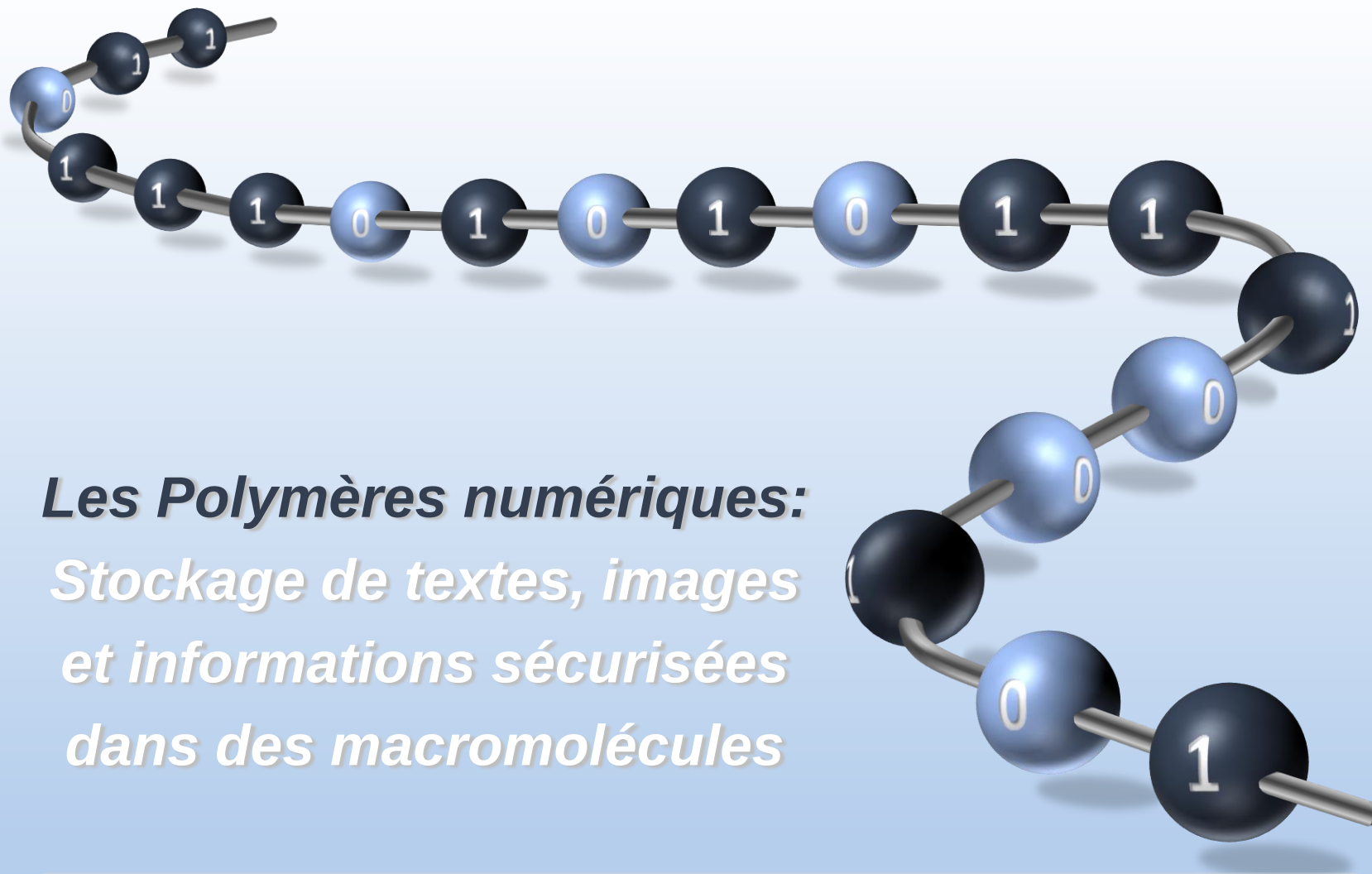




Jean-François Lutz

Institut Charles Sadron, CNRS, Strasbourg, France

*Le langage
des
polymères*

*Ecrire sur
des
polymères*

*Lire, effacer
et modifier*

*Applications
et
perspectives*

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



*Le langage
des
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*Ecrire sur
des
polymères*

*Lire, effacer
et modifier*

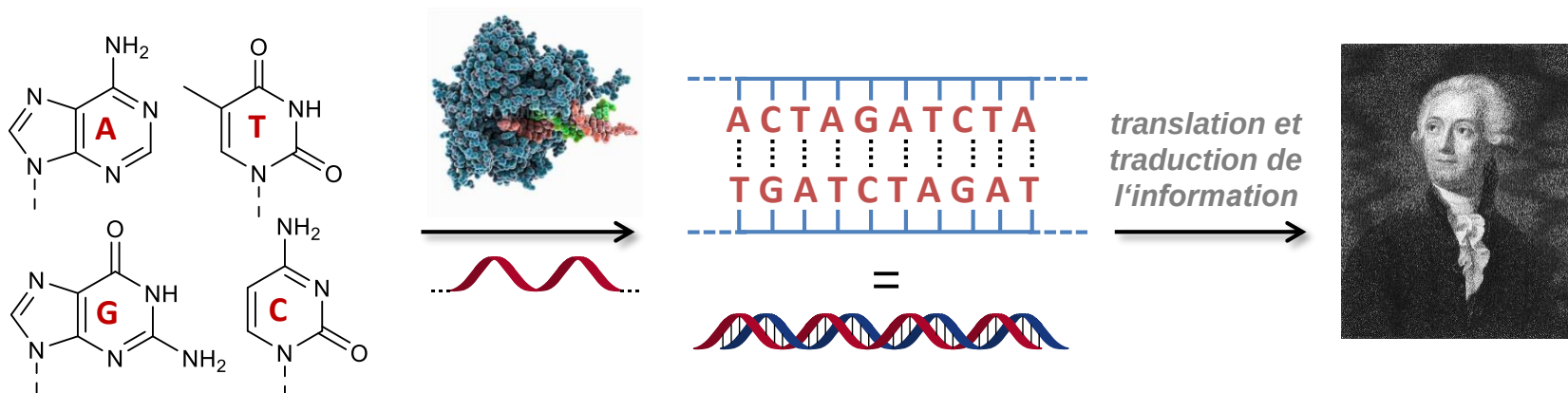
*Applications
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Polymères informationnels

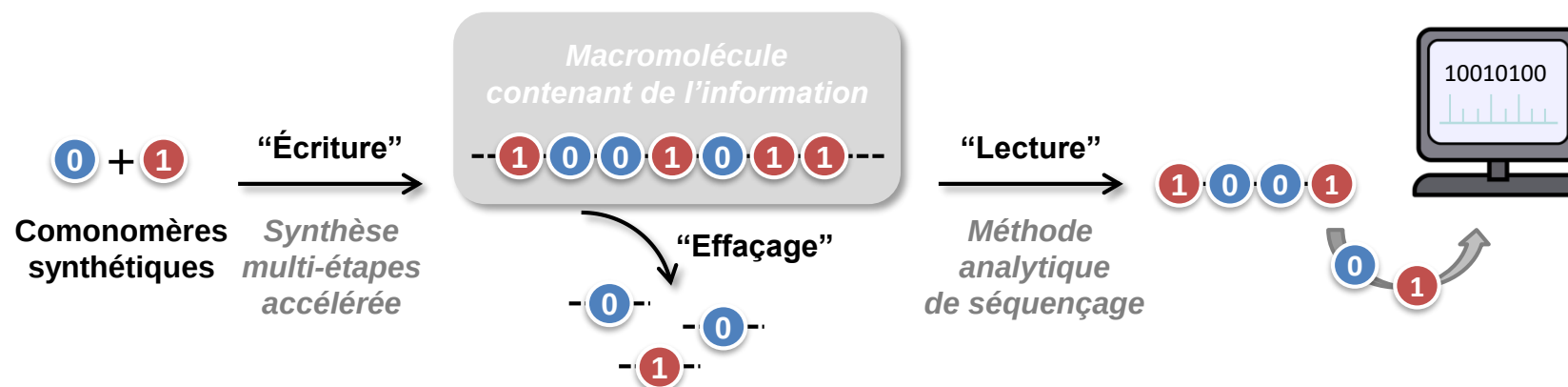
H. M. Colquhoun, J.-F. Lutz, *Nature Chemistry*, 6, 455-456 (2014)

ATATGCTGCTAGCGATGCGTCGTTGCACTGATAGTAGTCATGATGGATGATGTTGATACCTACGT



ATATGCTGCTAGCGATGCGTCGTTGCACTGATAGTAGTCATGATGGATGATGTTGATACCTACGT

011001001101010100110111011001010110101011011101101101001010110001011101101101111



011001001101010100110111011001010110101011011101101101001010110001011101101101111

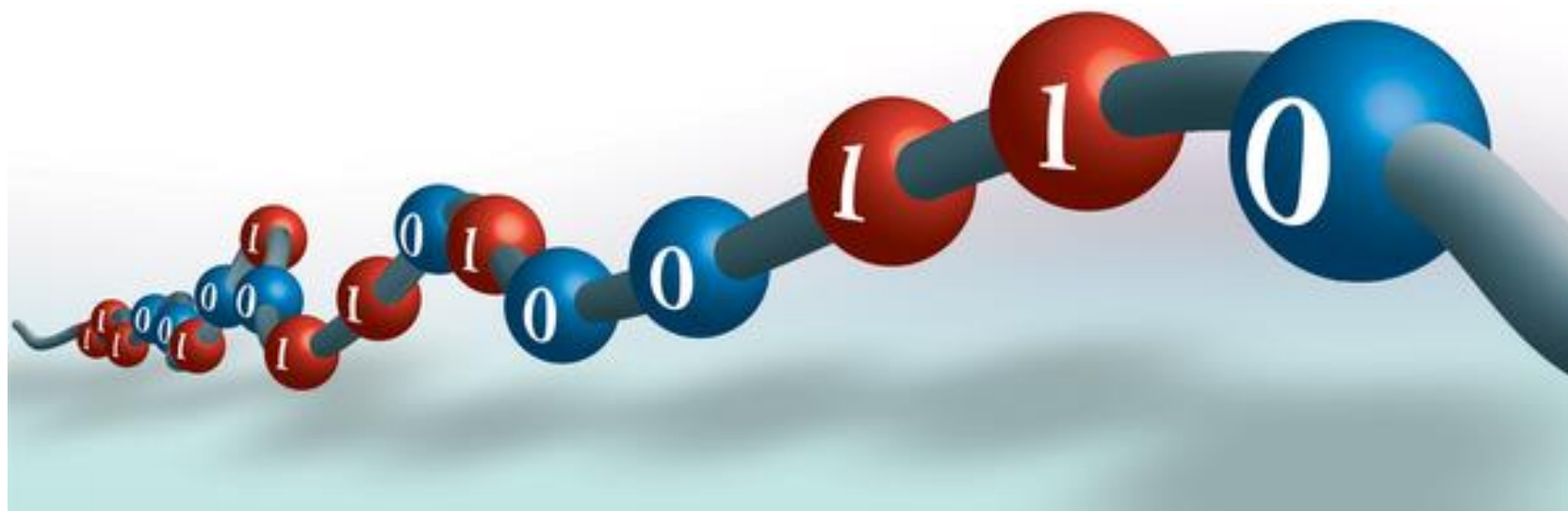
Le langage
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polymères

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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)

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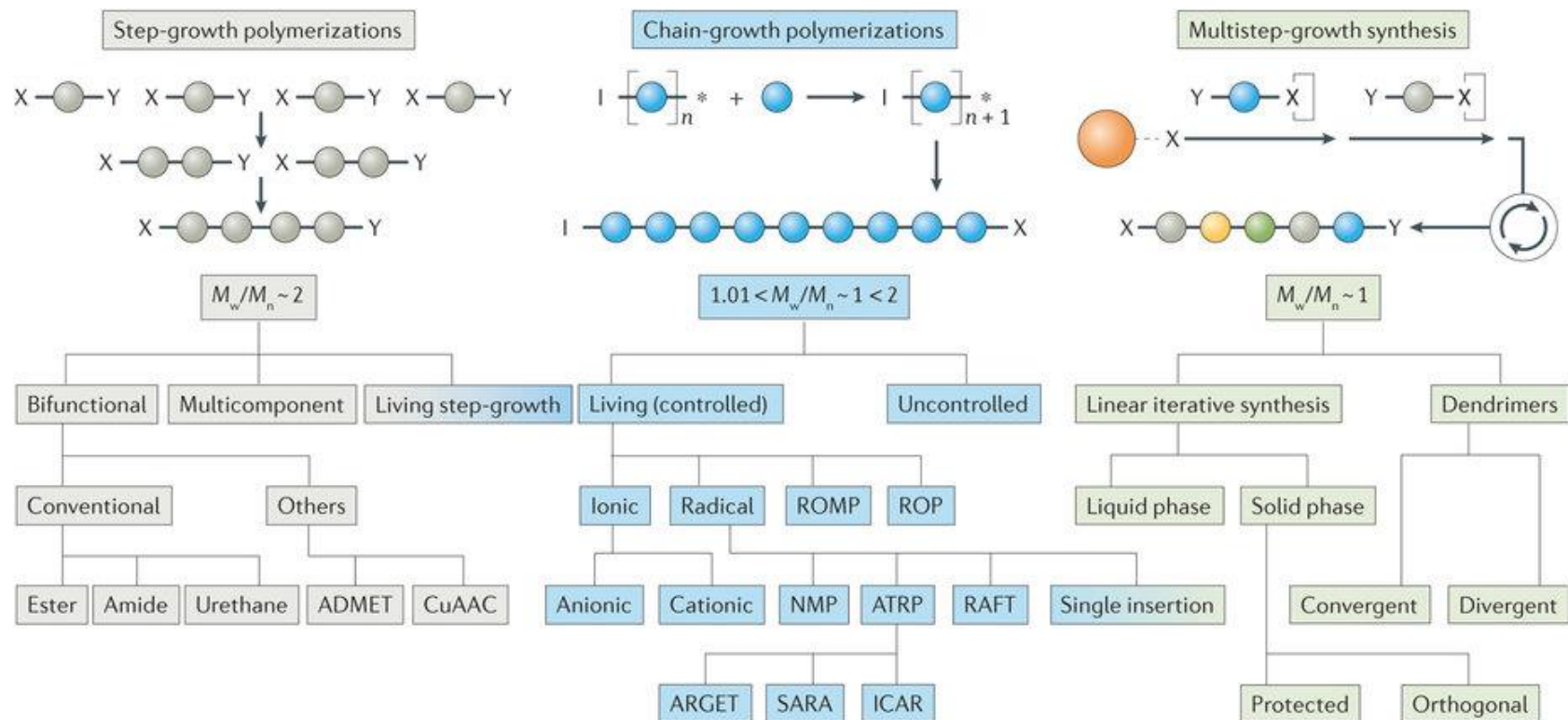
*Applications
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Macromolécules contenant de l'information :

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

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

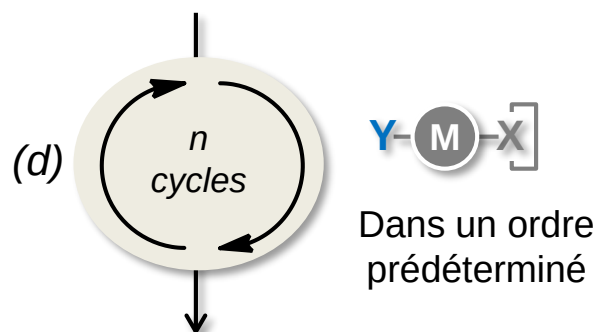
J.-F. Lutz, M. Ouchi, D. R. Liu, M. Sawamoto, *Science*, **341**, 1238149 (2013)



A = Amorceur

M = Monomère

(d) = Deprotection



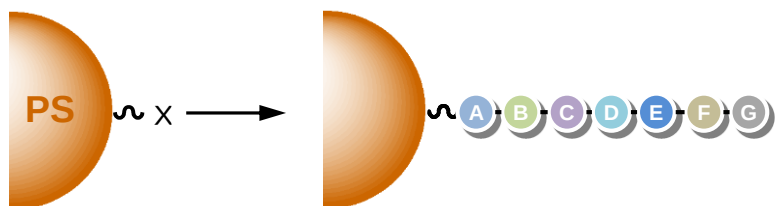
*Le langage
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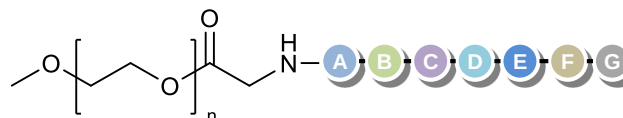
*Lire, effacer
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En phase solide - Merrifield, 1963

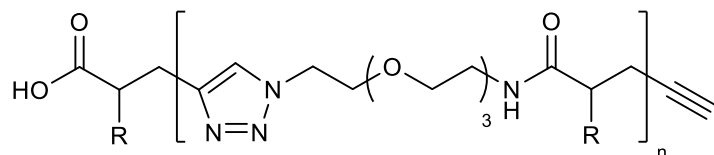


En phase liquide – Mutter, 1972



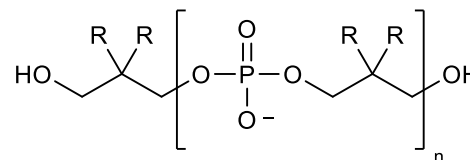
Polymères numériques

Poly(triazole amide)s



R = Me (1), H (0)

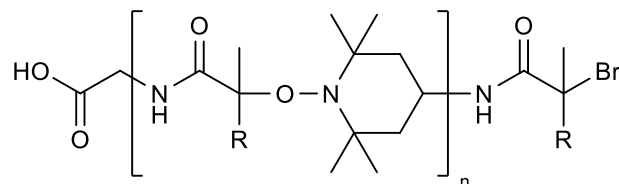
Poly(phosphodiester)s



R = Me (1), H (0)

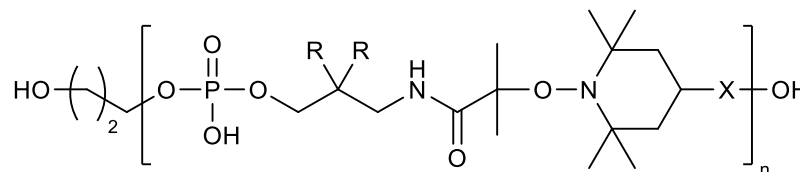
Le langage
des
polymères

Poly(alcoxyamine amide)s



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

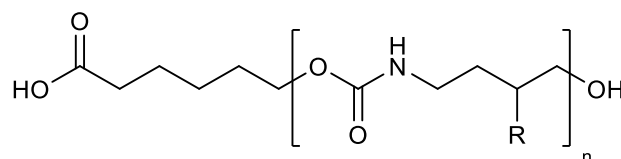
Poly(alcoxyamine phosphodiester)s



R = Me (1), H (0)

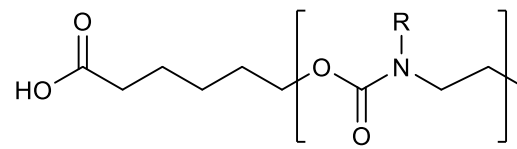
Lire, effacer
et modifier

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)

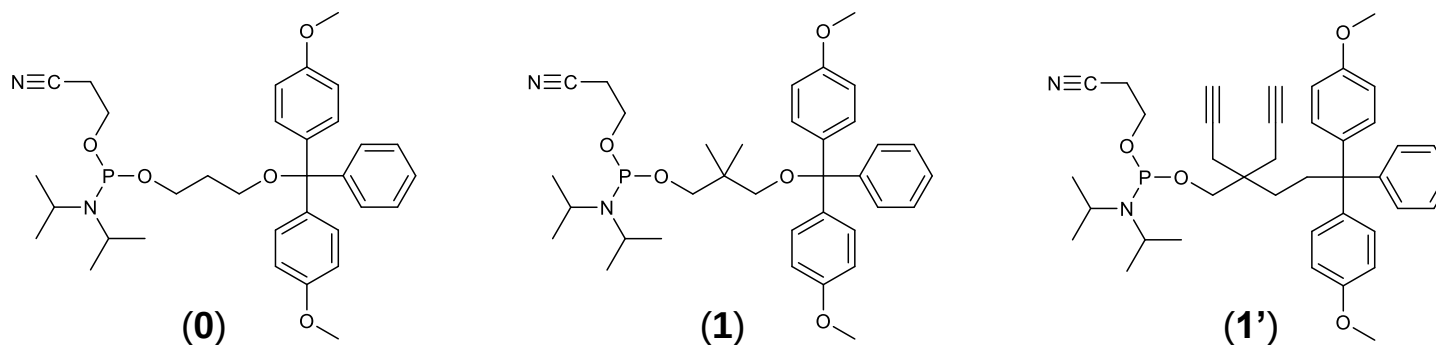
Le langage
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polymères

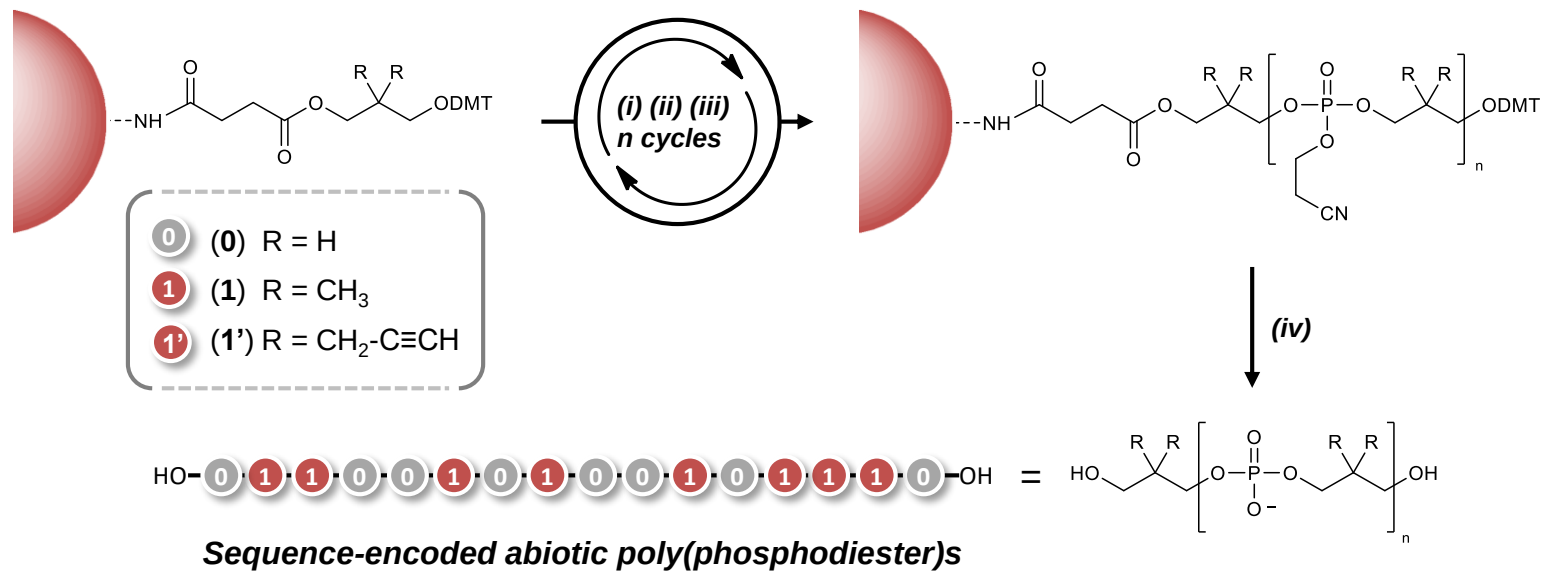
Lire, effacer
et modifier

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a.



b.



Le langage des polymères

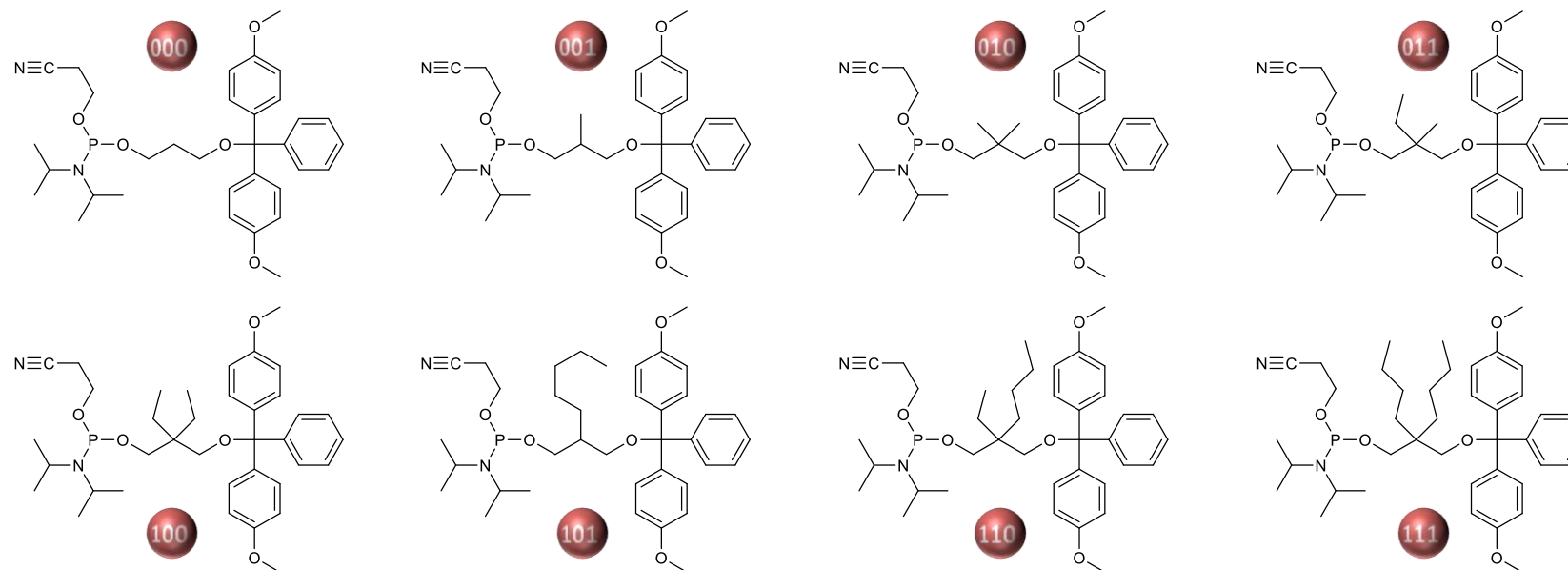


Lire, effacer et modifier


$$\begin{aligned} M_{th} &= 16806.8 \\ M_{exp} &= 16806.2 \end{aligned}$$


Alphabets augmentés

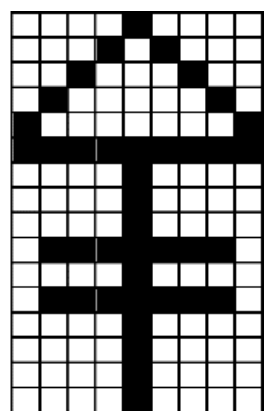
E. Laurent, D. Gigmes, L. Charles, J.-F. Lutz, *Macromolecules*, **53**, 4022–4029 (2020)



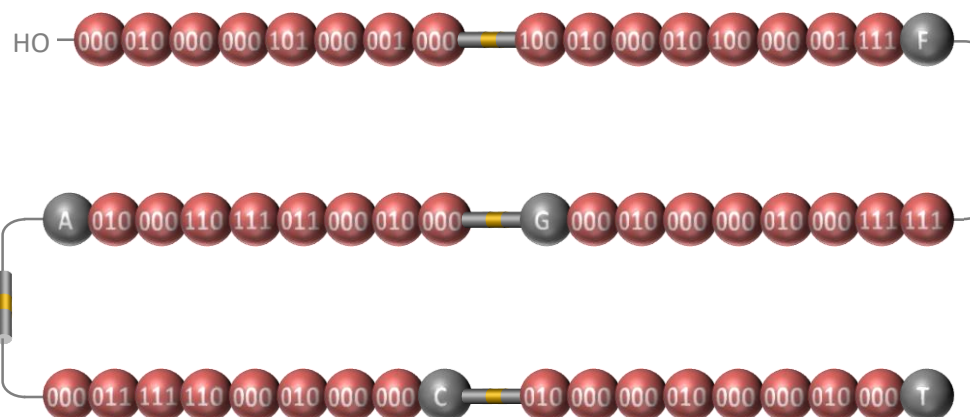
**Le langage
des
polymères**

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des
polymères**

**Lire, effacer
et modifier**

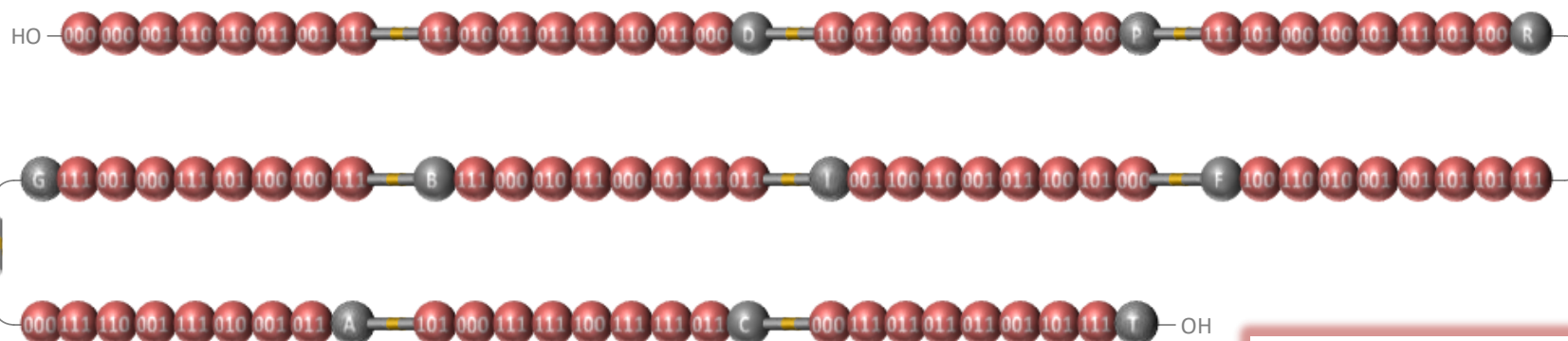


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100010000010
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000011111110
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000000010000
```



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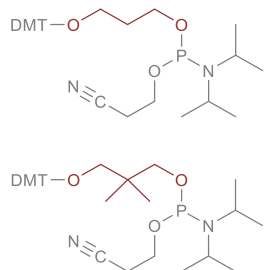
440 bits/chaîne
3 bits/monomère



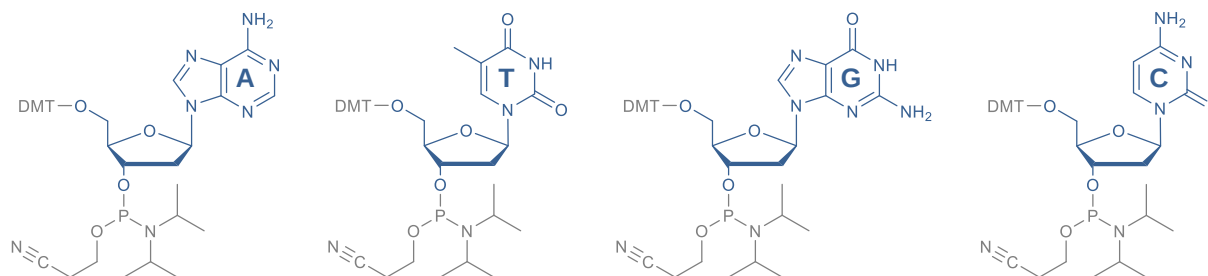
Chaînes ultra-longues

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

Abiotic alphabet



Biological alphabet

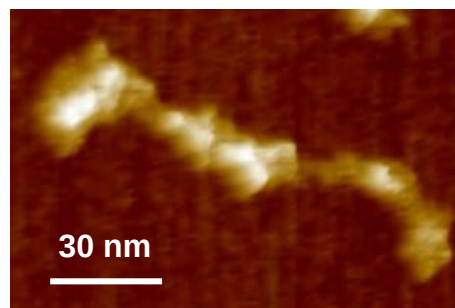
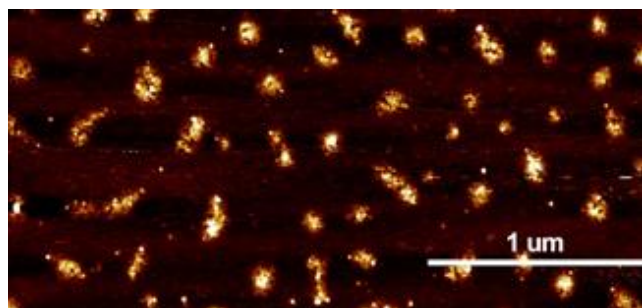
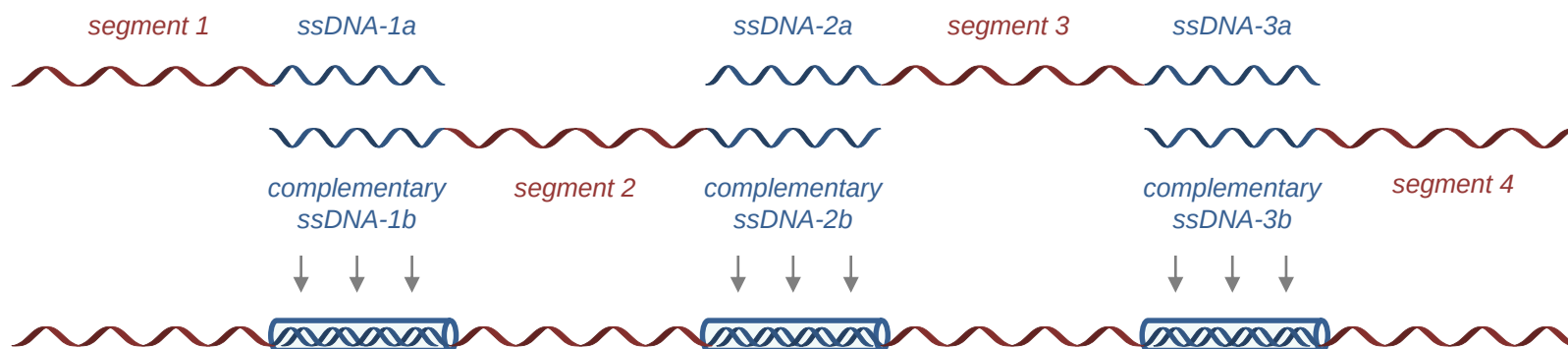


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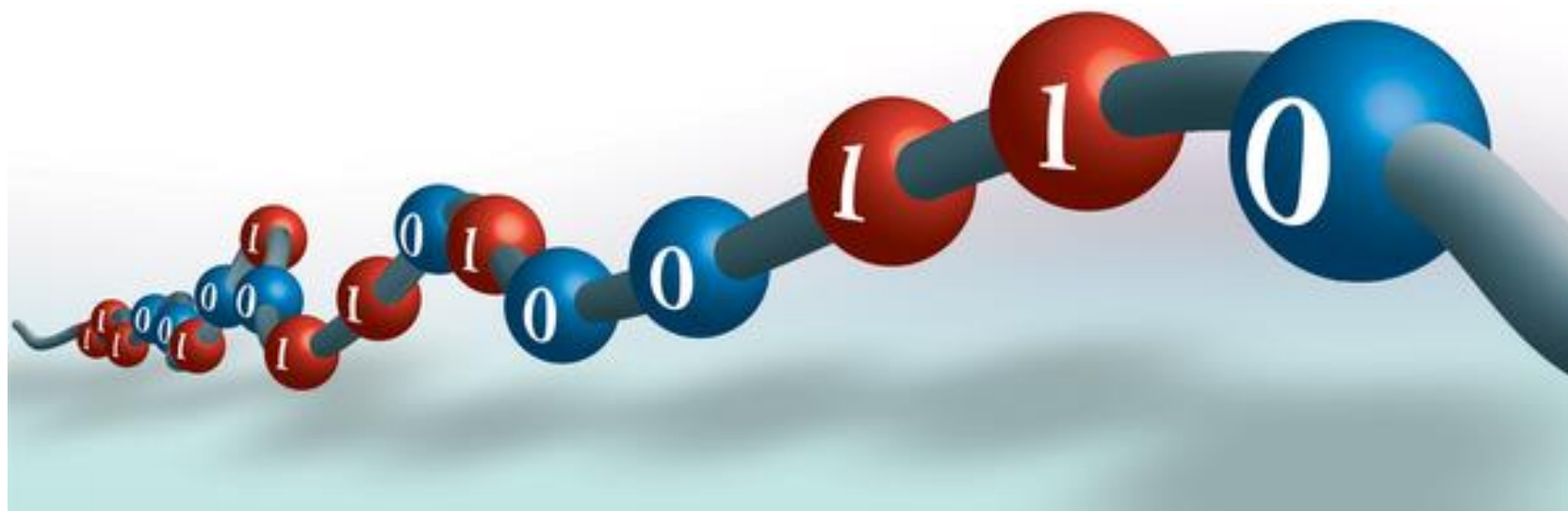
Lire, effacer
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Applications
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352 monomères
synthétiques
90 nucléotides

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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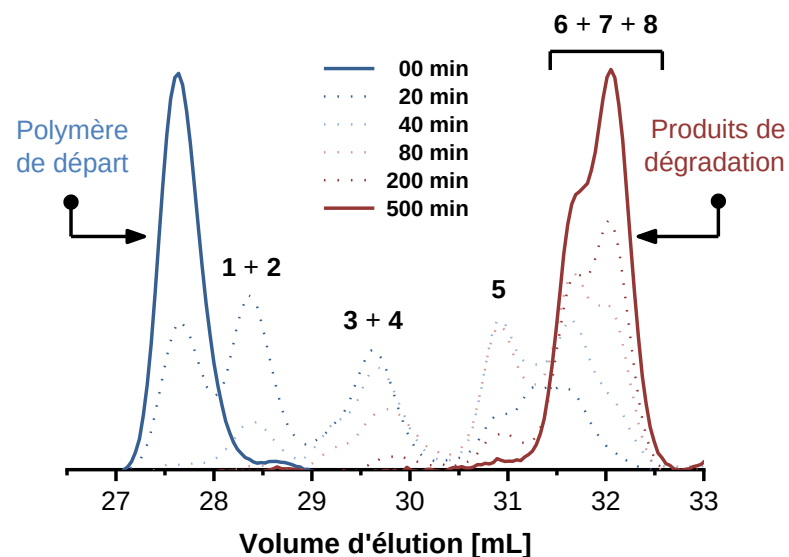
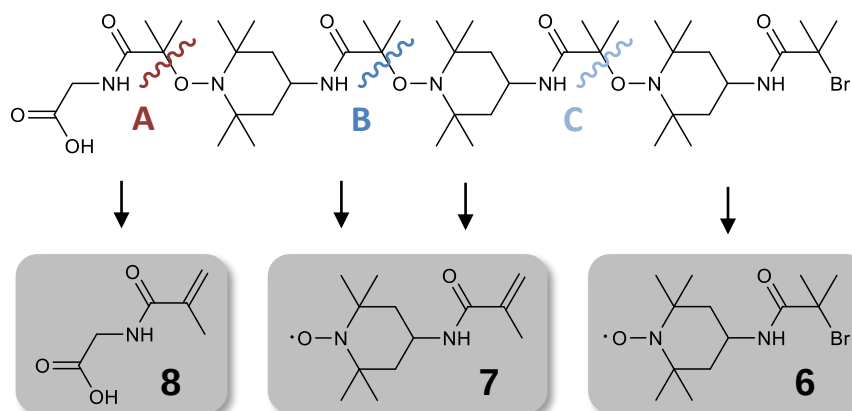
Macromolécules contenant de l'information :

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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

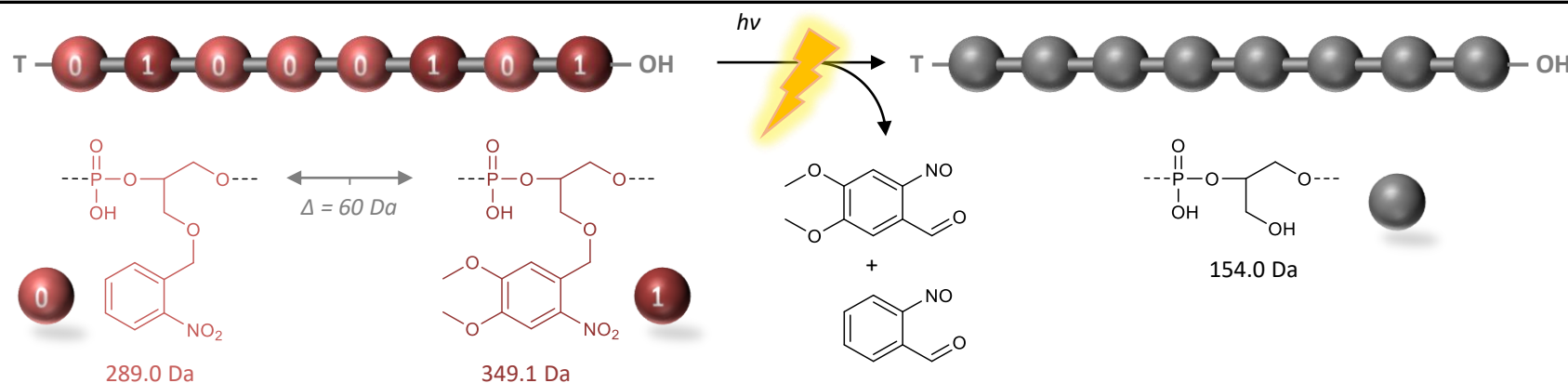


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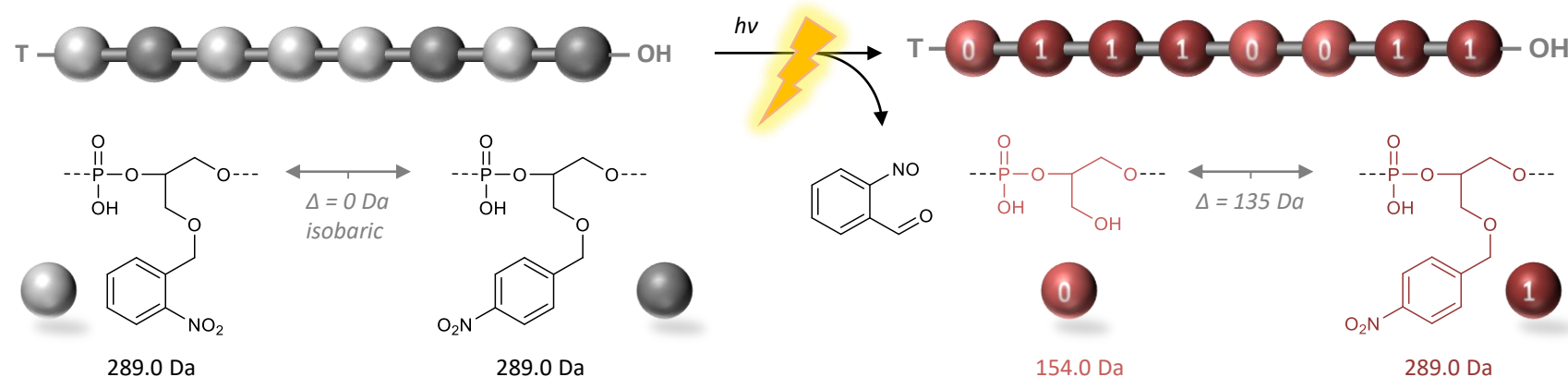
N. F. König, L. Charles, J.-F. Lutz, et al. *Nature Communications*, 10:3774 (2019)



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Utilisation d'un révélateur lumineux

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



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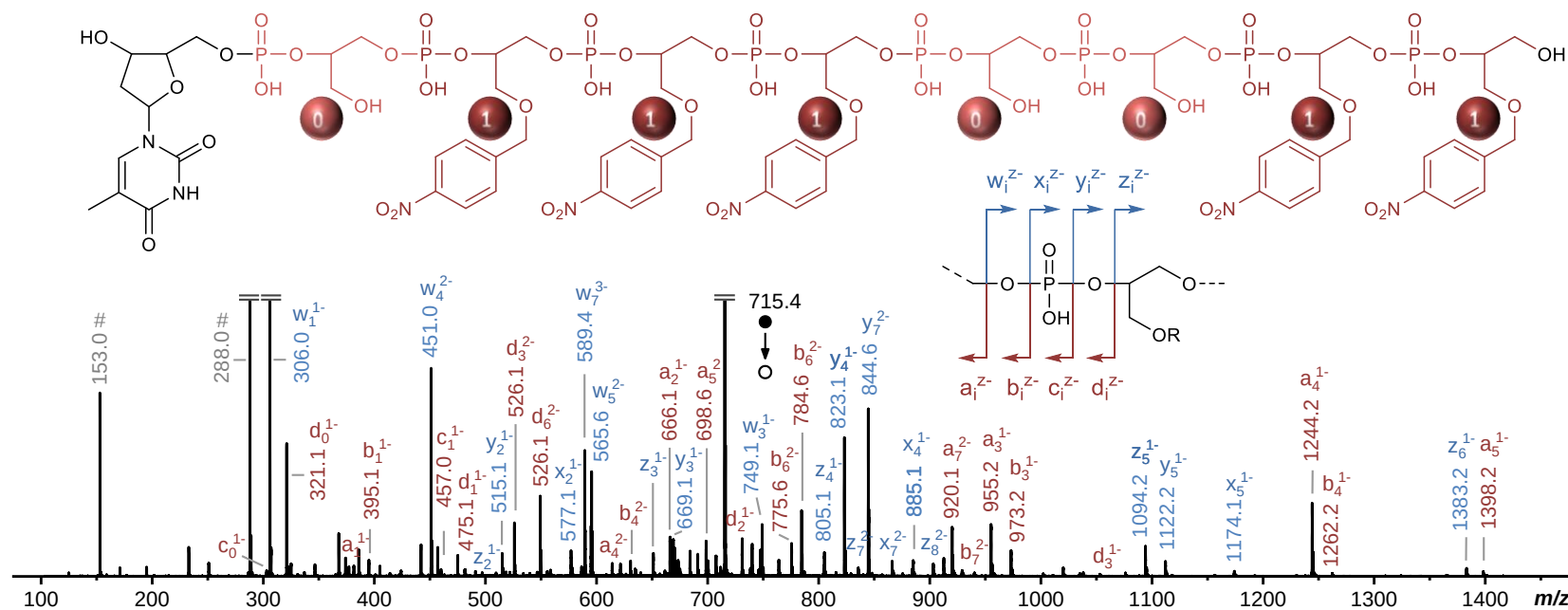
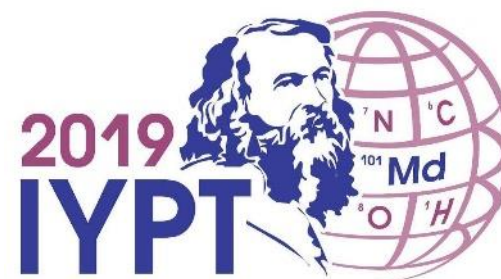
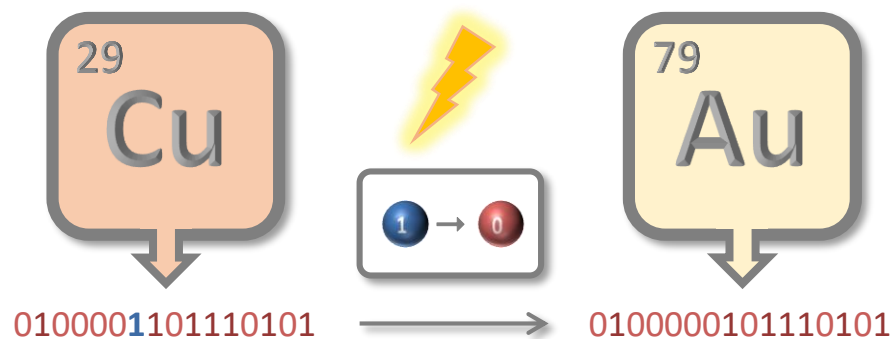
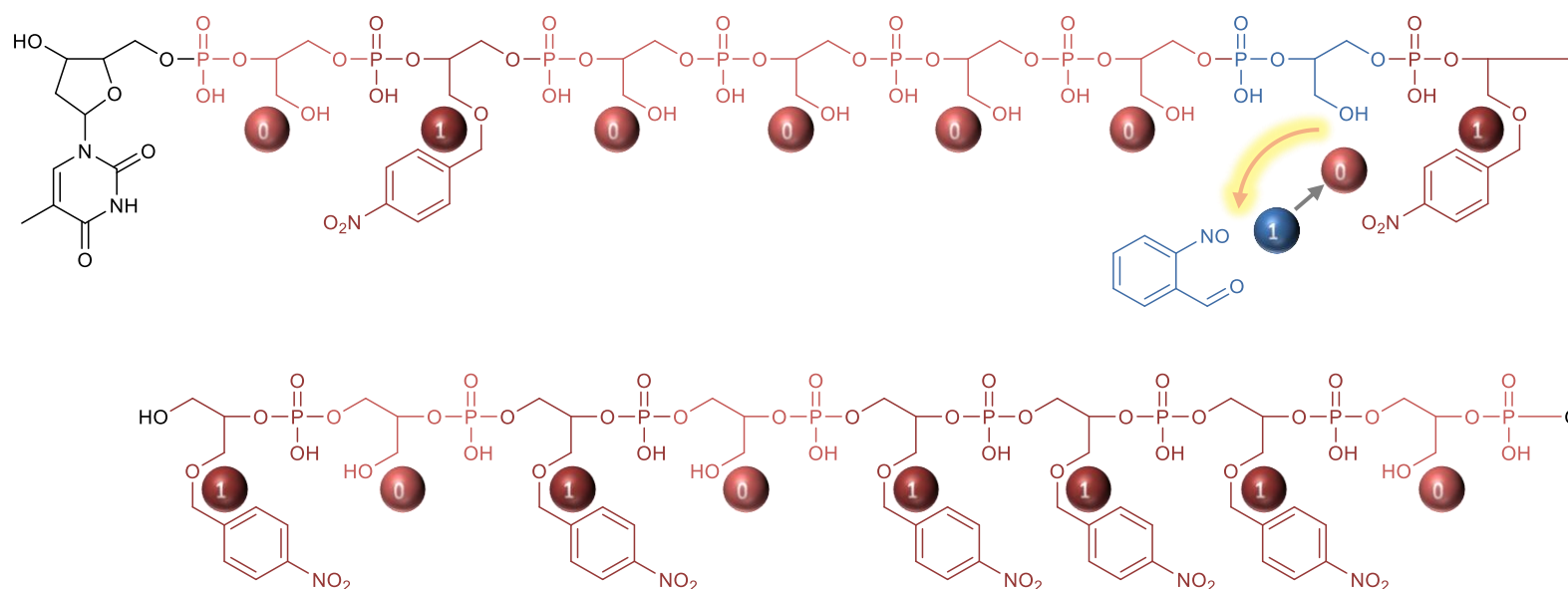


Photo-mutagénèse artificielle

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



Le langage
des
polymères

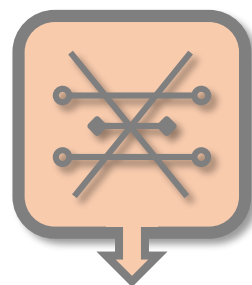
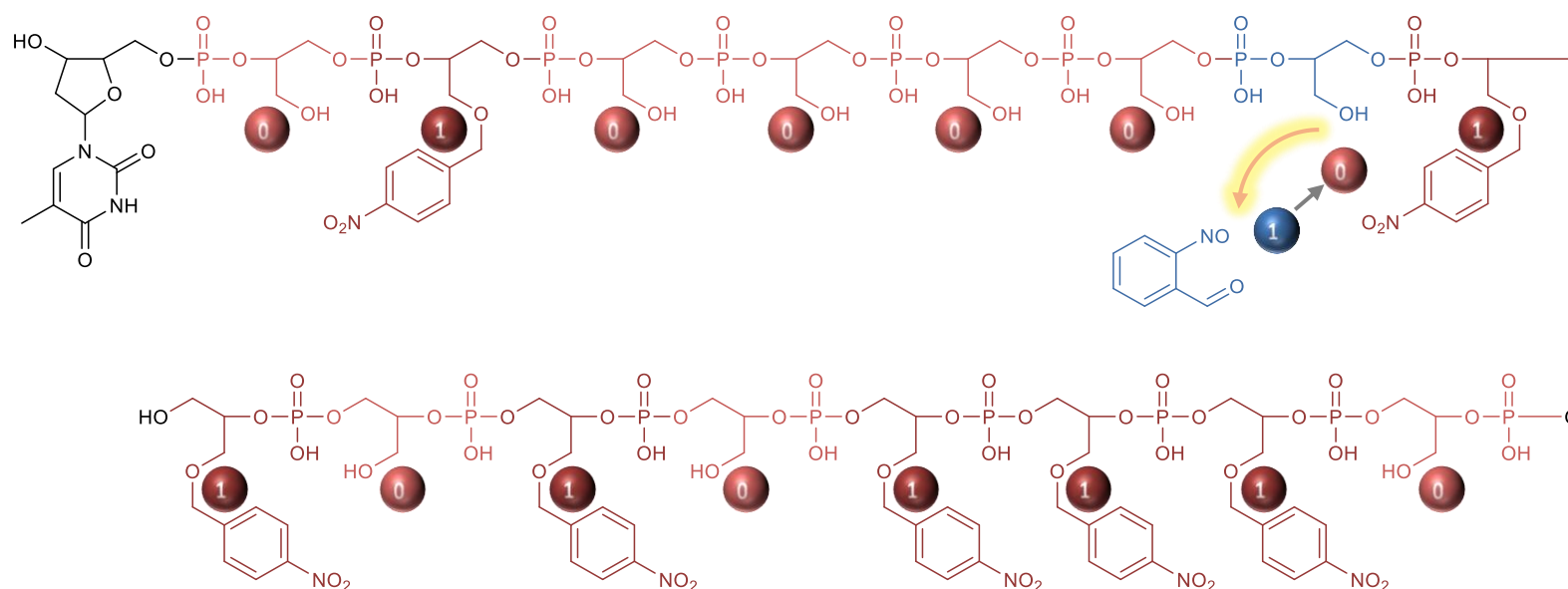
Ecrire sur
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polymères

Lire, effacer
et modifier

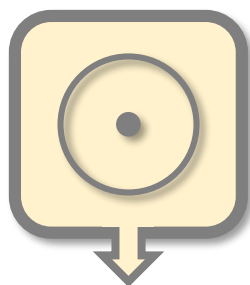
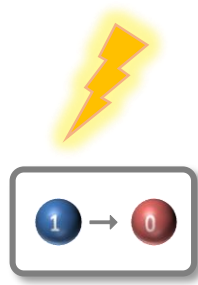
Applications
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Photo-mutagénèse artificielle

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



0100001101110101



0100000101110101



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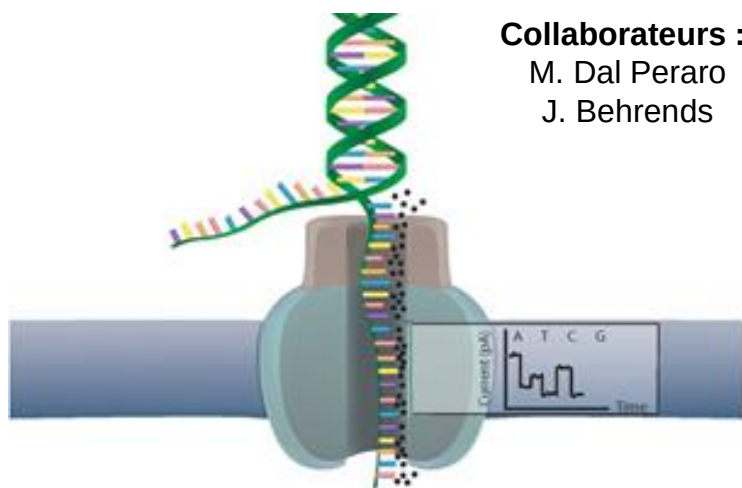
Ecrire sur
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et modifier

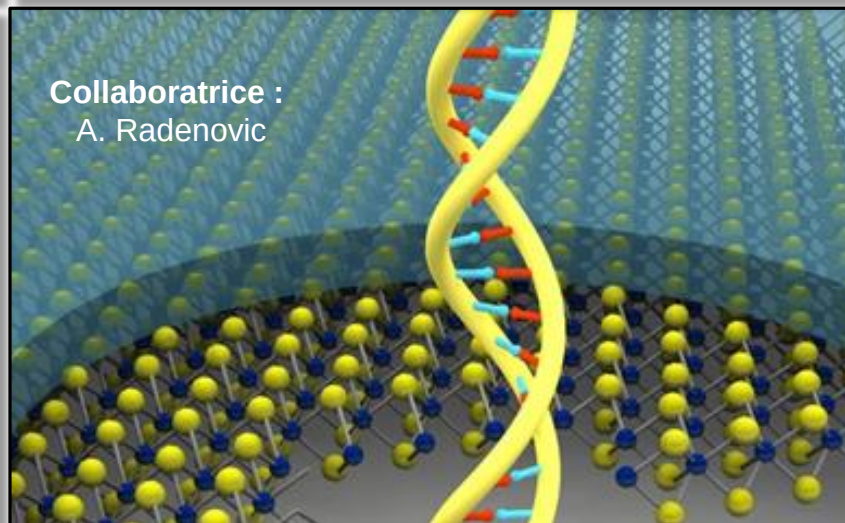
Applications
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Séquençage des polymères

Séquençage dans un pore biologique



Séquençage dans un pore artificiel



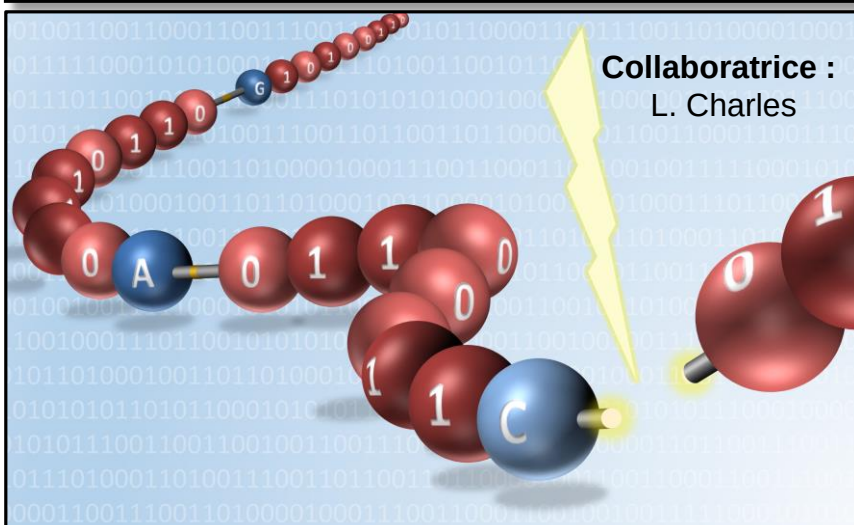
**Le langage
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polymères**

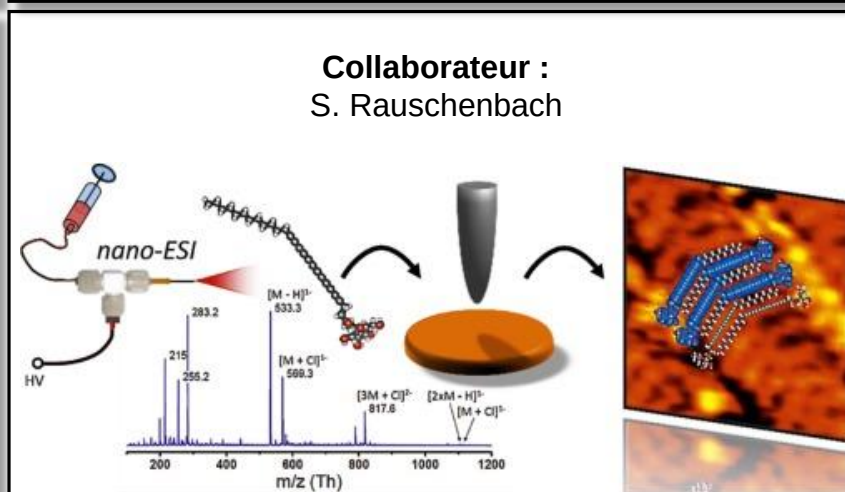
**Lire, effacer
et modifier**

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Spectrométrie de masse en tandem

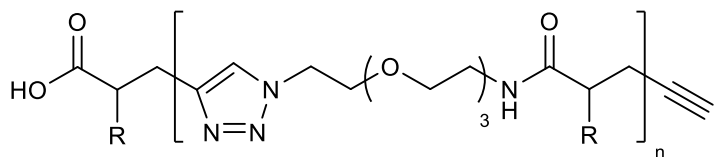


Déposition ESI et imagerie STM



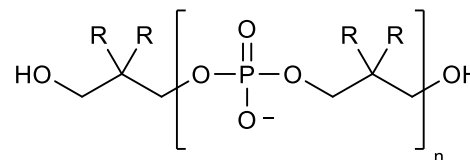
Spectrométrie de masse en tandem

Poly(triazole amide)s



R = Me (1), H (0)

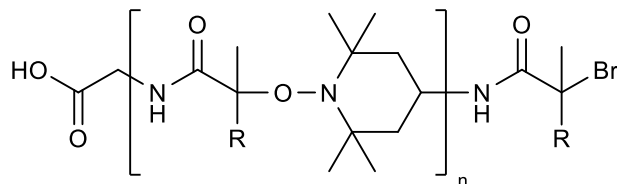
Poly(phosphodiester)s



R = Me (1), H (0)

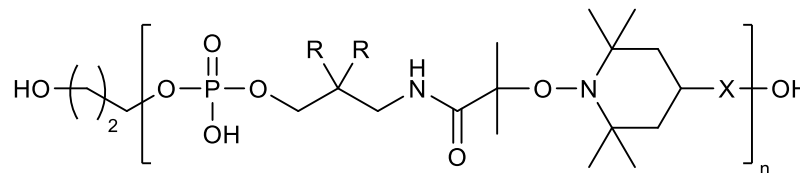
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Poly(alcoxyamine amide)s



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

Poly(alcoxyamine phosphodiester)s

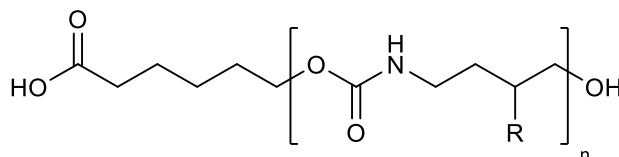


R = Me (1), H (0)

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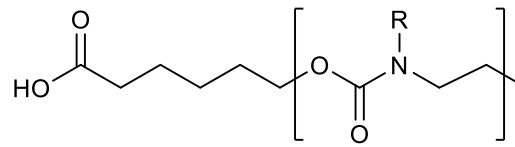
**Lire, effacer
et modifier**

Polyuréthanes



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

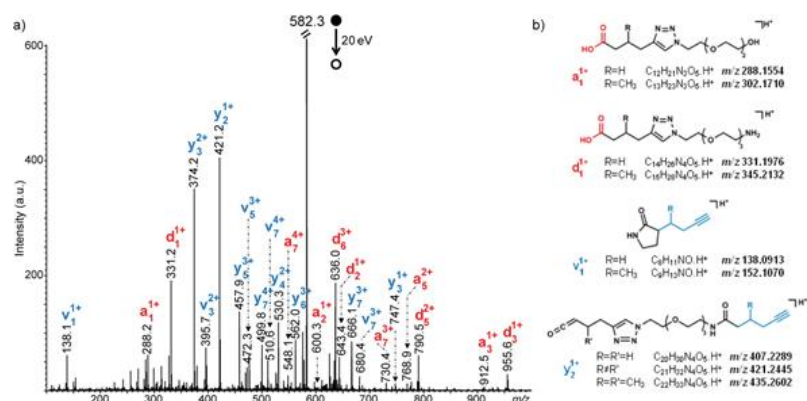
Polyuréthanes N-substitués



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

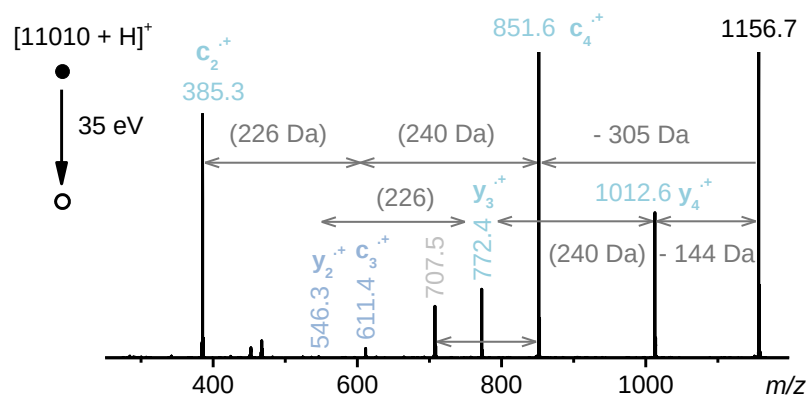
**Applications
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Poly(triazole amide)s



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)

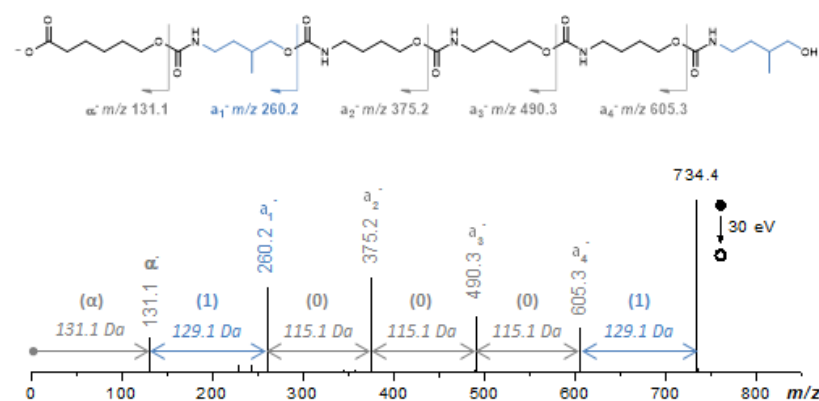
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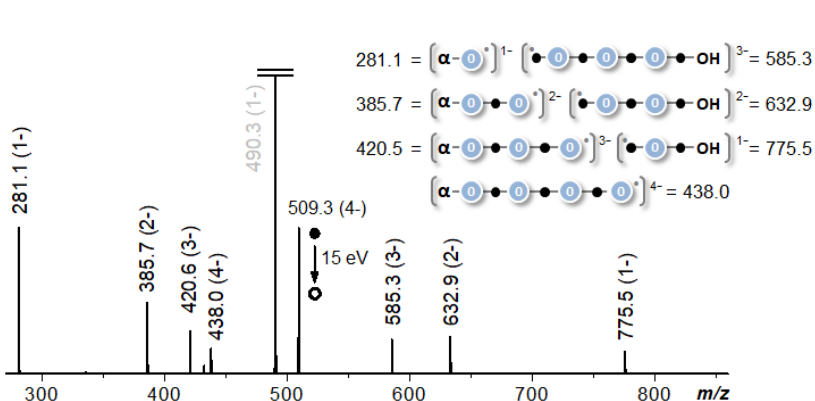
Applications
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Polyuréthanes



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

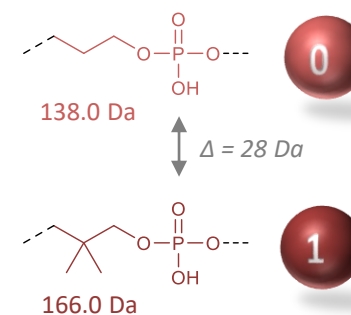
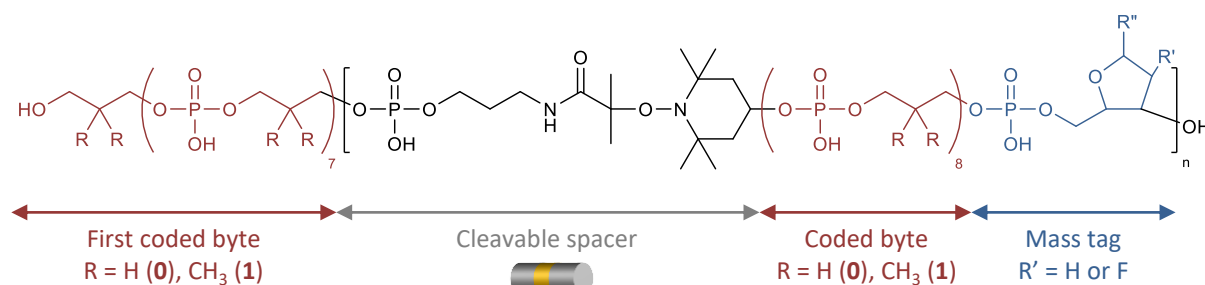
Poly(alcoxyamine phosphodiester)s



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)

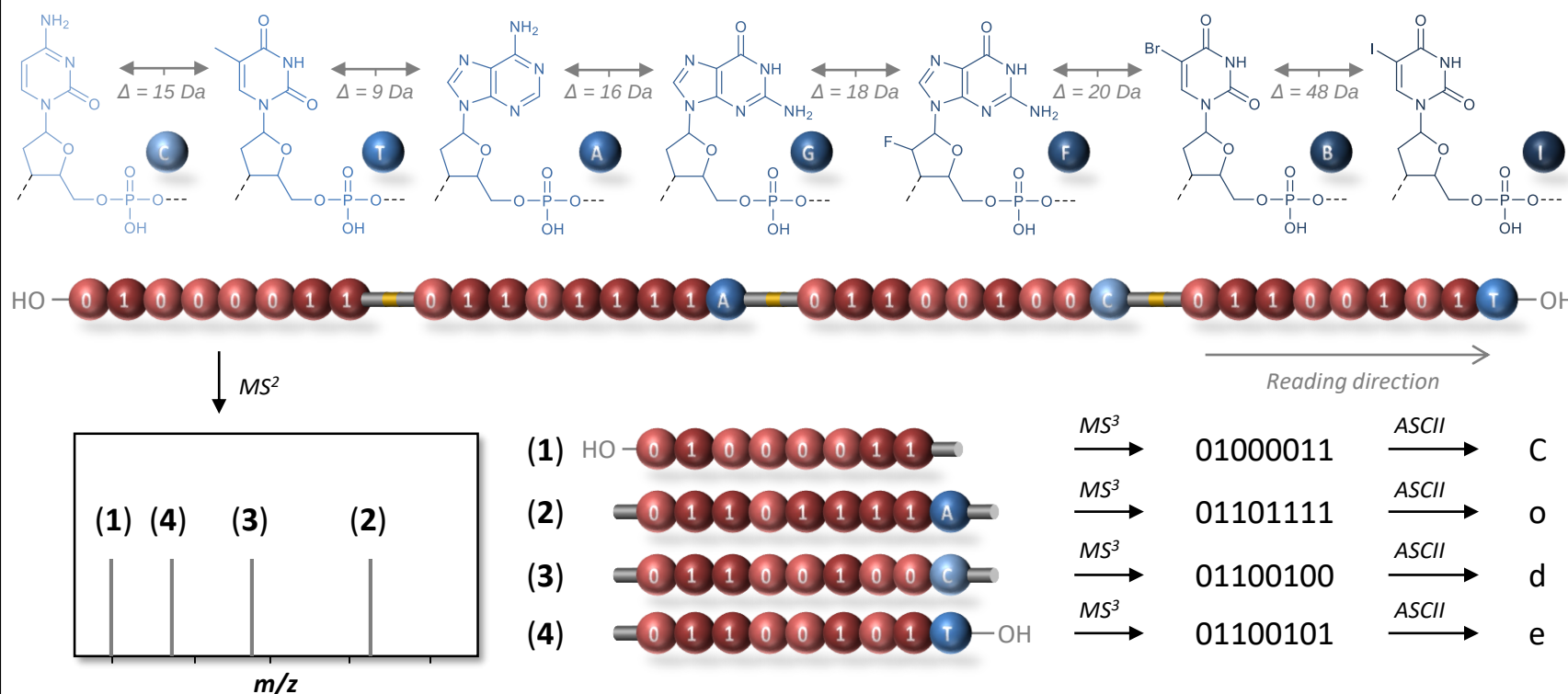


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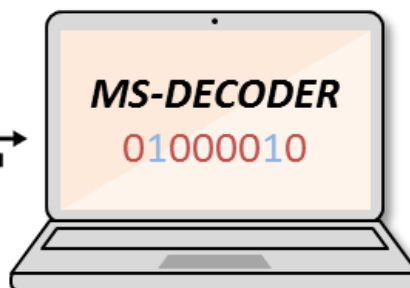
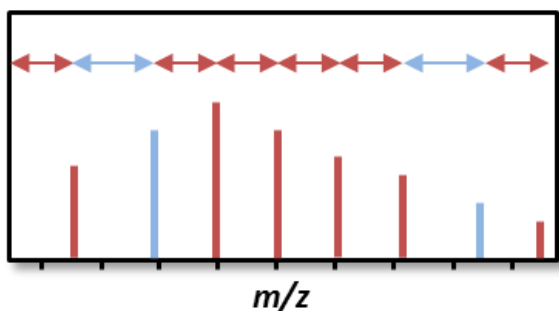
Lire, effacer
et modifier

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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
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MS-DECODER 1.4.2

File Edit Help

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5_R1-C4_DK154_490.3.txt	100
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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
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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

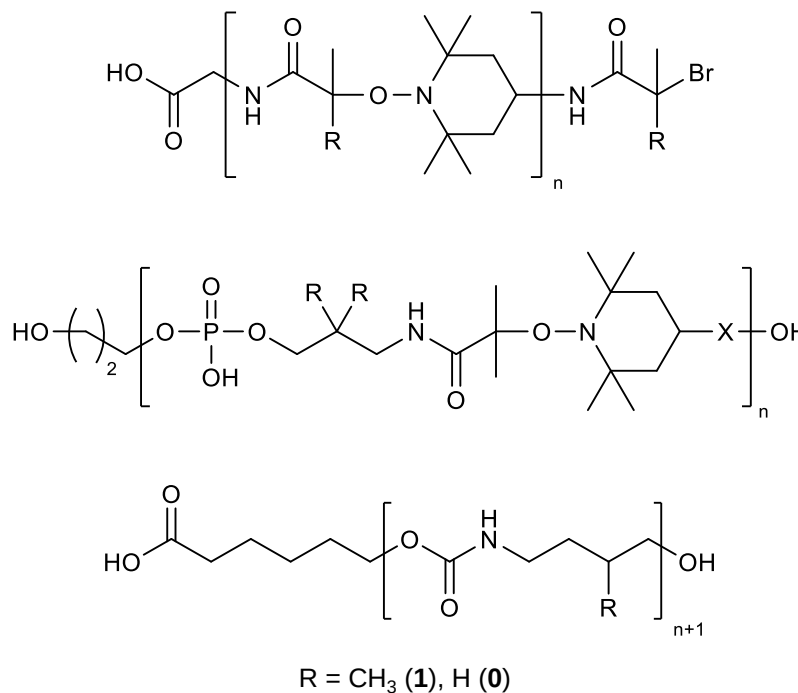
Intensity threshold: 5

First isotope searched threshold: 35

Start

[Copy results to clipboard](#)

Open files Remove all items



Décodage automatisé de longues chaînes

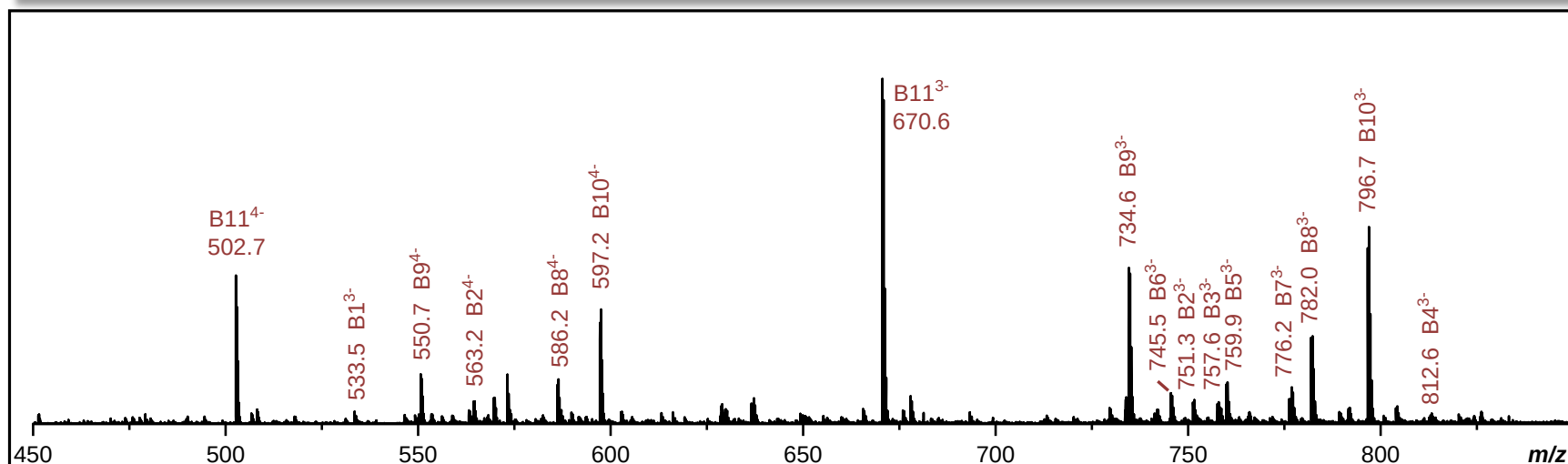
E. Laurent, L. Charles, C. Carapito, M.-A. Delsuc, J.-F. Lutz et al. *C.R. Chimie*, 24, 69-76 (2021)

Le langage
des
polymères

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polymères

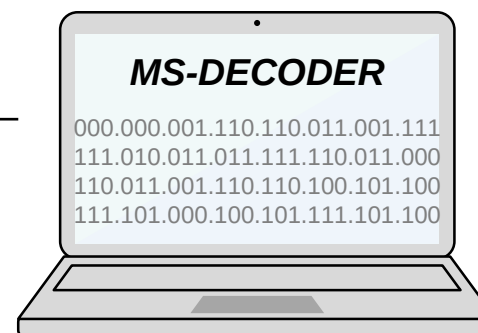
Lire, effacer
et modifier

Applications
et
perspectives

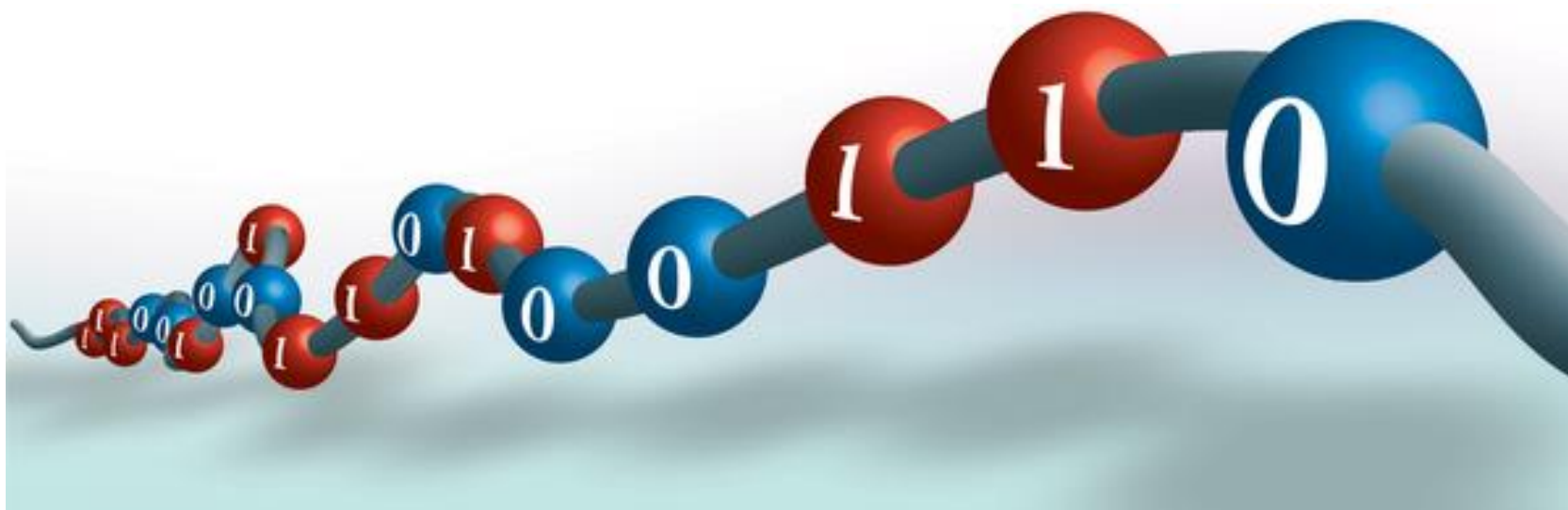


MS-Decoder 2.3.1

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



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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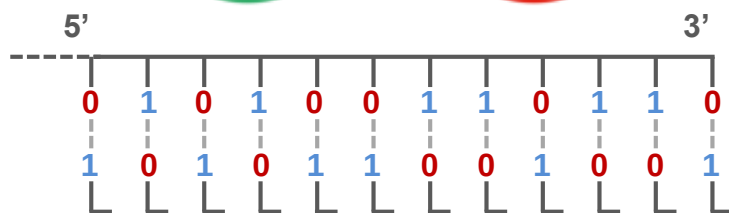
*Applications
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Macromolécules contenant de l'information :

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

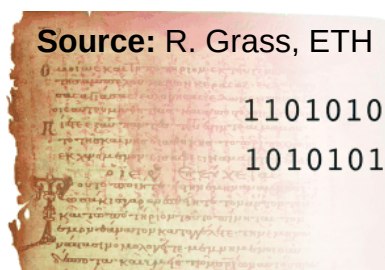
Applications potentielles

Stockage moléculaire de données



Stockage sur le long-terme

Source: R. Grass, ETH



0101001101100101011100010111010101100101011011100110
 0011011001010000110100001010010100110110010101110001
 0111010101100101011011100110001101100101000011010000
 1010010100110110010101110001011101010110010101101110
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**Le langage
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polymères**

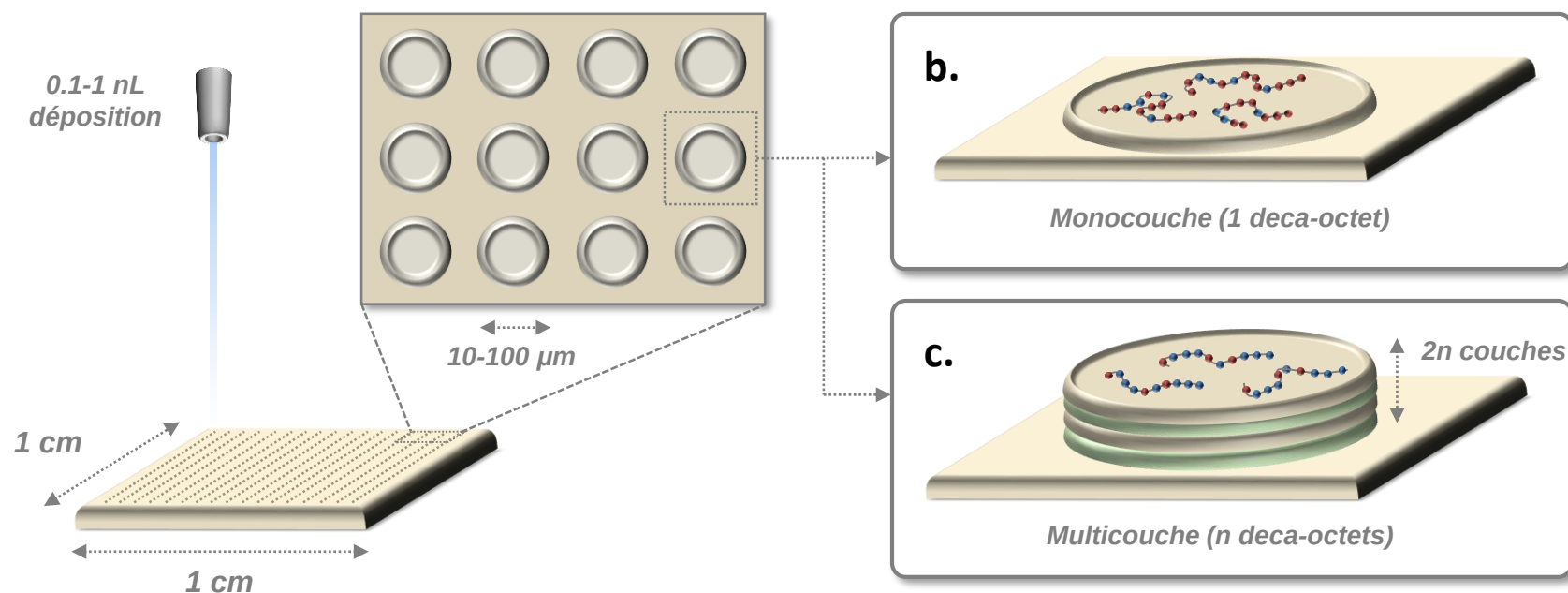
**Ecrire sur
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polymères**

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et modifier**

**Applications
et
perspectives**

Matière codée organisée

Organisation 2D

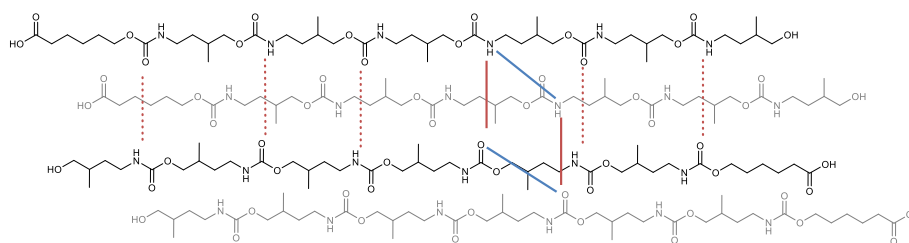
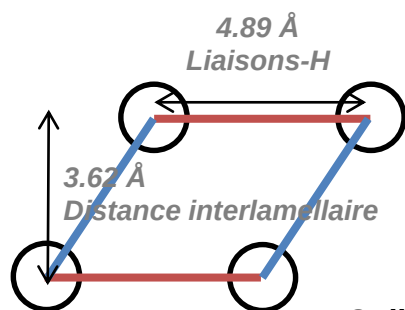
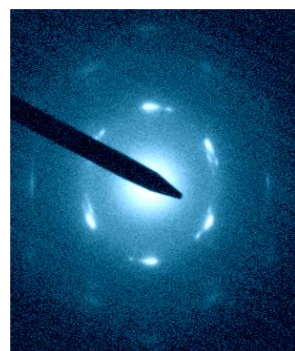


Le langage
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des
polymères

Lire, effacer
et modifier

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



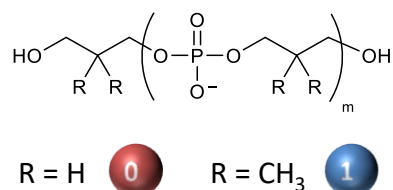
Collaborateur : B. Lotz

Applications
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perspectives

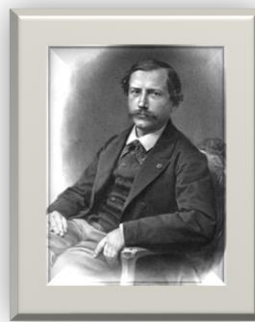
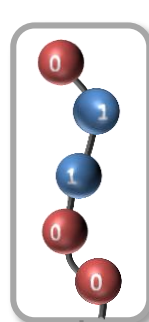
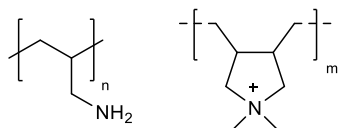
Stockage multicouches

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

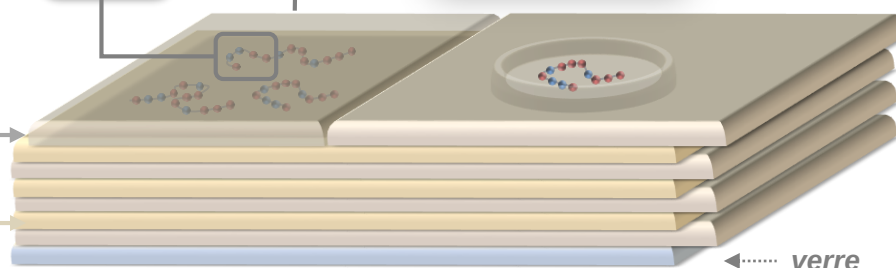
Polyanion numérique



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

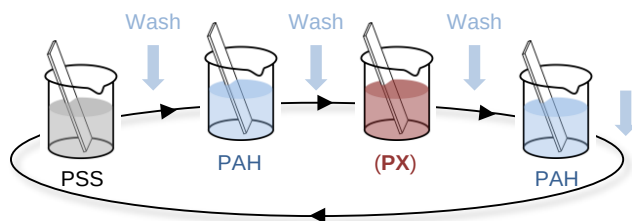
16 couches codées
63 couches au total

← verre

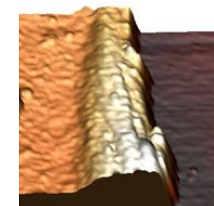
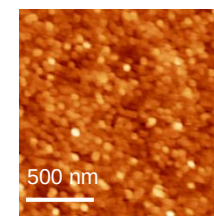
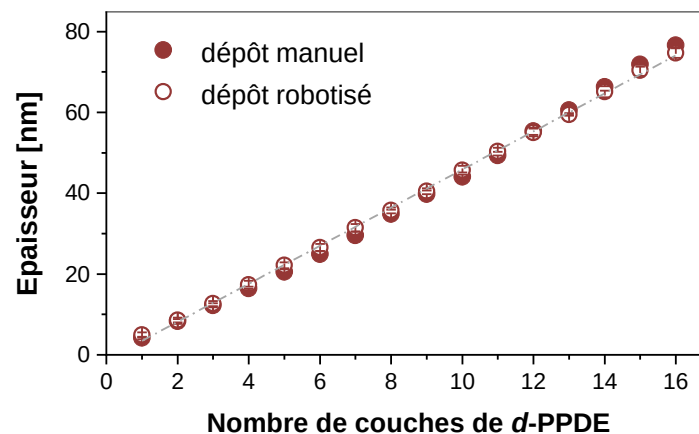
**Le langage
des
polymères**

**Ecrire sur
des
polymères**

**Lire, effacer
et modifier**



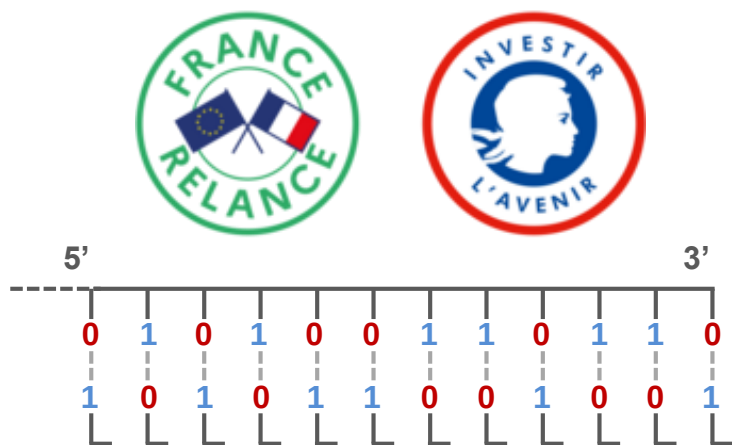
Stockage d'une chimiothèque de 16 polyanions
160 octets (codage ASCII)
63 couches de polyélectrolytes



**Applications
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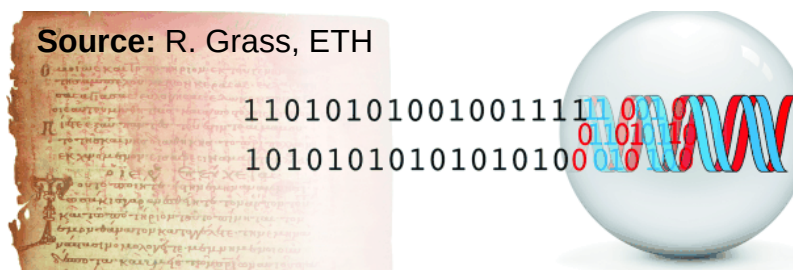
Applications potentielles

Stockage moléculaire de données



Stockage sur le long-terme

Source: R. Grass, ETH



```
0101001101100101011100010111010101100101011011100110
0011011001010000110100001010010100110110010101110001
0111010101100101011011100110001101100101000011010000
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0110001101100101000011010000101001010011011001010111
```

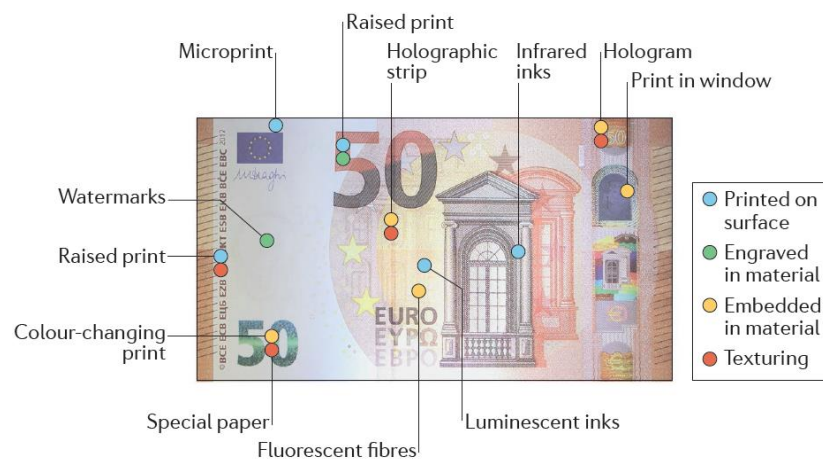
Le langage des polymères

Ecrire sur des polymères

Lire, effacer et modifier

Applications et perspectives

Lutte anti-contrefaçon



Source: T. J. Sørensen

Traçabilité et recyclage

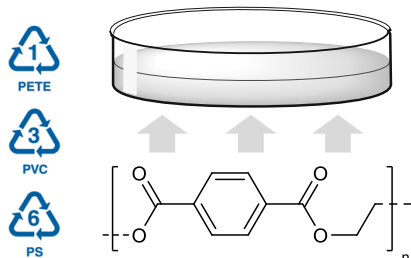


Etiquettes moléculaires



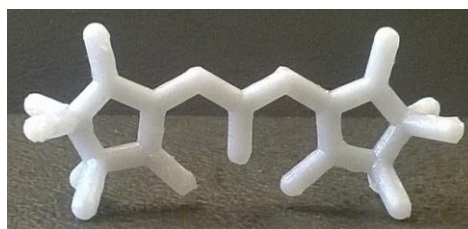
**Le langage
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Plastiques



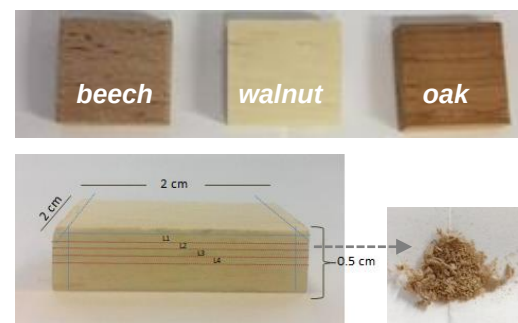
Macromol. Rapid Commun., 38, 1700426 (2017)

Impression 3D



Chem, 1, 114 (2016)

Bois



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

Implants intraoculaires



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

Implants intravasculaires



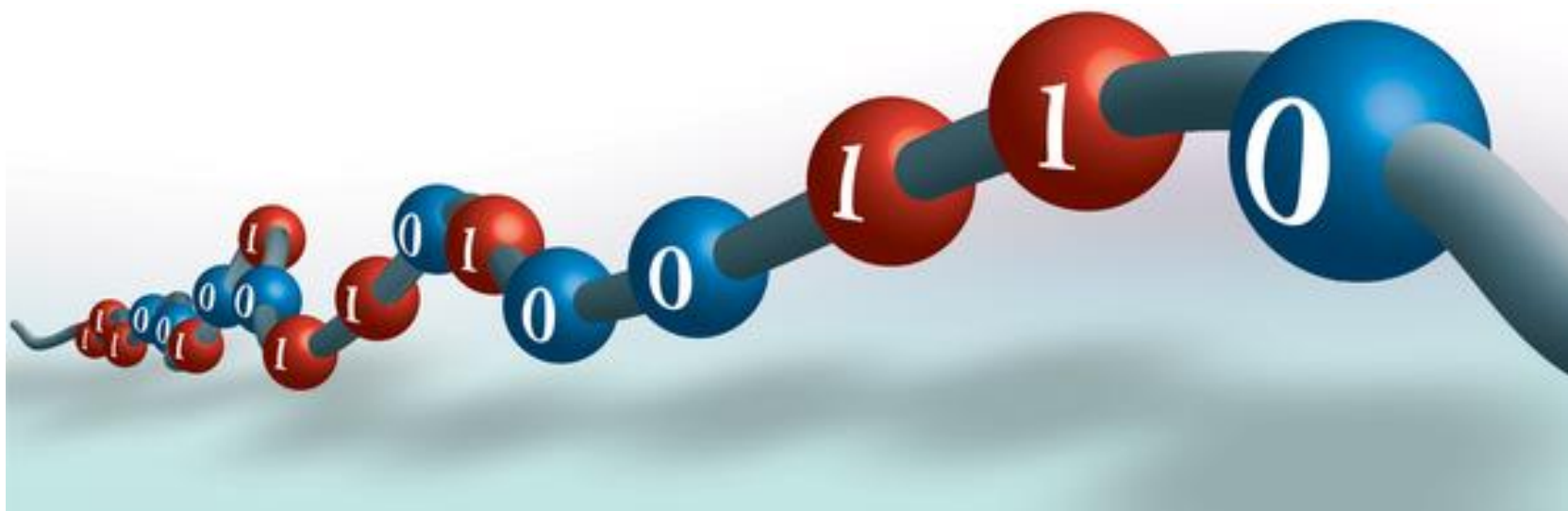
Collaborateur : D. Letourneur

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

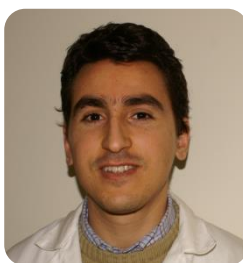
Laurence Charles



Maria Nerantzaki



Aziz Al Ouahabi



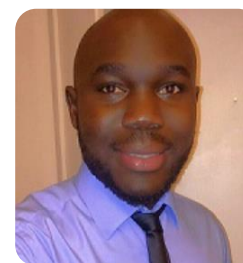
Itab Youssef



Tathagata Mondal



Seydina Kebe



**Le langage
des
polymères**

Evgeniia Konishcheva



Ian Roszak



Svetlana SamokhvalovaThibault Schutz



Eline Laurent



Niklas König



**Ecrire sur
des
polymères**

Denise Karamessini



Gianni Cavallo



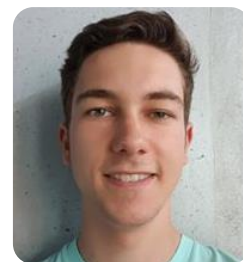
Ariitea Peu



Kevin Flesch



Vincent Greff



Laurence Oswald



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et
perspectives**