : 26 pm

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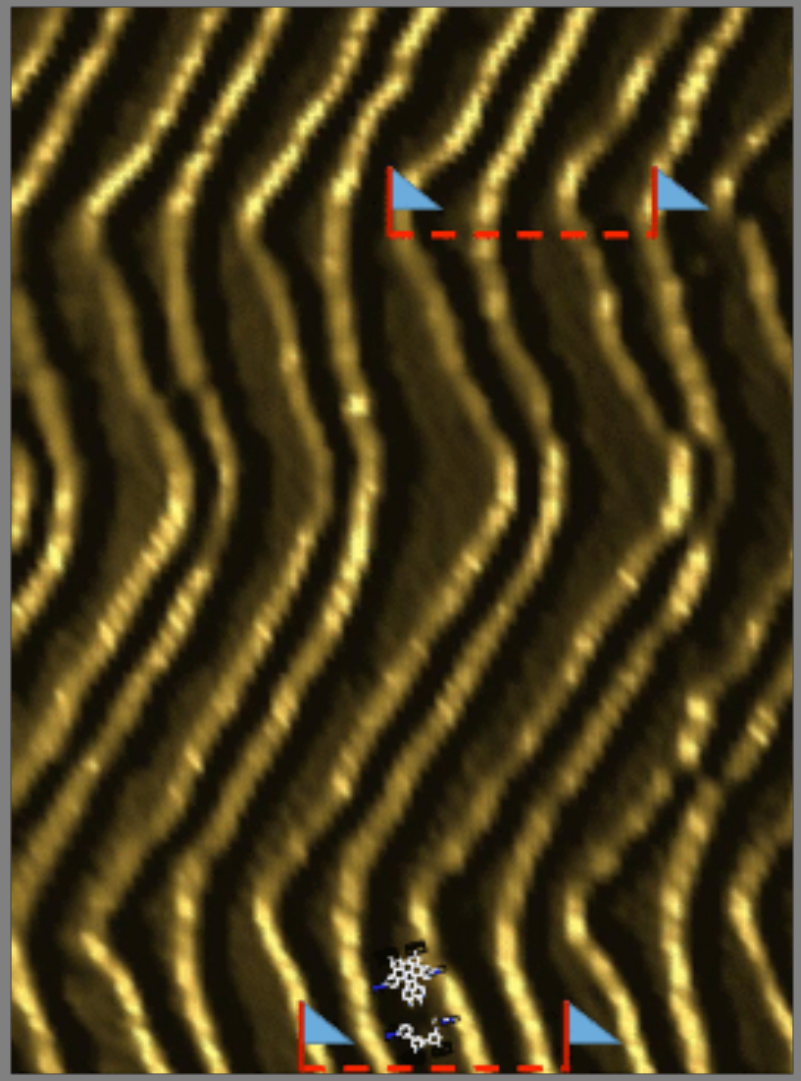
La nano-course de voiture

Règles



Piste : Au(111)

Manipuler une molécule individuelle entre les lignes de départ et d'arrivée

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The nanocar race

The 38h Grand Prix
28-29 avril 2017
11am (Paris)

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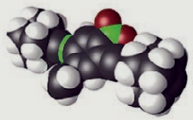
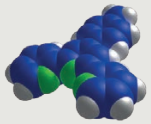
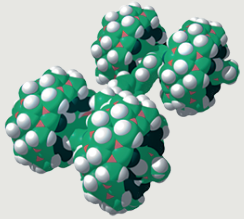
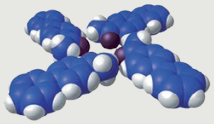
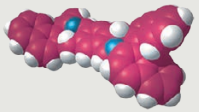
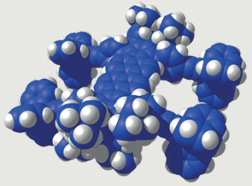
The nanocar race

Rice–Graz	Basel	Ohio	Dresden	Tsukuba	Toulouse
1st	1st	3rd	4th	Fair play	Best images
					
Team leader(s)					
Leonhard Grill and James Tour	Remy Pawlack	Saw-Wai Hla and Eric Masson	Francesca Moresco	Waka Nakanishi	Gwénaël Rapenne
Surface					
Ag(111)	Au(111) (shared)	Au(111)	Au(111) (shared)	Au(111) (shared)	Au(111) (shared)
Propulsion mechanism					
Dipolar	Inelastic	Dipolar	Inelastic	Inelastic	Inelastic
Driving distance					
150 nm 1.5 hours	133 nm 6 hours	43 nm 29 hours	11 nm First hour	1 nm First hour	25 nm by pulling (not allowed)
Incidents					
–	–	–	Molecule was stuck on a defect; molecule destroyed	Motor blocked	Molecule jumped on the tip

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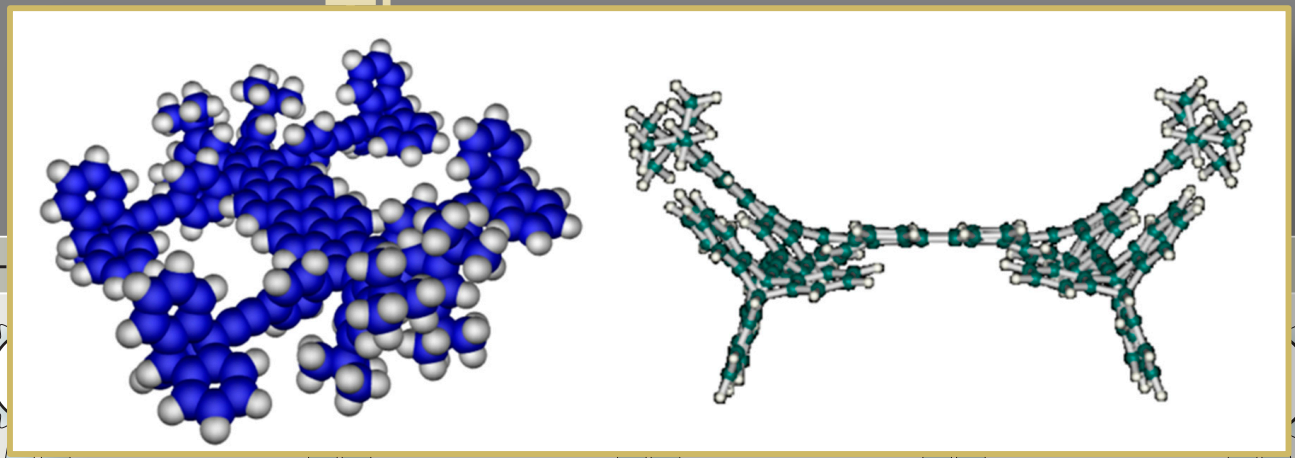
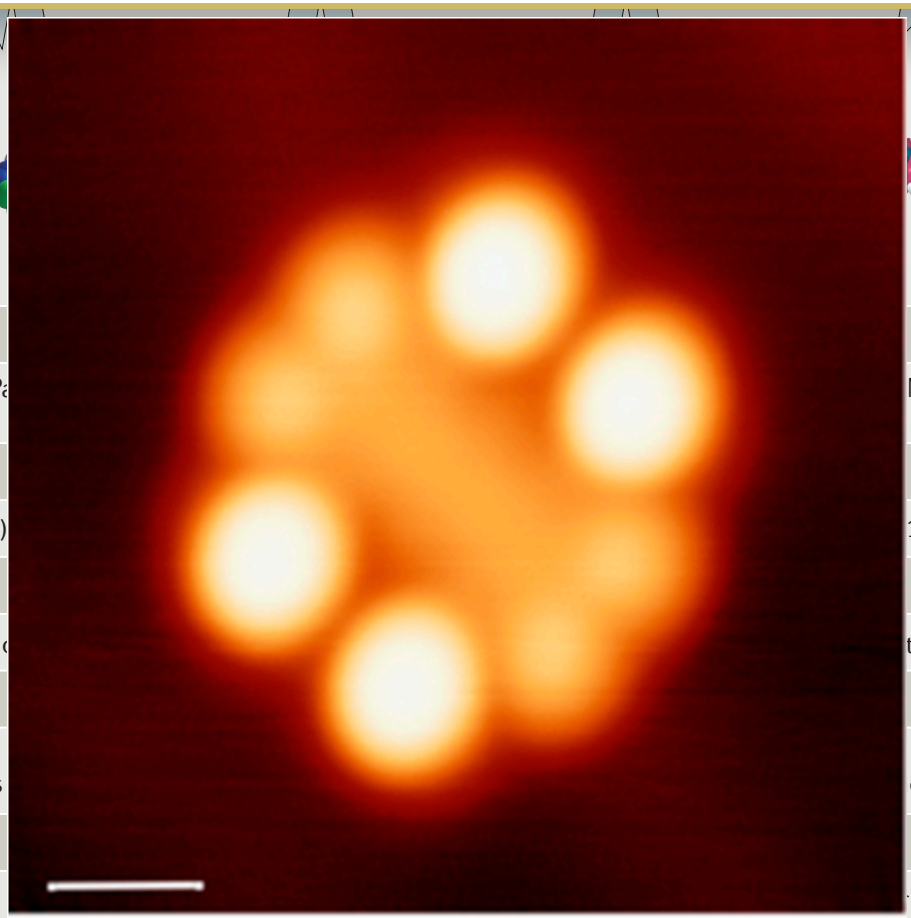
Séminaire
X-Aristote
13 juin 2019





Rice–				Toulouse
				Best images
Team leader(s)				
Leonhard Grill and James Tour	Remy Pa		Nakanishi	Gwénaël Rapenne
Surface				
Ag(111)	Au(111)		1) (shared)	Au(111) (shared)
Propulsion mechanism				
Dipolar	Inelastic		tic	Inelastic
Driving distance				
150 nm 1.5 hours	133 nm 6 hours		our	25 nm by pulling (not allowed)
Incidents				
–	–	on a defect; molecule destroyed	blocked	Molecule jumped on the tip

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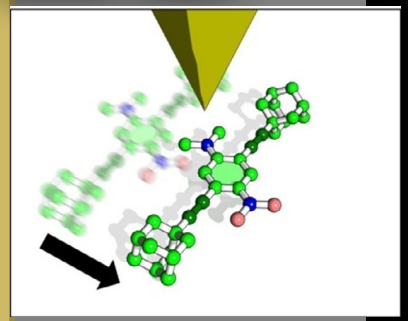
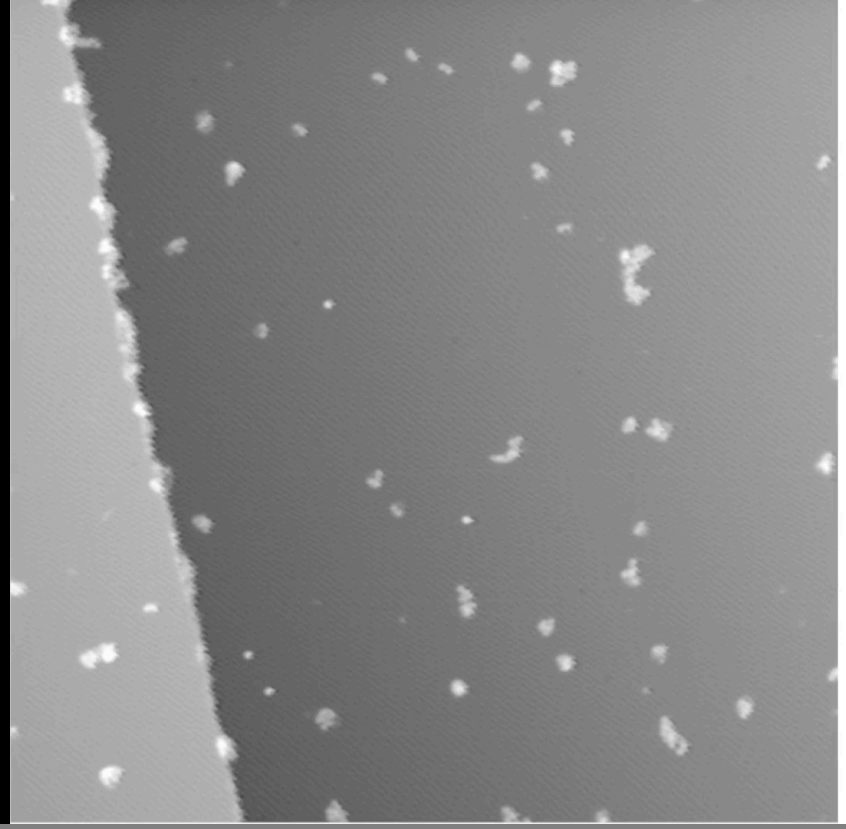
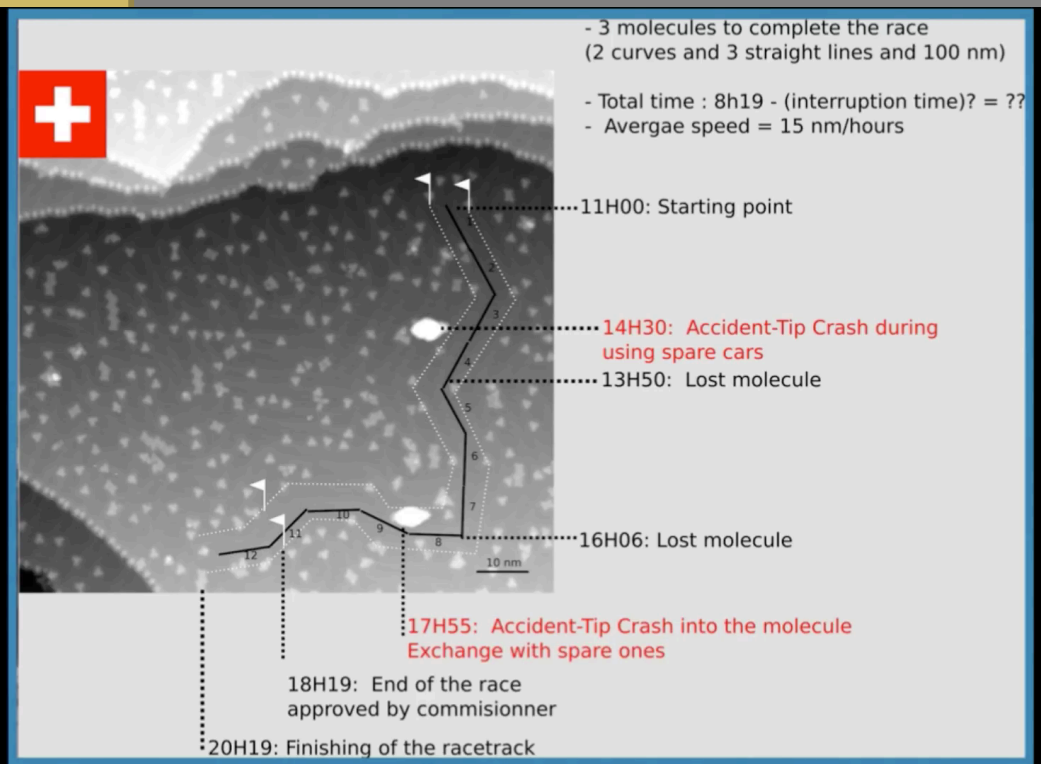




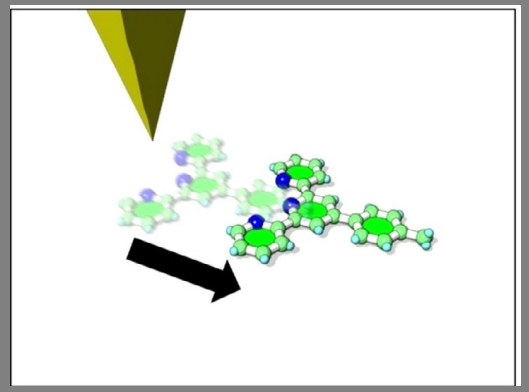
Race Time:
00 h 00 min

Actual Speed:
0.0 nm/h

Average Speed:
0.0 nm/h



Copyright L. Grill (University of Graz)



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Website for Nanocar Race II in 2021:
https://memo-project.eu/flatCMS/index.php/Nanocar-Race-II

Websites for Nanocar Race I in 2017:
http://nanocar-race.cnrs.fr
http://www.cemes.fr/Molecule-car-Race

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Structure versus fonction

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Structure versus fonction

Inspiration : reproduire la fonction mais pas la structure

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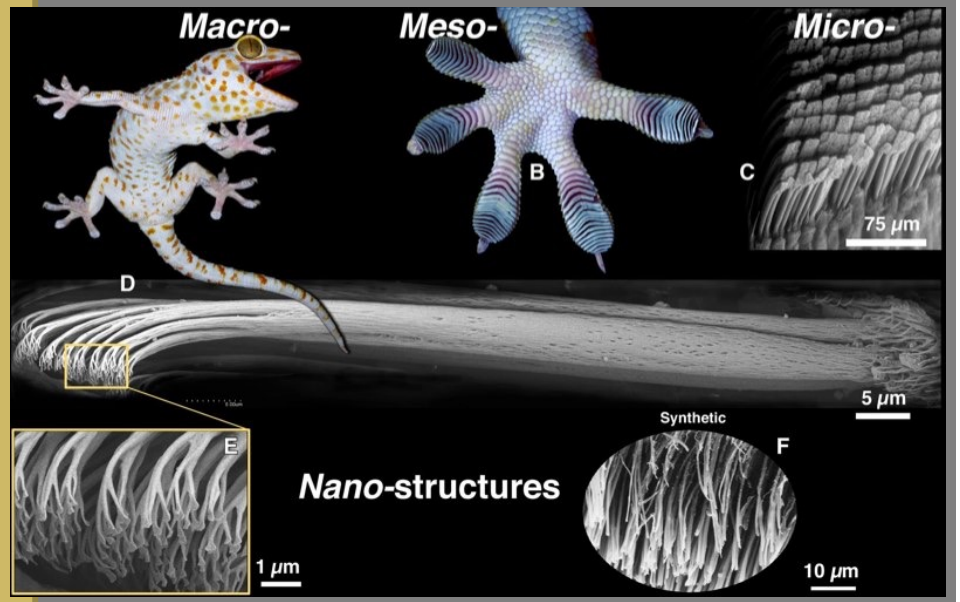
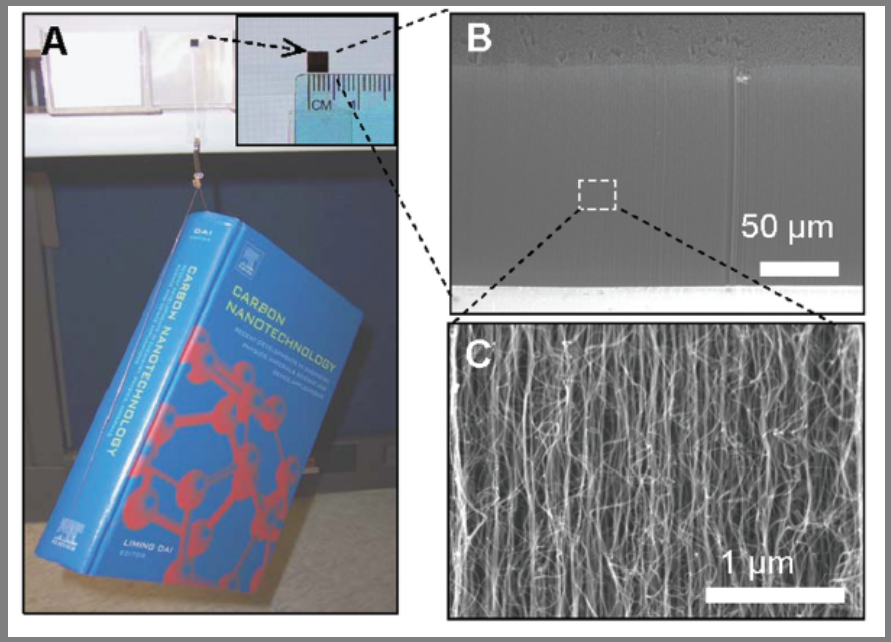
Structure versus fonction

Inspiration : reproduire la fonction mais pas la structure

Mimétisme : reproduire les propriétés d'une structure naturelle





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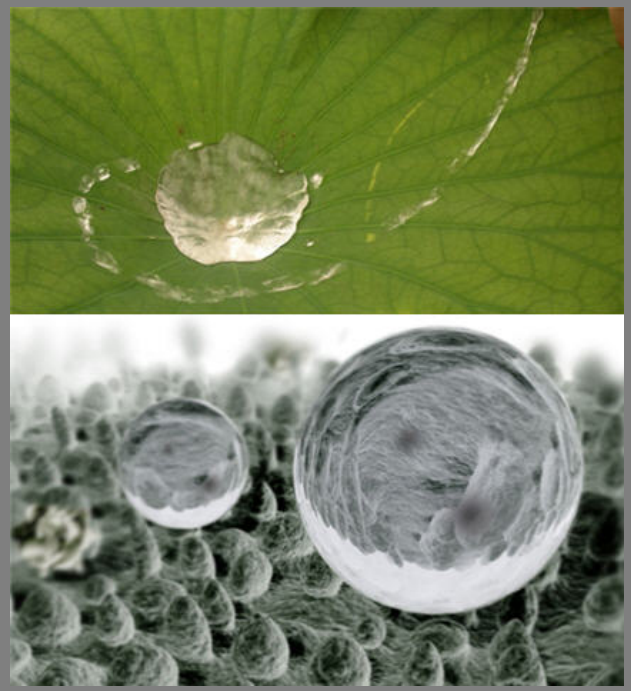
Structure versus fonction

Inspiration : reproduire la fonction mais pas la structure

Mimétisme : reproduire les propriétés d'une structure naturelle

Réplication : reproduire directement la structure naturelle



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Problème - Message

À partir de fonctions usuelles d'objets ou de machines macroscopiques, concevoir le design d'objets équivalents à l'échelle nanoscopique (qui conservent les fonctions) en prenant en compte les contraintes (forces différentes) liées aux faibles dimensions

Molécule-machine artificielle

⇓

Molécule déformée une fois déposée sur la surface

Rétro-engineering ?

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Molécule-machine artificielle

Molécule déformée une fois déposée sur la surface

Nazif Topçuoglu - « Lamentations » 2007

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Molécule-machine artificielle

Molécule déformée une fois déposée sur la surface

Nazif Topçuoglu - « Lamentations » 2007

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Molécule-machine artificielle

DESIGN

APPROCHES NUMÉRIQUES

Molécule déformée une fois déposée sur la surface

Dynamique moléculaire
Mécanique moléculaire
Système interactif

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X-Aristote
13 juin 2019

Molécule-machine artificielle

APPROCHES NUMÉRIQUES

SAMSON
Software for Adaptive Modeling and Simulation Of Nanosystems

1Å SAMSON Connect

Stéphane Redon

X. Bouju
CEMES-CNRS

Merci pour votre attention

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CEMES-
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