

Le XXI^{ème} siècle: siècle de l'information



*Le langage
des
polymères*

*Ecrire sur
des
polymères*

*Lire, effacer
et modifier*

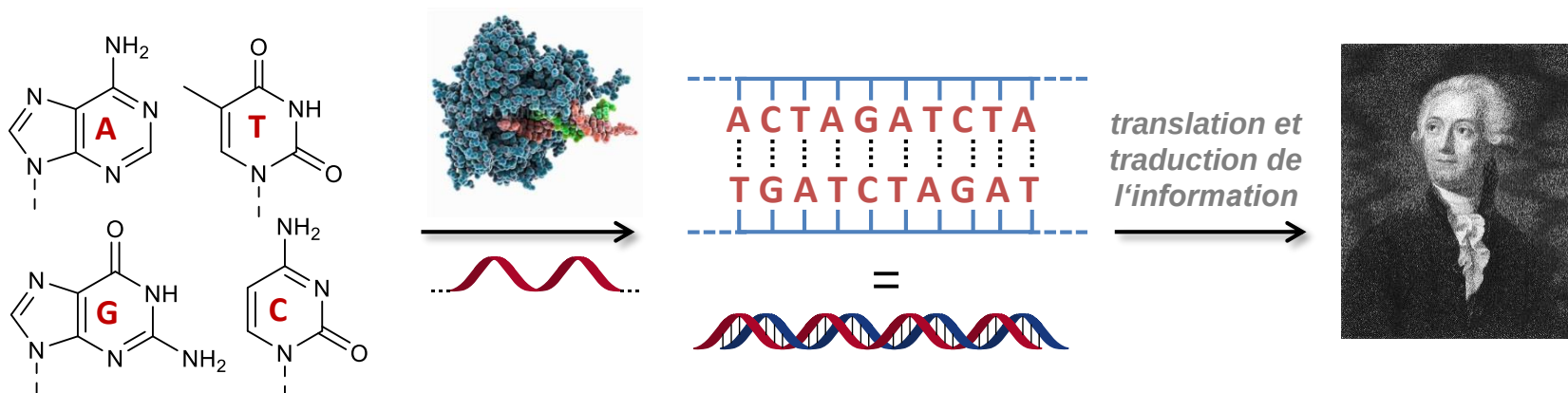
*Applications
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perspectives*



Polymères informationnels

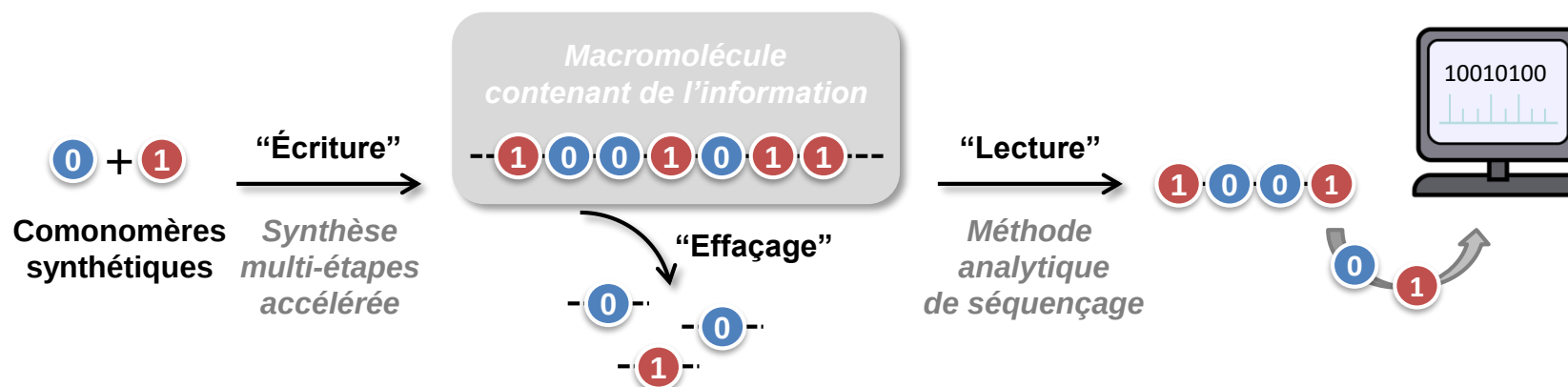
H. M. Colquhoun, J.-F. Lutz, *Nature Chemistry*, 6, 455-456 (2014)

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ATATGCTGCTAGCGATGCGTCGTTGCACTGATAGTAGTCATGATGGATGATGTTGATACCTACGT

011001001101010100110111011001010110101011011101101101001010110001011101101101111



011001001101010100110111011001010110101011011101101101001010110001011101101101111

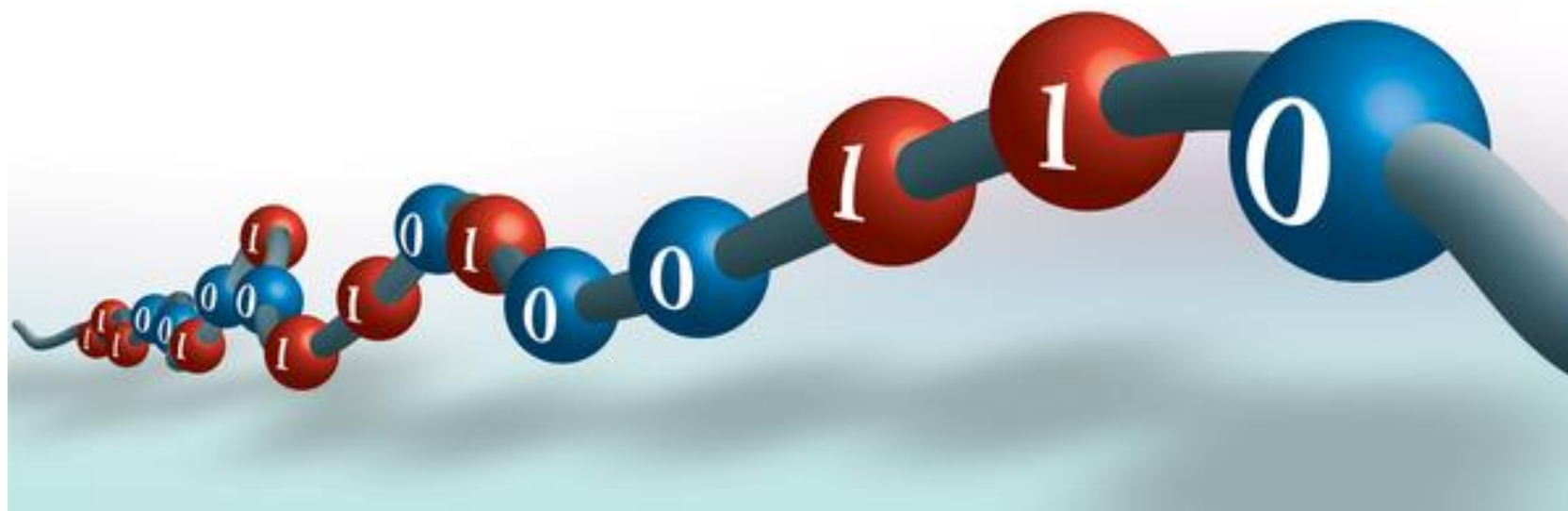
Le langage
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Polymères informationnels



Science, 341, 1238149 (2013); *Nature*, 473, 40 (2011); *Nature Chem.*, 3, 234 (2011)
Nature Chem., 3, 917 (2011); *Nature Chem.*, 5, 455 (2014); *Nature Rev. Mater.*, 1:16024 (2016)
Nature Commun., 6:8237 (2015); *Nature Commun.*, 8:967 (2017); *Nature Commun.*, 10:3774 (2019)

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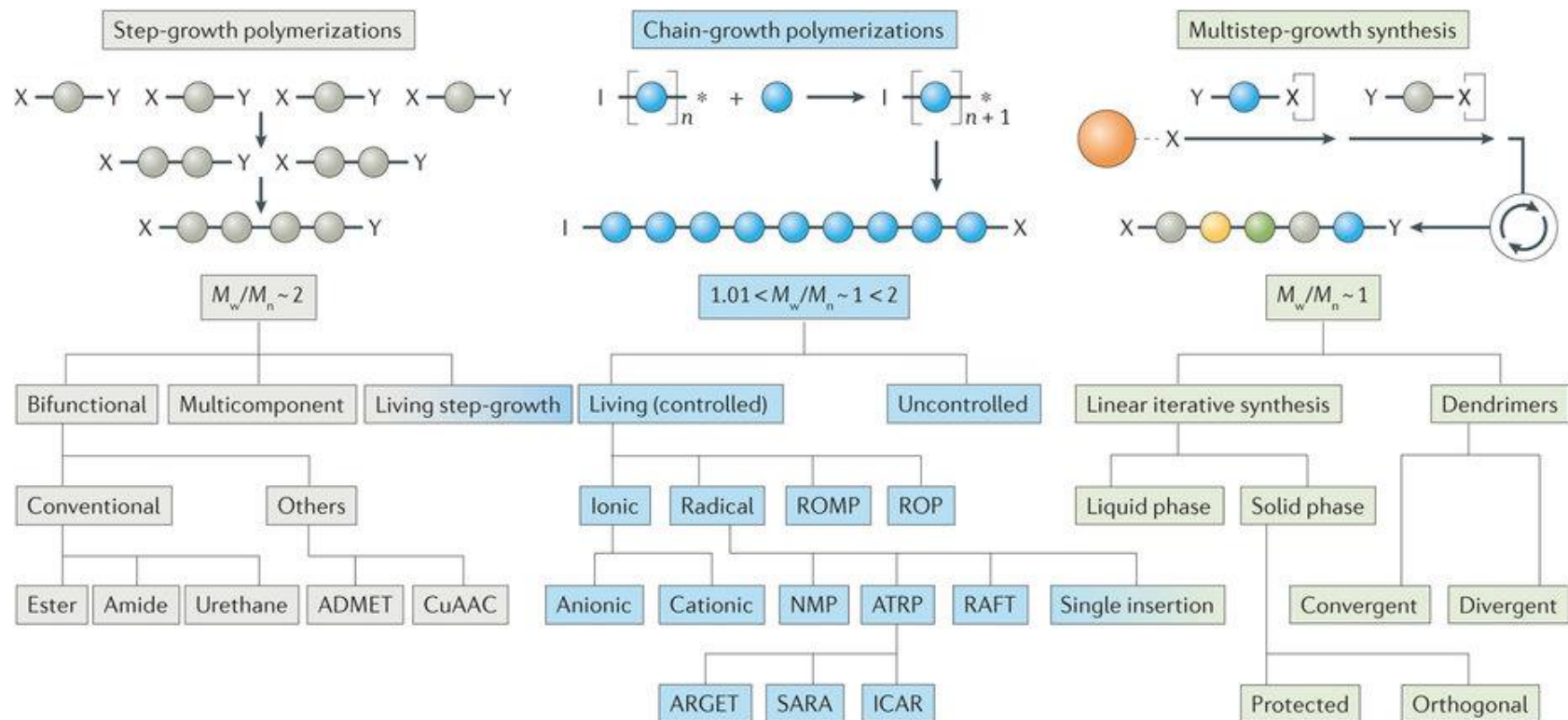
*Applications
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Macromolécules contenant de l'information :

1. Écriture: Contrôle de la structure primaire des polymères
2. Lecture: Séquençage des polymères synthétiques
3. Effaçage: Développement de séquences codées dégradables
4. Edition: Développement de séquences modifiables

Les outils du polymériste

J.-F. Lutz, J.-M. Lehn, E. W. Meijer, K. Matyjaszewski, *Nature Rev. Mater.*, 1:16024 (2016)



Nature Reviews | Materials

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**Chimie
macromoléculaire
de précision**

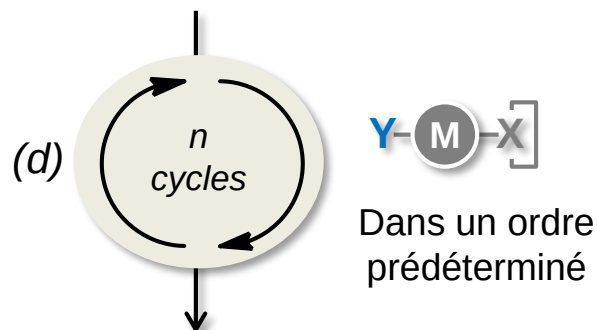
1. *Contrôle de la structure primaire des polymères synthétiques*
2. *Contrôle de la structure secondaire*
3. *Influence de la structure primaire sur les propriétés*

Synthèse multi-étapes

J.-F. Lutz, M. Ouchi, D. R. Liu, M. Sawamoto, *Science*, 341, 1238149 (2013)



A = Amorceur
M = Monomère
(d) = Deprotection



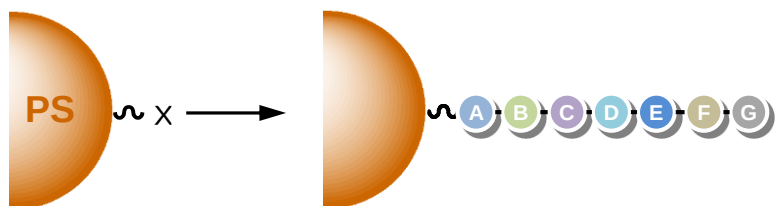
*Le langage
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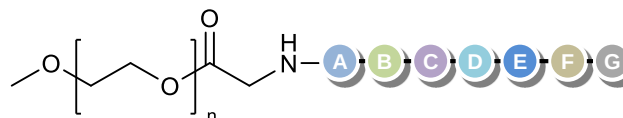
*Lire, effacer
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En phase solide - Merrifield, 1963

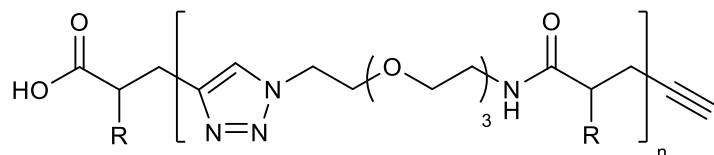


En phase liquide – Mutter, 1972



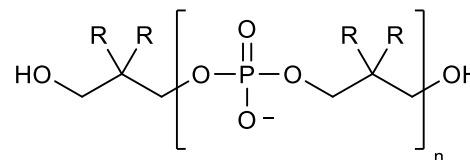
Polymères numériques

Poly(triazole amide)s



R = Me (1), H (0)

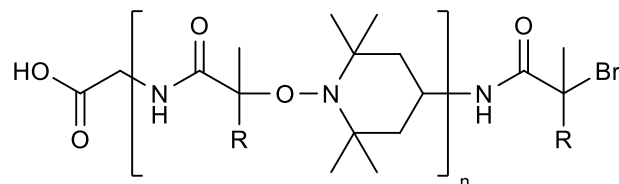
Poly(phosphodiester)s



R = Me (1), H (0)

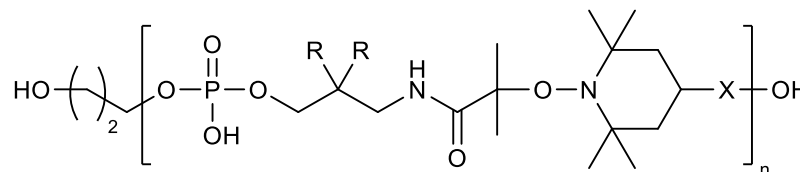
**Le langage
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Poly(alcoxyamine amide)s



R = Me (1), H (0) [PCT Int. Appl. WO/2015/033045A1](#)

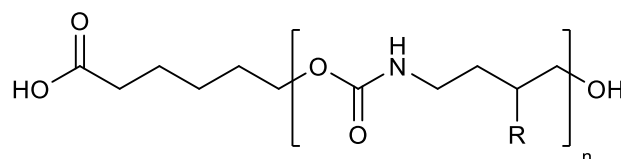
Poly(alcoxyamine phosphodiester)s



R = Me (1), H (0)

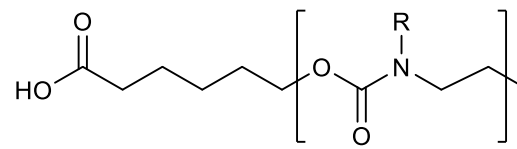
**Lire, effacer
et modifier**

Polyuréthanes



R = Me (1), H (0) [PCT Int. Appl. EP2017/061375](#)

Polyuréthanes N-substitués



R = Me (00), Et (01), Pr (10), Bu (11)

**Applications
et
perspectives**

Exemple de chimie

A. Al Ouahabi, L. Charles, J.-F. Lutz, *JACS*, **137**, 5629–5635 (2015)

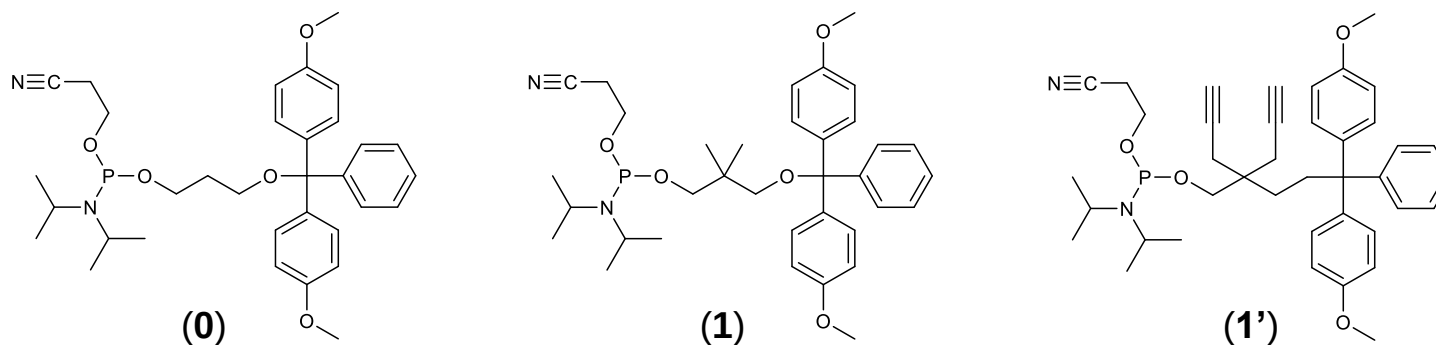
Le langage
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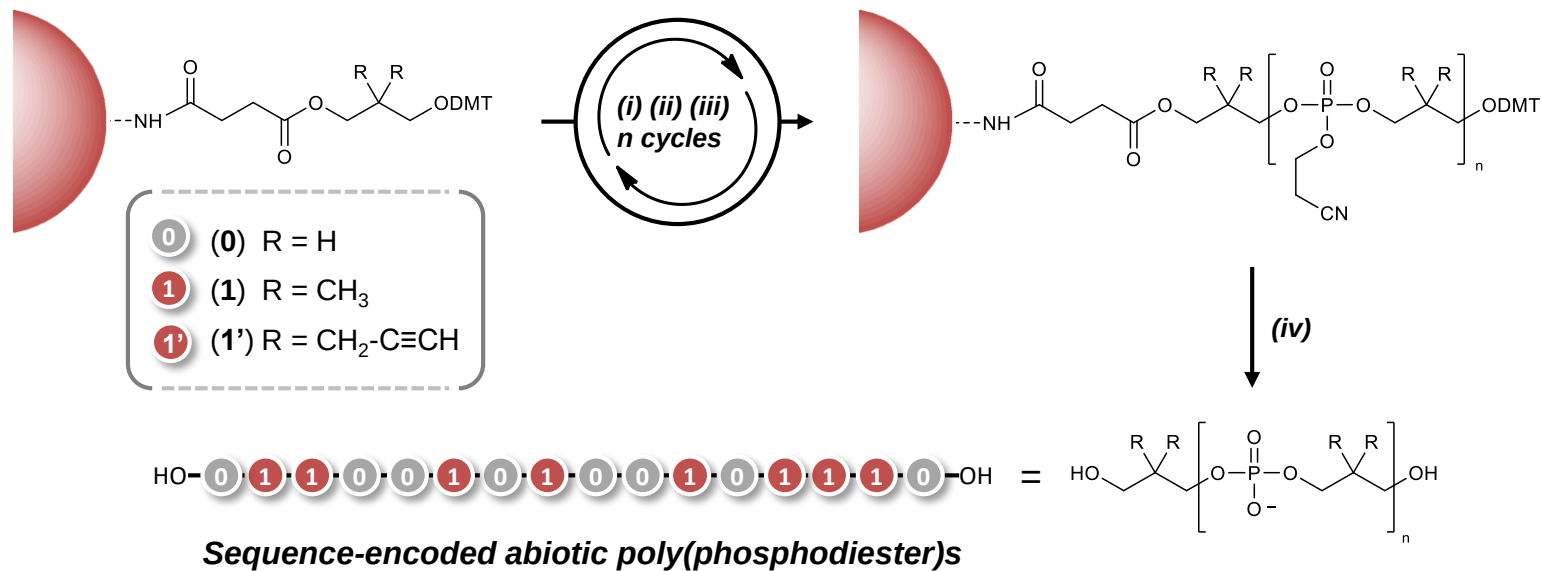
Lire, effacer
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a.

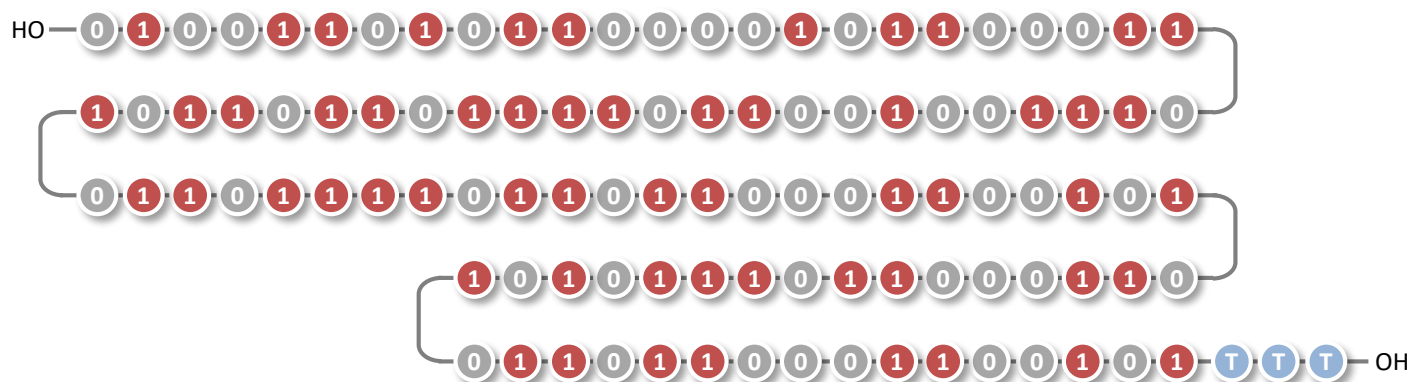


b.

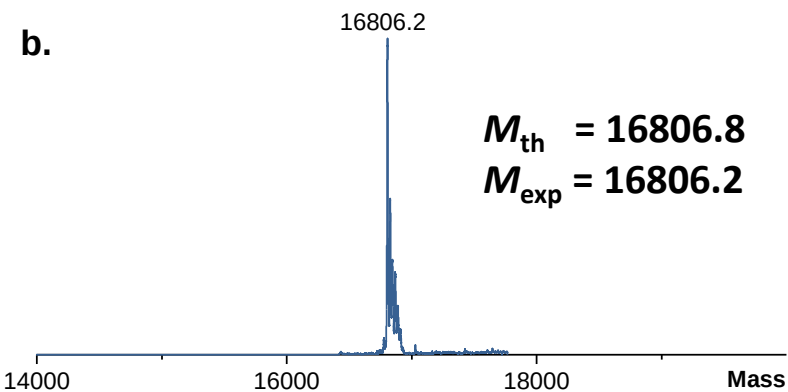
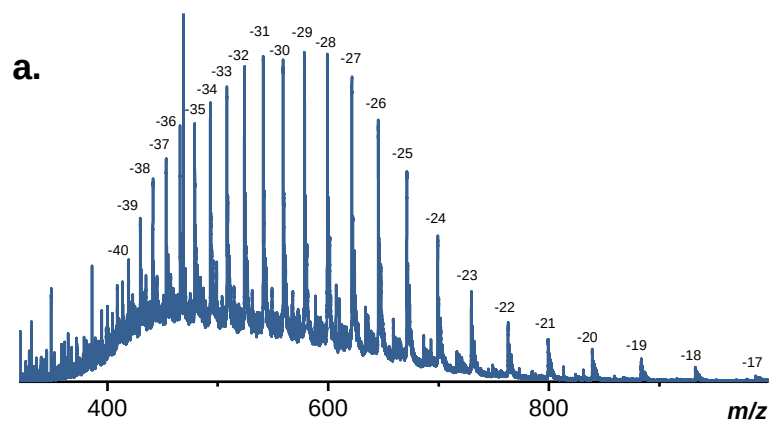


Préparation de longues chaînes

A. Al Ouahabi, M. Kotera, L. Charles, J.-F. Lutz, *ACS Macro Lett.*, **4**, 1077–1080 (2015)



(M) 01001101 (a) 01100001 (c) 01100011 (r) 01110010 (o) 01101111 (m) 01101101
(o) 01101111 (l) 01101100 (e) 01100101 (c) 01100011 (u) 01110101 (l) 01101100 (e) 01100101



Le langage des polymères

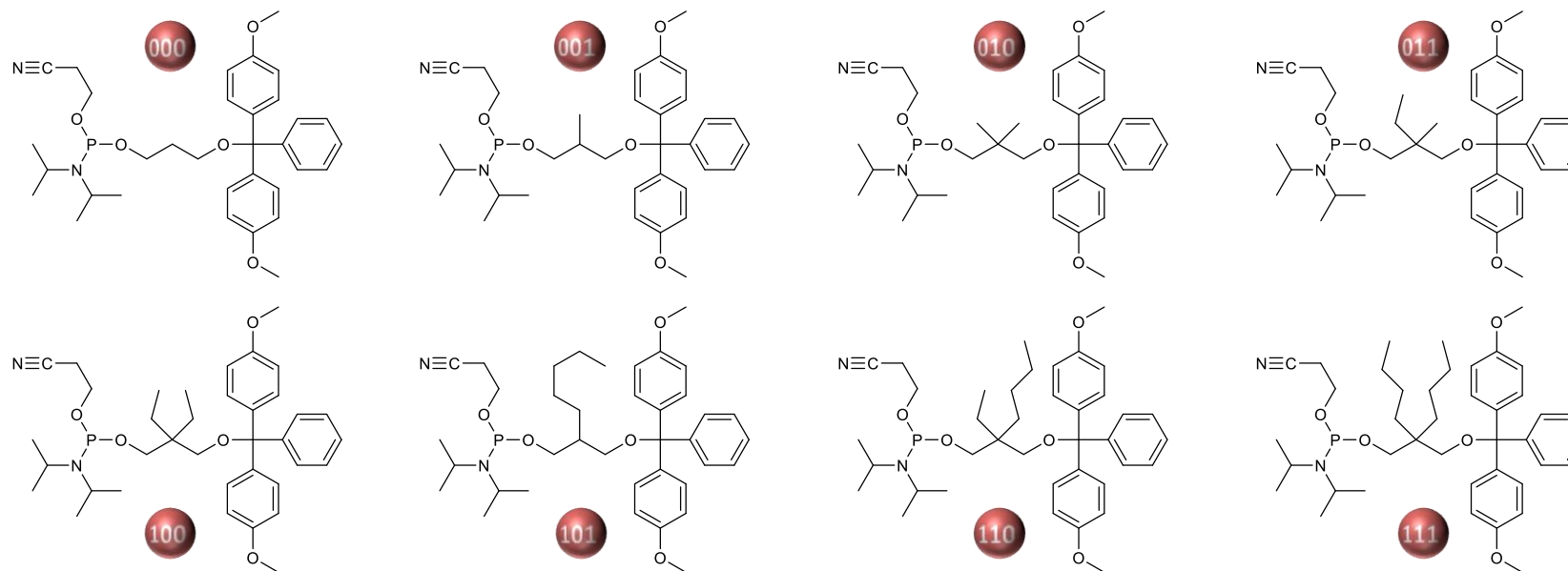
Ecrire sur des polymères

Lire, effacer et modifier

Applications et perspectives

Alphabets augmentés

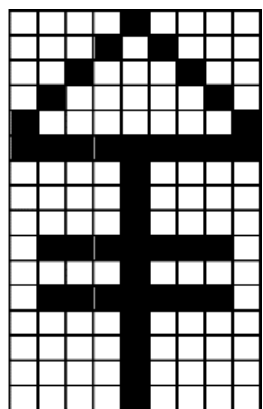
E. Laurent, D. Gimes, L. Charles, J.-F. Lutz, *Macromolecules*, **53**, 4022–4029 (2020)



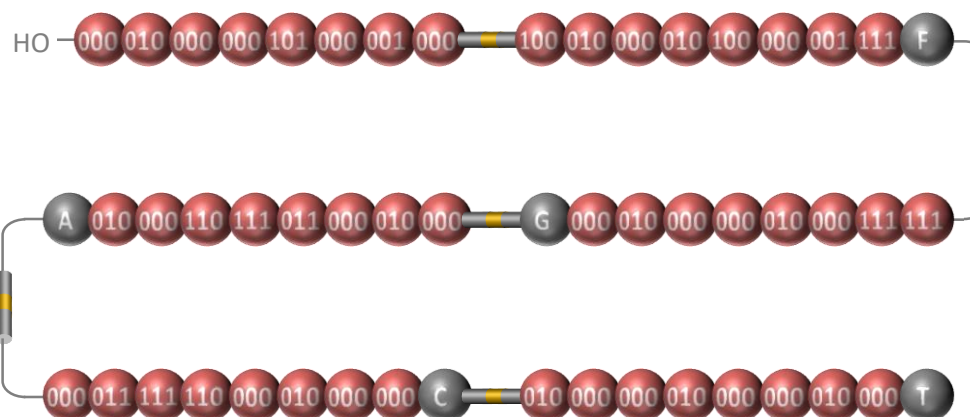
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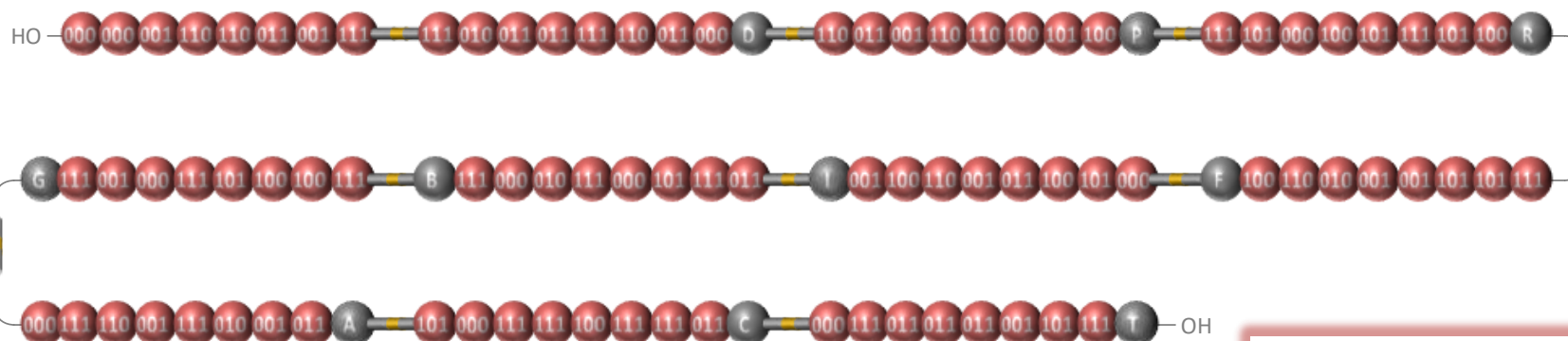


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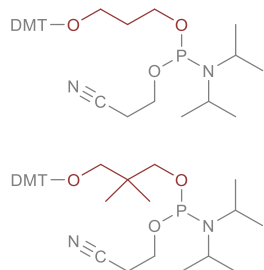
440 bits/chaîne
3 bits/monomère



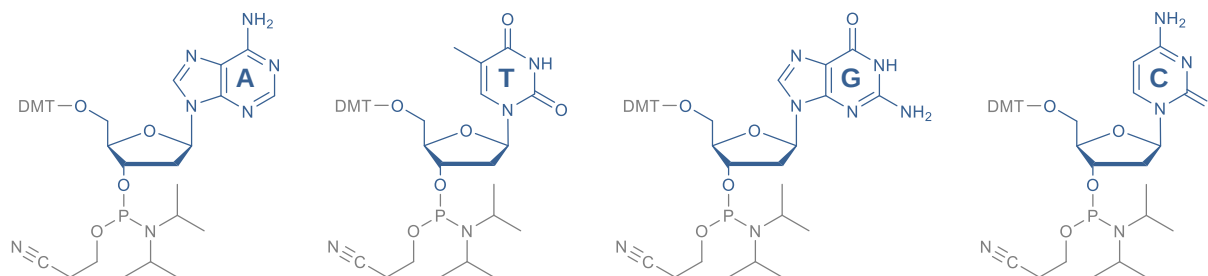
Chaînes ultra-longues

T. Mondal, M. Nerantzaki, M. Maaloum, J.-F. Lutz et al., *Macromolecules*, 54, 3423-3429 (2021)

Abiotic alphabet



Biological alphabet

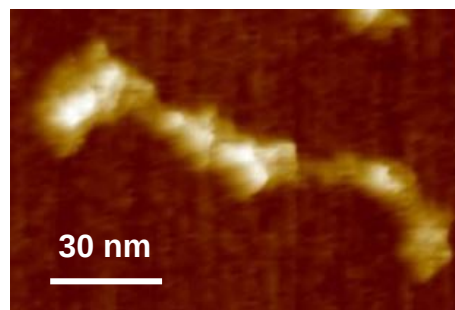
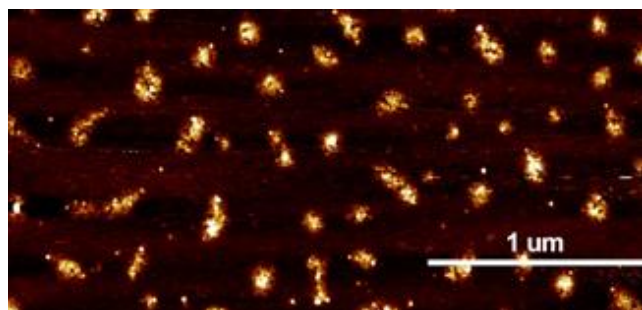
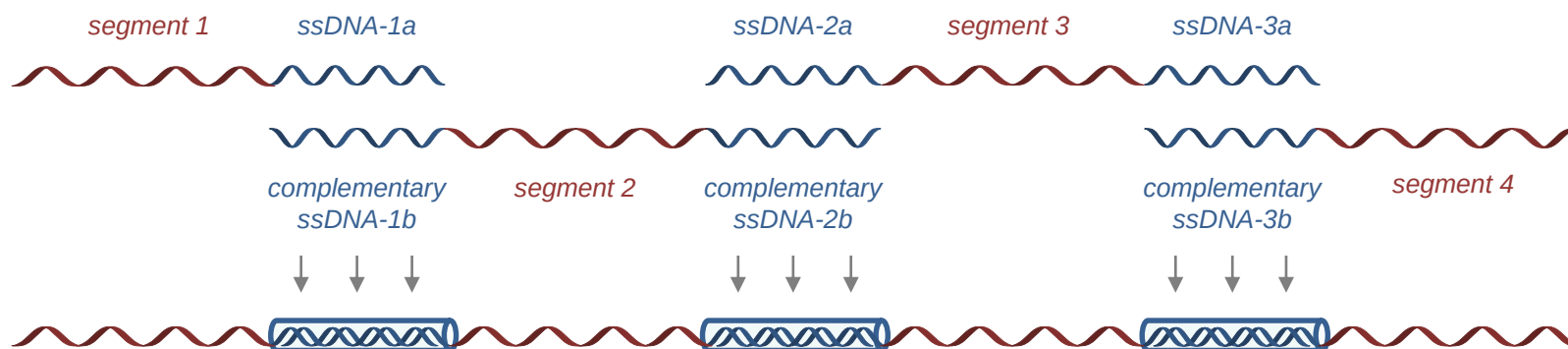


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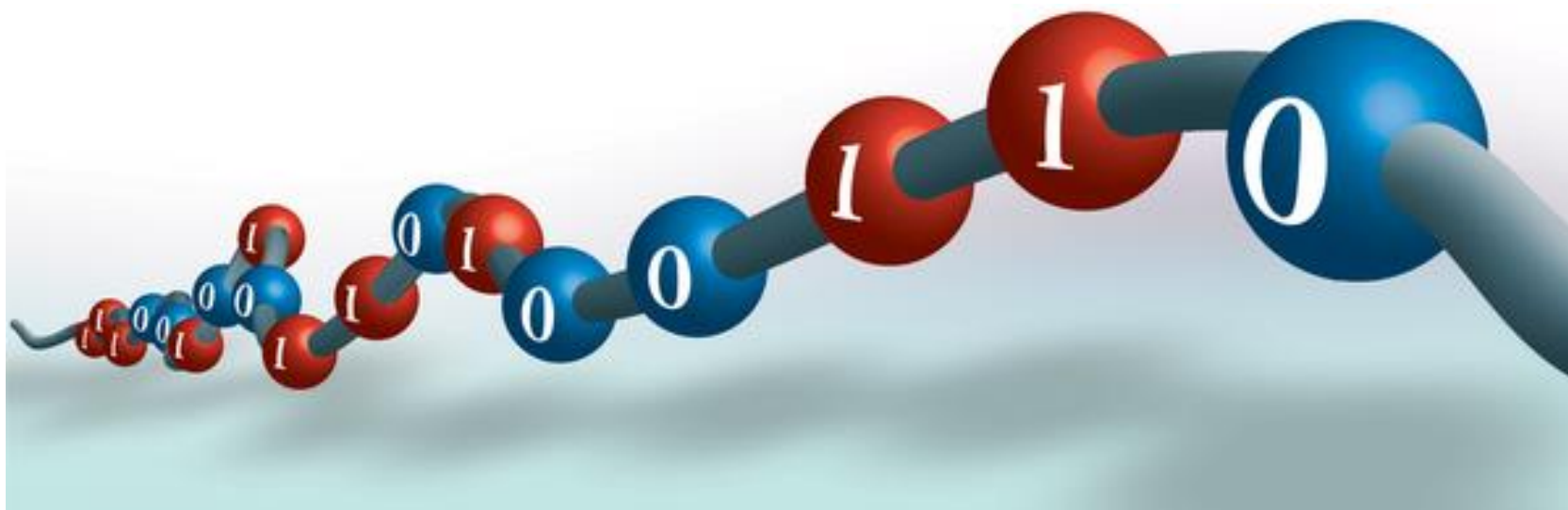
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352 monomères
synthétiques
90 nucléotides

Polymères informationnels



Science, 341, 1238149 (2013); *Nature*, 473, 40 (2011); *Nature Chem.*, 3, 234 (2011)
Nature Chem., 3, 917 (2011); *Nature Chem.*, 5, 455 (2014); *Nature Rev. Mater.*, 1:16024 (2016)
Nature Commun., 6:8237 (2015); *Nature Commun.*, 8:967 (2017); *Nature Commun.*, 10:3774 (2019)

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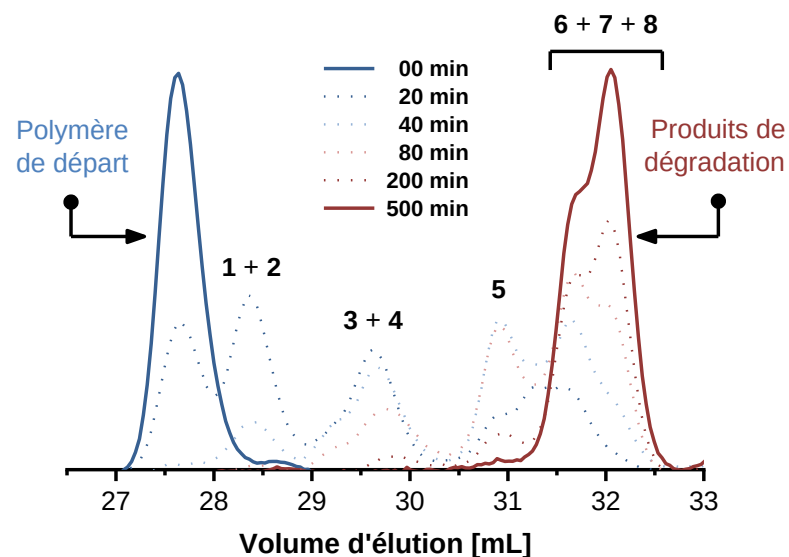
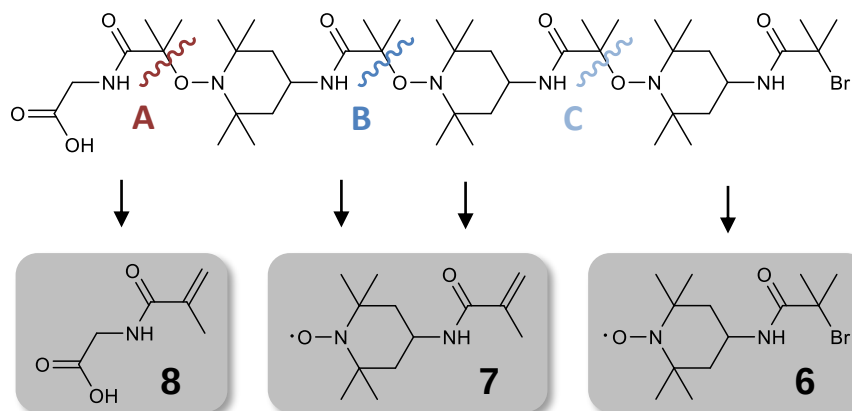
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3. Effaçage: Développement de séquences codées dégradables
4. Edition: Développement de séquences modifiables

Effaçage de l'information

R. K. Roy, C. Laure, L. Charles, J.-F. Lutz et al., *Nature Communications*, 6:7237 (2015)

Stable pour de nombreux mois à 25°C
Dégradation rapide par chauffage au dessus de 65°C

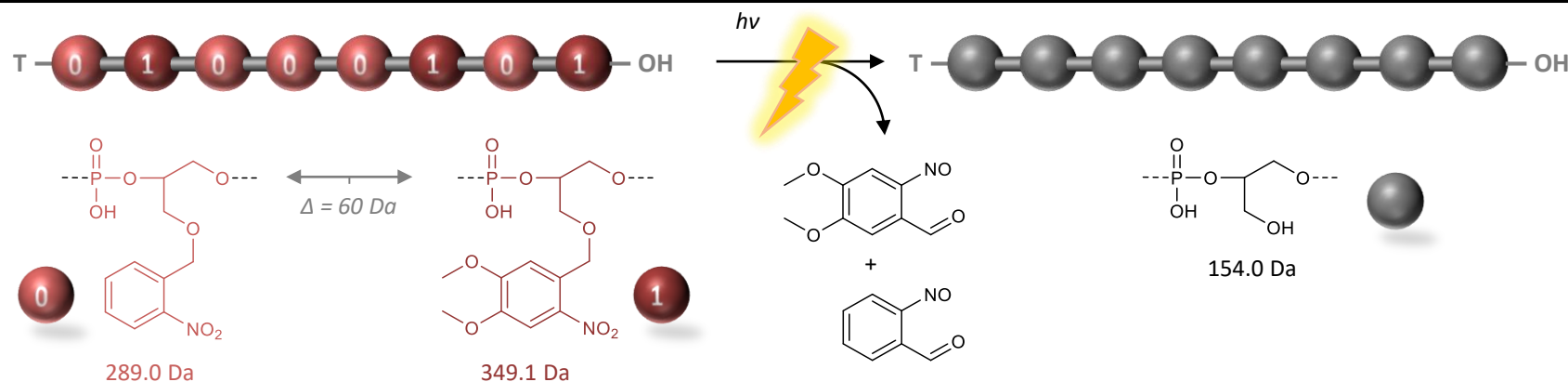


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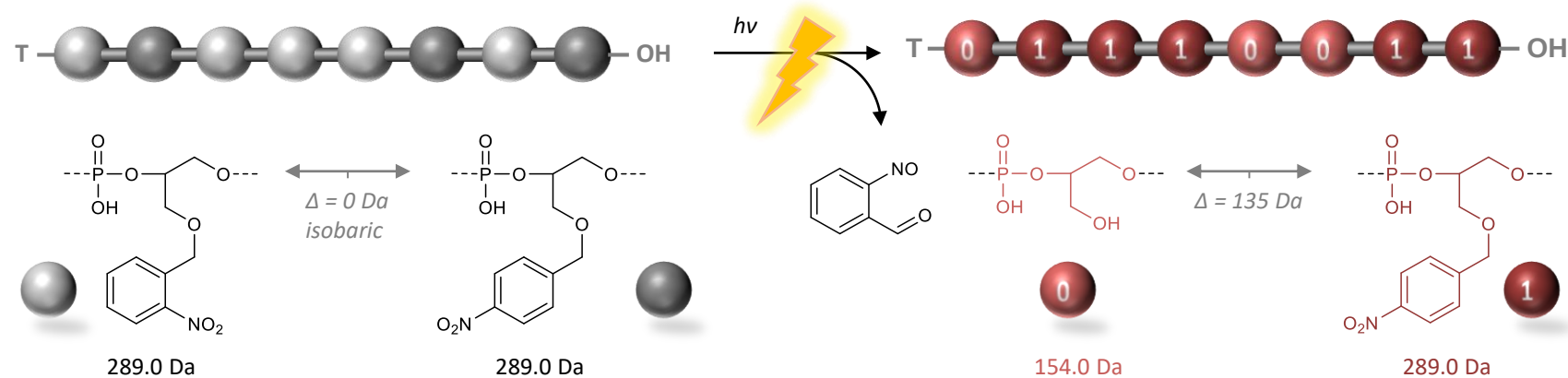
N. F. König, L. Charles, J.-F. Lutz, et al. *Nature Communications*, 10:3774 (2019)



Applications
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Utilisation d'un révélateur lumineux

N. F. König, L. Charles, J.-F. Lutz, et al. *Nature Communications*, 10:3774 (2019)



Le langage des polymères

Ecrire sur des polymères

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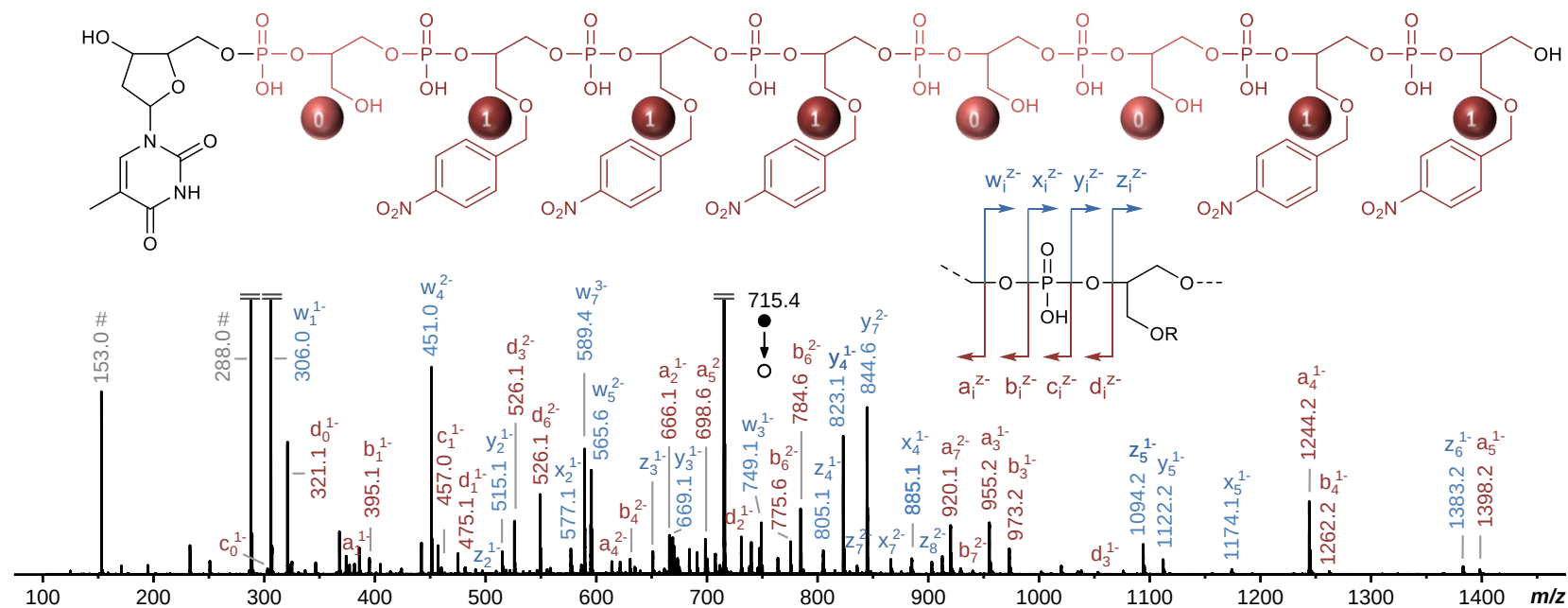
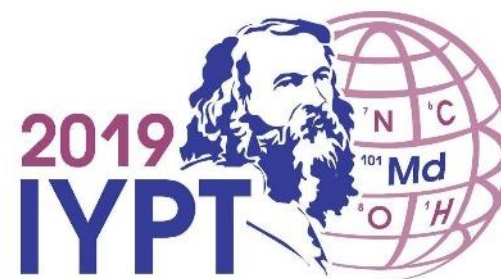
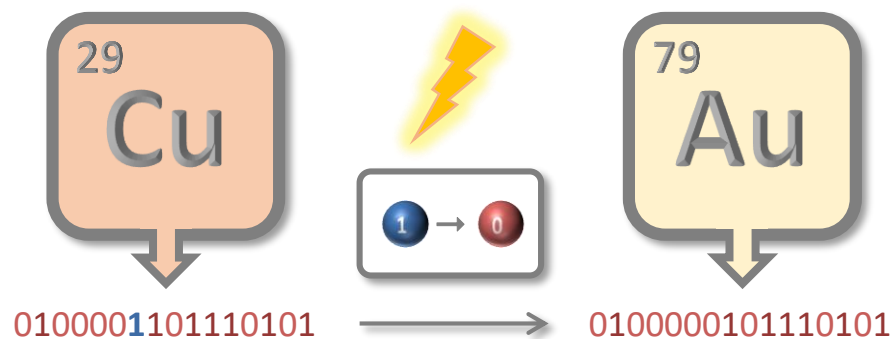
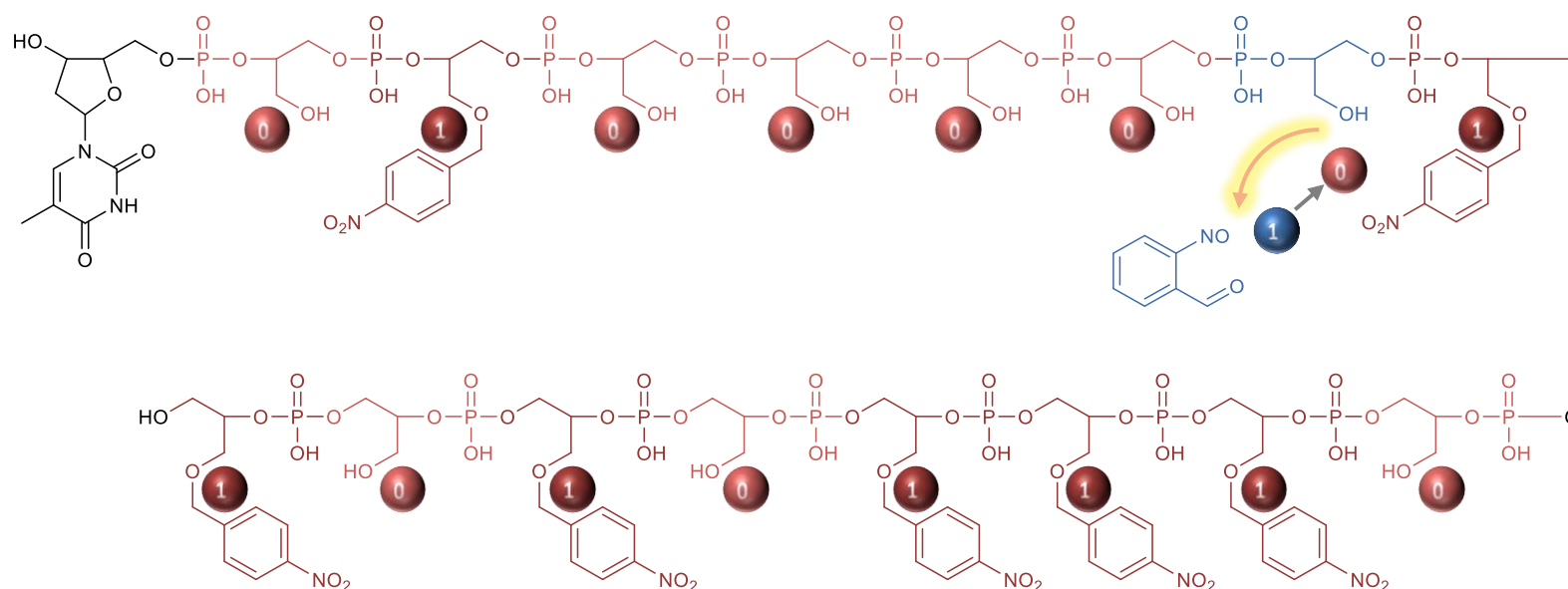


Photo-mutagénèse artificielle

N. F. König, L. Charles, J.-F. Lutz, et al. *Nature Communications*, 10:3774 (2019)



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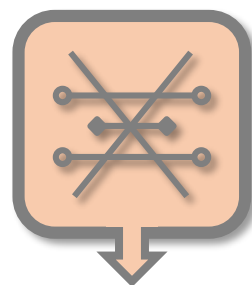
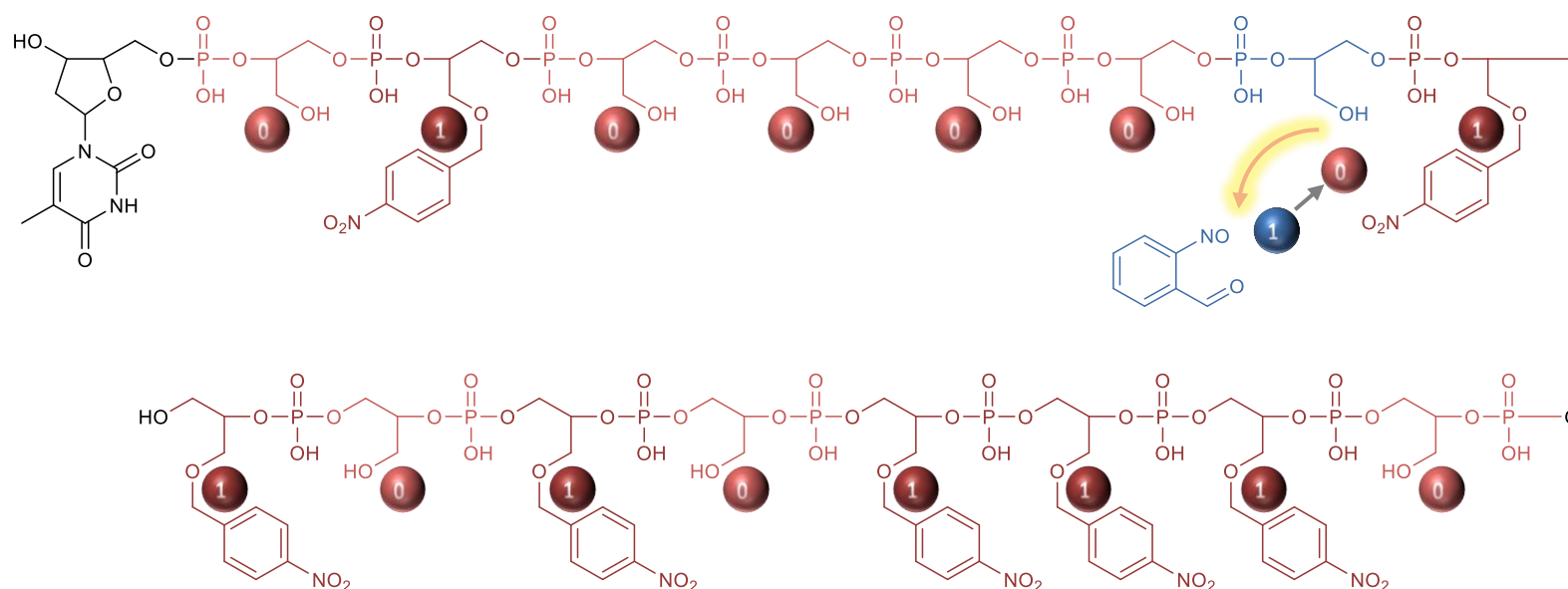
Ecrire sur
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Lire, effacer
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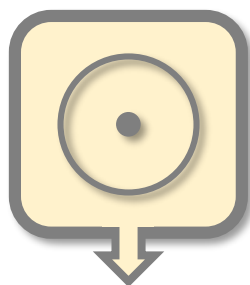
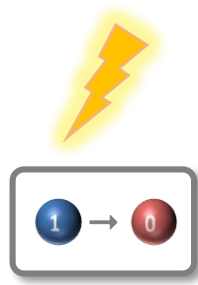
Applications
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Photo-mutagénèse artificielle

N. F. König, L. Charles, J.-F. Lutz, et al. *Nature Communications*, 10:3774 (2019)



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Le langage
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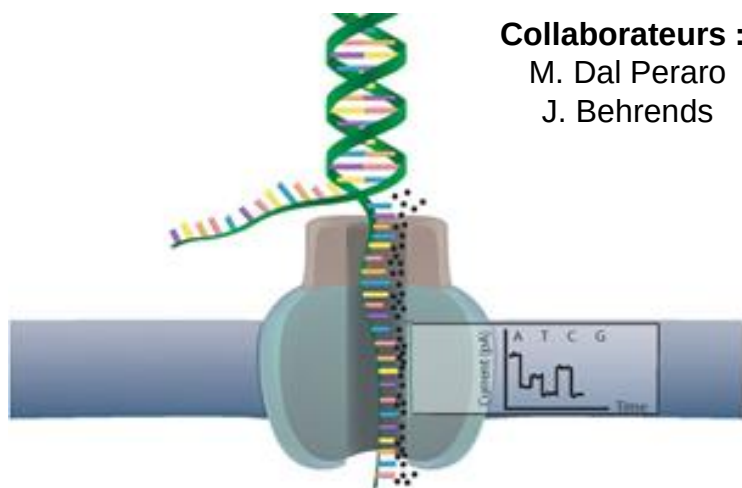
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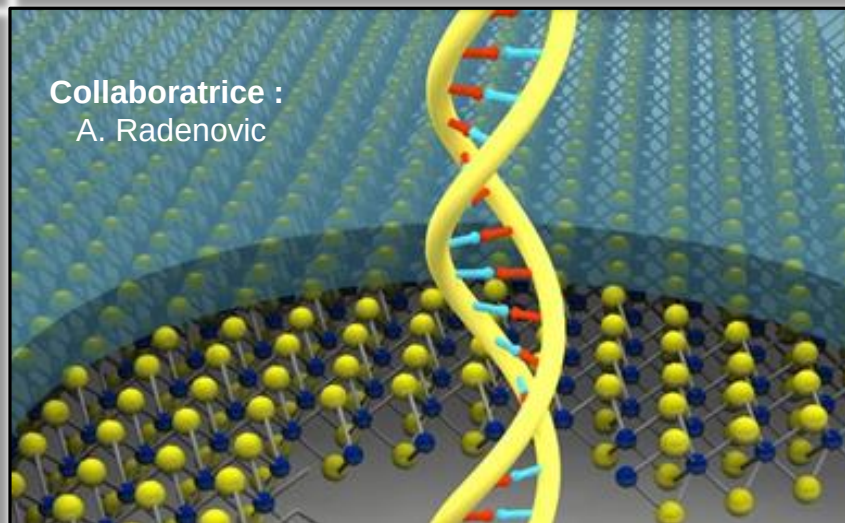
Applications
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Séquençage des polymères

Séquençage dans un pore biologique



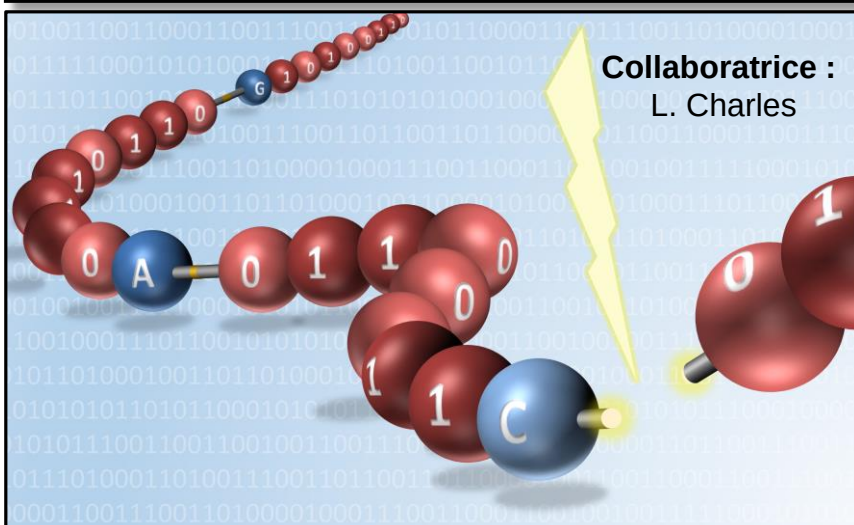
Séquençage dans un pore artificiel



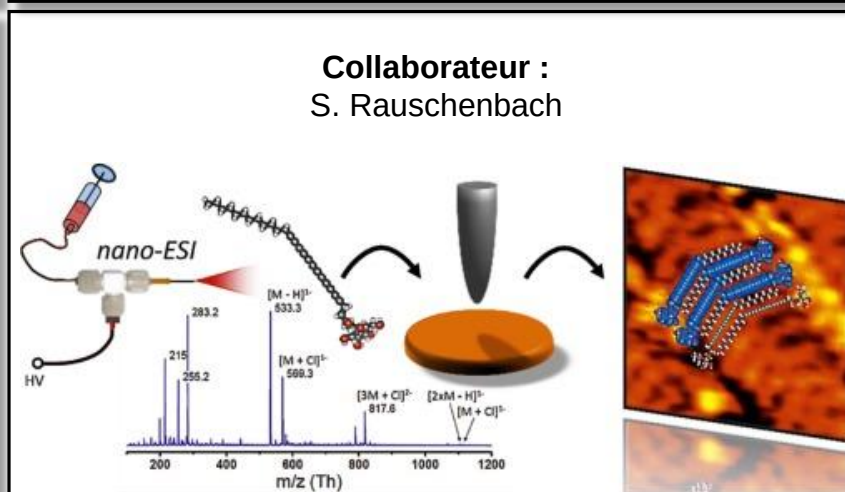
**Le langage
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**Ecrire sur
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Spectrométrie de masse en tandem



Déposition ESI et imagerie STM

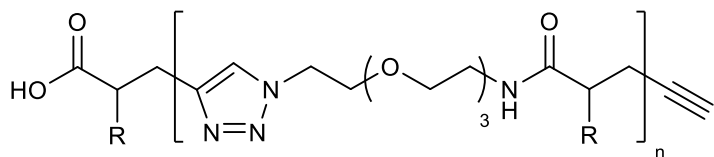


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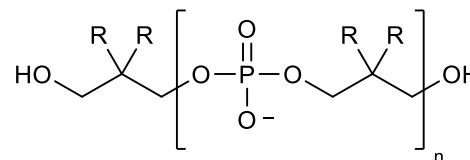
Spectrométrie de masse en tandem

Poly(triazole amide)s



R = Me (1), H (0)

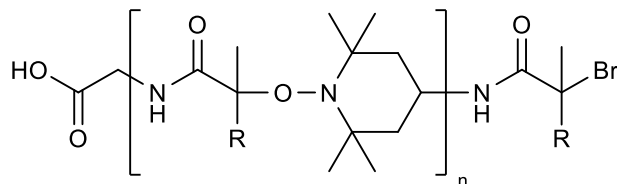
Poly(phosphodiester)s



R = Me (1), H (0)

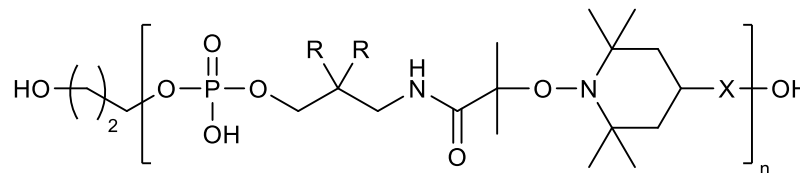
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Poly(alcoxyamine amide)s



R = Me (1), H (0) [PCT Int. Appl. WO/2015/033045A1](#)

Poly(alcoxyamine phosphodiester)s

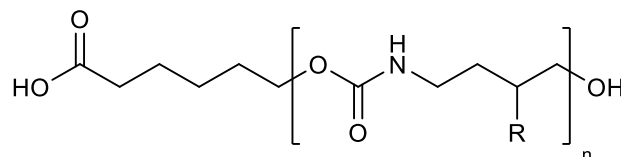


R = Me (1), H (0)

**Ecrire sur
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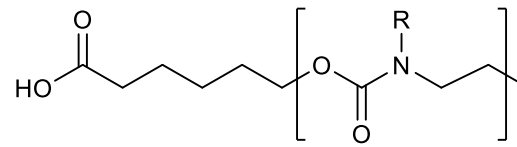
**Lire, effacer
et modifier**

Polyuréthanes



R = Me (1), H (0) [PCT Int. Appl. EP2017/061375](#)

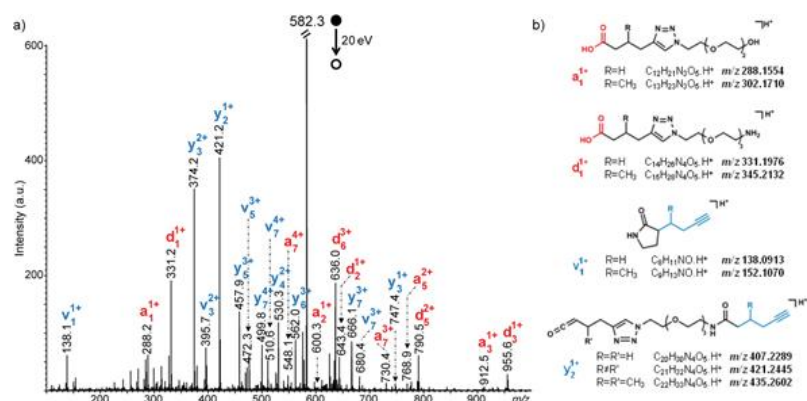
Polyuréthanes N-substitués



R = Me (00), Et (01), Pr (10), Bu (11)

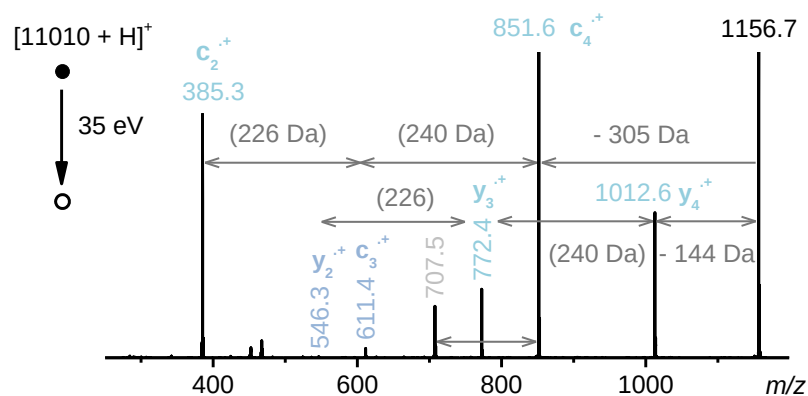
**Applications
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Poly(triazole amide)s



Anal. Chem. **88**, 3715 (2016)
J. Am. Soc. Mass Spectrom. **28**, 1149 (2017)

Poly(alcoxyamine amide)s



Nat. Commun., **6**:7237 (2015); *Macromolecules*, **48**, 4319 (2015)
Rapid Commun. Mass Spectrom., **30**, 22 (2016)

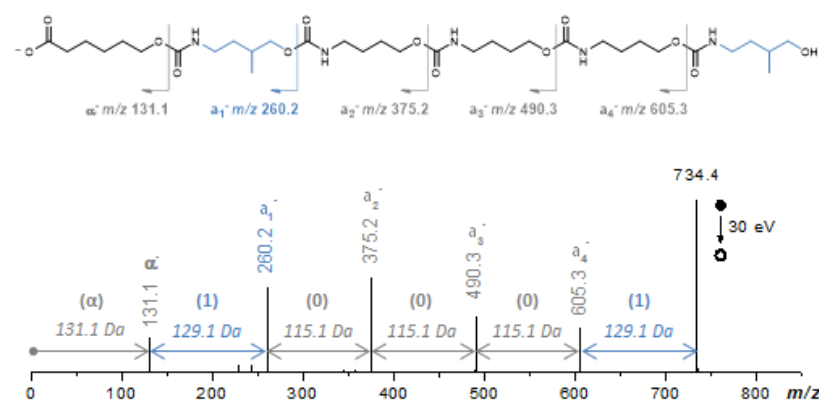
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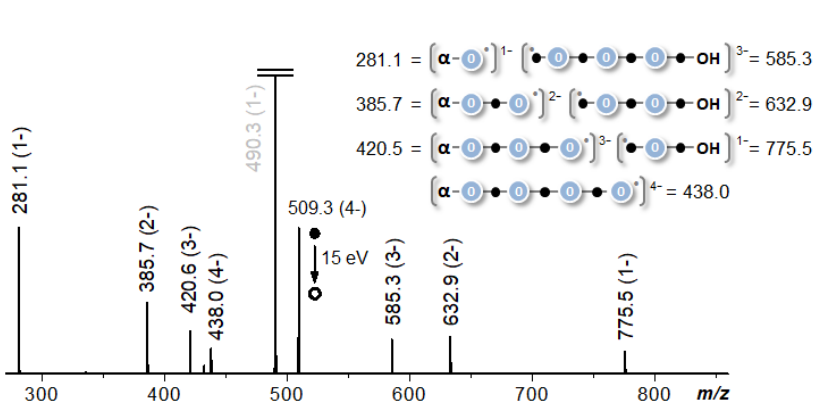
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Polyuréthanes



Chem, **1**, 114 (2016); *Int. J. Mass Spectrom.*, **421**, 271 (2017)

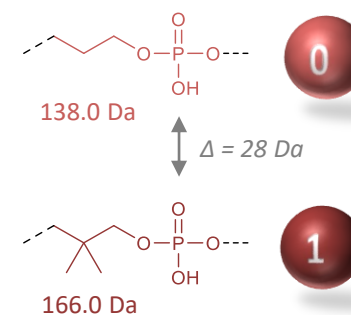
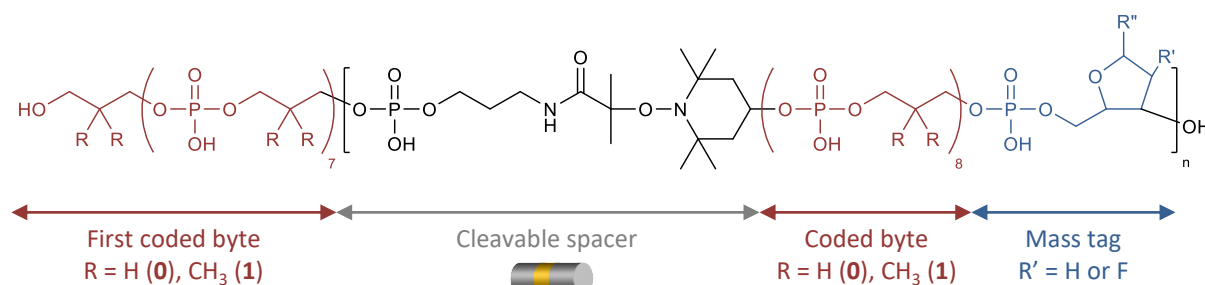
Poly(alcoxyamine phosphodiester)s



JACS, **138**, 5629 (2016); *J. Mass Spectrom.*, **52**, 788 (2017)

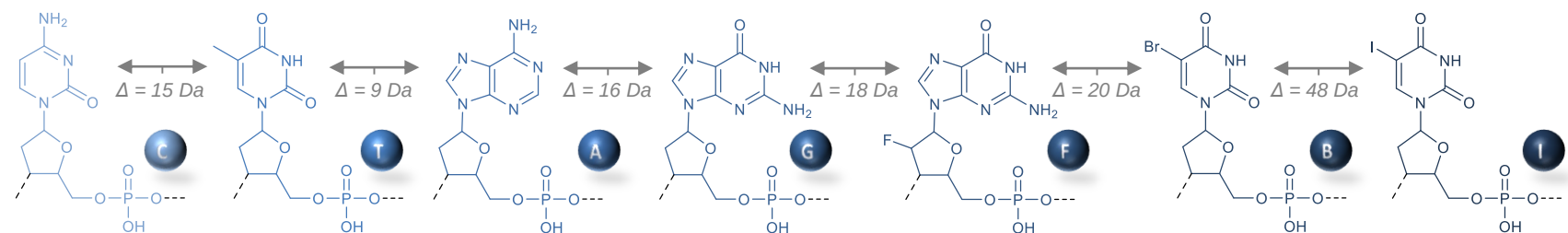
Séquençage de longues chaînes

A. Al Ouahabi, J.-A. Amalian, L. Charles, J.-F. Lutz, *Nature Communications*, 8:967 (2017)



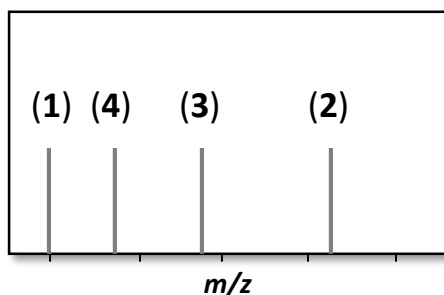
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MS^2

Reading direction



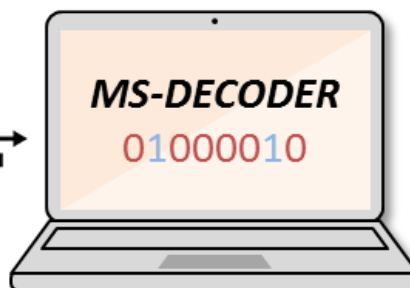
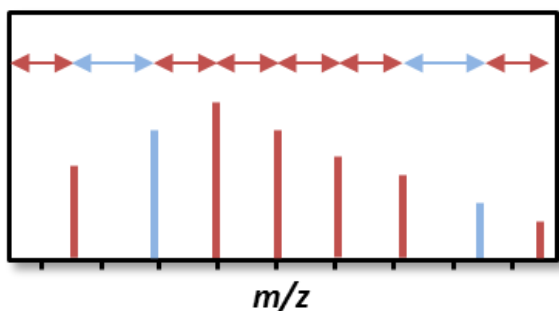
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(2)	0 1 1 0 1 1 1 1 A	MS^3	01101111	ASCII	o
(3)	0 1 1 0 0 1 0 0 C	MS^3	01100100	ASCII	d
(4)	0 1 1 0 0 1 0 1 T - OH	MS^3	01100101	ASCII	e

Lire, effacer
et modifier

Applications
et
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A. Burel, C. Carapito, J.-F. Lutz, L. Charles, *Macromolecules*, 50, 8290-8296 (2017)

Fichier (.txt)
MS/MS



Séquence décodée
obtenue en 1-10
millisecondes

Le langage
des
polymères

Ecrire sur
des
polymères

Lire, effacer
et modifier

Applications
et
perspectives

MS-DECODER 1.4.2

File Edit Help

Files	Code
1_R1-C4_BP150-1_361.2.txt	00
2_R1-C4_DK-124_375.2.txt	01
3_R1-C4_DK138_476.3.txt	000
4_R1-C4_BP150-1_490.3.txt	001
5_R1-C4_DK154_490.3.txt	100
6_R1-C4_DK161_591.3.txt	0000
7_R1-C4_BP-005_605.4.txt	0001
8_R1-C4_BP-025_605.4.txt	0010
9_R1-C4_BP-038_605.4.txt	0100
10_R1-C4_BP-029_605.4.txt	1000
11_R1-C4_BP-090_619.4.txt	0011
12_R1-C4_BP-040_619.4.txt	1001
13_R1-C4_DK161_706.4.txt	0 0000
14_R1-C4_DK161_720.4.txt	0 0001
15_R1-C4_PC39_734.4.txt	0 0011
16_R1-C4_BP-050_734.4.txt	1 0001
17_R1-C4_INIT_748.4.txt	0 1101
18_R1-C4_BP-051_748.4.txt	0 1110
19_R1-C4_DK161_835.5.txt	00 0001
20_R1-C4_BP-073_849.5.txt	00 0101
21_R1-C4_BP-046_863.5.txt	00 0111
22_R1-C4_BP-053_863.5.txt	10 1010

Settings

Autodetect: Autodetect

m/z tolerance: 0,05 Da

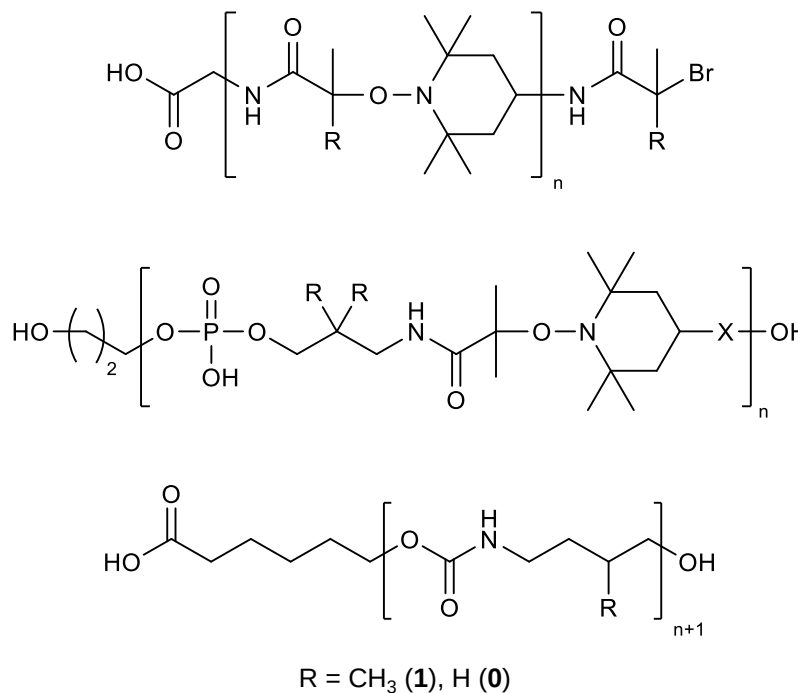
Intensity threshold: 5

First isotope searched threshold: 35

Start

[Copy results to clipboard](#)

Open files Remove all items



Décodage automatisé de longues chaînes

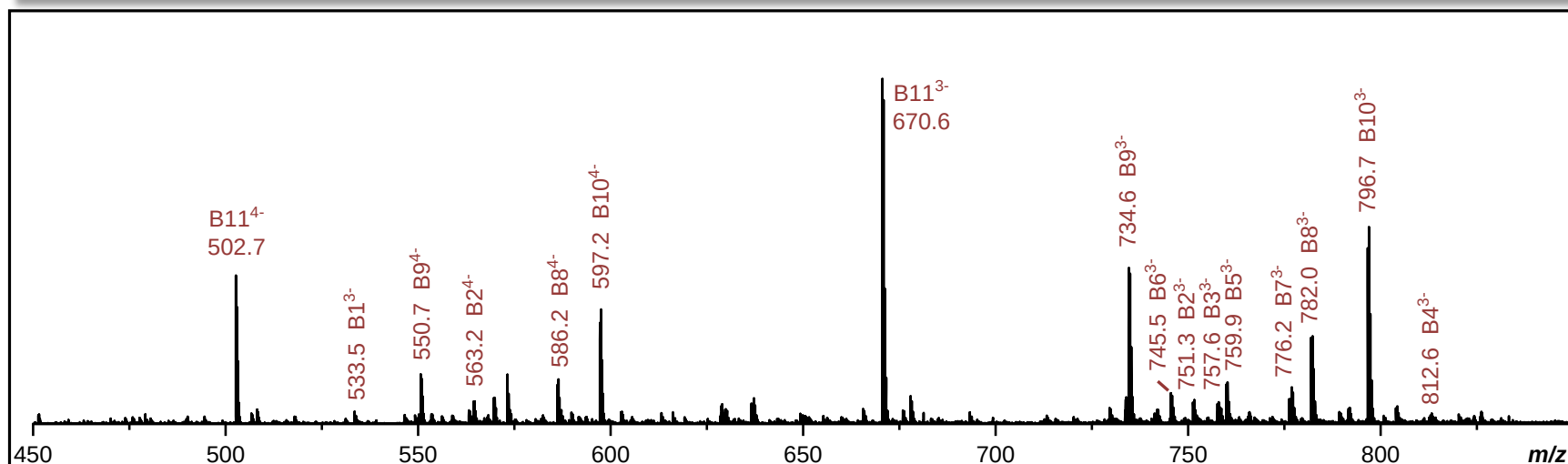
E. Laurent, L. Charles, C. Carapito, M.-A. Delsuc, J.-F. Lutz et al. *C.R. Chimie*, 24, 69-76 (2021)

Le langage
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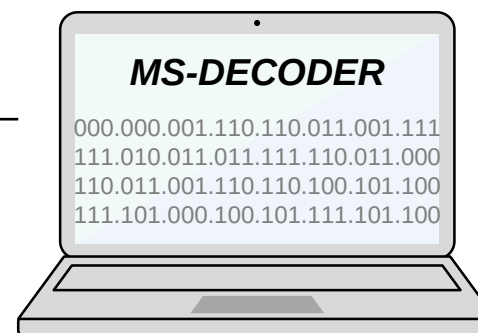
Lire, effacer
et modifier

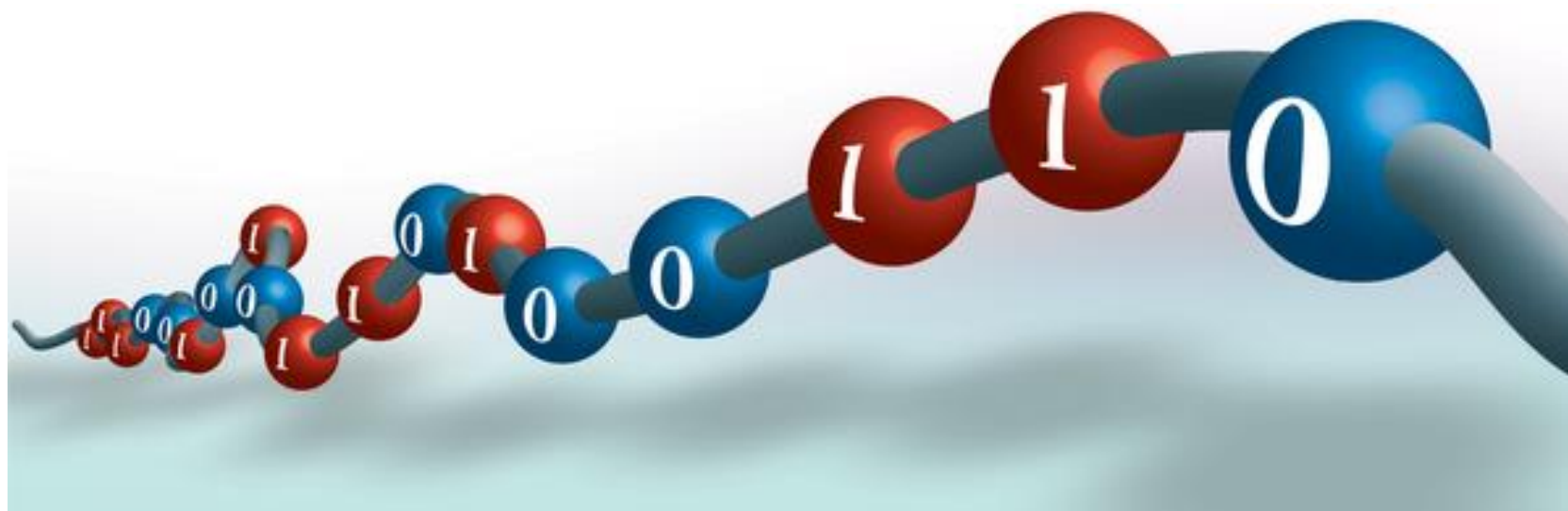
Applications
et
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MS-Decoder 2.3.1

Spectrum file	Prec m/z	Charge	Code
R48-triad_EL275_533.5_3.txt	533.5	3	0000 0000 1110 1100 1100 1111
R48-triad_EL275_670.6_3.txt	670.6	3	0001 1101 1011 0110 0110 1111
R48-triad_EL275_734.6_3.txt	734.6	3	0001 1111 0001 1110 1000 1011
R48-triad_EL275_745.5_3.txt	745.5	3	0001 0110 0011 0011 1010 0001
R48-triad_EL275_751.3_3.txt	751.3	3	1110 1001 1011 1111 1001 1000
R48-triad_EL275_757.6_3.txt	757.6	3	1100 1100 1110 1101 0010 1100
R48-triad_EL275_776.2_3.txt	776.2	3	0111 1110 1000 1110 1000 0111
R48-triad_EL275_782.0_3.txt	782.0	3	1111 0010 0101 1110 0000 1111
R48-triad_EL275_792.9_3.txt	792.9	3	1111 0110 1001 0010 1011 0100
R48-triad_EL275_796.7_3.txt	796.7	3	1010 0011 1111 1001 1111 1011
R48-triad_EL275_812.6_3.txt	812.6	3	1111 0100 0100 1011 1110 1100





Science, 341, 1238149 (2013); *Nature*, 473, 40 (2011); *Nature Chem.*, 3, 234 (2011)
Nature Chem., 3, 917 (2011); *Nature Chem.*, 5, 455 (2014); *Nature Rev. Mater.*, 1:16024 (2016)
Nature Commun., 6:8237 (2015); *Nature Commun.*, 8:967 (2017); *Nature Commun.*, 10:3774 (2019)

*Le langage
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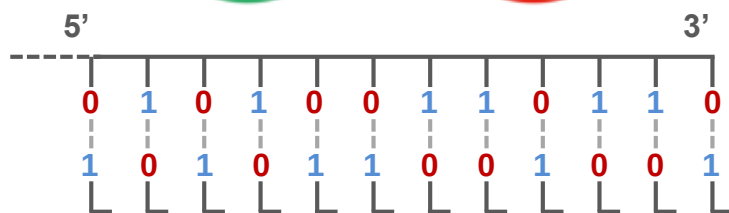
*Applications
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Macromolécules contenant de l'information :

1. Écriture: Contrôle de la structure primaire des polymères
2. Lecture: Séquençage des polymères synthétiques
3. Effaçage: Développement de séquences codées dégradables
4. Edition: Développement de séquences modifiables

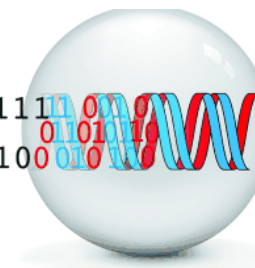
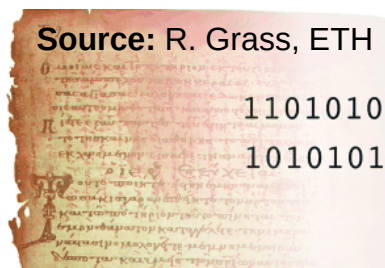
Applications potentielles

Stockage moléculaire de données



Stockage sur le long-terme

Source: R. Grass, ETH



0101001101100101011100010111010101100101011011100110
 0011011001010000110100001010010100110110010101110001
 0111010101100101011011100110001101100101000011010000
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**Le langage
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polymères**

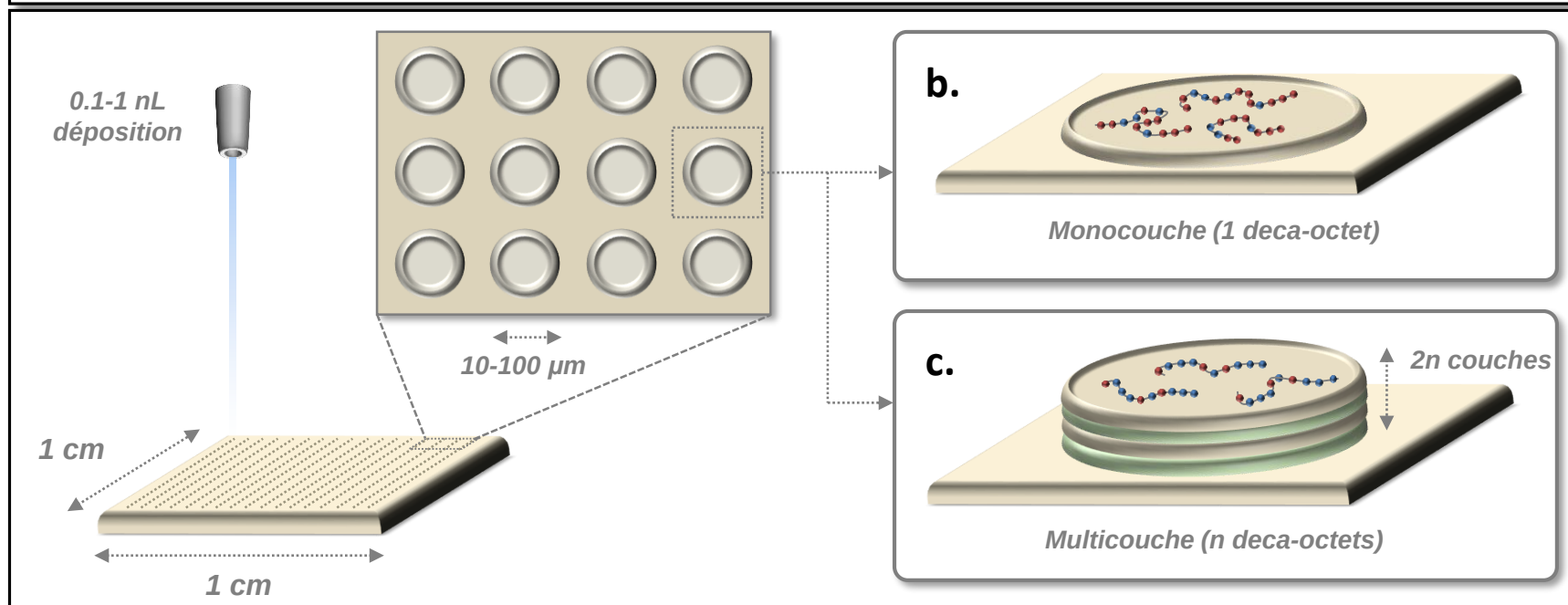
**Ecrire sur
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polymères**

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et modifier**

**Applications
et
perspectives**

Matière codée organisée

Organisation 2D

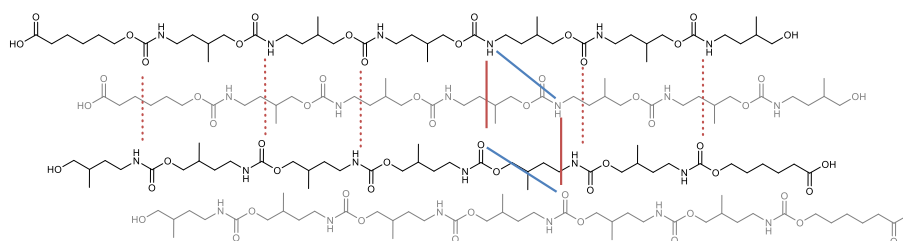
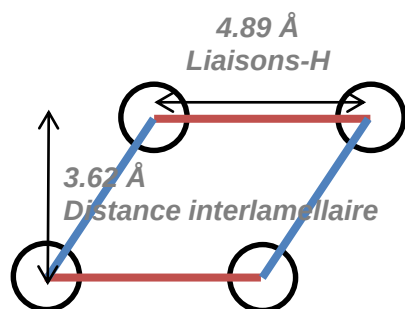
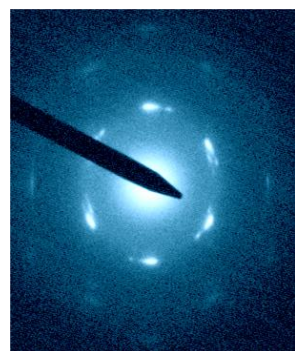


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Lire, effacer
et modifier

B. E. Petit, B. Lotz, J.-F. Lutz, *ACS Macro Letters*, 8, 779-782 (2019)



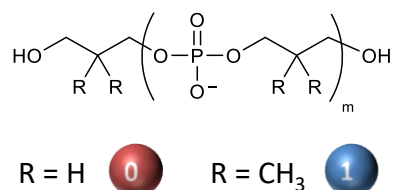
Collaborateur : B. Lotz

Applications
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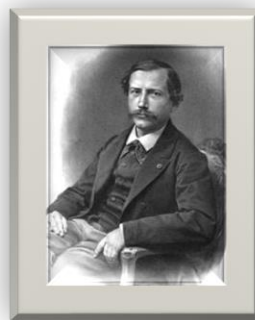
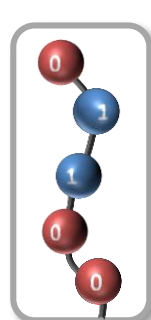
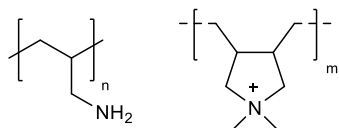
Stockage multicouches

R. Szweda, O. Felix, G. Decher, J.-F. Lutz, *Angew. Chem., Int. Ed.*, **57**, 15817-15821 (2018)

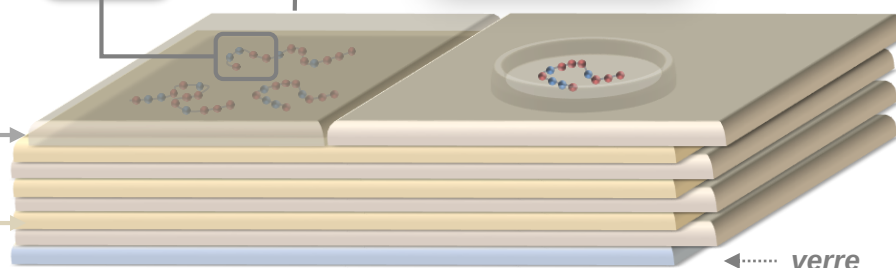
Polyanion numérique



Polycation non-codé



« La chimie crée son objet.
Cette faculté créatrice,
semblable à celle de l'art lui-
même, la distingue
essentiellement des sciences
naturelles et historiques. »
Marcellin Berthelot 1876



← Couche codée 1
← Couche codée 2
← Couche codée 3
← Couche codée 4

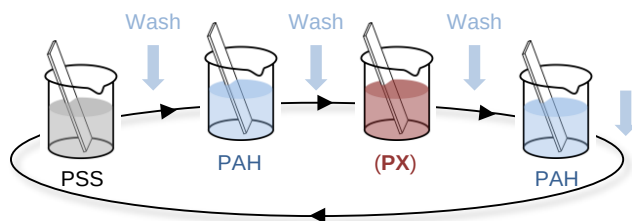
16 couches codées
63 couches au total

← verre

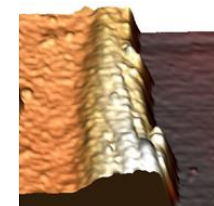
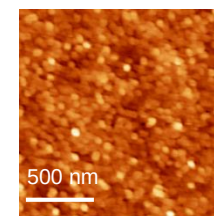
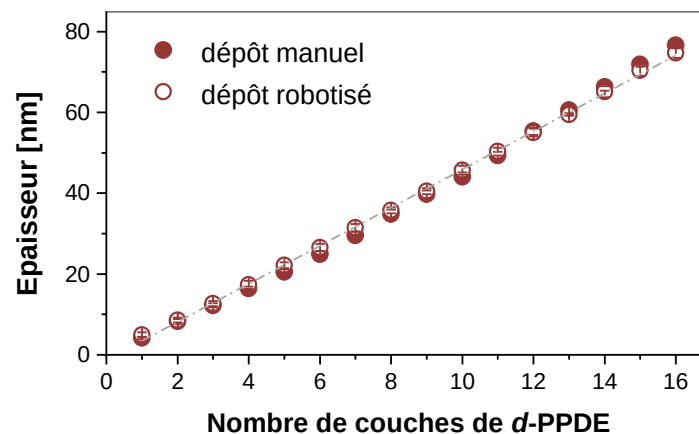
**Le langage
des
polymères**

**Ecrire sur
des
polymères**

**Lire, effacer
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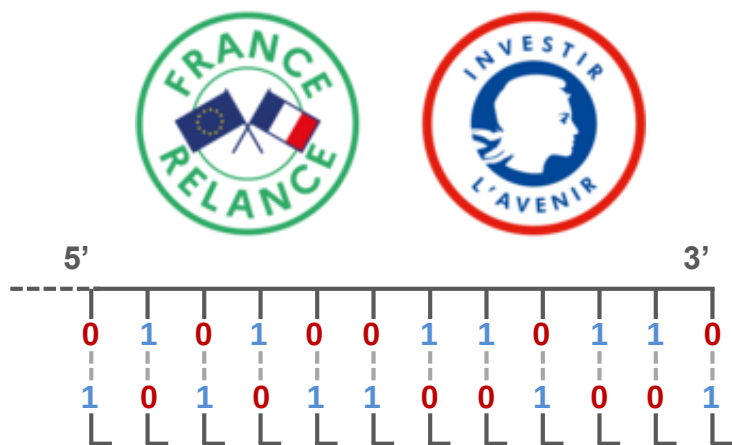
Stockage d'une chimiothèque de 16 polyanions
160 octets (codage ASCII)
63 couches de polyélectrolytes



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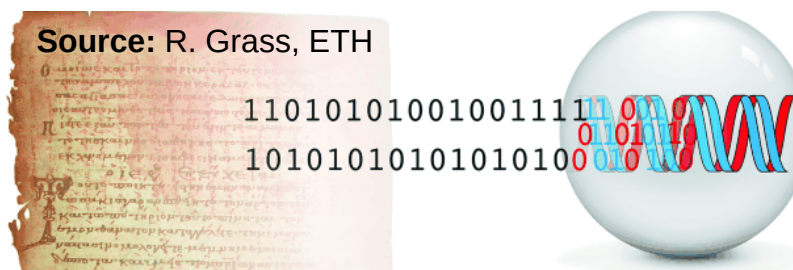
Applications potentielles

Stockage moléculaire de données



Stockage sur le long-terme

Source: R. Grass, ETH



```
0101001101100101011100010111010101100101011011100110
0011011001010000110100001010010100110110010101110001
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0110001101100101000011010000101001010011011001010111
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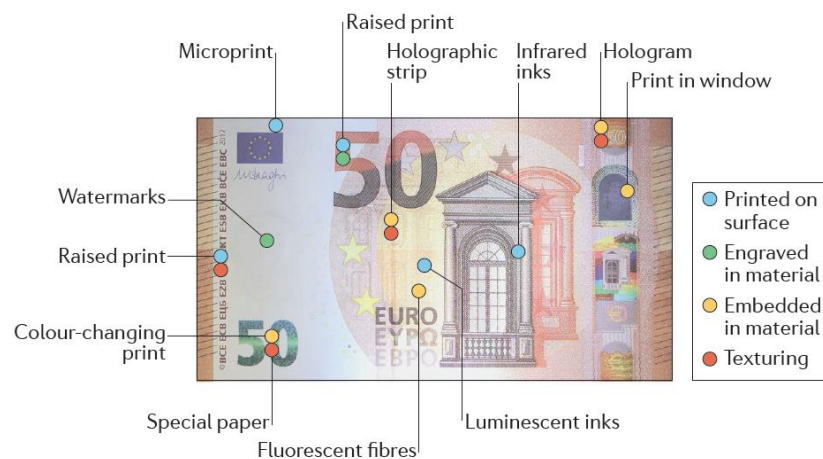
Le langage des polymères

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Applications et perspectives

Lutte anti-contrefaçon



Source: T. J. Sørensen

Traçabilité et recyclage

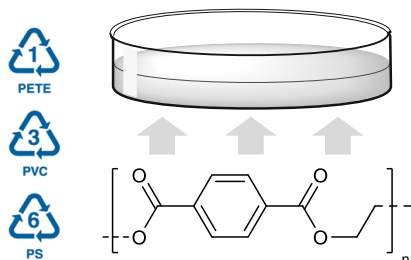


Etiquettes moléculaires



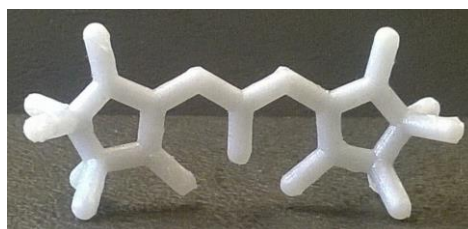
**Le langage
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polymères**

Plastiques



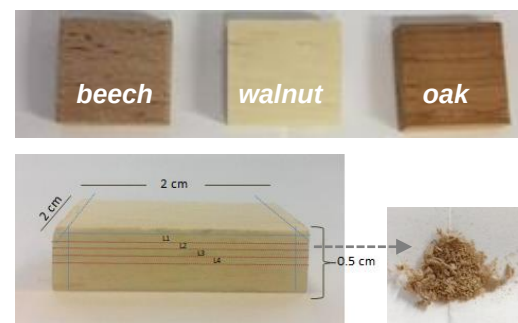
Macromol. Rapid Commun., 38, 1700426 (2017)

Impression 3D



Chem, 1, 114 (2016)

Bois



**Ecrire sur
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et modifier**

Implants intraoculaires



Adv. Funct. Mater., 1, 114 (2017)

Implants intravasculaires



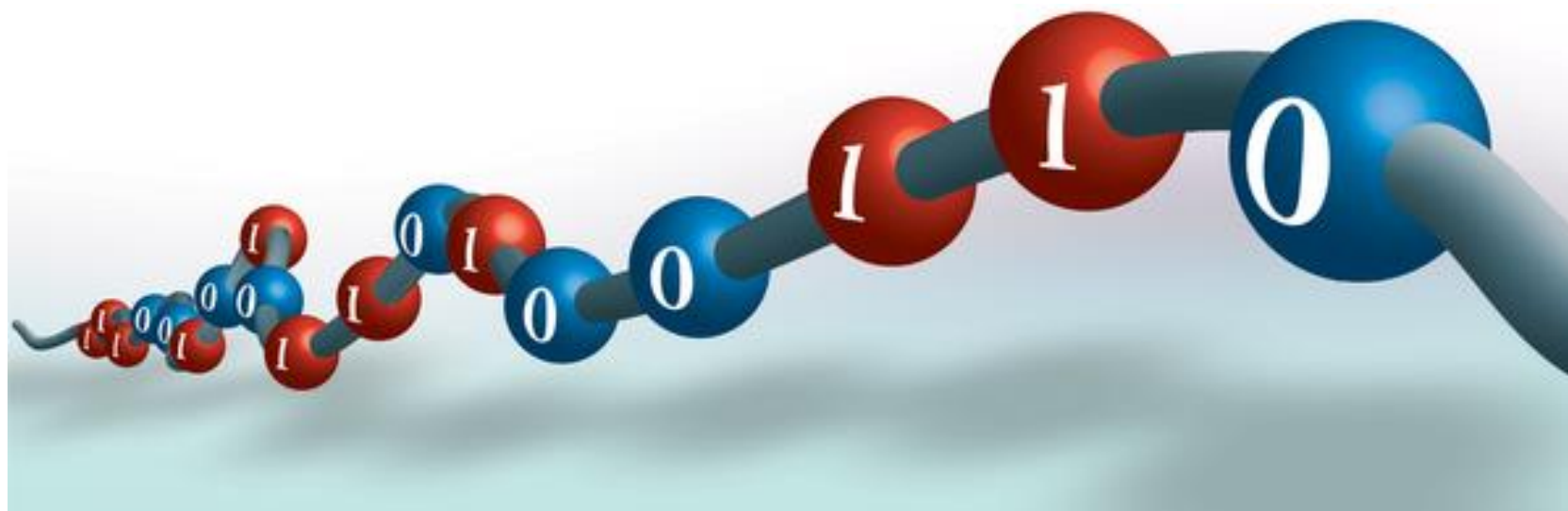
Collaborateur : D. Letourneur

Angew. Chem., Int. Ed., 50, 10574 (2018)

Commercialisation



**Applications
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Science, 341, 1238149 (2013); *Nature*, 473, 40 (2011); *Nature Chem.*, 3, 234 (2011)
Nature Chem., 3, 917 (2011); *Nature Chem.*, 5, 455 (2014); *Nature Rev. Mater.*, 1:16024 (2016)
Nature Commun., 6:8237 (2015); *Nature Commun.*, 8:967 (2017); *Nature Commun.*, 10:3774 (2019)

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Futurs challenges dans le domaine des polymères numériques

1. Chimie des polymères: taille des chaînes, vitesse d'écriture, synthèse parallèles
2. Chimie analytique: vitesse d'écriture, gestion des erreurs, rapport signal/bruit
3. Physico-chimie: solubilité, repliement, cristallisation
4. Nanotechnologie: organisation spatiale en 2D ou en 3D, gestion spatiale

Remerciements

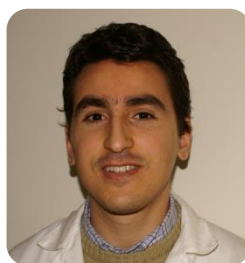
Laurence Charles



Maria Nerantzaki



Aziz Al Ouahabi



Itab Youssef



Tathagata Mondal



Seydina Kebe



*Le langage
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polymères*

Evgeniia Konishcheva



Ian Roszak



Svetlana Samokhvalova Thibault Schutz



Capucine Loth



Eline Laurent



*Ecrire sur
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Denise Karamessini



Niklas König



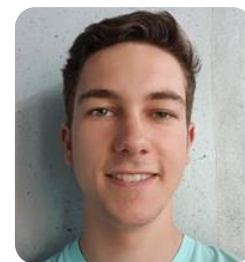
Gianni Cavallo



Kevin Flesch



Vincent Greff



Laurence Oswald



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