Rhythms

Introduction

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Brain rhythms

Introduction:

What are they?

Where do they come from?

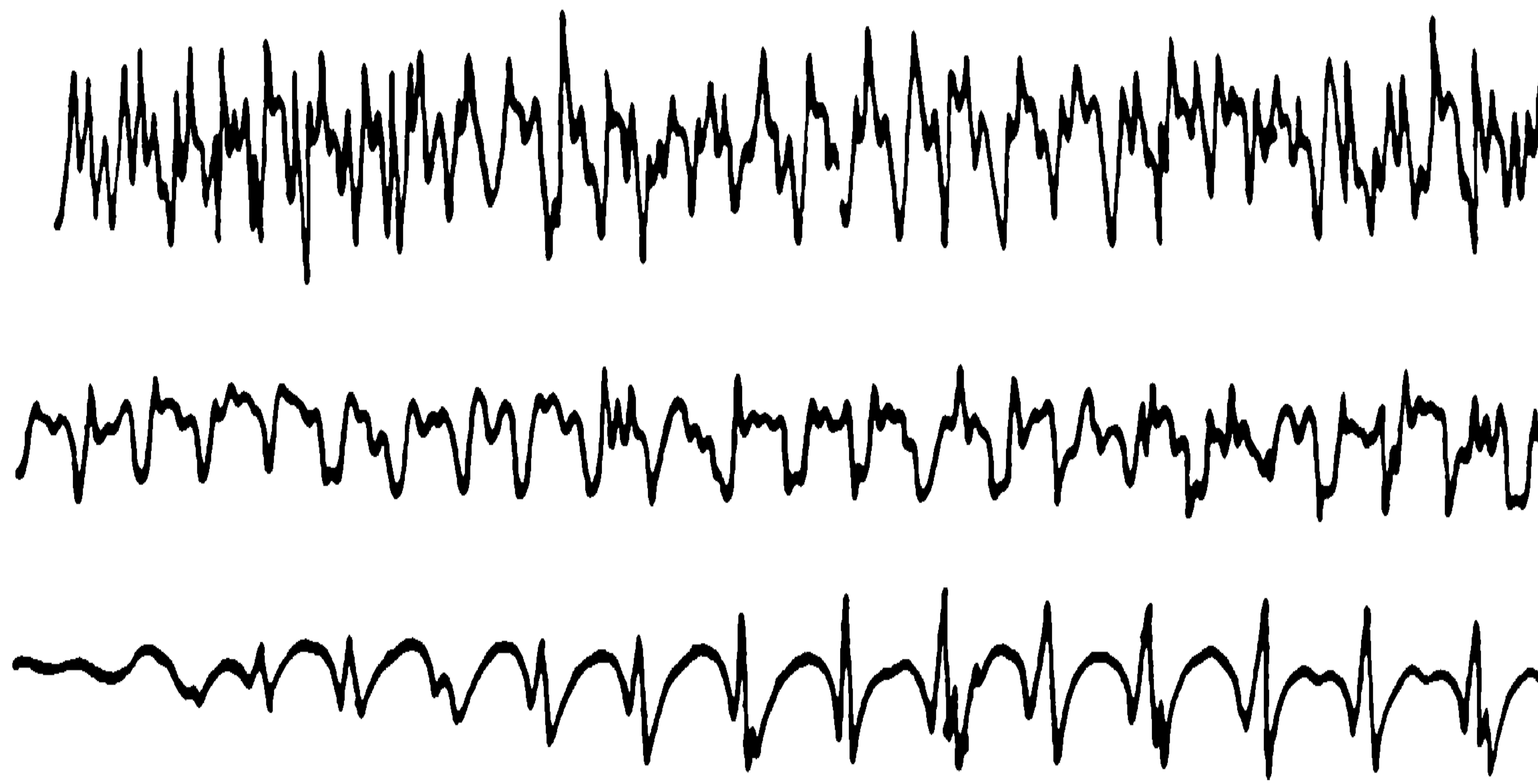
Method of analysis.

Brain rhythms

Fact: The brain can generate rhythmic activity.

Ex: Scalp electroencephalogram (EEG)

Note: Rhythms also appear in LFP, MEG, fMRI, ...

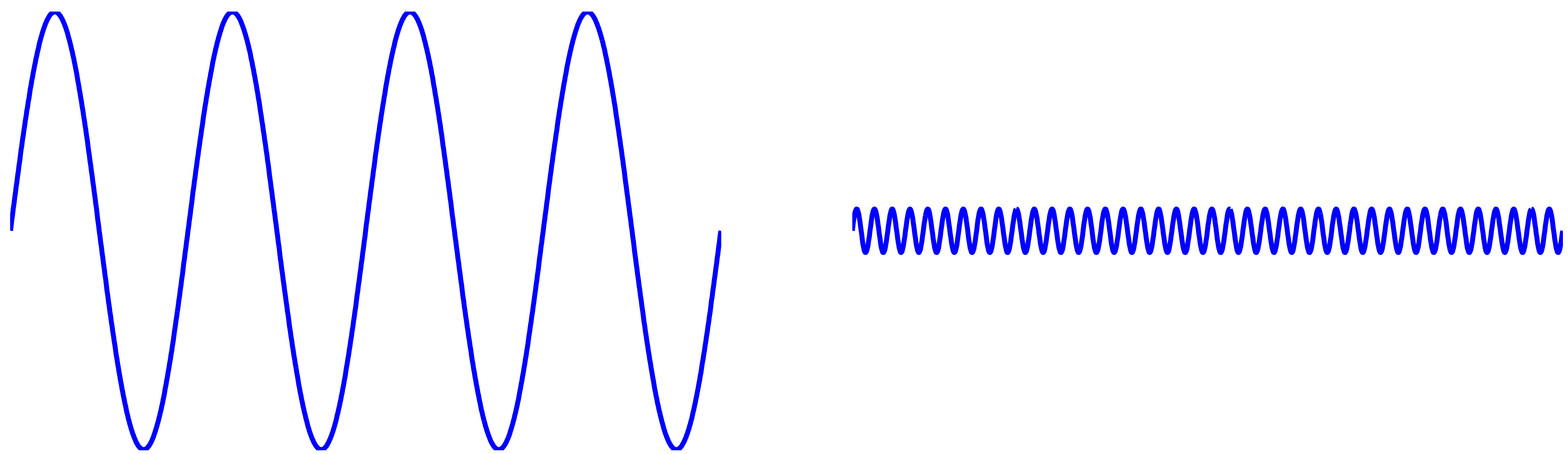


Observe: Different shapes. Different frequencies.

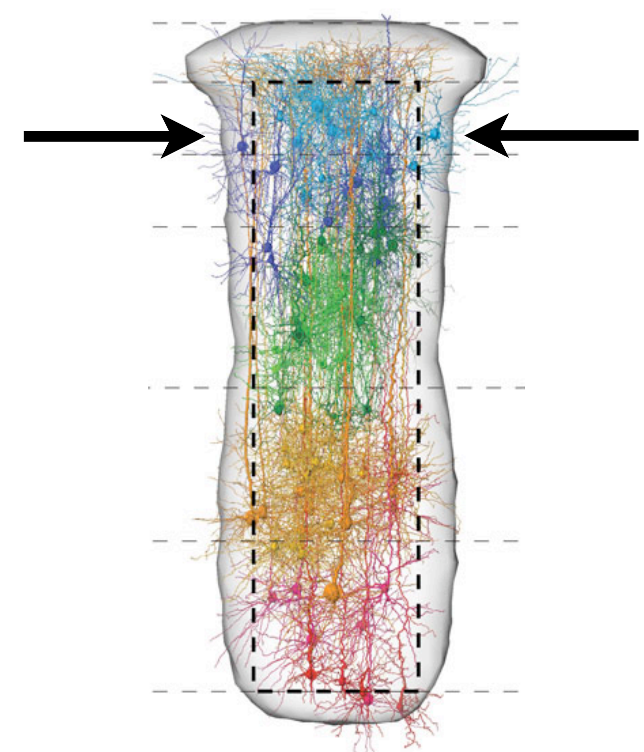
Brain rhythms: basic facts

Some basic facts about EEG rhythms:

- Slower rhythms tend to be larger amplitude.



- The EEG is thought to be (mostly) generated by coordinated synaptic transmembrane currents of many neurons.



Very complicated.

Not completely understood.

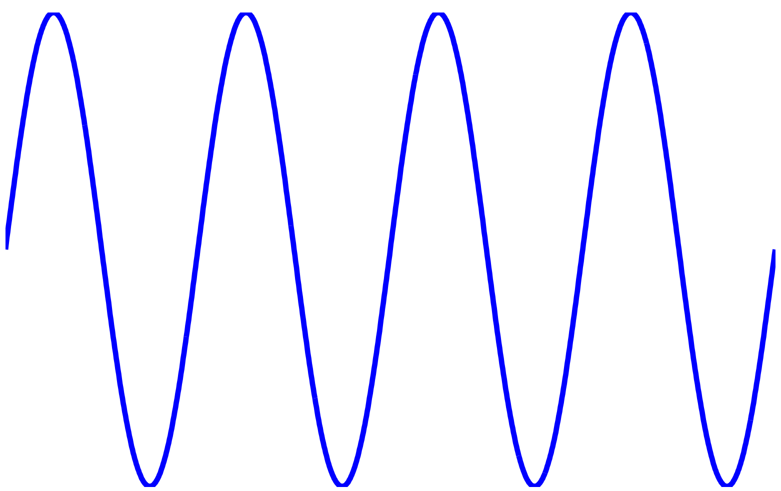
[Buzsáki et al. Nat Rev Neurosci (2012)]

Brain rhythms: basic facts

EEG measures cortical arousal

– Appears in the firing patterns of cortical neurons, measured in the EEG.

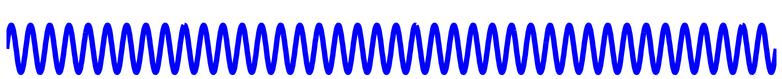
Low frequency, high amplitude: low cortical arousal



Neural activities are . . . synchronized.

Groups of cells act in concert = large EEG signal.

High frequency, low amplitude: high cortical arousal



Neural activities are . . . desynchronized.

Groups of cells involved in separate activities = small EEG signal.

Note: A healthy brain is a desynchronized brain.

Brain rhythms: characterization

Q: How do we characterize these rhythms?

To start, we can visualize and describe the rhythms.

Typical features:

Amplitude: Large or small ?

Frequency: Fast or slow ?

Shape: Sinusoidal, square, triangle, . . . ?

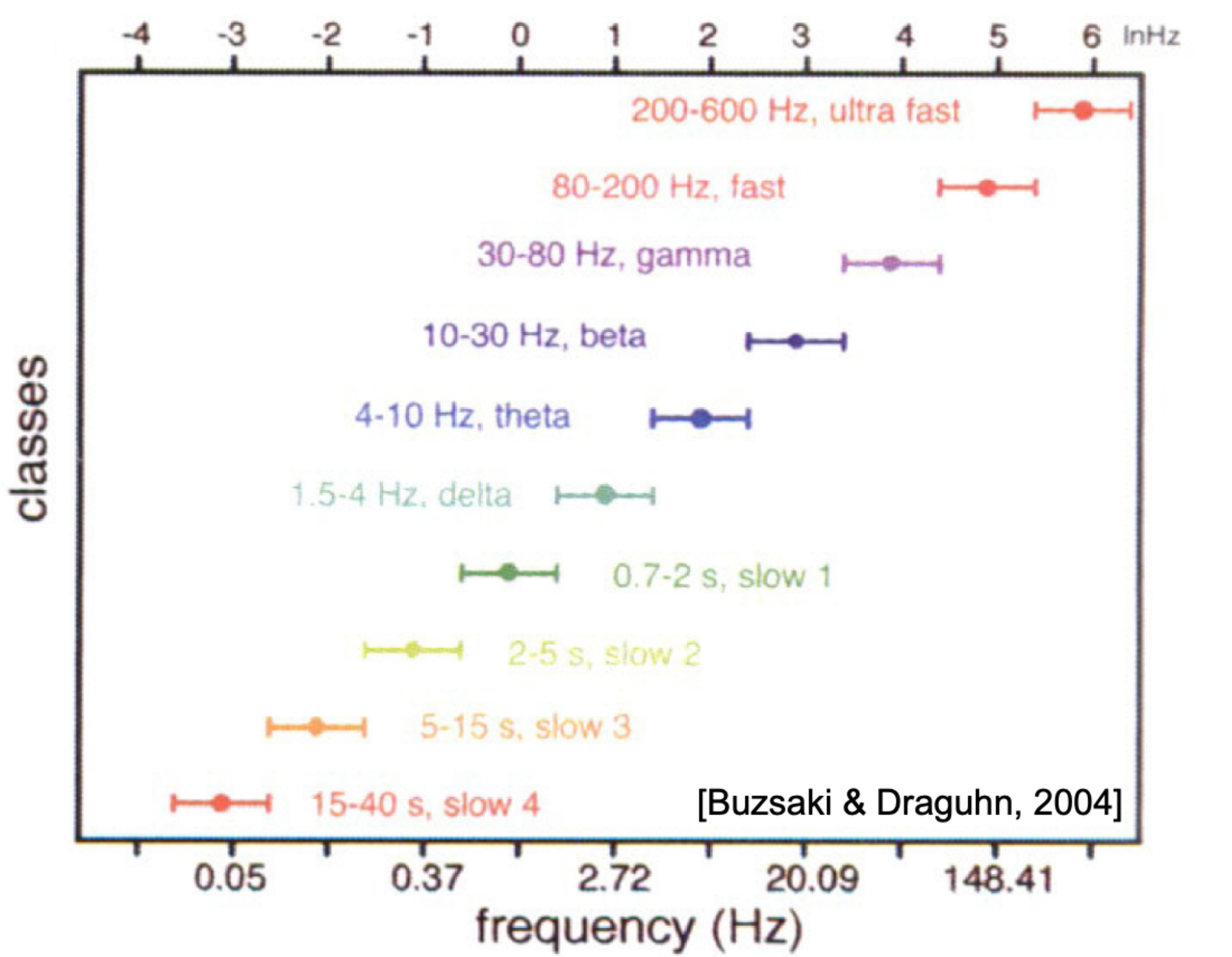
Our focus (usually) is frequency: How fast or slow is a rhythm?

Q: Why? Because different frequency rhythms are associated with different functions ...

Brain rhythms and functions

Many frequency bands, each associated with different functions.

Ex:

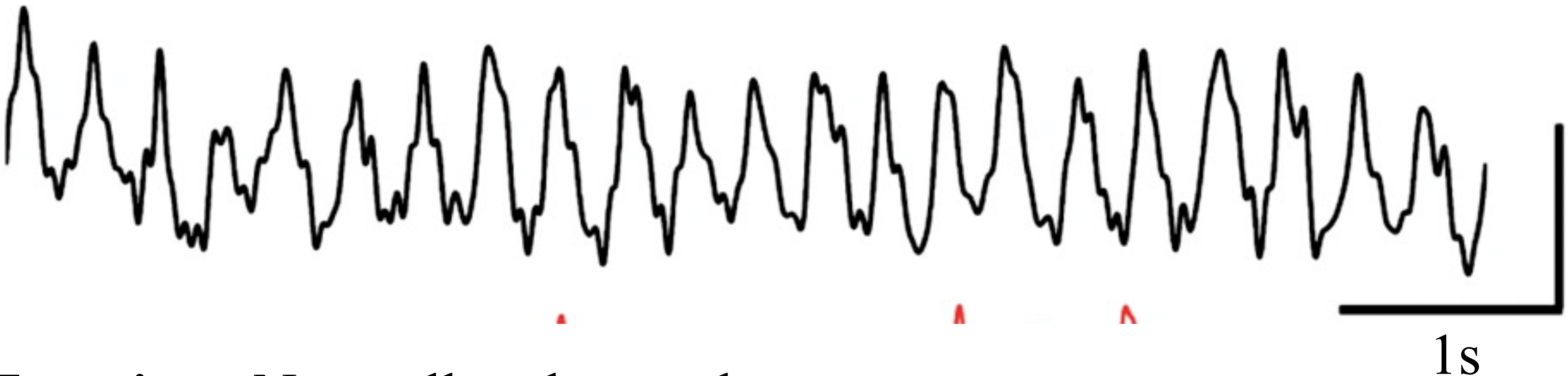


[Buzsáki & Draguhn, Science, 2004]

Let’s look more carefully at some of these frequency bands . . .

Brain rhythms: theta

Theta: 4-8 Hz Note: Theta frequency range different; the borders of ranges are not exact.



Function: Not well understood.

In rats:
- learning and memory
- location
- motor behavior
- sleep
- emotional arousal
- fear conditioning

Brain rhythms: alpha

Alpha: 8-12 Hz Note: This band not in Slide #7 !

- The first EEG wave studies [Berger 1931]
- In EEG, strongest above occipital lobes when eyes closed at rest.

Function: "idling rhythm" - alert but still brain state
cortical operations in the absence of sensory inputs
disengagement of task-irrelevant brain areas

However, alpha also associated with attention, sensory awareness.

Brain rhythms: beta

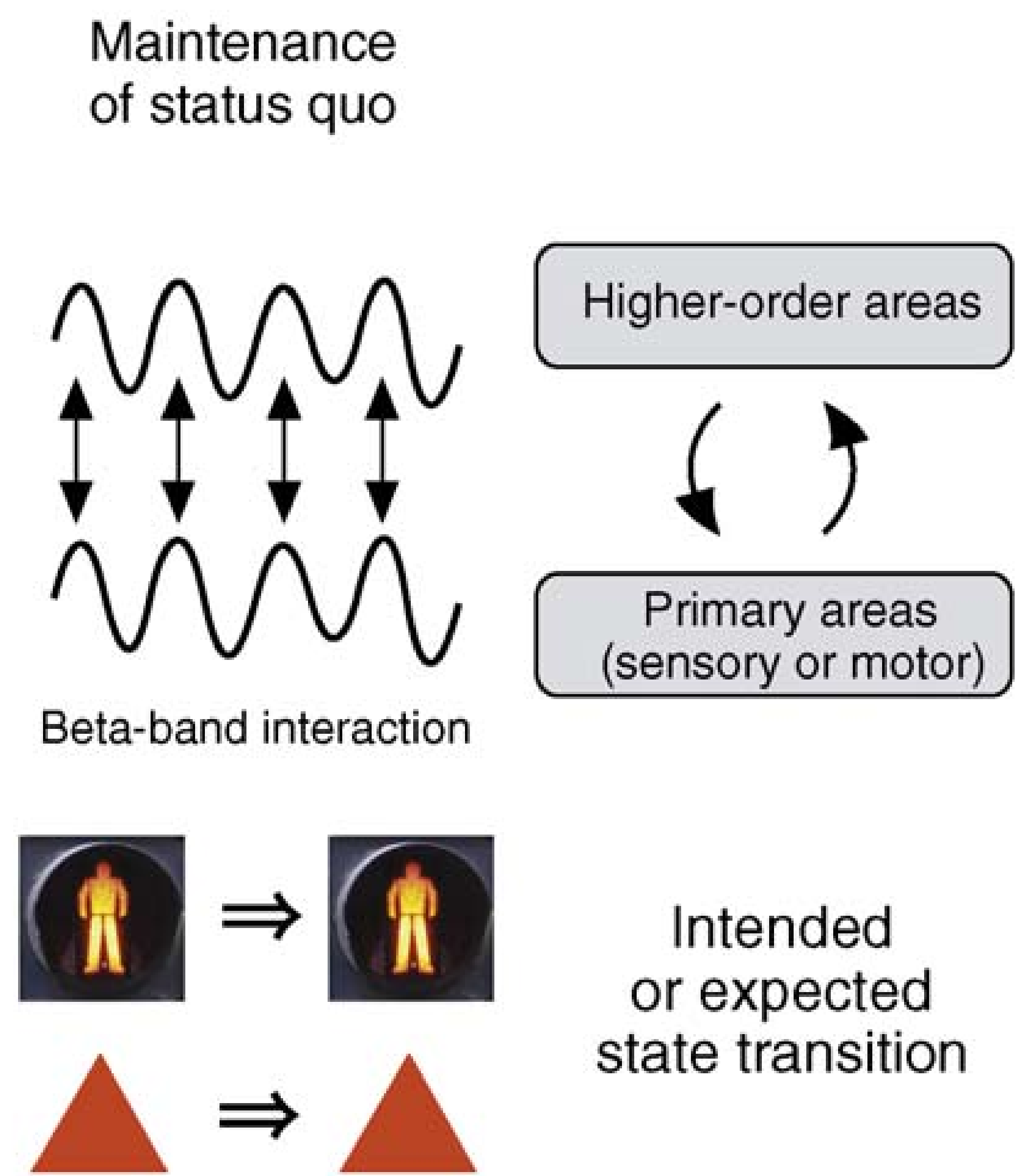
Beta: 12-30 Hz

Function: Not well understood.

motor functions (e.g., steady-state contractions).

"Maintenance of the status quo"

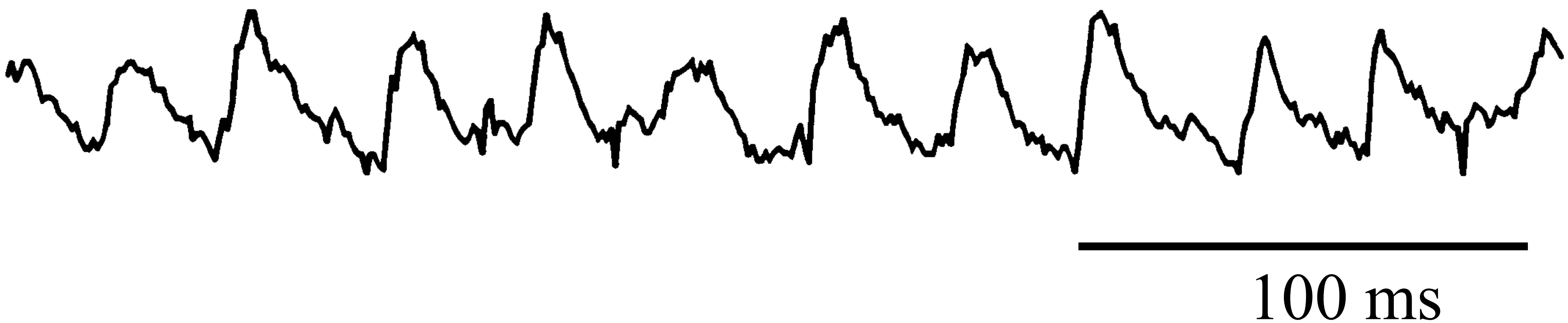
"Couple" distant brain regions.



[Engel, Fries 2010]

Brain rhythms: gamma

Gamma: 30-50 Hz



Function: Associated with a broad range of processes:
"binding"
attention
movement preparation
memory formation
conscious awareness

<u>Note</u>: Typically hard to see in EEG. Q: Why?

Brain rhythms: Other bands

There are many other frequency bands . . .

Slower

- **Delta**: 1-4 Hz — Sleep, learning, motivation
- **Slow cortical potential**: < 1 Hz — Emergence of consciousness?

Faster

- **High gamma**: 50-120 Hz — Coordination of neural activity
- **Ripples, HFO, UFO**: > 120 Hz — Replay of memories, onset of seizures . . .

Brain rhythms in disease

Rhythms are sometimes associated with pathologies.

Ex: Seizure

Q: What rhythms do we see?

HFO Beta Alpha Theta Delta

Q: How does the amplitude change?

Note: Used the band labels, but "function" very different.

Brain rhythms are meaningless . . .

H: Brain rhythms are epiphenomena.

Large buildings: sway in the wind.

These oscillations are not performing a function, in fact they're unwanted.

Q: Is the same true in the brain? Oscillations are an echo of some underlying function?

Q: Why so many oscillations?

Big questions

Q: Why do we observe rhythms in the brain?
–Functional role
–Epiphenomena

Q: What mechanisms support rhythms?
–Biological
–Dynamical

Q: Why do we observe different frequency bands, not a continuum?

Q: Why do rhythms interact?
–Mechanisms
–Functions
–Measures . . .

We need answers to these questions ...
Data analysis and models ...

Characterize brain rhythms

Many sophisticated tools to do so.

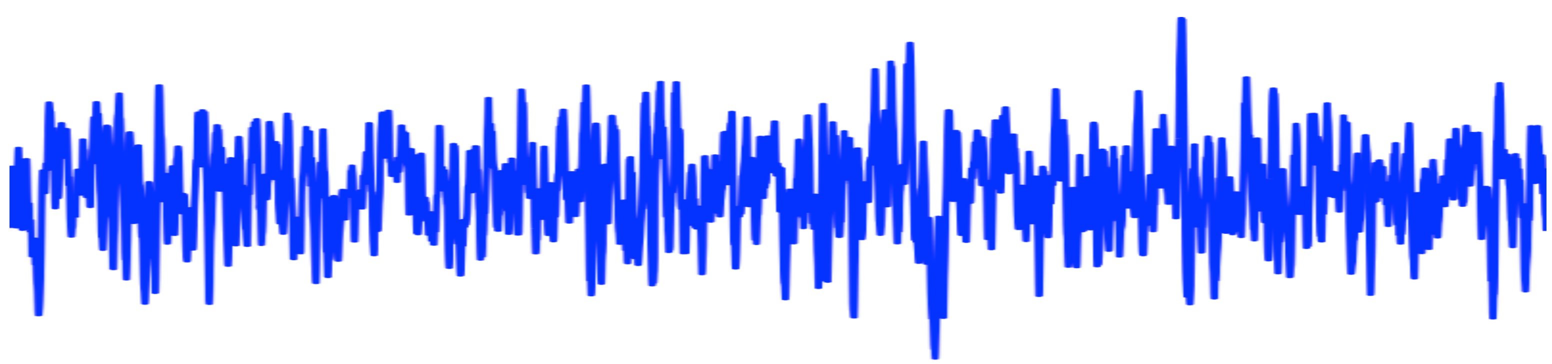
Today, consider two:

–Visual inspection

–Intuition for the power spectrum

Idea:

Visual inspection: Plot the data. What do you see?



Power spectrum: Break down the data into sinusoids . . .

Remember: sinusoids . . .

$$V[t] = A\cos(2\pi f t)$$

Voltage as a function of time

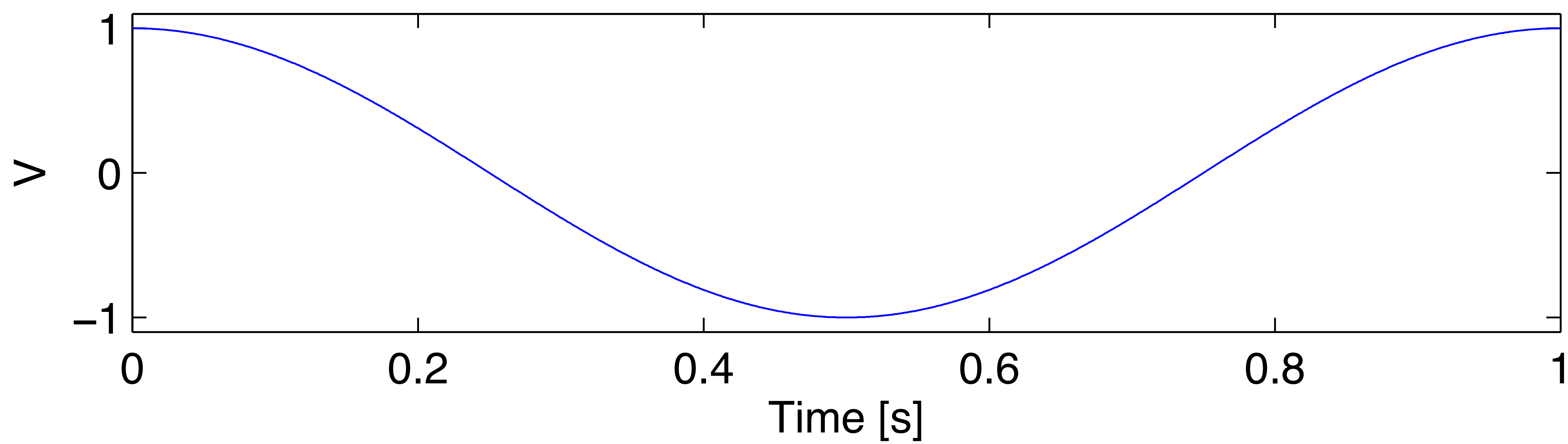
Amplitude

Frequency [Hz]

Time [s]

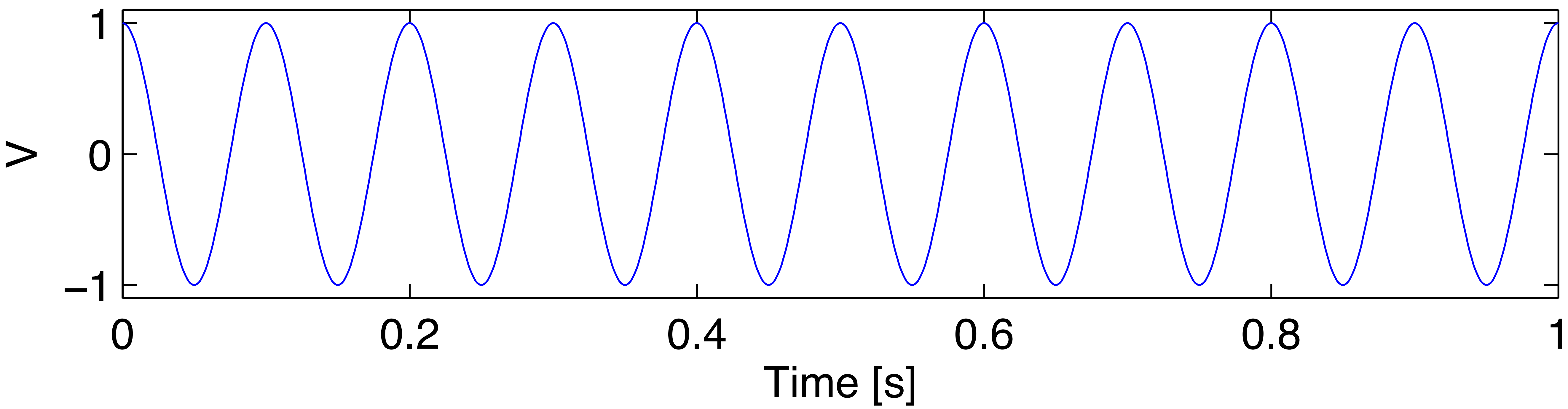
Ex. Consider: f = 1 Hz

Q: What does it look like?



Remember: sinusoids . . .

Q: What is the frequency of this sinusoid?



A: 10 cycles in 1 second, so 1 Hz.

<u>Note</u>: Visual inspection is often useful.

Remember: sinusoids . . .

In addition to cosine, there's also sine:

$$V[t] = B\sin(2\pi f t)$$

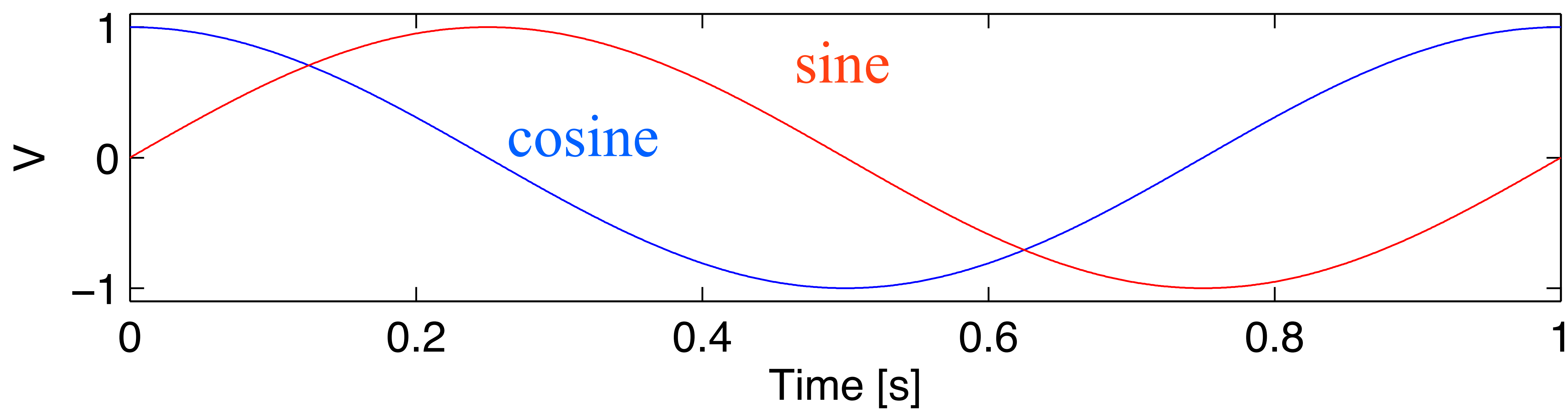
Voltage as a function of time

Amplitude

Frequency [Hz]

Time [s]

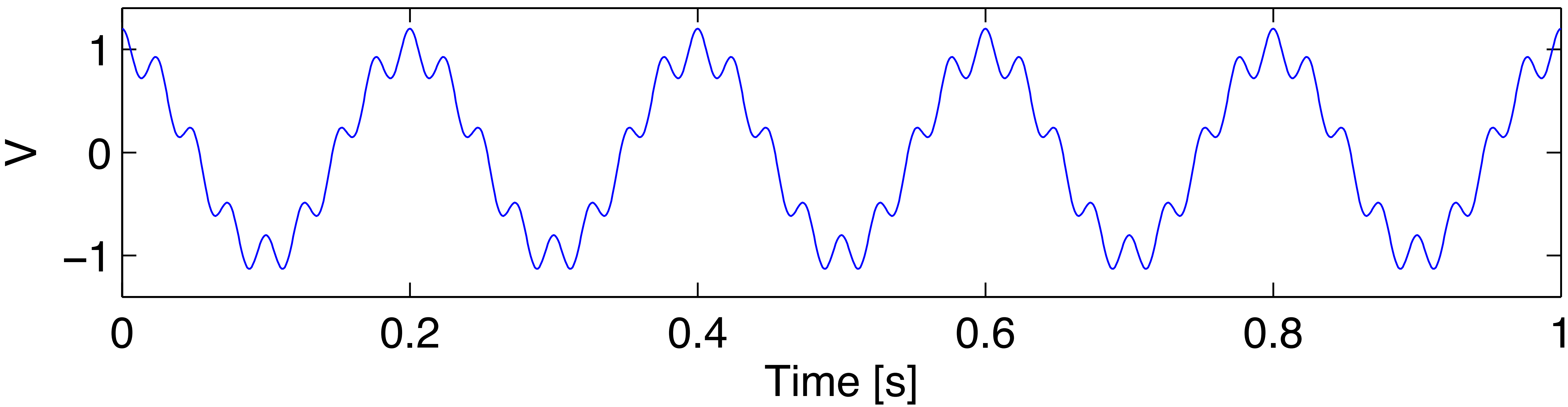
Ex. Consider: f = 1 Hz



Q: What's the difference?

Example: rhythmic signal

Consider the signal below:



Q: What are the rhythms?

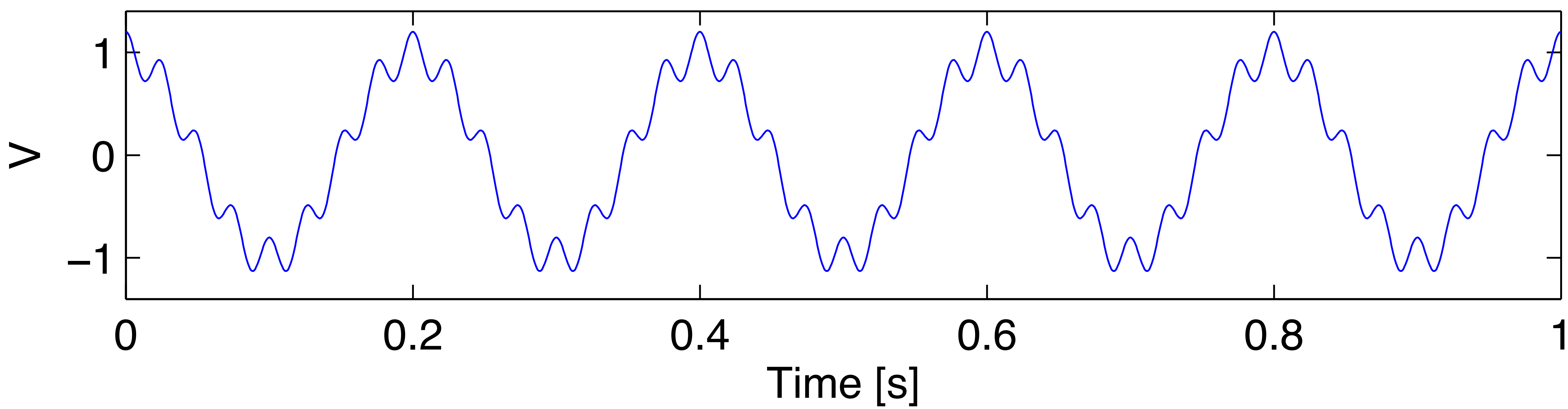
A: Apply visual inspection . . . Slow and fast

5 Hz 40 Hz

Q: What has larger amplitude?

Example: rhythmic signal

So, we can represent this signal . . .



. . . as the sum of two sinusoids:

A slow, large amplitude sinusoid + a fast, small amplitude sinusoid

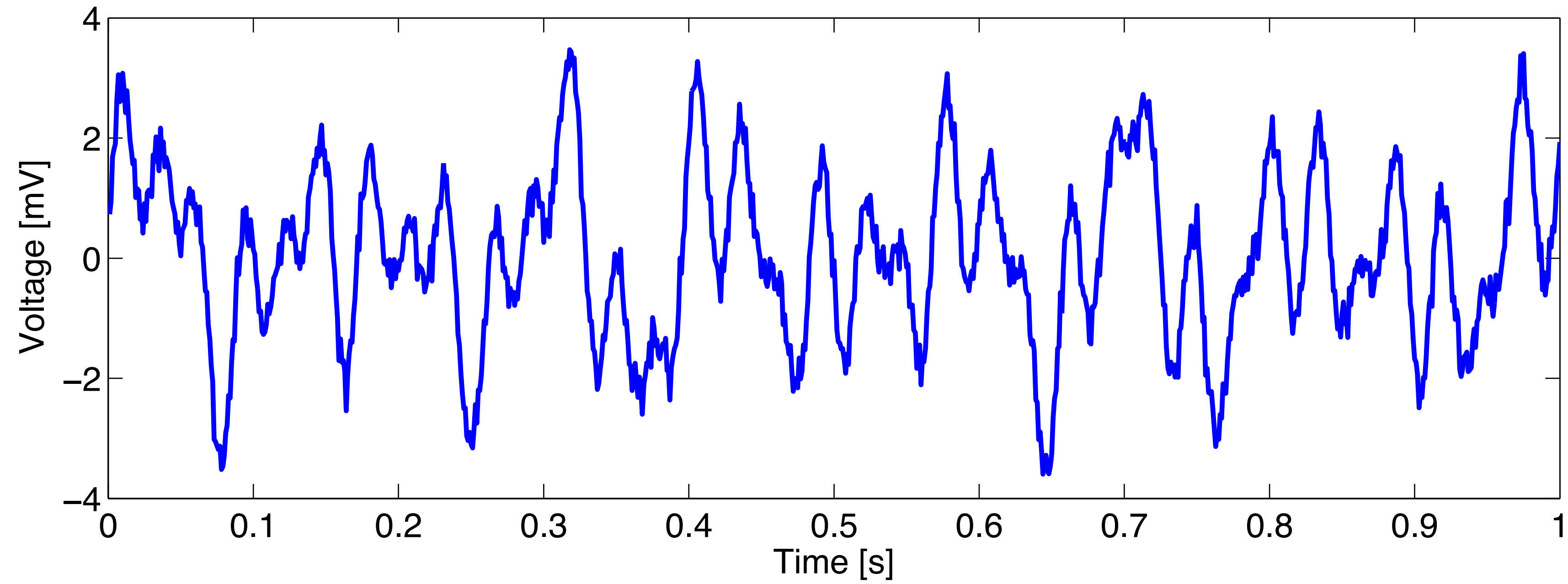
$$V[t] = \underset{1.0}{A_1} \cos(2\pi \underset{5\text{ Hz}}{f_1} t) + \underset{0.1}{A_2} \cos(2\pi \underset{40\text{ Hz}}{f_2} t)$$

We get a simpler representation of the signal. That's the idea of the power spectrum.

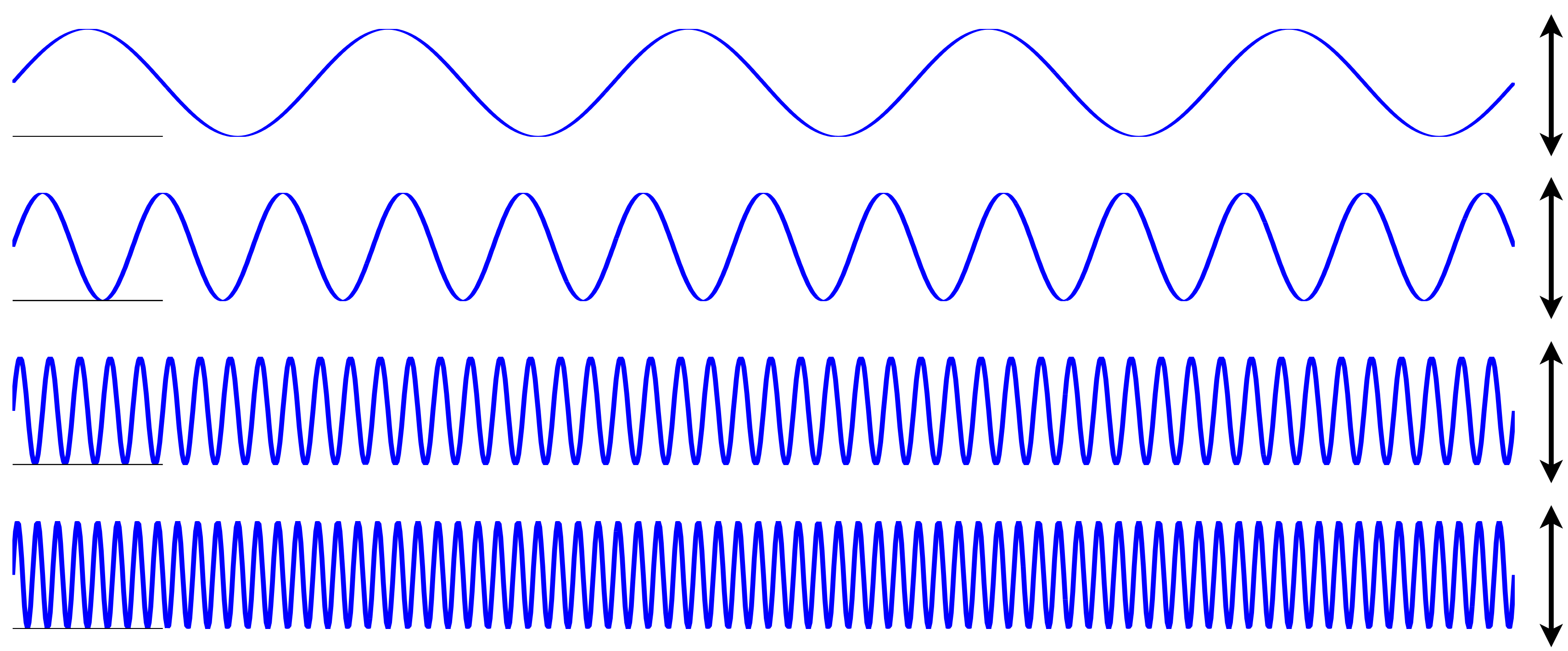
Idea: Power spectrum

Consider:

$V =$



- Decompose signal into oscillations at different frequencies.



$V =$ A_1 f_1

$+$ A_2 f_2

$+$ A_3 f_3

$+$ A_4 f_4

$+ \ \ldots$

Represent V as a sum of sinusoids (e.g., part 7 Hz, part 10 Hz, . . .)

Idea: Power spectrum

So, in equations:

$$V[t] = A_1 \cos(2\pi f_1 t) + B_1 \sin(2\pi f_1 t) + A_2 \cos(2\pi f_2 t) + B_2 \sin(2\pi f_2 t) + \ldots$$

amplitude frequency amplitude frequency

Or, more generally:

$$V[t] = \sum_j A_j \cos(2\pi f_j t) + B_j \sin(2\pi f_j t)$$

sum over all possible frequencies

amplitude

oscillation at frequency f_j

<u>Note</u>: A_j and B_j can be zero.
(some rhythms make no contribution to V[t])

<u>Note:</u> A_j and B_j are large when f_j is a good match to the data.

Idea: Power spectrum

<u>Note</u>: Think of sine & cosine as accounting for **phase**.

$$C_j \cos(2\pi f_j t + \phi_j)$$

Aside: $\cos(a + b) = \cos(a)\cos(b) - \sin(a)\sin(b)$

$$= \underbrace{\boxed{C_j} \cos(2\pi f_j t) \boxed{\cos(\phi_j)}}_{A_j} - \underbrace{\boxed{C_j} \sin(2\pi f_j t) \boxed{\sin(\phi_j)}}_{B_j}$$

$$= \boxed{A_j} \cos(2\pi f_j t) + \boxed{B_j} \sin(2\pi f_j t)$$

Decompose V[t] into sine/cosine or amplitude/phase.

Idea: Power spectrum

Q: How doe we find A_j and B_j ?

A: Consider A_j and use **orthogonality of sinusoids**.

$$\int_0^T \cos(2\pi f_j t)\ \cos(2\pi f_k t)\, dt = \begin{cases} 0 & \text{if} \quad f_j \neq f_k \\ \text{T/2} & \text{if} \quad f_j = f_k \end{cases}$$

Choose T so f_j and f_k complete an integer number of cycles.

frequencies

integrate over time

Idea: Power spectrum

Python

Idea: Power spectrum

Q: How doe we find A_j and B_j ?

A: Consider A_j and use **orthogonality of sinusoids**.

$$\int_0^T \cos(2\pi f_j t)\ \sin(2\pi f_k t)\, dt = \ 0 \qquad \text{for all} \quad f_j\,, f_k$$

sine

Idea: Power spectrum

Return to our original equation

$$V[t] = \sum_j A_j \cos(2\pi f_j t) + B_j \sin(2\pi f_j t)$$

Pick frequency f_k , multiply both sides by $\cos(2\pi f_k t)$, and integrate over time …

$$\int_0^T V[t]\cos(2\pi f_k t)dt = \int_0^T \sum_j A_j \cos(2\pi f_j t)\cos(2\pi f_k t)dt$$

$$+\int_0^T \sum_j B_j \sin(2\pi f_j t)\cos(2\pi f_k t)dt$$

Consider each integral …

Idea: Power spectrum

by orthogonality

$$\boxed{\int_0^T} \sum_j A_j \boxed{\cos(2\pi f_j t)\cos(2\pi f_k t)dt} \quad = 0 \text{ if } f_j \neq f_k \text{ , or T/2 if } f_j = f_k$$

$$\boxed{\int_0^T} \sum_j B_j \boxed{\sin(2\pi f_j t)\cos(2\pi f_k t)dt} \quad = 0$$

$$A_k\, T/2 \text{ if } j = k, \text{ 0 otherwise}$$

So $$\int_0^T V[t]\cos(2\pi f_k t)dt = \int_0^T \sum_j A_j \cos(2\pi f_j t)\cos(2\pi f_k t)dt$$

$$+ \underbrace{\cancel{\int_0^T \sum_j B_j \sin(2\pi f_j t)\cos(2\pi f_k t)dt}}_{0}$$

$$= A_k\, T/2$$

Idea: Power spectrum

$$\int_0^T V[t]\cos(2\pi f_k t)dt = A_k T/2$$

Solve for A_k

$$A_k = \frac{2}{T}\int_0^T V[t]\cos(2\pi f_k t)dt$$

We can solve for amplitude A_k

Depends on observed data V[t] multiplied by cosine we choose (f_k)

Idea: Power spectrum

Return to our original equation

$$V[t] = \sum_j A_j \cos(2\pi f_j t) + B_j \sin(2\pi f_j t)$$

Q: How doe we find A_j and B_j ?

A: Consider A_j and use **orthogonality of sinusoids**.

Similarly

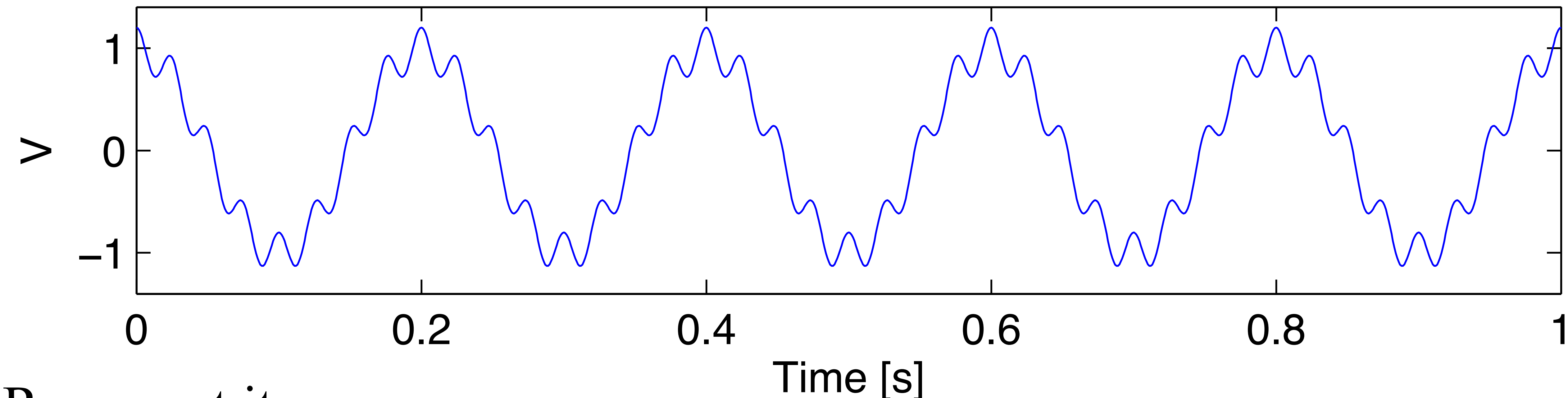
$$A_k = \frac{2}{T}\int_0^T V[t]\cos(2\pi f_k t)dt \qquad B_k = \frac{2}{T}\int_0^T V[t]\sin(2\pi f_k t)dt$$

Big idea: We can decompose V[t] into a sum of sin/cos functions, and we know how to find the amplitudes A_j , B_j

Example: rhythmic signal

Q: So what?

A: Represent V[t] in a simpler way … remember:



Represent it as:

$$V[t] = A_1 \cos(2\pi f_1 t) + A_2 \cos(2\pi f_2 t)$$

1.0 5 Hz 0.1 40 Hz

To represent V[t] we need 4 numbers:

Amplitudes = {1, 0.1}

Frequencies = {5, 40} Hz

These 4 numbers completely summarize the data.

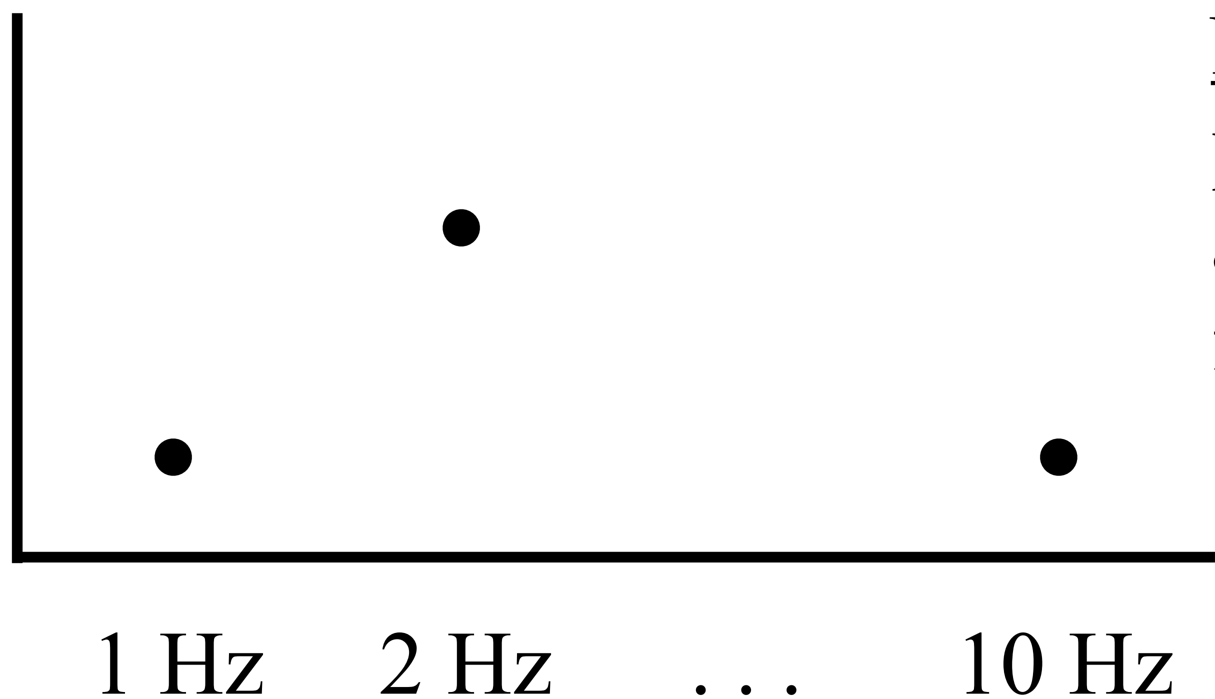
Plot: Power spectrum

We can represent these amplitudes and frequencies graphically:

Plot: $\dfrac{A_j^2 + B_j^2}{2}$ versus f_j for each n

<u>Note</u>: The summed amplitudes squared. Called the "power"

$$\frac{A_j^2 + B_j^2}{2}$$



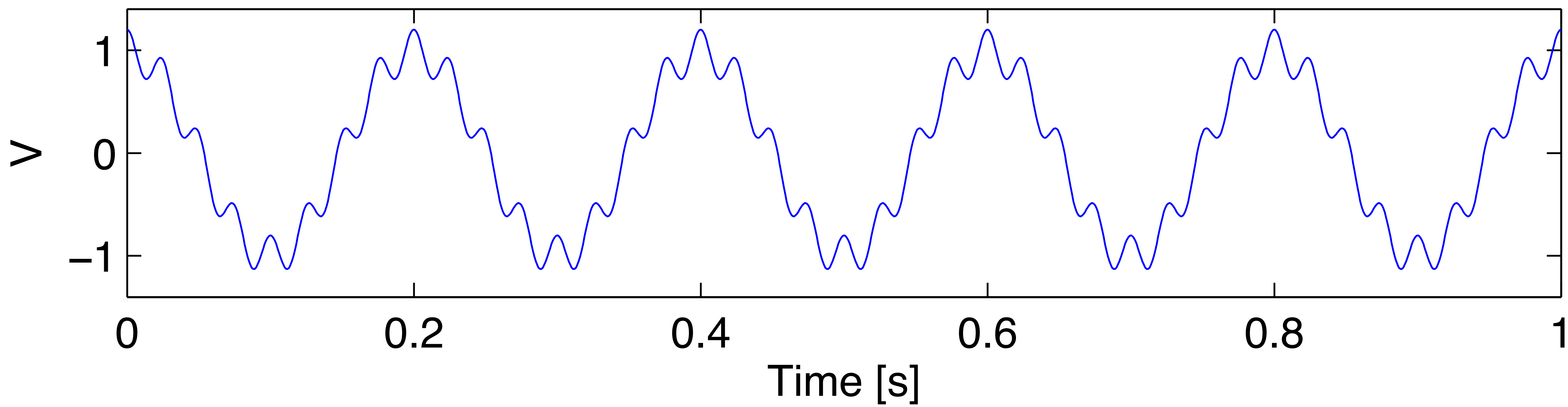
f_j

<u>Note</u>: This is called the **power spectrum**; a plot of power versus frequency

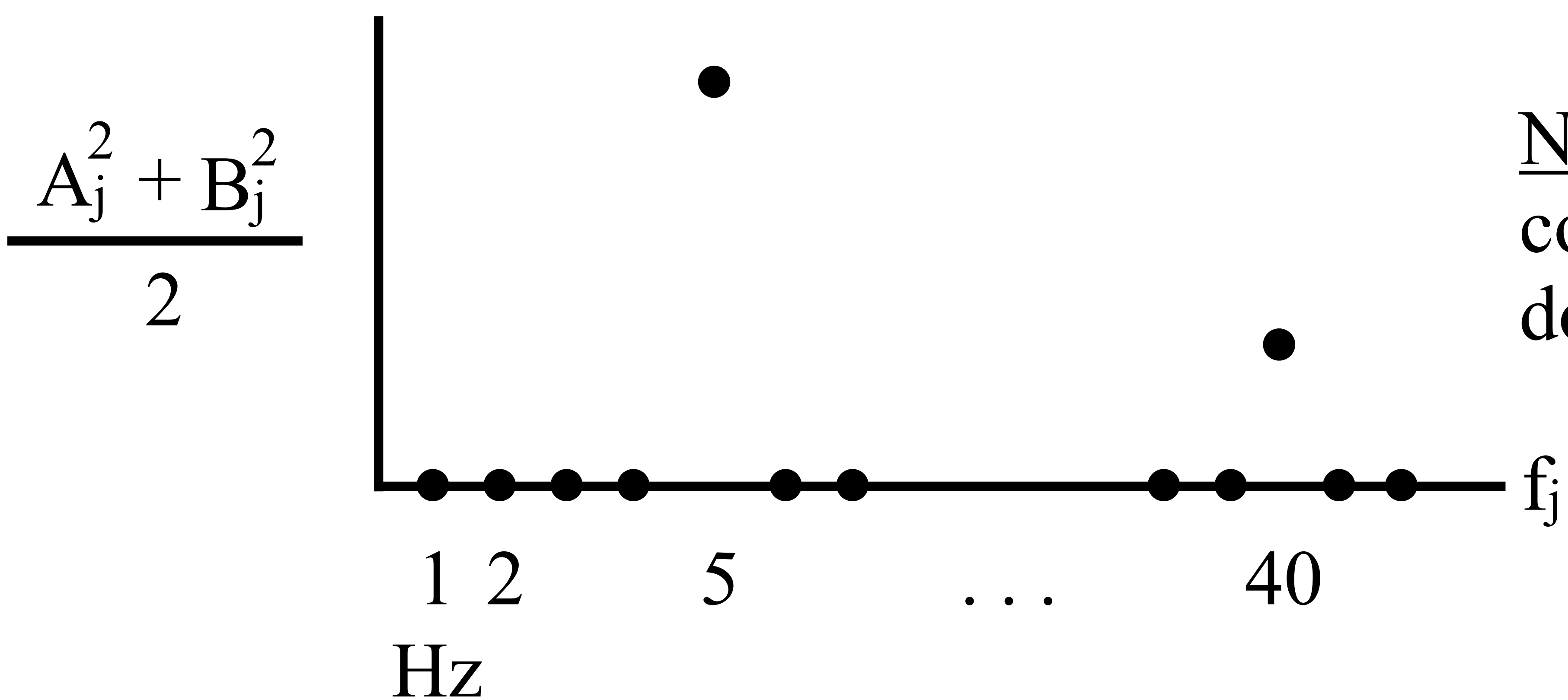
The peaks represent the <u>dominant rhythms</u> in the signal.

Example: rhythmic signal

Ex:



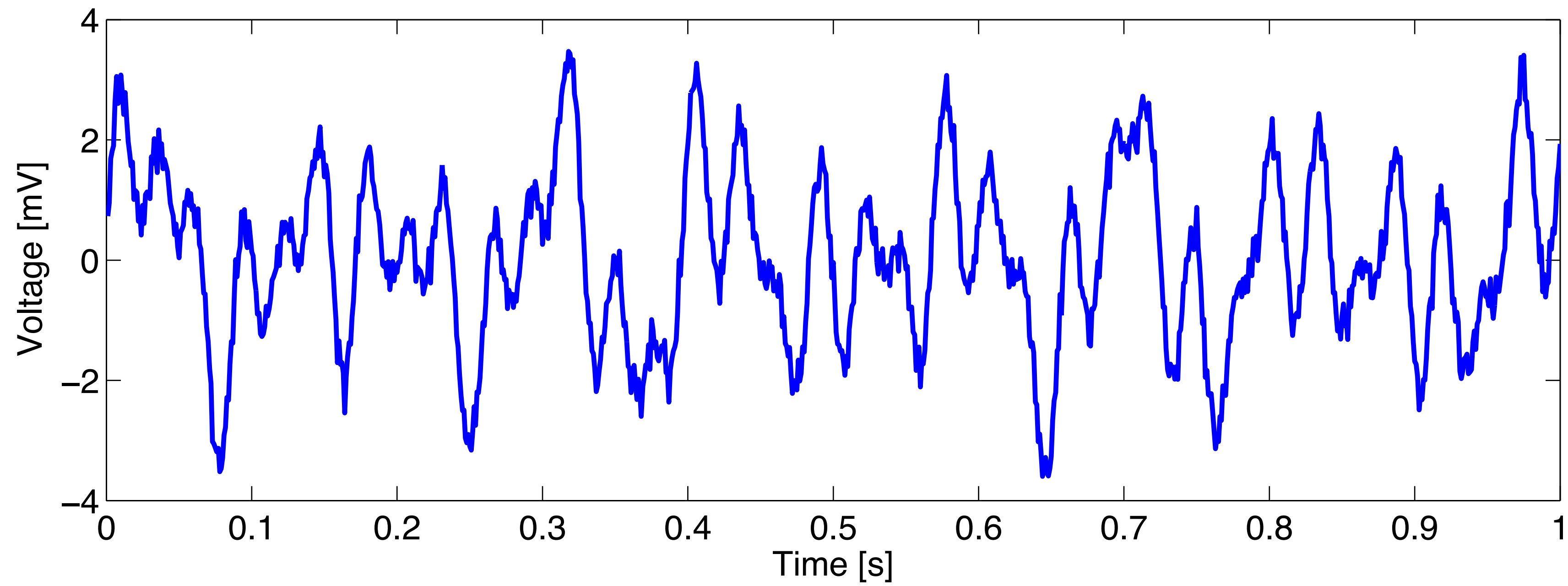
Plot the power spectrum:



<u>Note</u>: The peaks correspond to the dominant rhythms

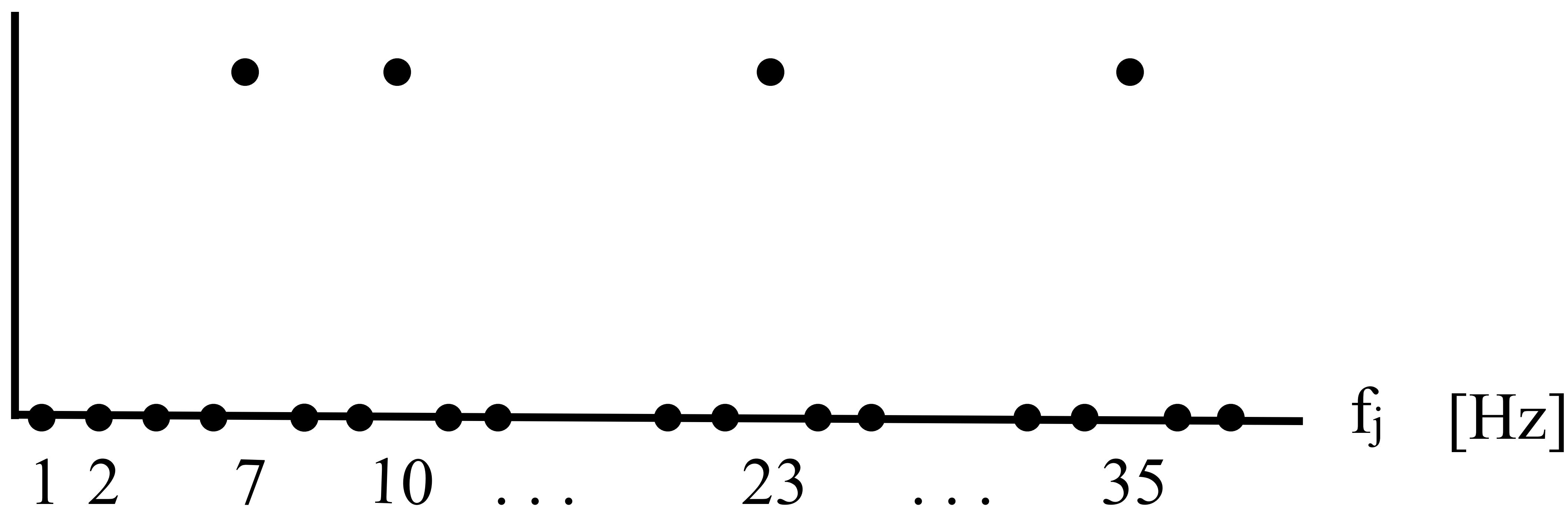
Example: rhythmic signal

Ex.

$V =$ 

<u>Note</u>: It's complicated   Plot the power spectrum:

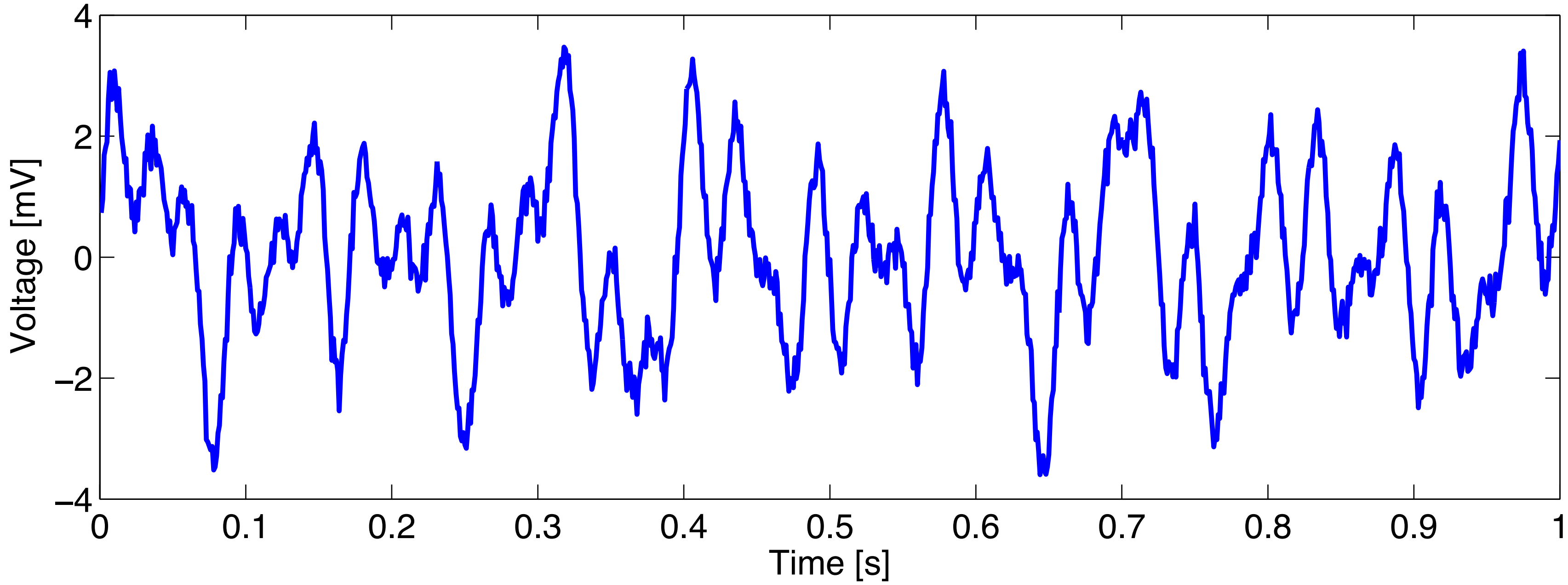
$$\frac{A_j^2 + B_j^2}{2}$$



Q: What's happening here?

Example: rhythmic signal

So, by computing the power spectrum, we find the complicated signal:

V = 

We find it's the sum of 4 sinusoids at frequencies:

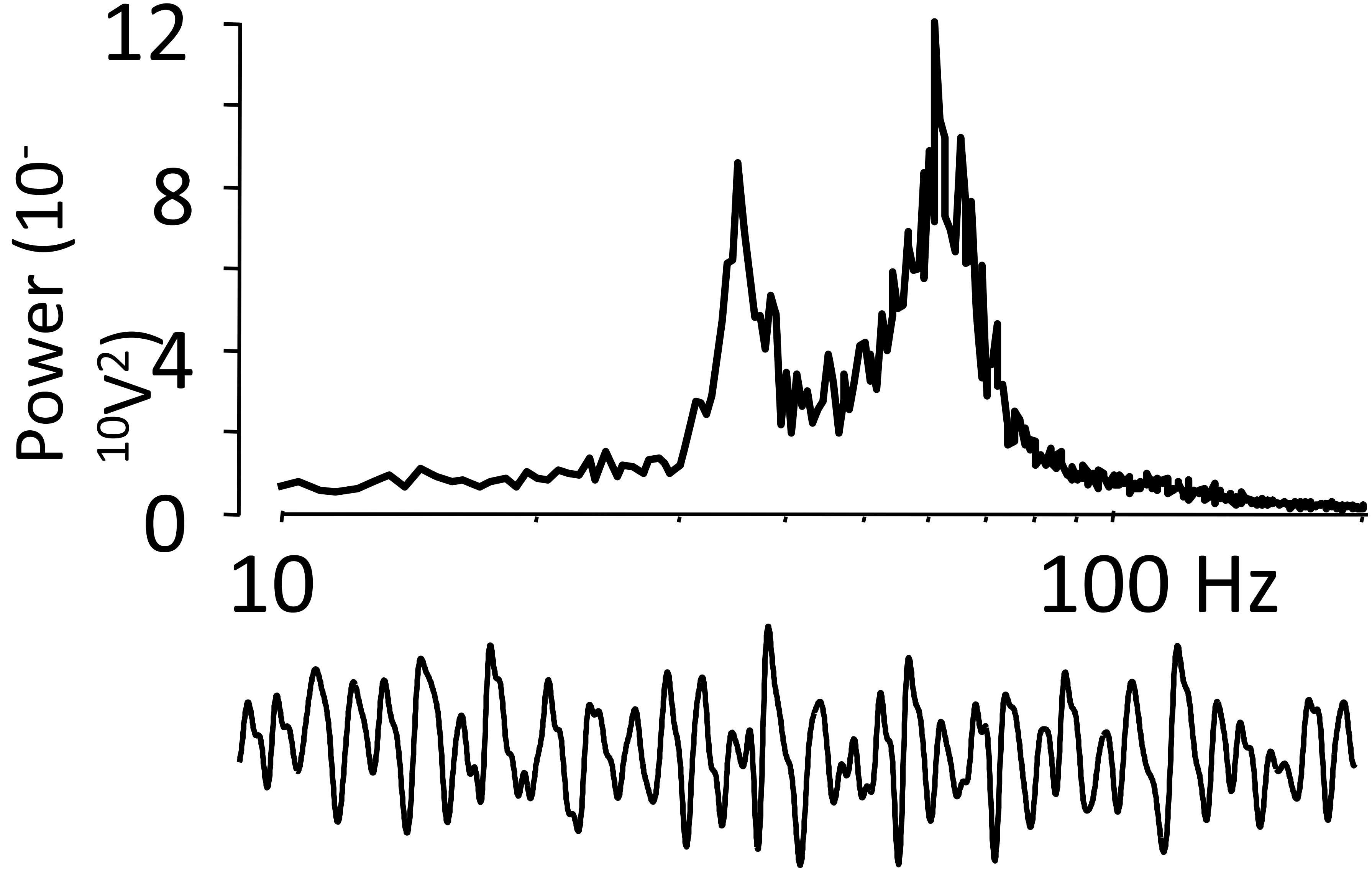
7 Hz, 10 Hz, 23 Hz, and 35 Hz

A much simpler representation of brain activity.

Example: Real world

Q: What does the power spectrum of real-world brain signals look like?

Ex. From a slice of rat cortex:



[Ainsworth et al, Neuron, 2012]

Q: What rhythms are dominant?

Next

A simple answer to one big rhythm question …