

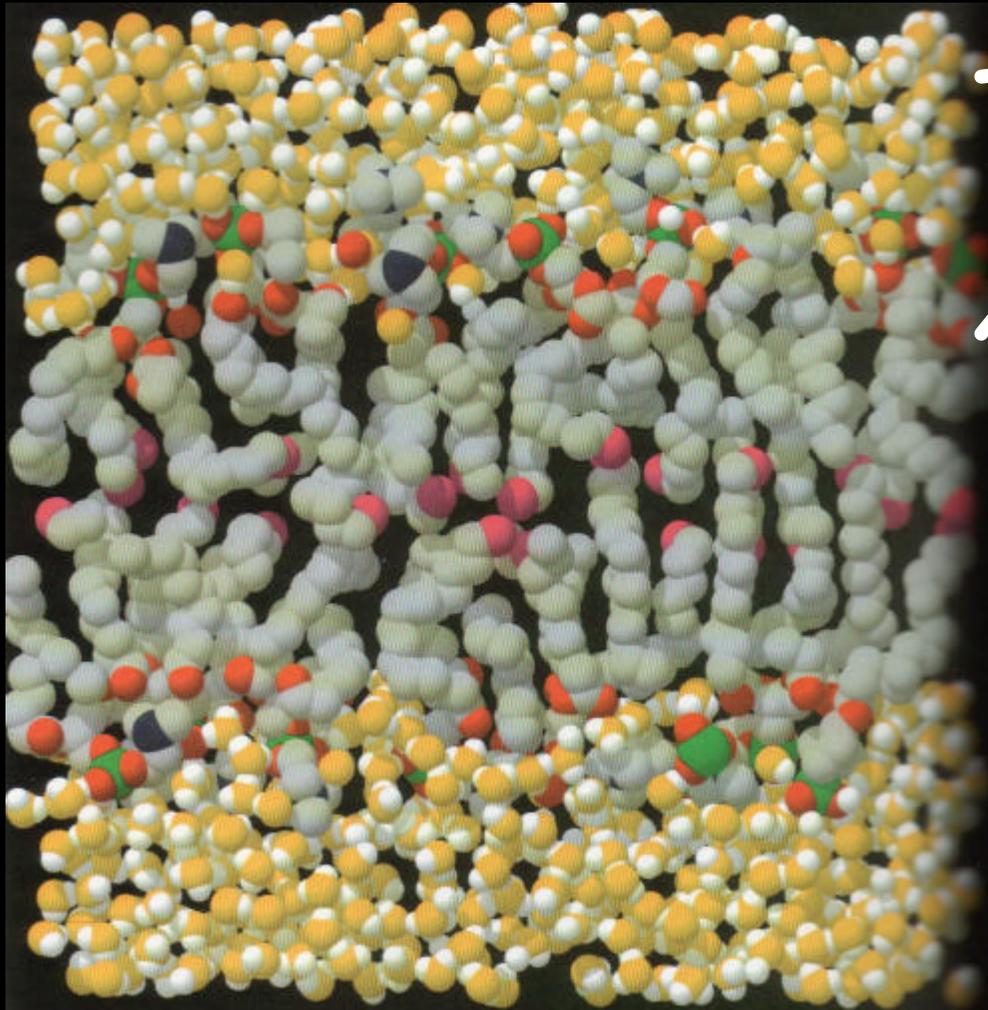
# CAOS EM REDES NEURAIS BIOLÓGICAS (parte 2)



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**Depto. Física Geral – IFUSP**

# A membrana celular:

fora



dentro

Fosfolipídeos:  
cabeças hidrofílicas  
caudas hidrofóbicas

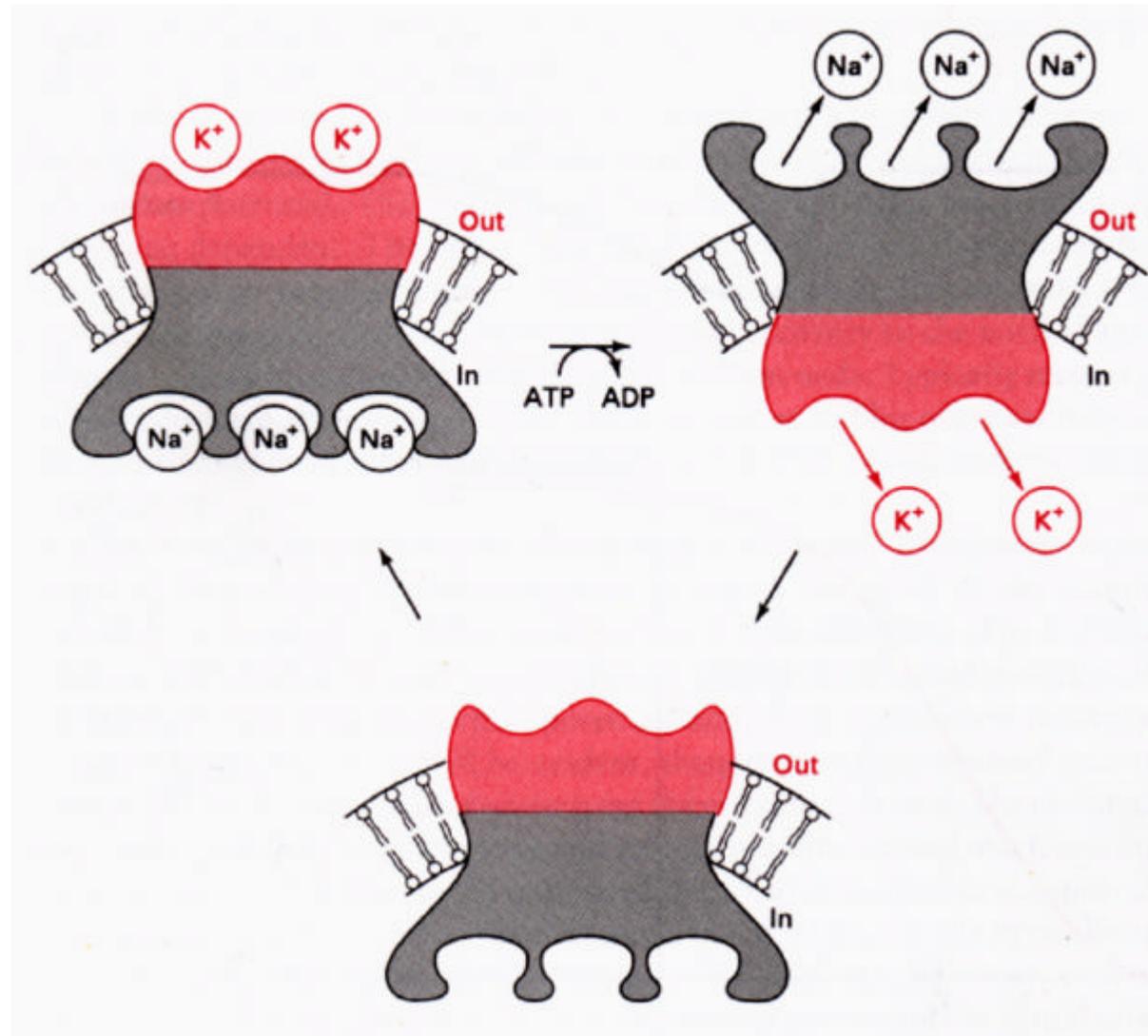
Lipídios → gorduras  
→ Isolante

6 a 8 nm de espessura  
60 mV →  $E = 10 \text{ kV/mm}$

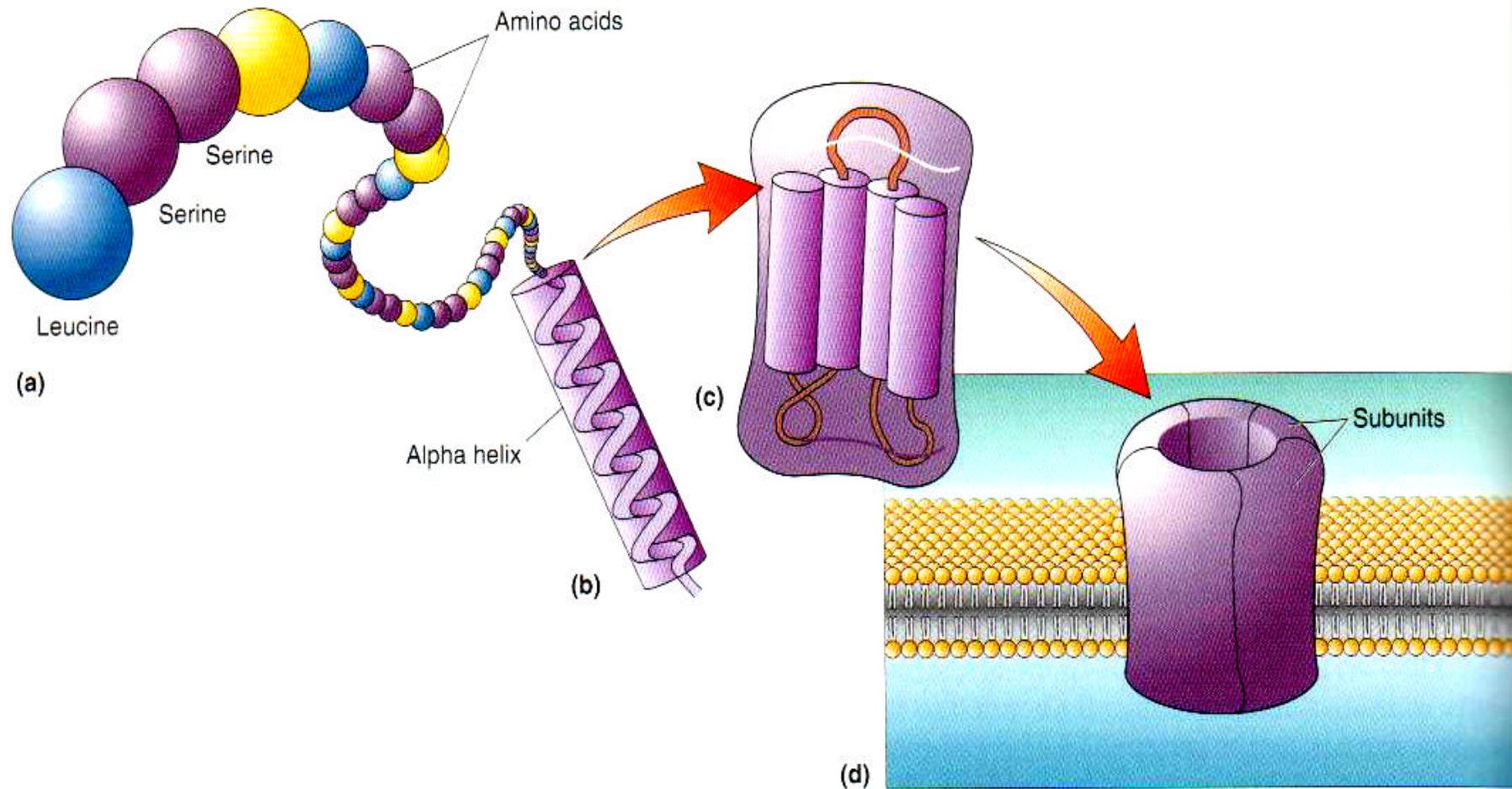
isolação máx.  
ar seco =  $1 \text{ kV/mm}$

# Bombas de sódio-potássio

(Sódio-potássio ATPase)

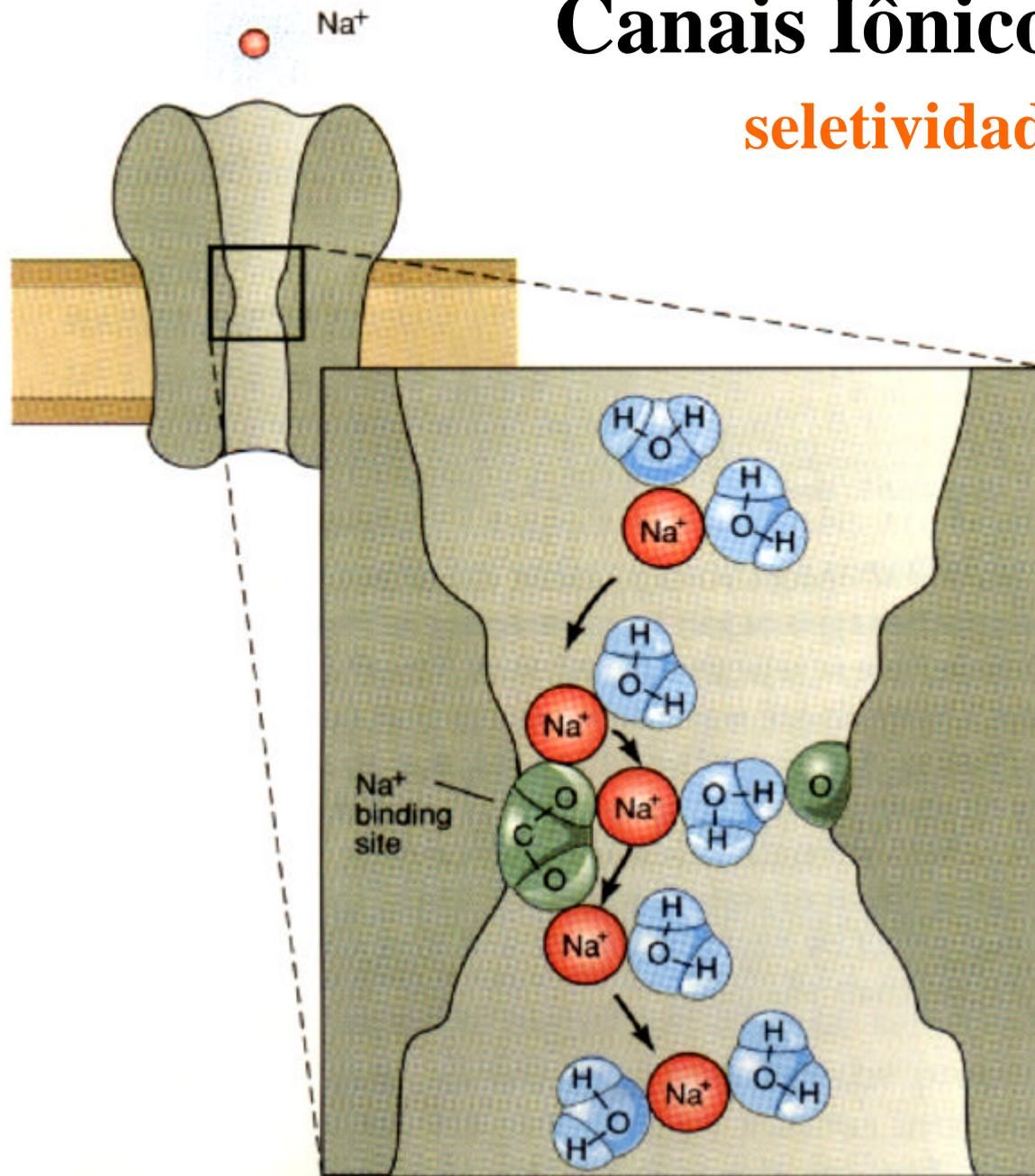


# Canais Iônicos - proteínas

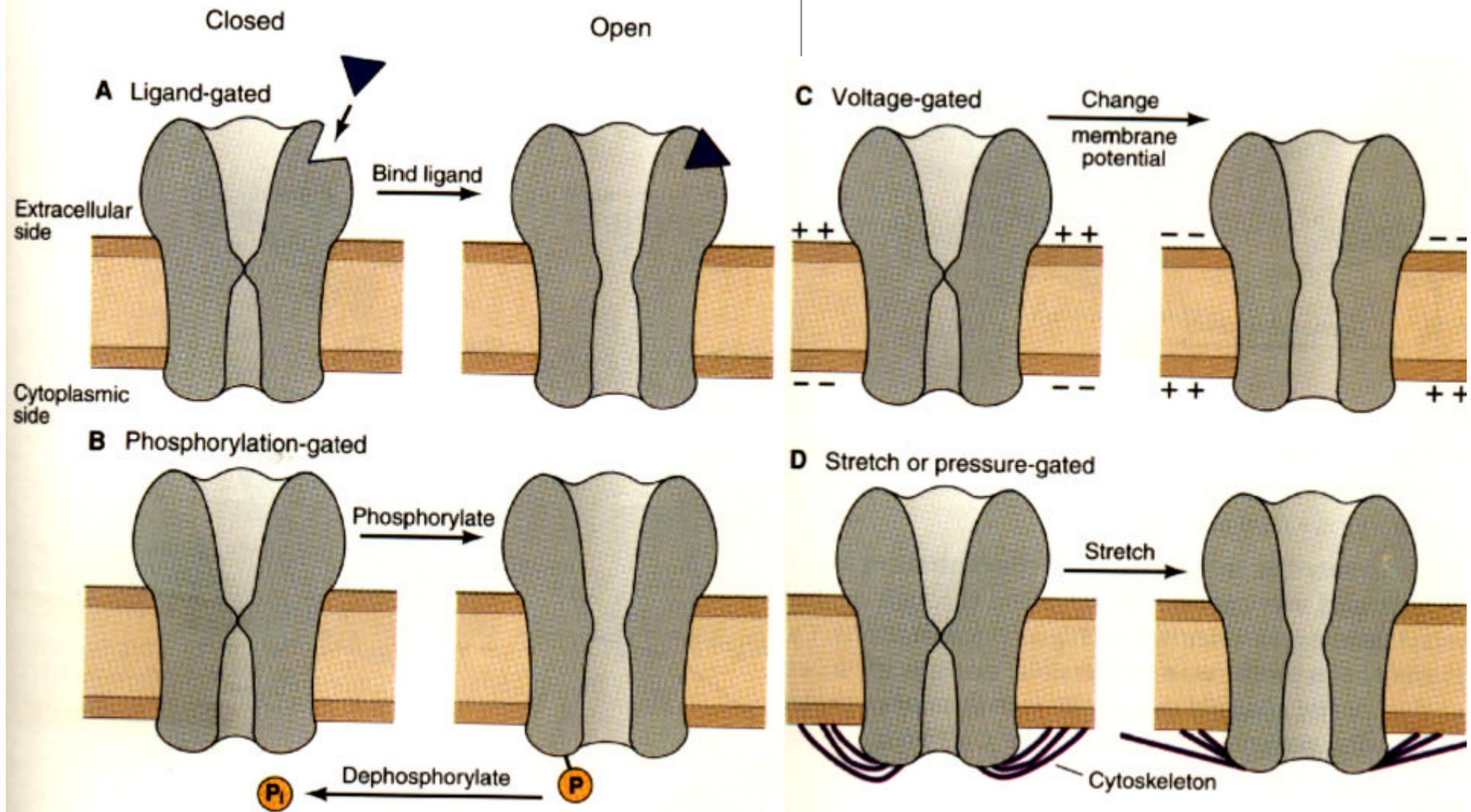


# Canais Iônicos

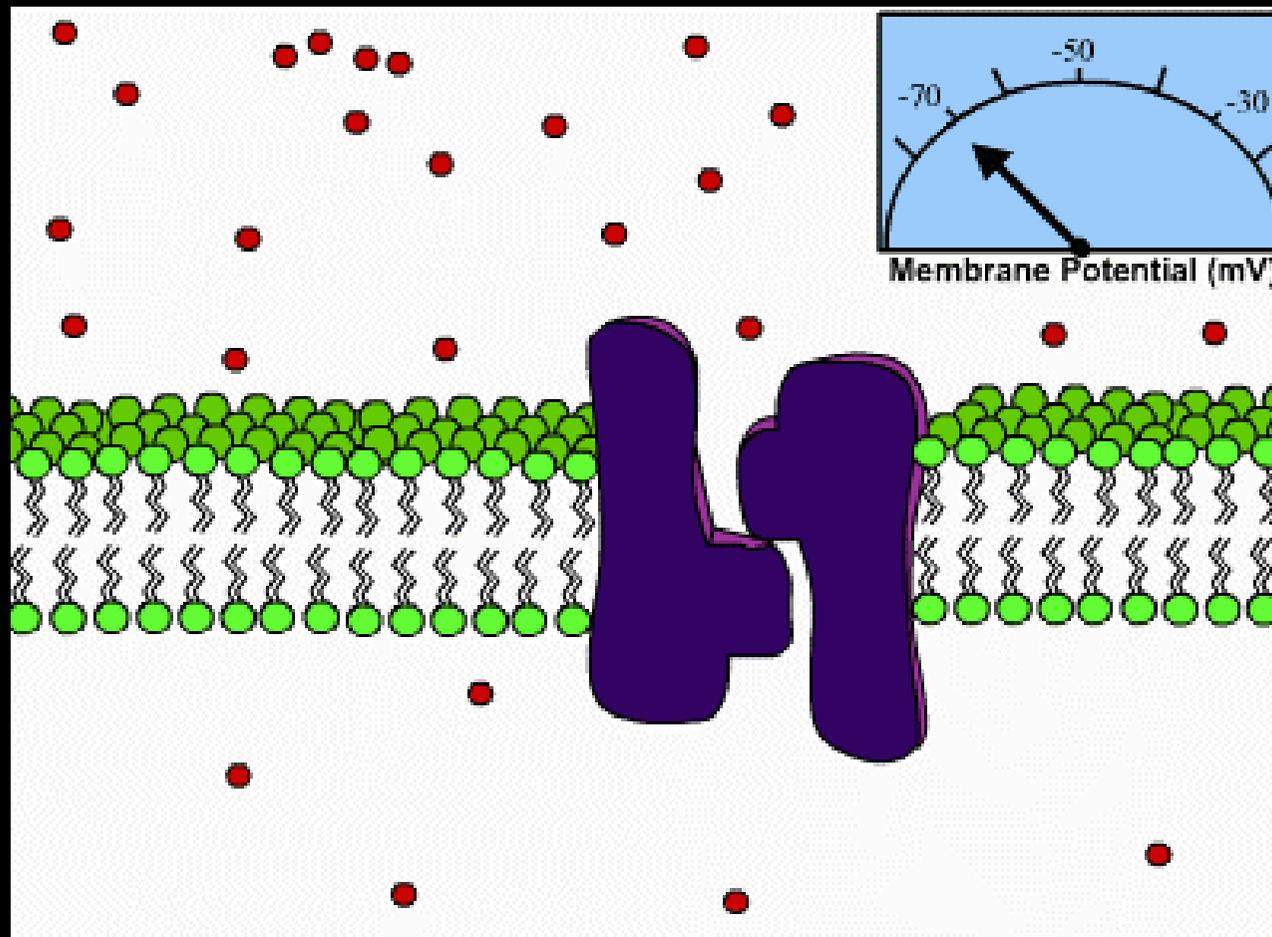
seletividade



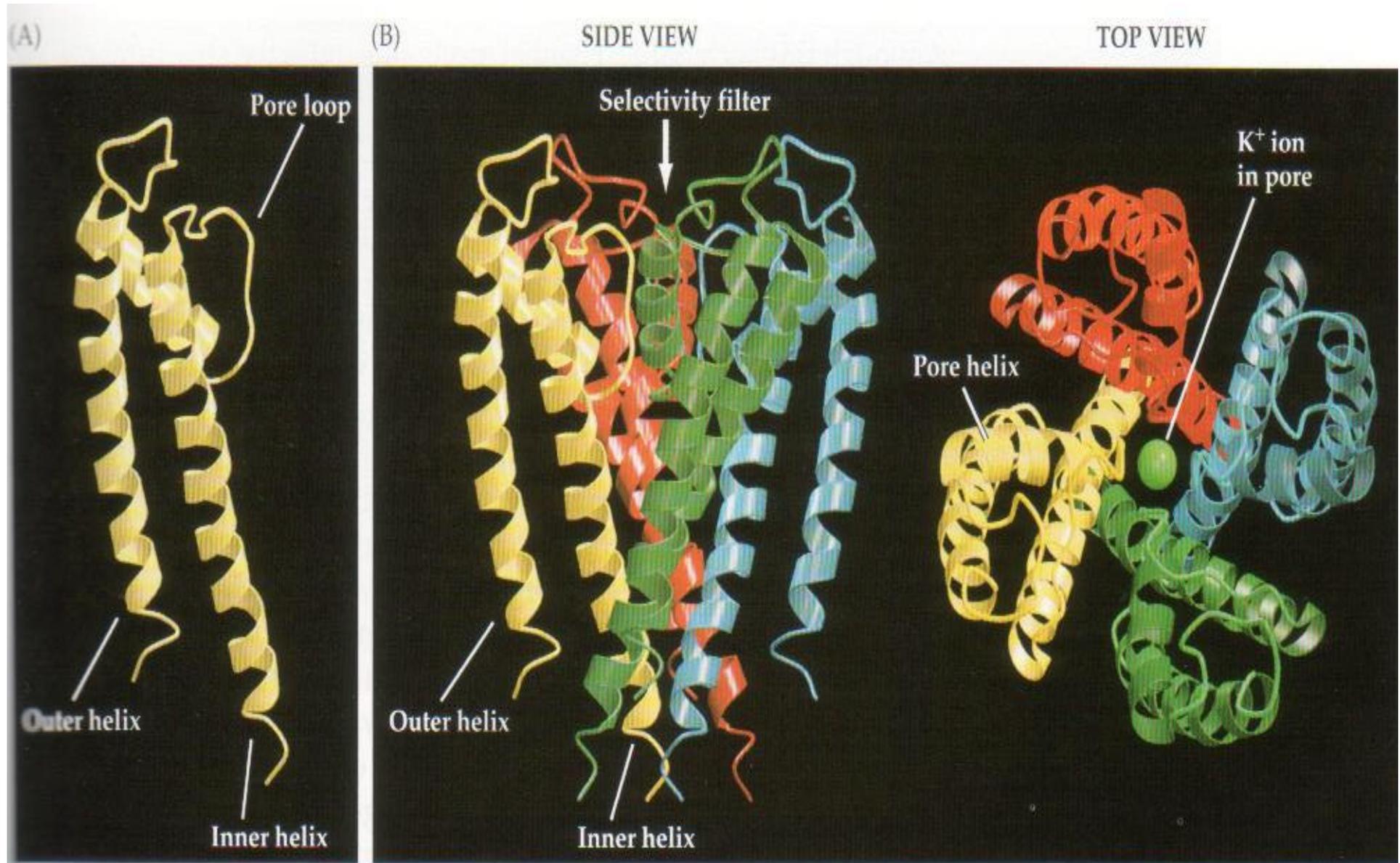
# Diferentes tipos de Canais Iônicos



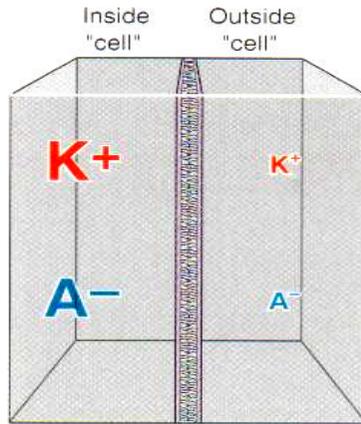
# Canais Iônicos sensíveis à voltagem



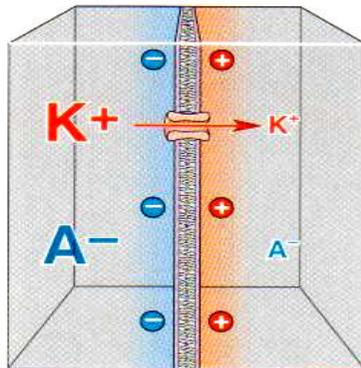
# Canais Iônicos – modelo canal $K^+$



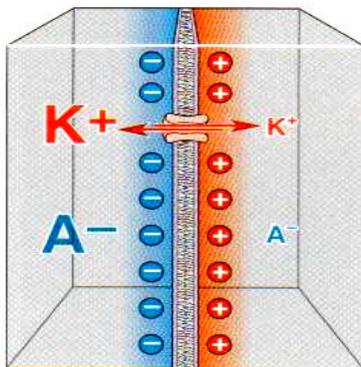
# Equilíbrio e o Potencial de Nernst



(a)



(b)



(c)

$$E_i = \frac{RT}{zF} \ln \frac{C_{out}}{C_{in}}$$

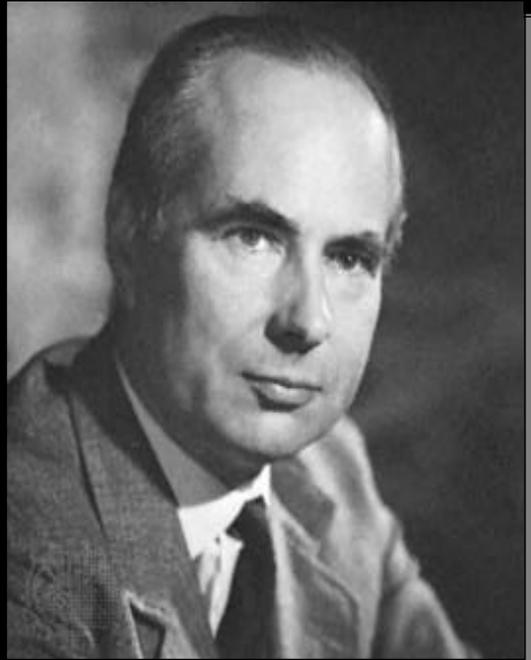
<u>Íon</u>	<u>Potencial de Nernst (mV)</u>
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K <sup>+</sup>	-75
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Na <sup>+</sup>	+55
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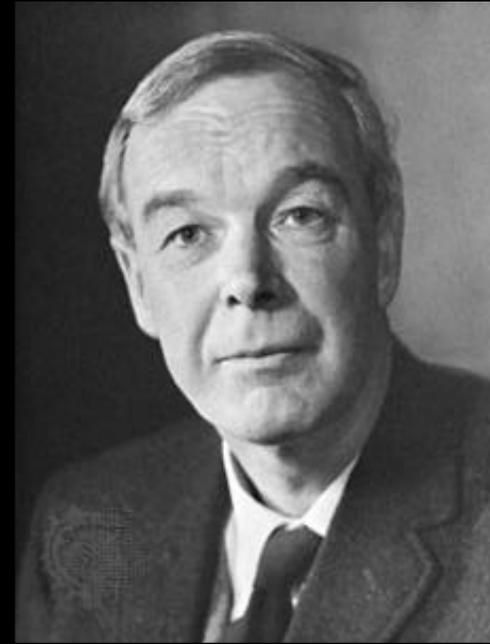
Cl <sup>-</sup>	-60
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$$I_i = g_i (V - E_i)$$



**Sir Andrew F. Huxley**

(1917-)

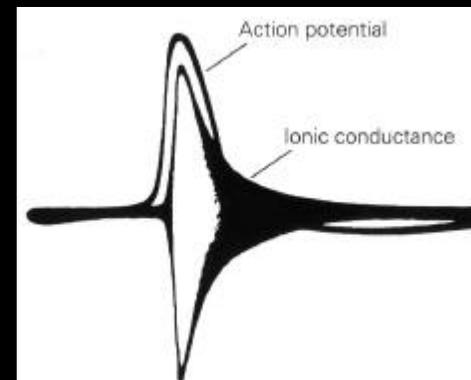


**Sir Alan Hodgkin**

(1914-1998)

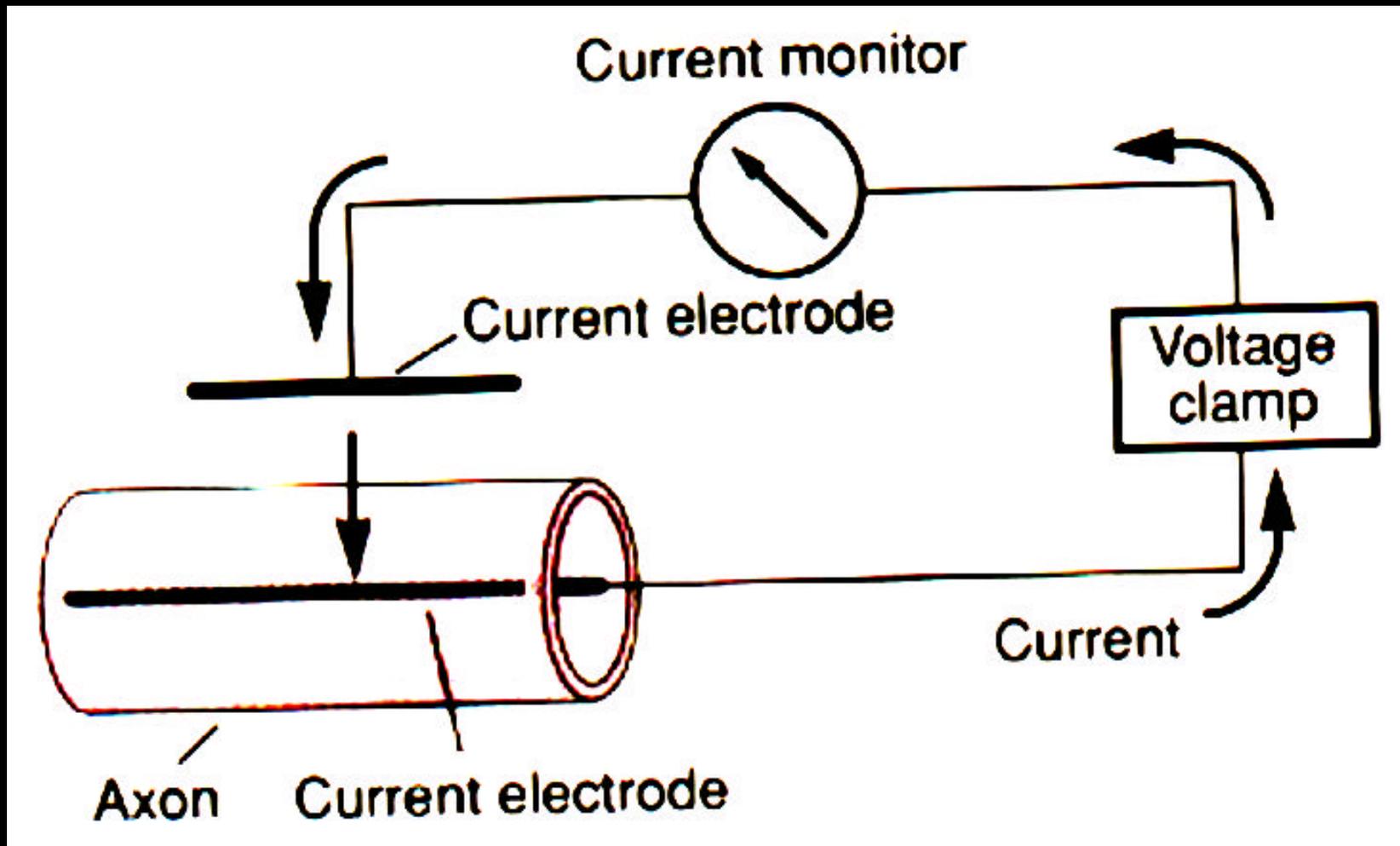


*Loligo forbesi*



**NOBEL**  
em 1963

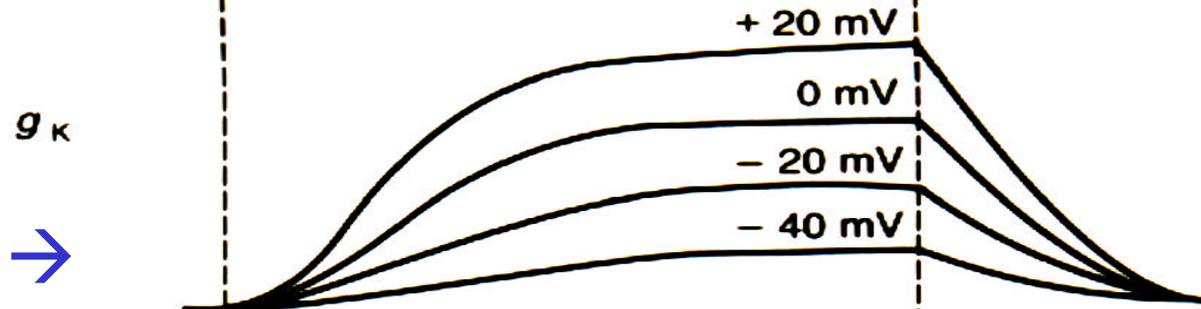
# Voltage Clamp e os experimentos com o axônio gigante de *loligo* (~1940)



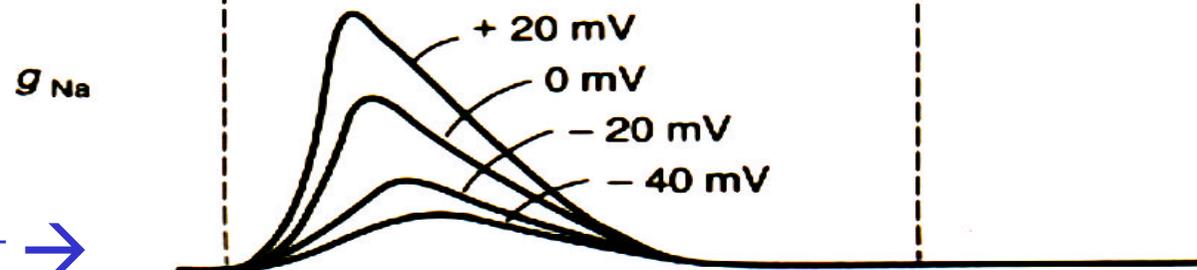
voltage clamp →



Solução só com  $K^+$  →



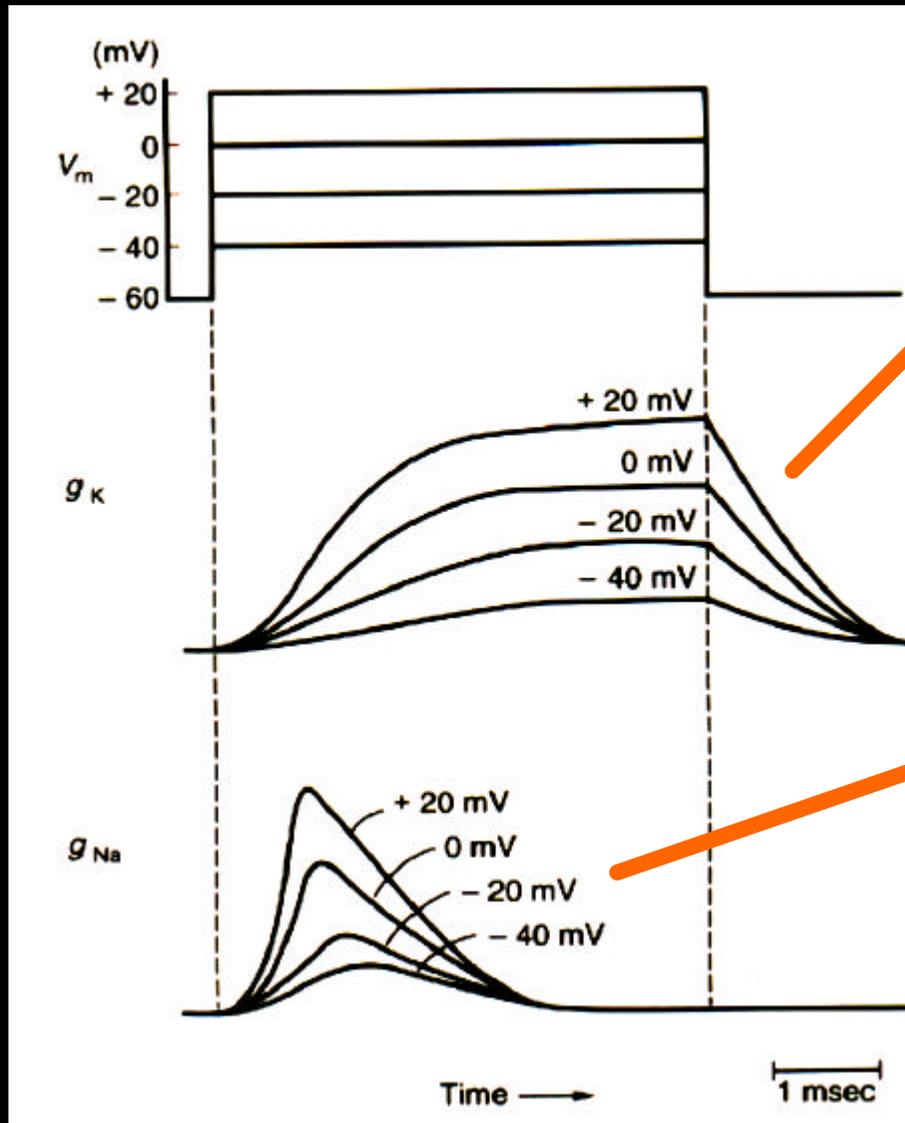
Solução só com  $Na^+$  →



Time →

1 msec

# Interpretação de Hodgkin-Huxley



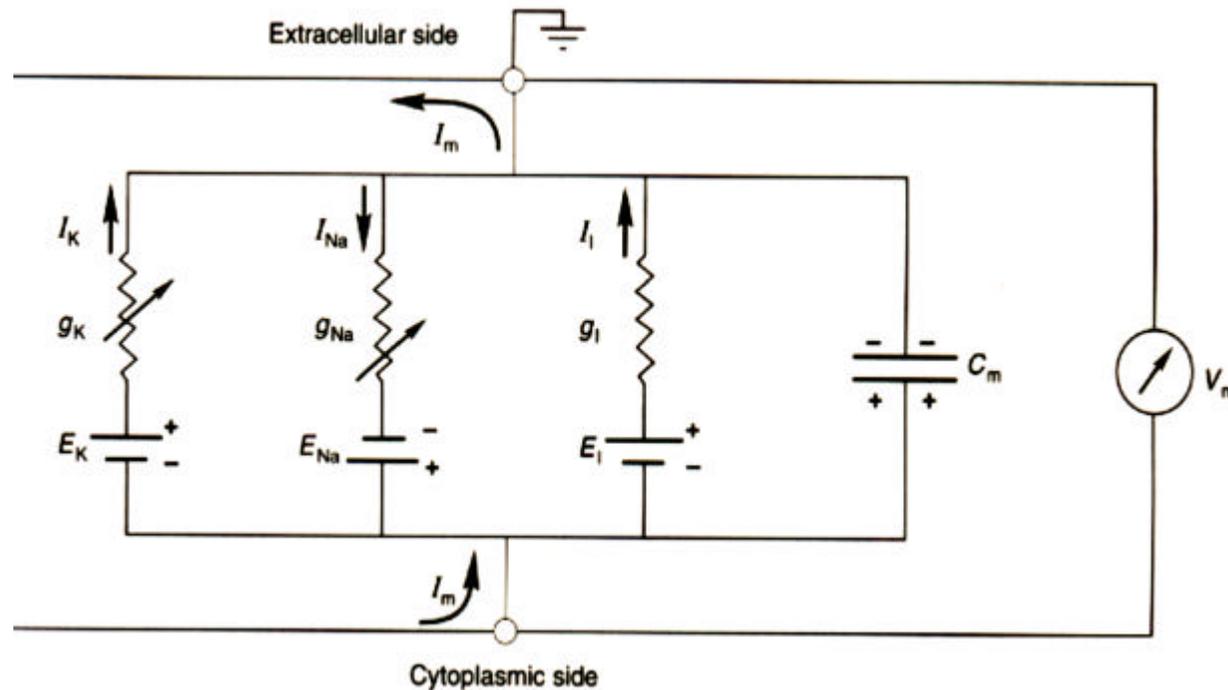
Ativação e saturação da corrente de  $K^+$

→ condutância só com termo de ativação dependendo da voltagem

Ativação seguida por desativação da corrente de  $Na^+$

→ condutância com termos de ativação e inativação dependendo da voltagem

# Modelo de Hodgkin-Huxley do potencial de ação



$$dV_m = \frac{1}{C_c} \frac{dQ}{dt}$$

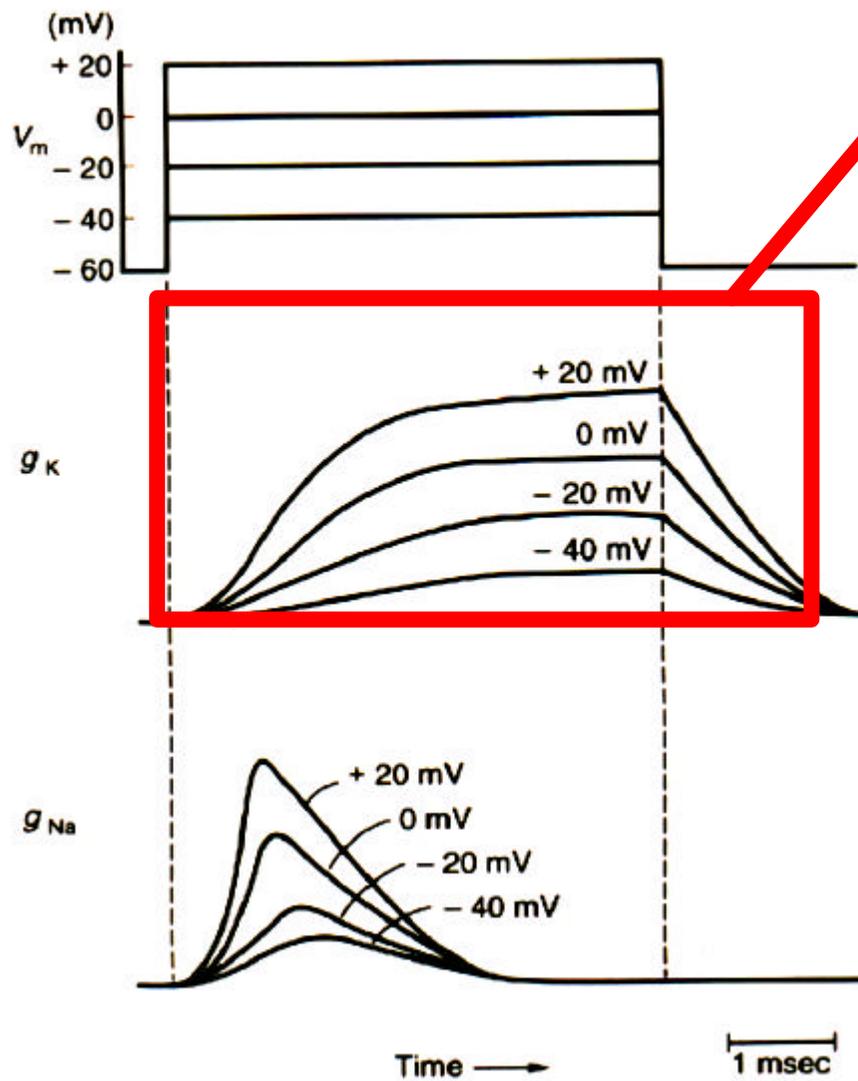
$$I_n = \sum_{i=1}^n I_i$$

$$I_i = G_i (V_m - E_i)$$

$$dV_m = \frac{I_n}{C_c}$$

$$I_n = I_K + I_{Na} + I_p$$

# Corrente de K<sup>+</sup>



$$i_K = g_K \cdot (V_m - E_K)$$

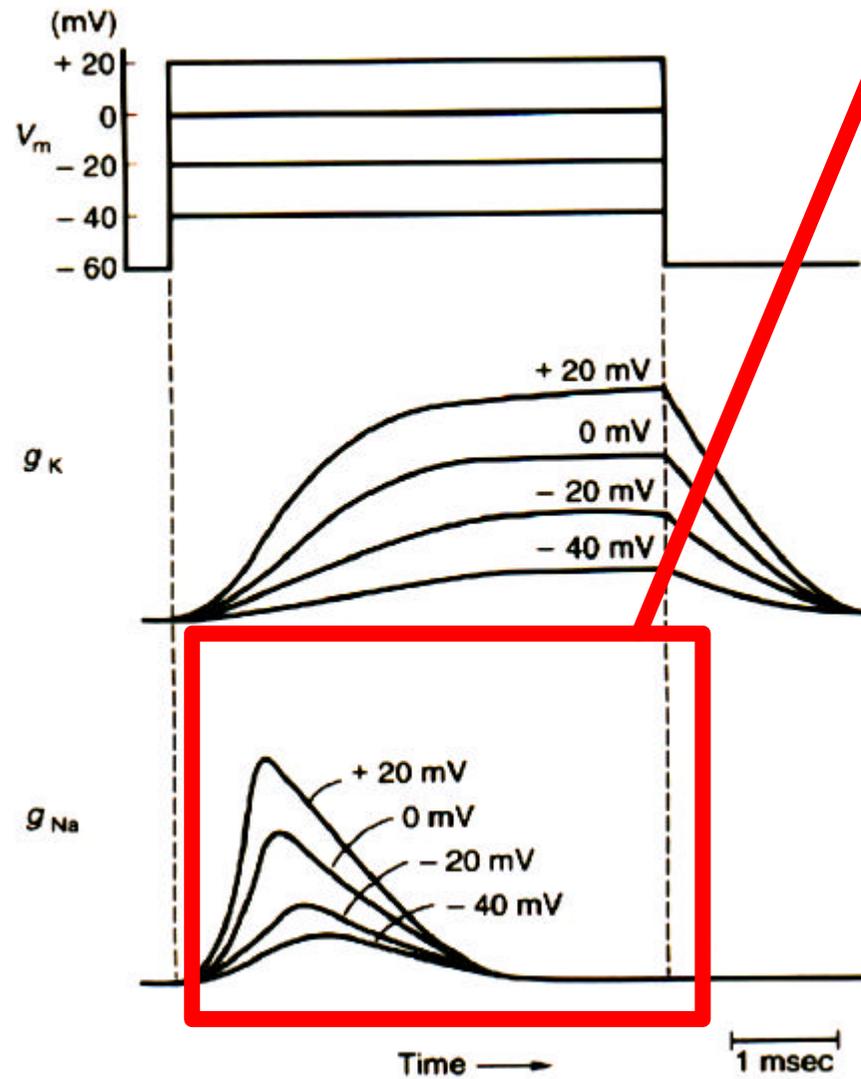
$$= g_{K,max} \cdot n^4 (V_m - E_K)$$

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

$$\alpha_n = \frac{0.01 \cdot (V_m + 10.0)}{\exp(0.1 \cdot (V_m + 10.0)) - 1.0}$$

$$\beta_n = 0.125 \cdot \exp\left(\frac{V_m}{80.0}\right)$$

# Corrente de Na<sup>+</sup>



$$i_{Na} = g_{Na} \cdot (V_m - E_{Na})$$

$$= g_{Na,max} \cdot m^3 \cdot h \cdot (V_m - E_{Na})$$

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

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

$$\alpha_m = \frac{0.1 \cdot (V_m + 25.0)}{\exp(0.1 \cdot (V_m + 25.0)) - 1.0}$$

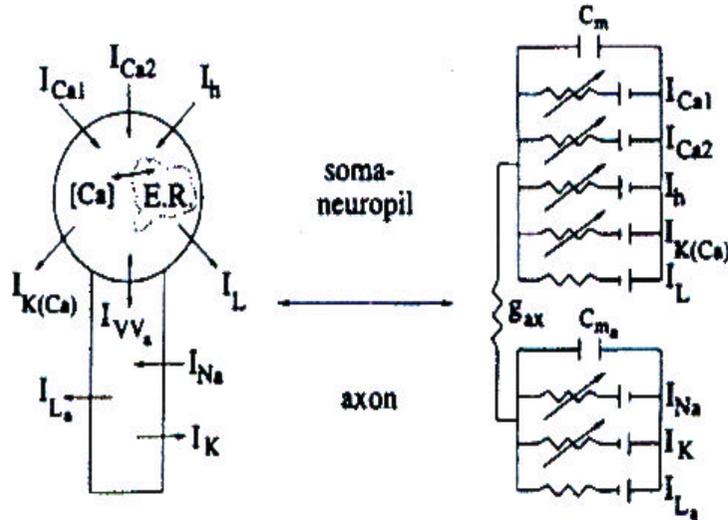
$$\beta_m = 4 \cdot \exp\left(\frac{V_m}{18.0}\right)$$

$$\alpha_h = 0.07 \cdot \exp\left(\frac{V_m}{20.0}\right)$$

$$\beta_h = \frac{1.0}{\exp(0.1 \cdot (V_m + 30.0)) + 1.0}$$

**Hora da simulação**

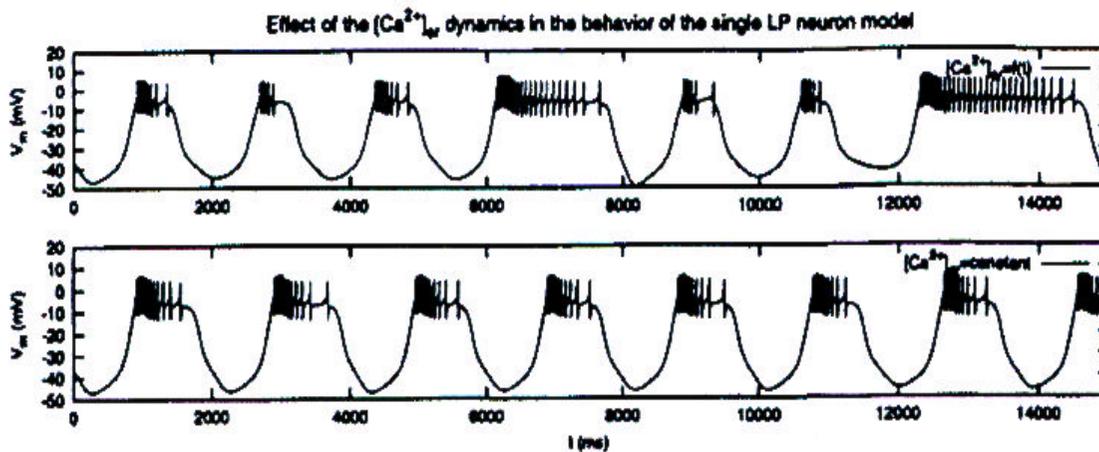
# Modelo tipo Hodgkin-Huxley de um neurônio LP isolado



Dinâmica da Voltagem =  
2 equações diferenciais

Dinâmica das correntes =  
8 equações diferenciais

Dinâmica da [Ca] =  
2 equações diferenciais

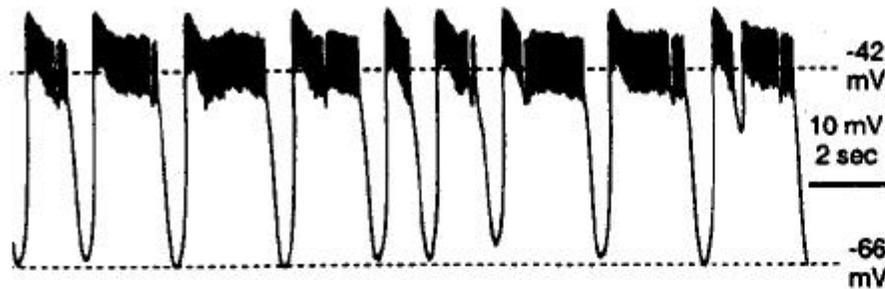


**TOTAL =**  
**12 equações diferenciais**

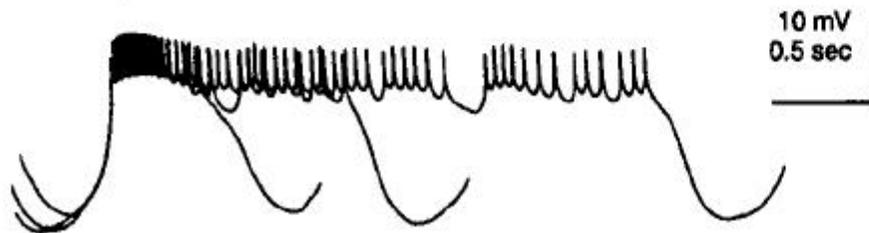
→ Espaço de fase com  
12 dimensões

## Mas lembrando ...

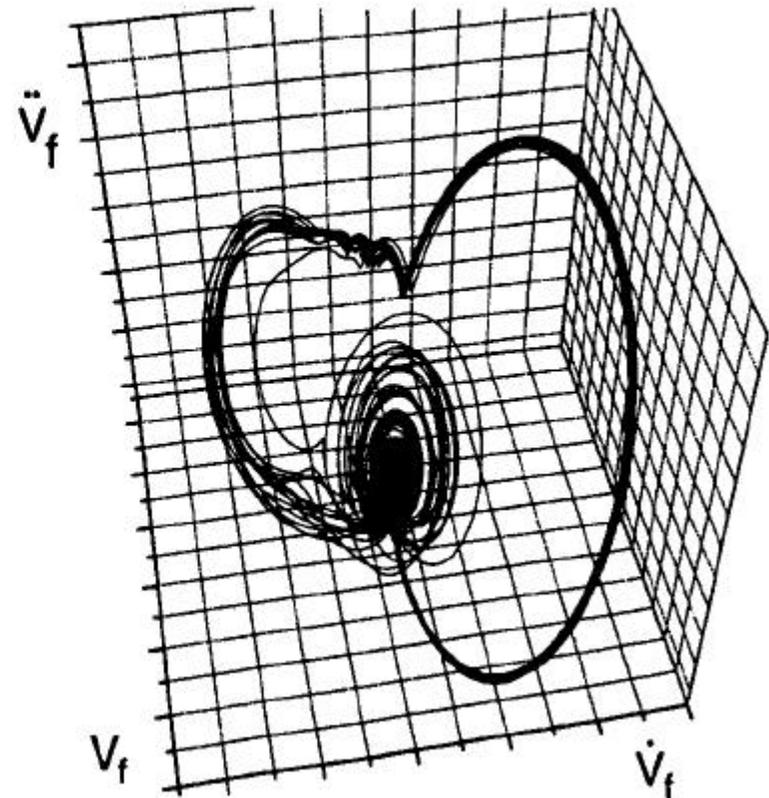
1: irregular bursting of synaptically-isolated LP neuron



2: aligned and superimposed bursts

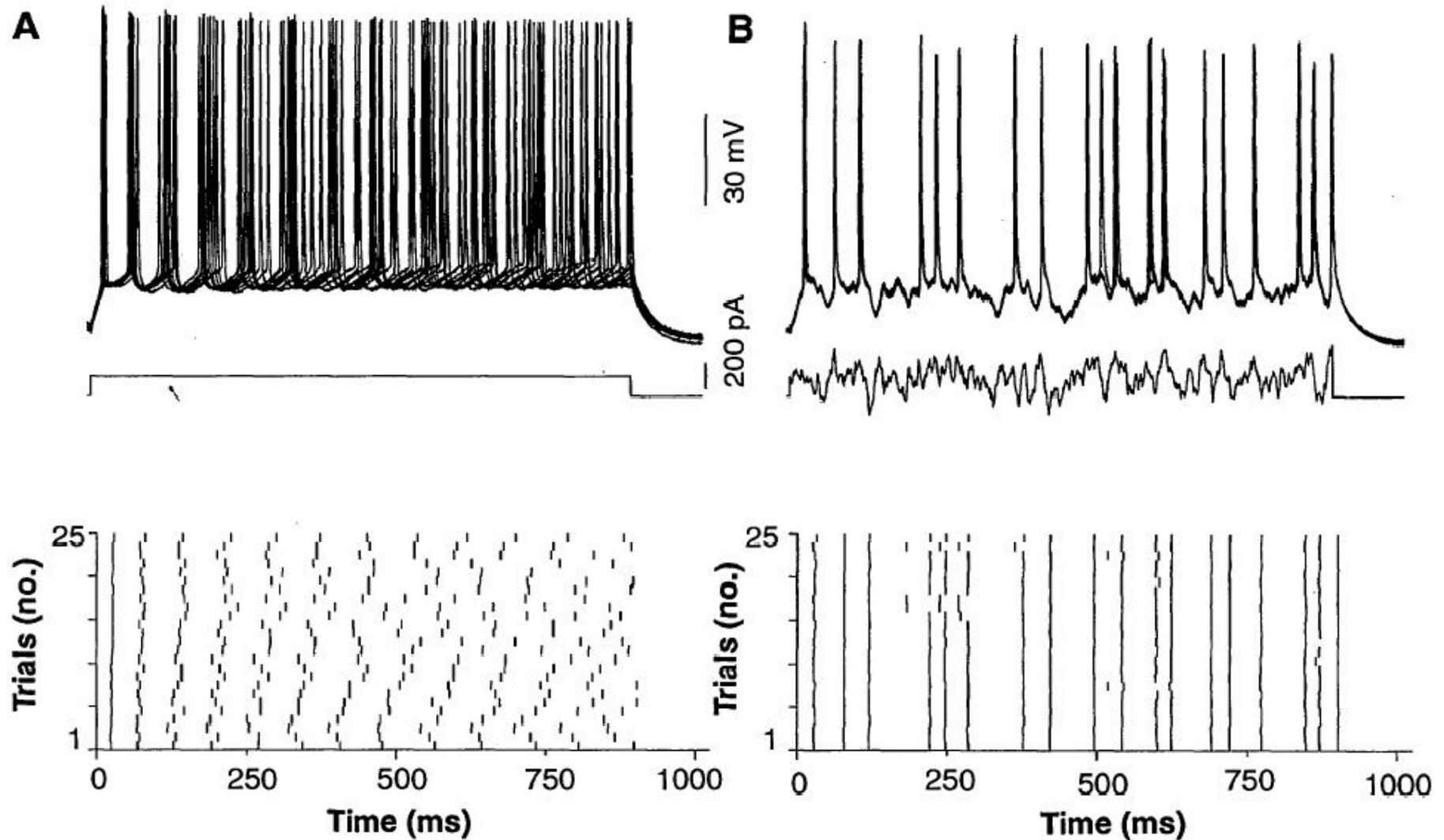


3: phase diagram of slow voltage oscillation



o atrator do sistema biológico ocupa um número muito menor de dimensões (apenas 3 ou 4).

Mainen, Z. F., & Sejnowski, T. (1995). Reliability of spike timing in neocortical neurons. *Science*, 268, 1503–1508.



Elad Schneidman, Barry Freedman, and Idan Segev  
Ion Channels and the Reliability of Spike Timing  
*Neural Computation* 10, 1679–1703 (1998)

