Rhythms

Introduction (Part 1)

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Brain rhythms

Introduction

What are they?

Where do they come from?

What do they do?

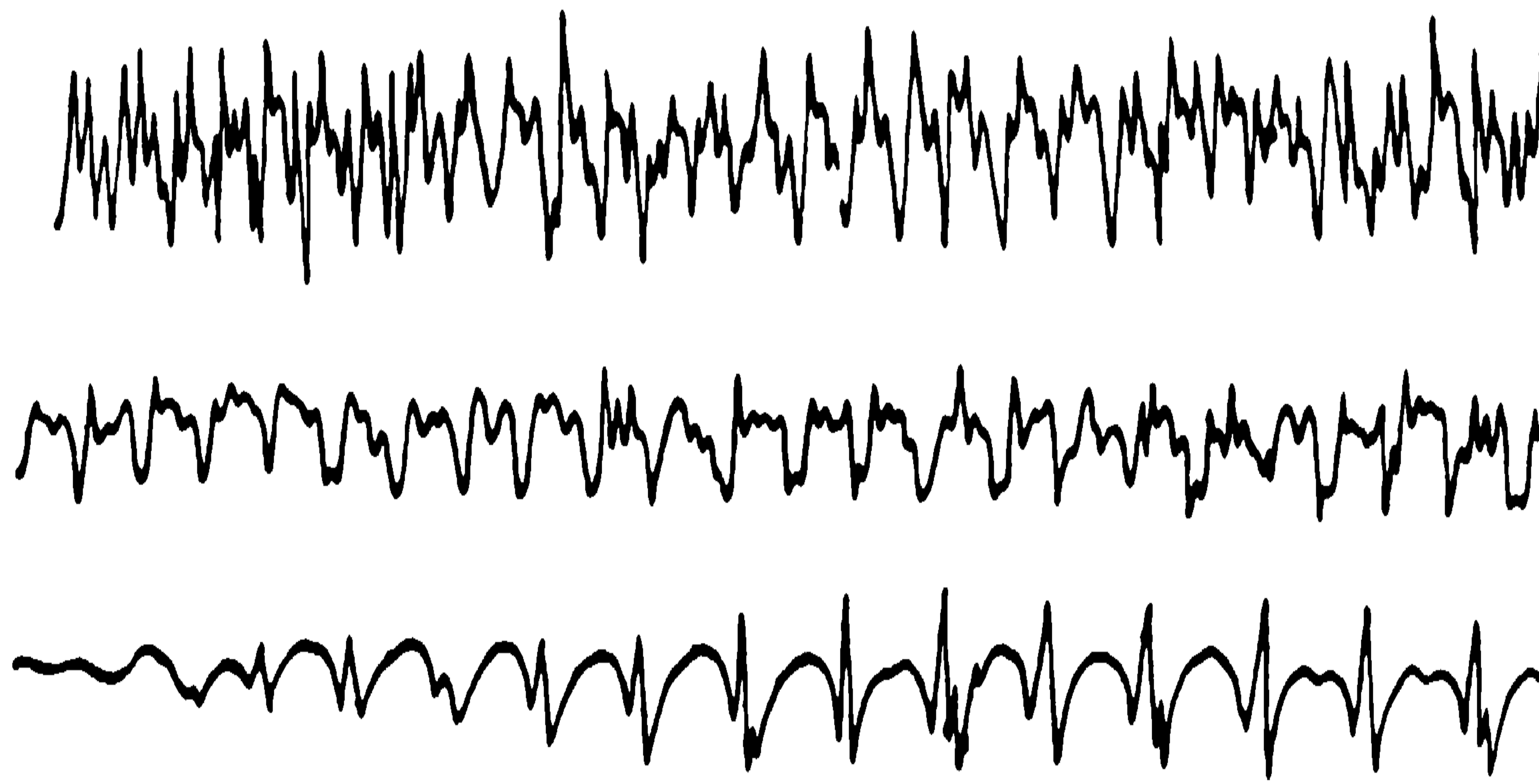
Method of analysis

Brain rhythms

<u>Fact</u>: The brain can generate <u>rhythmic activity</u>.

Ex: Scalp electroencephalogram (EEG)

<u>Note</u>: Rhythms also appear in LFP, MEG, fMRI, ...

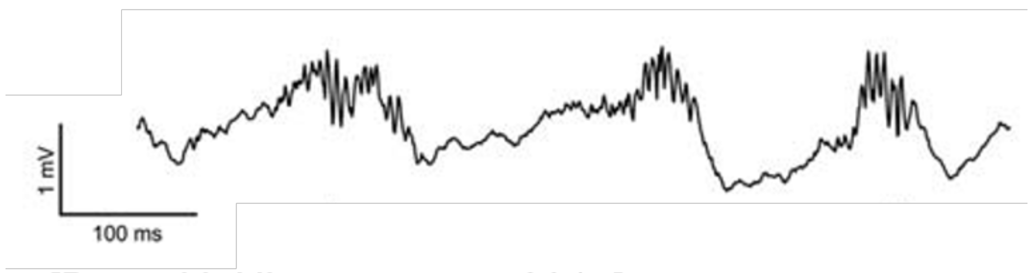


<u>Observe</u>: Different shapes. Different frequencies.

Brain rhythms

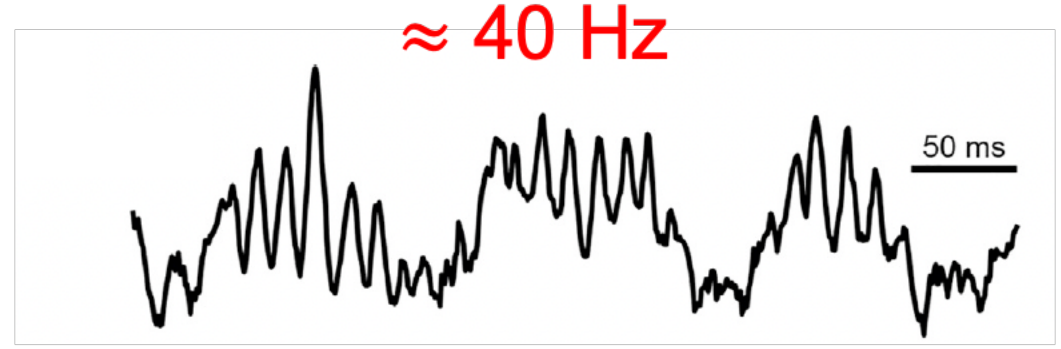
<u>Fact</u>: The brain can generate <u>rhythmic activity</u>.

≈ 150 Hz



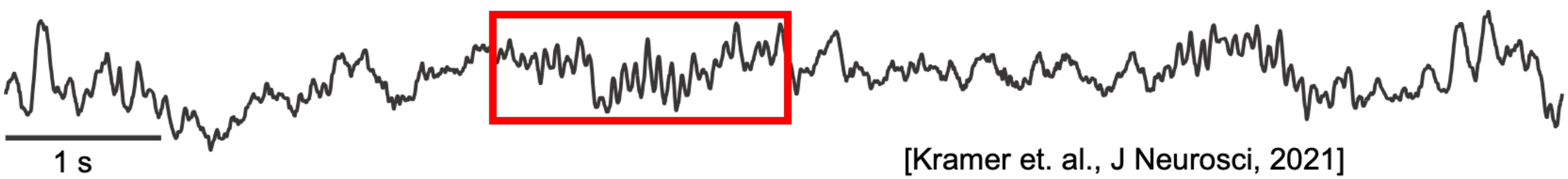
[Buzsaki, Hippocampus, 2015]

≈ 40 Hz



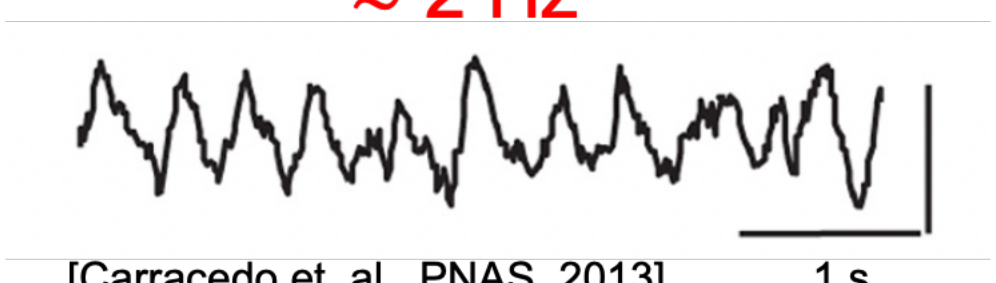
[Fernandez-Ruiz et al., Neuron, 2023]

≈ 12 Hz



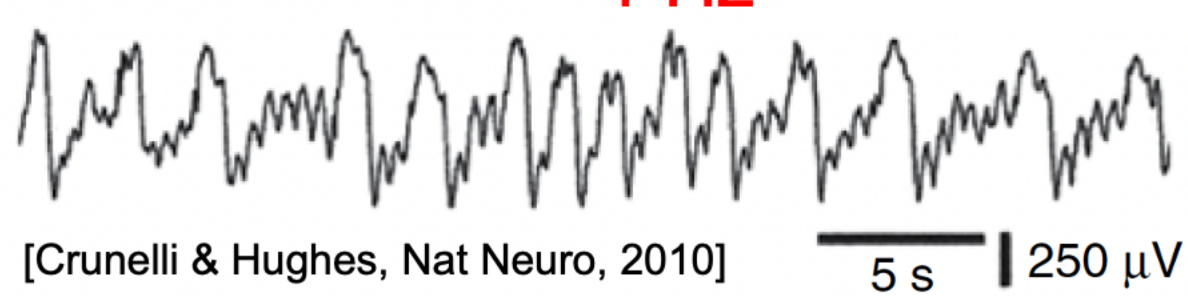
[Kramer et. al., J Neurosci, 2021]

≈ 2 Hz



[Carracedo et. al., PNAS, 2013]

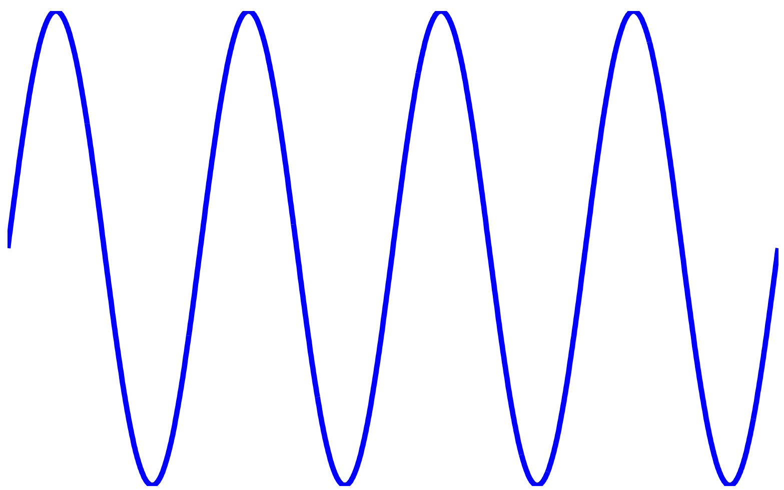
< 1 Hz

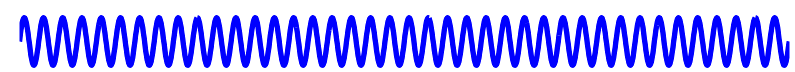


[Crunelli & Hughes, Nat Neuro, 2010]

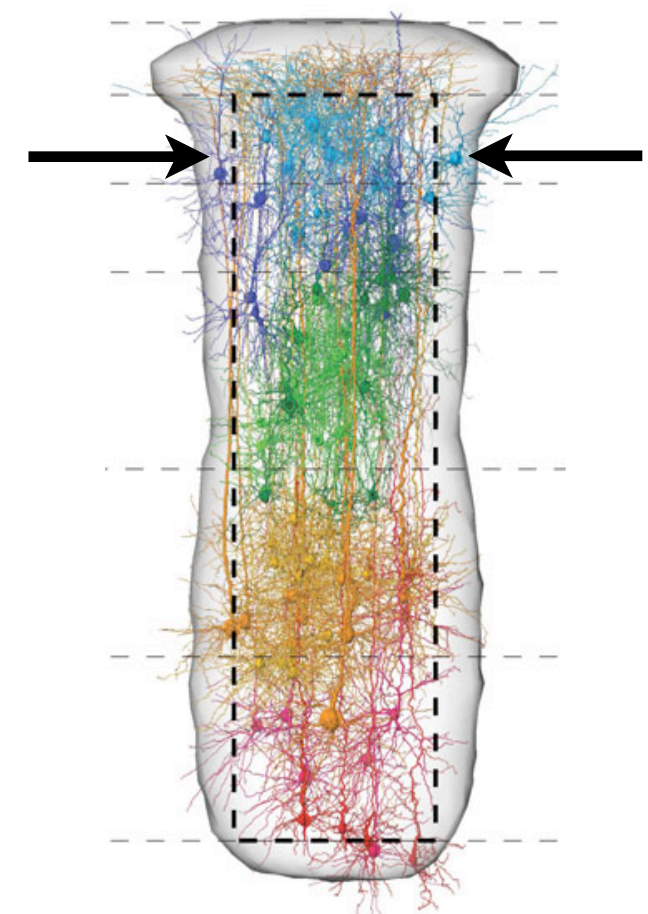
Brain rhythms: "facts"

• Slower rhythms tend to be larger amplitude.





• The EEG ≈ generated by coordinated synaptic transmembrane currents of many neurons.



Very complicated.

Not completely understood.

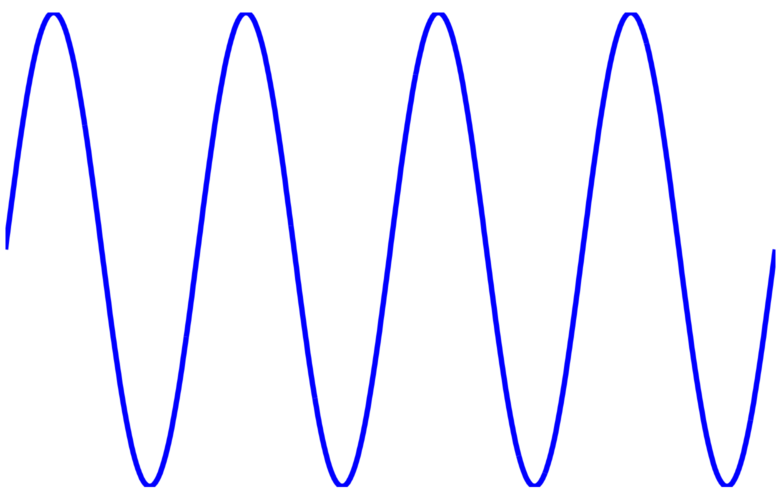
[Buzsáki et al. Nat Rev Neurosci (2012)]

Brain rhythms: "facts"

Rhythms indicate cortical arousal

–Modulate the firing patterns of neurons.

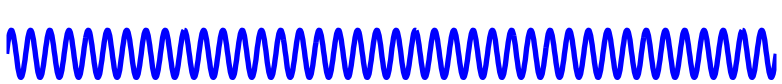
Low frequency, high amplitude: low cortical arousal



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, . . . ?

Duration: Long or short lasting ?

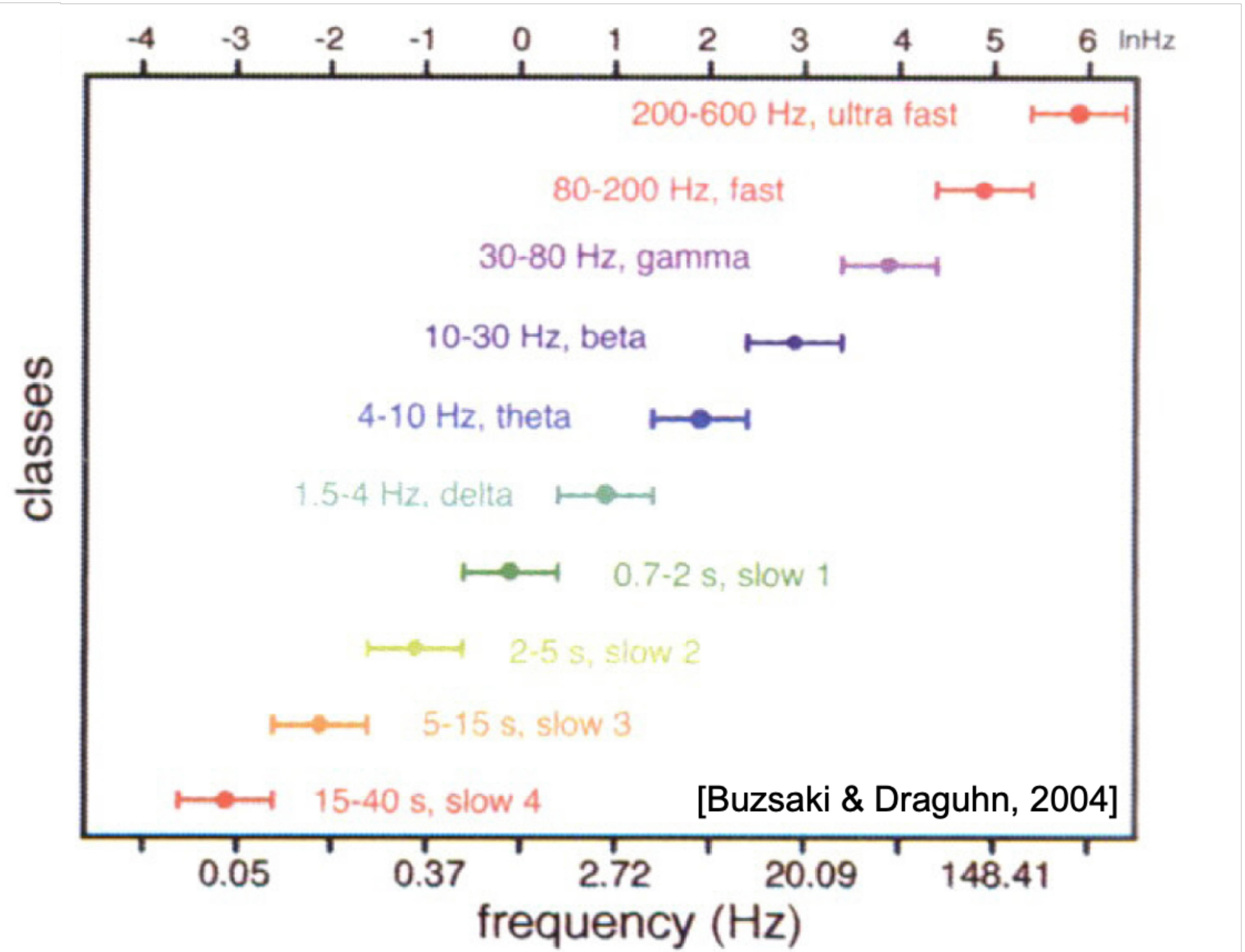
Our focus (usually) is frequency: How fast or slow is a rhythm?

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

Brain rhythms and functions

Many frequency bands, each associated with different functions.

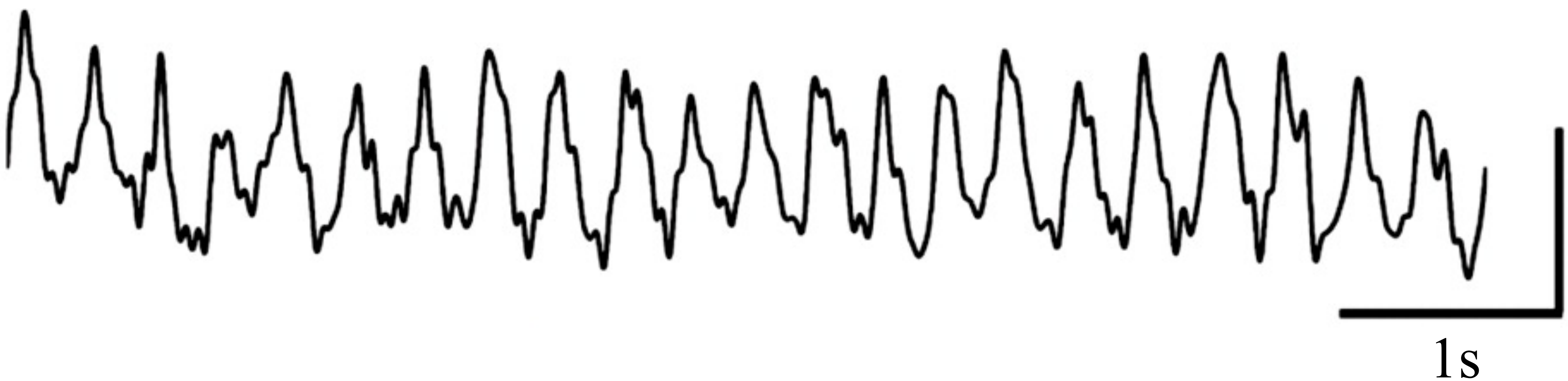
Ex:



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.

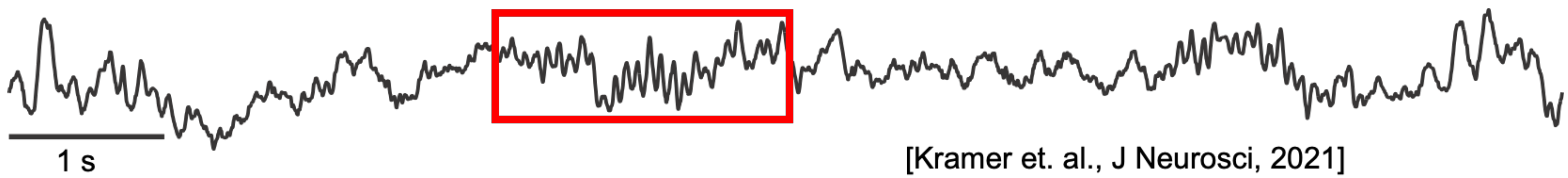


Function: Not completely understood.

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 !



[Kramer et. al., J Neurosci, 2021]

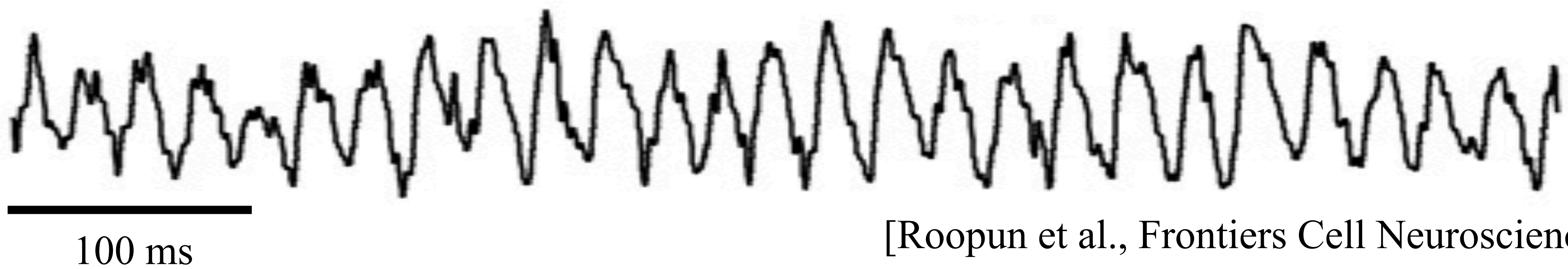
- The first EEG wave studies [Berger 1931]
- In EEG, strongest above occipital lobes when eyes closed at rest.

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



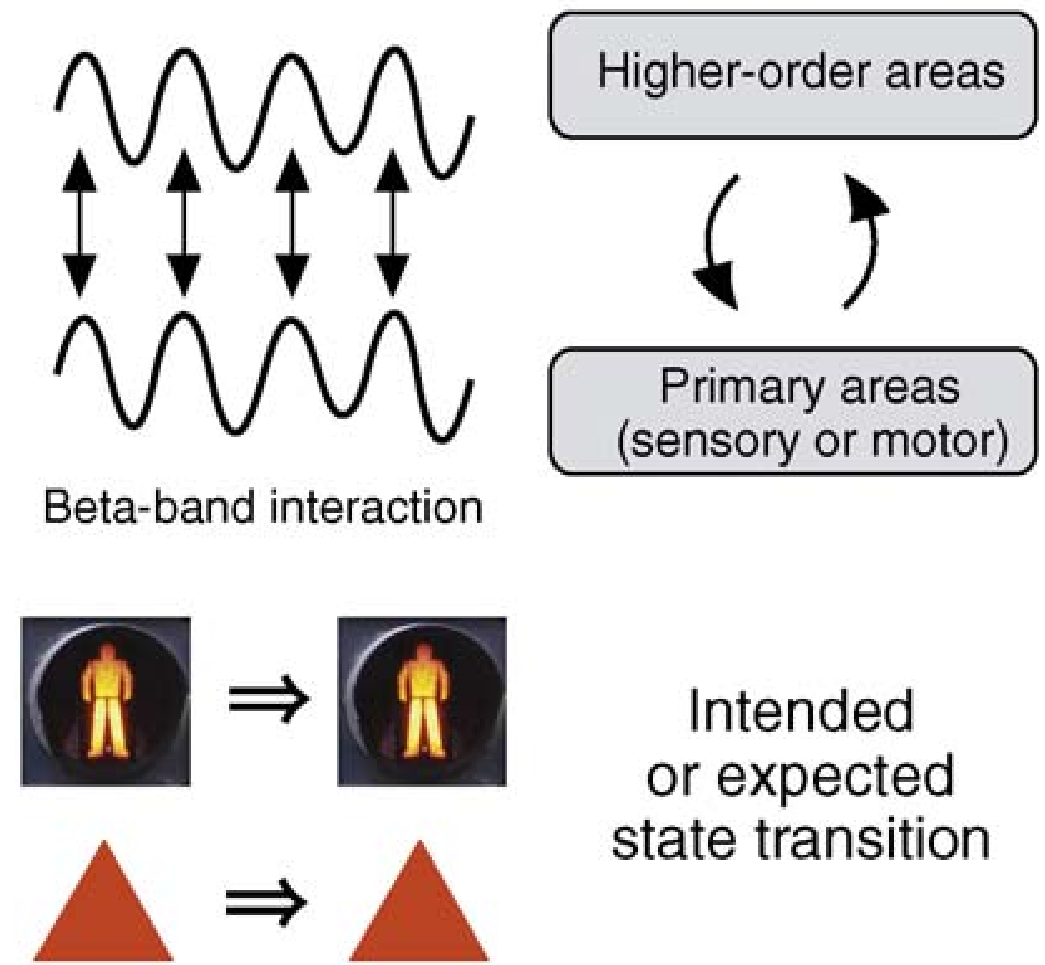
[Roopun et al., Frontiers Cell Neuroscience, 2008]

Function: Not fully understood.

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

"Maintenance of the status quo"

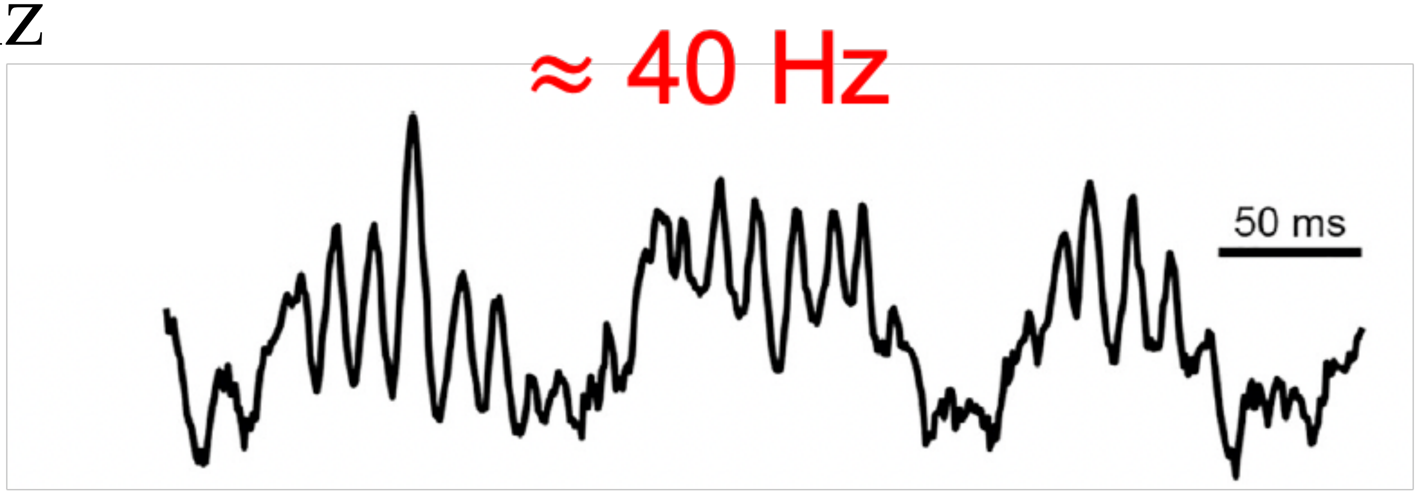
"Couple" distant brain regions.



[Engel, Fries 2010]

Brain rhythms: gamma

Gamma: 30-50 Hz



[Fernandez-Ruiz et al., Neuron, 2023]

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?

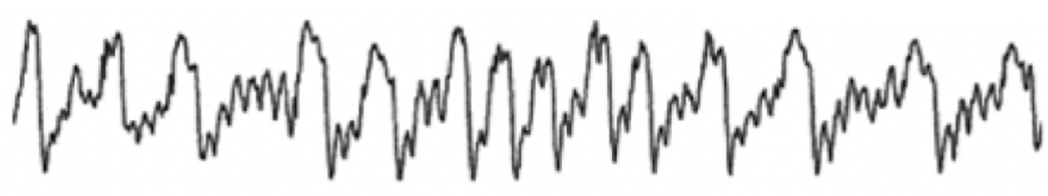
Brain rhythms: Other bands

There are many other frequency bands . . .

<u>Slower</u>

–**Delta**: 1-4 Hz — Sleep, learning, motivation

–**Slow cortical potential**: < 1 Hz — Emergence of consciousness?



[Crunelli & Hughes, Nat Neuro, 2010]

<u>Faster</u>

– **High gamma**: 50-120 Hz — Coordination of neural activity

– **Ripples, HFO, UFO**: > 120 Hz — Replay of memories, onset of seizures . . .

[Buzsaki, Hippocampus, 2015]

Brain rhythms in disease

Rhythms are sometimes associated with pathologies.

Ex: Seizure

[Martinet et al., Nat Comm, 2017]

Q: What rhythms do we see?

HFO Beta Alpha Theta Delta

Q: How does the amplitude change?

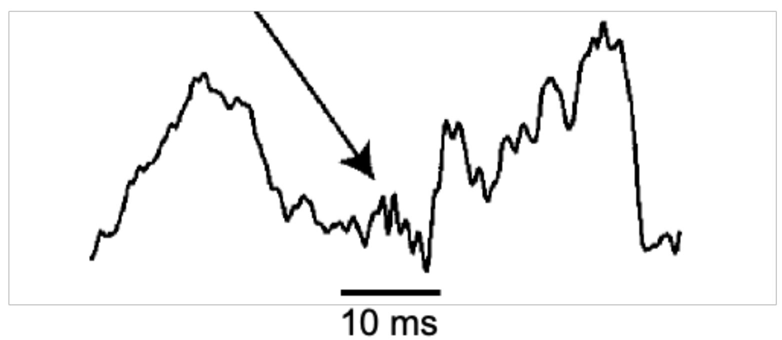
Note: Used the band labels, but "function" very different.

Brain rhythms in disease

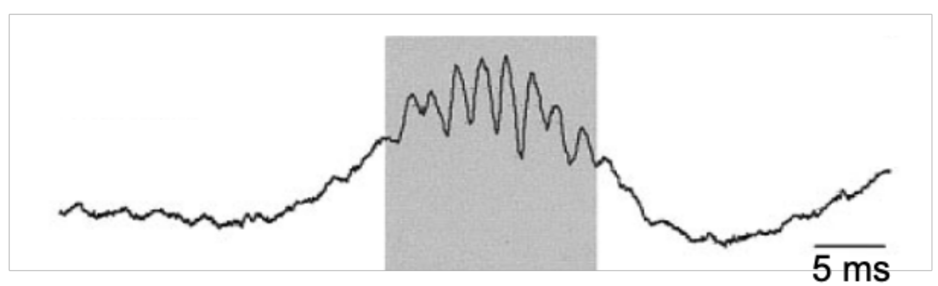
Rhythms are sometimes associated with pathologies.

Pathological ripples

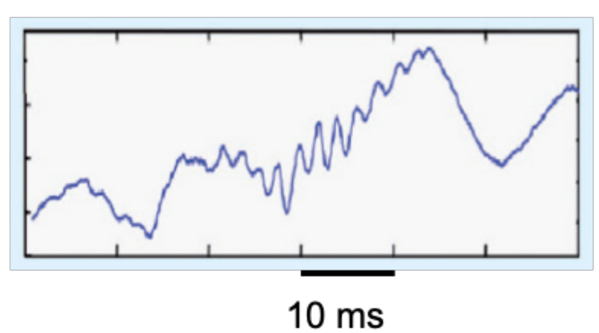
[Jacobs et al, 2012]



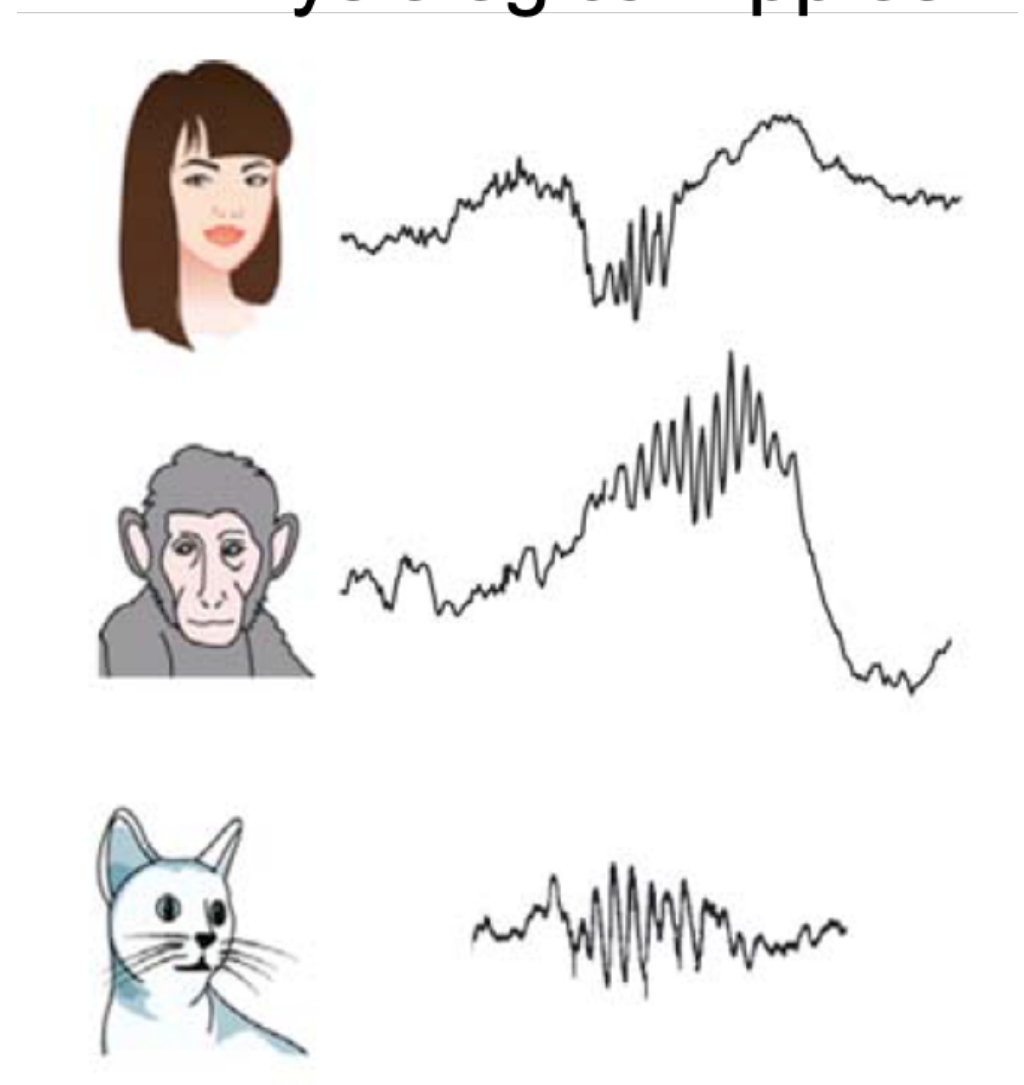
[Staba et al, 2002]



[Worell & Gotman, 2011]



Physiological ripples



[Buzsáki, Hippocampus, 2015]

<u>Note</u>: Used the band label, but “function” very different.

Brain rhythms are meaningless . . .

H: Brain rhythms are epiphenomena.

<u>Large buildings</u>: sway in the wind.

These oscillations are <u>not</u> 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.

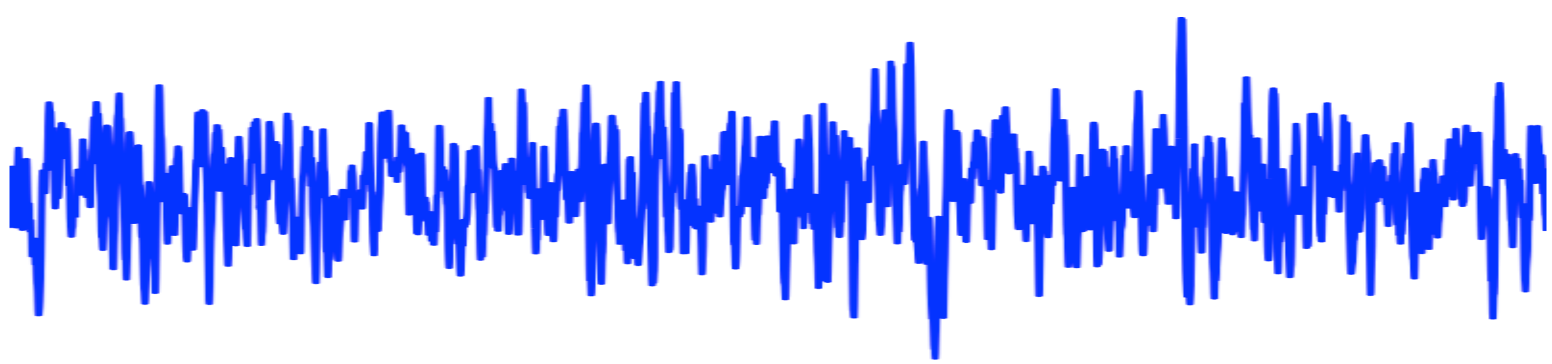
Today, consider two:

–Visual inspection

–Intuition for the spectrum

Idea:

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



Spectrum: Break down the data into sinusoids . . .

Remember: sinusoids . . .

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

Voltage as a function of time

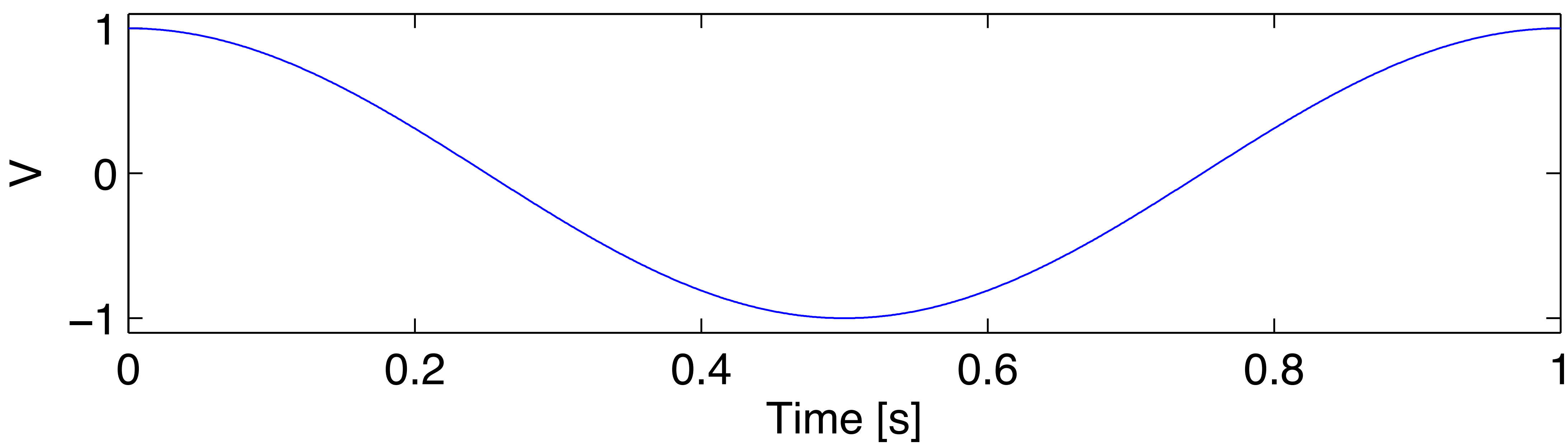
Amplitude

Frequency [Hz]

Time [s]

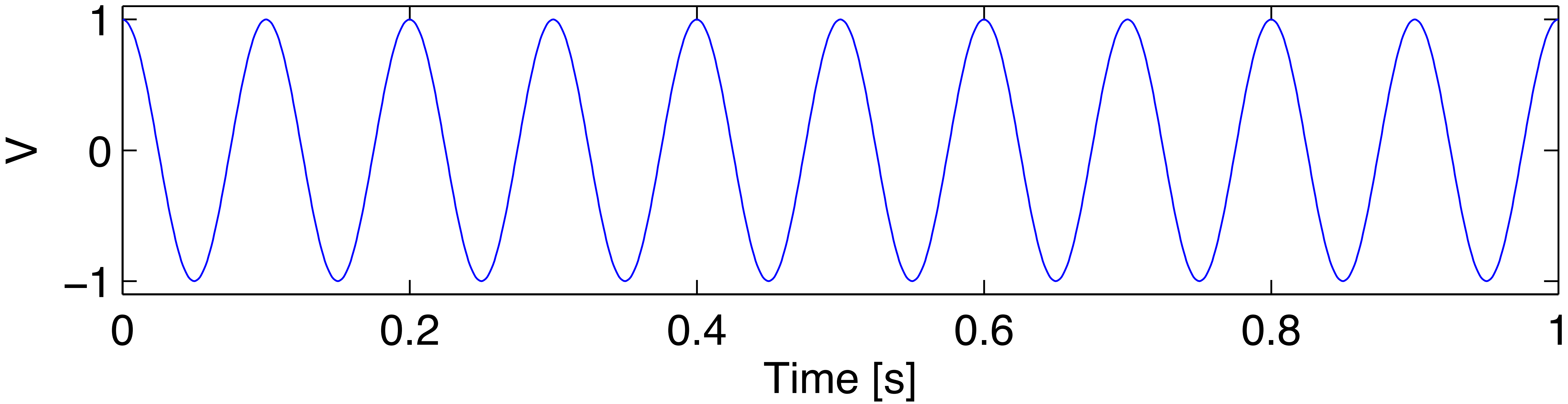
Ex. Consider: f = 1 Hz

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:

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

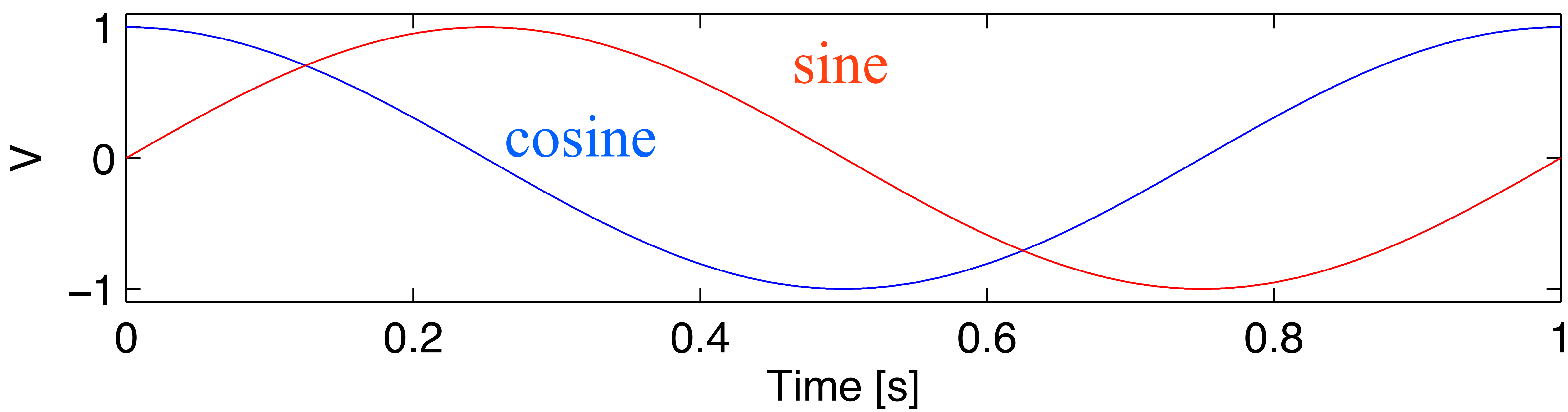
Voltage as a function of time

Amplitude

Frequency [Hz]

Time [s]

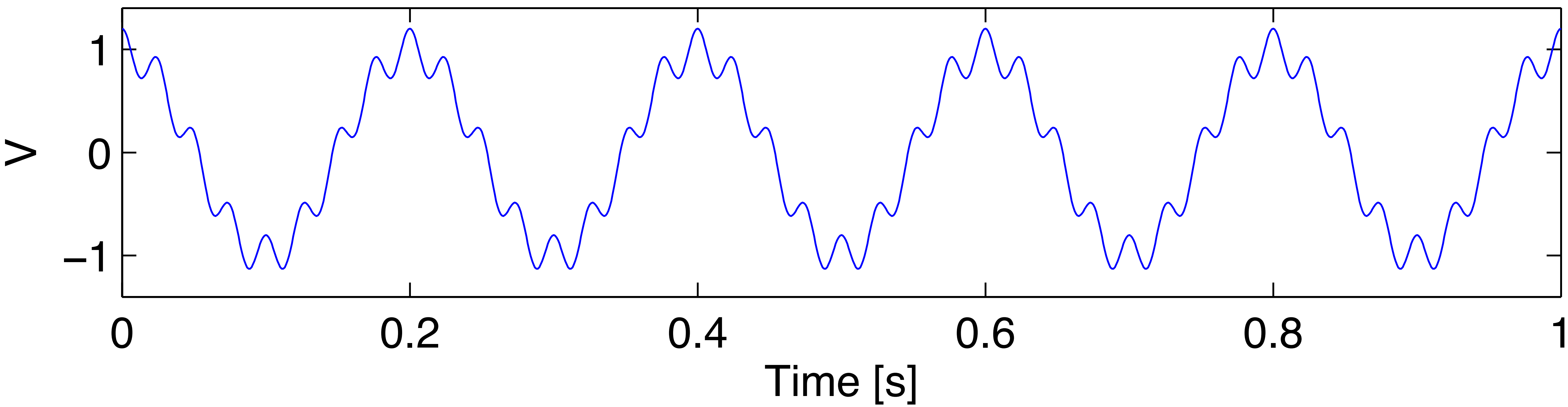
Ex. Consider: f = 1 Hz



Q: What's the difference?

Example: rhythmic signal

Consider the signal below:



Q: What are the rhythms?

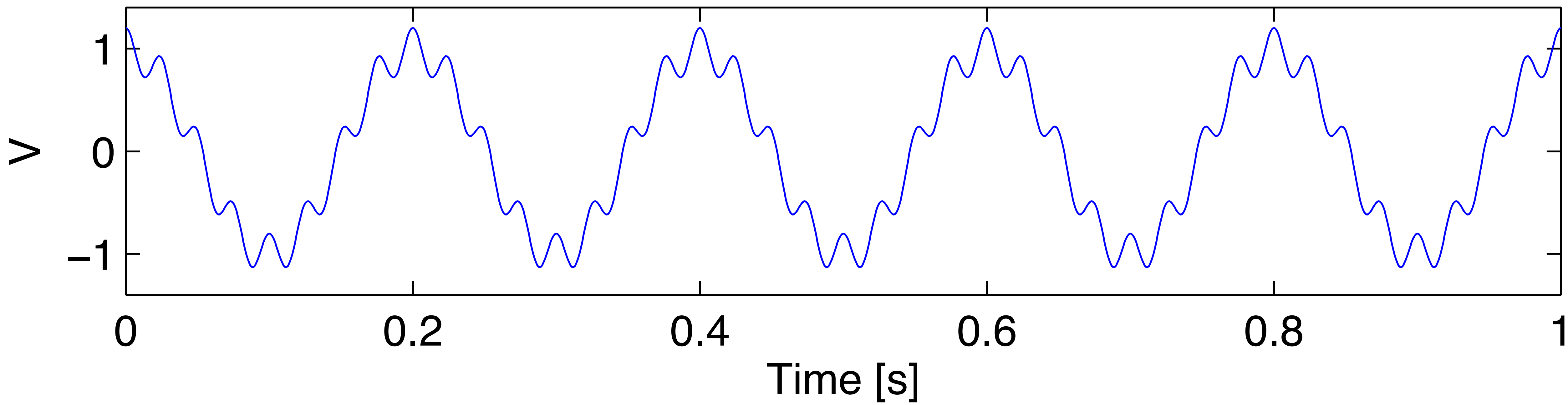
A: Apply visual inspection . . . Slow and fast

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

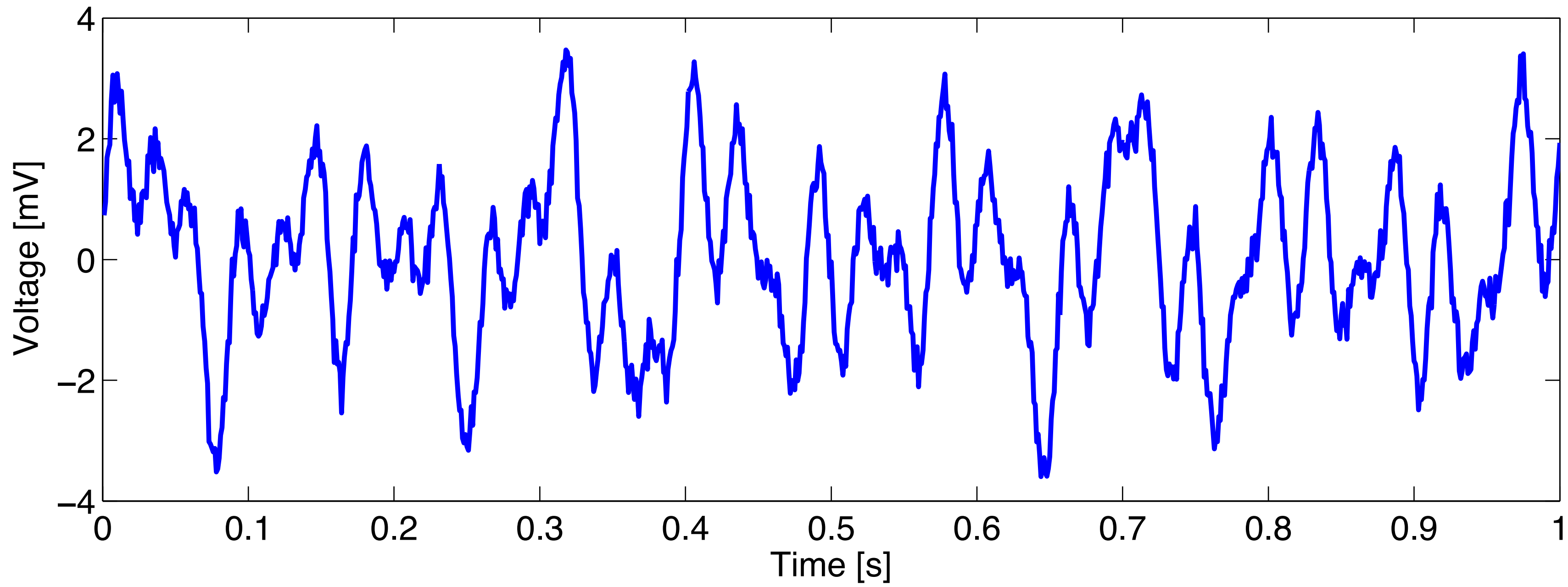
$$V[t] = \underset{1.0}{A_1} \cos(2\pi \underset{5\text{ Hz}}{f_1} t) + \underset{0.1}{A_2} \cos(2\pi \underset{40\text{ Hz}}{f_2} t)$$

We get a <u>simpler</u> representation of the signal. That's the idea of the spectrum.

Idea: Spectrum

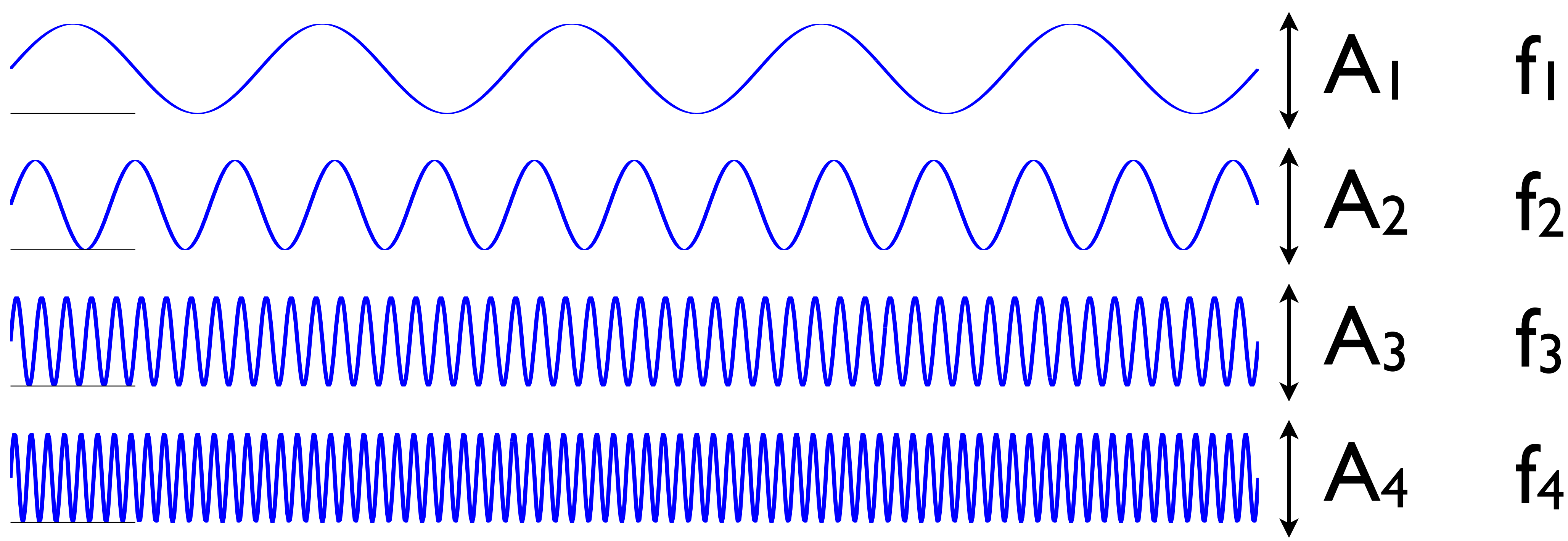
Consider:

$V =$



- Decompose signal into oscillations at different frequencies.

$V =$ $+$ $+$ $+$



$+ \ \ldots$

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

Idea: 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 many 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: Spectrum

Note: Think of sine & cosine as accounting for **phase**.

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

amplitude freq phase

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

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

A_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: Spectrum

Q: How do we find A_j and B_j ?

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

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

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

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

frequencies

integrate over time

Idea: Spectrum

Python

Idea: Spectrum

Q: How do we find A_j and B_j ?

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

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: Spectrum

Return to our original equation

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

<u>Task</u>: find A_j, B_j

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: Spectrum

by orthogonality

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

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

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

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

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

$$= A_k\,T/2$$

Idea: 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've solved for amplitude A_k

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

Idea: 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 do we find A_j and B_j ?

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

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

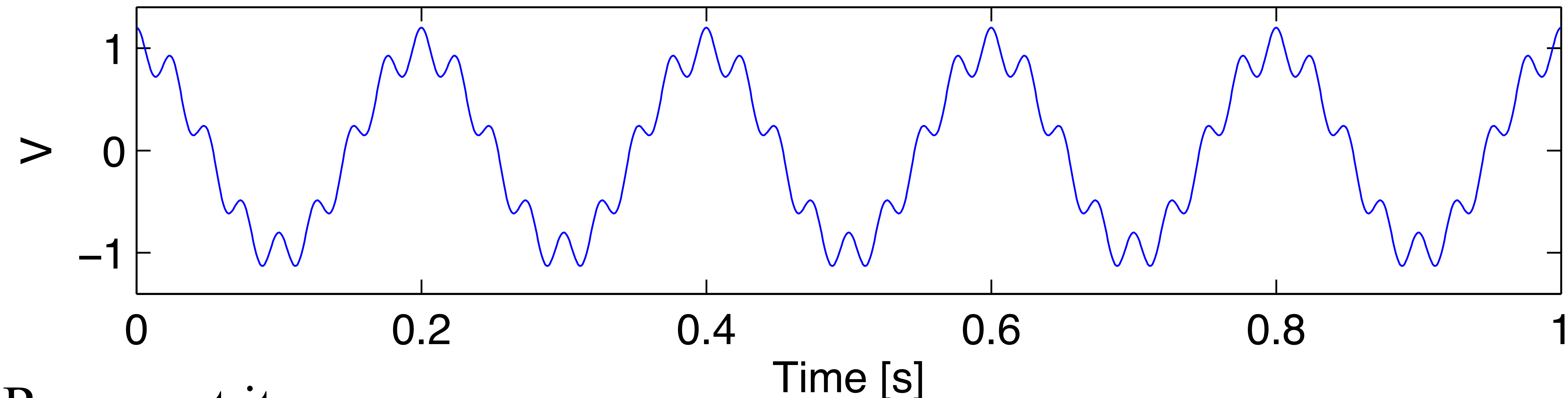
Similarly

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

<u>Big idea</u>: We can decompose V[t] into a sum of sin/cos functions, and we have a strategy 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

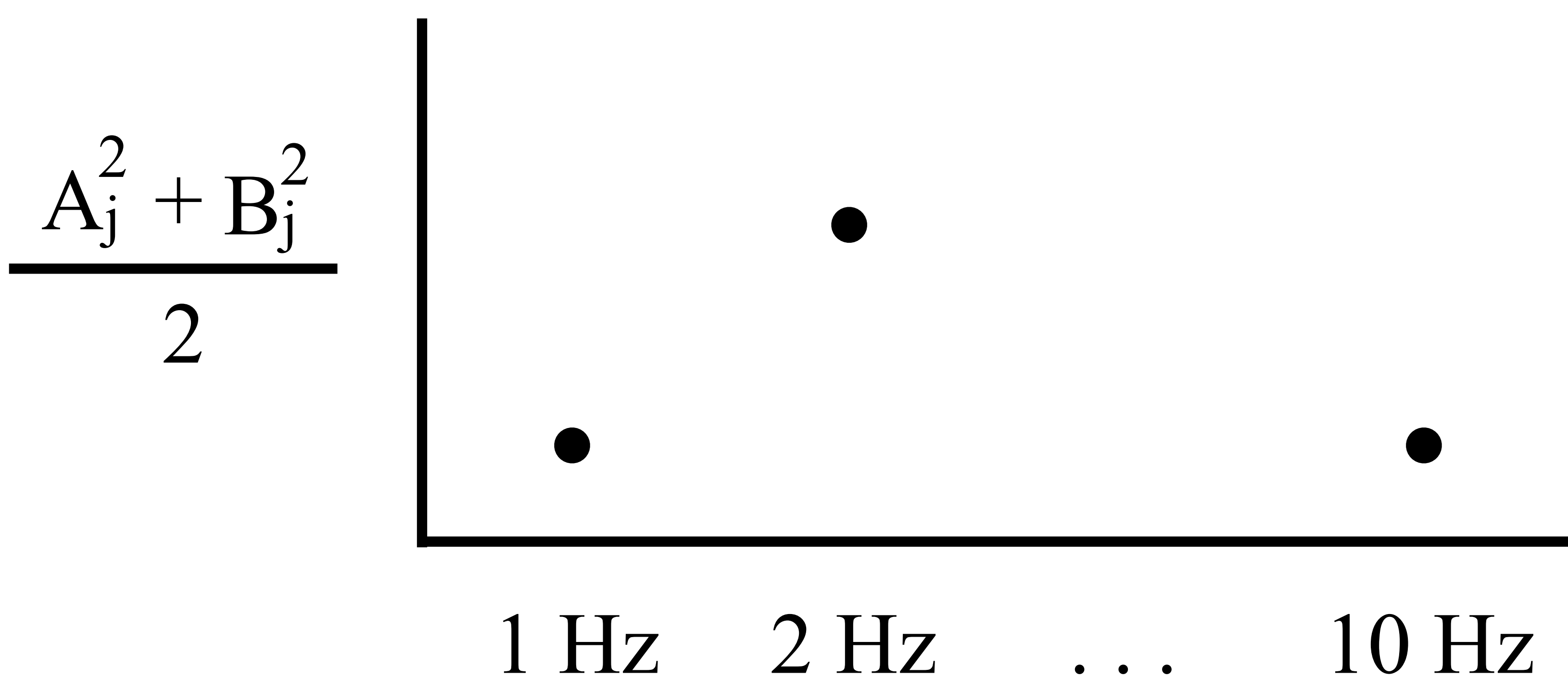
These 4 numbers completely summarize the data.

Plot: Spectrum

We can represent these amplitudes and frequencies graphically:

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

Note: The summed amplitudes squared.
Called the "power"

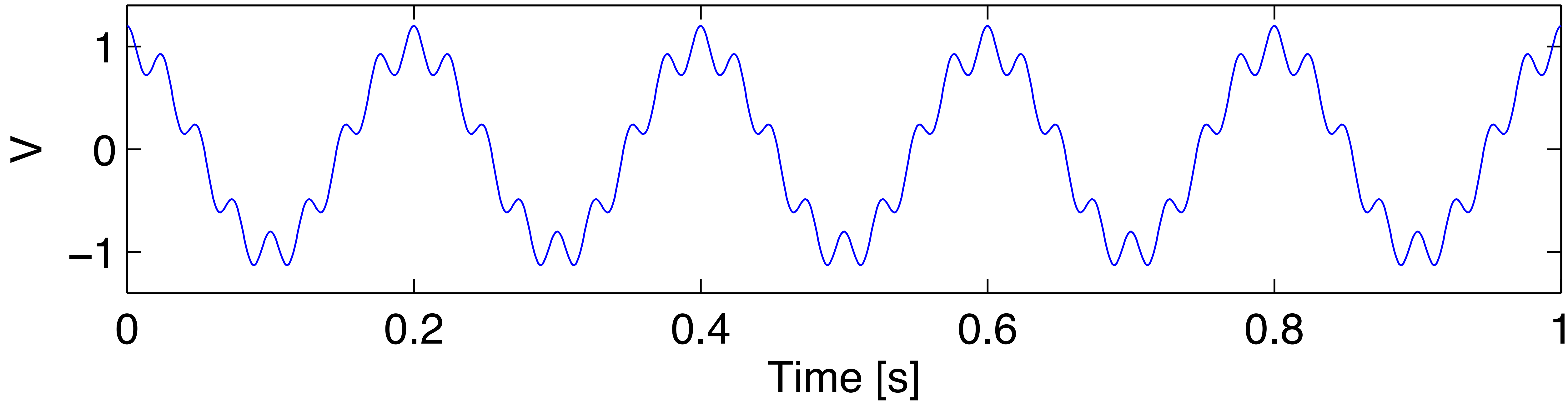


Note: This is called the **spectrum**; a plot of power versus frequency

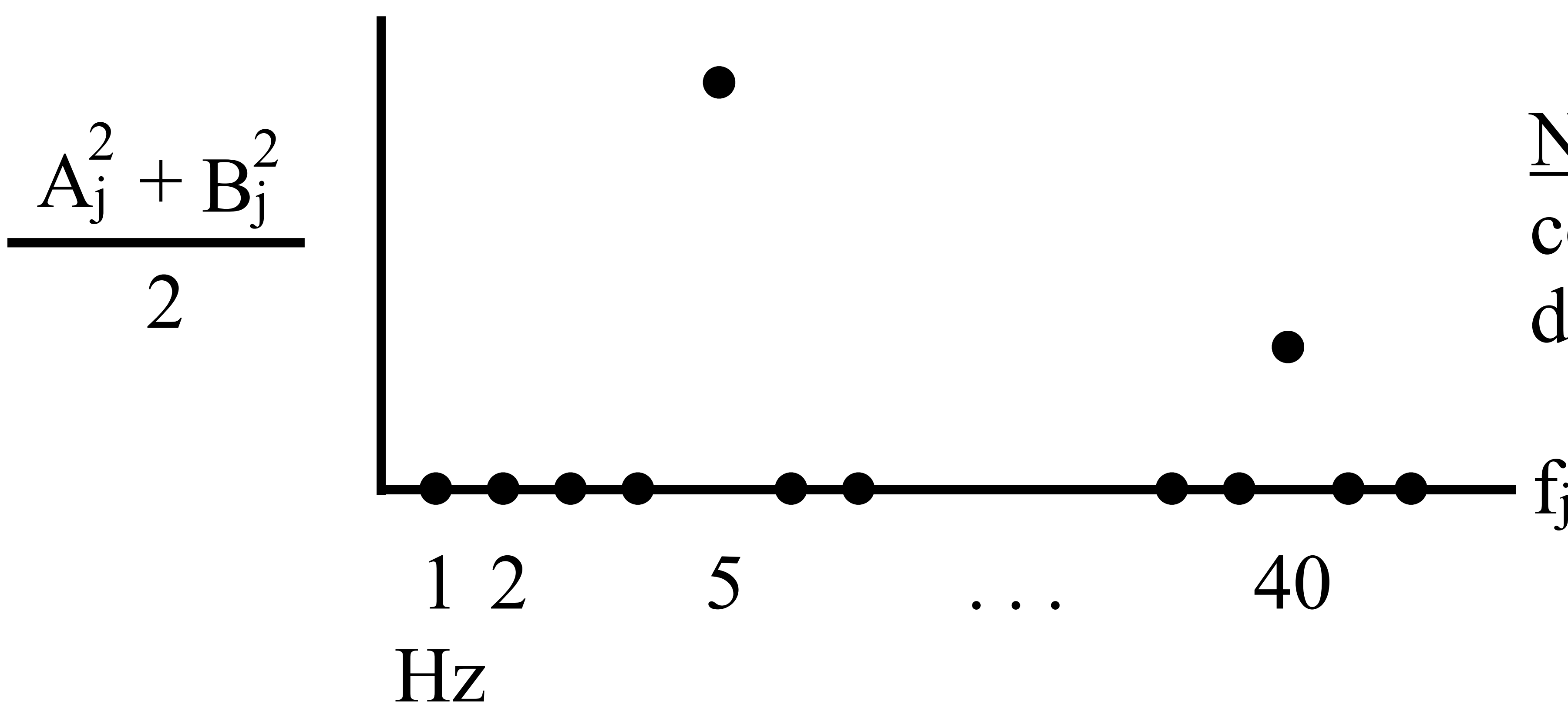
The peaks represent the dominant rhythms in the signal.

Example: rhythmic signal

Ex:



Plot the spectrum:

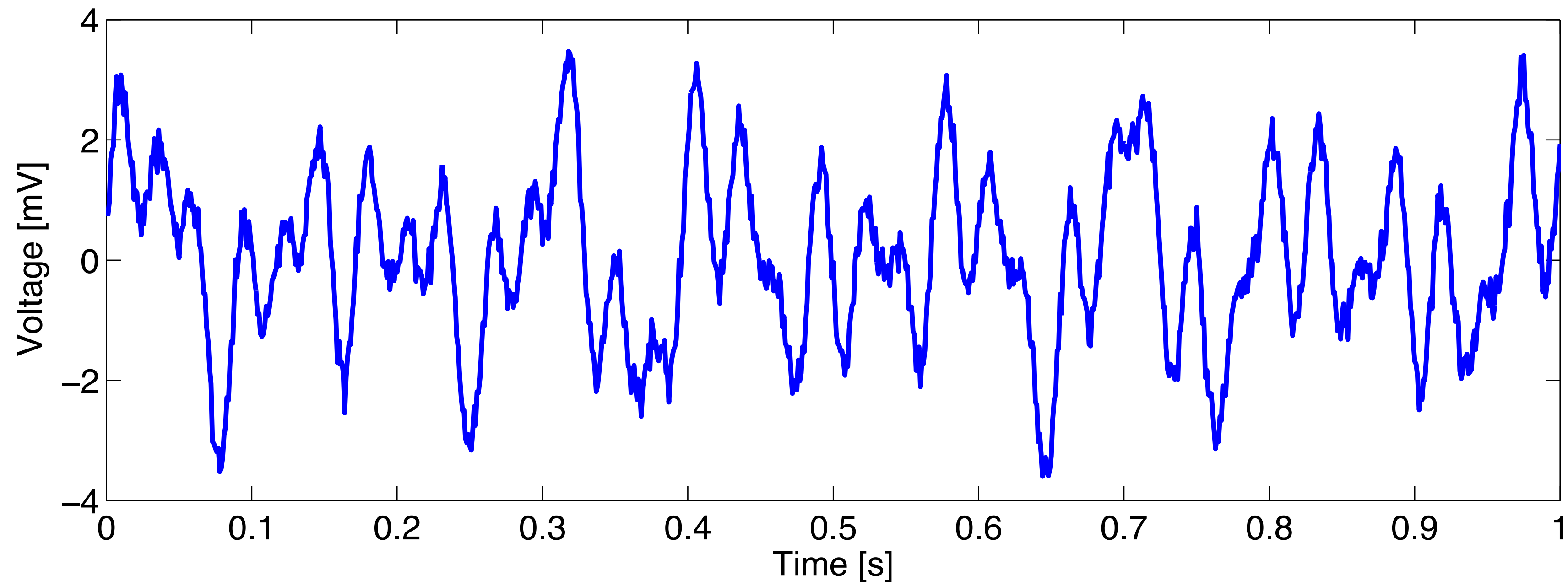


Note: The peaks correspond to the dominant rhythms

Example: rhythmic signal

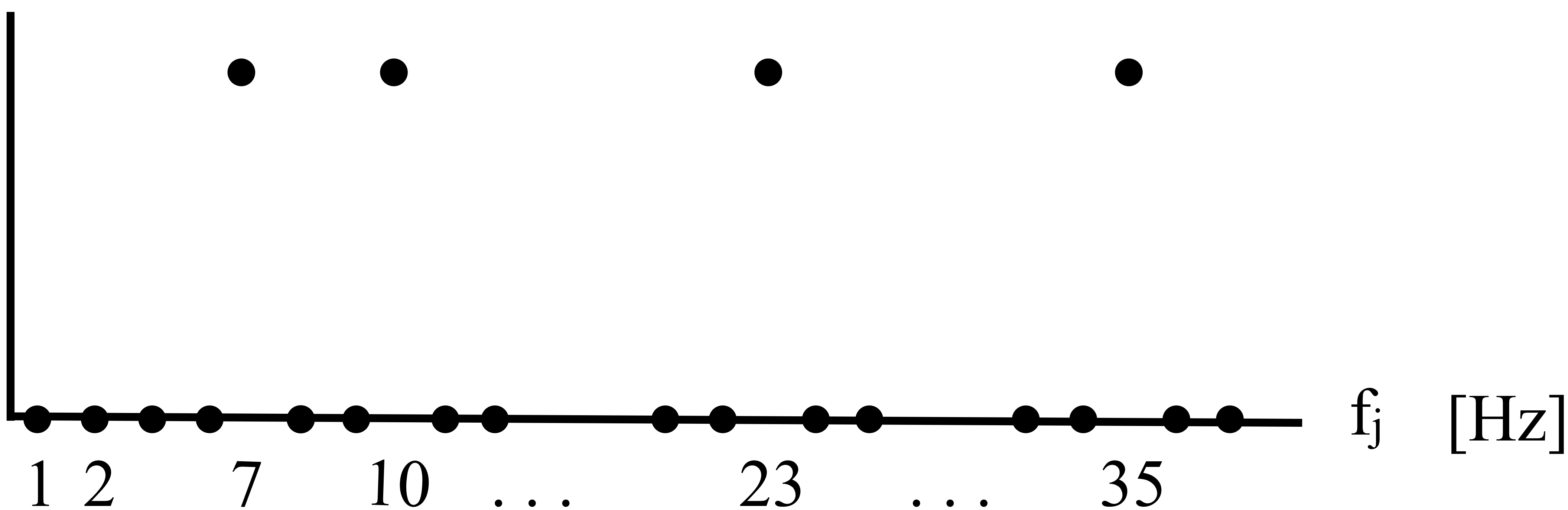
Ex.

$V =$



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

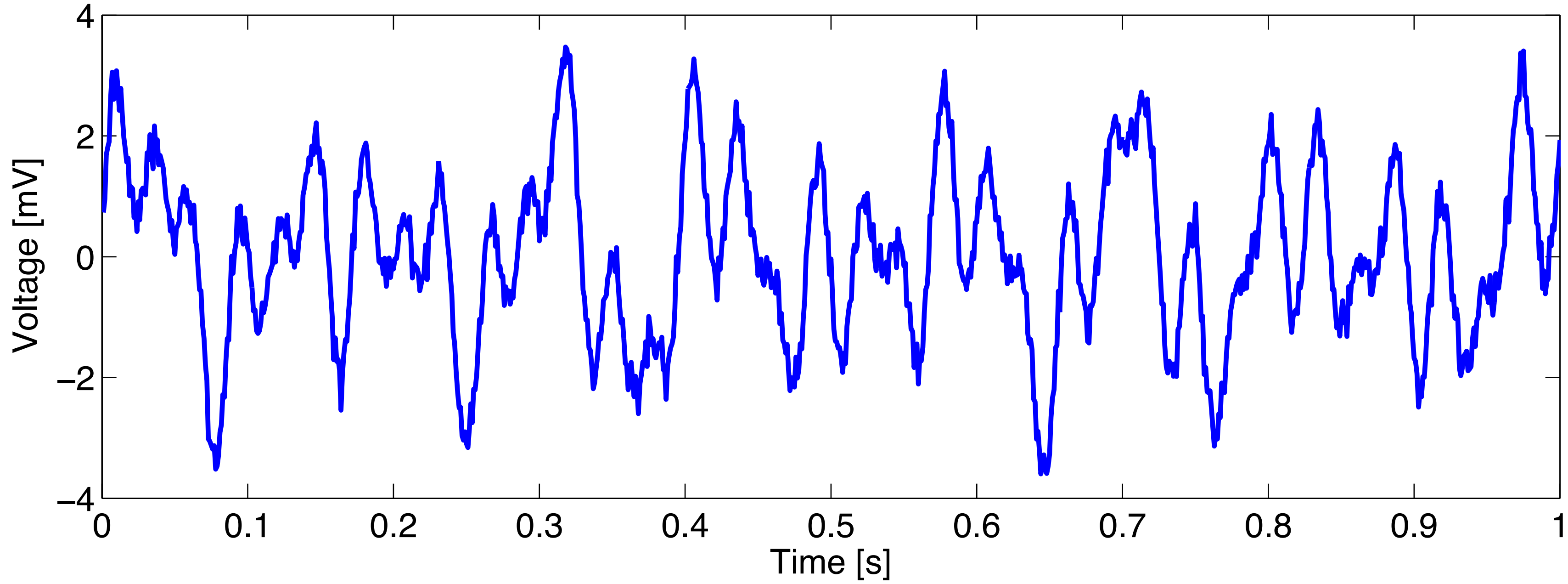
$$\frac{A_j^2 + B_j^2}{2}$$



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:

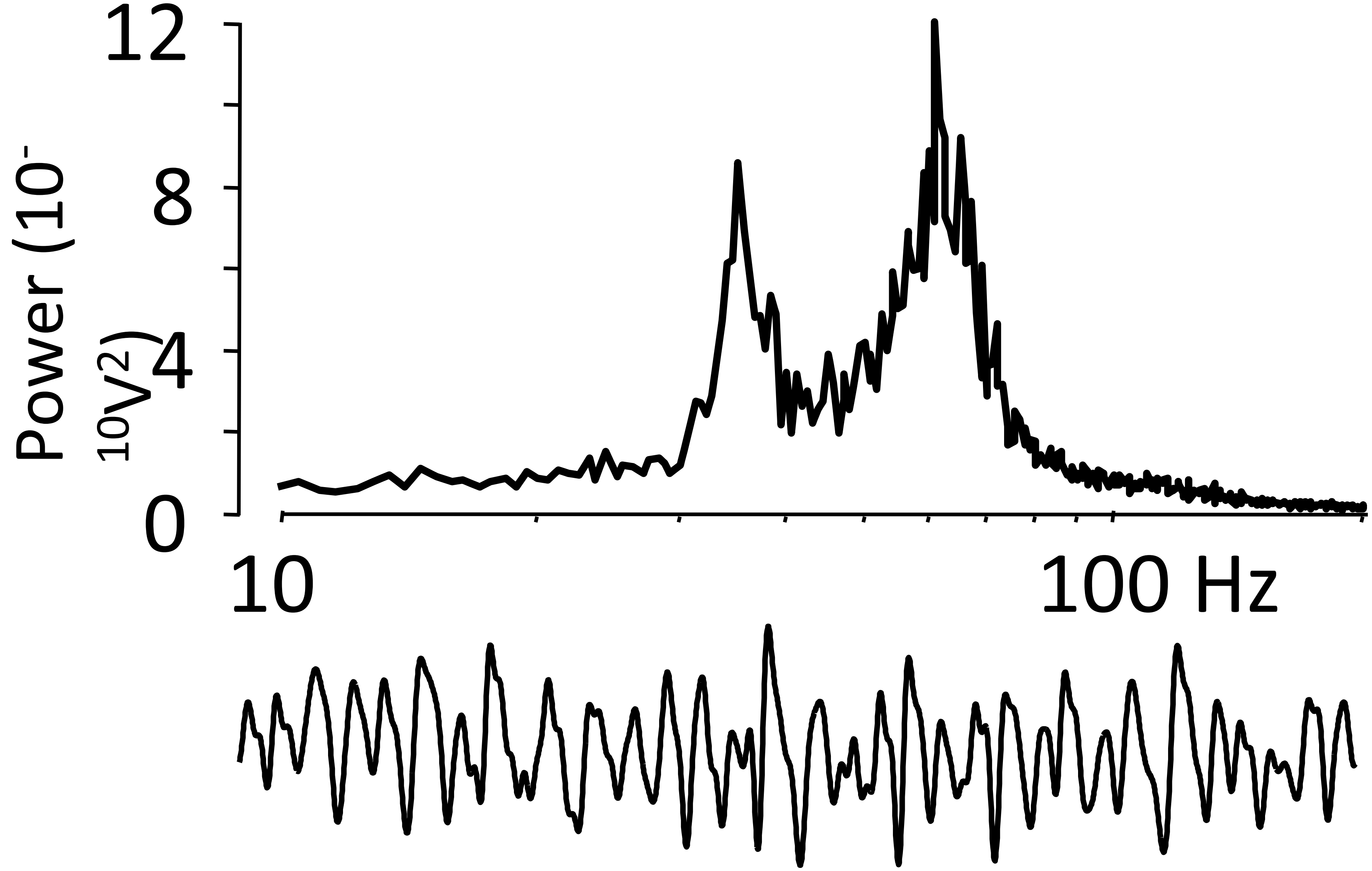
7 Hz, 10 Hz, 23 Hz, and 35 Hz

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

Practical notions …

A simple answer to one big rhythm question …