

Un peu de mathématiques en physique, et autres géométries inattendues

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11 Avril 2023,
Fianarantsoa

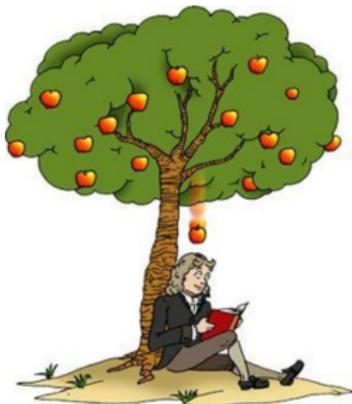
L'infiniment grand et l'infiniment petit

La déraisonnable efficacité des mathématiques

1. Vidéo cosmic eye

Mécanique : l'horlogerie du monde

Mécanique Newtonienne



$$\vec{F} = m\vec{a}$$

$$\vec{F}_g = G \frac{m_1 m_2}{d^2}$$

Mécanique Newtonienne : Prédictions – Mécanique orbitale

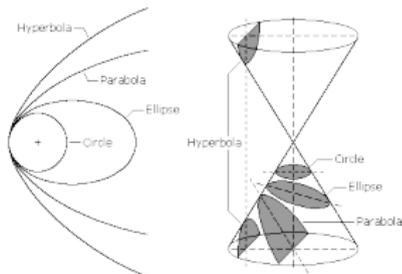
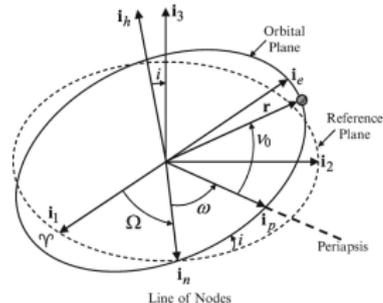
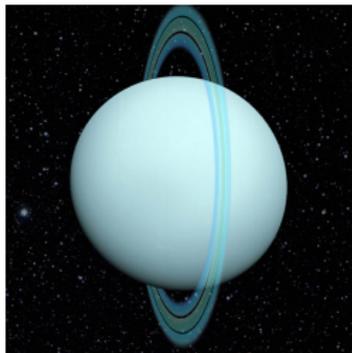


Figure 4.1

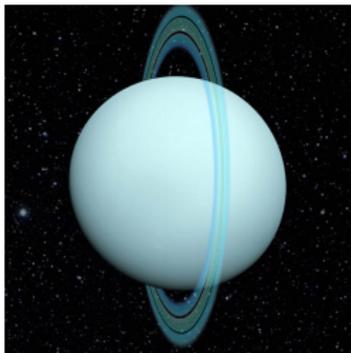


Découverte de Neptune

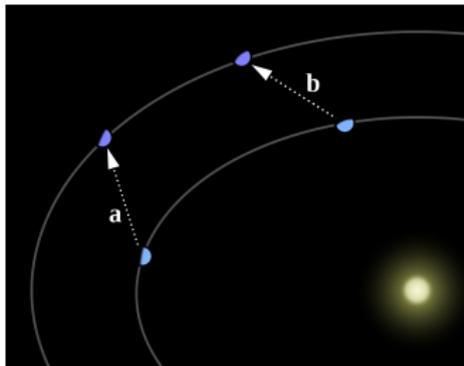


Uranus

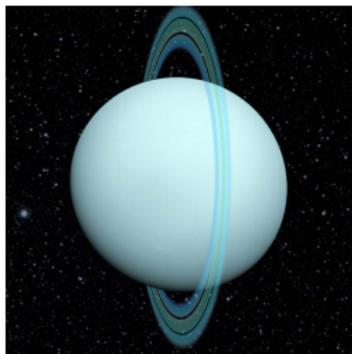
Découverte de Neptune



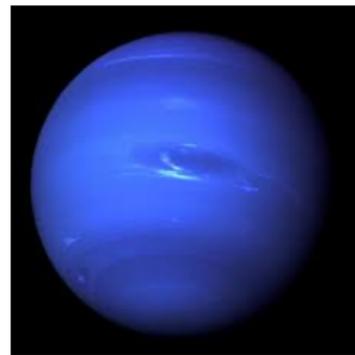
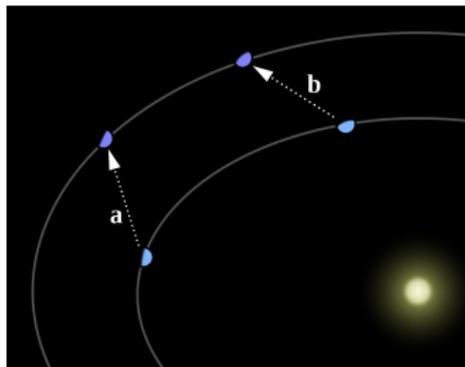
Uranus



Découverte de Neptune

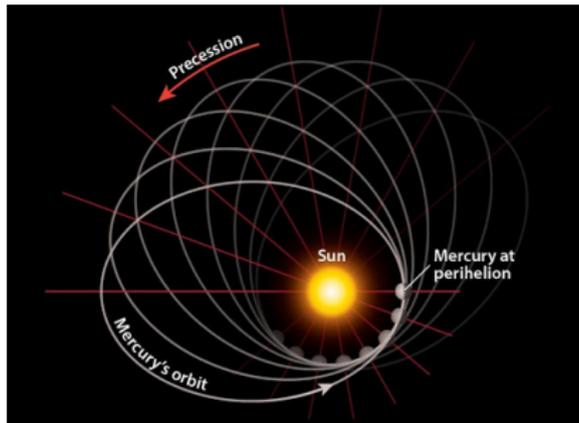


Uranus

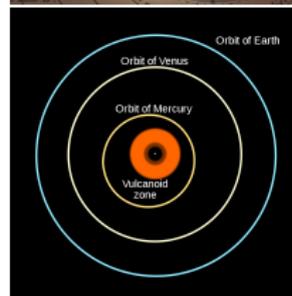
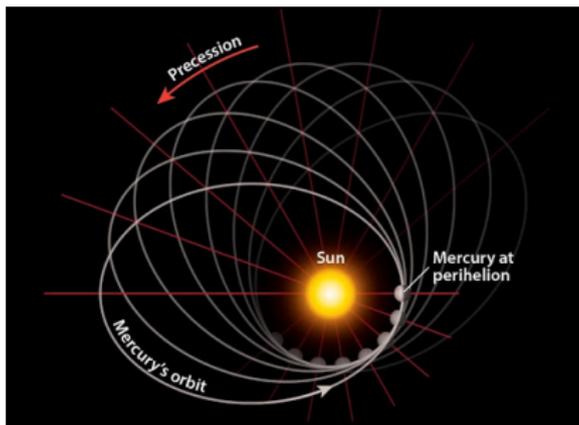


Neptune

Précession du périhélie de Mercure



Précession du périhélie de Mercure

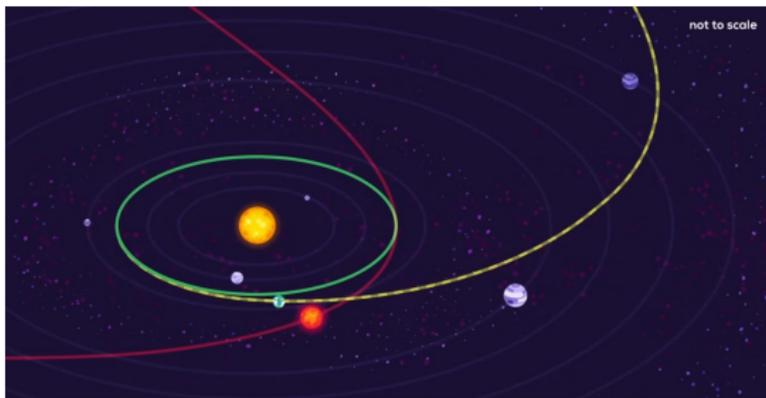


Vulcan ?

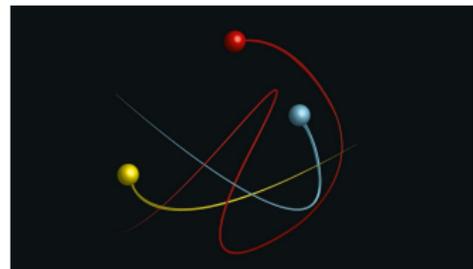
Des tas d'applications...



... mais encore beaucoup d'inconnues



Stabilité du système solaire ?

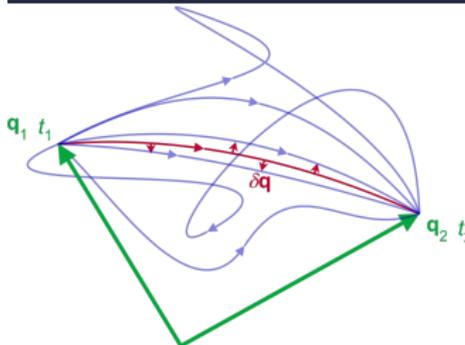
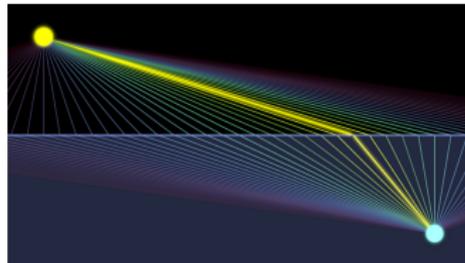


Problème à 3 corps

Mécanique Lagrangienne – Principe de moindre action

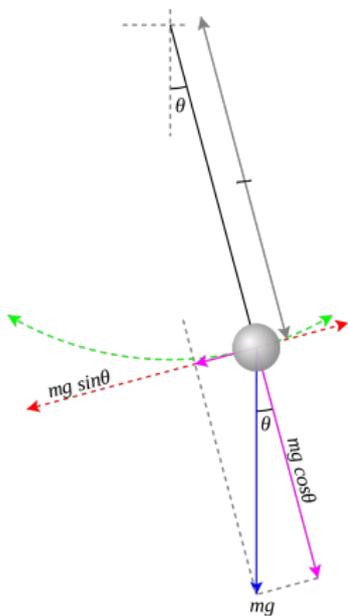


$$\mathcal{L}(q_i, \dot{q}_i, t) = E_c - E_p$$

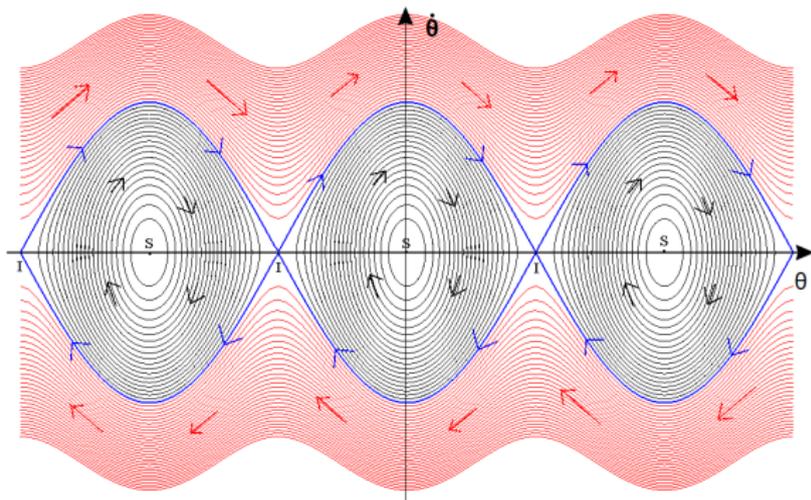


« Lorsqu'il arrive quelque changement dans la nature, la quantité d'action, nécessaire pour ce changement, est la plus petite qui soit possible. »

Mécanique Hamiltonienne – Espace des phases

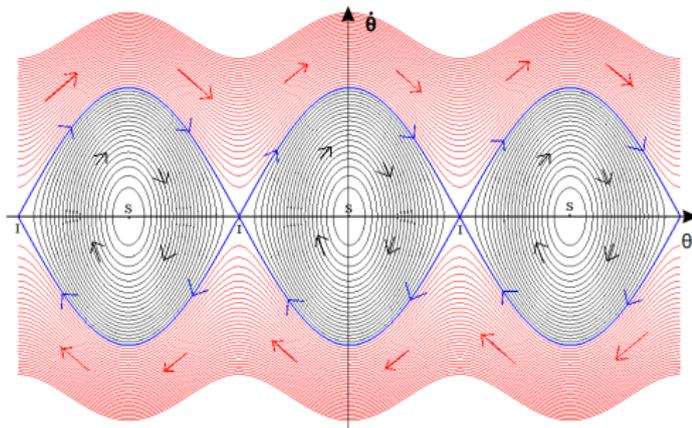
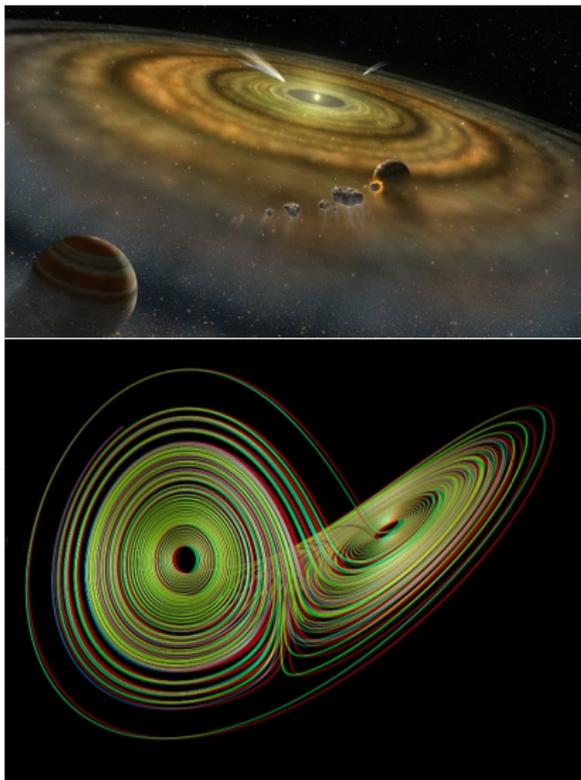


Pendule

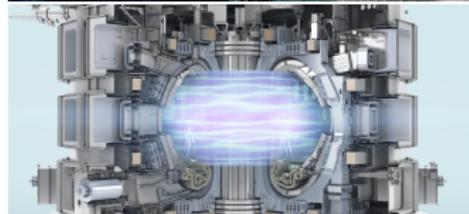
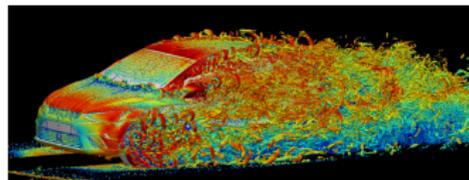
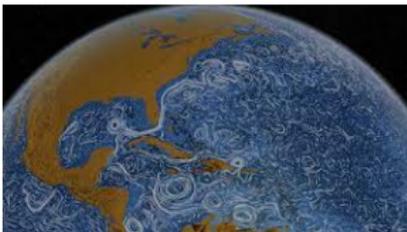


$$p_i := \frac{\partial \mathcal{L}}{\partial \dot{q}_i}, \quad \mathcal{H}(q_i, p_i, t) = \sum \dot{q}_k p_k - \mathcal{L}(q_i, \dot{q}_i, t)$$

Théorie du chaos, des perturbations, ...



Une question contemporaine : mécanique des fluides



Navier-Stokes

$$\nabla \cdot u = 0$$

$$\rho \frac{du}{dt} = -\nabla p + \mu \nabla^2 u + F$$

Equations

L'univers et ses symétries

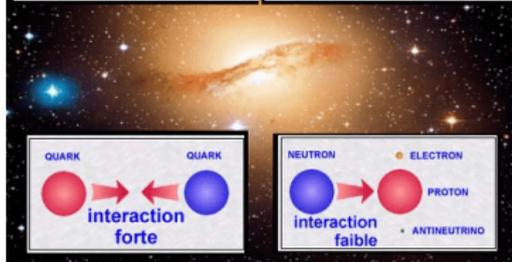
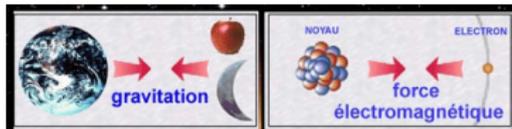
Une introduction physique à la théorie des groupes

La physique de 2023...

La physique de 2023... C'est compliqué

$$\begin{aligned}
 \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\mu g_\nu^\rho \partial_\nu g_\mu^\rho - g_\mu f^{abc} \partial_\nu g_\rho^a g_\nu^b g_\mu^c - \frac{1}{4}g_\mu^2 f^{abc} f^{ade} g_\nu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\mu W_\nu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\mu Z_\nu^0 \partial_\nu Z_\mu^0 - \frac{1}{2}M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\nu A_\mu - igc_w(\partial_\mu Z_\nu^0(W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0(W_\mu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+) + Z_\nu^0(W_\mu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+)) - \\
 & ig_s(\partial_\mu A_\nu(W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu(W_\mu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+) + A_\nu(W_\nu^+ \partial_\mu W_\mu^- - \\
 & W_\mu^- \partial_\nu W_\nu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\nu^+ W_\mu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\nu^+ W_\mu^- + g^2 s_w^2 (Z_\mu^0 W_\nu^+ Z_\nu^0 W_\mu^- - \\
 & Z_\mu^0 W_\nu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\nu^+ A_\nu W_\mu^- - A_\mu A_\nu W_\nu^+ W_\mu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\nu^0 W_\mu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\nu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\nu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\nu \phi^0 - \\
 & \beta_h \left(\frac{2M_h^2}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M_h^2}{g^2} \alpha_h - \\
 & \frac{g\alpha_h M}{2} (H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-) - \\
 & \frac{1}{2}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
 & gM W_\mu^+ W_\nu^- H - \frac{1}{2}g \frac{g^2}{c_w} Z_\mu^0 Z_\nu^0 H - \\
 & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\nu \phi^- - \phi^- \partial_\nu \phi^0) - W_\nu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
 & \frac{1}{2}g (W_\mu^+ (H\partial_\nu \phi^- - \phi^- \partial_\nu H) + W_\nu^- (H\partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H\partial_\nu \phi^0 - \phi^0 \partial_\nu H) + \\
 & M (\frac{1}{c_w} Z_\mu^0 \partial_\nu \phi^0 + W_\mu^+ \partial_\nu \phi^- + W_\nu^- \partial_\mu \phi^+)) - ig \frac{g^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\nu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - \\
 & W_\nu^- \phi^+) - ig \frac{1-2s_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\nu \phi^- - \phi^- \partial_\nu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\nu \phi^- - \phi^- \partial_\nu \phi^+) - \\
 & \frac{1}{2}g^2 W_\mu^+ W_\nu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{2}g^2 \frac{1}{c_w} Z_\mu^0 Z_\nu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\
 & \frac{1}{2}g^2 \frac{g^2}{c_w} Z_\mu^0 (W_\nu^+ \phi^- + W_\nu^- \phi^+) - \frac{1}{2}ig \frac{g^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\nu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\nu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\nu^- \phi^+) - g^2 \epsilon \epsilon (2c_w^2 - 1) Z_\mu^0 A_\nu \phi^+ \phi^- - \\
 & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2}ig_\mu \lambda_\mu^2 (\tilde{g}_\mu^a \gamma^\mu \tilde{g}_\mu^a) g_\mu^2 - e^3 (\gamma\theta + m_\Delta^2) e^3 - e^3 (\gamma\theta + m_\Delta^2) \nu^\lambda - u_\Delta^2 (\gamma\theta + \\
 & m_\Delta^2) u_\Delta^2 - d_\Delta^2 (\gamma\theta + m_\Delta^2) d_\Delta^2 + ig s_w A_\mu (- (e^3 \gamma^\mu e^3) + \frac{2}{3} (u_\Delta^2 \gamma^\mu u_\Delta^2) - \frac{1}{3} (d_\Delta^2 \gamma^\mu d_\Delta^2)) + \\
 & \frac{ig}{2c_w} Z_\mu^0 ((\nu^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^3 \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^3) + (d_\Delta^2 \gamma^\mu (\frac{2}{3}s_w^2 - 1 - \gamma^5) d_\Delta^2) + \\
 & (u_\Delta^2 \gamma^\mu (1 - \frac{2}{3}s_w^2 + \gamma^5) u_\Delta^2)) + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\nu^\lambda \gamma^\mu (1 + \gamma^5) U^{lep}_{\lambda e}) + (u_\Delta^2 \gamma^\mu (1 + \gamma^5) C_{\Delta u} d_\Delta^2)) + \\
 & \frac{ig}{2\sqrt{2}} W_\mu^- ((e^3 U^{lep}_{\lambda e} \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (d_\Delta^2 C_{\Delta d} \gamma^\mu (1 + \gamma^5) u_\Delta^2)) + \\
 & \frac{ig}{2M} \phi^+ (-m_\Delta^2 (\nu^\lambda U^{lep}_{\lambda e} (1 - \gamma^5) e^3) + m_\Delta^2 (\nu^\lambda U^{lep}_{\lambda e} (1 + \gamma^5) e^3) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_\Delta^2 (e^3 U^{lep}_{\lambda e} (1 + \gamma^5) \nu^\lambda) - m_\Delta^2 (e^3 U^{lep}_{\lambda e} (1 - \gamma^5) \nu^\lambda) - \frac{g}{2} \frac{m_\Delta^2}{M} H (\nu^\lambda \nu^\lambda) - \\
 & \frac{g}{2} \frac{m_\Delta^2}{M} H (e^3 e^3) + \frac{ig}{2} \frac{m_\Delta^2}{M} \phi^0 (\nu^\lambda \nu^\lambda \nu^\lambda) - \frac{ig}{2} \frac{m_\Delta^2}{M} \phi^0 (e^3 \nu^\lambda e^3) - \frac{1}{2} \nu_\lambda M_\mu^R (1 - \gamma_5) \partial_\mu - \\
 & \frac{1}{2} \nu_\lambda M_\mu^R (1 - \gamma_5) \partial_\mu + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_\Delta^2 (u_\Delta^2 C_{\Delta u} (1 - \gamma^5) d_\Delta^2) + m_\Delta^2 (u_\Delta^2 C_{\Delta u} (1 + \gamma^5) d_\Delta^2) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_\Delta^2 (d_\Delta^2 C_{\Delta d}^1 (1 + \gamma^5) u_\Delta^2) - m_\Delta^2 (d_\Delta^2 C_{\Delta d}^1 (1 - \gamma^5) u_\Delta^2) - \frac{g}{2} \frac{m_\Delta^2}{M} H (u_\Delta^2 u_\Delta^2) - \\
 & \frac{g}{2} \frac{m_\Delta^2}{M} H (d_\Delta^2 d_\Delta^2) + \frac{ig}{2} \frac{m_\Delta^2}{M} \phi^0 (u_\Delta^2 \gamma^\mu u_\Delta^2) - \frac{ig}{2} \frac{m_\Delta^2}{M} \phi^0 (d_\Delta^2 \gamma^\mu d_\Delta^2) + \tilde{G}^a \theta^a G^a + g_\mu f^{abc} \partial_\nu \tilde{G}^a G^b g_\mu^c - \\
 & X^+ (\partial^2 - M^2) X^+ + \tilde{X}^- (\partial^2 - M^2) X^- + X^0 (\partial^2 - \frac{M_X^2}{c_w^2}) X^0 + Y \partial^2 Y + ig c_w W_\mu^+ (\partial_\mu \tilde{X}^0 X^0 - \\
 & \partial_\mu \tilde{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \tilde{Y} X^- - \partial_\mu \tilde{X}^+ Y) + ig c_w W_\mu^- (\partial_\mu \tilde{X}^- X^0 - \\
 & \partial_\mu \tilde{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \tilde{X}^- Y - \partial_\mu \tilde{Y} X^+) + ig c_w Z_\mu^0 (\partial_\mu \tilde{X}^+ X^+ - \\
 & \partial_\mu \tilde{X}^- X^-) + ig s_w A_\mu (\partial_\mu \tilde{X}^+ X^+ - \\
 & \partial_\mu \tilde{X}^- X^-) - \frac{1}{2}gM (X^+ X^+ H + \tilde{X}^- X^- H + \frac{1}{c_w} X^0 X^0 H) + \frac{1-2s_w^2}{2c_w} igM (X^+ X^0 \phi^+ - \tilde{X}^- X^0 \phi^-) + \\
 & \frac{1}{2c_w} igM (\tilde{X}^0 X^- \phi^+ - \tilde{X}^0 X^+ \phi^-) + ig M s_w (X^0 X^- \phi^+ - \tilde{X}^0 X^+ \phi^-) + \\
 & \frac{1}{2}igM (X^+ X^0 \phi^- - X^- X^0 \phi^0) .
 \end{aligned}$$

La physique de 2023... C'est compliqué ?



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}_i \gamma_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

THE STANDARD MODEL OF PARTICLE PHYSICS

THE STANDARD MODEL

QUARKS
UP, CHARM, TOP, DOWN, STRANGE, BOTTOM, GLEUON

LEPTONS
ELECTRON, MUON, TAU, NEUTRINO

GAUGE BOSONS
PHOTON, Z BOSON, W BOSON

CONSERVATION LAWS
ENERGY, CHARGE, BARYON NUMBER, LEPTON NUMBERS, STRANGENESS

WEAK FORCE

ELECTROMAGNETIC FORCE

STRONG FORCE

FORCE INTERACTIONS
INTERACT WITH THE ELECTROMAGNETIC FORCE
INTERACT WITH THE STRONG FORCE
INTERACT WITH THE WEAK FORCE
INTERACT WITH THE HIGGS FIELD

ALL THE FUNDAMENTAL PARTICLES

STANDARD MODEL INTERACTIONS

BY DOMINIC WALLIMAN © 2021 | YOUTUBE | DOMAIN OF SCIENCE

L'idée géniale d'Emmy Noether

The diagram illustrates the correspondence between symmetries and conservation laws, known as Noether's theorem. It is presented as a double-headed arrow pointing from left to right, indicating the direction of the theorem's application.

Left Side (Symmetries and Conservation Laws):

- $i\hbar \frac{\partial}{\partial t} |\Psi\rangle = \hat{H} |\Psi\rangle$ (Schrödinger equation)
- $U \cdot \nabla U = 0$ (Hamiltonian mechanics)
- $\vec{F}_{\text{ext}} = m\vec{a}$ (Newton's second law)
- $R_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$ (Einstein's field equations)
- $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi} \not{D} \Psi + D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi) + \bar{\Psi}_L \hat{Y} \Phi \Psi_R + h.c.$ (Lagrangian density)

Right Side (Conservation Laws and Symmetries):

- $i\hbar \frac{\partial}{\partial t} |\Psi\rangle = \hat{H} |\Psi\rangle$ (Schrödinger equation)
- $U \cdot \nabla U = 0$ (Hamiltonian mechanics)
- $\sum \vec{F}_{\text{ext}} = m\vec{a}$ (Newton's second law)
- $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$ (Einstein's field equations)
- $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi} \not{D} \Psi + D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi) + \bar{\Psi}_L \hat{Y} \Phi \Psi_R + h.c.$ (Lagrangian density)

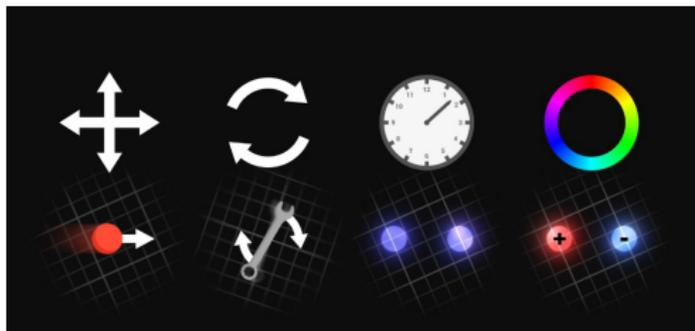
The central white arrow points from the left side to the right side, indicating the direction of the theorem's application.

L'idée géniale d'Emmy Noether



« À toute symétrie de l'univers correspond une grandeur physique conservée »

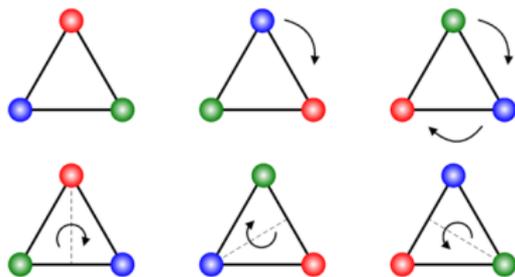
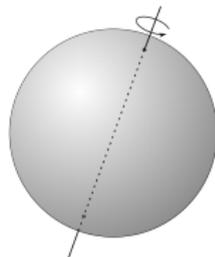
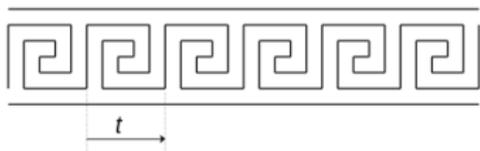
L'idée géniale d'Emmy Noether



« À toute symétrie de l'univers correspond une grandeur physique conservée »

Pour comprendre les lois de l'univers, il suffit de trouver ses symétries.

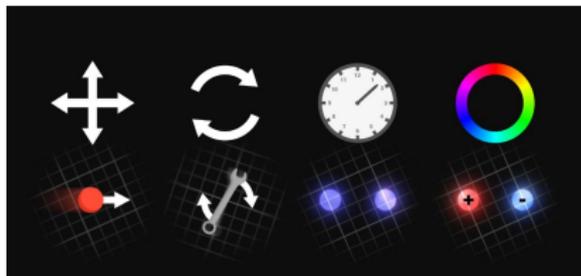
Mais qu'est-ce qu'une symétrie ?



Une symétrie est une transformation qui laisse le système inchangé.
 Pour un système, on peut étudier toutes les manières dont il est symétrique, et la manière dont ces symétries se composent : c'est son groupe de symétrie.

Symétrie de l'univers

Quand les lois de l'univers sont invariantes par une transformation.



Symétrie de l'univers

Quand les lois de l'univers sont invariantes par une transformation.



- Et la vitesse de la lumière...

Symétrie de l'univers

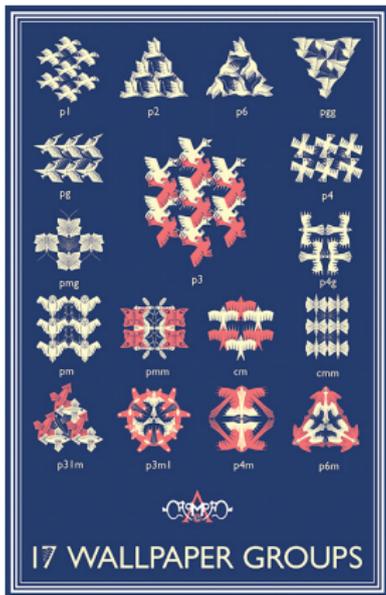
Quand les lois de l'univers sont invariantes par une transformation.



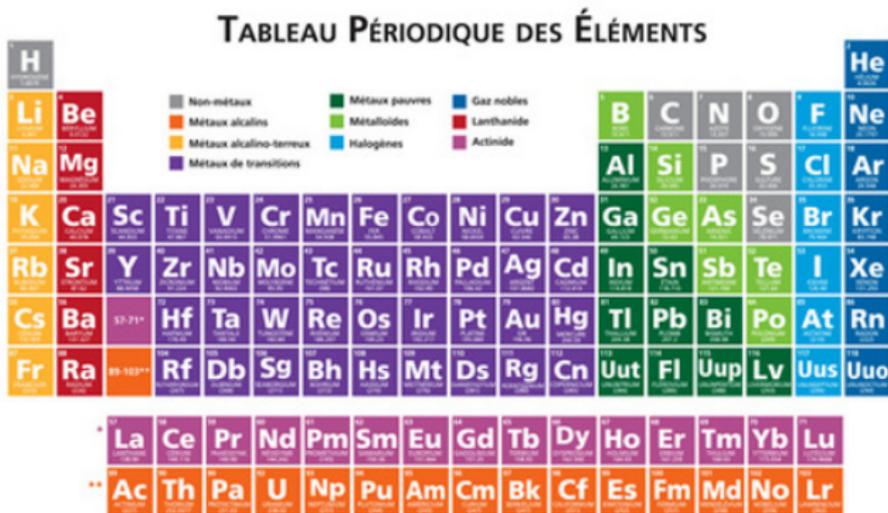
- Et la vitesse de la lumière...
- D'autres symétries microscopiques.
 $U(1)$ pour l'électromagnétisme, $SO(2)$ pour l'interaction faible, $SO(3)$ pour les symétries de couleur de la chromodynamique des quarks, ...

La symétrie chez les mathématiciens (1)

« Les 17 groupes de papier peint »



La symétrie chez les mathématiciens (2)



La symétrie chez les mathématiciens (2)

The Periodic Table Of Finite Simple Groups

B,C,F ₄		Dynkin Diagrams of Simple Lie Algebras														C ₂				
1																2				
A ₁ (4), A ₃ (3)		A ₅ (2)		E ₇ (2)		E ₈ (2)		G ₂ (3)		F ₄ (2)		I ₂ (n)		B ₂ (2)		D ₄ (2)		G ₂ (2)		C ₃
A ₅		A ₁ (7)																		3
A ₇		A ₁ (11)		E ₆ (2)		E ₇ (2)		G ₂ (3)		F ₄ (2)		I ₂ (n)		B ₂ (2)		D ₄ (2)		G ₂ (2)		4
2330		540		184320		184320		184320		184320		184320		184320		184320		184320		5
A ₉ , B ₃ , D ₅		F ₄ (2)		E ₆ (2)		E ₇ (2)		G ₂ (3)		F ₄ (2)		I ₂ (n)		B ₂ (2)		D ₄ (2)		G ₂ (2)		5
A ₉		A ₁ (8)																		6
360		361		184320		184320		184320		184320		184320		184320		184320		184320		7
A ₇		A ₁ (13)		E ₆ (2)		E ₇ (2)		G ₂ (3)		F ₄ (2)		I ₂ (n)		B ₂ (2)		D ₄ (2)		G ₂ (2)		7
2330		540		184320		184320		184320		184320		184320		184320		184320		184320		8
A ₁₁		A ₁ (13)		E ₆ (3)		E ₇ (3)		G ₂ (4)		F ₄ (3)		I ₂ (n)		B ₂ (3)		D ₄ (3)		G ₂ (3)		11
20160		1900		184320		184320		184320		184320		184320		184320		184320		184320		11
A ₉		A ₁ (17)		E ₆ (4)		E ₇ (4)		G ₂ (5)		F ₄ (4)		I ₂ (n)		B ₂ (4)		D ₄ (4)		G ₂ (4)		13
110160		2160		184320		184320		184320		184320		184320		184320		184320		184320		13
A ₁₃		A ₁ (q)		E ₆ (q)		E ₇ (q)		G ₂ (q)		F ₄ (q)		I ₂ (2q+1)		B ₂ (q)		D ₄ (q)		G ₂ (q)		C _q
∑ _{q=2} [∞]		∑ _{q=2} [∞]		∑ _{q=2} [∞]		∑ _{q=2} [∞]		∑ _{q=2} [∞]		∑ _{q=2} [∞]		∑ _{q=2} [∞]		∑ _{q=2} [∞]		∑ _{q=2} [∞]		∑ _{q=2} [∞]		P

- Alternating Groups
- Classical Chevalley Groups
- Chevalley Groups
- Classical Twisted Groups
- Steinberg Groups
- Suzuki Groups
- Lie Groups and Tits Groups*
- Sporadic Groups
- Cyclic Groups

Alternator*
Symbol
Order*

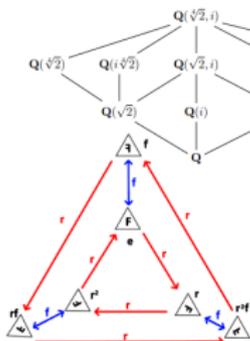
M ₁₁	M ₁₂	M ₂₂	M ₂₃	M ₂₄	J ₁	J ₂	J ₃	J ₄	HS	McL	He	Ru
7920	95040	441504	10320960	244423680	175368	660480	50322960	244423680	441504	10320960	441504	10320960

*The groups J₁ and J₂ are the Janko groups. The groups J₃ and J₄ are the Janko groups. The groups J₁ and J₂ are the Janko groups. The groups J₃ and J₄ are the Janko groups.

S ₂	O'N	O	O	O	O	O	O	O	O	O	O	O
Sw2	ON	O3	O2	O1	HN	Ly	Tb	F22	F43	F44	B	M
168	2448	2448	2448	2448	2448	2448	2448	2448	2448	2448	2448	2448

La symétrie chez les mathématiciens (3)

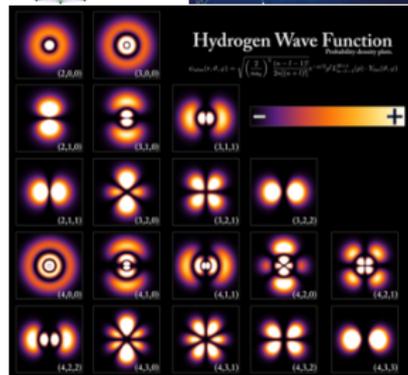
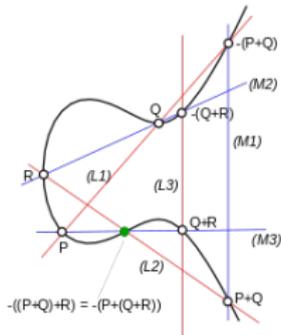
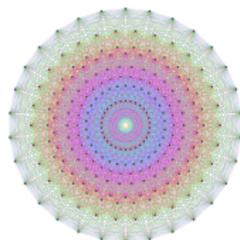
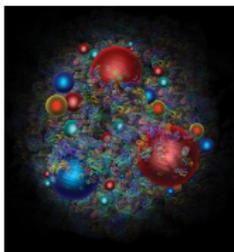
Une aventure démarrée par le jeune Galois...



$$x^5 + ax^4 + bx^3 + cx^2 + dx + e = 0$$

La symétrie chez les mathématiciens (4)

Une aventure démarrée par le jeune Galois...
et toujours de nouvelles applications

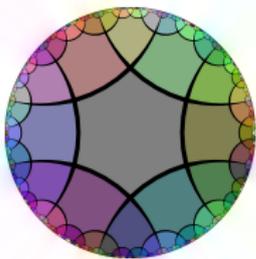
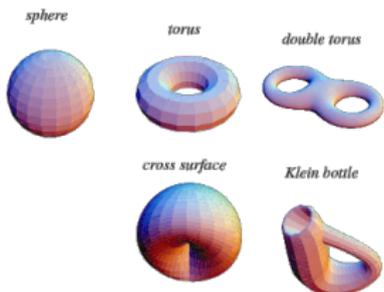


Géométrie non-euclidienne

Géométrie non-euclidienne

Changeons les règles du jeu !

- Étant donné un point et une droite ne passant pas par ce point, il existe une seule droite passant par ce point et parallèle à la première.



Flat

Triangle: sum of angles is 180° .

Parallel Lines: remain parallel.

Circle: $C = 2\pi r$.

Straightest Possible Path: is a straight line.

Spherical

Triangle: sum of angles is greater than 180° .

Parallel Lines: eventually converge.

Circle: $C < 2\pi r$.

Straightest Possible Path: is a piece of a great circle.

Hyperbolic

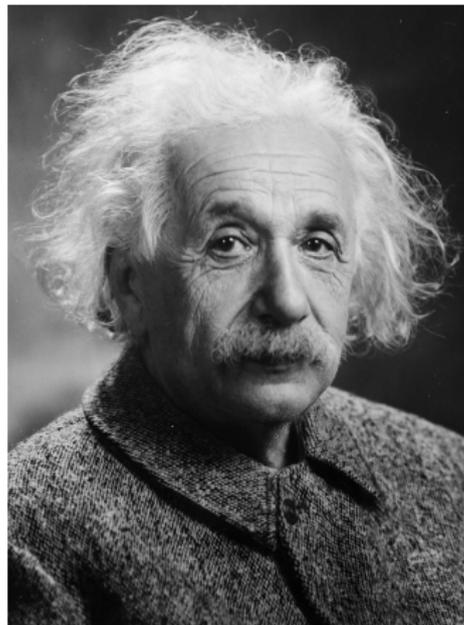
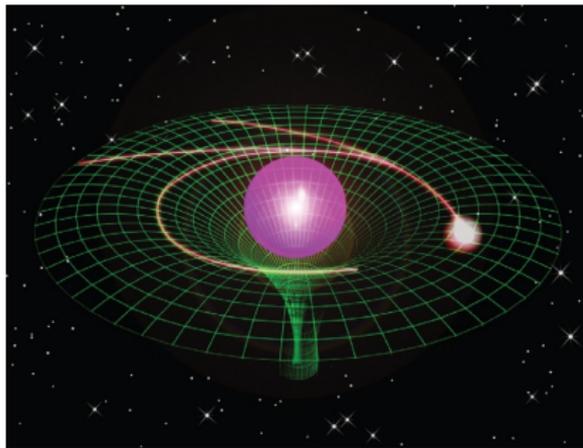
Triangle: sum of angles is less than 180° .

Parallel Lines: eventually diverge.

Circle: $C > 2\pi r$.

Straightest Possible Path: is a piece of a hyperbola.

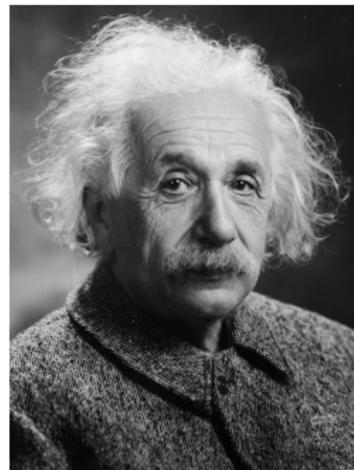
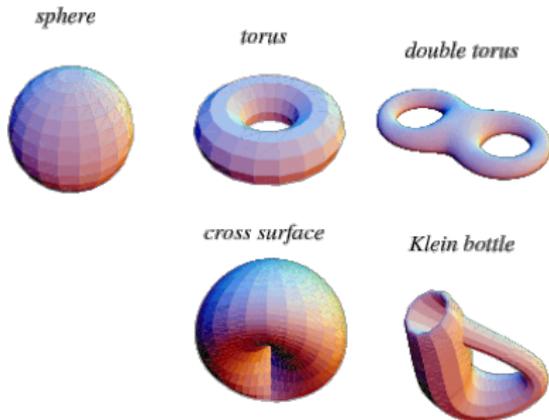
... L'univers est non-euclidien !



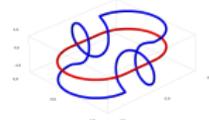
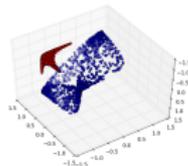
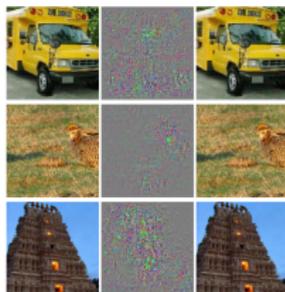
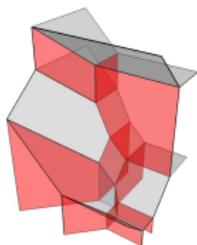
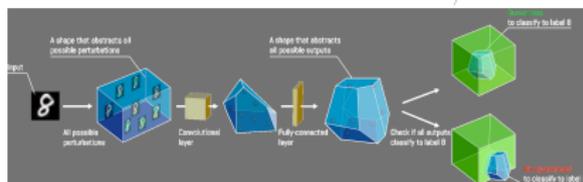
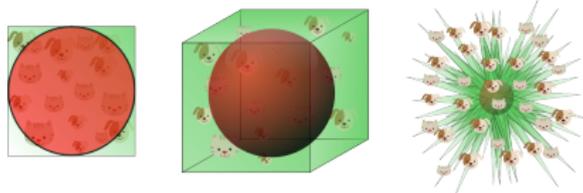
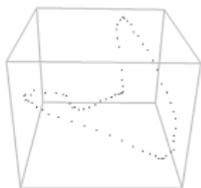
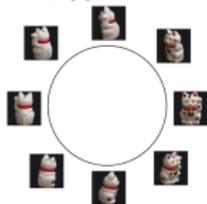
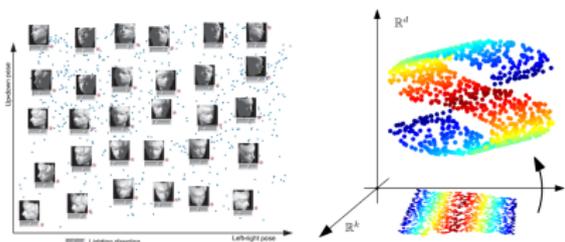
... L'univers est non-euclidien !

Autres questions :

- Quelle est sa topologie ?
- Est-il "vraiment" de dimension 3 ? Ou 4 ?
Ou 11 ?



Ouverture(s) : géométrie et topologie en informatique



Ouverture(s) : physique statistique

Faire le lien entre infiniment petit et infiniment grand

Conclusion

Conclusion

Merci !