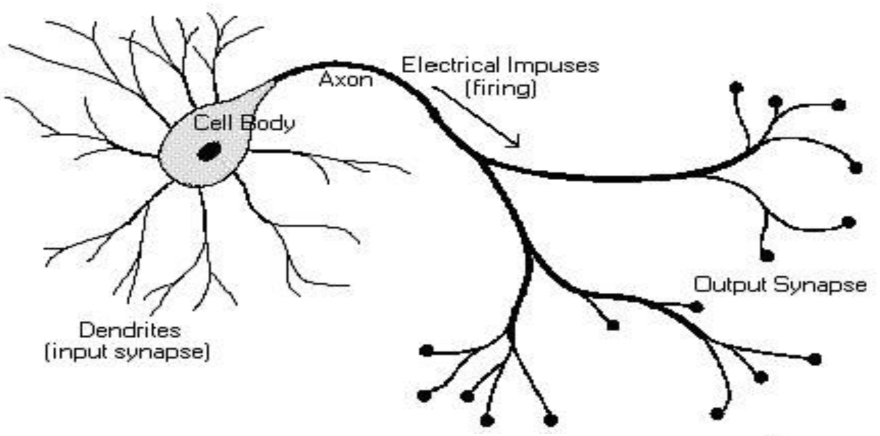
Neuroscience & Experience

Weeks 1234

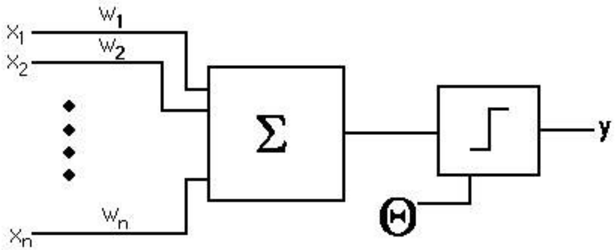
Neurophysiology

- Examination of neurological structures suggest more complex interactions than are accounted for by integrate and fire – Koch asserts the existence of many nonlinear interactions within the dendritic tree and at synapses.
- Temporality, and therefore a natural basis for temporal synchronization absent from IFNs

Standard Neural Model



Biological Neuron



Computational Neuron

Action potential production

- Neuron membrane potential rests at −70mV
- Innervating action potentials arrive at synapses and cause a depolarisation of, on average, 1 millivolt.
- When the target neuron is depolarised by about 15 to 20 millivolts, the depolarisation becomes self sustaining, through the opening of voltage gated sodium channels.
- Positively charged sodium ions flow across the membrane, further increasing the membrane potential, until it reaches a peak of about +30 mV. At this point the ionic driving force becomes smaller, the membrane has depolarised toward the sodium equilibrium potential.
- At this point, Potassium channels open, Potassium ions flow down their concentration gradient out of the cell.

Signalling and Representation

- Eccles' Frequency Coding – the intensity of the stimulus encoded in the frequency of firing.
- Population Coding – Georgopolous, intensity encoded through frequency, but content encoded through spatial patterns of activity.
- Feature detection neurons, the Grandmother cell hypothesis.

Temporal coincidence coding

- Implicated in solutions to the binding problem.
- Neurons representing features fire synchronously to enable innervated neurons to “bind” the features into qualia.
- Standard formulations require a definite hierarchy of feature layers.
- More recent formulations posit the existence of groups of neurons that iteratively “observe” each others’ productions.

Hodgkin Huxley

- Thorough model of ionic flow across neural membrane.
- Differential equation relating membrane potential to existing potential and the pervading concentration of sodium and potassium ions.
- The equation is used in compartmental simulators with success. Computationally expensive.
- Sub-threshold activity has not been given deserved attention. Izhikevic points out that the neuron obeying Hodgkin – Huxley can behave as a resonator.

Spectral Domain

- Pribram's work on perception emphasised the fundamentality of the spectral domain and the centrality of the Fourier transform as the mechanism underlying perception.
- Conventional ANNs are ill-suited to performing FTs, if FT is truly the basis of the perceptual process, surely evolution would have designed an efficient substrate that supports the operation naturally

Importance of the Dendritic field

- Pribram emphasises the dynamics of the dendritic field as housing the mechanisms suited to computation in the spectral domain.
- Fast sub-threshold oscillations in membrane potential.
- Aggregations of dendritic structures capable of supporting complex interactions.
- The “holoscape” is fundamental to perception, patterns of AM waves in dendrites.
- The integrate and fire model completely ignores the dynamics of the dendritic field.
- Decided to examine a re-formulation of the computational neuron with a view to accommodating these dynamics.

Neural Network Models

- Hodgkin-Huxley equations
- Compartment models
  - Computationally expensive
- Integrate and fire model
  - Computationally efficient
  - Universal function approximator
  - Variety of learning algorithms

Compare and contrast

Properties

- Action potential
  - Digital
  - Low attenuation
  - Resistant to error
  - Long distance
  - Slow
- Subthreshold oscillation
  - Analog
  - High attenuation
  - Short distance
  - Fast

Purpose

- Action potential
  - Data transmission
- Subthreshold oscillation
  - Computation

Auditory

- All auditory sensation is naturally encoded as power spectra.
- Why is the note middle – C the “same” as C an octave higher – does this indicate a fundamental property of the perceptual apparatus?

Visual

- Pribram asserts that neurons in V1 are attuned to spatial frequencies. (DeValois & DeValois 1980) – cortical neurons respond most strongly to a Sine wave grating; variation in the width of the grating gives the bandwidth of the tuning curve.
- Points, Lines and Manifolds are the products of perception, not the fundamental components.
- Fundamental components are power spectra derived from spatial frequency analysis.

Mechanoreceptors

- Depolarized by direct stimulus
- All stimuli encoded as analog signals
- Mechanoreceptors: Type I – small RF with well defined boundary Meissner's corpuscles and Merkel's disks
- Type II Ruffini corpuscles and Pacinian corpuscles
- Human skin sensitive to vibration between 5 and 500 Hz
- Meissner's sensitive to vibration <40Hz
- Pacinian sensitive to higher frequency, optimal is 200Hz. Frequencies in this range can be perceived at skin indentations of less than 1 millionth of a meter

Mechanoreceptors are tuned to frequency bands.

Key Points

- Sensory data, visual, auditory or tactile, can be efficiently described with power spectra.
- Integrate and fire networks do not process power spectra efficiently.

Pribram’s Holonomic theory

- Large aggregations of neurons’ dendritic fields support a process and a set of state variables.
- The points at which state variables (e.g. membrane potential) are equal form contours.
- These contours form a “holoscape”, an internal pattern of activity not tied to a spatial location that constitutes a representation of perception.
- *A particular pattern of activity can be supported by dendritic aggregations of appropriate form and structure.*
- *The experience of perception requires structures of appropriate form and complexity in order to support representations of the external world.*

Resonate and Fire model

- Based on properties of Hodgkin-Huxley
- Computationally efficient
- Accommodates sensory data naturally
- Supports wave interference interactions in the dendritic field.

Resonate and Fire Neurons

- Theoretical basis:
  - Pribram (1991) membrane potential and the subthreshold fast oscillation.
  - Fourier Transforms.
  - QM and the cytoskeleton. The primacy of the Fourier Transform in QM algorithms (Shor et al).
  - Physics of resonance systems, harmonic oscillators.
- Properties:
  - Ongoing sub-threshold evolution of membrane potential
  - Dendritic microprocess handles spectral data.

Mathematical Model

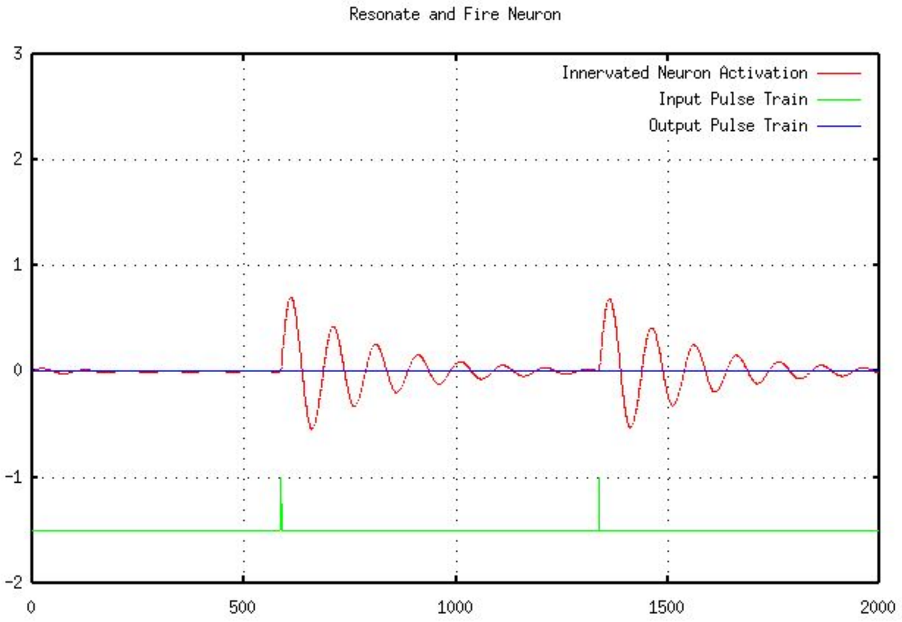
The delta rule describes the relationship between current axonal inputs, dendritic inputs The current displacement of the membrane potential, and the future state of the membrane potential

$$\Delta\dot{\psi}_i = (\Sigma d^t_{ij}(\psi_j - \psi_i)) + (\Sigma w^t_{ij} o_j) - \frac{w_0^2 \psi}{f_c} - \beta\dot{\psi}_i \qquad (5.15)$$

Elementary operating scenarios

- We examine the simplest event sequences.
- Subthreshold oscillation
- In phase doublets
- Out of phase doublet
- Zap response

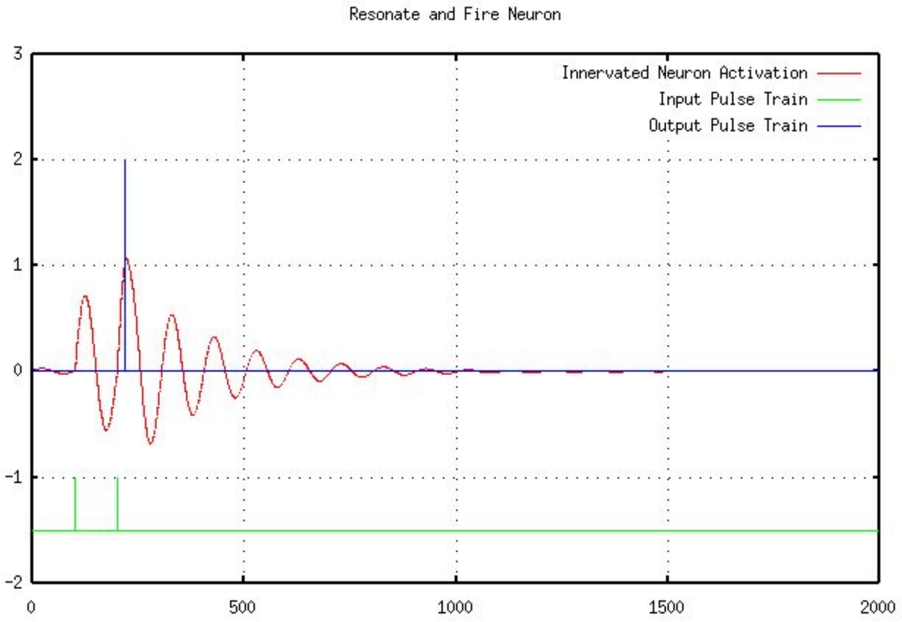
Subthreshold Oscillation



Subthreshold oscillation

- Input causes membrane potential to rise but is of insufficient magnitude to breach threshold.
- Membrane potential returns to resting state but oscillates as it does so.

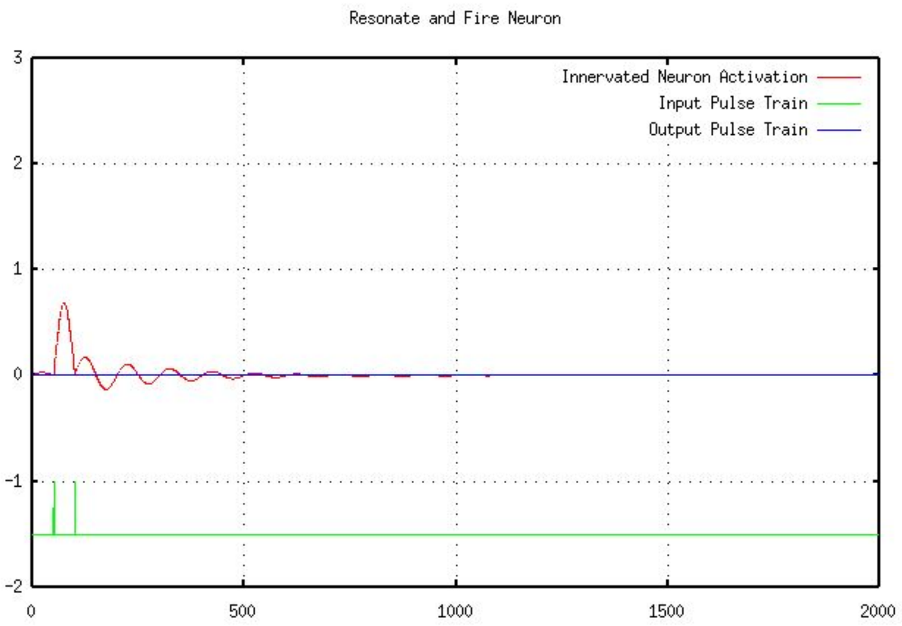
In Phase Doublet



In Phase Doublet

- Two separate action potentials co-operate to push membrane potential across the threshold value.
- Action potentials could originate from a single neuron (selective innervation through frequency coding)
- Action potentials could originate from two separate neurons, a behaviour demonstrating co-operation through synchronous firing.
- Where two innervating neurons are members of distinct functional groups, the innervated neuron is performing a binding function.

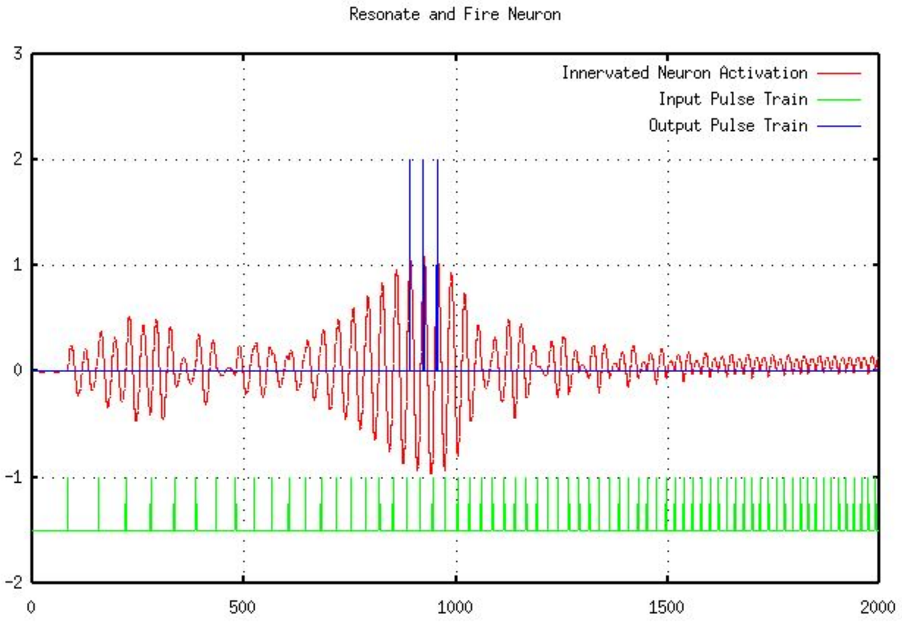
Out Of Phase Doublet



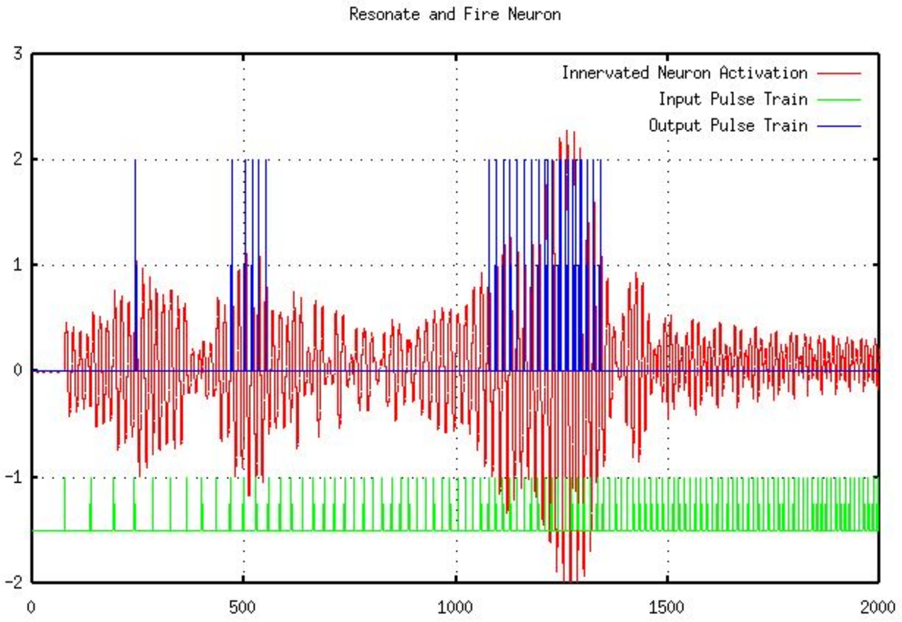
Out of Phase Doublet

- A second action potential dampens the oscillation.
- Where both arrive from the same presynaptic neuron, this constitutes the inverse of selective innervation.
- When arriving from two separate neurons, this constitutes competition and selective inhibition.
- When the two neurons are members of distinct functional groups, the innervated neuron represents a property that is excluded by the presence of the other two.

Zap Response



Zap Response 2



Zap Response

- Characterises the response of the neuron to an input pulse train across all input frequencies.
- Illustrates harmonic oscillations at whole fraction frequencies.
- Could it be that such neurons are involved in perception, and does this explain the equivalence of octave-separated notes?

Implications of simple behaviours

- Dynamic relationships between neurons; two groups can alternately compete and co-operate over short time frames.
- Tuning to a resonant “eigenfrequency” is a key property that permits automatic feature detection in spectral data domains.
- Fourier transforms are performed by arrays of neurons innervated by a single source with monotonically varied resonant frequencies.
- The pure Fourier transform is performed as the number of neurons in the array tends toward infinity. For smaller groups, the operation approximates the Gabor transform used in wavelet analysis which is of proven utility in machine-vision systems.

RFN Networks

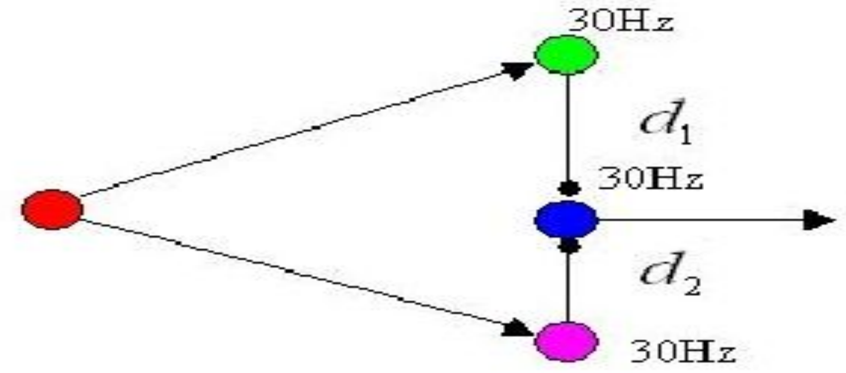
Dendro Dendritic connections

- Each connection has associated weight and propagation delay.
- Innervating neurons create an interference space in which the target neuron can locate itself by modifying the delay of the connection.
- Through somatic selection, populations of neurons explore the interference space of innervating neurons.

Interference Effects in the Dendritic field.

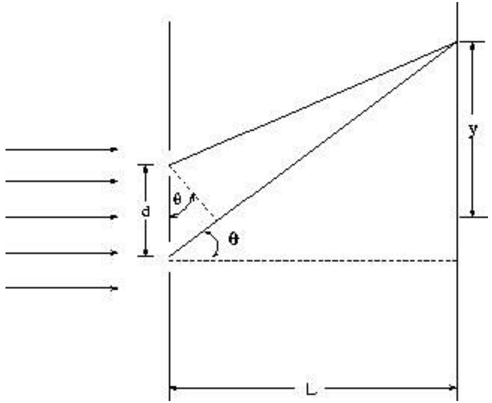
- Dendro-dendritic connections create aggregations of dendritic fields.
- Membrane potential in an individual neuron body is influenced by that of neurons in the aggregate.
- The ensemble can support interference effects.
- Each dendritic field is a miniature workspace.

Interference Network



RFN Interference Network

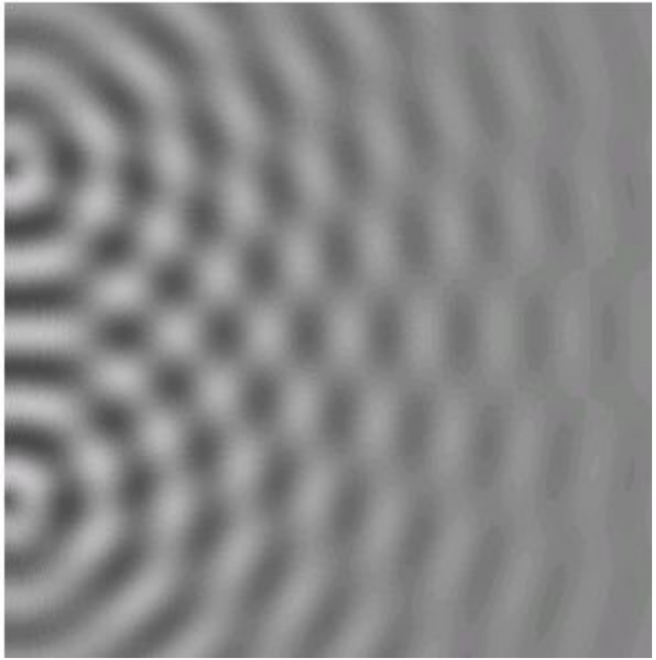
Young's Slit Experiment



Interference Network

- Input neuron supplies action potentials at approximately 30Hz
- Target neurons are tuned to 30Hz and so will fire rapidly.
- Final neuron(s) explores the interference space of the other two.
- The interference space is the realm in which activity of innervating neurons is bound.

Two dimensional interference space



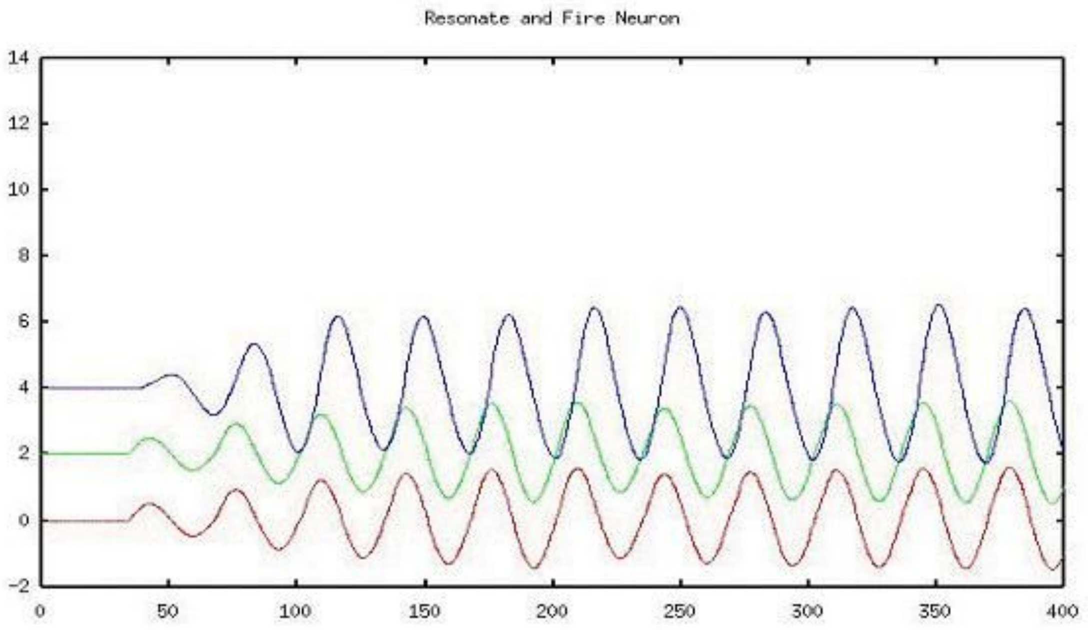
Interference space in classical wave system.

By analogy, RFN neurons search this space by “modification” of connection strength and delay.

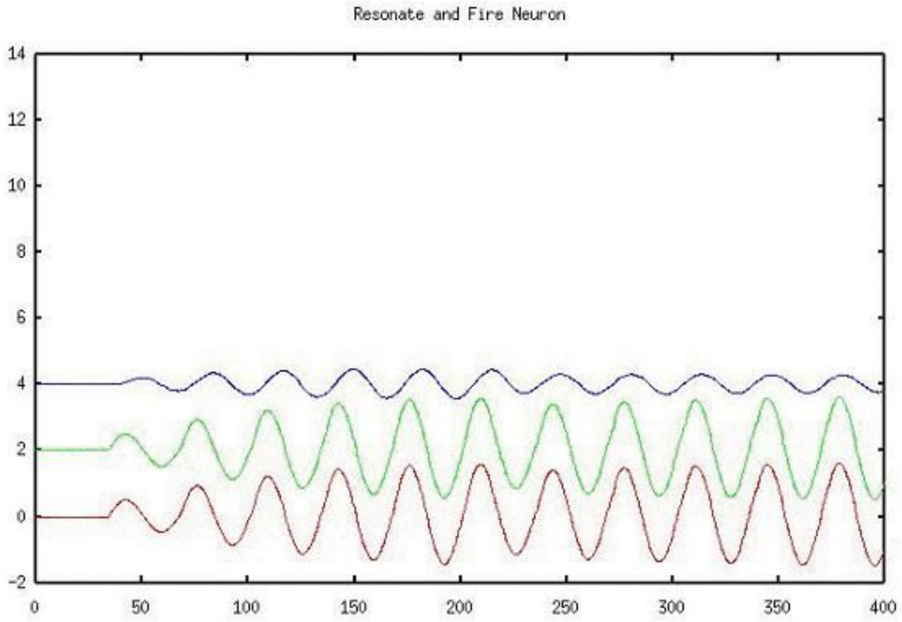
Constructive and destructive interference conditions

- Where the distance is an integral multiple of the wavelength, interference is constructive.
- Where distance is a multiple of half a wavelength, destructive interference ensues.

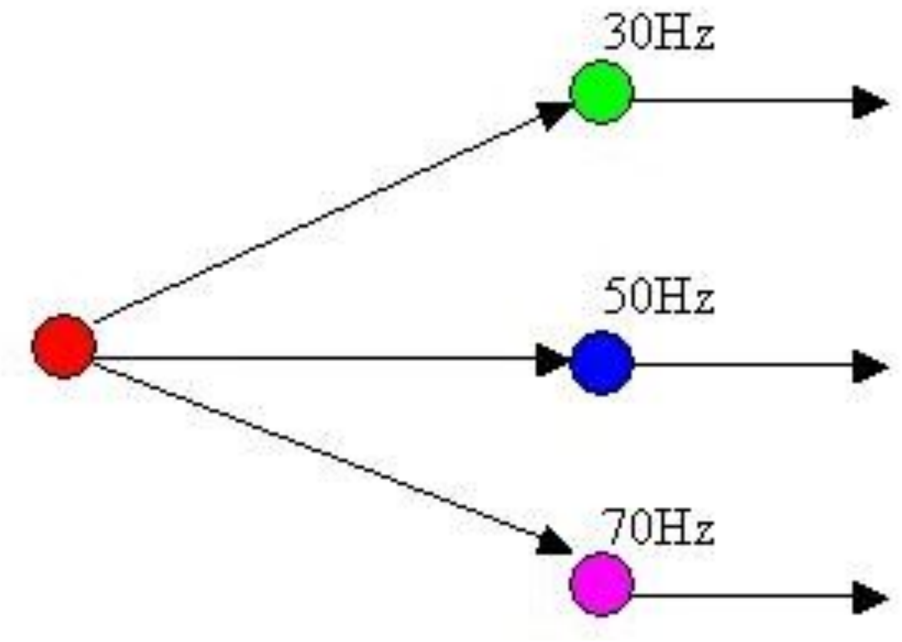
Constructive Interference in Activity levels of RFN



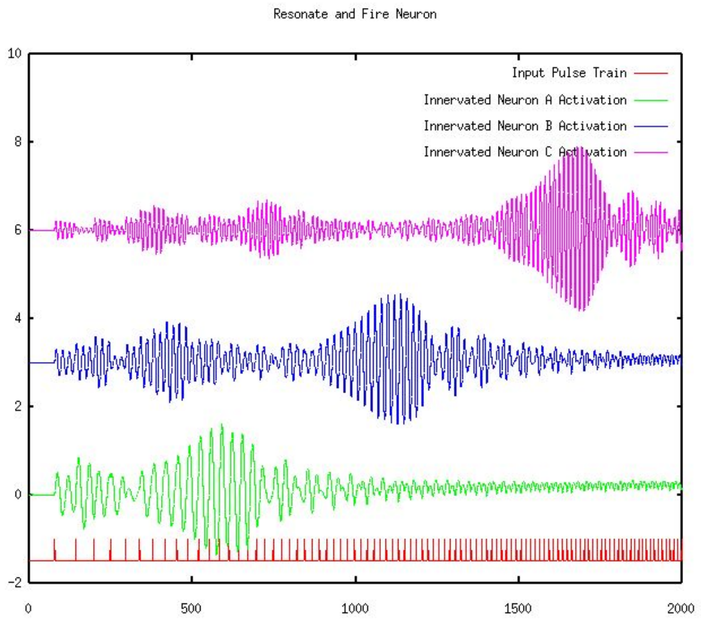
Destructive interference



Fourier Transform Network



Zap Response of Fourier Net Nodes



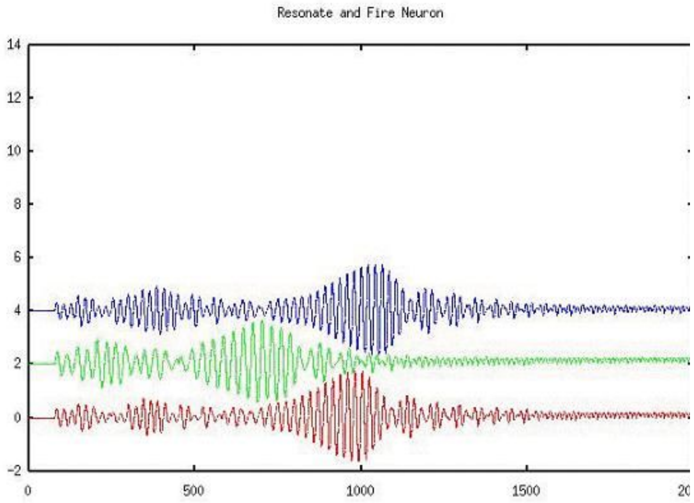
Training using SOM

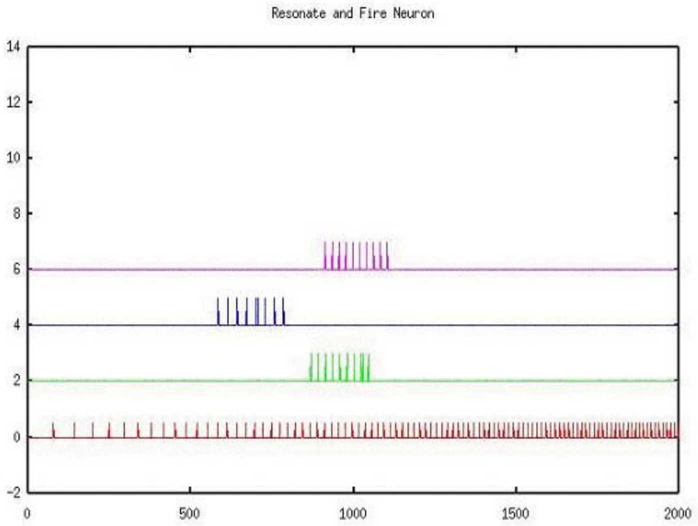
- Self organising maps, unsupervised learning mechanism.
- Winner take-all.
- Initially lateral inhibition is long-range, this is gradually reduced during training.

Algorithm

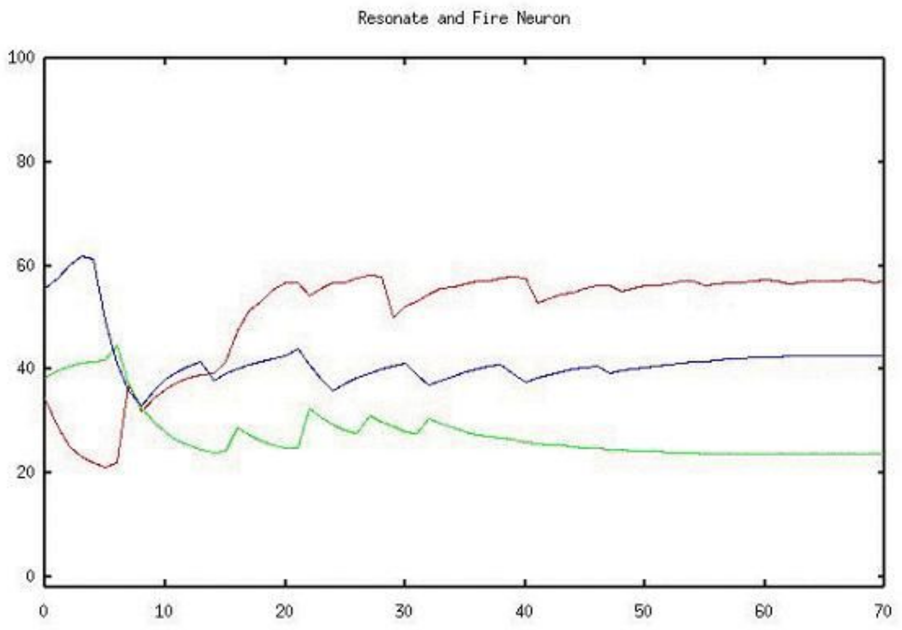
$$f_n = (1 - \alpha) f_n + \alpha f_i \tag{6.1}$$

Initial configuration

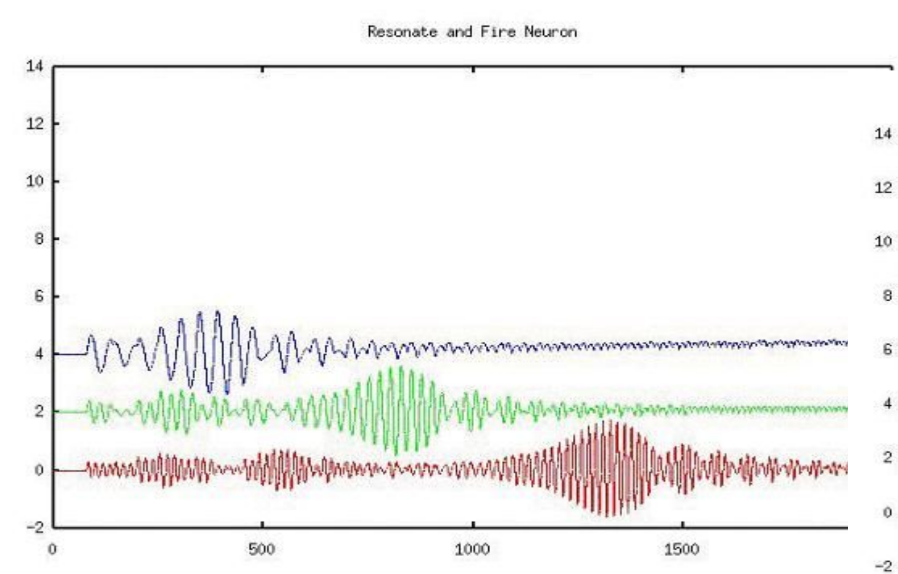


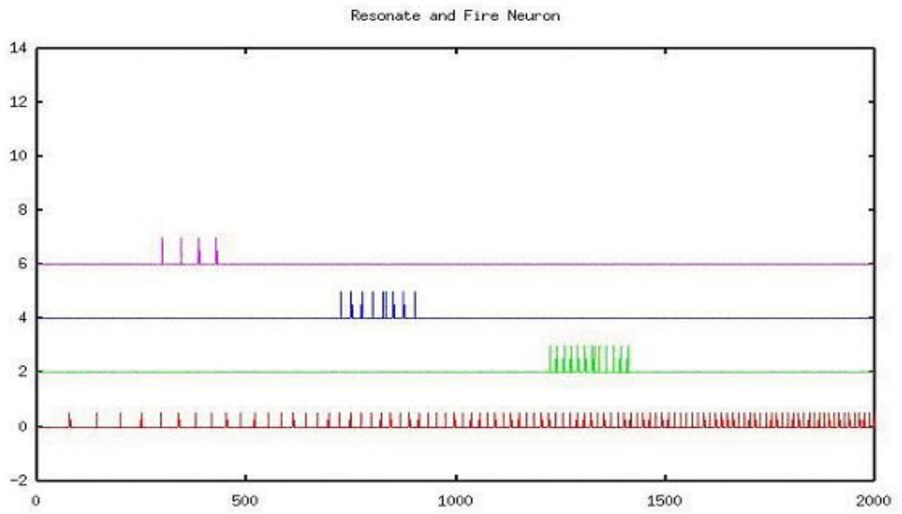


Resonant frequency evolution



Post Training configuration





Explanatory Power of RFN

- Any revision of existing theory must offer greater explanatory power.

Dynamic Core & Functional Groups

- Group A and B alternately co-operate and compete.
- Group C receives afferents from A and B.
- A RFN neuron in C receiving inputs from A and B will fire most regularly when input action potentials from A and B are in-phase, and synchronised.
- Therefore, neurons in A and B synchronize their firing in order to co-operate to evoke action potentials from neurons in C.
- Neurons in A and B desynchronize their firing or synchronize out-of-phase in order to inhibit neurons in C.

Perception

- Auditory and visual input encoded as power spectra.
- The act of binding of perceptual data involves the interference of the waves describing the perceptions.
- These waves interfere to create a new pattern of activity which is the finally perceived, integrated content of consciousness.
- Functional groups in the dynamic core observe this integrated waveform.

Summary

- RFN is based on sound mathematical framework.
- Is inspired by neurophysiology and is physiologically plausible.
- Demonstrated the ability to form topographic maps, central to the organisation of perceptual structures.
- It informs issues of importance, such as perceptual processes, binding, thalamocortical interaction, dynamics of functional groups.
- Draws together themes:
  - Holonomic brain theory.
  - Global workspace.
  - Harmonic Analysis
  - Fourier and Gabor Transforms.
  - Nonlinear dynamics.
  - Physics of resonance systems
  - Supra-computational capacity of classical wave systems, and by inference, the computational behaviour of QM systems.

Summary (continued)