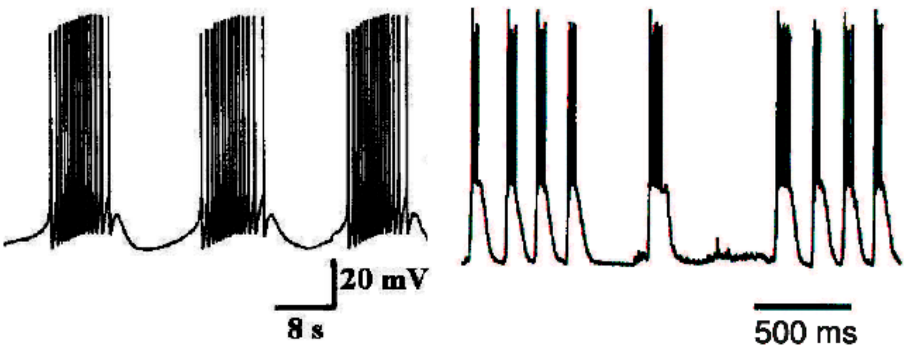
Bursting Neuron



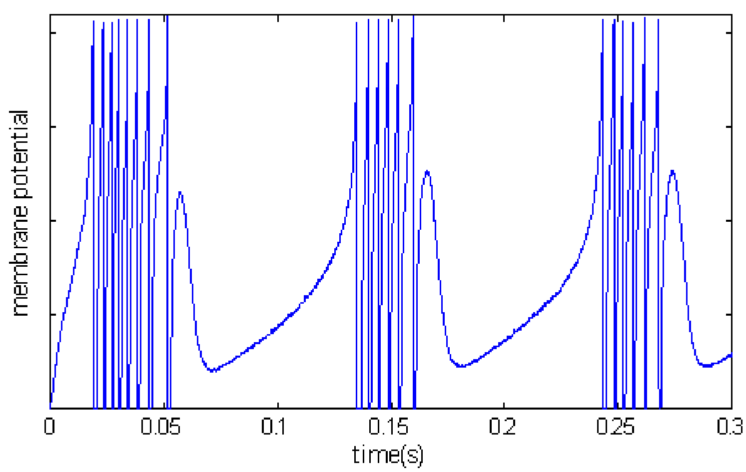
Bursting in Aplysia (left) and in thalamic reticular neuron (right)

Has two stable states: Rest and spiking

And mechanism(s) to switch between them

Requires an inward-current proportional to spike rate

Model simulation



Adding a Ca^{2+} current converts the adapting neuron into a bursting neuron.

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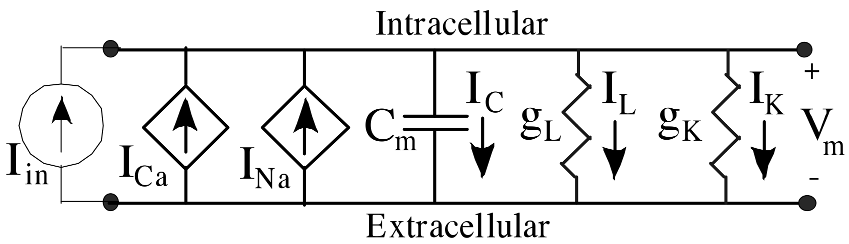
Membrane-voltage equation



Slow voltage-dependent, high-threshold Ca^{2+} current (I_{Ca}) added.

Like the K-channels, these Ca-channels open only during a spike:

$$C_m \frac{dV_m}{dt} + g_{lk} V_m + g_K V_m = I_{in} + I_{Ca} + \frac{1}{3}\left(\frac{V_m}{V_{th}}\right)^2 g_{lk} V_m$$

where $I_{Ca} = \Delta I_{Ca}\, \tau_{Ca}\, f$

We model the Ca-current in the same way as the M-current, the only difference being that it is inward rather than outward. Thus, the Ca-current is proportional to spike rate, with proportionality constant determined by the increase in Ca-current each spike evokes (ΔI_{Ca}) and the time-constant with which the Ca-current decays (τ_{Ca}).

In dimensionless form, we have:

$$\tau_m \frac{dx}{dt} + (1+g)\, x = r_{in} + r_{Ca} + \frac{1}{3} x^3$$

$$r_{Ca}[f] = \Delta r_{Ca}\, \tau_{Ca}\, f$$

where $\tau_m = \frac{C_m}{g_{lk}}$, $x = \frac{V_m}{V_{th}}$, $r_{in} = \frac{I_{in}}{g_{lk} V_{th}}$, $g = \frac{g_K}{g_{lk}}$, $\Delta r_{Ca} \equiv \frac{\Delta I_{Ca}}{g_{lk} V_{th}}$

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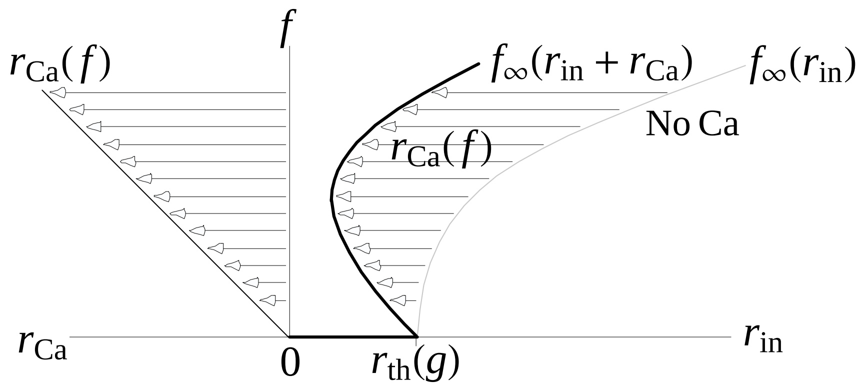
Effect of Ca-current



Ca-current lowers input current required to spike at a given frequency.

Adding the Ca-current ($r_{\mathrm{Ca}}(f)$) generated by a given spike-rate (f) to the input current (r_{in}) and substituting that into the neuron's frequency-current relationship ($f_\infty(r)$), yields a new frequency-current relationship ($f_\infty(r_{\mathrm{in}} + r_{\mathrm{Ca}})$). When plotted, this new relationship yields a curve that is shifted to the left by the amount $\Delta \mathrm{r}_{\mathrm{Ca}}\, \tau\, f$ for each frequency f. This additional current makes it possible to sustain spiking with an input current lower than the minimum ($r_{\mathrm{th}}(g)$) required to start it!

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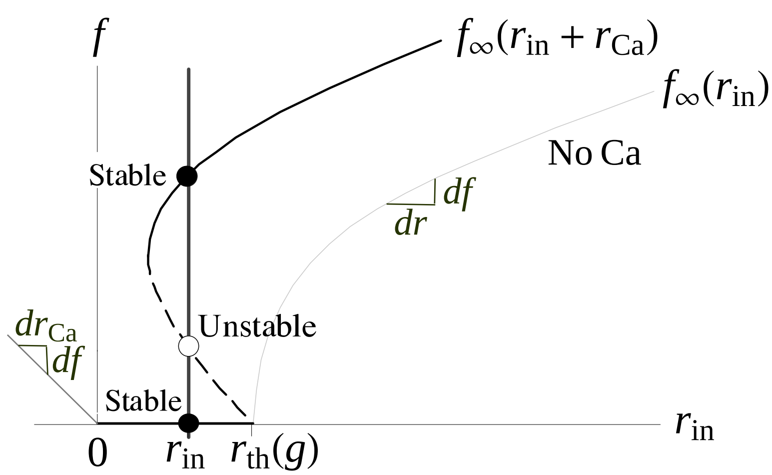
Ca-current produces bistability



Three distinct spike-rates are possible for this input current r_{in}.

For input currents in a certain range, there are three distinct frequencies at which the neuron can fire. The middle fixed-point (intermediate spike-rate) is unstable: A slight increase in spike-rate Δf increases the Ca-current by an amount greater than the amount of current required to sustain that increase in spike rate (i.e., $dr_{\mathrm{Ca}}/df > \mathrm{dr}/df$).

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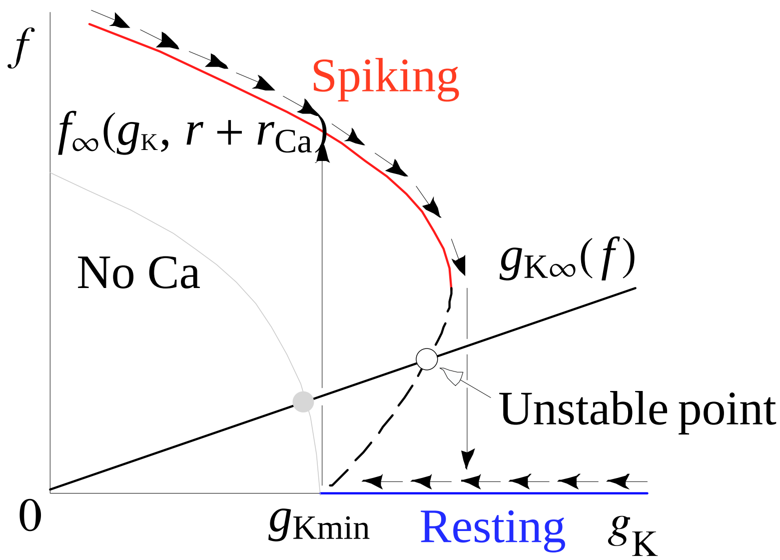
M-current ($g_{K\infty}(f)$) switches between states



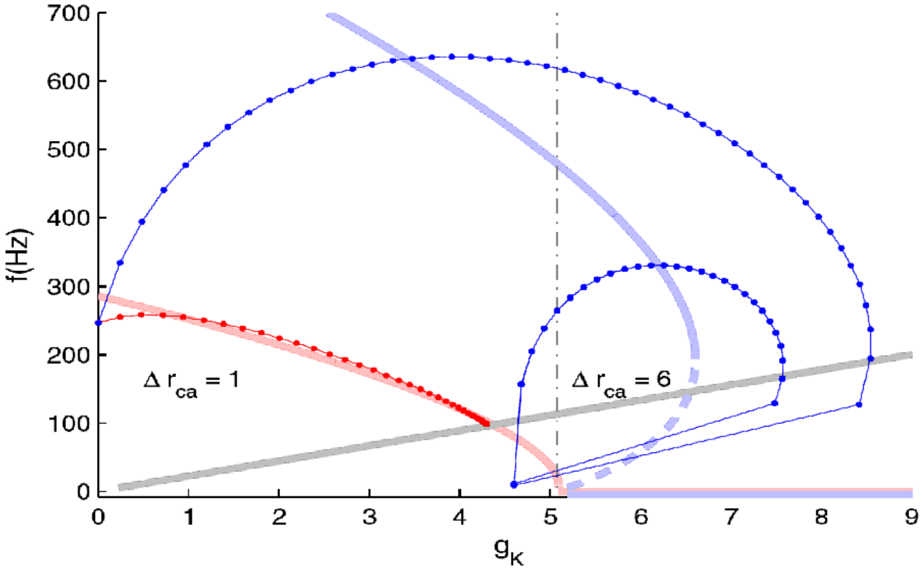
The trajectory (arrows) orbits the unstable-point—a limit-cycle.

As we increase the Ca-current's strength (either ΔI_{Ca} or τ_{Ca}), the stable-point (gray, No Ca) becomes unstable (white, $f_\infty(g_K, r + r_{Ca})$).

The trajectory follows $f_\infty(g_K, r + r_{Ca})$'s upper (spiking) or lower (resting) parts, approaching $g_{K\infty}(f)$ in both cases.

The trajectory switches from one part to the other (resting to spiking or vise-versa) when it reaches the unstable region (slope reversal).

Phase portrait



Adapts or bursts (red or blue dotted-lines) when $\Delta r_{Ca} = 1$ or 6, respectively ($\tau_K = 180$ ms and $\tau_{Ca} = 10$ ms).

In actuality, the tracjectory deviates from $f_\infty(g_K, r + r_{Ca})$ because f does not respond instantaneously to changes in g_K.

The trajectory crosses $g_{K\infty}(f)$ vertically—$g_{K\infty}$is constant briefly—which makes sense since that's $g_{K\infty}$'s steady-state value for the value of f at that point.

Similarly, the trajectory crosses $f_\infty(g_K, r + r_{Ca})$ horizontally—f is constant briefly—since that's f's correct value for g_K's value at that point.

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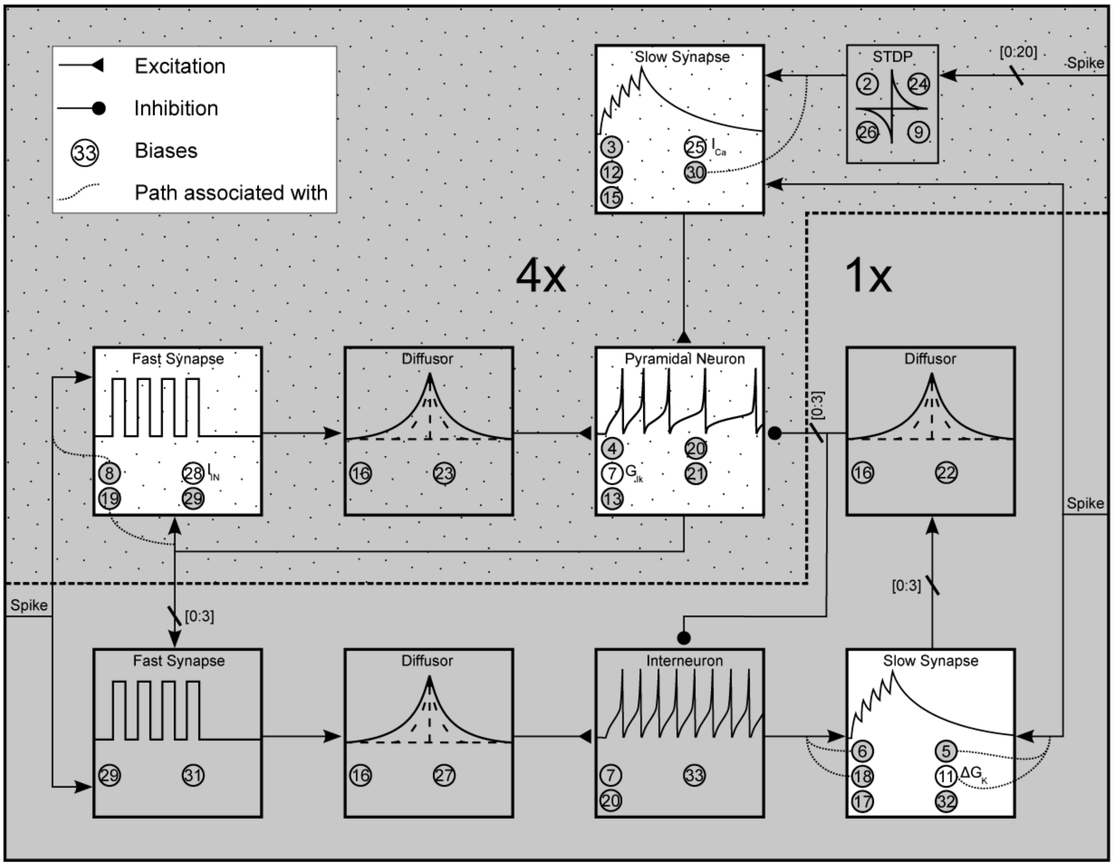
Lab 3: Set-up

1	Vrefd2a	reference voltage - leave at 2.530	18	VMAGGABA	(-) increases inhibitory synapse strength (inhibitory interneuron input)
2	VQAPRE	(-) increases LTP-side of STDP curve's height	19	VQAAMPA2	(-) increases fast excitatory synapse strength pulse-width (pyramidal neuron input)
3	VLEAKDNMDA	(+) increases slow excitatory synapse rise-time	20	VLEAKREFRACT	(+) increases absolute refractory period
4	VMAGK	(-) increases m-type potassium channel strength	21	VLEAKK	(+) increases m-type potassium decay-constant (and strength)
5	VLEAKDGABA2	(+) increases inhibitory synapse rise-time (external input)	22	VRI	(+) increases spread of inhibition
6	VLEAKDGABA	(+) increases inhibitory synapse rise-time (inhibitory interneuron input)	23	VRRC	(+) increases spread of fast excitation to pyramidal neurons
7	VLEAKSOMA	(+) increases somatic leak current	24	VLEAKPOST	(+) increases LTP-side of STDP curve's decay
8	VQAAMPA	(-) increases fast excitatory synapse strength pulse-width (external input)	25	VMAGNMDA	(-) increases slow excitatory synapse strength
9	VQAPOST	(-) increases LTD-side of STDP curve's height	26	VLEAKPRE	(+) increases LTD-side of STDP curve's decay
10	VLEAKLTP	not used	27	VRE	(+) increases spread of fast excitation to interneurons
11	VMAGGABA2	(-) increases inhibitory synapse strength (external input)	28	VMAGAMPARC	(+) increases fast excitatory synapse strength to pyramidal neurons
12	VQADNMDA2	(+) increases slow excitatory synapse rise-time	29	VLEAKAMPA	(-) increases fast excitatory synapse strength pulse-width
13	VANP	(+) increases pyramidal neuron sodium threshold	30	VQANMDA	(+) increases slow excitatory synapse rise-time
14	VLEAKLTD	not used	31	VMAGAMPAINT	(+) increases fast excitatory synapse strength to interneurons
15	VLEAKNMDA	(+) increases slow excitatory synapse decay-constant (and strength)	32	VQADGABA	(+) increases inhibitory synapse rise-time
16	VG	leave at 1.250	33	VANI	(+) increases interneuron sodium threshold
17	VLEAKGABA	(+) increases inhibitory synapse decay-constant (and strength)			



The neuron transitions from adapting to bursting as Δr_{Ca} increases.

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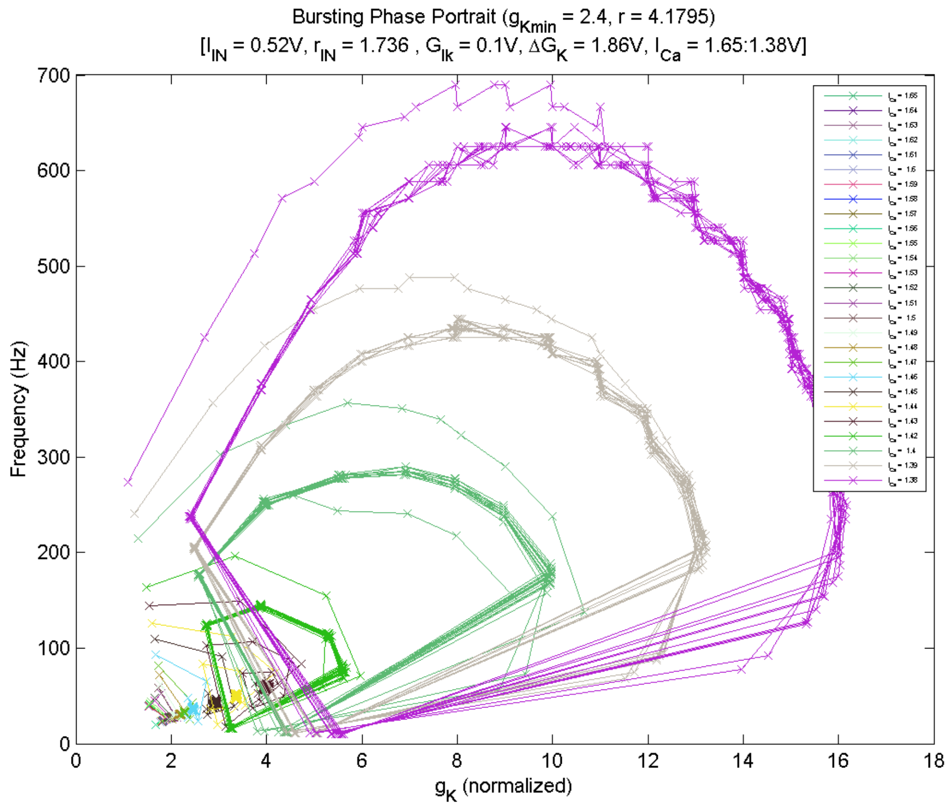
Lab 3: Data



The neuron transitions from adapting to bursting as Δr_{Ca} increases.

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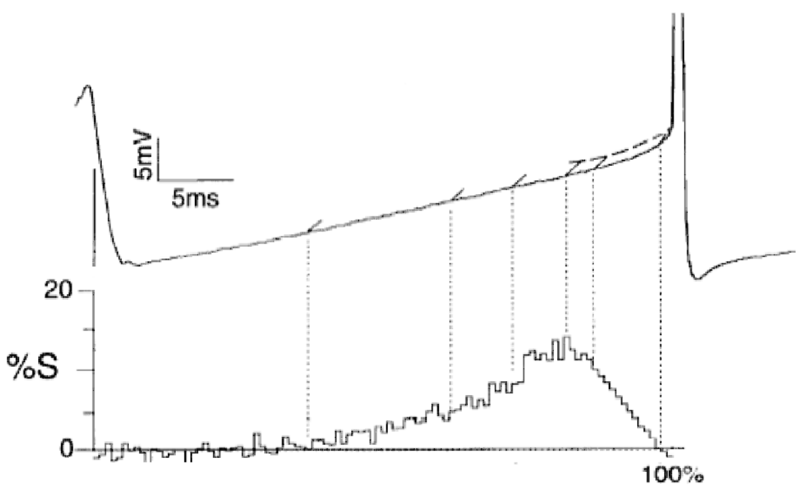
Next week: Phase-response curve



Current-pulses decrease a cortical neuron's period (Cat, Layer V) [Fetz93]