Information Coding in Nervous Systems: Responses to Regular and Irregular Discharges

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"So what is this mind of ours:
what are these atoms with consciousness?
Last week's potatoes! They can now remember
what was going on in my mind a year ago
— a mind which has long ago been replaced."
Richard P. Feynman

The Most Complex Thing

- The brain computes, but how?
- Simpler nervous systems also produce complex behaviors.
  - Nonlinear Dynamics: behavioral complexity does not require structural complexity.
- The micro level: the language of neurons.
  - Fundamental unit of neural computation: what one neuron tells another $\Longrightarrow$ synaptic coding.

Understanding Synaptic Coding

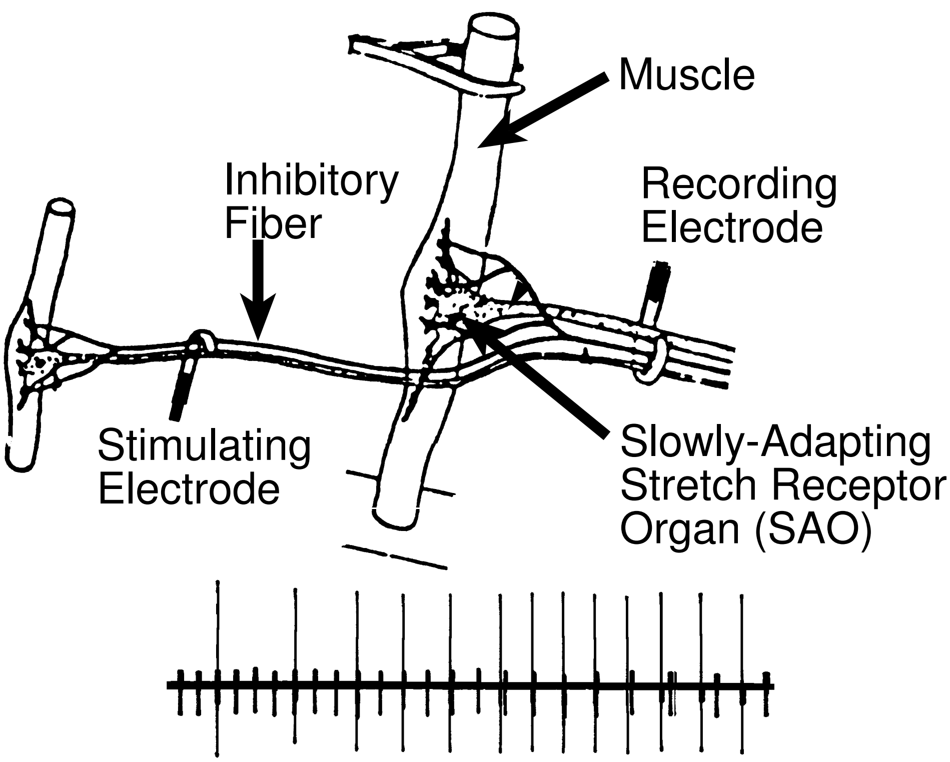
Methodology

- Describe synaptic coding in terms of dynamical laws it obeys.
- Close coupling between experiment and theory.
  - Living preparation: crayfish slowly adapting stretch receptor organ (SAO).
  - Model of crustacean stretch receptor with parameters adjusted to match details of SAO physiology.
  - Identical data analysis.

Relevant research areas neuroscience, scientific computing, nonlinear dynamics, information theory, statistics, artificial intelligence, . . .

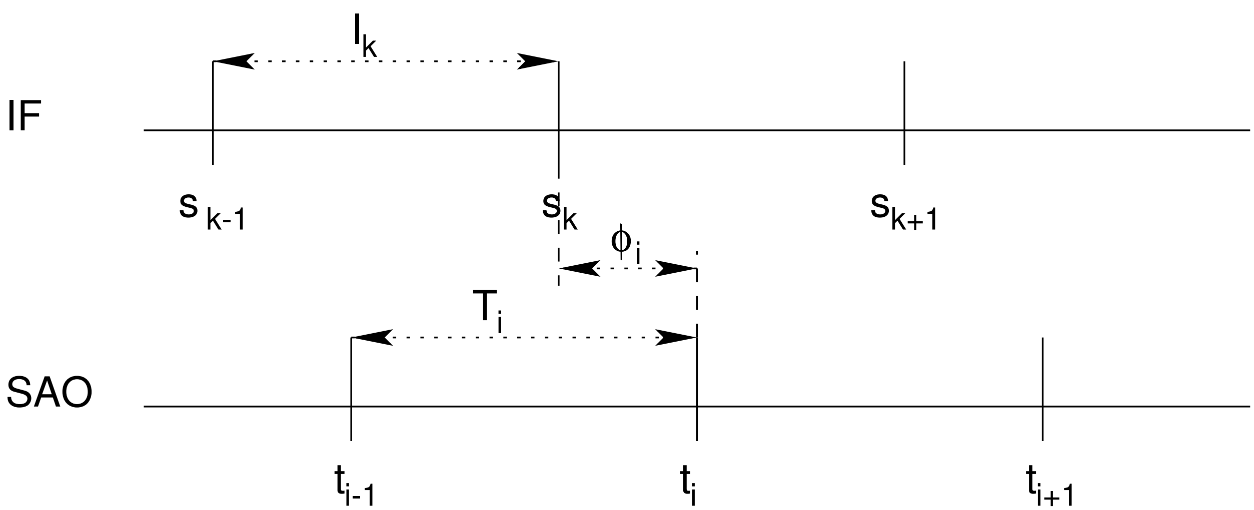
In the Beginning. . .

- The crayfish slowly adapting stretch receptor organ



- Prototypical living inhibitory synapse.
- IF discharge is control parameter; inputs to SAO are natural PSPs.

Assimilation of Spike Trains to Point Processes



Pacemaker Inhibition

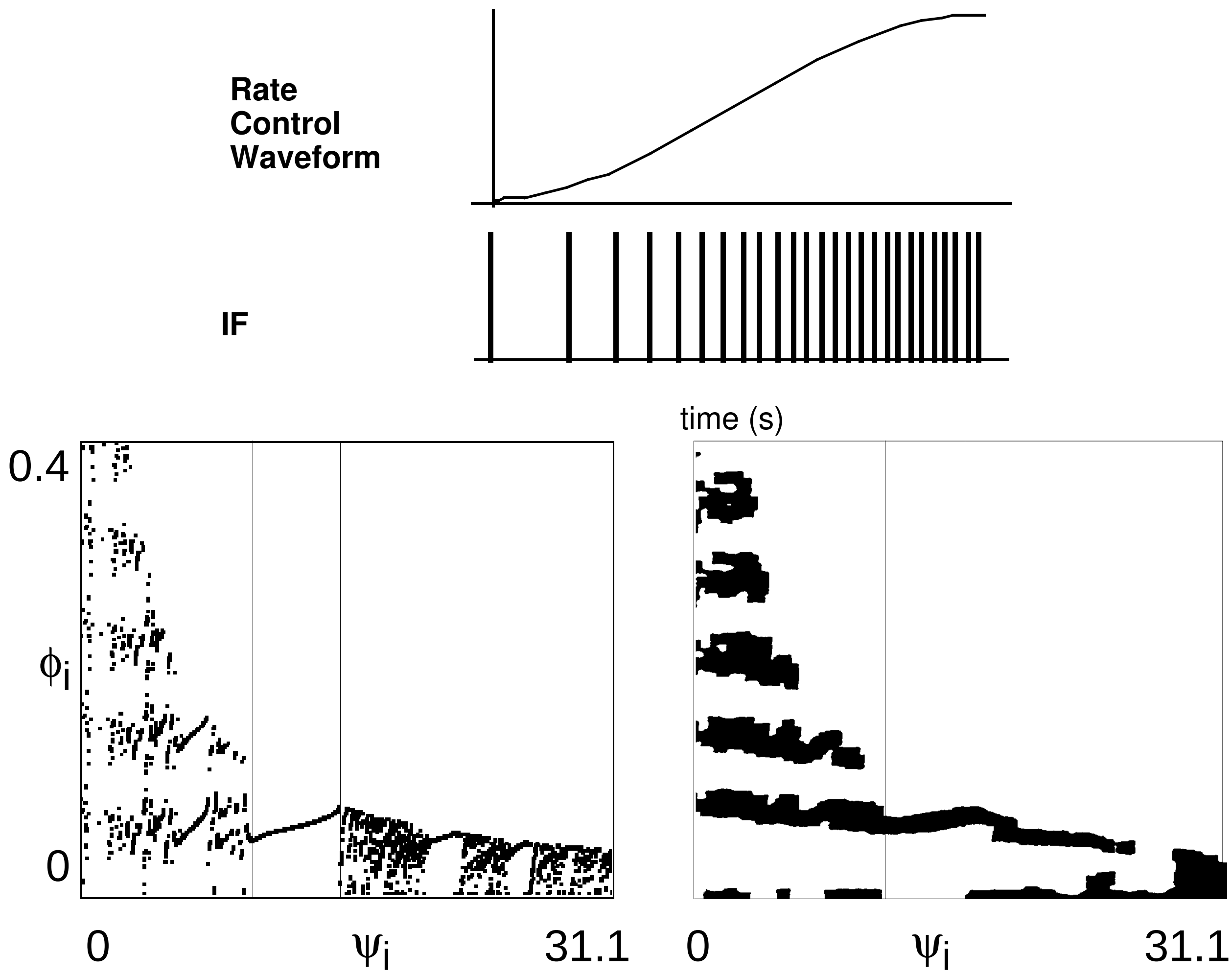
Average rates paradoxical acceleration [Kohn & Segundo, 1983].

Dynamical behaviors [Segundo *et al.*, 1991; Stiber, 1992; Nomura *et al.*, 1994]

- $p : q$ *locking* $\langle T_{i+1}, \ldots, T_{i+q} \rangle$ and $\langle \phi_{i+1}, \ldots, \phi_{i+q} \rangle$ repeat every p inputs.
- *Intermittency*: practically periodic; phase walkthroughs and quasiperiodicities.
- *Messy*: chaotic and stochastic.

Extended Transients

[Stiber *et al.*, 1997]



Bifurcation behavior; slow passages.

Brief Transients

- Moving farther from stationary behaviors.
- Infinite number of degrees of freedom.
- Questions we can ask:
  - How many inputs produce a dynamical behavior?
  - How precise is the necessary timing?
  - What is the role of noise in neural computation?
- Information theoretic approaches
  - Bits per spike implies timing precision.
  - Variation among multiple applications of same stimulus is noise.

Noise Versus Dynamical Complexity

Noise is [Segundo *et al.*, 1994]:

- Unpredictable dispersion from some central value.
- Waveform with a broad band.
- Subjective: whatever doesn't make up the signal of interest.

However, nonlinear dynamical systems can produce broad band, unpredictable, irregular outputs with arbitrary distributions.

Caveats for Applying Information Theory

- Noise should be stochastic.
- Variability in output not due to neural input: neuron *state*.
- A neuron is not a pure encoder (usually).
- Information theory doesn't tell you what the code is.

Codes can include *purposeful* redundancy: error correction.

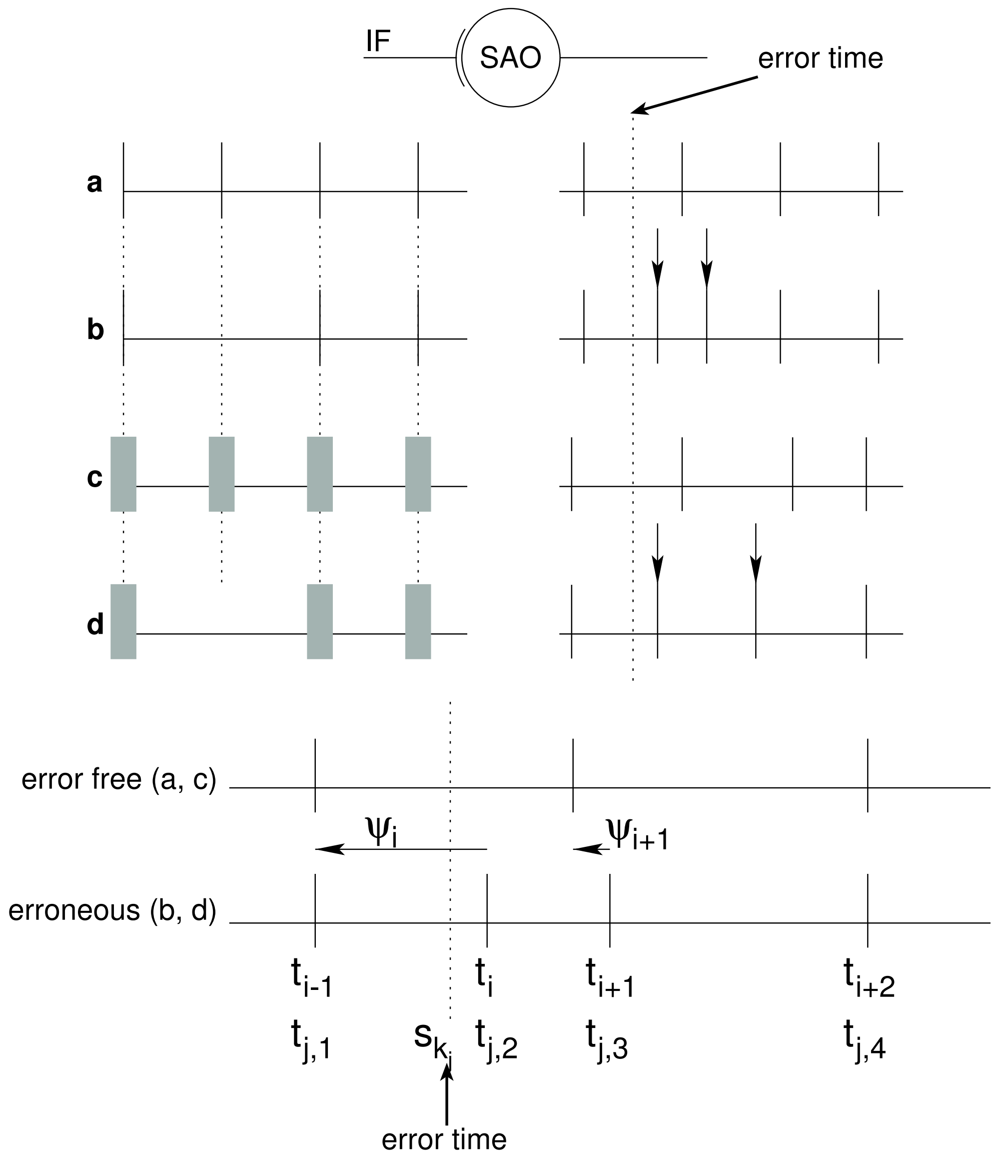
Physiological Model

$$
\begin{aligned}
\mathrm{d}V_m/\mathrm{d}t &= -(I_{Na} + I_K + I_{L,Na} + I_{L,K} + I_{L,Cl} \\
&\quad + I_p + I_{bias} + I_{syn})/C_m \\
I_{Na} &= A\overline{P}_{Na} m^2 hl \frac{V_m F^2}{RT} \\
&\quad \times \frac{[\mathrm{Na}^+]_o - [\mathrm{Na}^+]_i \exp FV_m/RT}{1 - \exp FV_m/RT} \\
I_K &= A\overline{P}_K n^2 r \frac{V_m F^2}{RT} \\
&\quad \times \frac{[\mathrm{K}^+]_o - [\mathrm{K}^+]_i \exp FV_m/RT}{1 - \exp FV_m/RT} \\
I_{syn} &= A\overline{P}_{syn} \frac{V_m F^2}{RT} \\
&\quad \times \frac{[\mathrm{Cl}^-]_o - [\mathrm{Cl}^-]_i \exp FV_m/RT}{1 - \exp FV_m/RT} \\
&\quad \times \sum_{\forall s_k < t} \left(e^{(s_k - t)/\tau_+} - e^{(s_k - t)/\tau_-}\right)
\end{aligned}
$$

Simulation and Analysis Methods

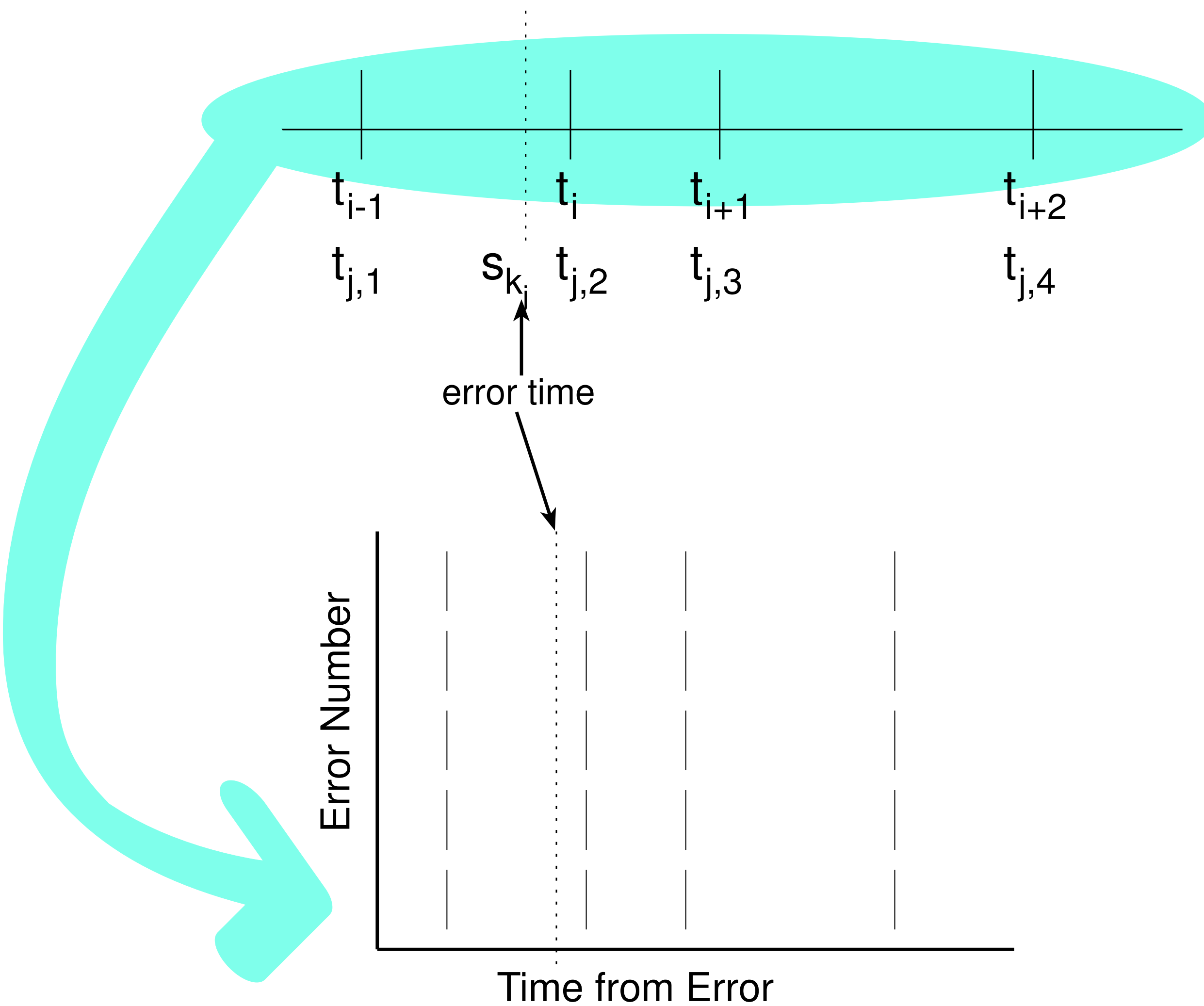
- System is moderately stiff (slowest/faster $\approx 10^4$).
- Need to record spike times ($V_m = 0$, d$V_m/$d$t > 0$).
- Used LSODAR routines from ODEPACK [Hindmarsh, 1983].
- Distributed simulation across cluster of 30 Intel machines running Red Hat Linux.
- Results ranged up to around 1GB.
- Analysis performed in MATLAB.

Experimental Methods

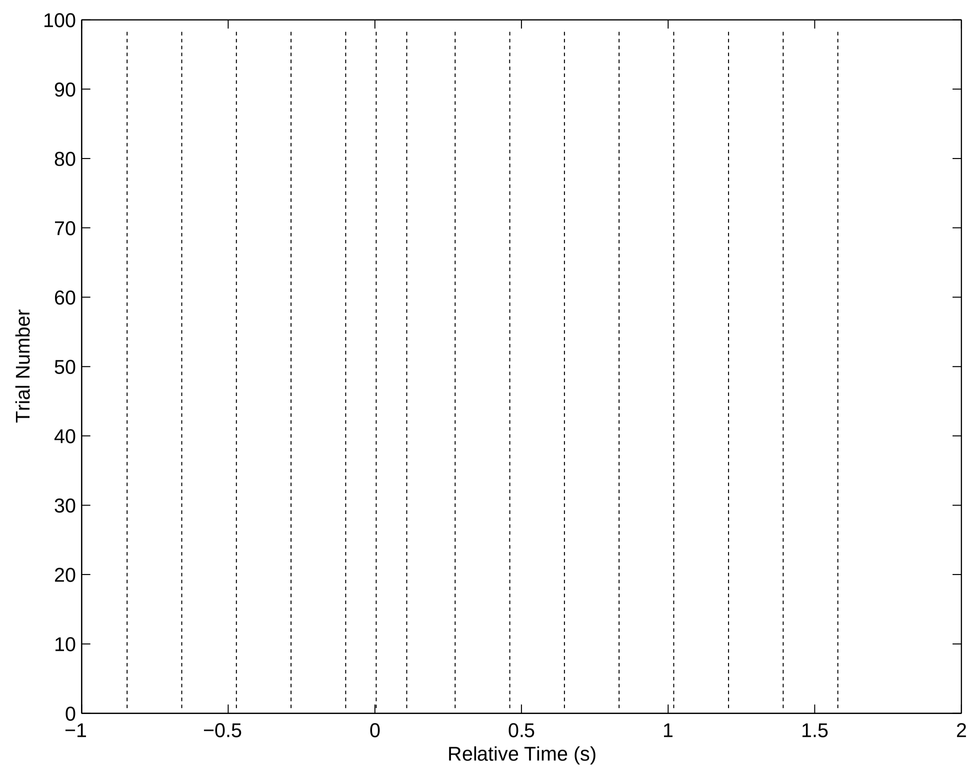


Strict definition of error correction.

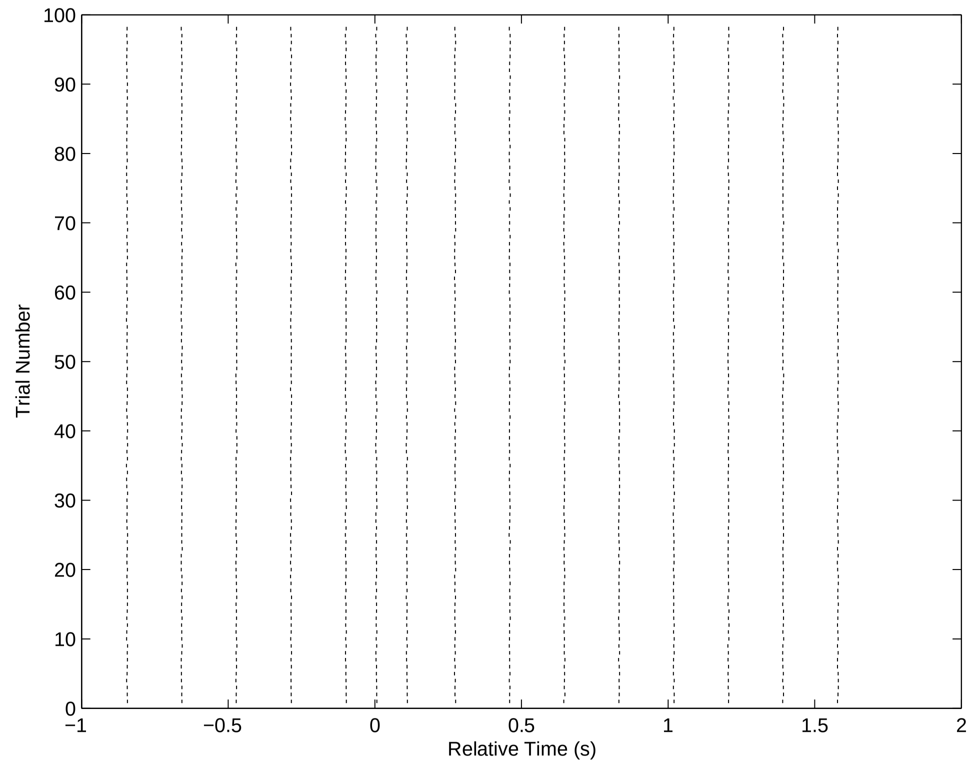
Raster Creation



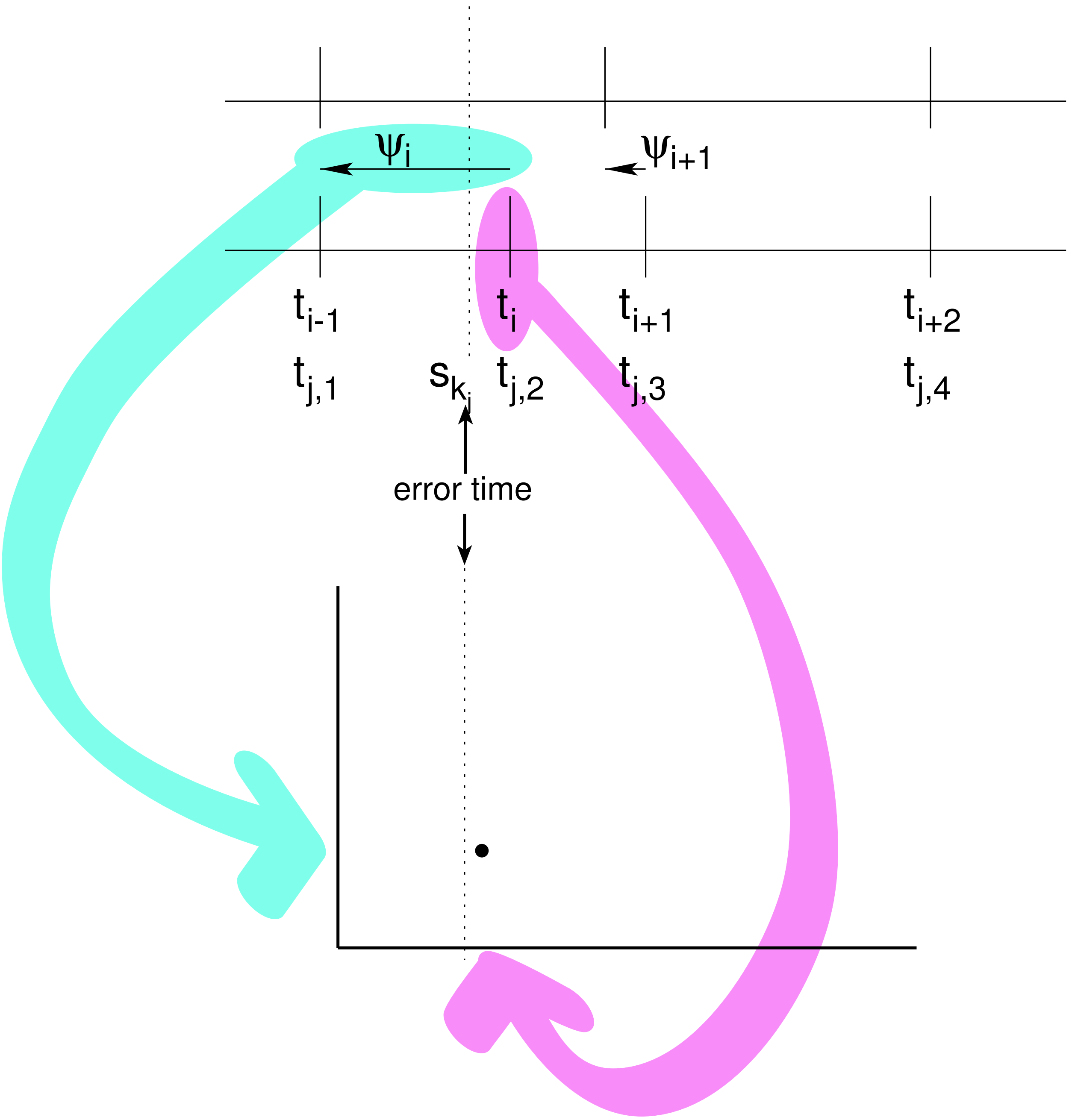
Raster: High Precision Error Responses



Raster: Low Precision Error Responses

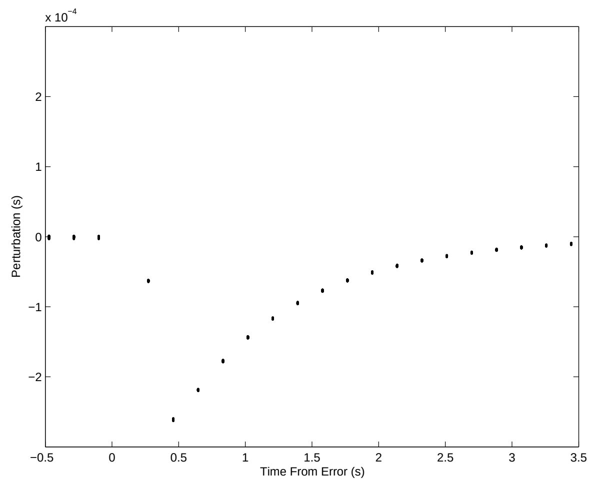


Perturbation Plot Creation

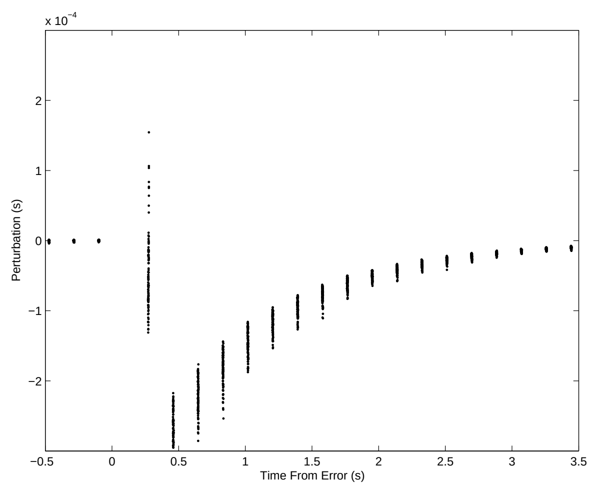


Induced Perturbations

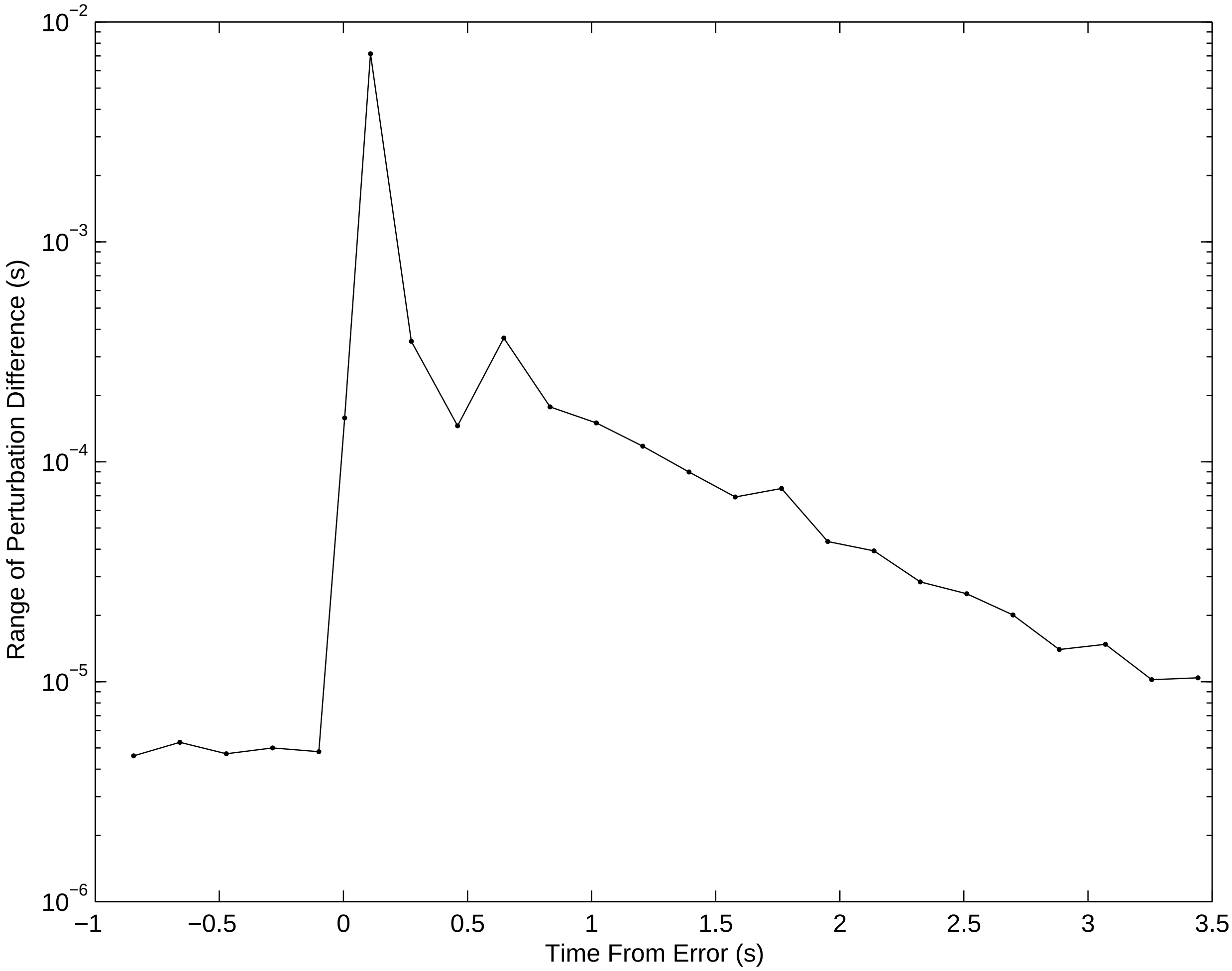
High precision inputs:



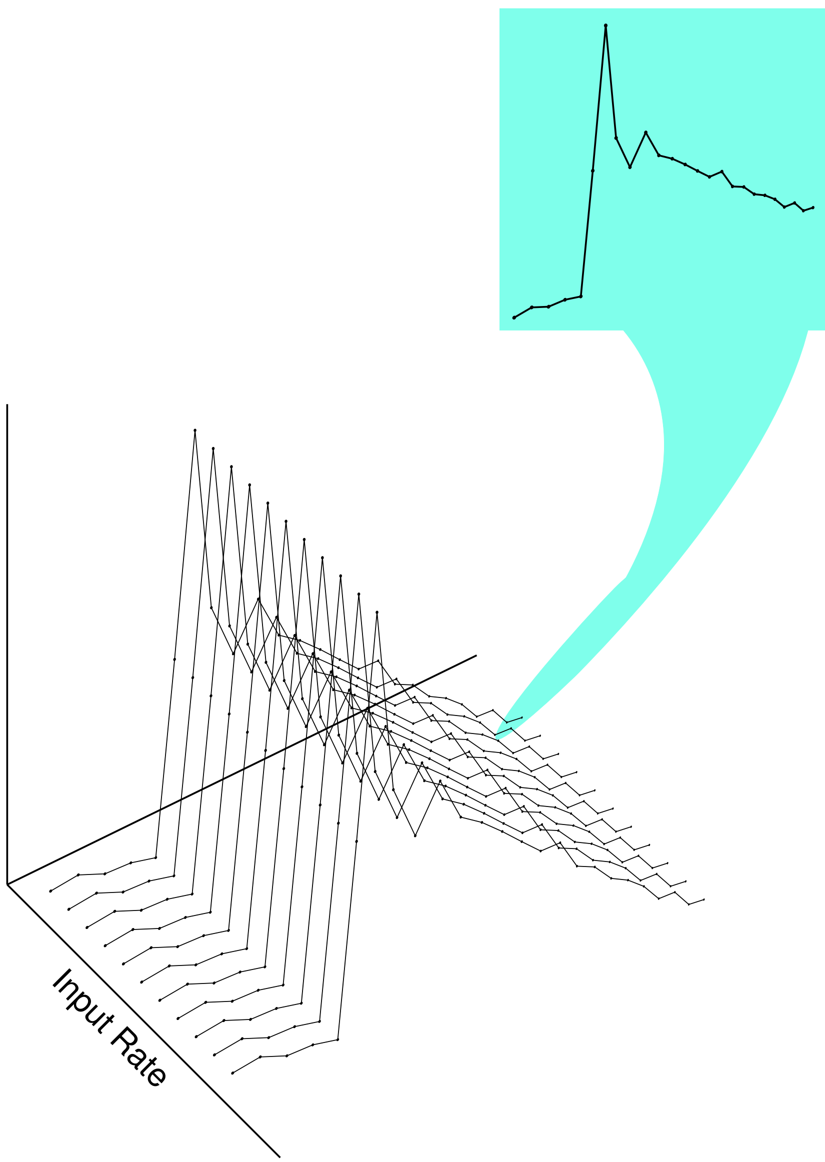
Low precision inputs:



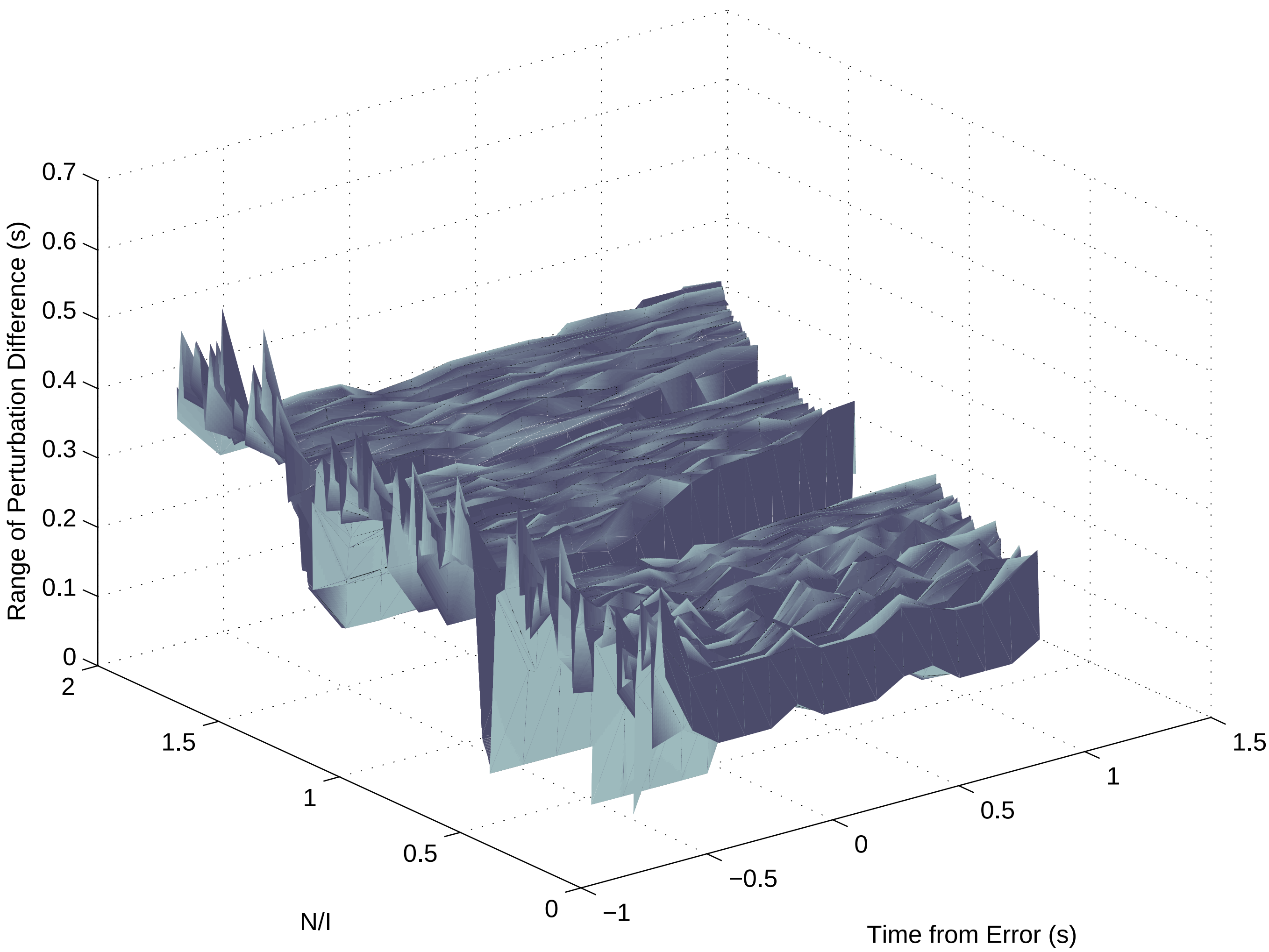
Perturbation Recovery Time



Recovery Bifurcation Diagram Creation

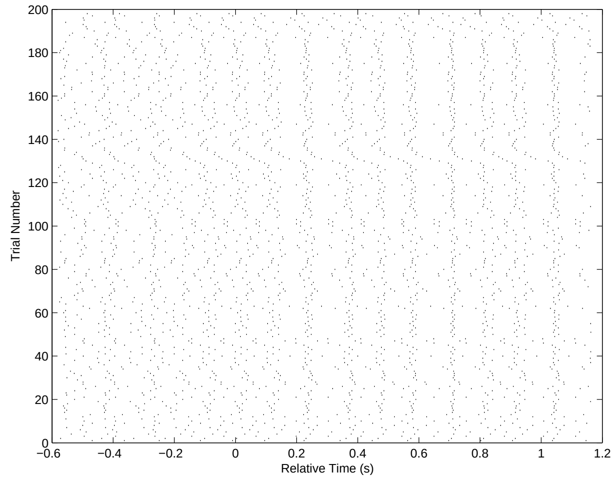


Recovery Bifurcation Behavior

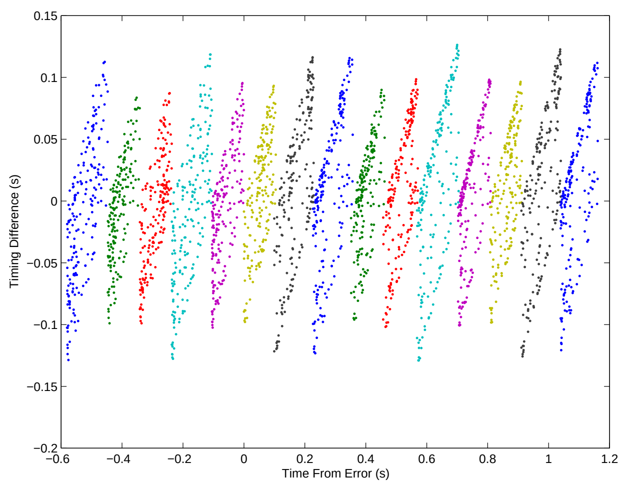


Non-Locked Behavior

High-precision error recovery:



Behaviors diverge after error:



Preliminary Conclusions

- Generality of perturbed pacemakers.
- Only locked behaviors obey this strict definition of error correction.
- Non-locked: the first error “desynchronizes” erroneous and canonical responses; they never resynchronize.
- Possible role for synchronous oscillations.
- Nonlinear communications and “resynchronization” of non-locked behaviors [Pecora *et al.*, 1997].

Acknowledgments

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