# Criticality
# The study of Self-organization

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moogsoft Continuous Assurance

UNIVERSITY OF SUSSEX

# Contents

How did the first person who clapped convince everyone to do it?

How did the first person who clapped convince everyone to do it?

Who decided how fast to clap?

How did the first person who clapped convince everyone to do it?

Who decided how fast to clap?

Who decided to stop?

There is no unit (bird) that has knowledge of the entire system

Yet, a small perturbation to the system can lead to dramatic changes in collective dynamics

# Probably all this information is enconded in the Genome right?

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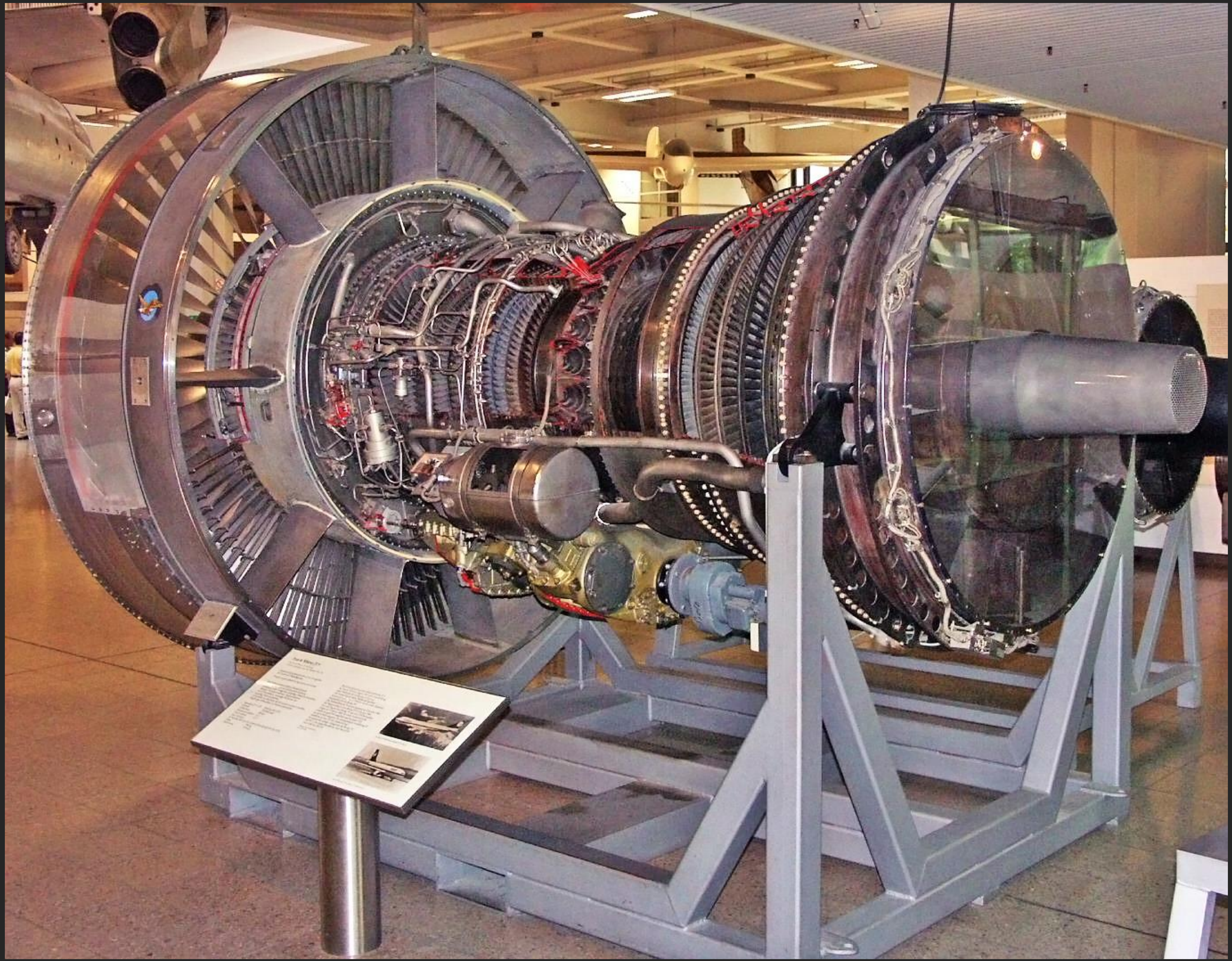
Well, it is not that simple… It's a bit like saying that since we know the human genome we know exactly how ancient Egyptians built the pyramids

There is no encoding in Nature of all possible "functions" that a system can do, functions emerge thanks to the collective effort of many "units" in a system

That is not how humans do “things”. Yet, one small little imprecision can be catastrophic!



# Nature’s creations are much more robust than human’s

# Nature's creations are much more robust than human's

| Reference | Experimental system | Total baseline synaptic change | % synaptic change that is activity / learning-independent |
|---|---|---|---|
| Pfeiffer et al., 2018 | Adult mouse hippocampus | 40% turnover over 4 days | NA |
| Loewenstein et al., 2011 | Adult mouse auditory cortex | >70% of spines changed size by >50% over 20 days | NA |
| Zuo et al., 2005 | Adult mouse (barrel, primary motor, frontal) cortex | 3–5% turnover over 2 weeks for all regions. 73.9 ± 2.8% of spines stable over 18 months (barrel cortex) | NA |
| Nagaoka et al., 2016 | Adult mouse visual cortex | 8% turnover per 2 days in visually deprived environment. 15% in visually enriched environment. 7–8% in both environments under pharmacological suppression of spiking. | $\approx 50\%$ (turnover) |
| Quinn et al., 2019 | Glutamatergic synapses, dissociated rat hippocampal culture | 28 ± 3.7% of synapses formed over 24 hr period. 28.6 ± 2.3% eliminated. Activity suppression through tetanus neurotoxin -light chain. Plasticity rate unmeasured. | $\approx 75\%$ (turnover) |
| Yasumatsu et al., 2008 | CA1 pyramidal neurons, primary culture, rat hippocampus | Measured rates of synaptic turnover and spine-head volume change. Baseline conditions vs activity suppression (NMDAR inhibitors). Turnover rates: 32.8 ± 3.7% generation/elimination per day (control) vs 22.0 ± 3.6% (NMDAR inhibitor). Rate of spine-head volume change: | $\approx 67 \pm 17\%$ (turnover). Size-dependent, but consistently >50% (spine-head volume) |
| Dvorkin and Ziv, 2016 | Glutamatergic synapses in cultured networks of mouse cortical neurons | Partitioned commonly innervated (CI) synapses sharing same axon and dendrite, and non-CI synapses. Quantified covariance in fluorescence change for CI vs non-CI synapses to estimate relative contribution of activity histories to synaptic remodelling | 62–64% (plasticity) |
| Minerbi et al., 2009 | Rat cortical neurons in primary culture | Created '*relative synaptic remodeling measure*' (RRM) based on frequency of changes in the rank ordering of synapses by fluorescence. Compared baseline RRM to when neural activity was suppressed by tetrodotoxin (TTX). RRM: 0.4 (control) vs 0.3 (TTX) after 30 hr. | $\approx 75\%$ (plasticity) |
| Kasthuri et al., 2015 | Adult mouse neocortex (Three-dimensional *post mortem* reconstruction using electron microscopy). | Data on 124 pairs of 'redundant' synapses sharing a pre/post-synaptic neuron was analysed in Dvorkin and Ziv, 2016. They calculated the correlation coefficient of spine volumes and post-synaptic density sizes between redundant pairs. This should be one if pre/post-synaptic activity history perfectly explains these variables. | 77% (post-synaptic density, $r^2 = 0.23$). 66% (spine volume, $r^2 = 0.34$) |
| Ziv and Brenner, 2018 | Literature review across multiple systems | '*Collectively these findings suggest that the contributions of spontaneous processes and specific activity histories to synaptic remodeling are of similar magnitudes*' | $\approx 50\%$ |

Table 1 from "Dhruva V Raman Timothy O'Leary (2021) Optimal plasticity for memory maintenance during ongoing synaptic change eLife 10:e62912."

# Nature’s creations are much more robust than human’s

Imagine doing this to the neural network layers of a LLM such as ChatGPT, the answers would be impossible to interpret

# Complexity Science is the study of Emergence

Macroscopic features and/or processes of a system that are independent of the underlying units of the system.

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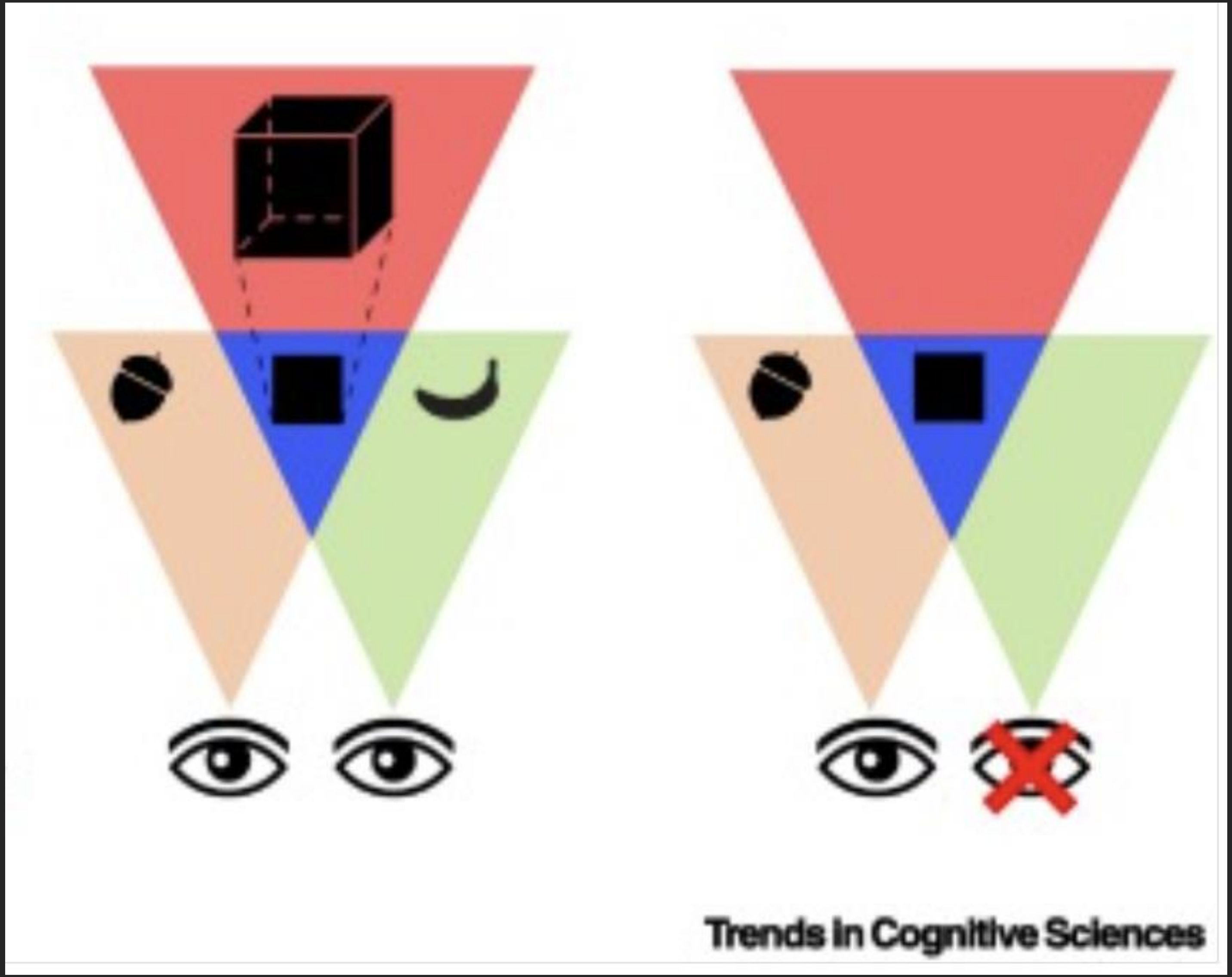
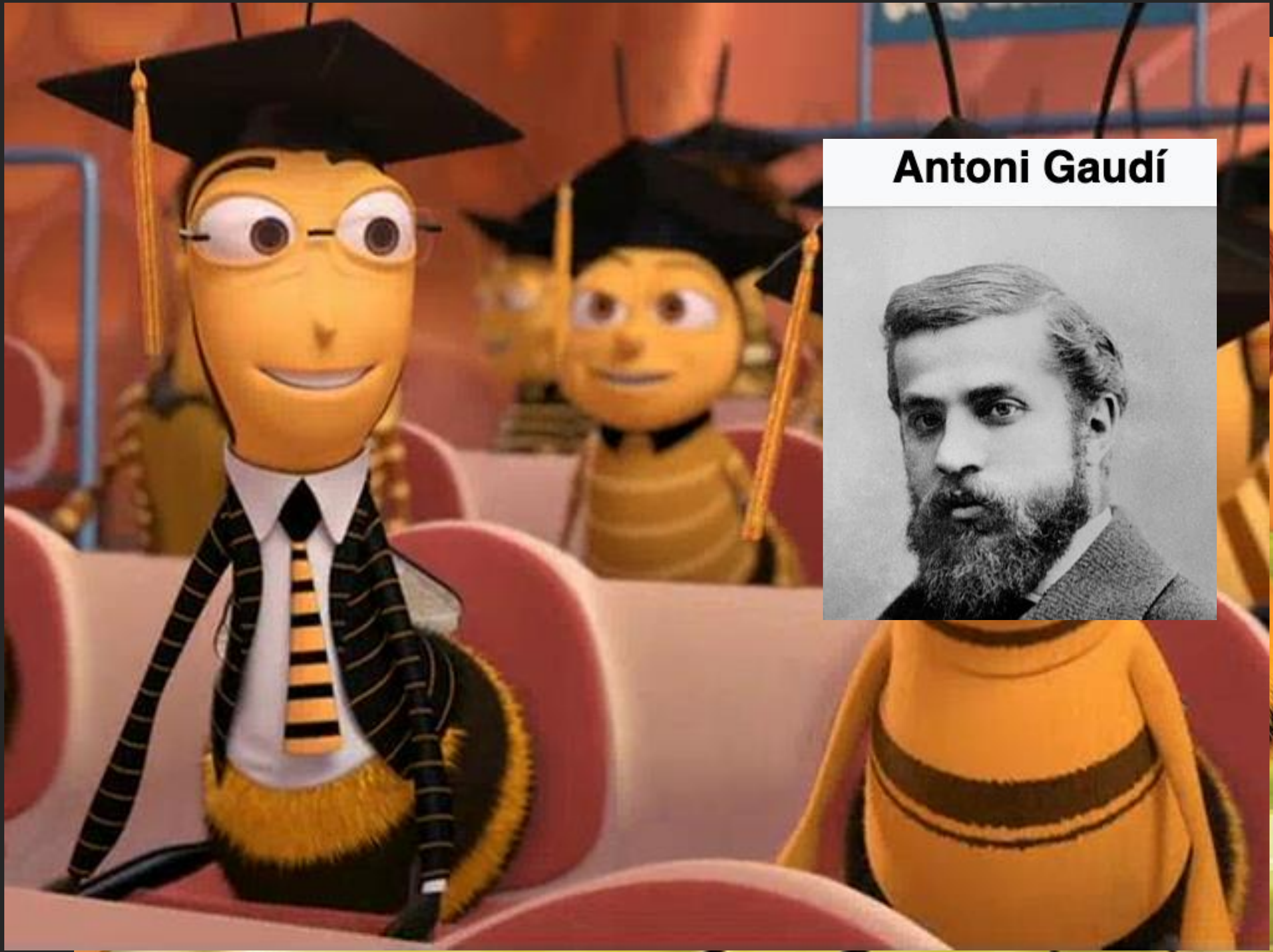
Macroscopic features and processes of a system that are independent of the underlying units of the system.




Luppi et al (2024) Information decomposition and the informational architecture of the brain

Put on your philosopher mask and to try to answer this, what is the difference between a thermite nest and the Sagrada Família?

Example taken from Daniel Dennett


Antoni Gaudí

# Contents

# Part 2
# The classical and quantum physicists’ secret

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Classical and quantum physics are cool …
Don't get me wrong

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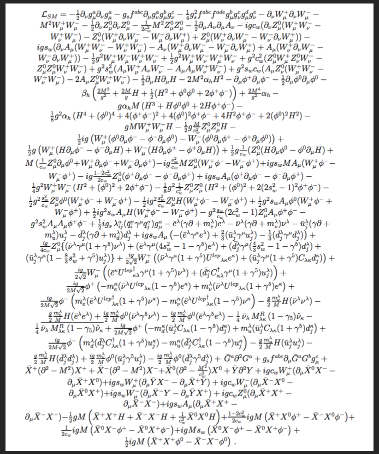
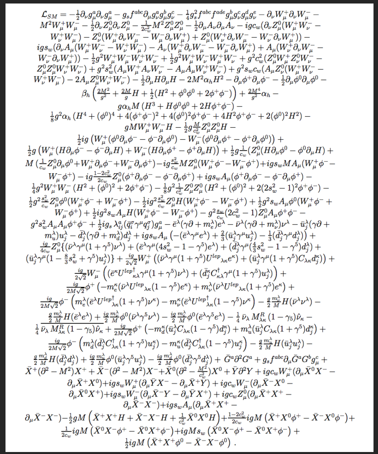


$10^{-14}$ $10^{-4}$ $10^{4}$ $10^{14}$ $10^{26}$

Meters

Orion Nebula, Webb Telescope



$10^{-14}$ $10^{-4}$ $10^{4}$ $10^{14}$ $10^{26}$

Meters

$$
\begin{gathered}
\mathcal{L}_{SM} = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \frac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\frac{1}{8}g^2\alpha_h \left(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\right) - \\
gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \\
\frac{1}{2}ig \left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\frac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\frac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\frac{1}{4}g^2 W^+_\mu W^-_\mu \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \frac{1}{8}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu \left(H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-\right) - \\
\frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu \phi^+\phi^- + \frac{1}{2}ig_s \lambda^a_{ij}(\bar q^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu - \bar e^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar\nu^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar u^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar d^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar e^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar d^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\frac{ig}{4c_w}Z^0_\mu\{(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar d^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar u^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \frac{ig}{2\sqrt2}W^+_\mu\left((\bar\nu^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\frac{ig}{2\sqrt2}W^-_\mu\left((\bar e^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\frac{ig}{2M\sqrt2}\phi^+\left(-m^\kappa_e(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\frac{ig}{2M\sqrt2}\phi^-\left(m^\lambda_e(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \frac{g}{2}\frac{m^\lambda_\nu}{M}H(\bar\nu^\lambda\nu^\lambda) - \\
\frac{g}{2}\frac{m^\lambda_e}{M}H(\bar e^\lambda e^\lambda) + \frac{ig}{2}\frac{m^\lambda_\nu}{M}\phi^0(\bar\nu^\lambda\gamma^5\nu^\lambda) - \frac{ig}{2}\frac{m^\lambda_e}{M}\phi^0(\bar e^\lambda\gamma^5 e^\lambda) - \frac{1}{4}\,\bar\nu_\lambda\, M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa - \\
\frac{1}{4}\,\overline{\bar\nu_\lambda\, M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa} + \frac{ig}{2M\sqrt2}\phi^+\left(-m^\kappa_d(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\frac{ig}{2M\sqrt2}\phi^-\left(m^\lambda_d(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar u^\lambda_j u^\lambda_j) - \\
\frac{g}{2}\frac{m^\lambda_d}{M}H(\bar d^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar G^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar G^a G^b g^c_\mu + \\
\bar X^+(\partial^2 - M^2)X^+ + \bar X^-(\partial^2 - M^2)X^- + \bar X^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar X^0 X^- - \\
\partial_\mu\bar X^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar Y X^- - \partial_\mu\bar X^+ Y) + igc_w W^-_\mu(\partial_\mu\bar X^- X^0 - \\
\partial_\mu\bar X^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar X^- Y - \partial_\mu\bar Y X^+) + igc_w Z^0_\mu(\partial_\mu\bar X^+ X^+ - \\
\partial_\mu\bar X^- X^-) + igs_w A_\mu(\partial_\mu\bar X^+ X^+ - \\
\partial_\mu\bar X^- X^-) - \frac{1}{2}gM\left(\bar X^+ X^+ H + \bar X^- X^- H + \frac{1}{c_w^2}\bar X^0 X^0 H\right) + \frac{1-2c_w^2}{2c_w}igM\left(\bar X^+ X^0\phi^+ - \bar X^- X^0\phi^-\right) + \\
\frac{1}{2c_w}igM\left(\bar X^0 X^-\phi^+ - \bar X^0 X^+\phi^-\right) + igMs_w\left(\bar X^0 X^-\phi^+ - \bar X^0 X^+\phi^-\right) + \\
\frac{1}{2}igM\left(\bar X^+ X^+\phi^0 - \bar X^- X^-\phi^0\right) .
\end{gathered}
$$

$$\mathcal{L}_{SM} = -\tfrac12\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac14 g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \tfrac12 \partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac12 \partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)) -$$
$$igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)) - \tfrac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu -$$
$$Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac12\partial_\mu H\partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \tfrac12\partial_\mu\phi^0\partial_\mu\phi^0 -$$
$$\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h -$$
$$g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) -$$
$$\tfrac18 g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) -$$
$$gMW^+_\mu W^-_\mu H - \tfrac12 g\tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H -$$
$$\tfrac12 ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) +$$
$$\tfrac12 g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac12 g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) +$$
$$M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$
$$\tfrac14 g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac18 g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-\right) -$$
$$\tfrac12 g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac12 ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \tfrac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac12 ig_s\lambda^a_{ij}(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar e^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda(\gamma\partial + m_\nu^\lambda)\nu^\lambda - \bar u^\lambda_j(\gamma\partial +$$
$$m_u^\lambda)u^\lambda_j - \bar d^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu\left(-(\bar e^\lambda\gamma^\mu e^\lambda) + \tfrac23(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac13(\bar d^\lambda_j\gamma^\mu d^\lambda_j)\right) +$$
$$\tfrac{ig}{4c_w}Z^0_\mu\{(\bar\nu$$
$$(\bar u^\lambda_j\gamma^\mu(1 - \tfrac83 s$$
$$\tfrac{ig}{2M\sqrt2}\phi^-\,($$
$$\tfrac{g}{2}\tfrac{m_e^\lambda}{M}H($$
$$\tfrac14\bar\nu_\lambda M^R_{\lambda\kappa}(1$$
$$\tfrac{ig}{2M\sqrt2}\phi^-$$
$$\tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j$$
$$\bar X^+(\partial^2 - M^2)$$
$$\partial_\mu$$
$$\partial_\mu$$
$$\partial_\mu\bar X^- X^-) - \tfrac12$$
$$\tfrac{1}{2c_w}i$$

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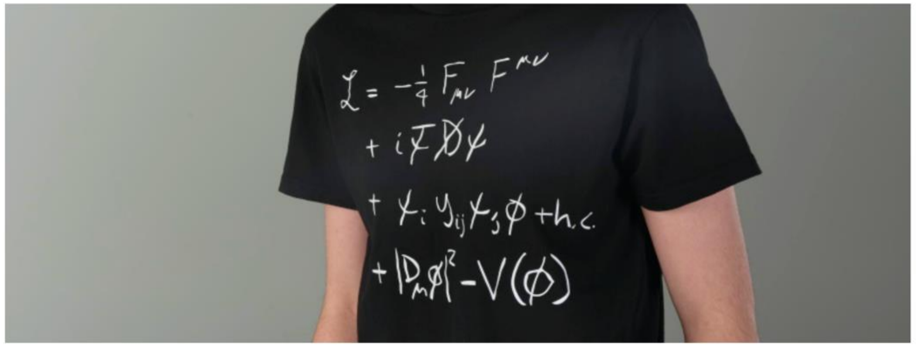
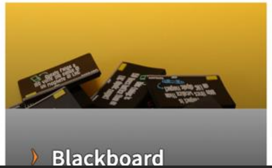
# Standard Model formula T-Shirt



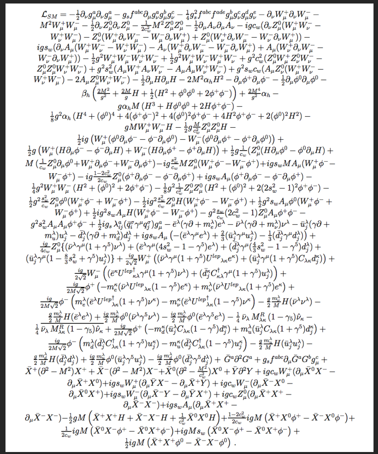

*"Lagrangian of the Standard Model of particle physics"*

**Other shop items**


$$\tfrac12 igM\left(\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0\right).$$

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4} g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left( \tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-) \right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8} g^2 \alpha_h \left(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\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2} ig \left( W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0) \right) + \\
\tfrac{1}{2} g \left( W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W^-_\mu (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H) \right) + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
M\left(\tfrac{1}{c_w} Z^0_\mu \partial_\mu \phi^0 + W^+_\mu \partial_\mu \phi^- + W^-_\mu \partial_\mu \phi^+\right) - ig \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w M A_\mu (W^+_\mu \phi^- - \\
W^-_\mu \phi^+) - ig \tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
\tfrac{1}{4} g^2 W^+_\mu W^-_\mu \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu \left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^-\right) - \\
\tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \tfrac{1}{2} ig^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \tfrac{1}{2} ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w}(2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- + \tfrac{1}{2} ig_s \lambda^a_{ij} (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu - \bar{e}^\lambda (\gamma\partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda (\gamma\partial + m^\lambda_\nu) \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + \\
m^\lambda_u) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + m^\lambda_d) d^\lambda_j + igs_w A_\mu \left( -(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j) \right) + \\
\tfrac{ig}{4c_w} Z^0_\mu \{ (\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}^\lambda_j \gamma^\mu (\tfrac{4}{3} s_w^2 - 1 - \gamma^5) d^\lambda_j) + \\
(\bar{u}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s_w^2 + \gamma^5) u^\lambda_j) \} + \tfrac{ig}{2\sqrt{2}} W^+_\mu \left( (\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) {U^{lep}}_{\lambda\kappa} e^\kappa) + (\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j) \right) + \\
\tfrac{ig}{2\sqrt{2}} W^-_\mu \left( (\bar{e}^\kappa {U^{lep}}^\dagger_{\kappa\lambda} \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda} \gamma^\mu (1+\gamma^5) u^\lambda_j) \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^+ \left( -m^\kappa_e (\bar{\nu}^\lambda {U^{lep}}_{\lambda\kappa} (1-\gamma^5) e^\kappa) + m^\lambda_\nu (\bar{\nu}^\lambda {U^{lep}}_{\lambda\kappa} (1+\gamma^5) e^\kappa) \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left( m^\lambda_e (\bar{e}^\lambda {U^{lep}}^\dagger_{\lambda\kappa} (1+\gamma^5) \nu^\kappa) - m^\kappa_\nu (\bar{e}^\lambda {U^{lep}}^\dagger_{\lambda\kappa} (1-\gamma^5) \nu^\kappa) \right) - \tfrac{g}{2} \tfrac{m^\lambda_\nu}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
\tfrac{g}{2} \tfrac{m^\lambda_e}{M} H (\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2} \tfrac{m^\lambda_\nu}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \tfrac{ig}{2} \tfrac{m^\lambda_e}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \tfrac{1}{4} \bar{\nu}_\lambda M^R_{\lambda\kappa} (1 - \gamma_5) \hat{\nu}_\kappa - \\
\tfrac{1}{4} \bar{\nu}_\lambda M^R_{\lambda\kappa} (1 - \gamma_5) \hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}} \phi^+ \left( -m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j) \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left( m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1-\gamma^5) u^\kappa_j) \right) - \tfrac{g}{2} \tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2} \tfrac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2} \tfrac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu + \\
\bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \\
\partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \\
\partial_\mu \bar{X}^0 X^+) + igs_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} gM \left( \bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H \right) + \tfrac{1-2c_w^2}{2c_w} igM \left( \bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^- \right) + \\
\tfrac{1}{2c_w} igM \left( \bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^- \right) + igMs_w \left( \bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^- \right) + \\
\tfrac{1}{2} igM \left( \bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0 \right) .
\end{gathered}
$$



$10^{-14}$ $10^{-4}$ $10^{4}$ $10^{14}$ $10^{26}$

Meters

## Taylor Series

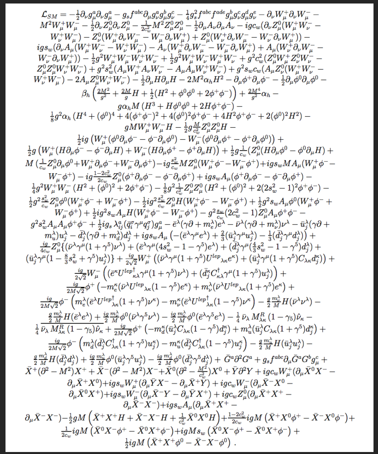
$$f(x \pm h) = f(x) \pm h\frac{df}{dx} + \frac{1}{2!}h^2\frac{d^2 f}{dx^2} \pm \frac{1}{3!}h^3\frac{d^3 f}{dx^3} + O(h^4)$$

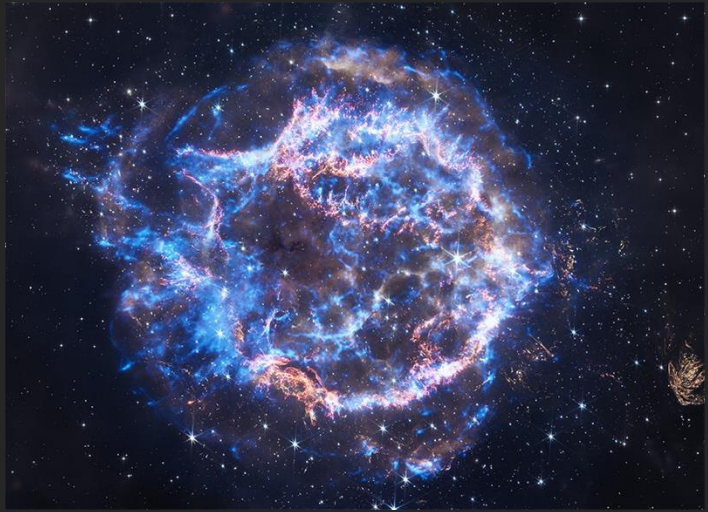
## Perturbation Theory

$$E_n = E_n^{(0)} + \lambda E_n^{(1)} + \lambda^2 E_n^{(2)} + \cdots$$

$$|n\rangle = \left|n^{(0)}\right\rangle + \lambda\left|n^{(1)}\right\rangle + \lambda^2\left|n^{(2)}\right\rangle + \cdots$$

## Renormalization and other Dimensionality Reduction Methods





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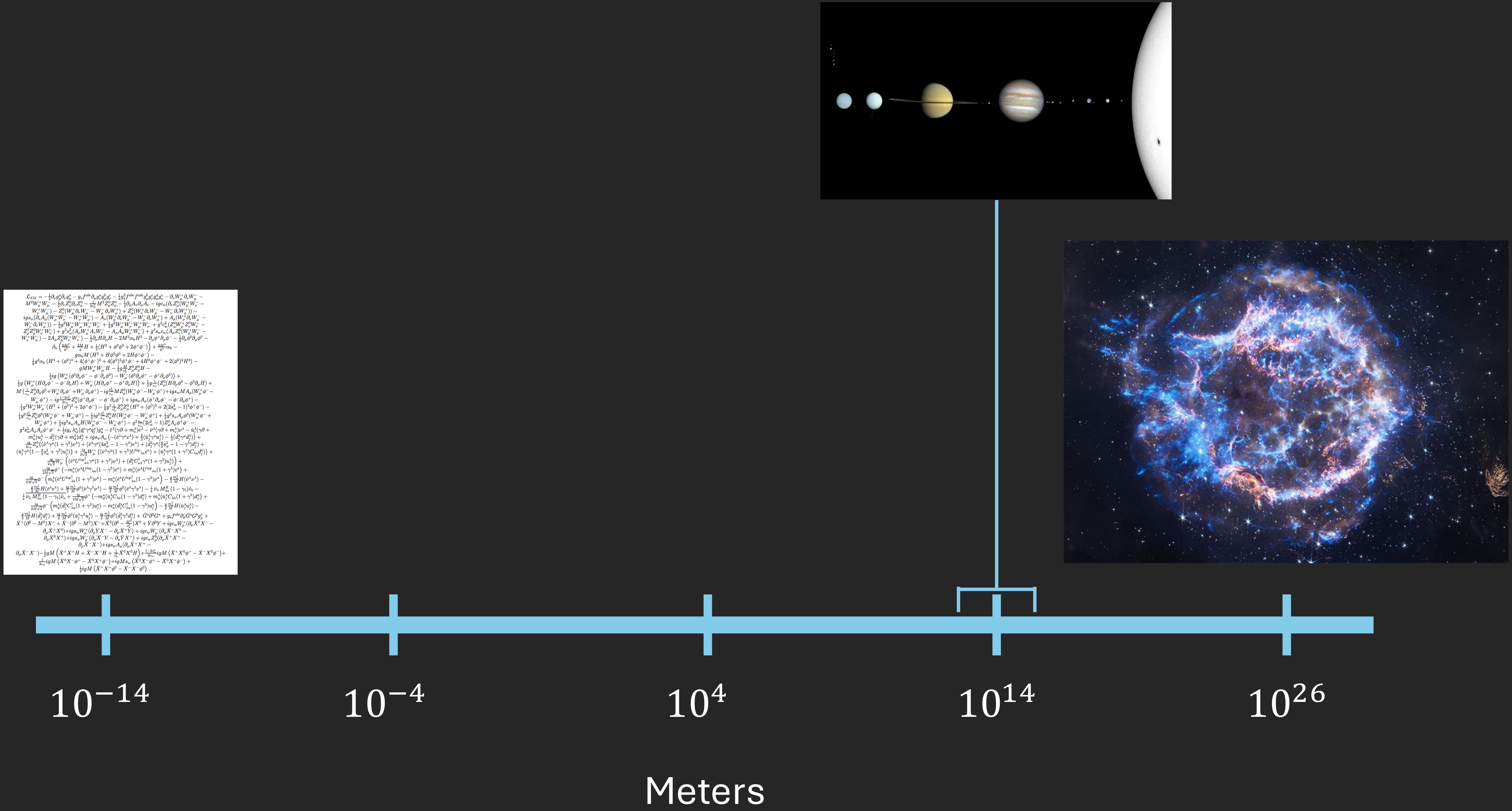
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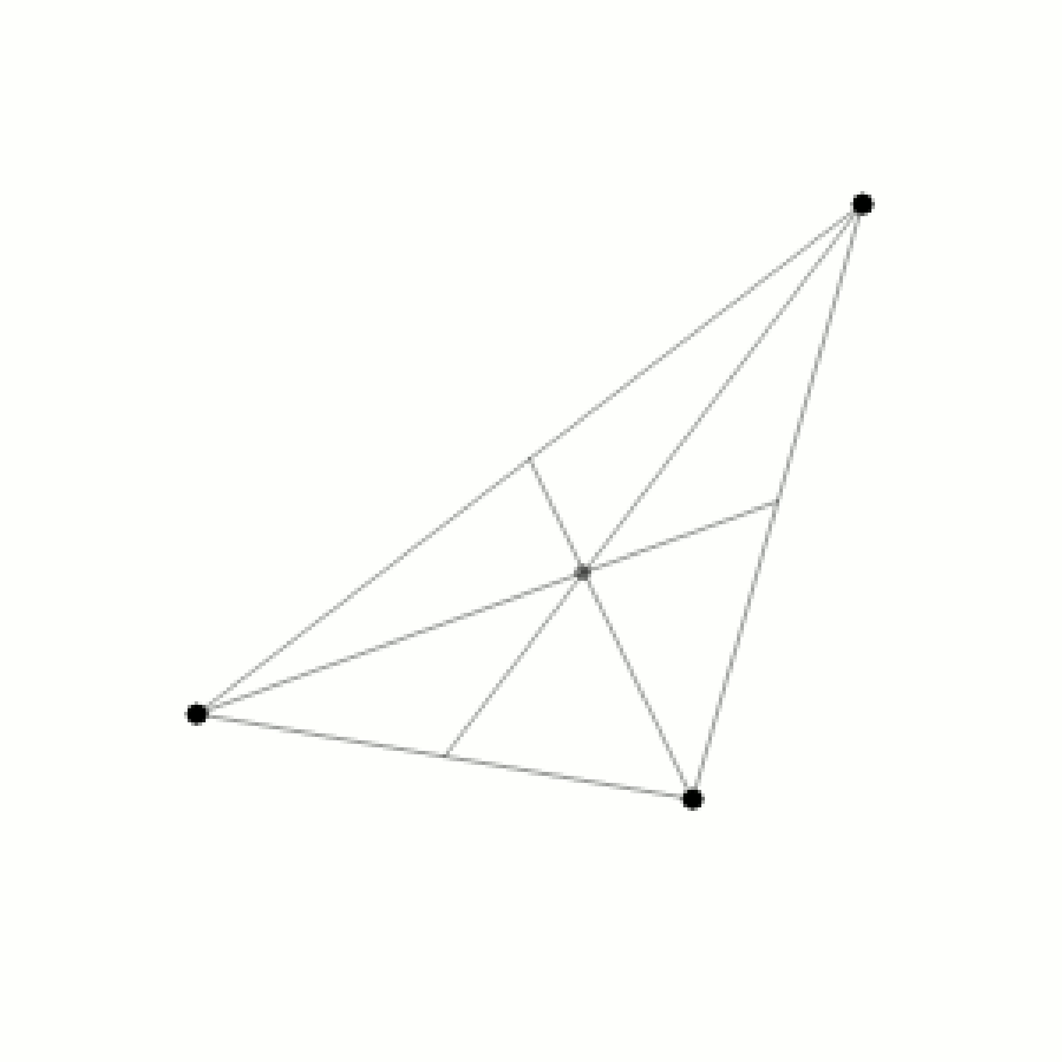
# But can you solve this?



**Three-body problem** equations (classical)

$$\ddot{\mathbf{r}}_1 = -Gm_2 \frac{\mathbf{r}_1 - \mathbf{r}_2}{|\mathbf{r}_1 - \mathbf{r}_2|^3} - Gm_3 \frac{\mathbf{r}_1 - \mathbf{r}_3}{|\mathbf{r}_1 - \mathbf{r}_3|^3},$$

$$\ddot{\mathbf{r}}_2 = -Gm_3 \frac{\mathbf{r}_2 - \mathbf{r}_3}{|\mathbf{r}_2 - \mathbf{r}_3|^3} - Gm_1 \frac{\mathbf{r}_2 - \mathbf{r}_1}{|\mathbf{r}_2 - \mathbf{r}_1|^3},$$

$$\ddot{\mathbf{r}}_3 = -Gm_1 \frac{\mathbf{r}_3 - \mathbf{r}_1}{|\mathbf{r}_3 - \mathbf{r}_1|^3} - Gm_2 \frac{\mathbf{r}_3 - \mathbf{r}_2}{|\mathbf{r}_3 - \mathbf{r}_2|^3}.$$

# Three-body problem

Article Talk

From Wikipedia, the free encyclopedia

*This article is about the physics theory. For other uses, see Three-body problem*

**The accessibility of this article is in question.** Relevant
the talk page. *(June 2024)*

**dy problem** equations (classical)

$$Gm_2\frac{\mathbf{r}_1-\mathbf{r}_2}{|\mathbf{r}_1-\mathbf{r}_2|^3}-Gm_3\frac{\mathbf{r}_1-\mathbf{r}_3}{|\mathbf{r}_1-\mathbf{r}_3|^3},$$

$$Gm_3\frac{\mathbf{r}_2-\mathbf{r}_3}{|\mathbf{r}_2-\mathbf{r}_3|^3}-Gm_1\frac{\mathbf{r}_2-\mathbf{r}_1}{|\mathbf{r}_2-\mathbf{r}_1|^3},$$

$$Gm_1\frac{\mathbf{r}_3-\mathbf{r}_1}{|\mathbf{r}_3-\mathbf{r}_1|^3}-Gm_2\frac{\mathbf{r}_3-\mathbf{r}_2}{|\mathbf{r}_3-\mathbf{r}_2|^3}.$$

In physics, specifically classical mechanics, the **three-body problem** involves taking the initial positions and velocities (or momenta) of three point masses that orbit each other in space and calculating their subsequent trajectories using Newton's laws of motion and Newton's law of universal gravitation.[1]

Unlike the two-body problem, the three-body problem has no general closed-form solution.[1] When three bodies orbit each other, the resulting dynamical system is chaotic for most initial conditions, and the only way to predict the motions of the bodies is to calculate them using numerical methods.

# Three-body problem

Article Talk

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## 3 Body Problem

TV-MA TV Series • 2024 • Adventure / Drama • IMDb 7.5 / 10

A fateful decision made in 1960s China reverberates in the present, where a group of scientists partner with a detective to confront an existential planetary threat.

Cast Where To Watch


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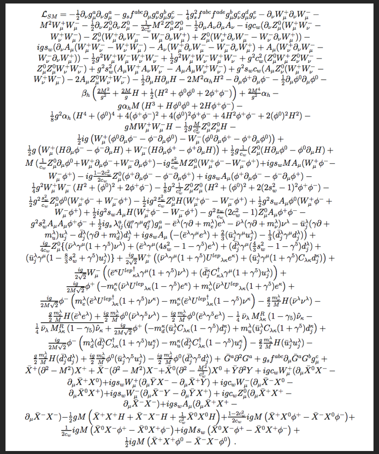

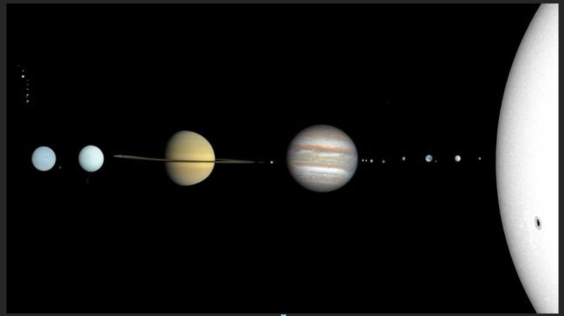

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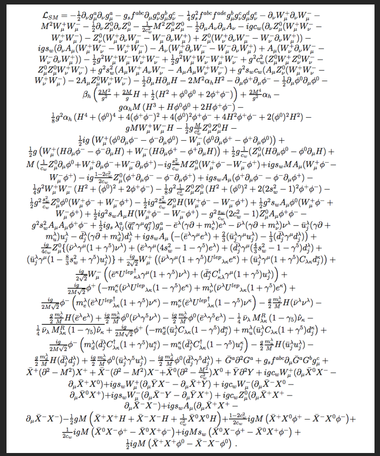

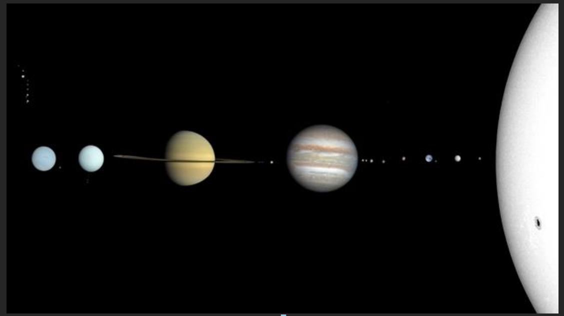

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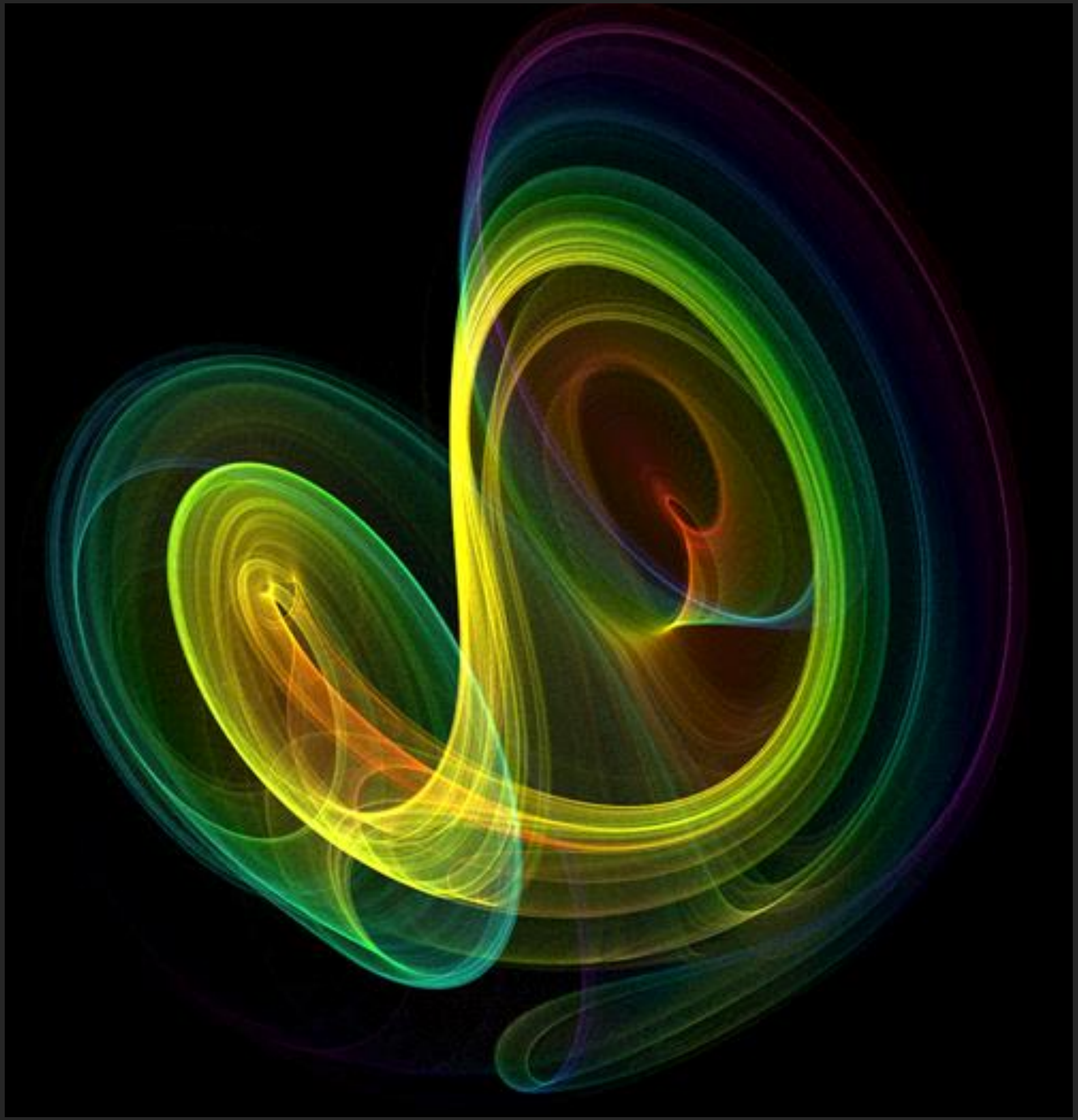
Meters

# Or this?



**Atmospheric Convection**
**Lorentz System**

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \sigma(y - x),$$

$$\frac{\mathrm{d}y}{\mathrm{d}t} = x(\rho - z) - y,$$

$$\frac{\mathrm{d}z}{\mathrm{d}t} = xy - \beta z.$$

# What do I mean by “we can’t solve these equations”, I’ve just shown some pretty graphs right?

(You can do that too, just download python and ask ChatGPT to write the code for you)

$$\begin{aligned}
\ddot{\mathbf{r}}_1 &= -Gm_2\frac{\mathbf{r}_1-\mathbf{r}_2}{|\mathbf{r}_1-\mathbf{r}_2|^3} - Gm_3\frac{\mathbf{r}_1-\mathbf{r}_3}{|\mathbf{r}_1-\mathbf{r}_3|^3},\\
\ddot{\mathbf{r}}_2 &= -Gm_3\frac{\mathbf{r}_2-\mathbf{r}_3}{|\mathbf{r}_2-\mathbf{r}_3|^3} - Gm_1\frac{\mathbf{r}_2-\mathbf{r}_1}{|\mathbf{r}_2-\mathbf{r}_1|^3},\\
\ddot{\mathbf{r}}_3 &= -Gm_1\frac{\mathbf{r}_3-\mathbf{r}_1}{|\mathbf{r}_3-\mathbf{r}_1|^3} - Gm_2\frac{\mathbf{r}_3-\mathbf{r}_2}{|\mathbf{r}_3-\mathbf{r}_2|^3}.
\end{aligned}$$

$$\begin{aligned}
\frac{\mathrm{d}x}{\mathrm{d}t} &= \sigma(y-x),\\
\frac{\mathrm{d}y}{\mathrm{d}t} &= x(\rho-z)-y,\\
\frac{\mathrm{d}z}{\mathrm{d}t} &= xy-\beta z.
\end{aligned}$$

Linear

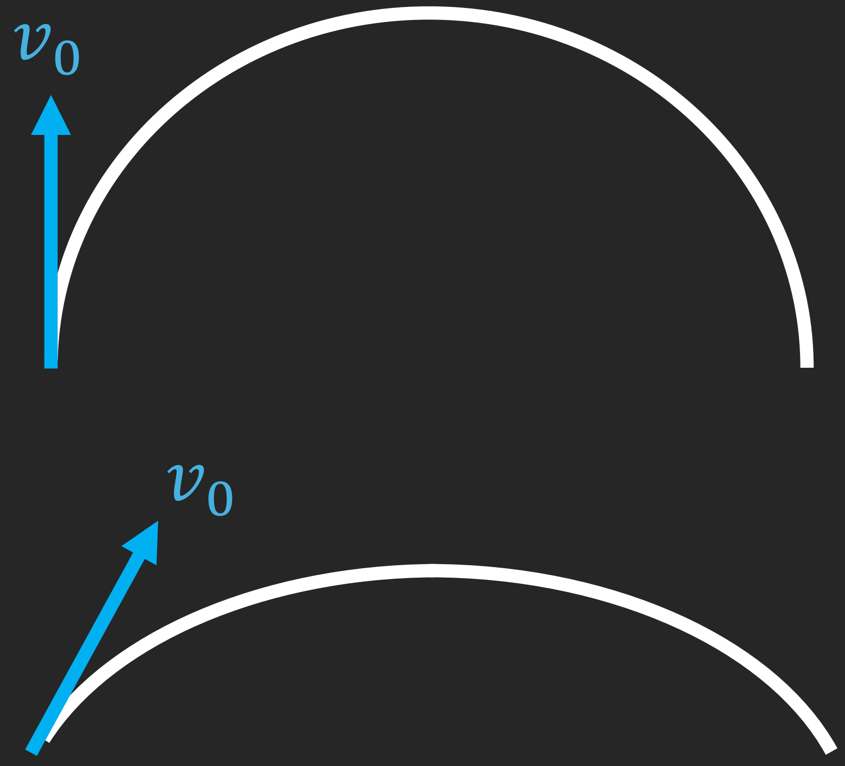
Non-linear

But every simulation is completely unique, change the initial parameters just a tiny bit, and everything breaks down

In other words, you have to restart your simulation all over again

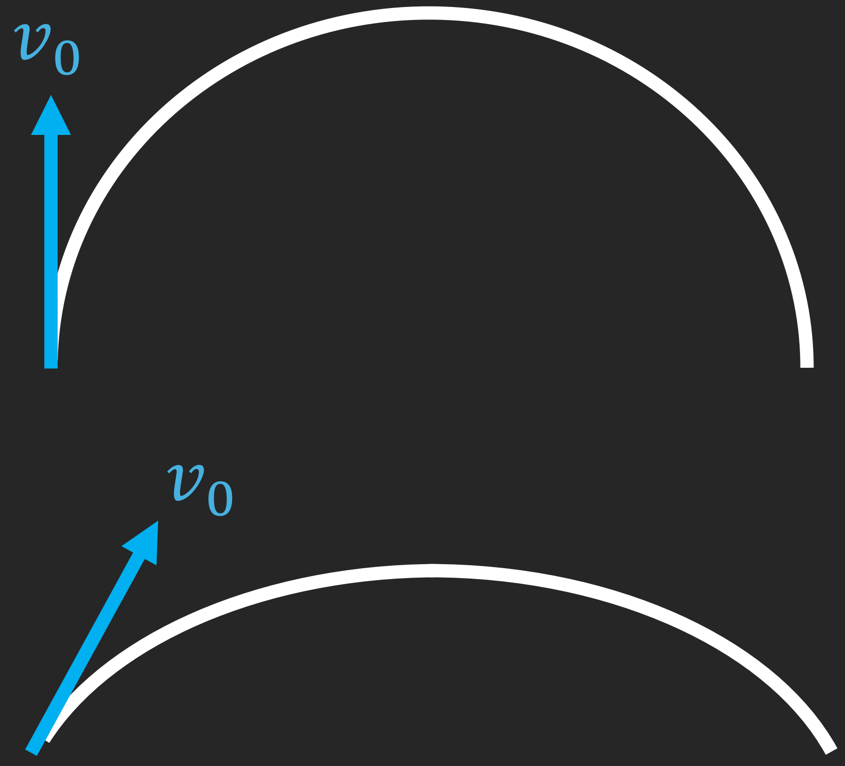
# Solvable System: Projectile motion

Given some initial condition ($v_0$)



# Solvable System: Projectile motion

Given some initial condition ($v_0$), we can solve the equations of motion and calculate where the cannon ball will be at each point in time




**Closed form solution**

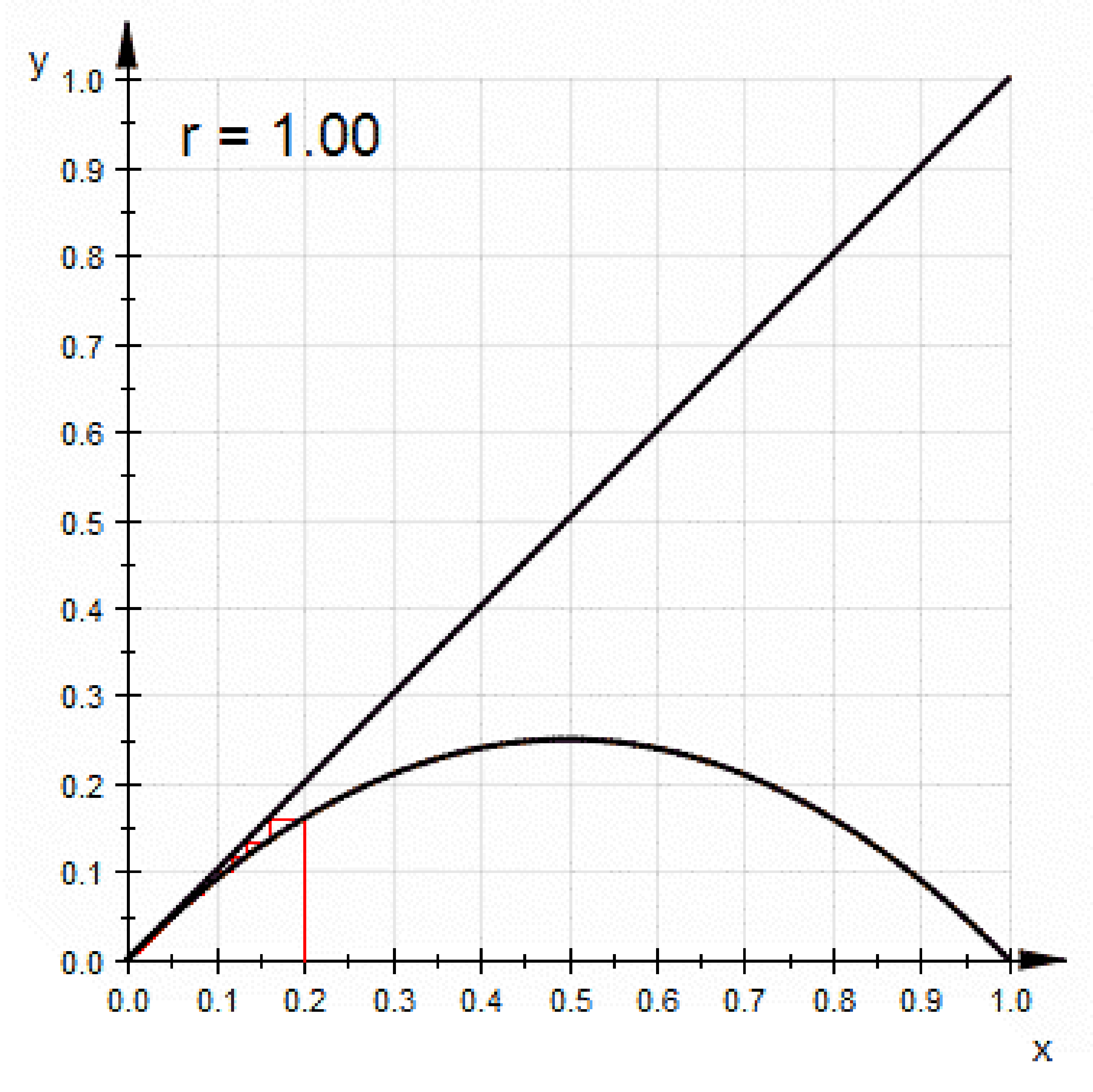
$$x = v_0 t \cos(\theta),$$
$$y = v_0 t \sin(\theta) - \frac{1}{2} g t^2.$$

# Non solvable system: Logistic map

We can't even solve the simplest complex system!

$$x_{n+1} = rx_n(1 - x_n),$$

Start with any value of x, if r is large enough every Single simulation will be completely different!

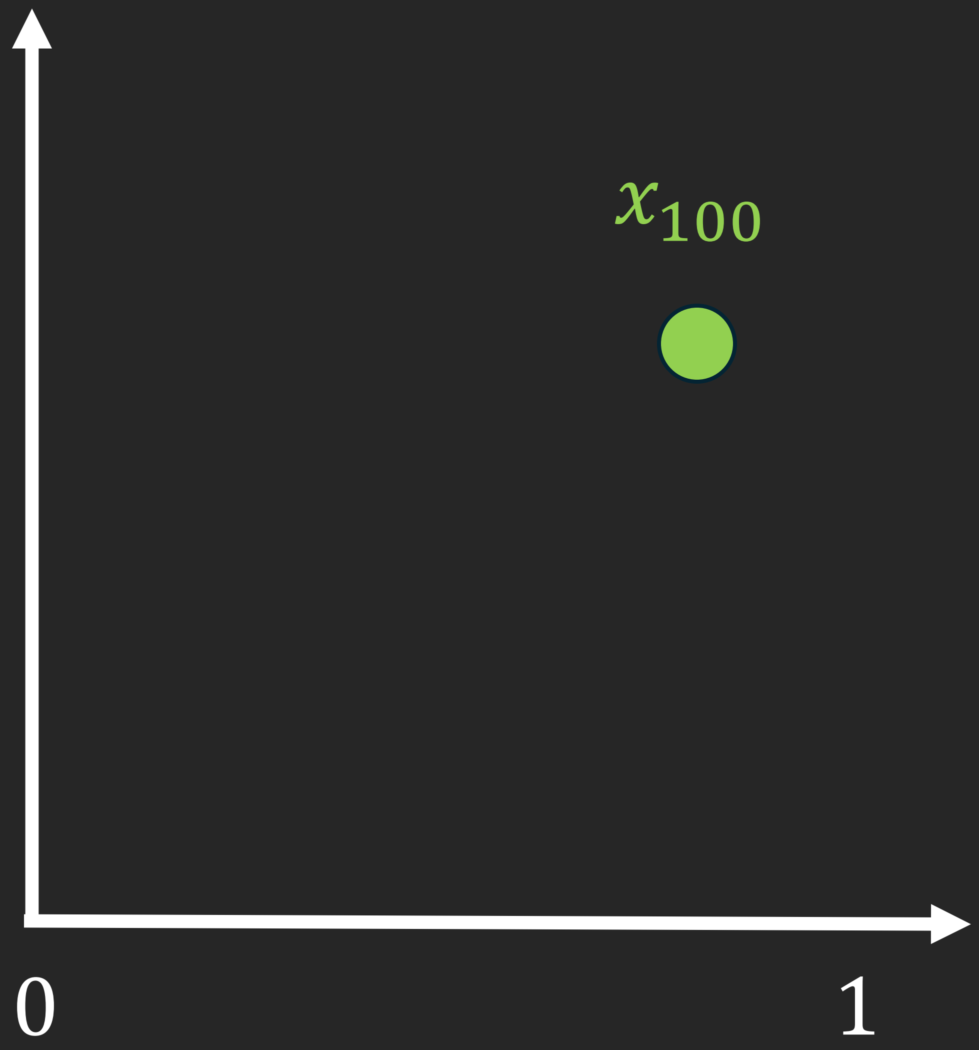


# Non solvable system: Logistic map

$$x_{n+1} = r x_n (1 - x_n),$$

Start with any value of x, if r is large enough every
Single simulation will be completely different!

$$x_0 = 0.2 \rightarrow x_{100} = 0.9$$



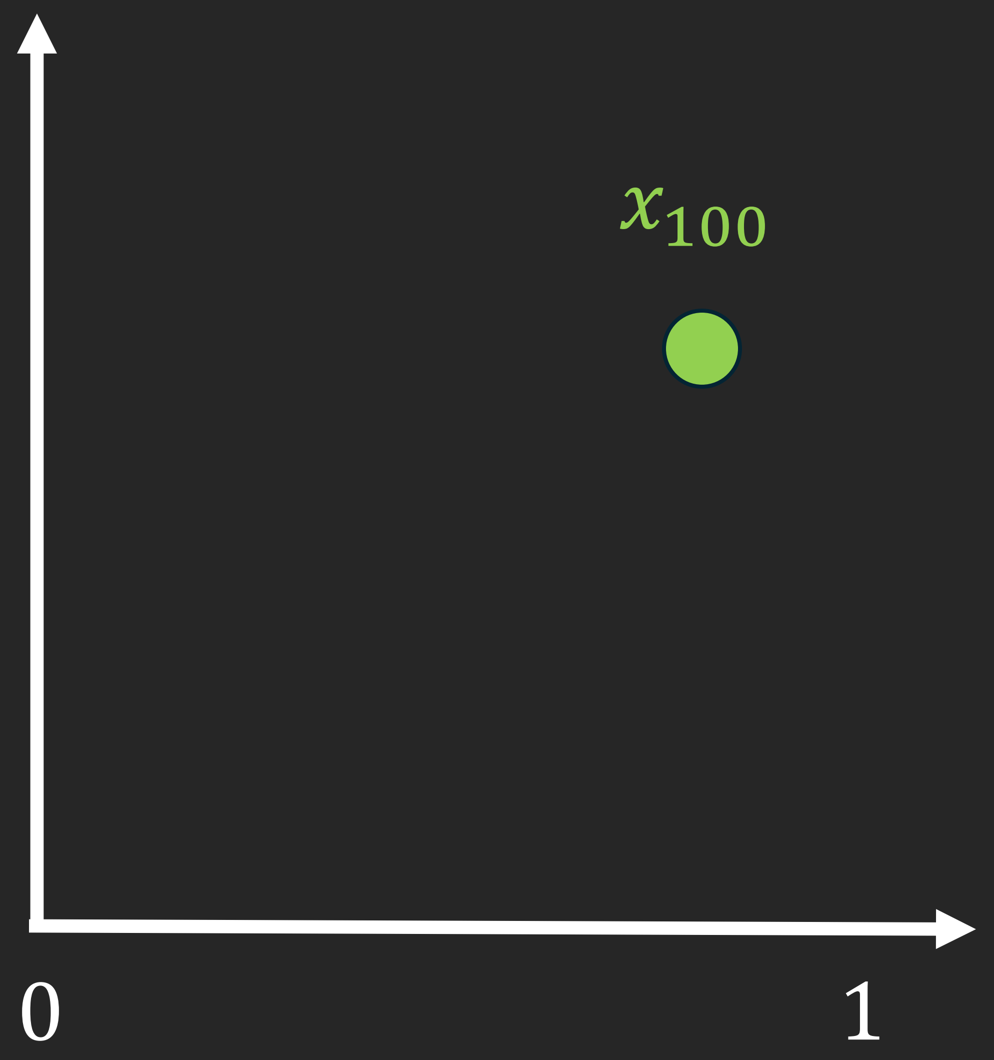
# Non solvable system: Logistic map

$$x_{n+1} = r x_n (1 - x_n),$$

Start with any value of x, if r is large enough every
Single simulation will be completely different!

$$x_0 = 0.2 \rightarrow x_{100} = 0.9$$

$$x_0 = 0.200000001 \rightarrow$$



# Non solvable system: Logistic map

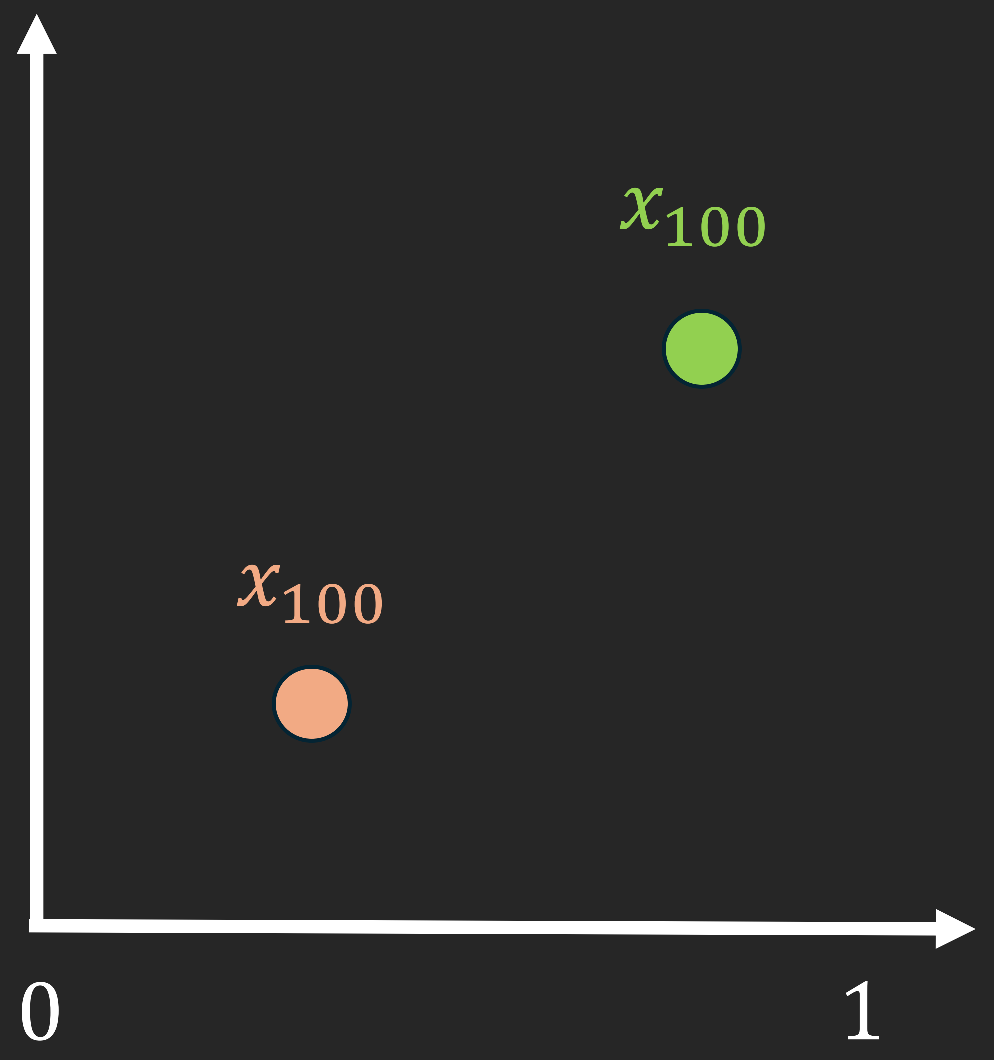
$$x_{n+1} = rx_n(1 - x_n),$$

Start with any value of x, if r is large enough every
Single simulation will be completely different!

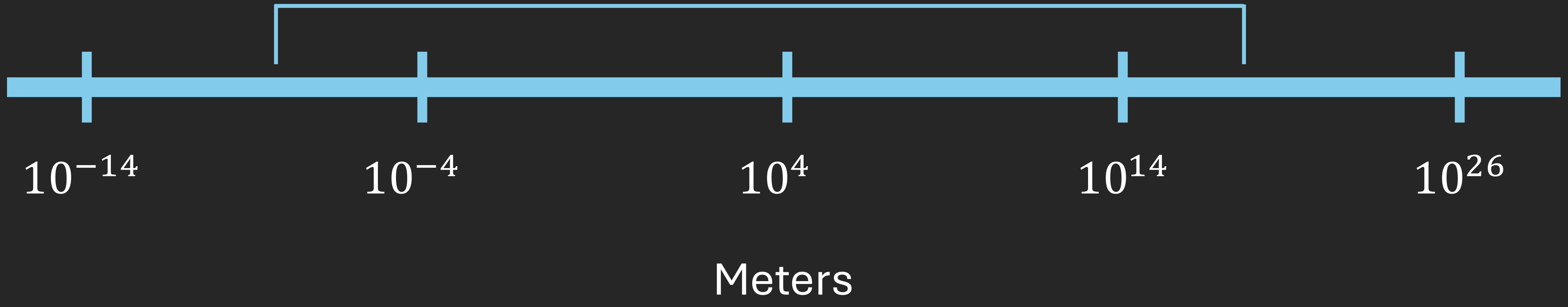
Now you can say you actually understand
what is known as the “buttlerfly effect”

$$x_0 = 0.2 \rightarrow x_{100} = 0.9$$

$$x_0 = 0.200000001 \rightarrow x_{100} = 0.3$$



But pretty much everything around us,
“at our scale”,
is described by nonlinear equations

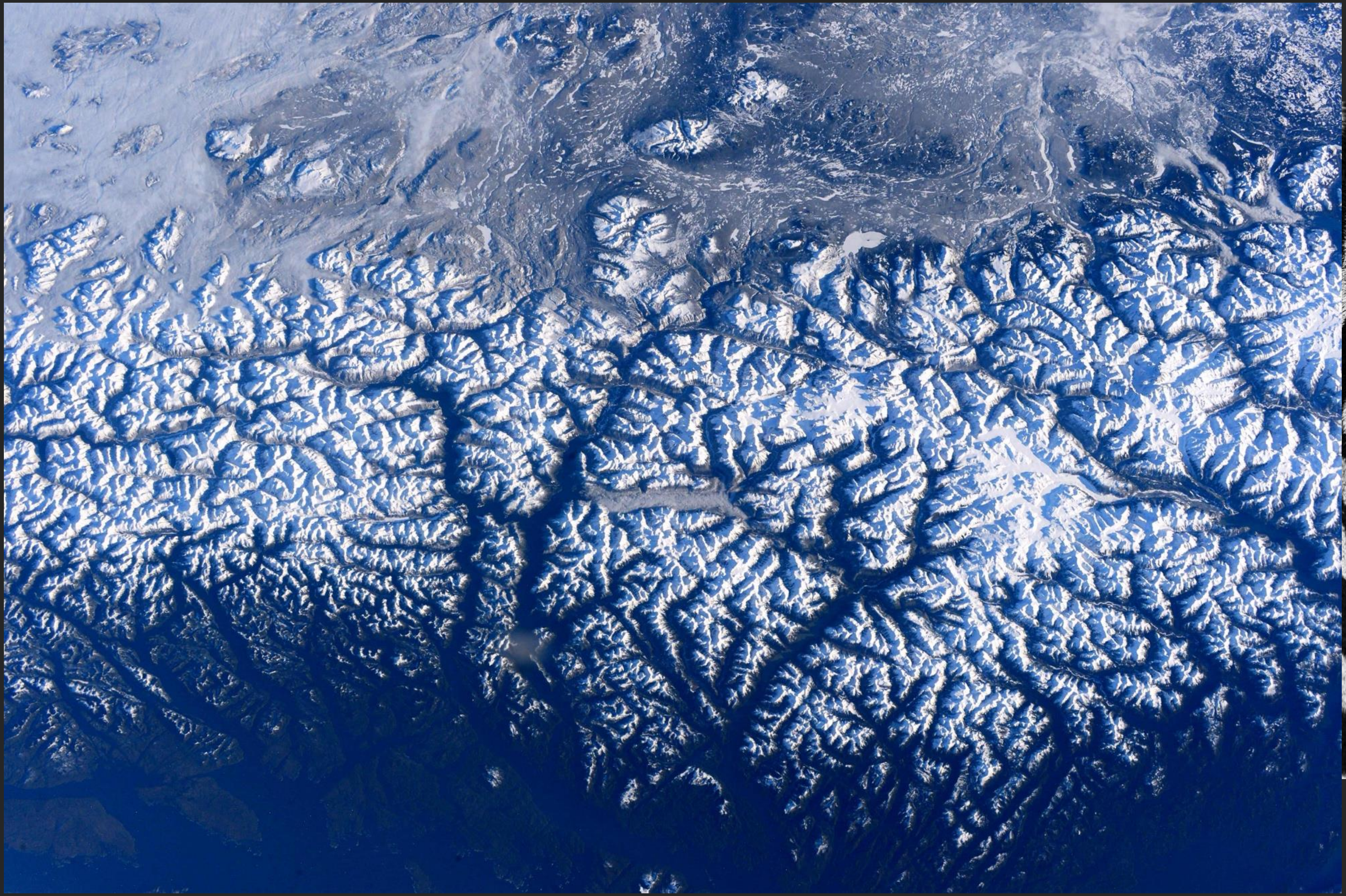


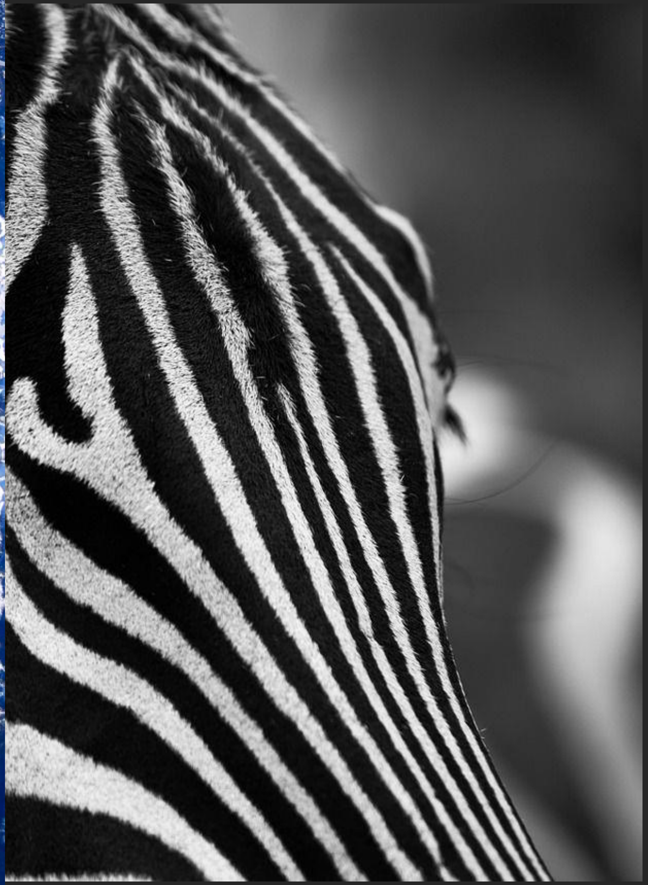
# Nature deals with nonlinear equations pretty well

Even though every single seed is slightly different, it evolves into a functioning plant

# Nature deals with nonlinear equations pretty well

# Nature deals with nonlinear equations pretty well





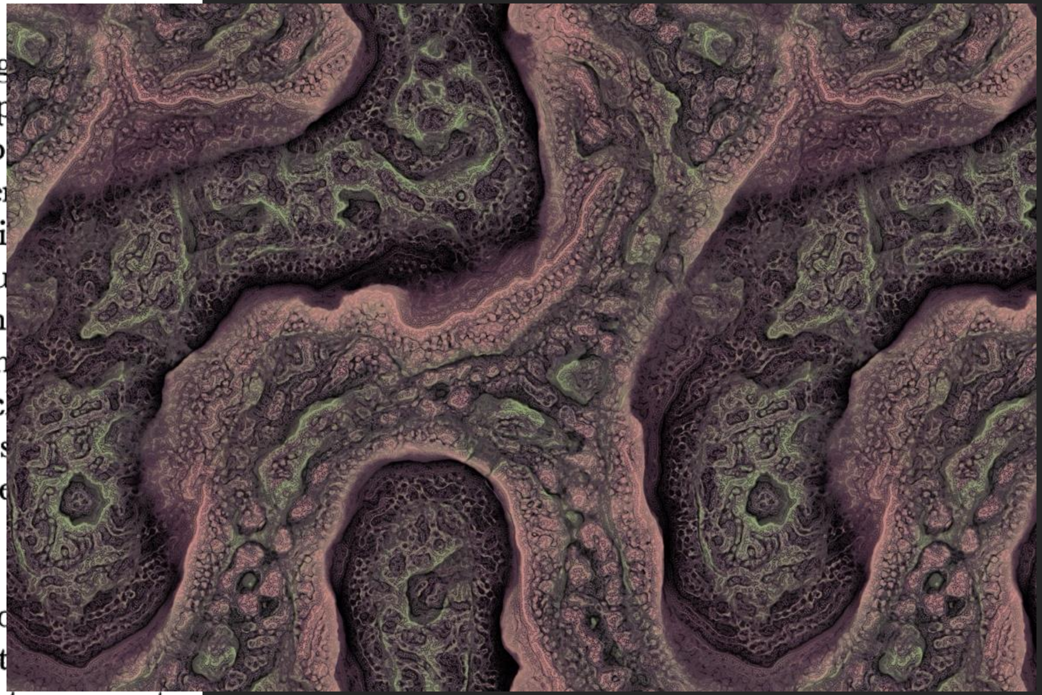
# THE CHEMICAL BASIS OF MORPHOGENESIS

By A. M. TURING, F.R.S. *University of Manchester*

(*Received* 9 *November* 1951—*Revised* 15 *March* 1952)

It is suggested that a system of chemical substances, called morphogens, reacting tog diffusing through a tissue, is adequate to account for the main phenomena of morp Such a system, although it may originally be quite homogeneous, may later develop or structure due to an instability of the homogeneous equilibrium, which is trigge random disturbances. Such reaction-diffusion systems are considered in some detail i of an isolated ring of cells, a mathematically convenient, though biologically unusu The investigation is chiefly concerned with the onset of instability. It is found that th essentially different forms which this may take. In the most interesting form station appear on the ring. It is suggested that this might account, for instance, for the tentac on *Hydra* and for whorled leaves. A system of reactions and diffusion on a sphere is sidered. Such a system appears to account for gastrulation. Another reaction syste dimensions gives rise to patterns reminiscent of dappling. It is also suggested that waves in two dimensions could account for the phenomena of phyllotaxis.

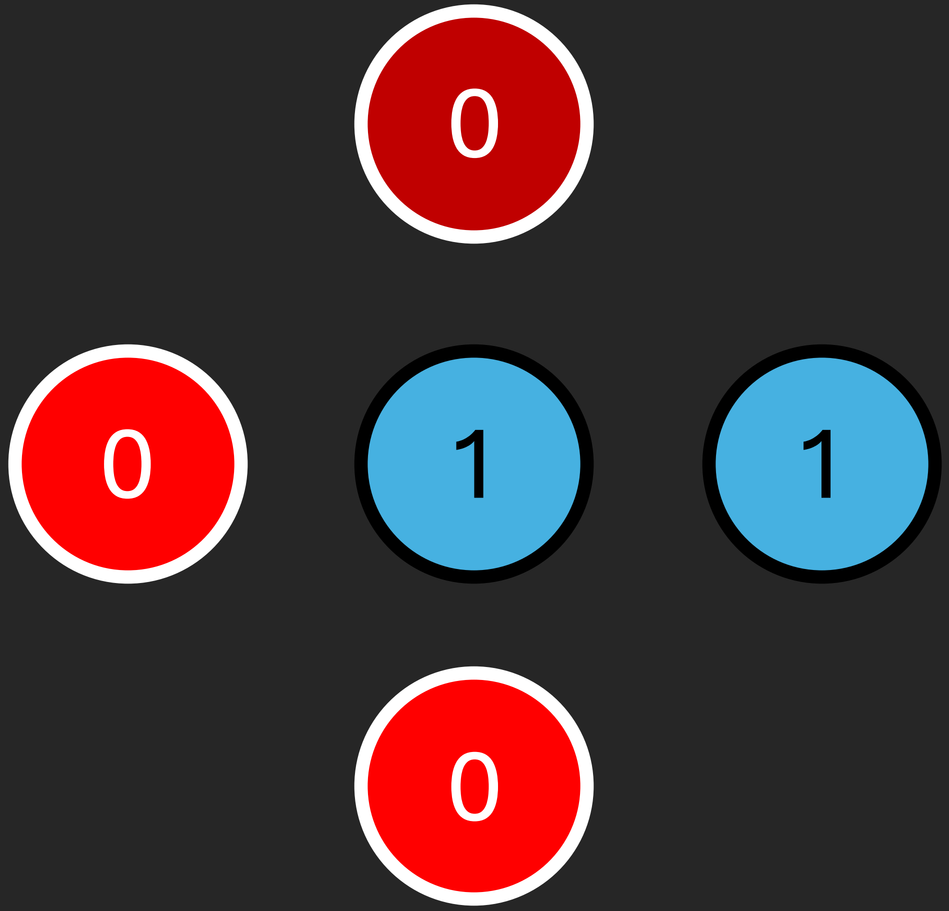
The purpose of this paper is to discuss a possible mechanism by which the genes o may determine the anatomical structure of the resulting organism. The theory does not new hypotheses; it merely suggests that certain well-known physical laws are sufficient to account for many of the facts. The full understanding of the paper requires a good knowledge of mathematics, some biology, and some elementary chemistry. Since readers cannot be expected to be experts in all of these subjects, a number of elementary facts are explained, which can be found in text-books, but whose omission would make the paper difficult reading.



https://rreusser.github.io/multiscale-turing-pattern-gallery/

# The Ising model

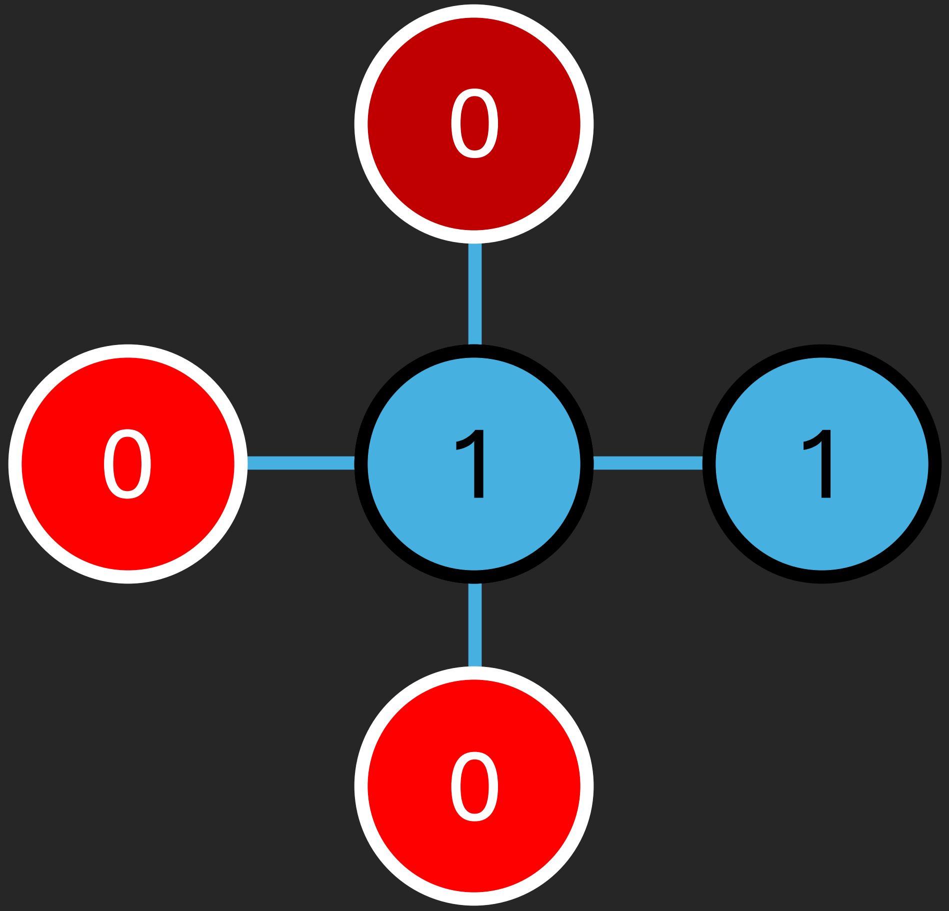
Consider a very simple object that can only take two values, either $\sigma = 0 \text{ or } 1$



# The Ising model

Consider a very simple object that can only take two values, either $\sigma = 0\ or\ 1$

Now make them interact



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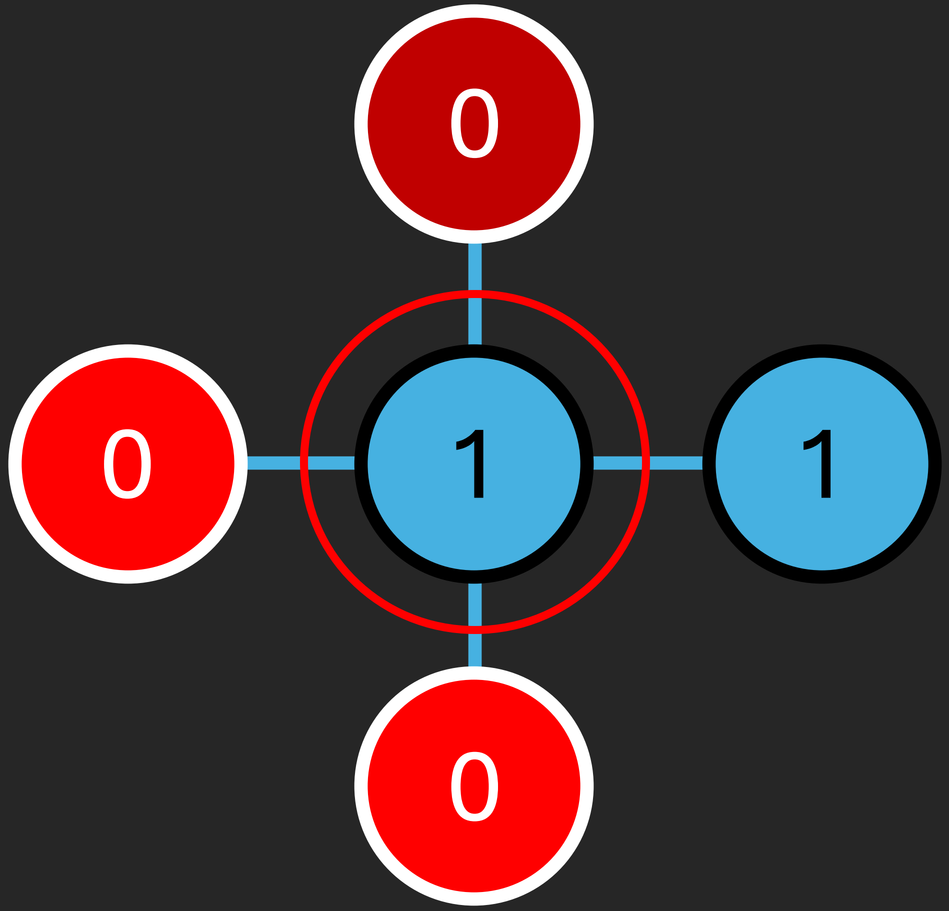
Finally, choose a “temperature” (basically, a parameter that controls how easily an object changes its value).



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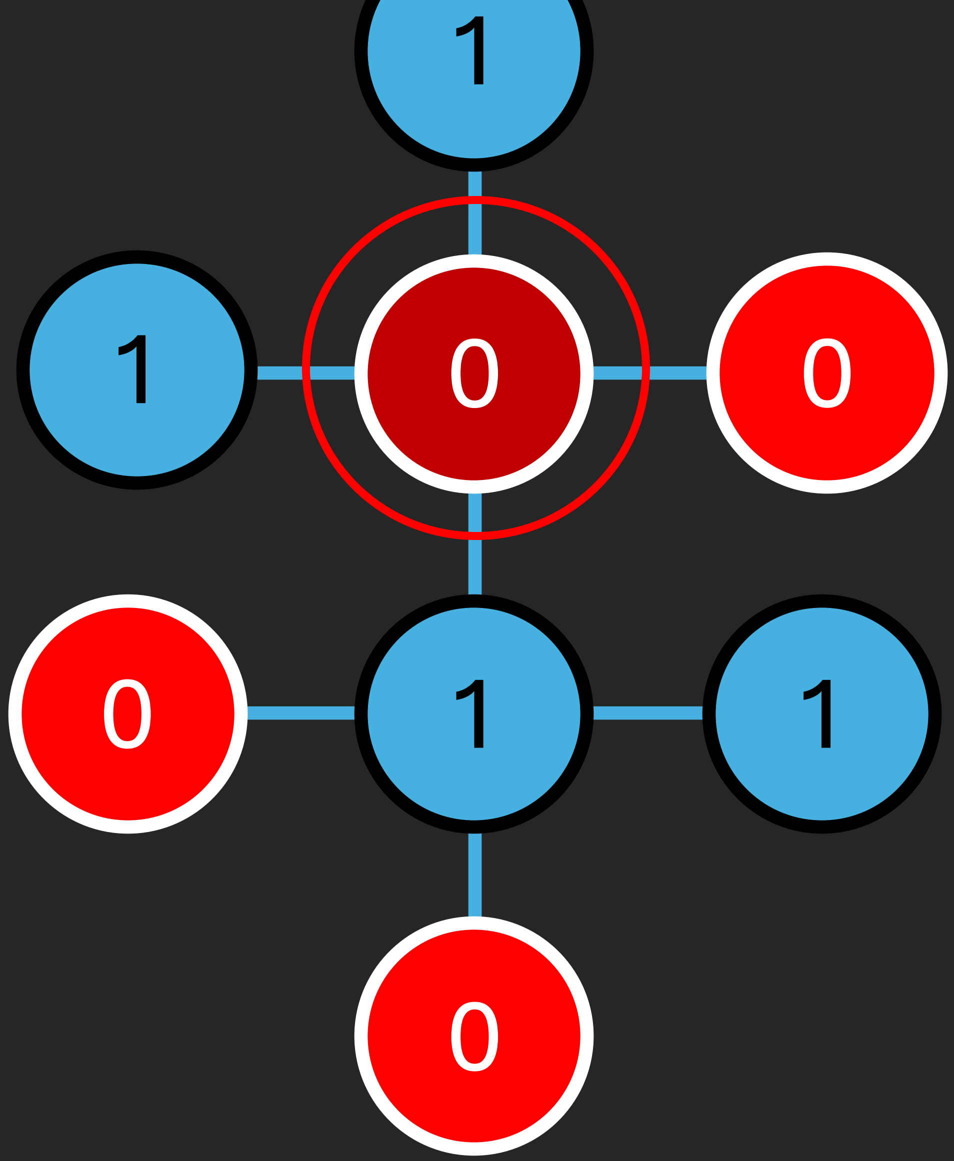
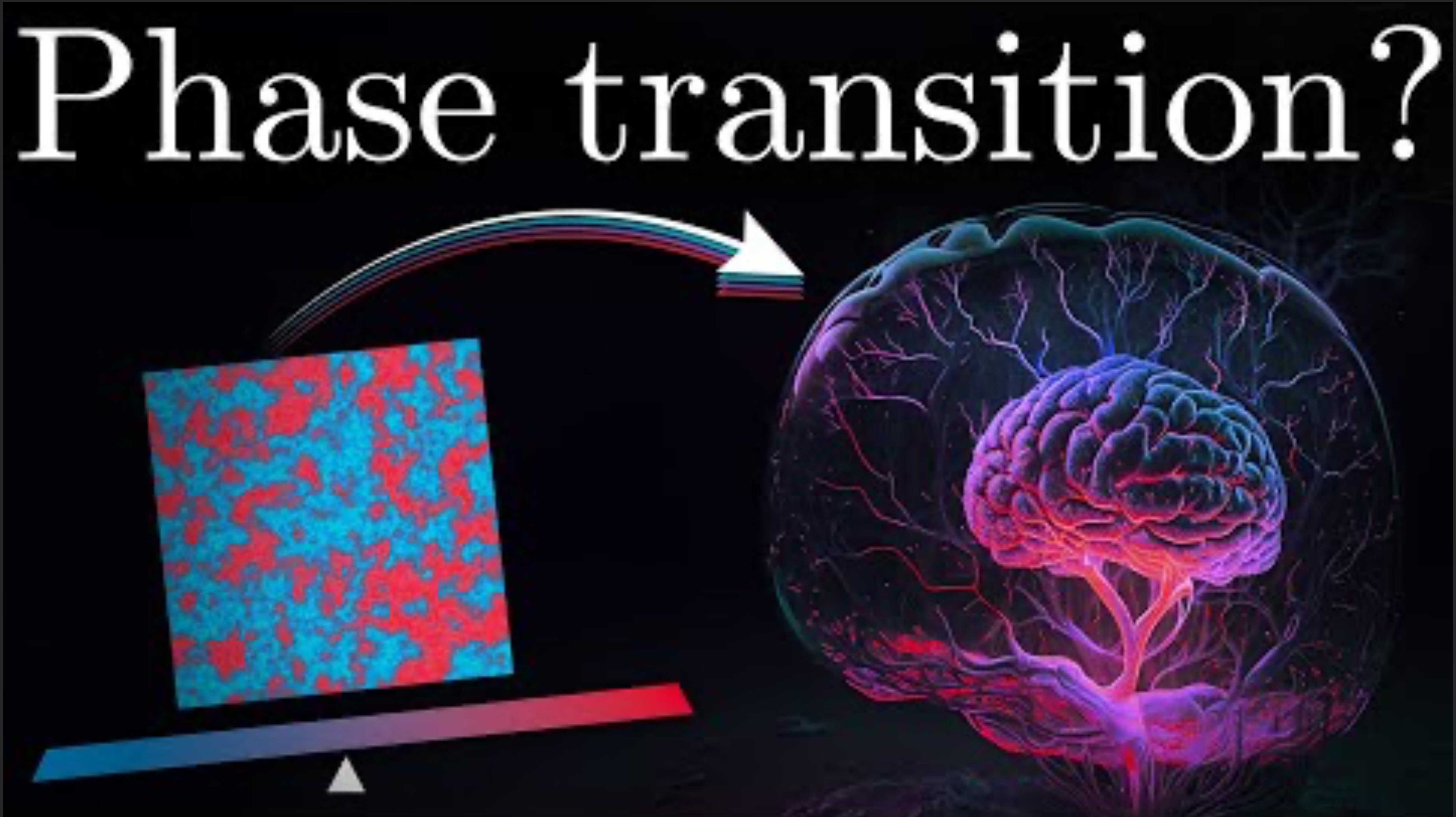
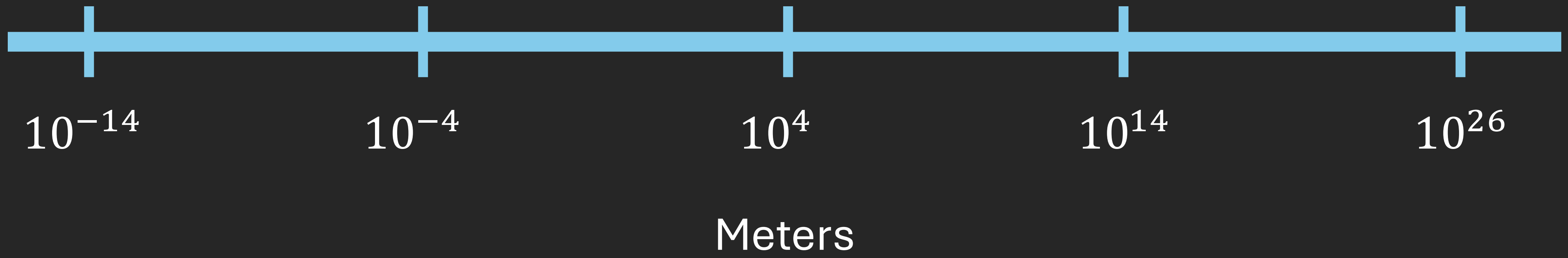
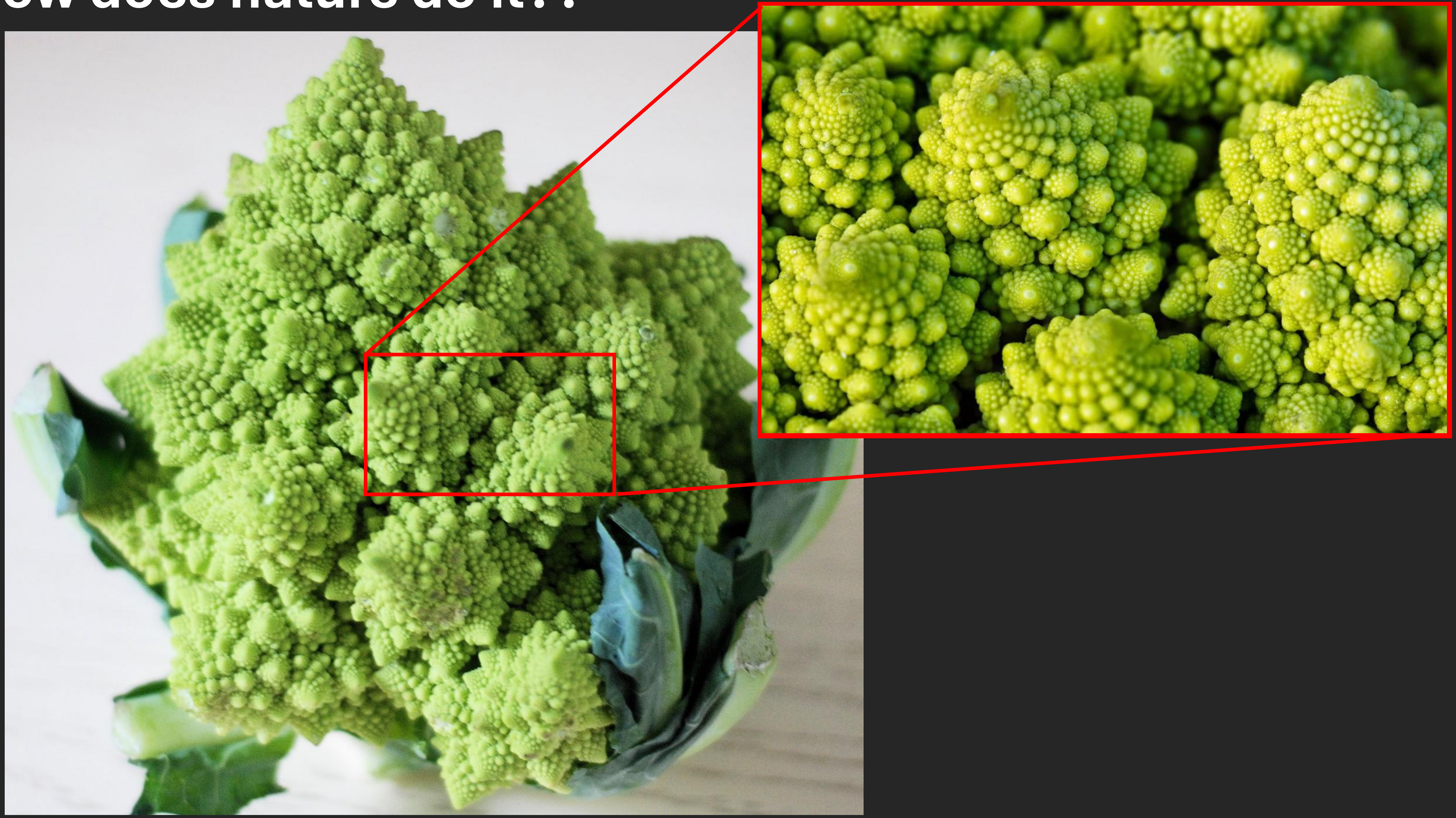



Phase transition?

At the critical point, we don’t care about scales anymore!



# But how does nature do it??



Things in Nature seem to self-organize at a critical point, in which hierarchies emerge and a “characteristic scale” ceases to exist

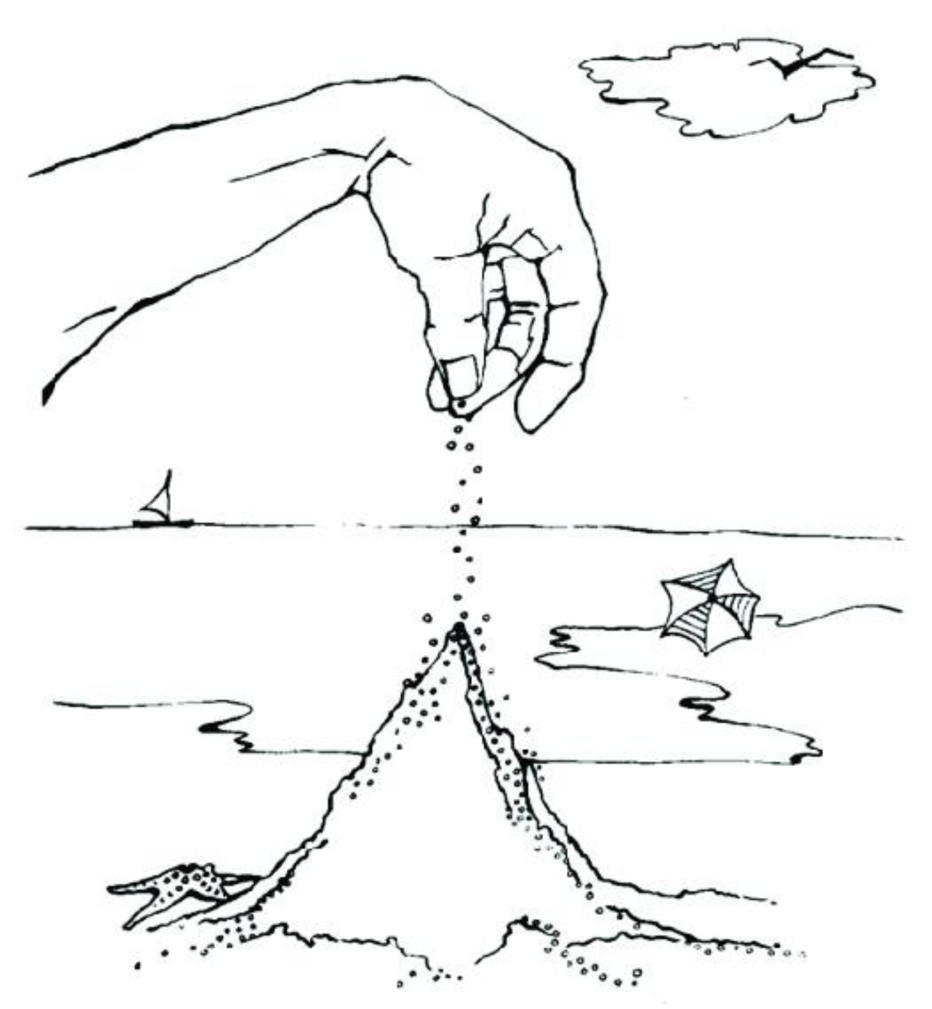
# Self-organized criticality: An explanation of the 1/*f* noise

Per Bak, Chao Tang, and Kurt Wiesenfeld
Phys. Rev. Lett. **59**, 381 – Published 27 July 1987



## ABSTRACT

We show that dynamical systems with spatial degrees of freedom naturally evolve into a self-organized critical point. Flicker noise, or *1/f* noise, can be identified with the dynamics of the critical state. This picture also yields insight into the origin of fractal objects.



## Self-Organized Criticality

Systems made of many degrees of freedom (**that interact non-linearly**) which **self-organize** into a critical point in which **scale invariant** phenomena occur

# Part 3: Criticality in Brains
# Last Example, I promise

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Systems made of many degrees of freedom (**that interact non-linearly**) which **self-organize** into a critical point in which **scale invariant** phenomena occur

# Part 3: Criticality in Brains
# Last Example, I promise

Everyday you wake up and
you are still the same person!

Systems made of many degrees of freedom (**that interact non-linearly**) which **self-organize** into a critical point in which **scale invariant** phenomena occur

# Part 3: Criticality in Brains

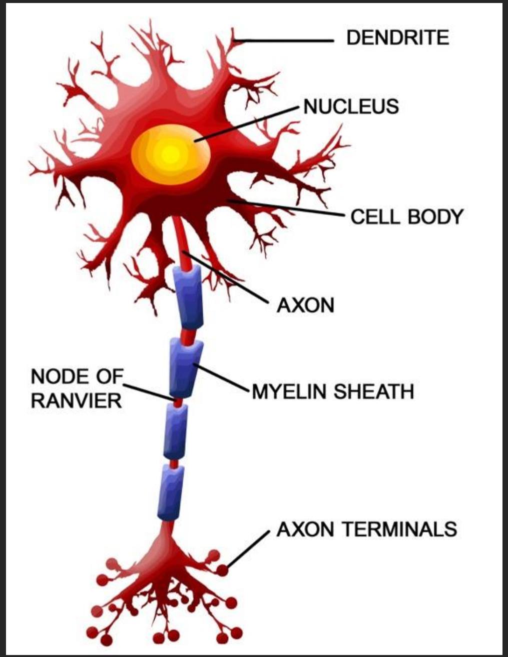
Let’s look at the brain as a system:

Systems made of many degrees of freedom (**that interact non-linearly**) which **self-organize** into a critical point in which **scale invariant** phenomena occur

# Part 3: Criticality in Brains

Let's look at the brain as a system:

90 billion neurons



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# Part 3: Criticality in Brains

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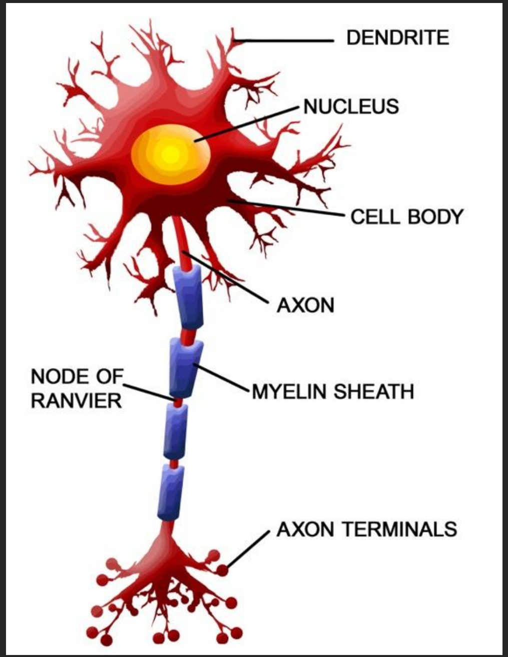


90 billion neurons

Trillions of synapses

$$I = C_m \frac{\mathrm{d}V_m}{\mathrm{d}t} + \bar{g}_{\mathrm{K}} n^4 (V_m - V_K) + \bar{g}_{\mathrm{Na}} m^3 h (V_m - V_{Na}) + \bar{g}_l (V_m - V_l),$$

$$\frac{dn}{dt} = \alpha_n(V_m)(1-n) - \beta_n(V_m)n$$

$$\frac{dm}{dt} = \alpha_m(V_m)(1-m) - \beta_m(V_m)m$$

$$\frac{dh}{dt} = \alpha_h(V_m)(1-h) - \beta_h(V_m)h$$

Systems made of many degrees of freedom (**that interact non-linearly**) which **self-organize** into a critical point in which **scale invariant** phenomena occur

# Part 3: Criticality in Brains

Let's look at the brain as a system:

90 billion neurons

Trillions of synapses

Systems made of many degrees of freedom (**that interact non-linearly**) which **self-organize** into a critical point in which **scale invariant** phenomena occur

# Part 3: Criticality in Brains

Let's look at the brain as a system:

90 billion neurons ☑ Many degrees of freedom

Trillions of synapses

# Part 3: Criticality in Brains

Systems made of many degrees of freedom (**that interact non-linearly**) which **self-organize** into a critical point in which **scale invariant** phenomena occur

Let’s look at the brain as a system:

| | | |
|---|---|---|
| 90 billion neurons | ☑ | Many degrees of freedom |
| Trillions of synapses | ☑ | Interact non-linearly |

Systems made of many degrees of freedom (**that interact non-linearly**) which **self-organize** into a critical point in which **scale invariant** phenomena occur

# Part 3: Criticality in Brains

Let's look at the brain as a system:

| | | |
|---|---|---|
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| | | Scale invariance? |

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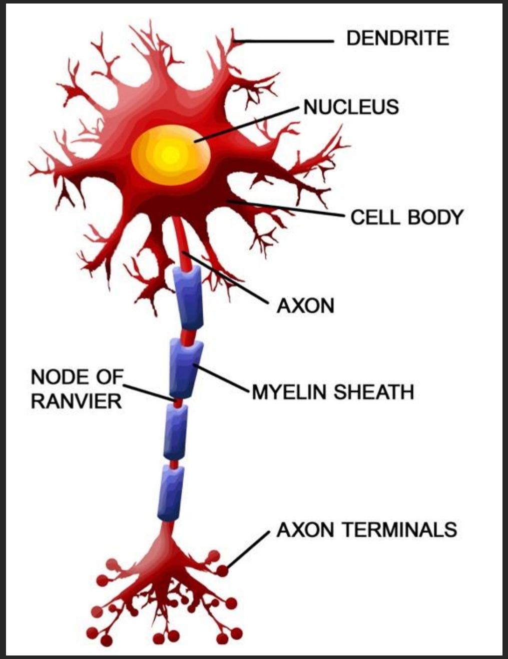

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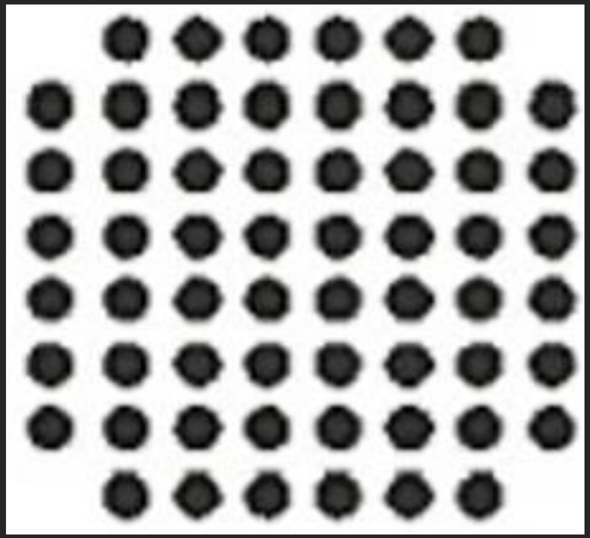

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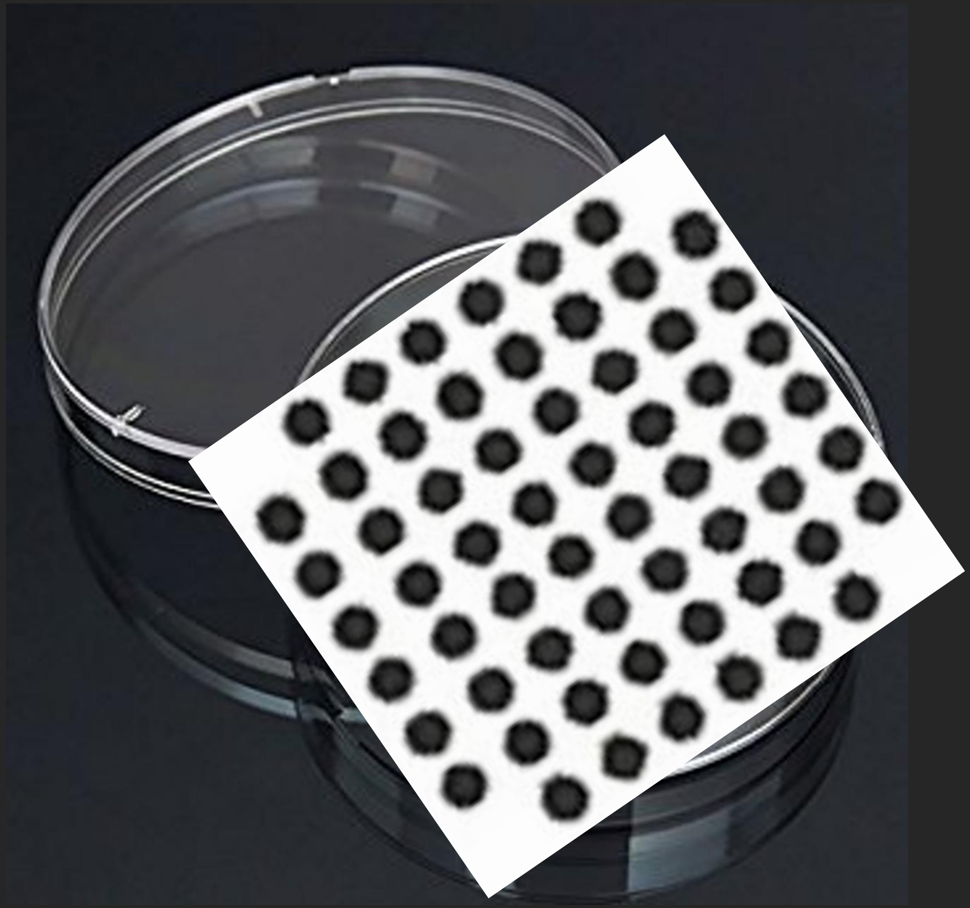

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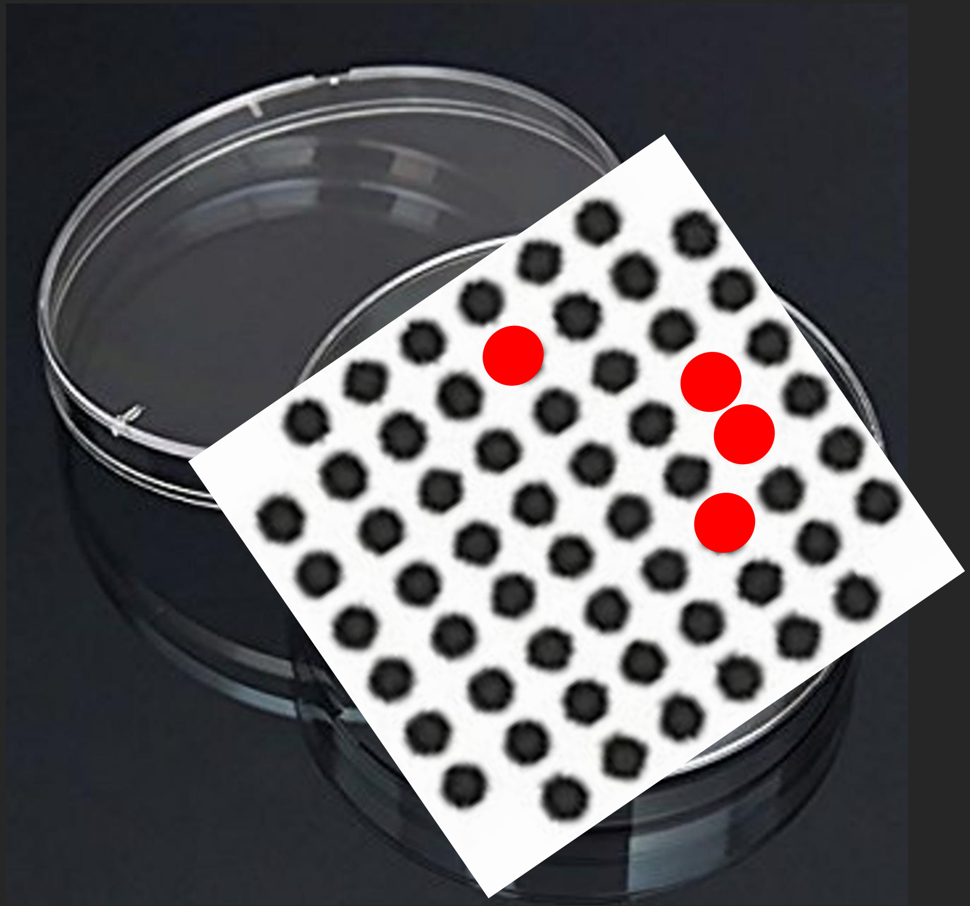

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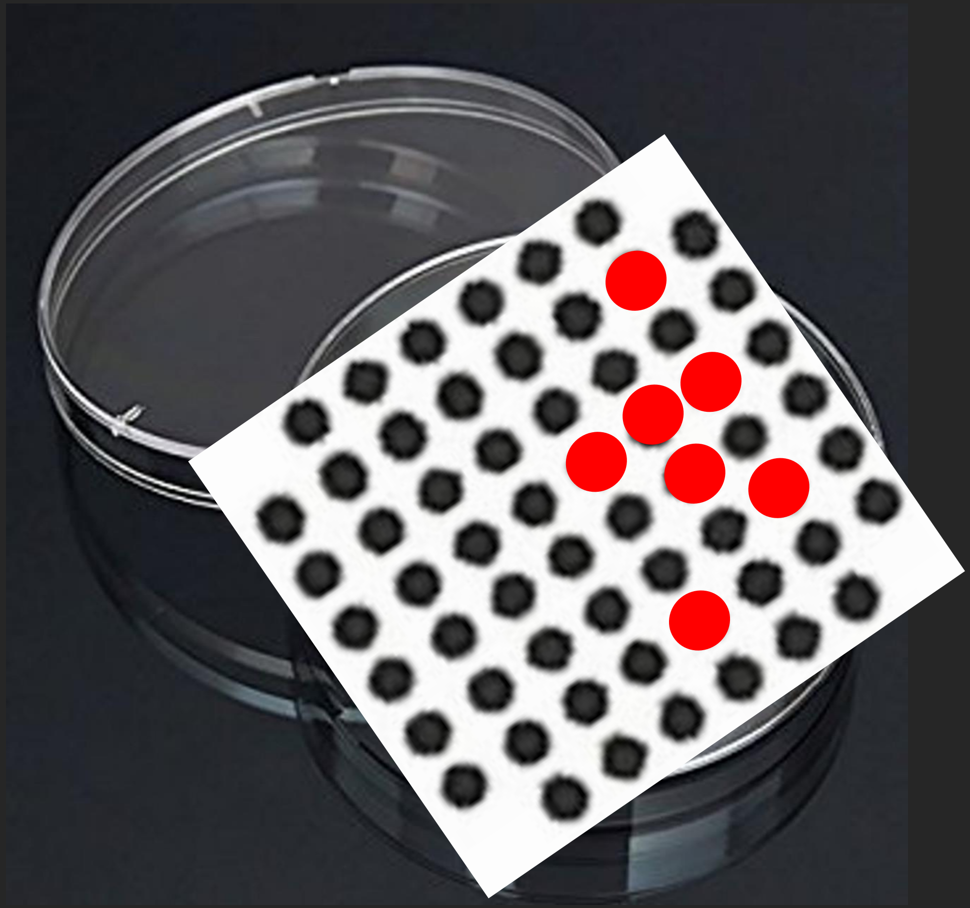

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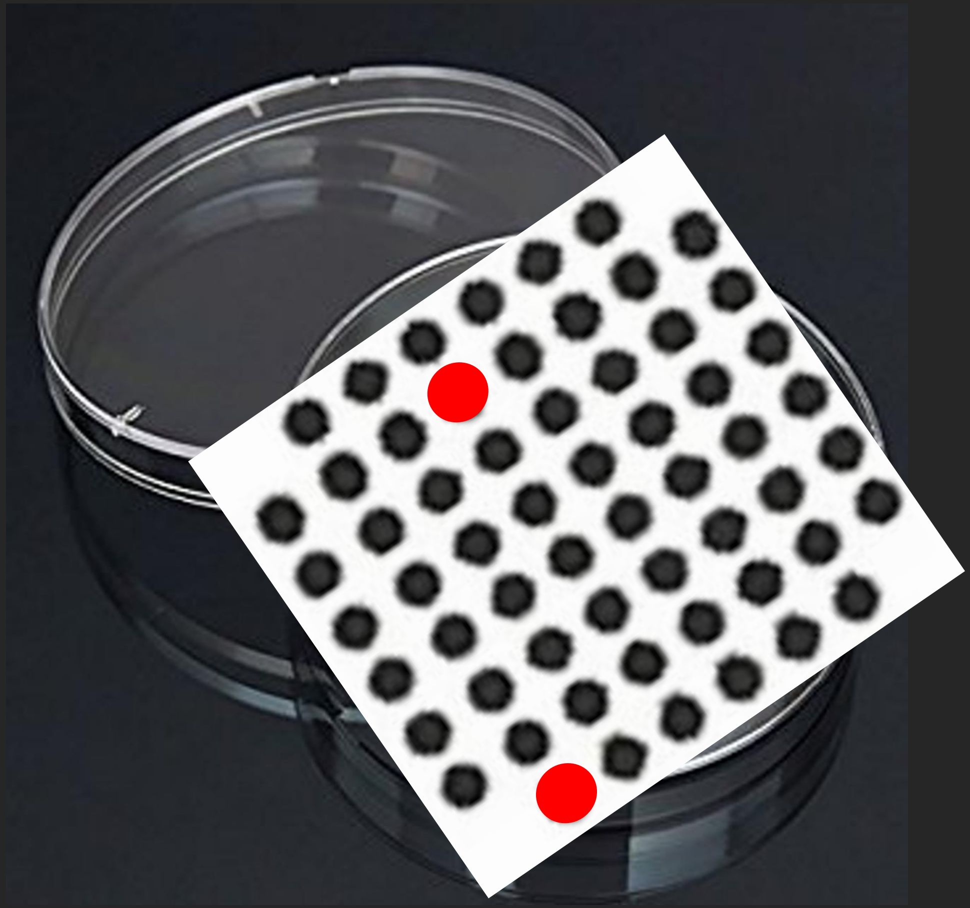

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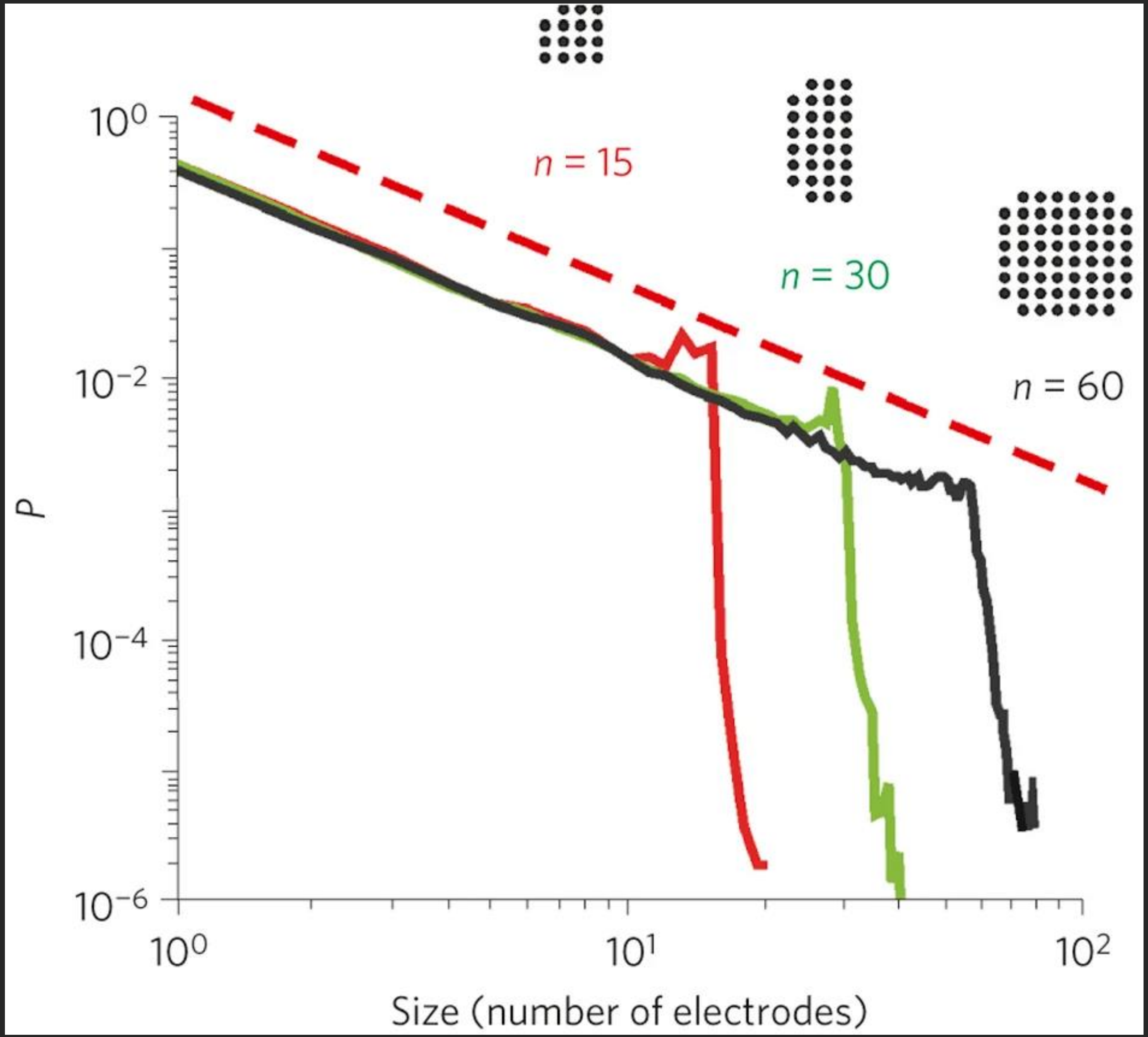
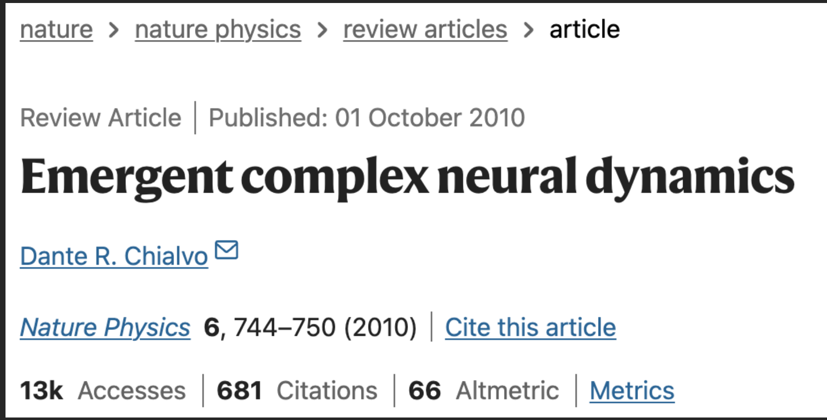



Figure from:


nature › nature physics › review articles › article

Review Article | Published: 01 October 2010

**Emergent complex neural dynamics**

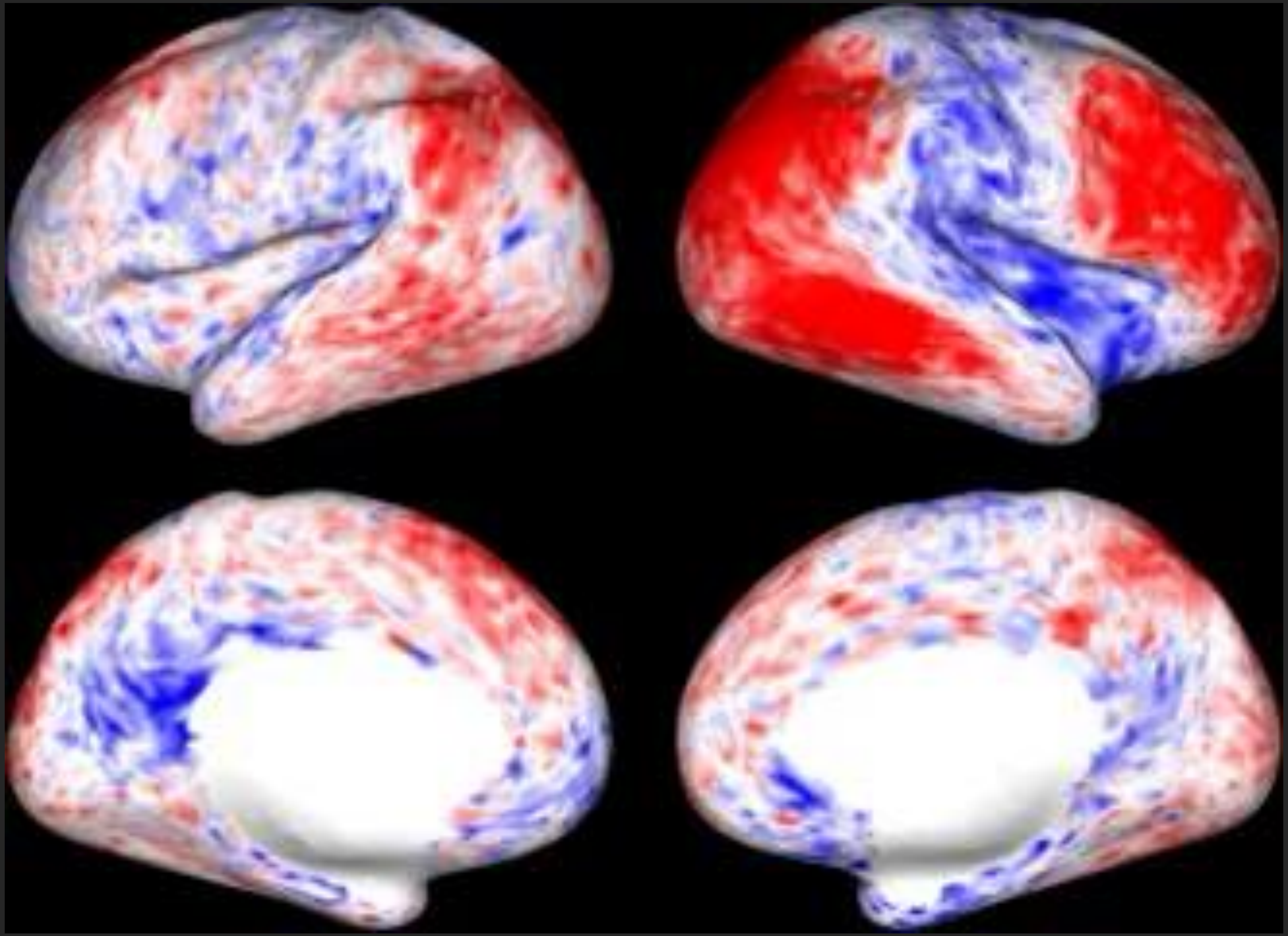
Dante R. Chialvo

*Nature Physics* **6**, 744–750 (2010) | Cite this article

**13k** Accesses | **681** Citations | **66** Altmetric | Metrics

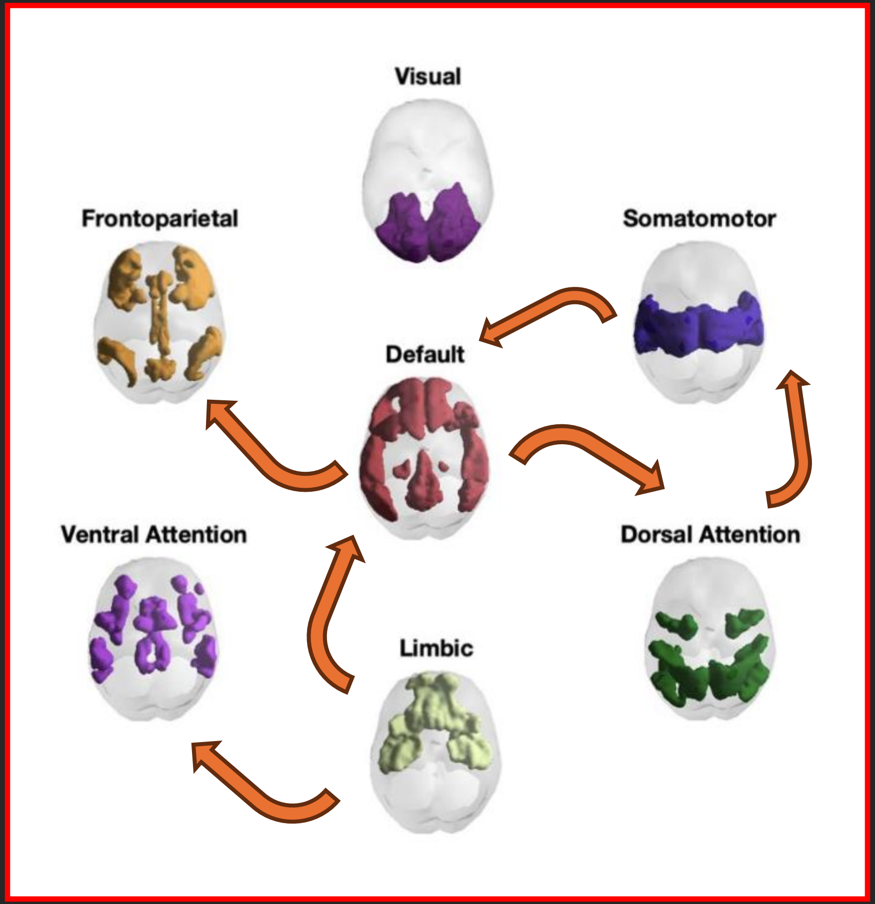
Okay, so I guess neurons display critical behaviours, so what?

# Brain Activity at Rest



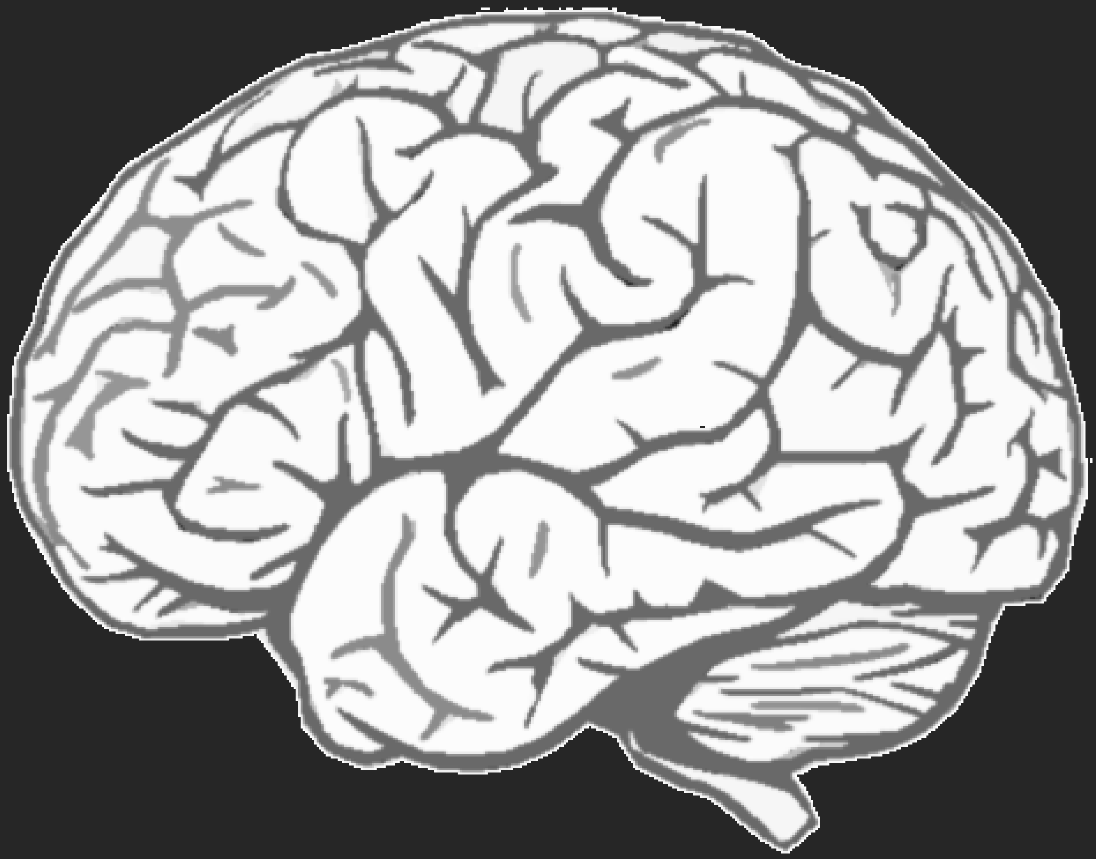
Bhushan et al (2016). "Temporal Non-Local Means Filtering Reveals Real-Time Whole-Brain Cortical Interactions in Resting fMRI". PLOS ONE. DOI:10.1371/journal.pone.0158504

2x speed
Real time brain
activity via fMRI




J. Vohryzek et al, "Ghost Attractors in Spontaneous Brain Activity: Recurrent Excursions Into Functionally-Relevant BOLD Phase-Locking States," Frontiers in Systems Neuroscience

# How to model this? Is it critical?



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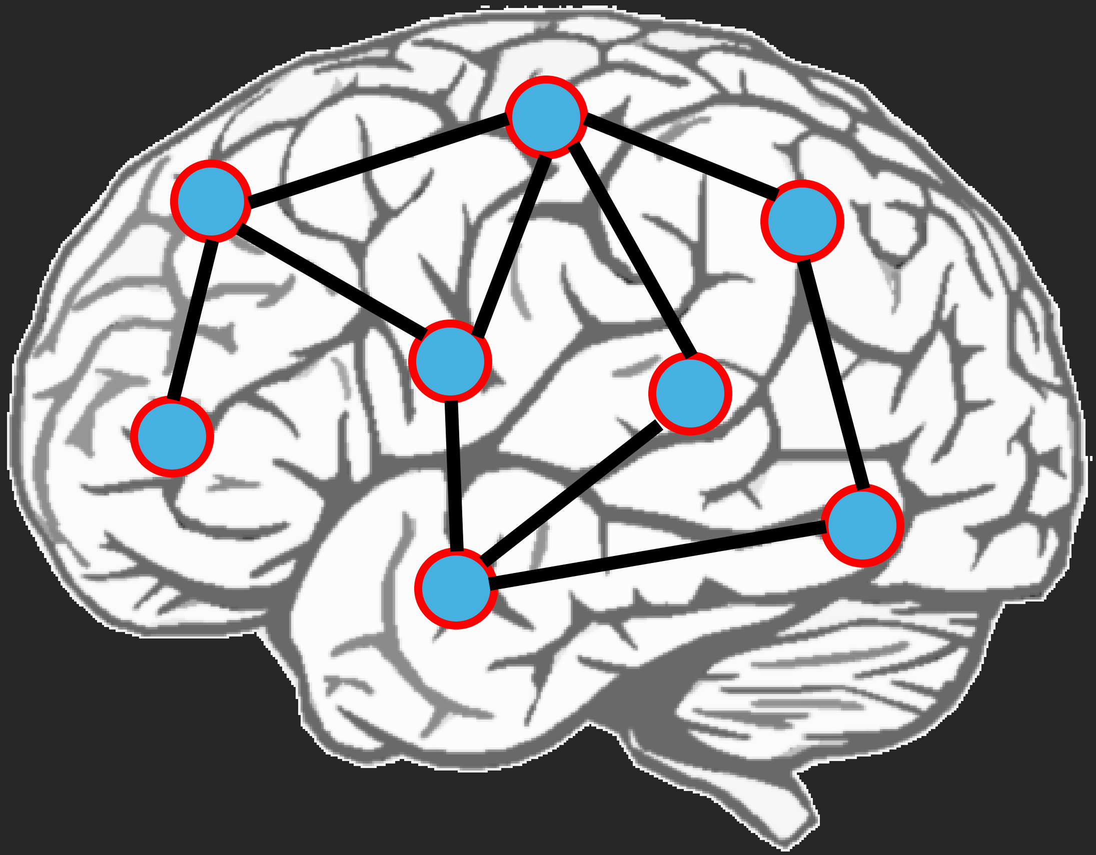

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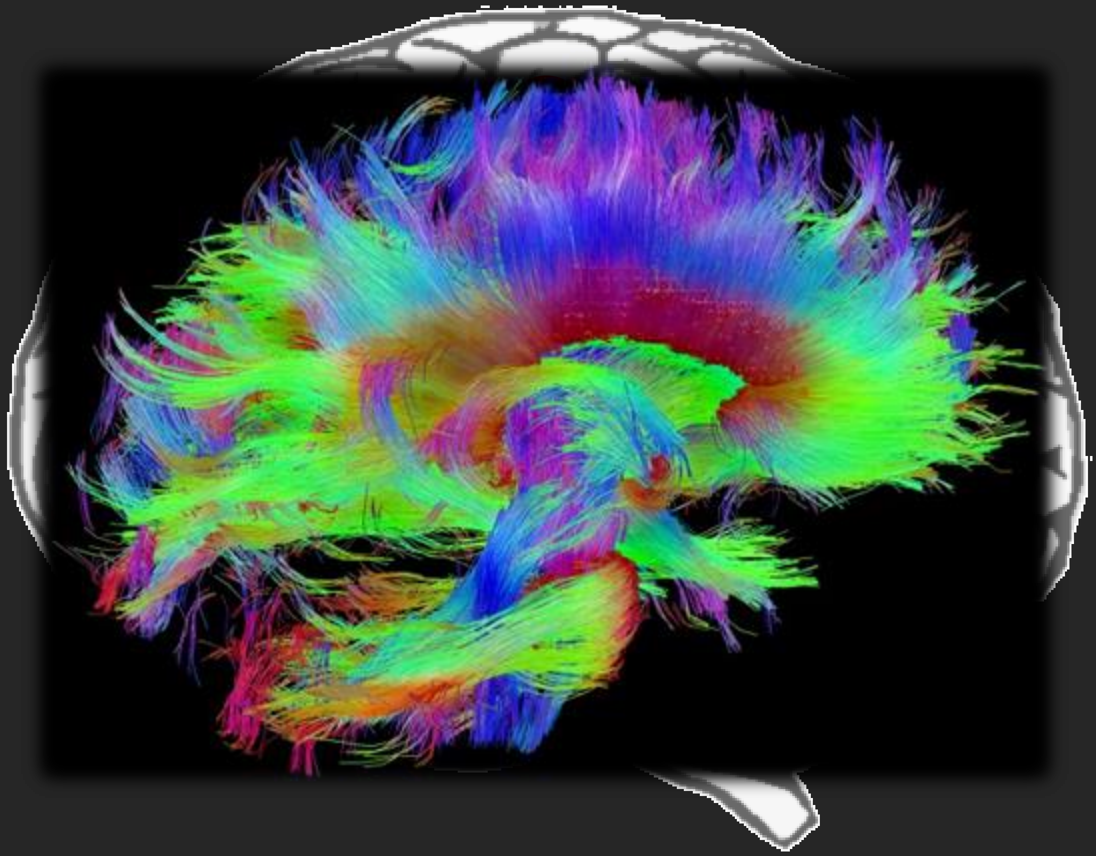

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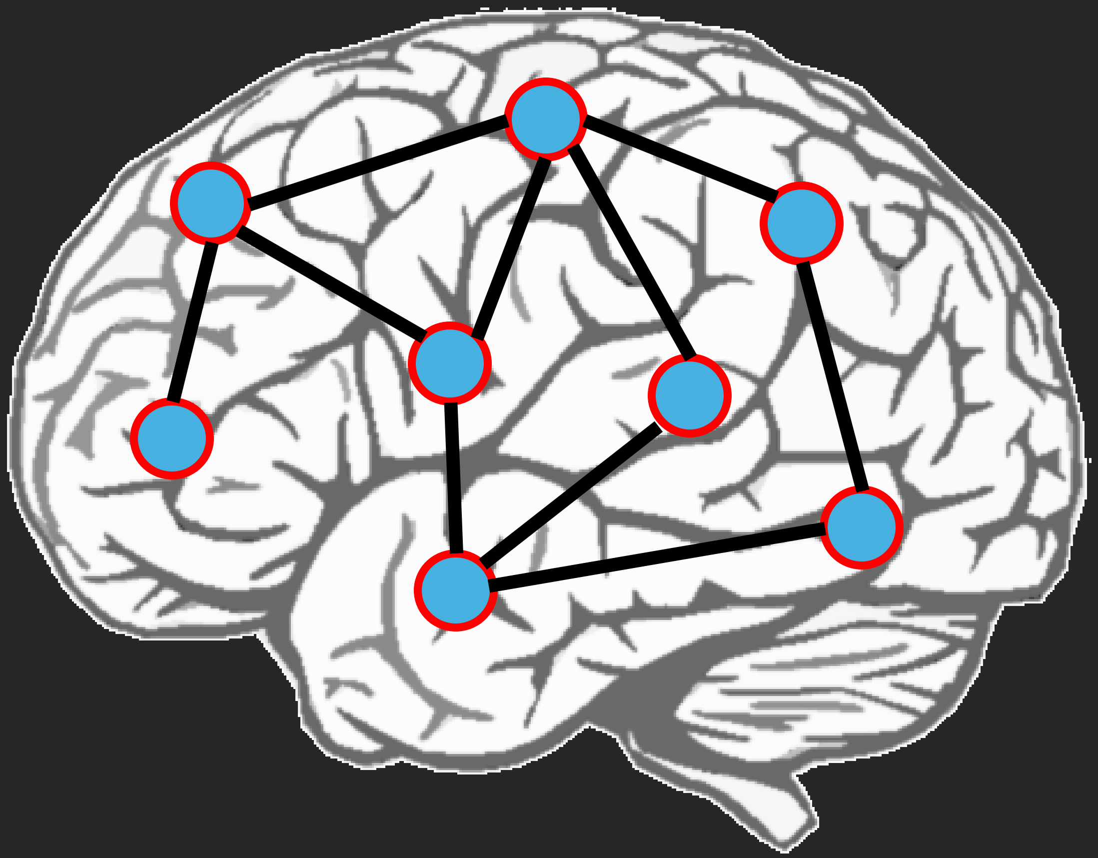

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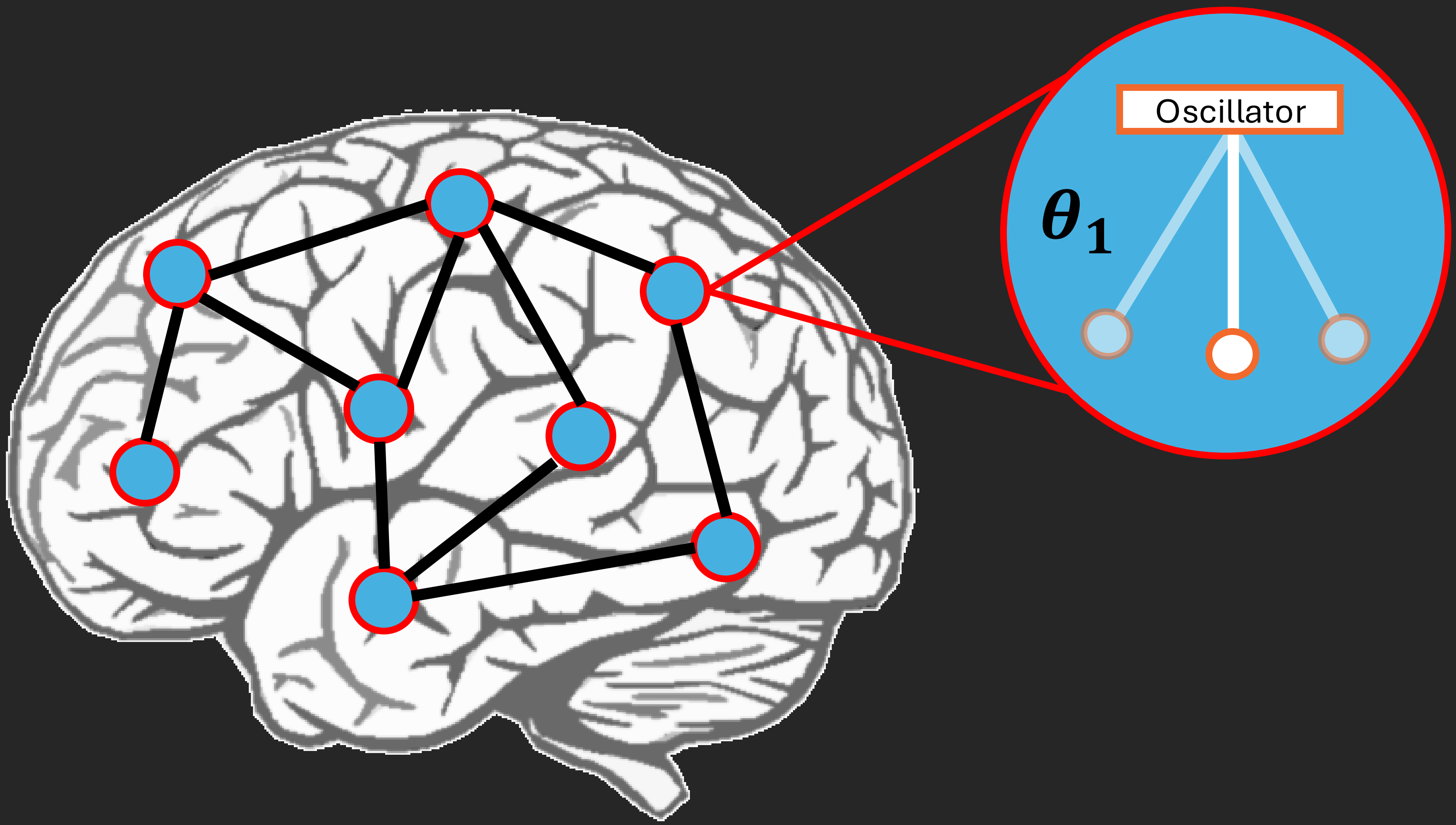

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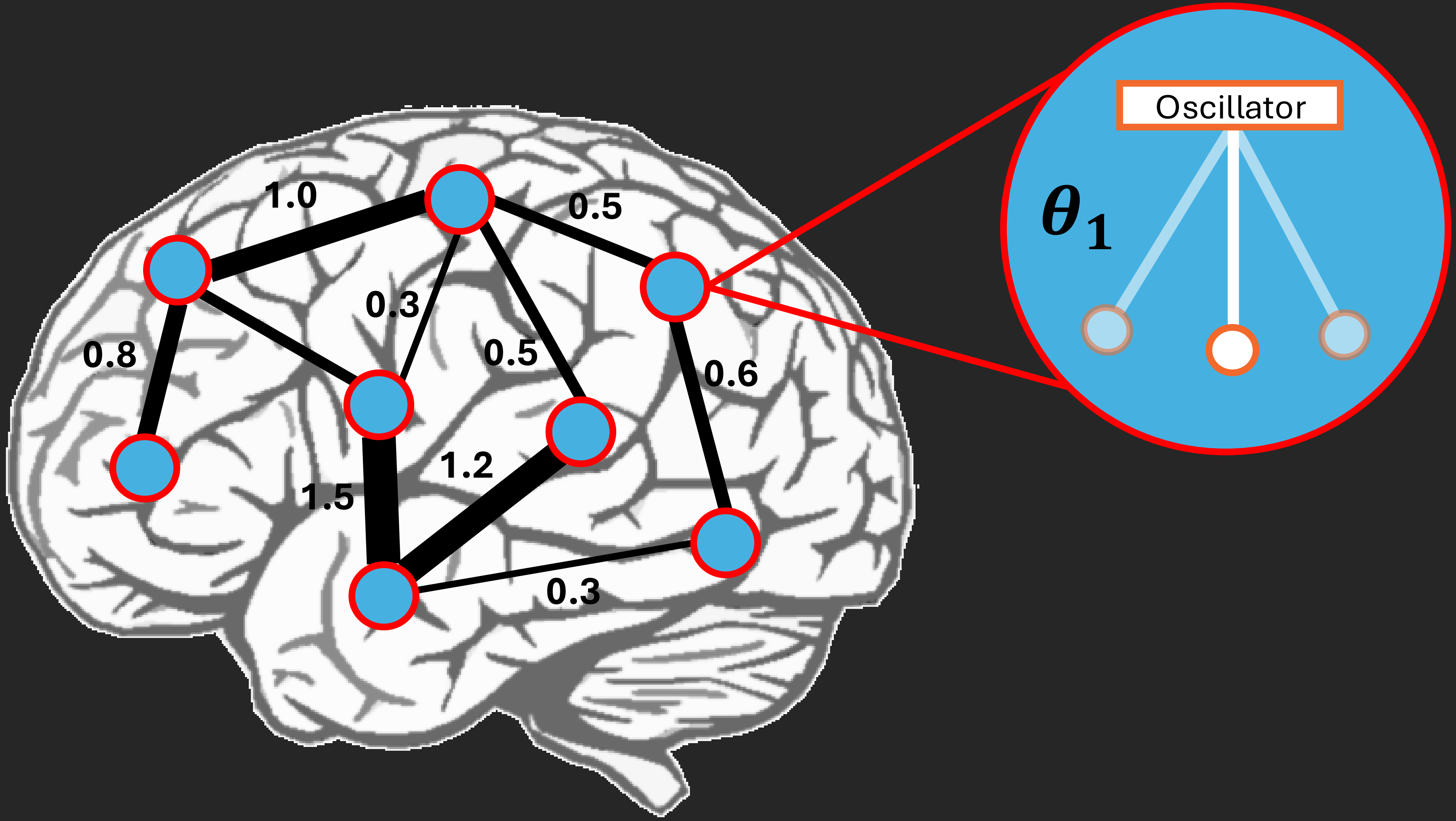

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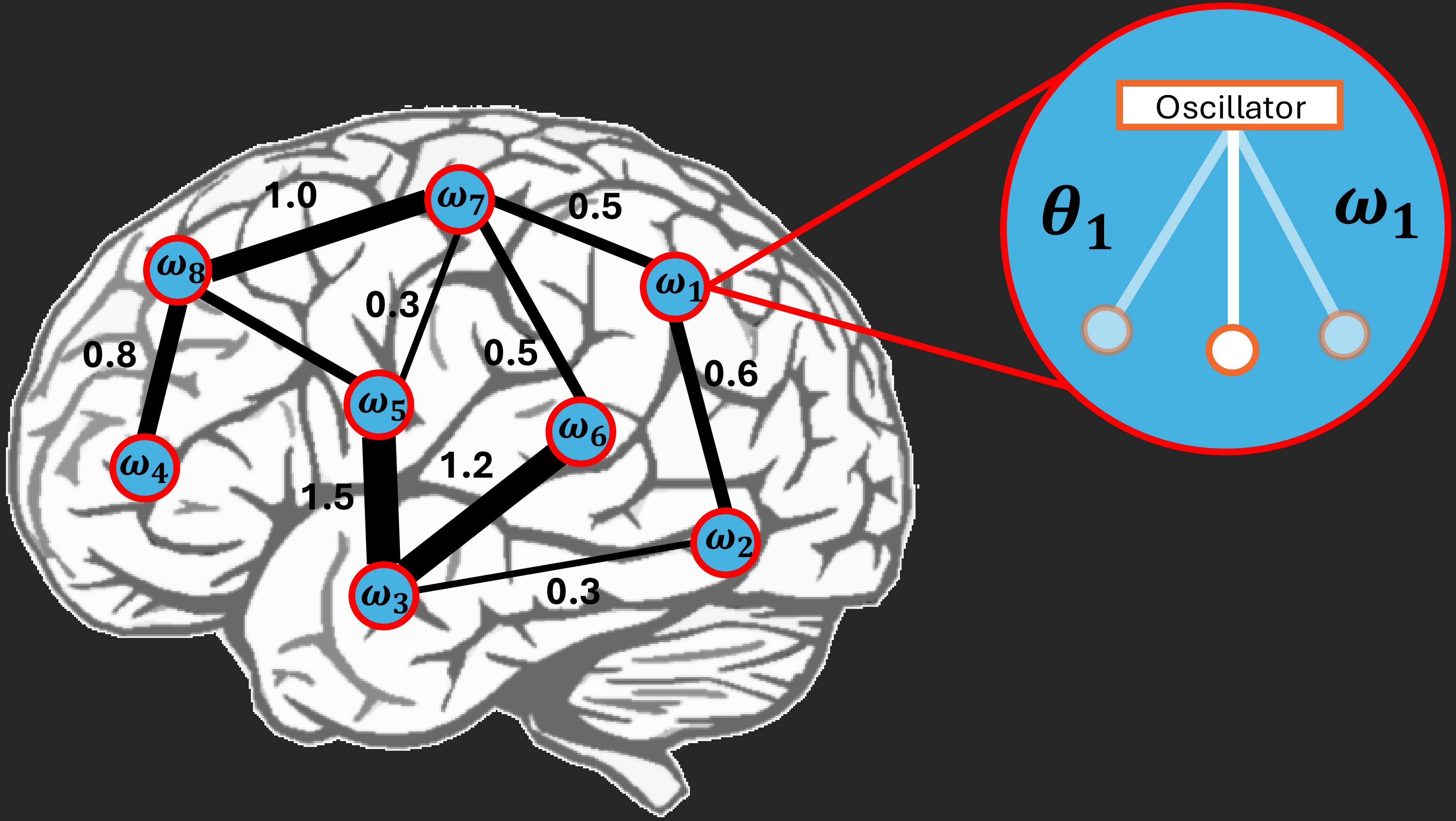
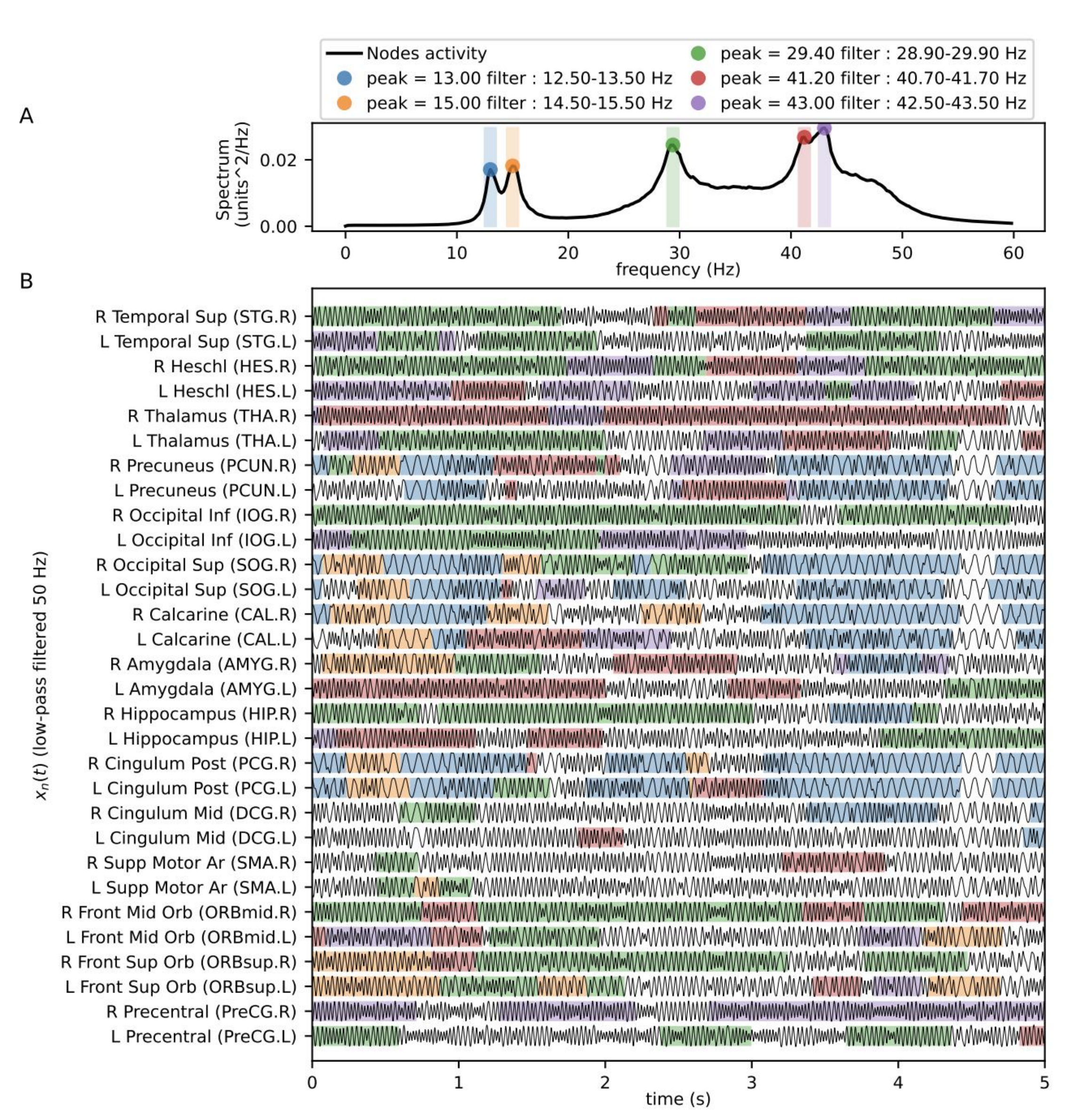
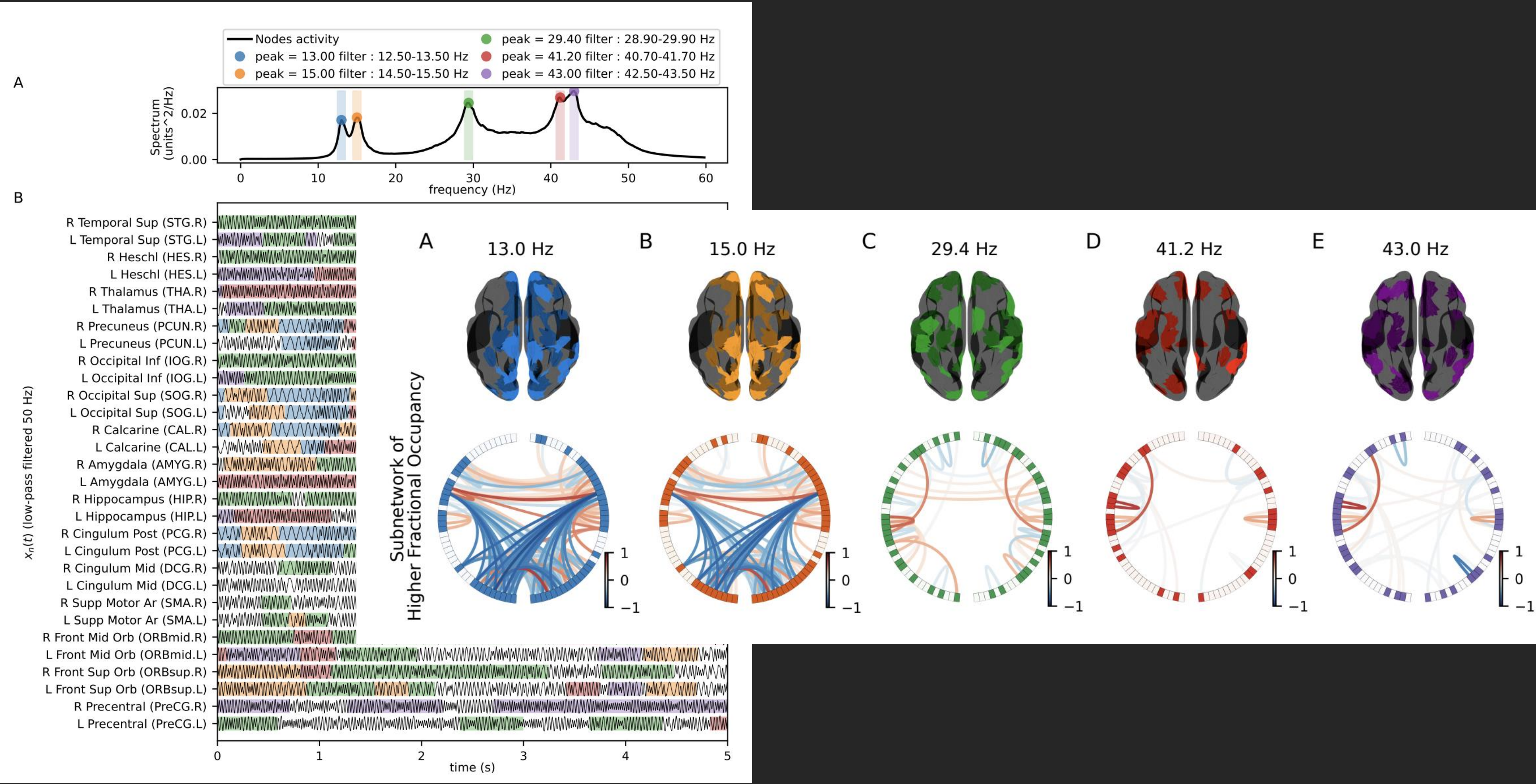





Torres et al (2024) Emergence of multiple spontaneous coherent subnetworks from a single configuration of human connectome-coupled oscillators model

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# Conclusions

## Emergent complex neural dynamics

Dante R. Chialvo

Nature Physics 6, 744–750 (2010) | Cite this article

13k A

## Social interactions dominate speed control in poising natural flocks near criticality

William Bialek[a,1], Andrea Cavagna[b,c], Irene Giardina[b,c], Thierry Mora[d], Oliver Pohl[b,c,2], Edmondo Silvestri[b,c], Massimiliano Viale[b,c], and Aleksandra M. Walczak[e]

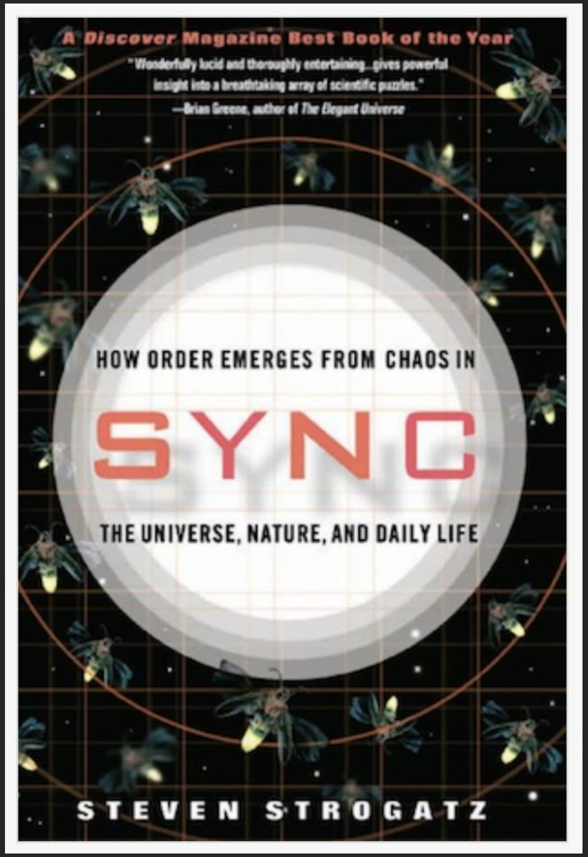
No. 4486 October 22, 1955 NATURE 795

The presence of uranium in the meteorite should result in the production of the 2·33-day

Magnitude and Energy of Earthquakes

## Criticality and scaling in evolutionary ecology

Ricard V. Solé [a], Susanna C. Manrubia [b], Michael Benton [c], Stuart Kauffman [d], Per Bak [e]



# Conclusions

Nature speaks the language of nonlinear equations, and nonlinear equations are really hard to solve

Adaptive systems of many units interacting nonlinearly often self-organize into a dynamical regime very close to the critical point