

Bursting (beta) rhythms

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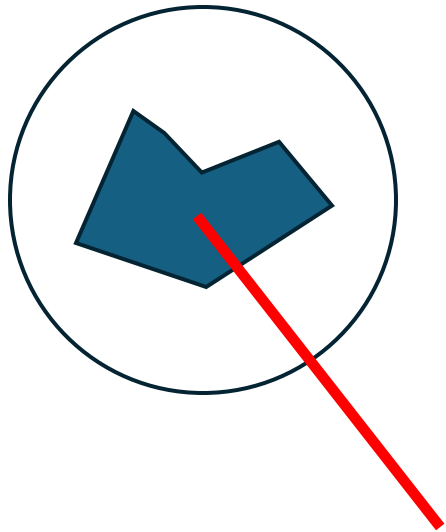
Today

Model of the bursting (beta) rhythm

Beta rhythms

20-30 Hz

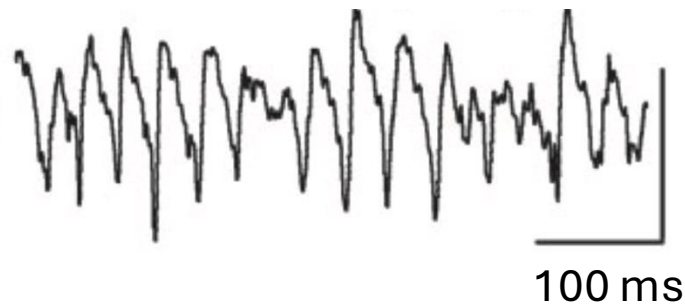
experiment



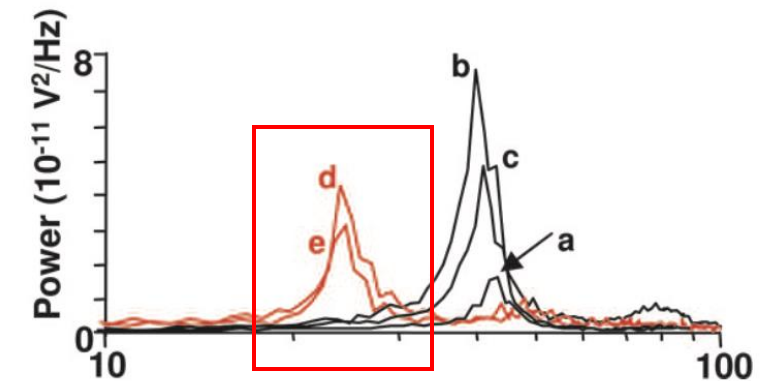
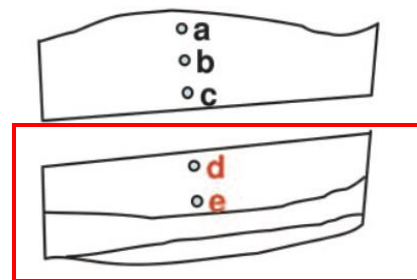
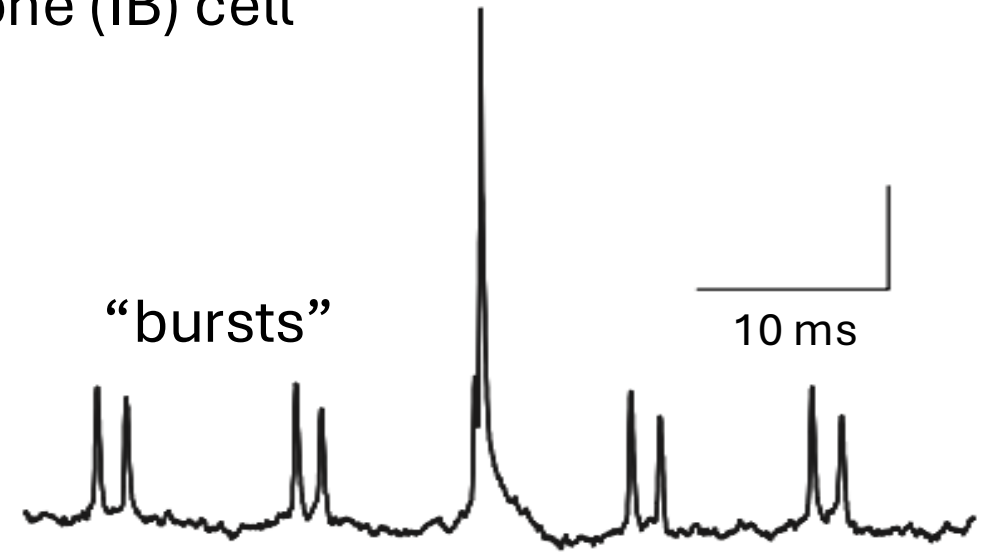
in vitro preparation

block synaptic transmission

record LFP



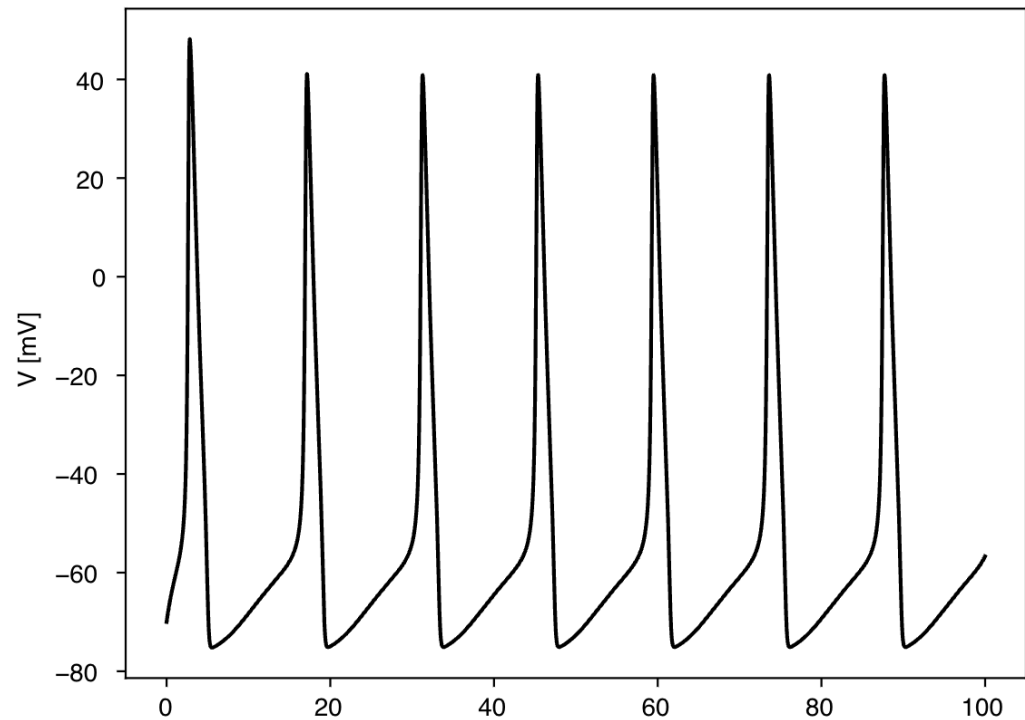
Record from one (IB) cell



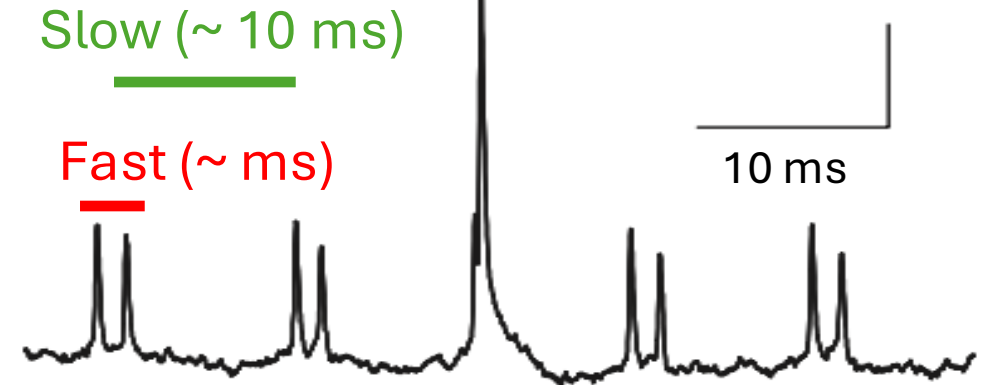
[Roopun et al., PNAS, 2006]

Beta rhythm model

Our existing models (LIF, HH, ING, PING) do **not** burst



one timescale



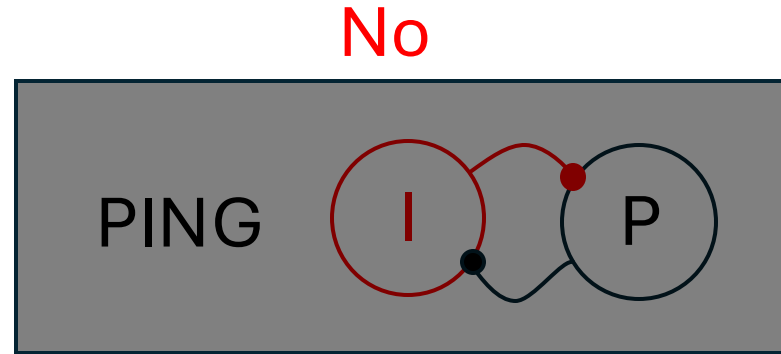
two timescales

Q. Model this?

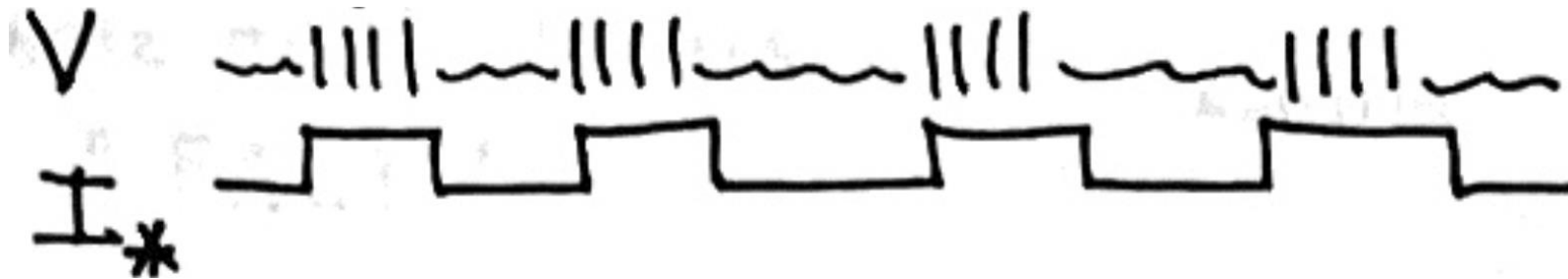
Beta rhythm model

Mechanisms

- not synaptic
- another ion current?



Intuition: imagine injecting a modulated current I_* to I&F model



bursting ... I_* sets the slow timescale

Idea: update HH model with a new current that acts like I_*

Beta rhythm model

Remember HH

$$C \frac{dV}{dt} = I_{\text{input}}(t) - \bar{g}_K n^4 (V - V_K) - \bar{g}_{\text{Na}} m^3 h (V - V_{\text{Na}}) - \bar{g}_L (V - V_L)$$

$$\frac{dn}{dt} = - \frac{n - n_{\infty}(V)}{\tau_n(V)}$$

$$\frac{dm}{dt} = - \frac{m - m_{\infty}(V)}{\tau_m(V)}$$

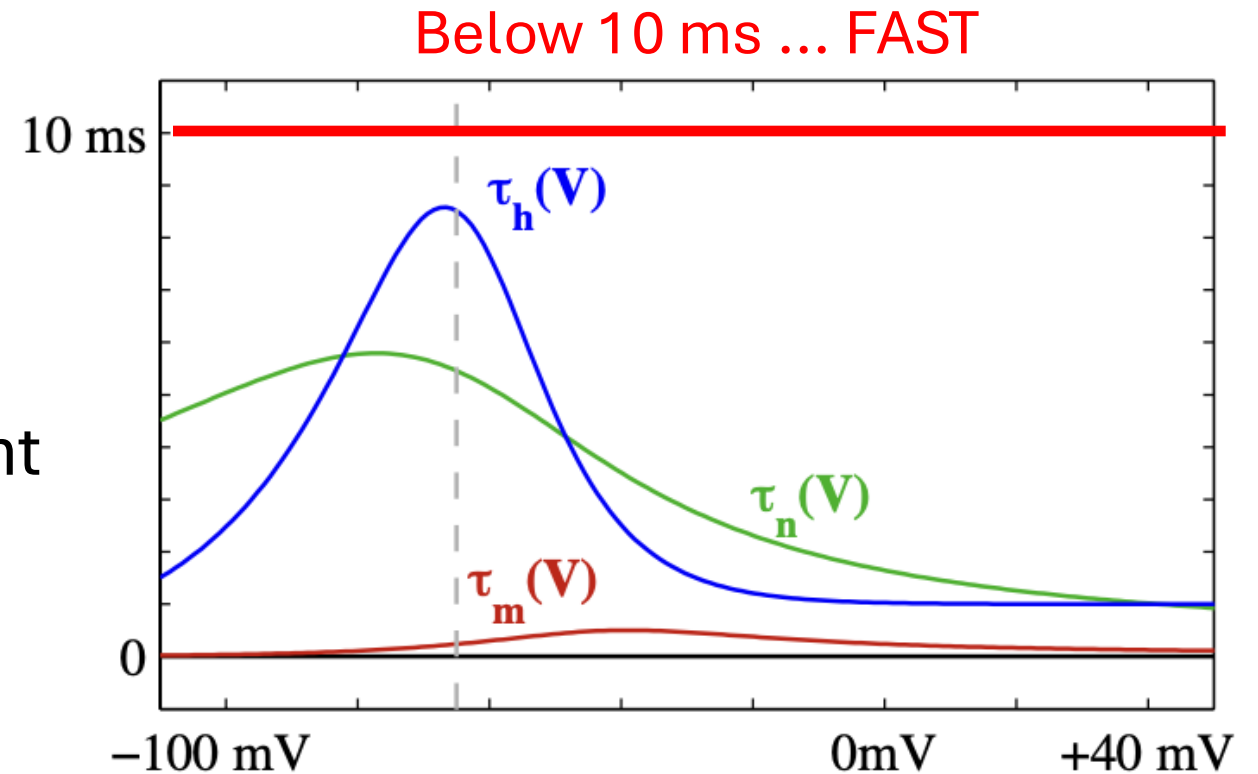
$$\frac{dh}{dt} = - \frac{h - h_{\infty}(V)}{\tau_h(V)}$$

Time constants are voltage dependent

The gate dynamics {n,m,h} are **fast**

➔ V changes quickly (~ ms spike)

➔ No slow dynamics in HH model



Beta rhythm model

Q. How do we add the slow dynamics?

A. Add a new current

$$C \frac{dV}{dt} = \boxed{I_{Na} + I_K + I_L + I_{inj}} + \boxed{I_{new}}$$

original HH (fast) new current (will set the slow timescale)

Q. What is I_{new} ?

Beta rhythm model

Currents

- “fast” sodium & “fast” potassium → original HH model
- many others exist

... with V-dependent steady-states & time constants

TABLE A2. Ionic conductance kinetic parameters

Conductance Type	Steady-State Activation/Inactivation	Time Constant (ms)
g_{Na} -transient: activation	$1/\{1 + \exp[(-V - 34.5)/10]\};$	$0.025 + 0.14 \exp[(V + 26.5)/10] \quad [V \leq -26.5]$ $0.02 + 0.145 \exp[(-V - 26.5)/10] \quad [V \geq -26.5]$
g_{Na} -transient: inactivation	$1/\{1 + \exp[(V + 59.4)/10.7]\};$	$0.15 + 1.15/\{1 + \exp[(V + 33.5)/15]\}$
g_{Na} -persistent: activation	$1/\{1 + \exp[(-V - 48)/10]\};$	$0.025 + 0.14 \exp[(V + 40)/10] \quad [V \leq -40]$ $0.02 + 0.145 \exp[(-V - 40)/10] \quad [V \geq -40]$
g_K -delayed rectifier: activation	$1/\{1 + \exp[(-V - 29.5)/10]\};$	$0.25 + 4.35 \exp[(V + 10)/10] \quad [V \leq -10]$ $0.25 + 4.35 \exp[(-V - 10)/10] \quad [V \geq -10]$
g_K -transient (“A”): activation	$1/\{1 + \exp[(-V - 60)/8.5]\};$	$0.185 + 0.5/\{\exp[(V + 35.8)/19.7] + \exp[(-V - 79.7)/12.7]\}$
g_K -transient (“A”): inactivation	$1/\{1 + \exp[(V + 78)/6]\};$	$0.5/ \quad [V \leq -63]$ $\{\exp[(V + 46)/5] + \exp[(-V - 238)/37.5]\}$ $9.5 \quad [V \geq -63]$
g_K -“K2”: activation	$1/\{1 + \exp[(-V - 10)/17]\};$	$4.95 + 0.5/\{\exp[(V - 81)/25.6] + \exp[(-V - 132)/18]\}$
g_K -“K2”: inactivation	$1/\{1 + \exp[(V + 58)/10.6]\};$	$60 + 0.5/\{\exp[(V - 1.33)/200] + \exp[(-V - 130)/7.1]\}$
g_{Ca} -low-threshold: activation	$1/\{1 + \exp[(-V - 56)/6.2]\};$	$0.204 + 0.333/\{\exp[(V + 15.8)/18.2] + \exp[(-V - 131)/16.7]\}$
g_{Ca} -low-threshold: inactivation	$1/\{1 + \exp[(V + 80)/4]\};$	$0.333 \exp[(V + 466)/66.6] \quad [V \leq -81]$ $9.32 + 0.333 \exp[(-V - 21)/10.5] \quad [V \geq -81]$
Anomalous rectifier	$1/\{1 + \exp[(V + 75)/5.5]\};$	$1/\{\exp[-14.6 - 0.086V] + \exp[-1.87 + 0.07V]\}$
Conductance Type	Forward Rate Function (α)	Backward Rate Function (β)
g_K -Ca- & V-dependent (“C”) (voltage-dependent term)	$0.053 \exp[(V + 50)/11 - (V + 53.5)/27] \quad [V \leq -10]$ $2 \exp[(-V - 53.5)/27] \quad [V \geq -10]$	$2 \exp[(V - 53.5)/27] - \alpha \quad [V \leq -10]$ $0 \quad [V \geq -10]$
g_K -“M”	$0.02/\{1 + \exp[(-V - 20)/5]\};$	$0.01 \exp[(-V - 43)/18]$
g_K -AHP	$\min(10^{-4} \chi, 0.01);$	0.01
g_{Ca} -high-threshold	$1.6/\{1 + \exp[-0.072(V - 5)]\};$	$0.02 (V + 8.9)/\{\exp[(V + 8.9)/5] - 1\}$

[Traub et al., J Neurophysiol, 2003]

Beta rhythm model

Ignore details & assume 4 candidate currents

$\{A, B, C, D\}$

We know their steady-state functions $x_{\infty}[V]$ and time constants $\tau_x[V]$



Note voltage dependent

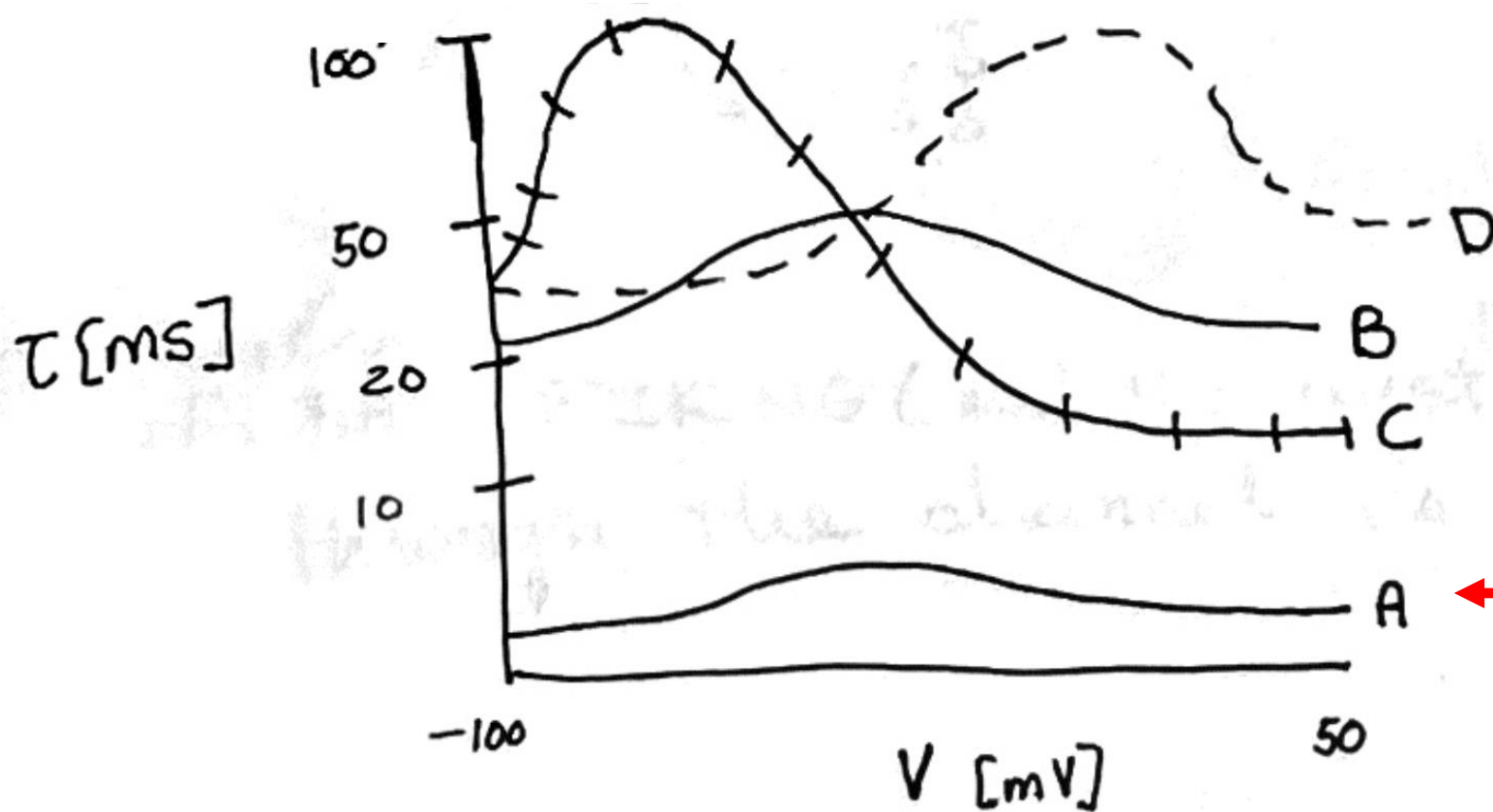
Goal: Determine which current could produce bursting we observe

A process of elimination ...

Beta rhythm model

~~A~~, B, C, D

Investigate the time constants $\tau_x[V]$



We want a **slow** current

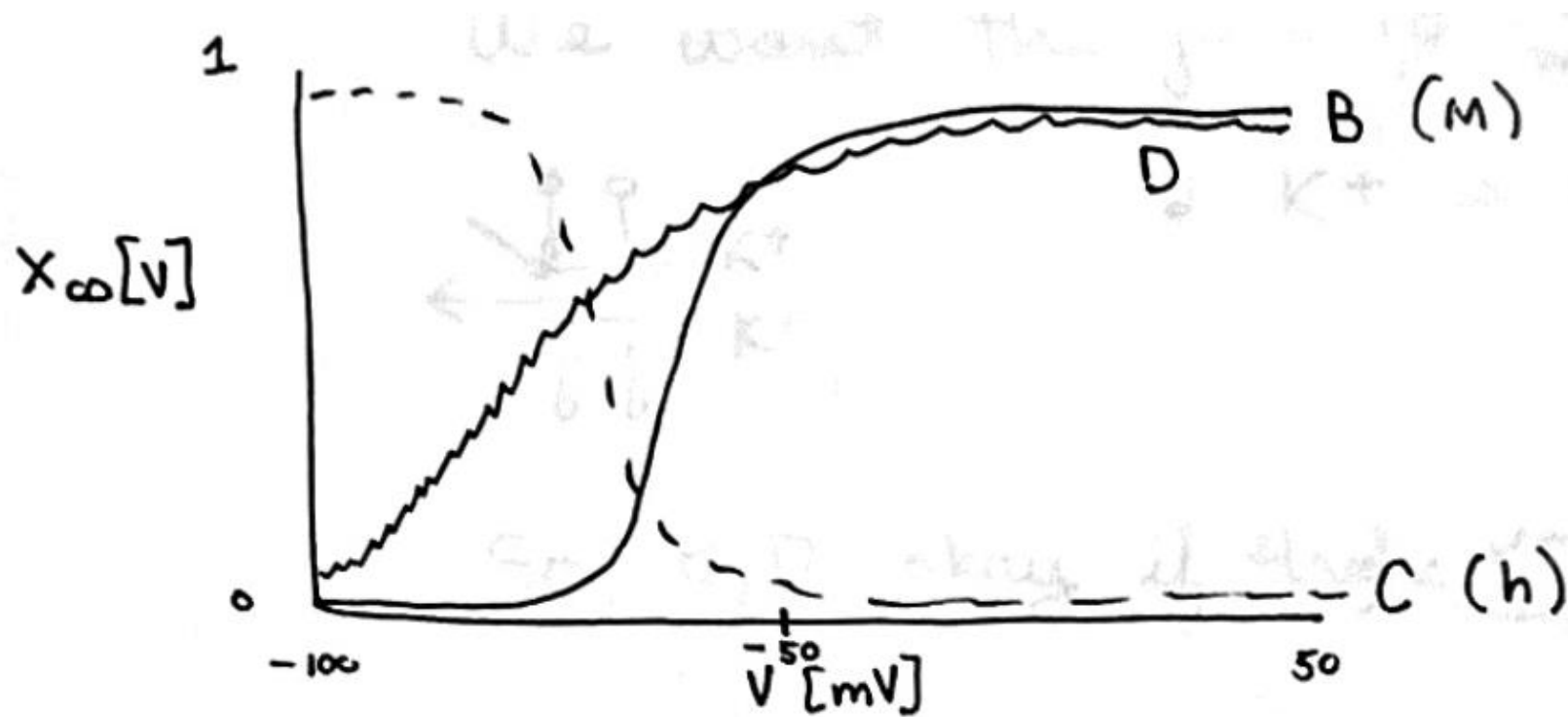
Eliminate A

- too fast for bursting

Beta rhythm model

~~A~~ B, C, D

Investigate the steady-state functions $x_\infty[V]$.

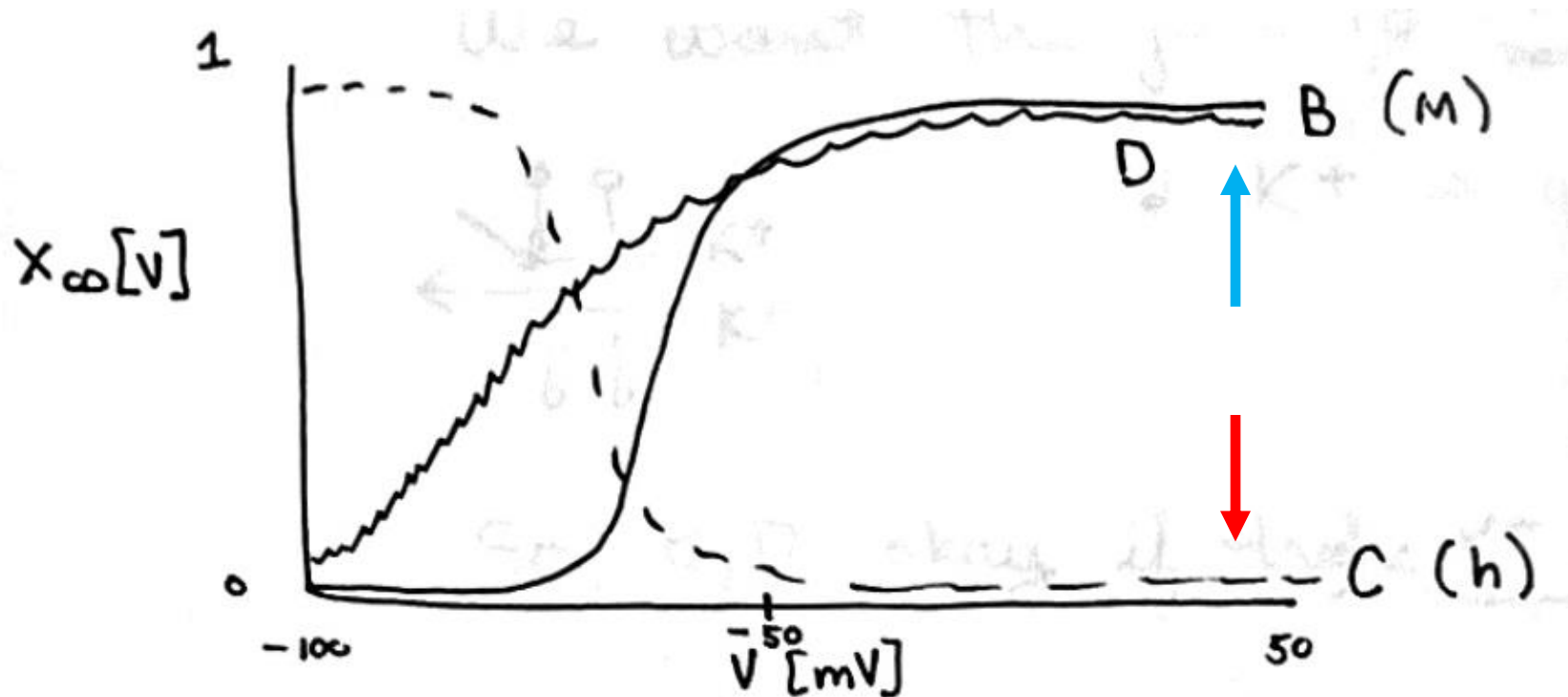


Q. Which one?

Beta rhythm model

~~{B, C, D}~~

Two cases: Gate changes (slowly) during the burst



burst \rightarrow a depolarized state

Gates: (B, D) “depolarization activated”
(C) “depolarization inactivated”

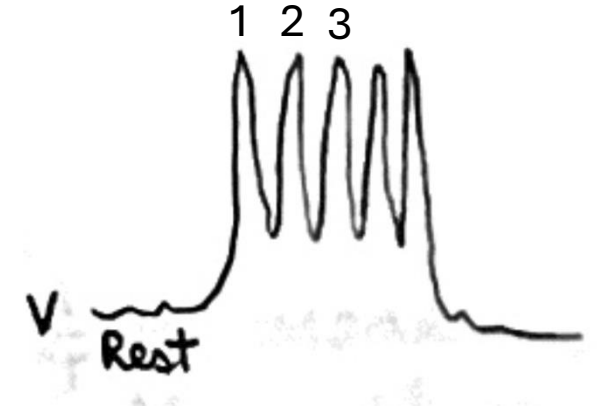
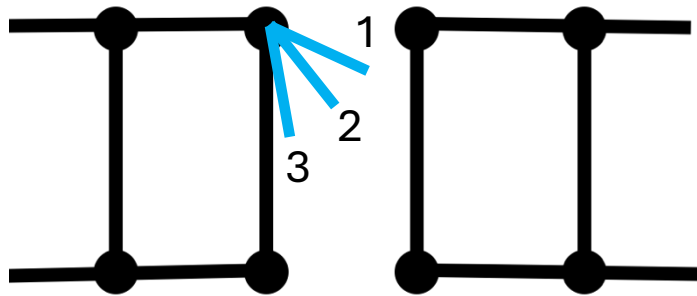
gates **open** during burst
gates **close** during burst

Beta rhythm model

~~{A, B, C, D}~~

Case 1: Gate **opens** (slowly) during the burst (B,D)

Each spike opens the gate a little bit



burst \rightarrow a depolarized state

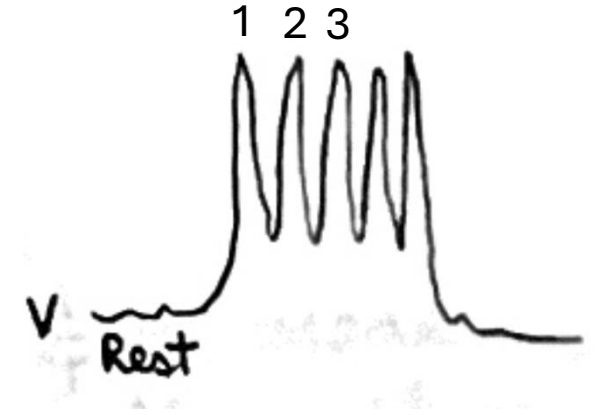
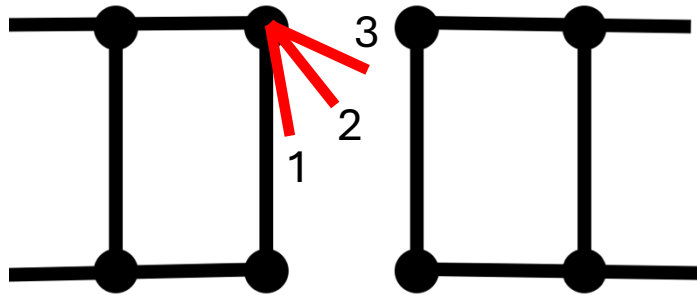
when gate is open enough, this current halts the spiking

Beta rhythm model

~~{A, B, C, D}~~

Case 2: Gate **closes** (slowly) during the burst (C)

Each spike closes the gate a little bit



burst → a depolarized state

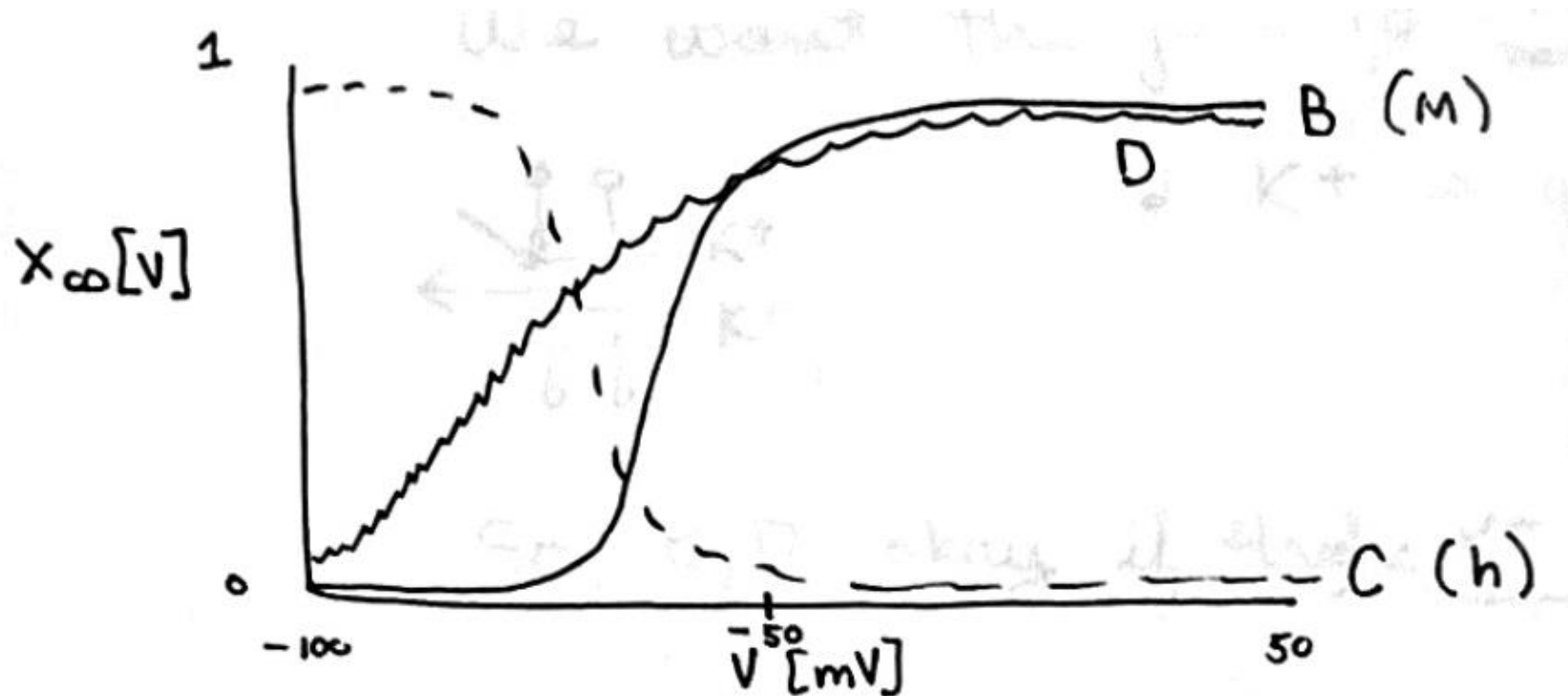
when gate is closed enough, this current halts the spiking

Beta rhythm model

~~{A, B, C, D}~~

Case 1: Gate **opens** (slowly) during the burst (B,D)

Case 2: Gate **closes** (slowly) during the burst (C)



In either case, to halt spiking (end the burst), the type of ion that flows through the channel is critical.

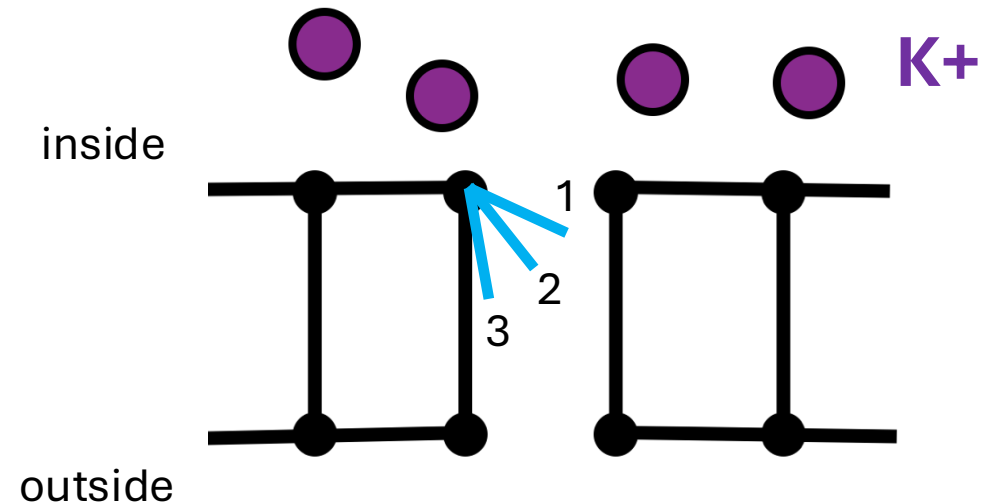
Beta rhythm model

~~A~~, B, C, D}

Case 1: Gate **opens** (slowly) during the burst (B,D)

Q. What ion is gated?

We want the gate to open & halt bursting



Gate opens enough
K⁺ released from cell
hyperpolarize neuron

So (B,D) work if they're K⁺ currents

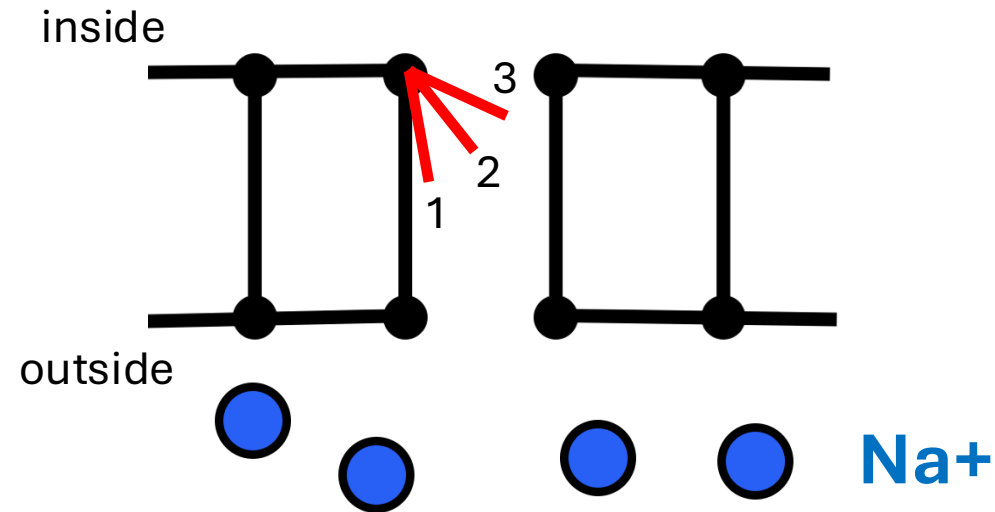
Beta rhythm model

~~A~~, B, C, D}

Case 2: Gate **closes** (slowly) during the burst (C)

Q. What ion is gated?

We want the gate to close & halt bursting

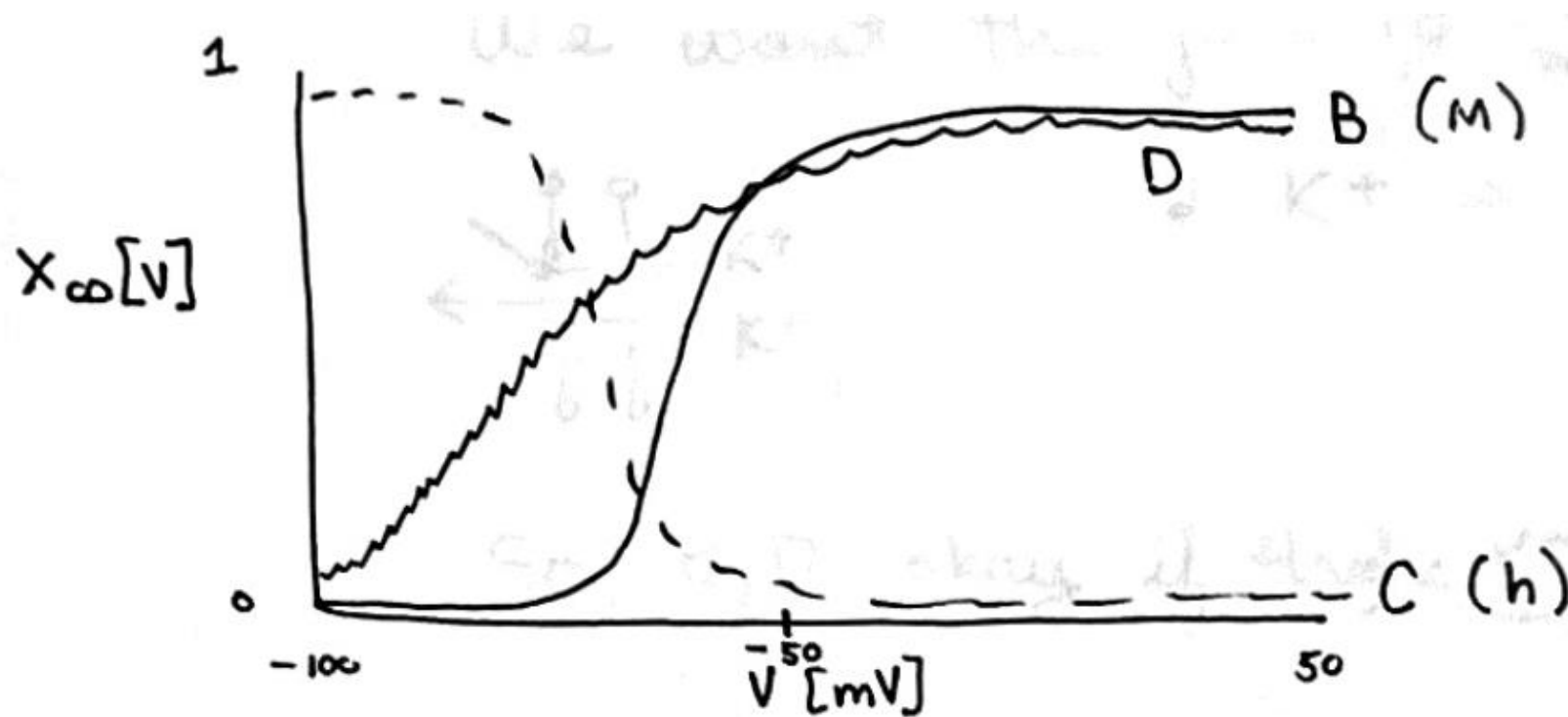


Gate closes enough
Na⁺ cannot enter cell
hyperpolarize neuron

So (C) works if it's Na⁺ (or Ca²⁺) currents

Beta rhythm model

Summary



(B,D)

okay if K⁺ current
slowly open & halt burst

(C)

okay if Na⁺ current
slowly close & halt burst

~~{A, B, C, D}~~
↑

We learn:

B gates K⁺



C gates Na⁺



D gates Na⁺



~~A~~, B, C, ~~D~~

Beta rhythm model

Two options remain for I_{new}

B: slow, depolarization activated, outward K⁺ current

C: slow, depolarization inactivated, inward Na⁺ current

Sketch a model for **B**

~~A~~, **B**, C, ~~D~~

$$C \frac{dV}{dt} = I_{\text{input}}(t) - \bar{g}_K n^4 (V - V_K) - \bar{g}_{Na} m^3 h (V - V_{Na}) - \bar{g}_L (V - V_L) - \boxed{g_B B (V - E_K)}$$

$\frac{dn}{dt} = -\frac{n - n_\infty(V)}{\tau_n(V)}$

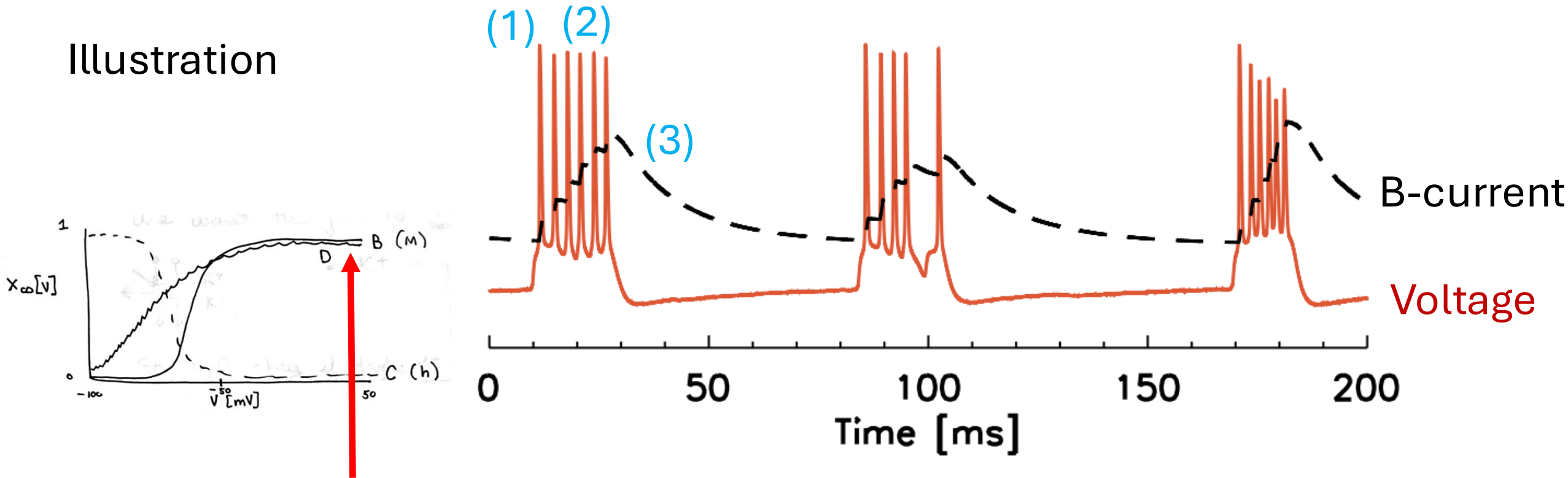
linear (from lit.) K+ current

Note: model now has 5 variables $\{V, n, m, h, B\}$

Beta rhythm model

~~A~~, B, ~~C~~, ~~D~~

Illustration



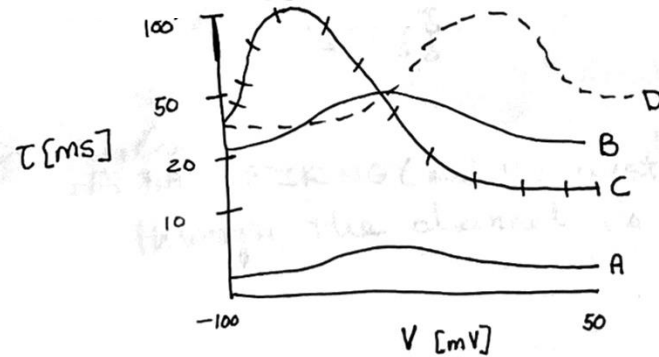
- (1) During spike, $B_\infty[V] \rightarrow 1$ so, $B \rightarrow 1$ but slowly so, B increases a little
- (2) repeat for multiple spikes $B \rightarrow 1$ B opens enough to halt spiking
- (3) B decays $\rightarrow 0$ another burst starts

Summary

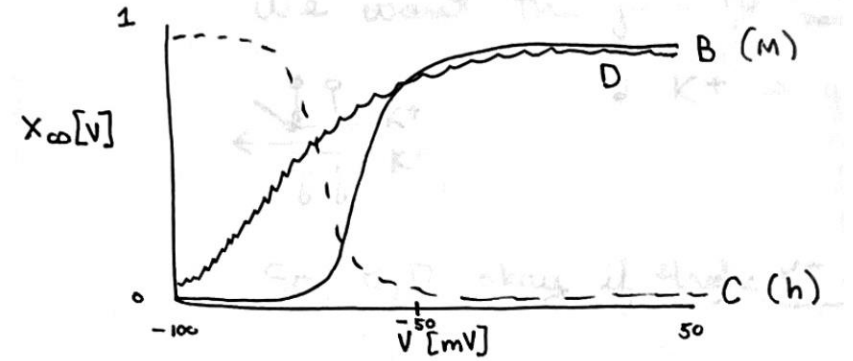
A procedure to classify the dynamic effects of a current on a neuron

3 questions

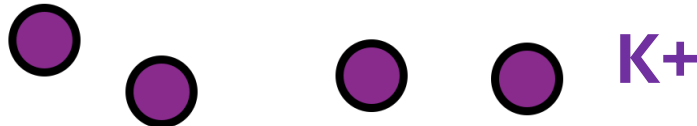
1. Is it fast or slow?



2. Is it depolarization activated or inactivated?



3. What ion is gated?



Then, we know enough to predict dynamic behavior.

Beta rhythm model

Python Homework