Rhythms

Introduction (Part 1)

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Brain rhythms

Introduction

What are they?

Where do they come from?

What do they do?

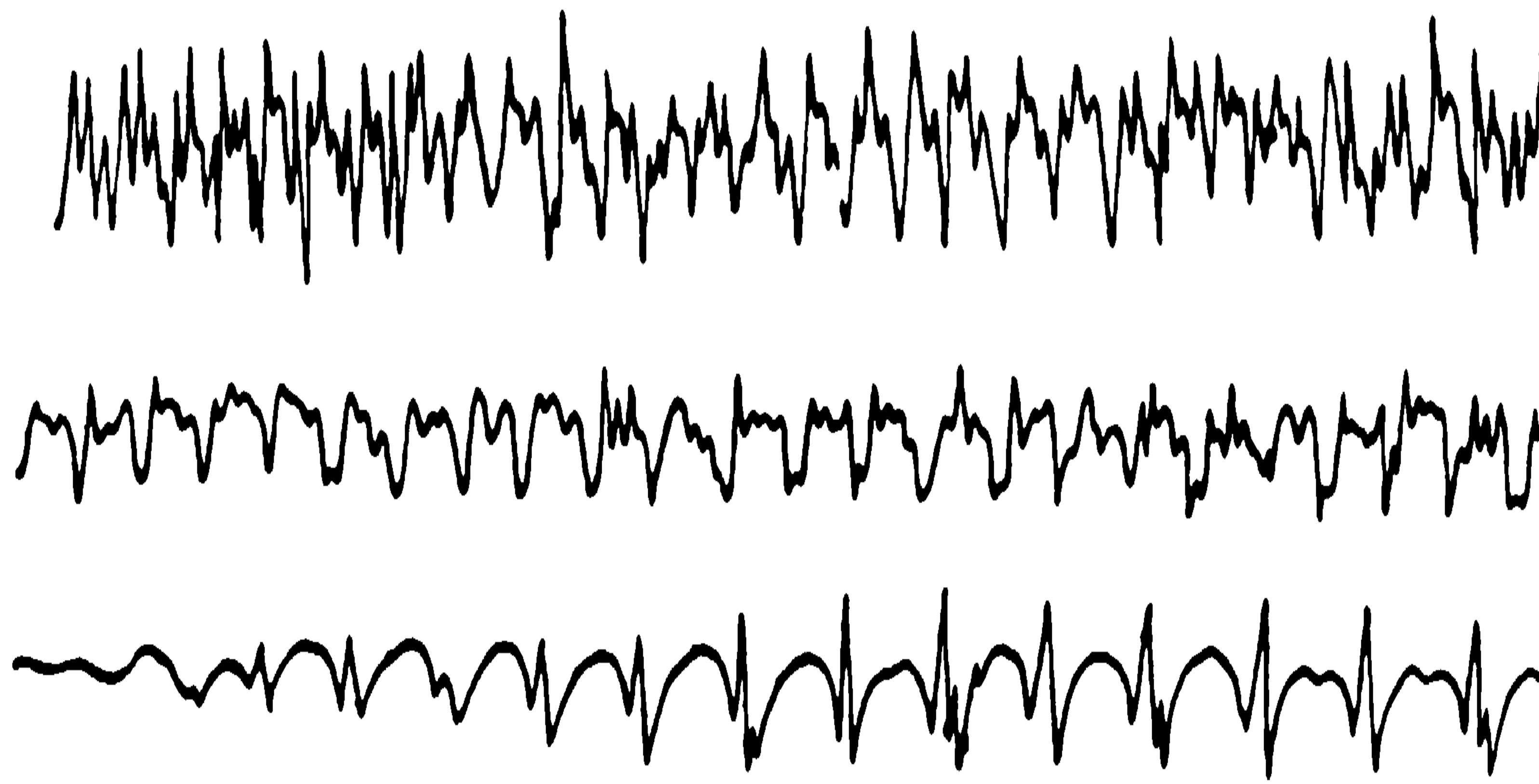
Method of analysis

Brain rhythms

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

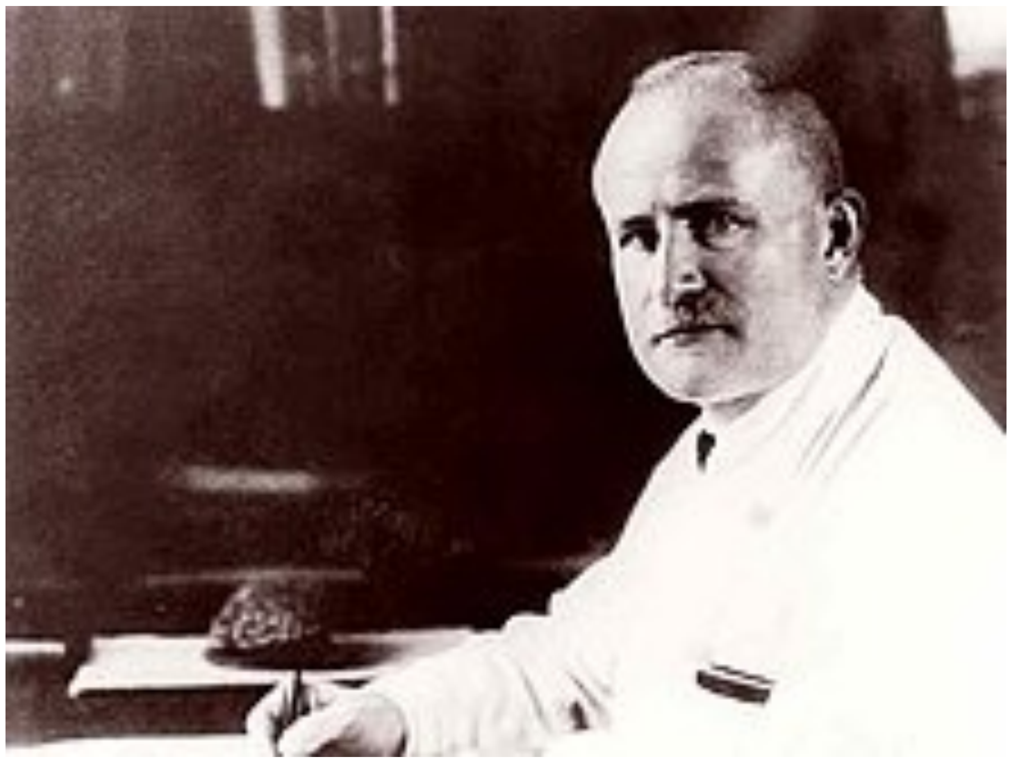
Ex: Scalp electroencephalogram (EEG)

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



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

Brain rhythms



Hans Berger (1873-1941)

Inventor of the EEG

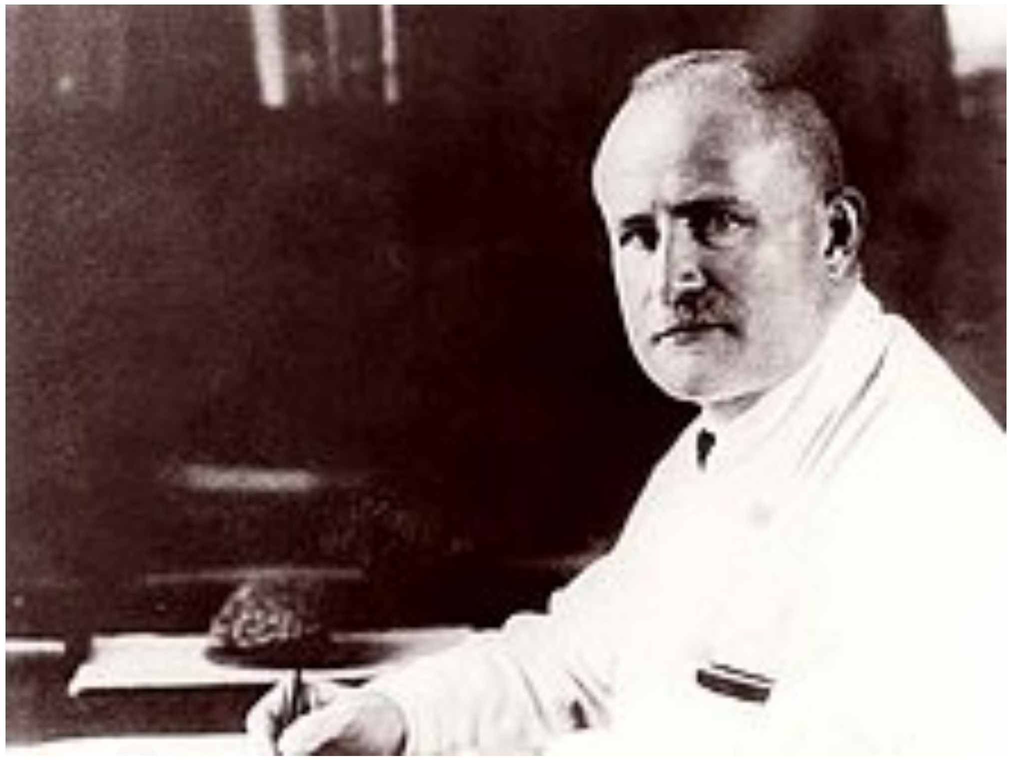
1893:

Mounted on a rearing and overturning horse in battery traveling in the valley of a narrow pass, I fell… and came to lie under the wheel of an artillery gun. At the last moment, the gun drawn by six harnessed horses stopped and I escaped with no more than a fright. This happened in the morning hours of a beautiful spring day. In the evening of the same day I received a telegraphed inquiry from my father asking how I was doing. It was the first and only time in my life that I received such an inquiry. My older sister, with whom I am in particularly intimate familial contact, had arranged this telegraphic inquiry since she suddenly told my parents that she distinctly knew that an accident had happened to me. My relatives lived in Coburg at that time. That was a case of spontaneous telepathy in which at the moment of mortal danger, envisioning certain death, I acted as sender and my sister, who was particularly close to me, acted as receiver.[8]

[Shure, Brain Waves, 2019]

Motivated by his telepathic experience

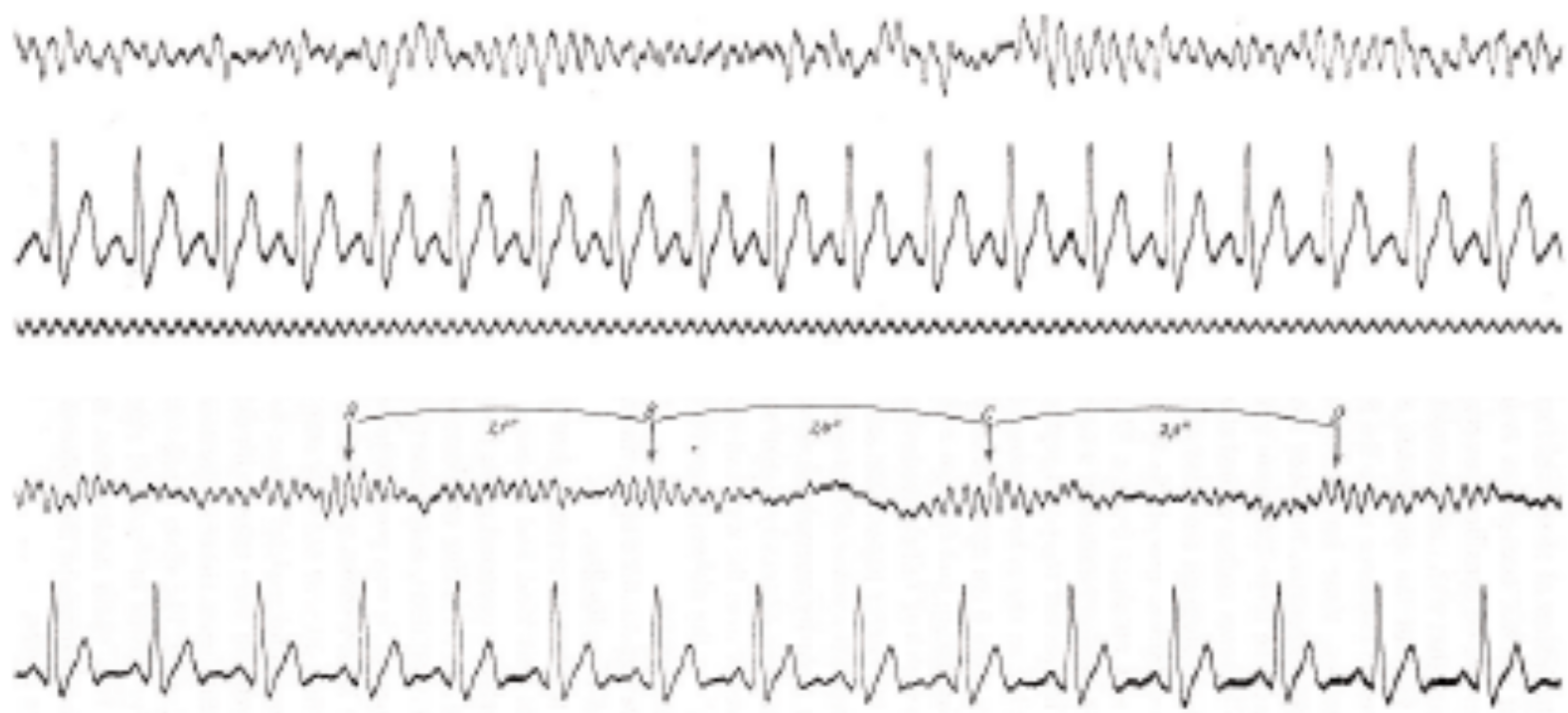
Brain rhythms



Hans Berger (1873-1941)

Inventor of the EEG
- first human brain voltage recording

1928-1928:



[Shure, Brain Waves, 2019]

Brain rhythms

Early days

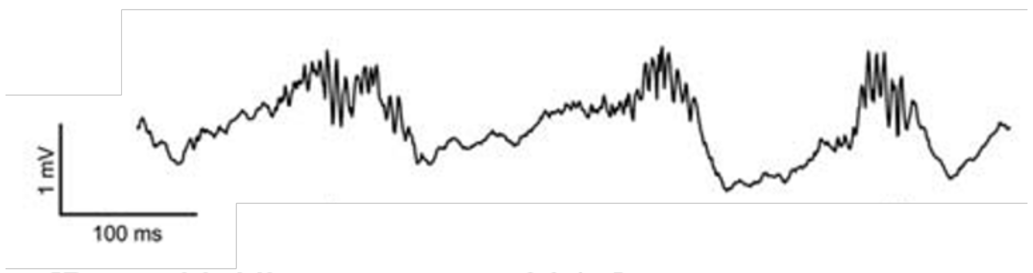
[The Devil Commands, 1941]

https://www.youtube.com/watch?v=tBWQBPa2Y6M see 2:00

Brain rhythms

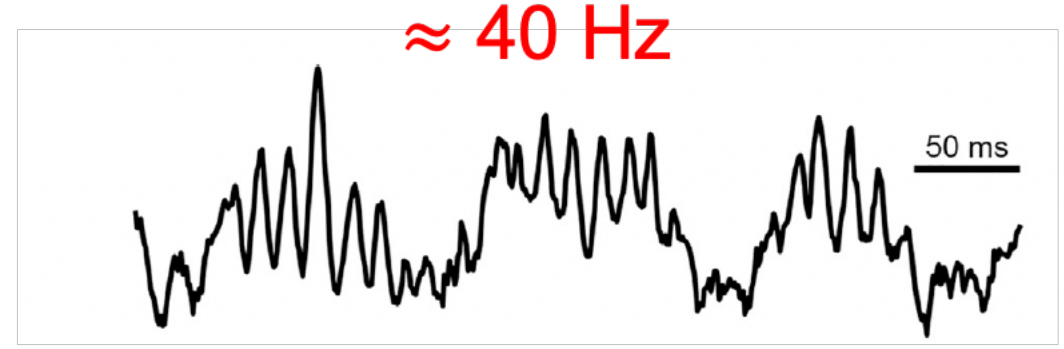
Fact: The brain can generate rhythmic activity.

≈ 150 Hz



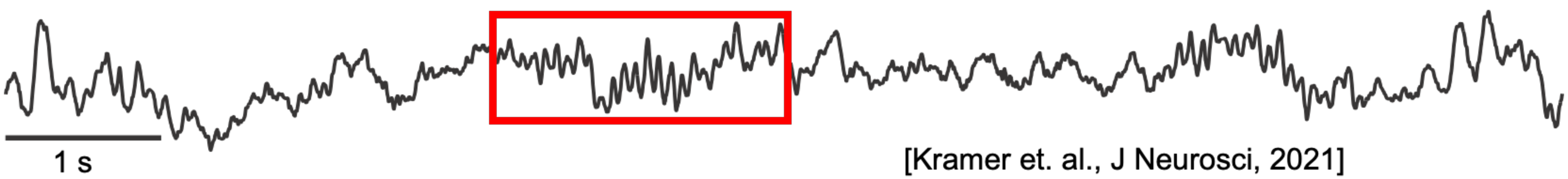
[Buzsaki, Hippocampus, 2015]

≈ 40 Hz



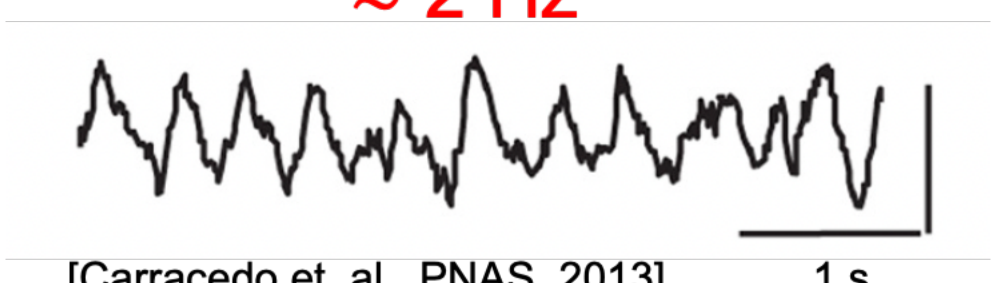
[Fernandez-Ruiz et al., Neuron, 2023]

≈ 12 Hz



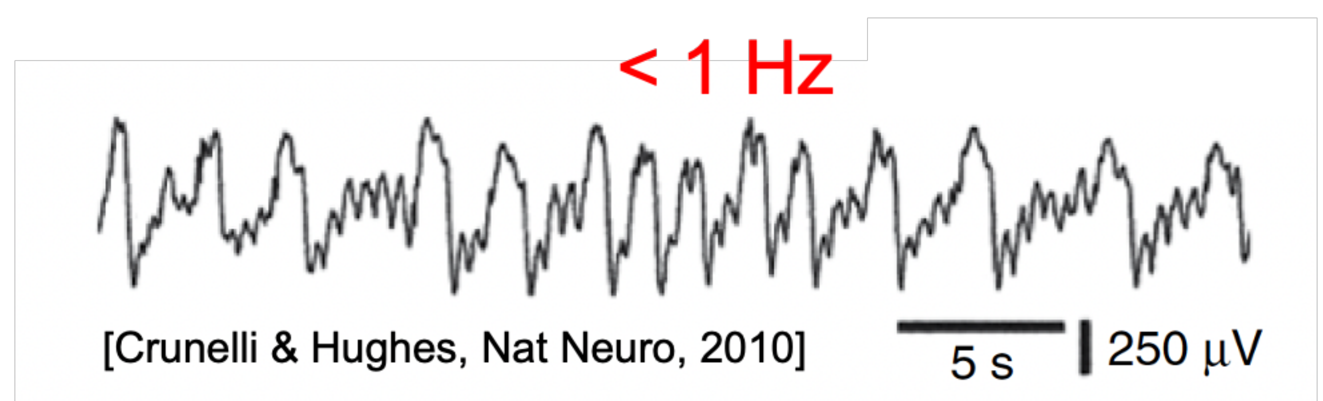
[Kramer et. al., J Neurosci, 2021]

≈ 2 Hz



[Carracedo et. al., PNAS, 2013]

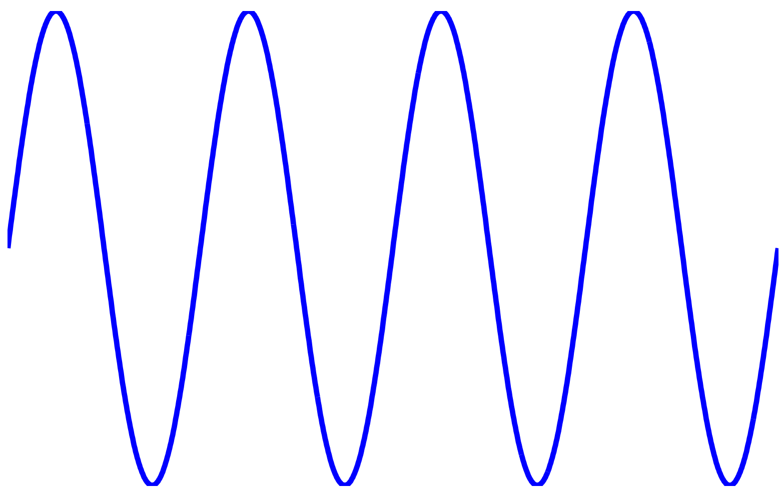
< 1 Hz

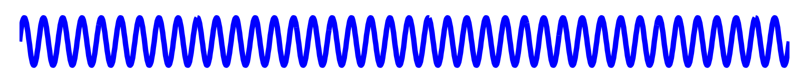


[Crunelli & Hughes, Nat Neuro, 2010]

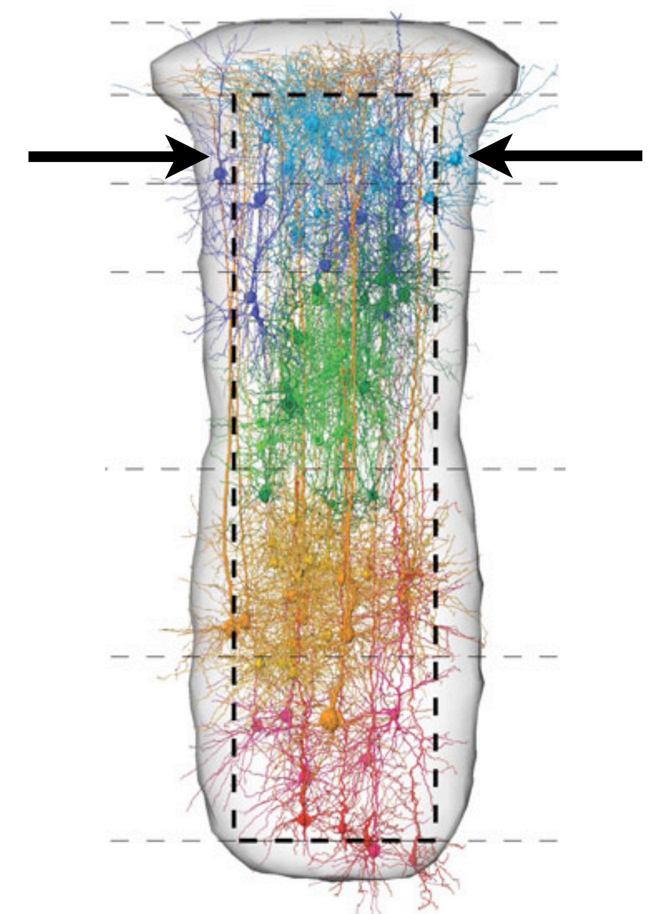
Brain rhythms: "facts"

- Slower rhythms tend to be larger amplitude.





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



Very complicated.

Not completely understood.

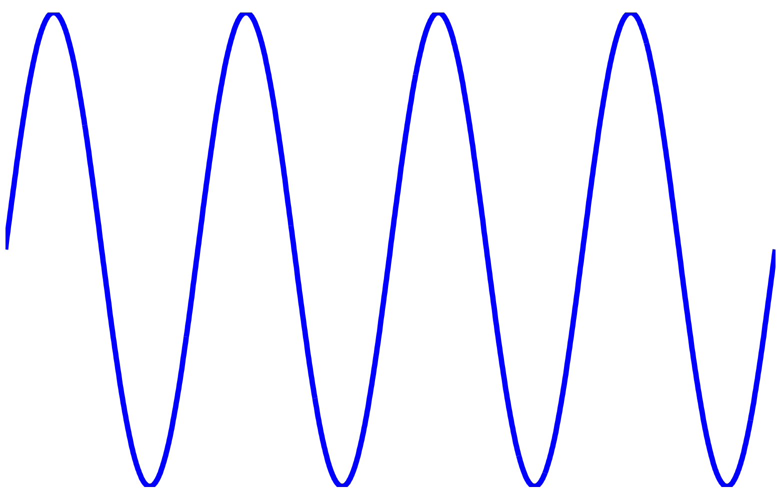
[Buzsáki et al. Nat Rev Neurosci (2012)]

Brain rhythms: "facts"

Rhythms indicate cortical arousal

–Modulate the firing patterns of neurons.

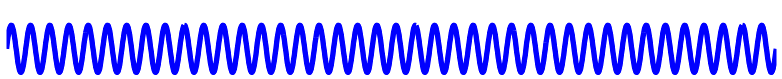
Low frequency, high amplitude: low cortical arousal



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 ?

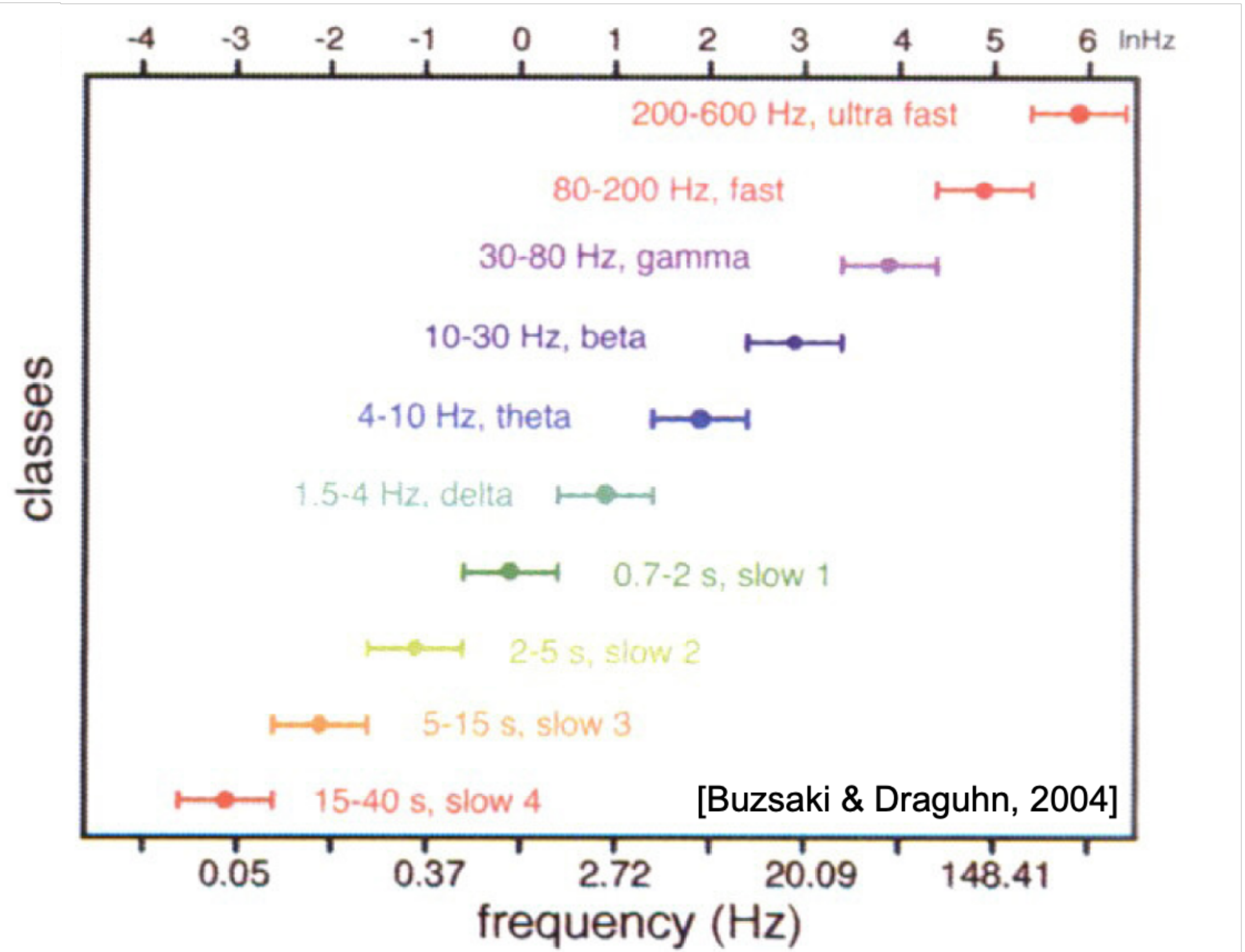
Our focus (usually) is frequency: How fast or slow is a rhythm?

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

Brain rhythms and functions

Many frequency bands, each associated with different functions.

Ex:

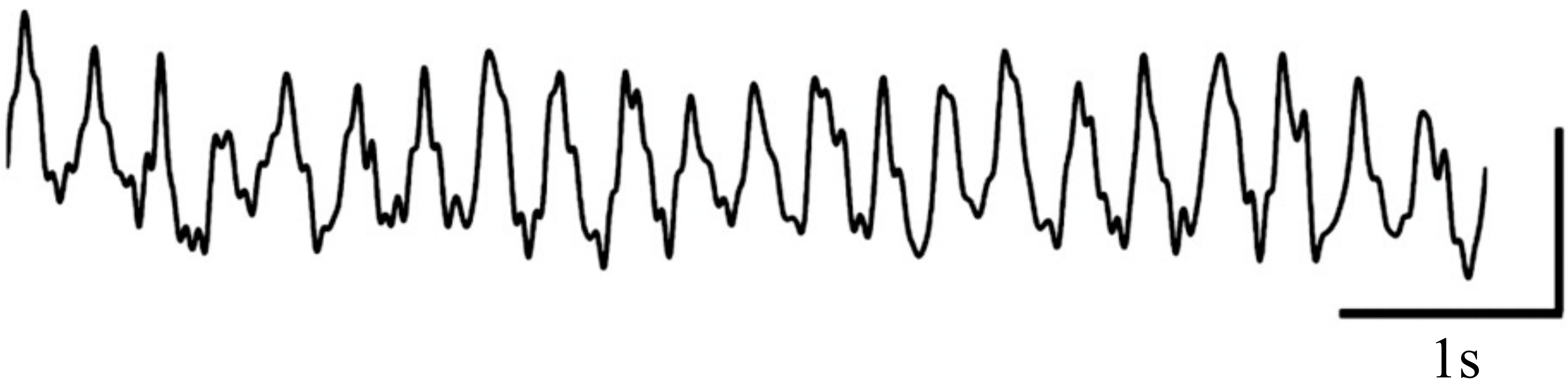


Let's look more carefully at some of these frequency bands . . .

Brain rhythms: theta

Theta: 4-8 Hz

<u>Note</u>: Theta frequency range different; the borders of ranges are not exact.

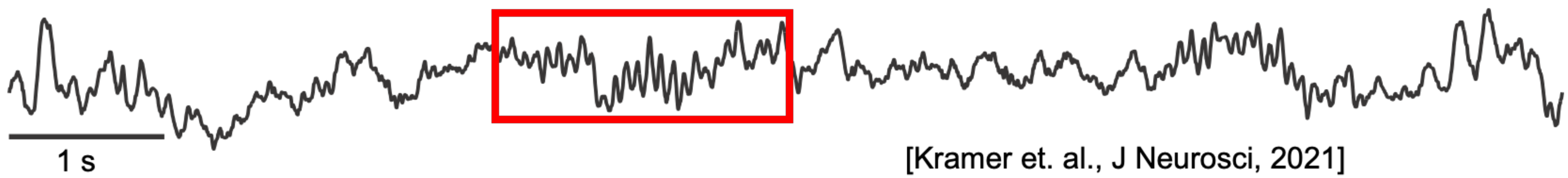


Function: Not completely understood.

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 !



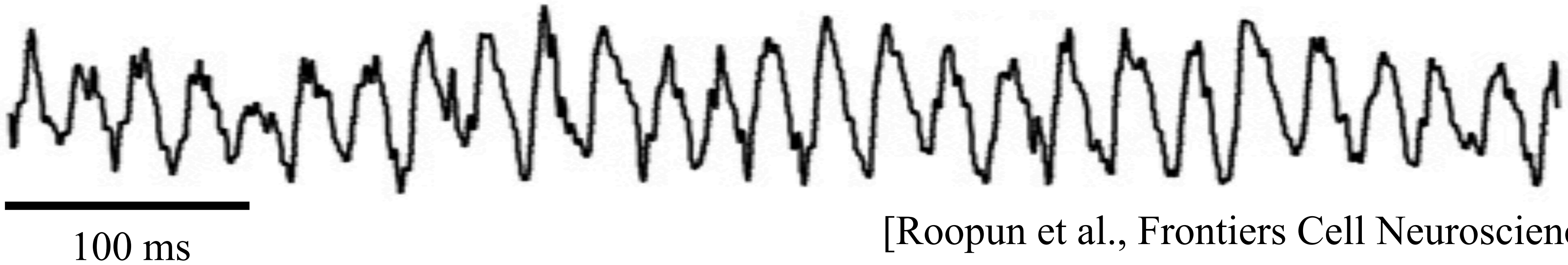
- The first EEG wave studies [Berger 1931]
- In EEG, strongest above occipital lobes when eyes closed at rest.

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



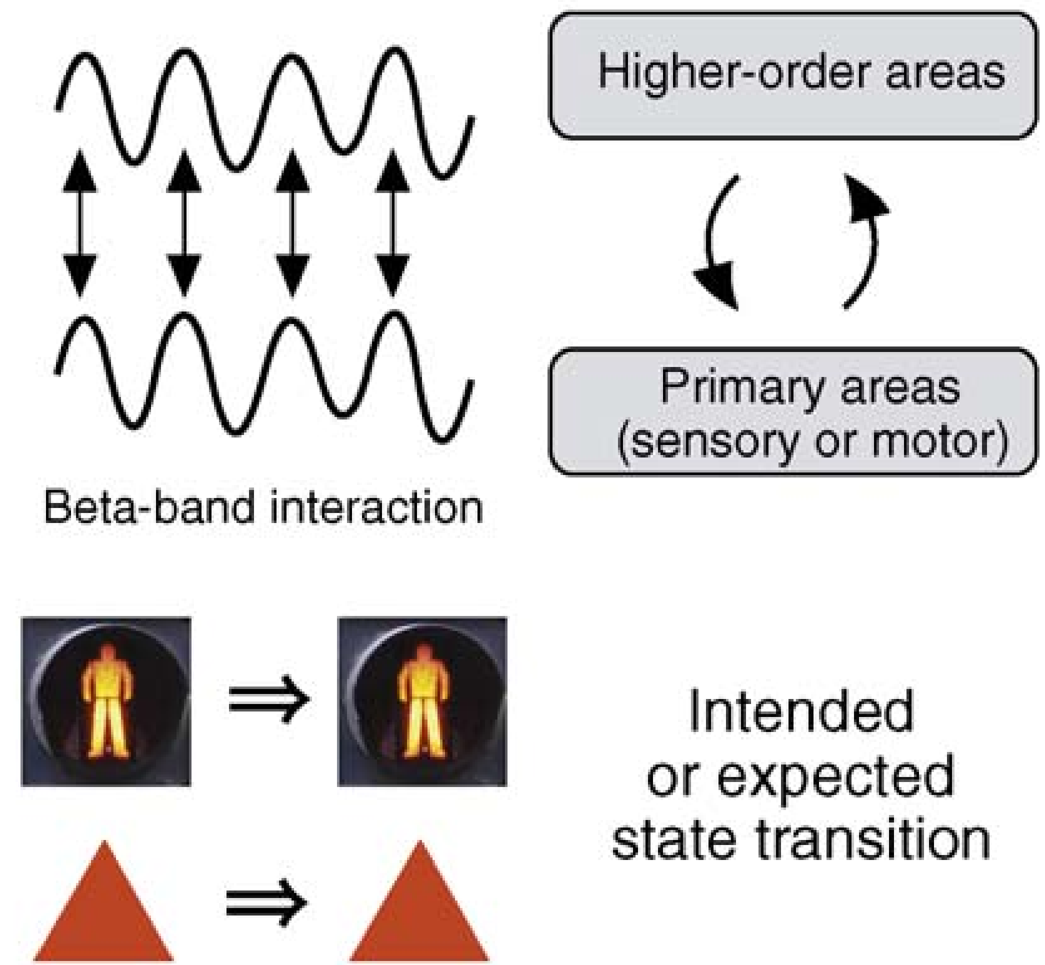
[Roopun et al., Frontiers Cell Neuroscience, 2008]

Function: Not fully understood.

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

"Maintenance of the status quo"

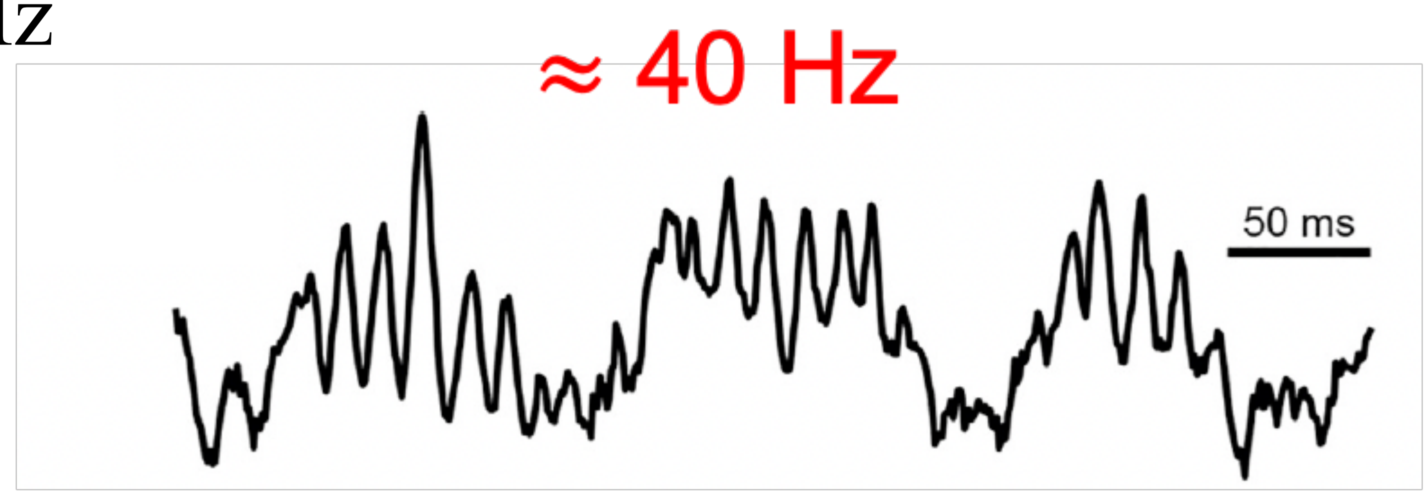
"Couple" distant brain regions.



[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 . . .

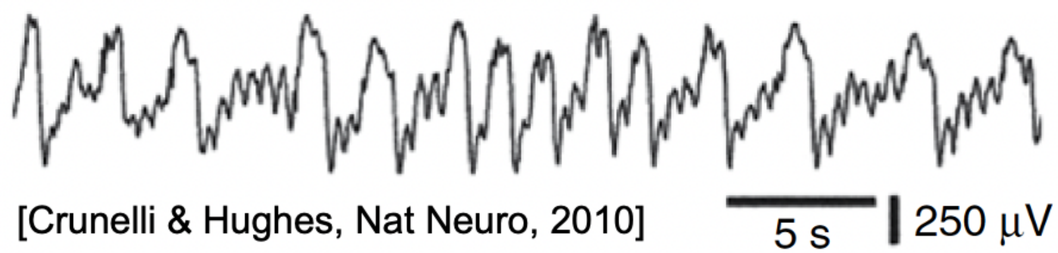
Slower

–**Delta**: 1-4 Hz

Sleep, learning, motivation

–**Slow cortical potential**: < 1 Hz

Emergence of consciousness?



[Crunelli & Hughes, Nat Neuro, 2010]

Faster

– **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

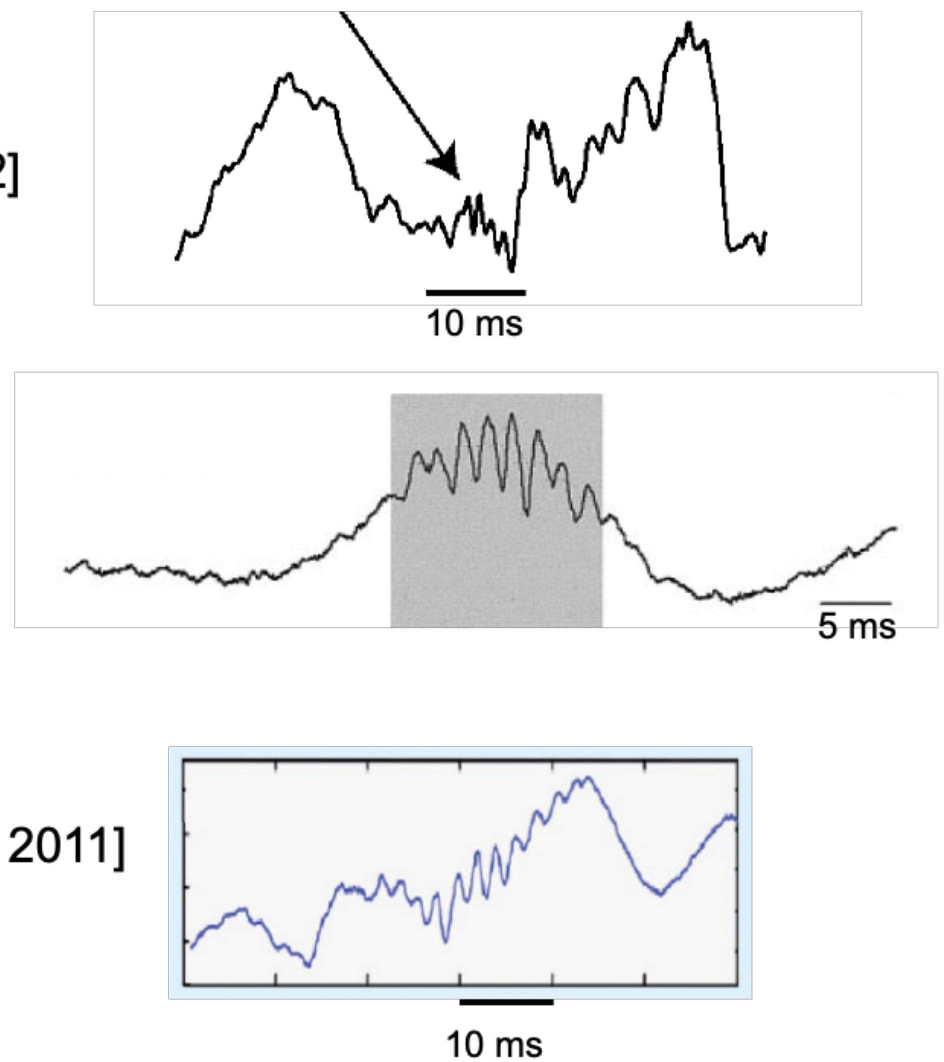
Rhythms are sometimes associated with pathologies.

Pathological ripples

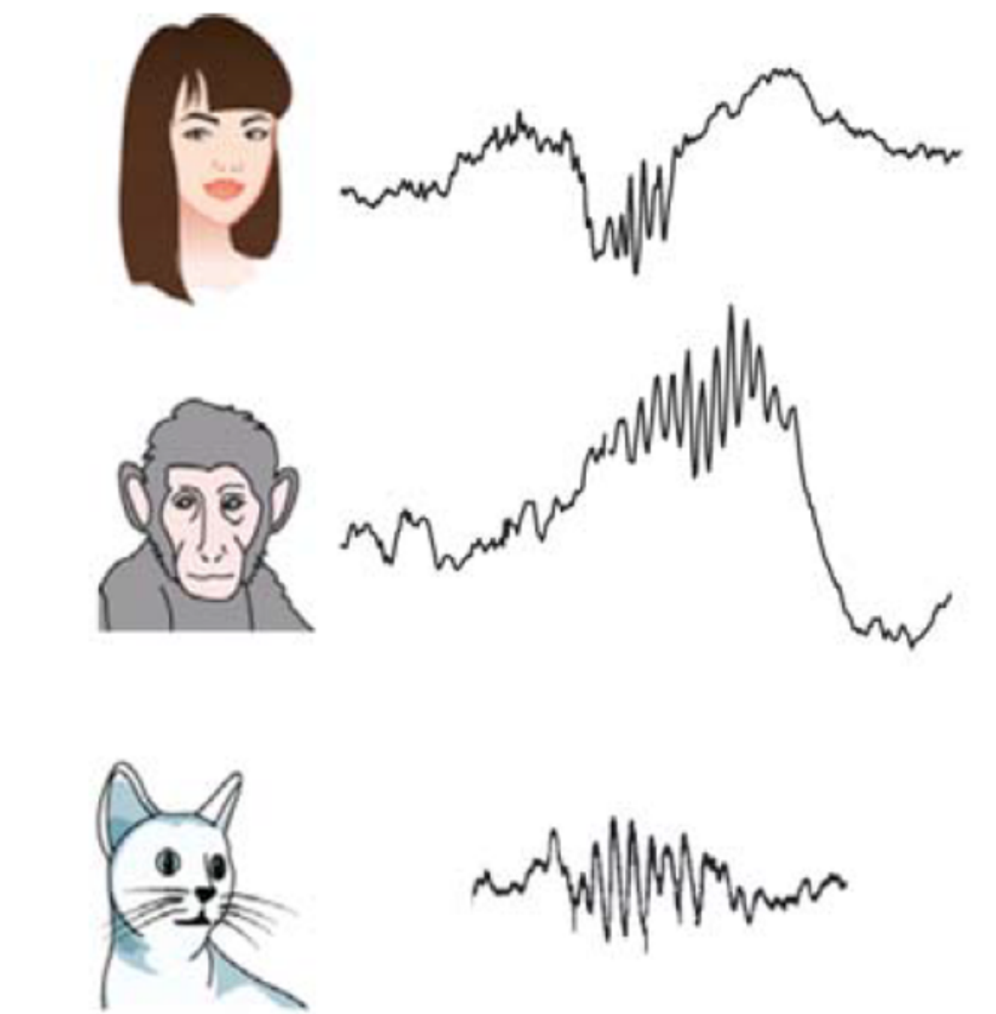
[Jacobs et al, 2012]

[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.

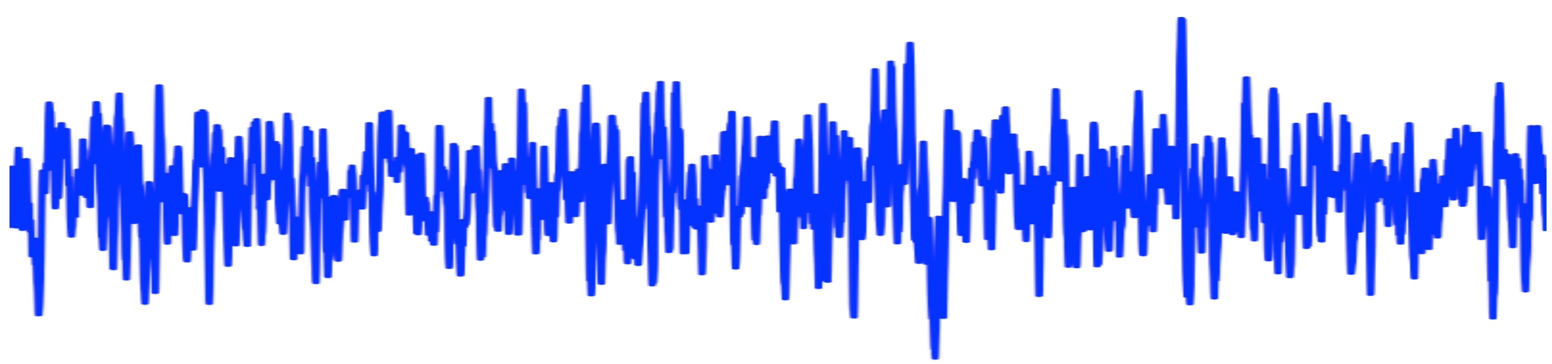
Today, consider two:

–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

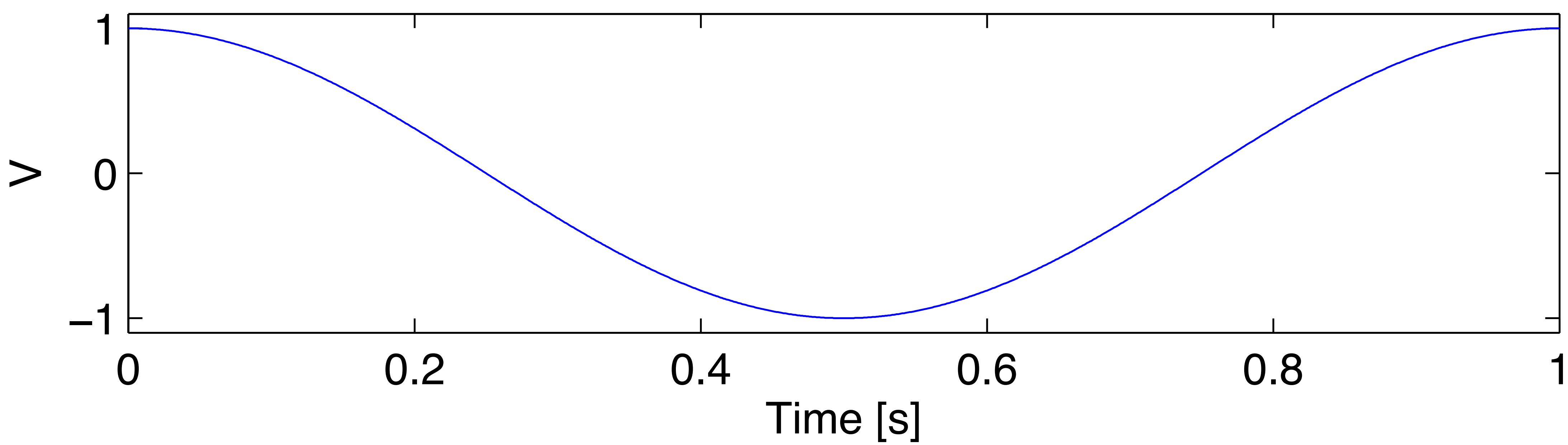
Amplitude

Frequency [Hz]

Time [s]

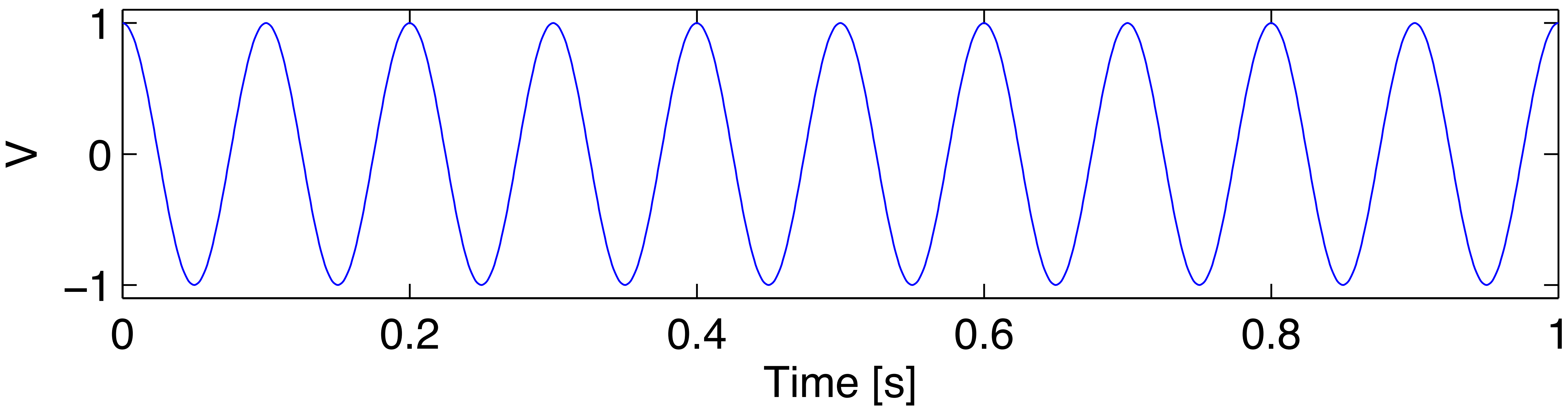
Ex. Consider: f = 1 Hz

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:

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

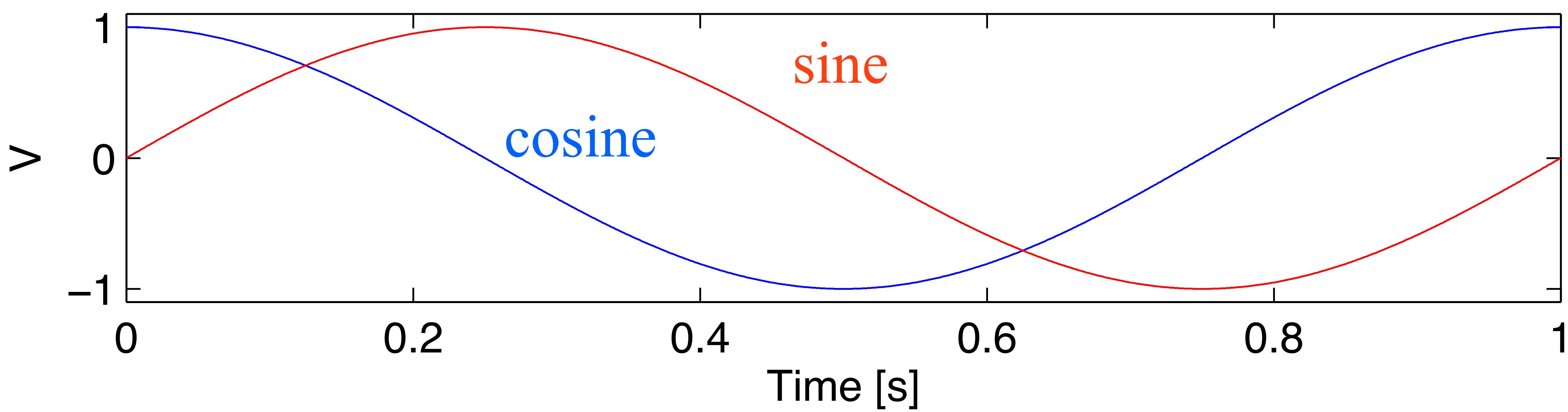
Voltage as a function of time

Amplitude

Frequency [Hz]

Time [s]

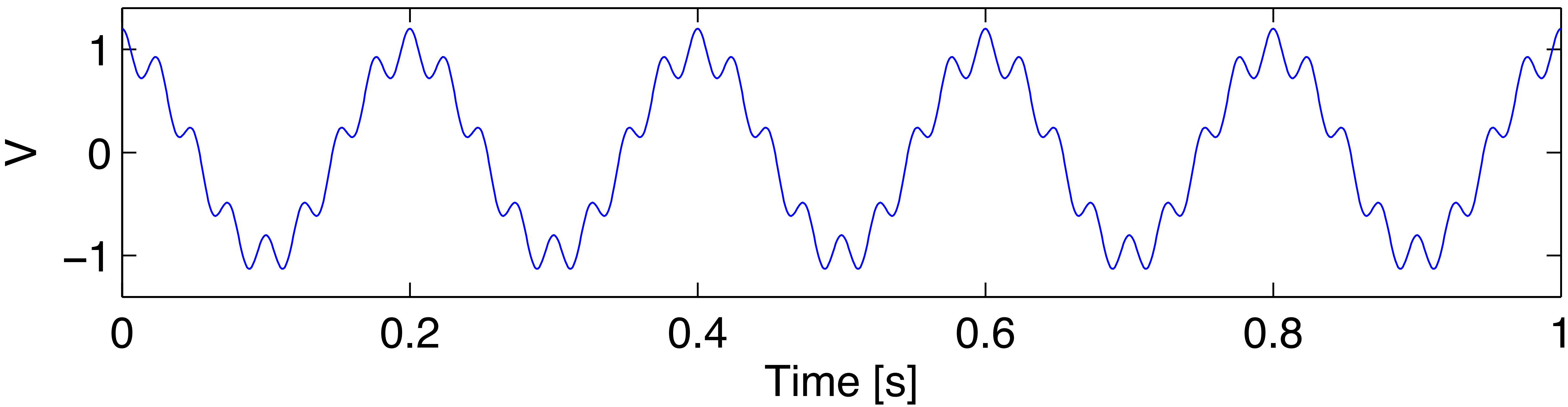
Ex. Consider: f = 1 Hz



Q: What's the difference?

Example: rhythmic signal

Consider the signal below:



Q: What are the rhythms?

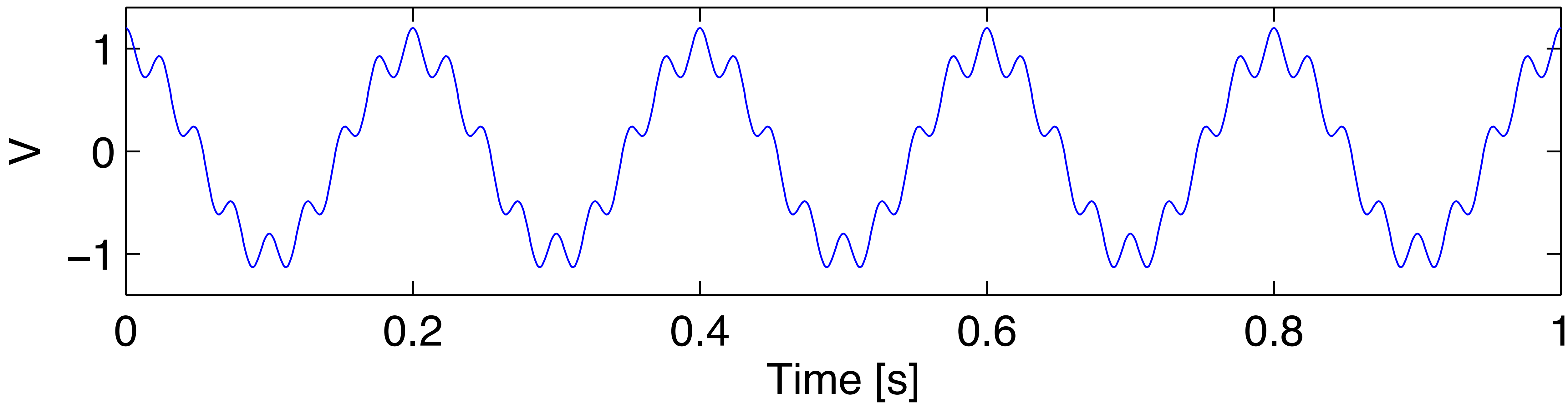
A: Apply visual inspection . . . Slow and fast

5 Hz 40 Hz

Q: What has larger amplitude?

Example: rhythmic signal

So, we can represent this signal . . .



. . . as the sum of two sinusoids:

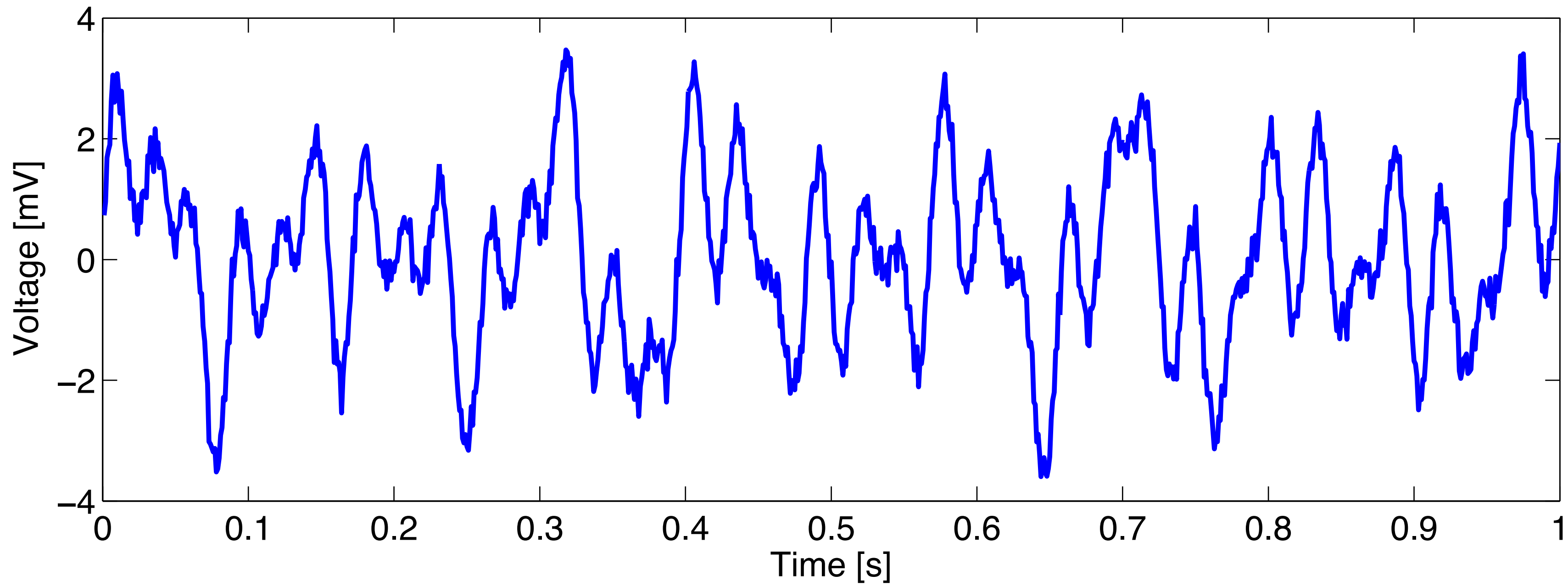
A slow, large amplitude sinusoid + a fast, small amplitude sinusoid

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

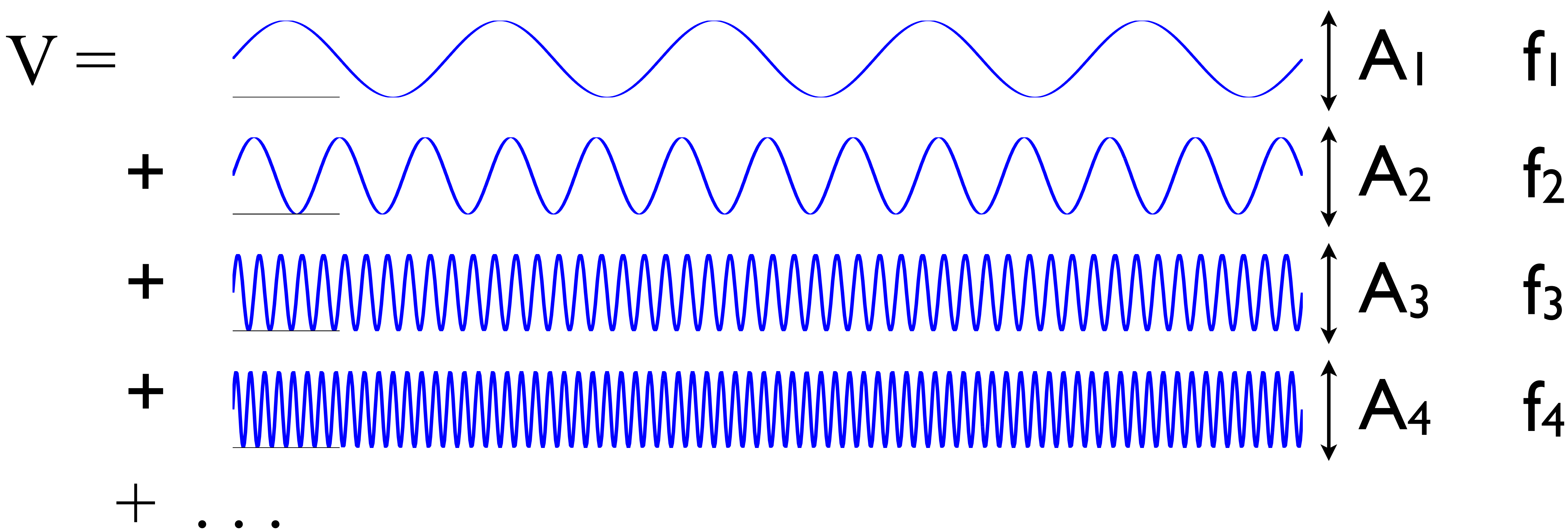
We get a <u>simpler</u> representation of the signal. That's the idea of the spectrum.

Idea: Spectrum

Consider:

$V =$ 

- Decompose signal into oscillations at different frequencies.



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

Idea: Spectrum

So, in equations:

$$V[t] = \underbrace{A_1}_{\text{amplitude}} \cos(2\pi \underbrace{f_1}_{\text{frequency}} t) + B_1 \sin(2\pi f_1 t) + \underbrace{A_2}_{\text{amplitude}} \cos(2\pi \underbrace{f_2}_{\text{frequency}} t) + B_2 \sin(2\pi f_2 t) + \ldots$$

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**.

$$\underbrace{C_j}_{\text{amplitude}} \cos(2\pi \underbrace{f_j}_{\text{freq}} t + \underbrace{\phi_j}_{\text{phase}})$$

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: 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**.

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

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

frequencies

integrate over time

Idea: 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**.

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

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

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

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

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

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: 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**.

Similarly

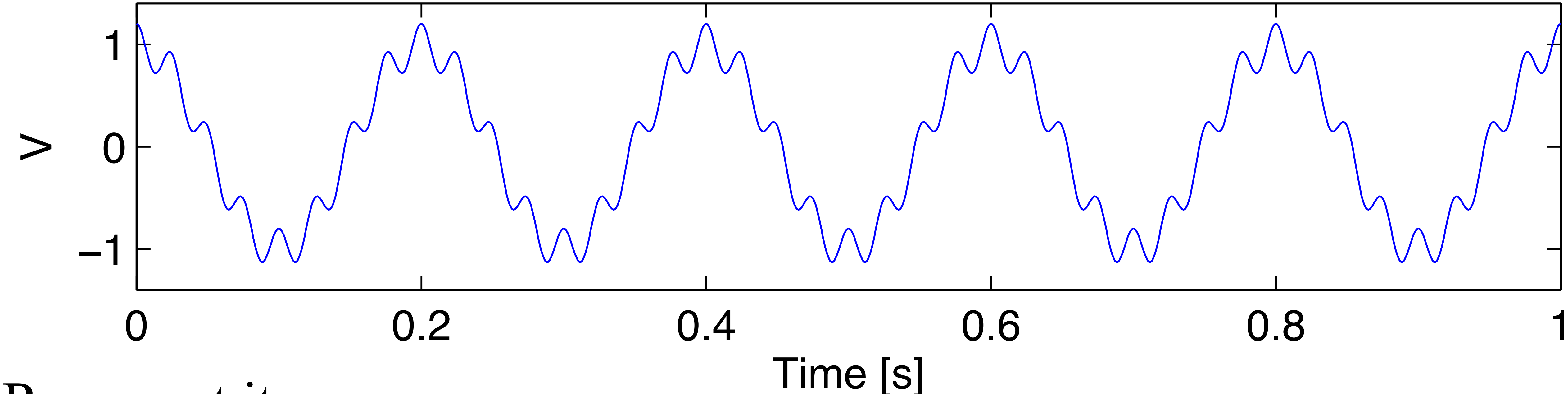
$$A_k = \frac{2}{T}\int_0^T V[t]\cos(2\pi f_k t)dt \qquad B_k = \frac{2}{T}\int_0^T V[t]\sin(2\pi f_k t)dt$$

<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

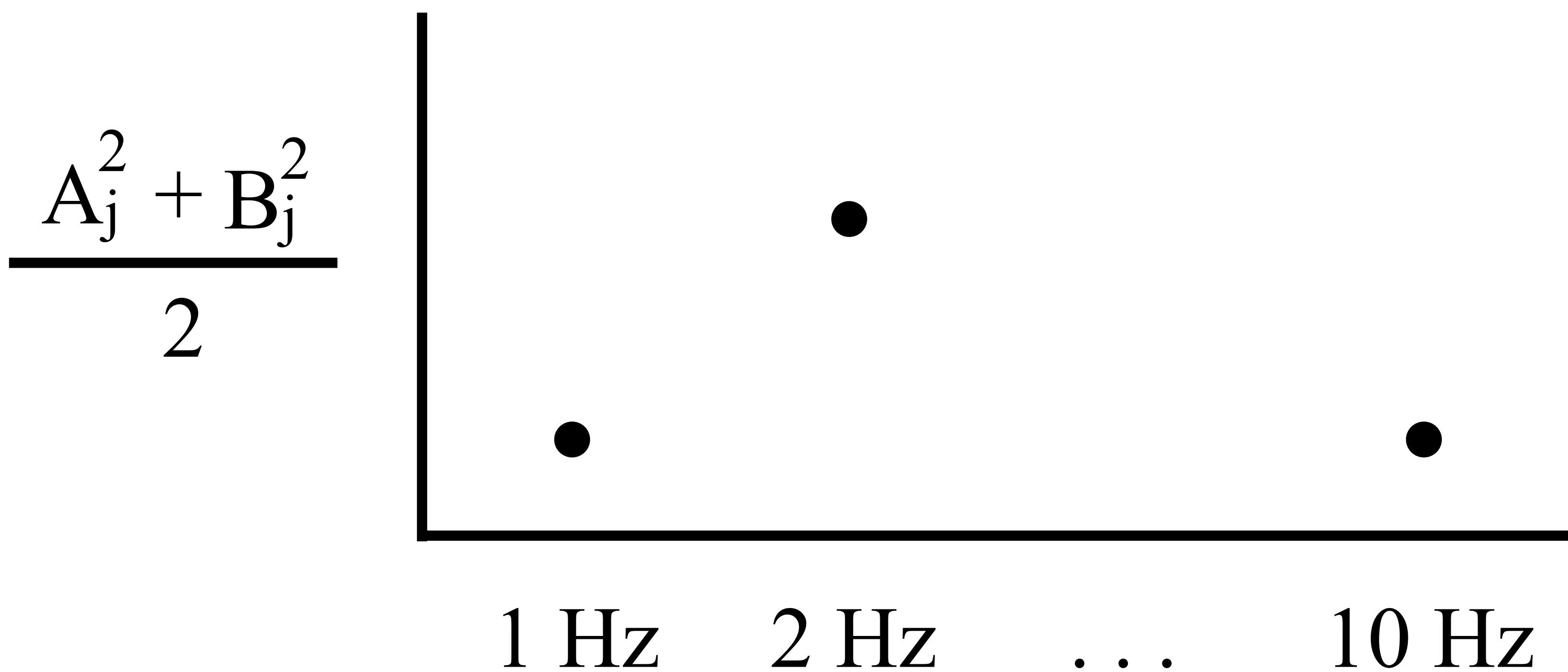
These 4 numbers completely summarize the data.

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

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

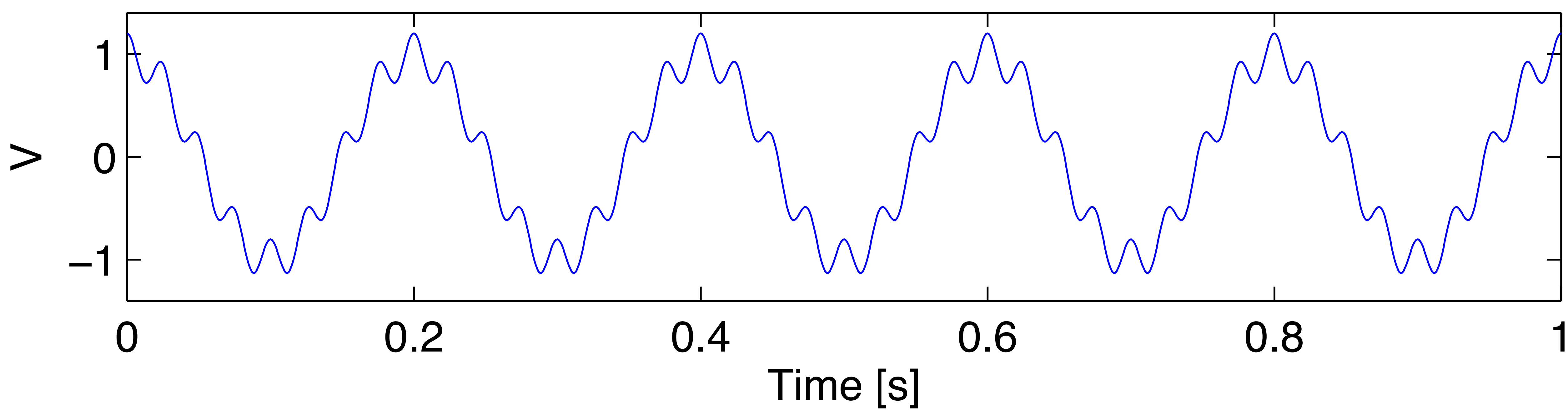


<u>Note</u>: This is called the **spectrum**; a plot of power versus frequency

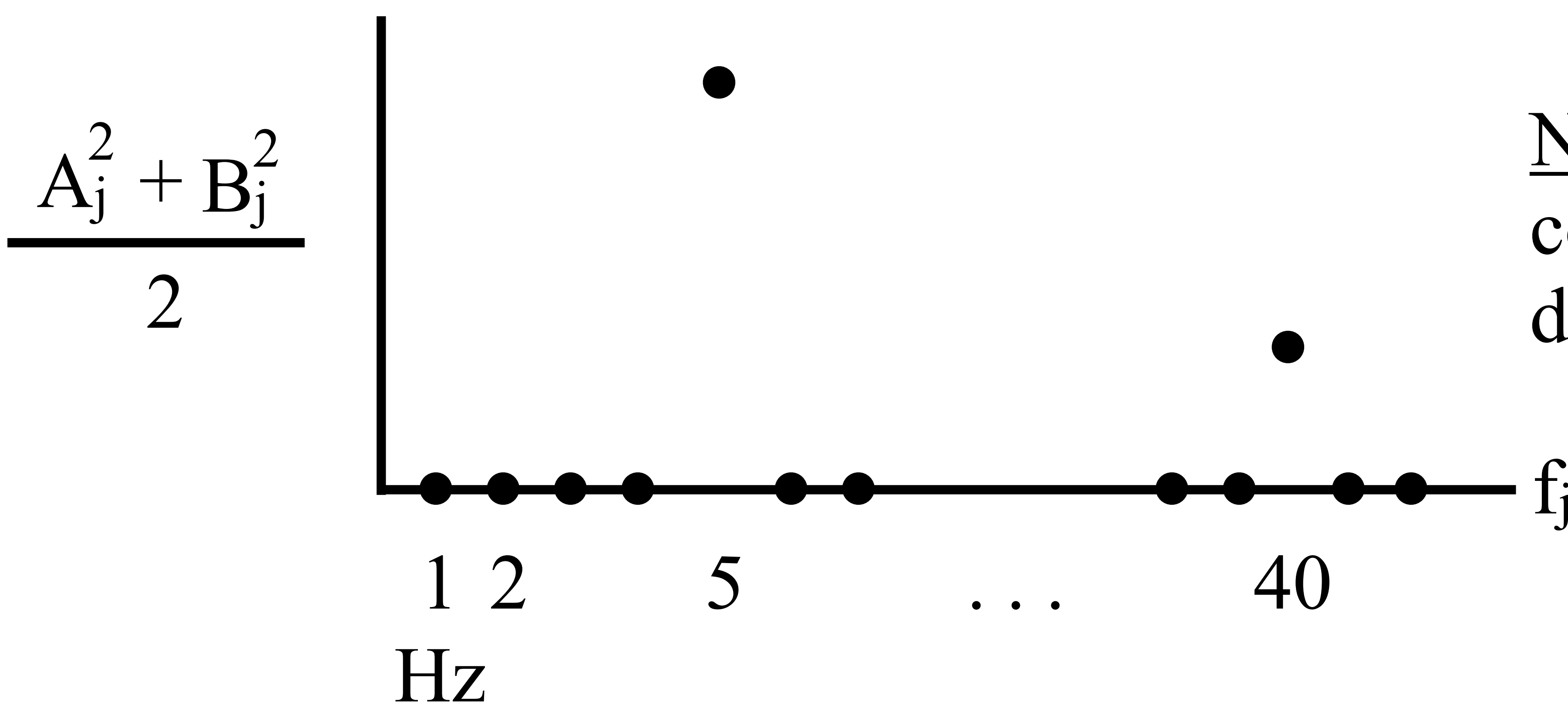
The peaks represent the <u>dominant rhythms</u> in the signal.

Example: rhythmic signal

Ex:



Plot the spectrum:

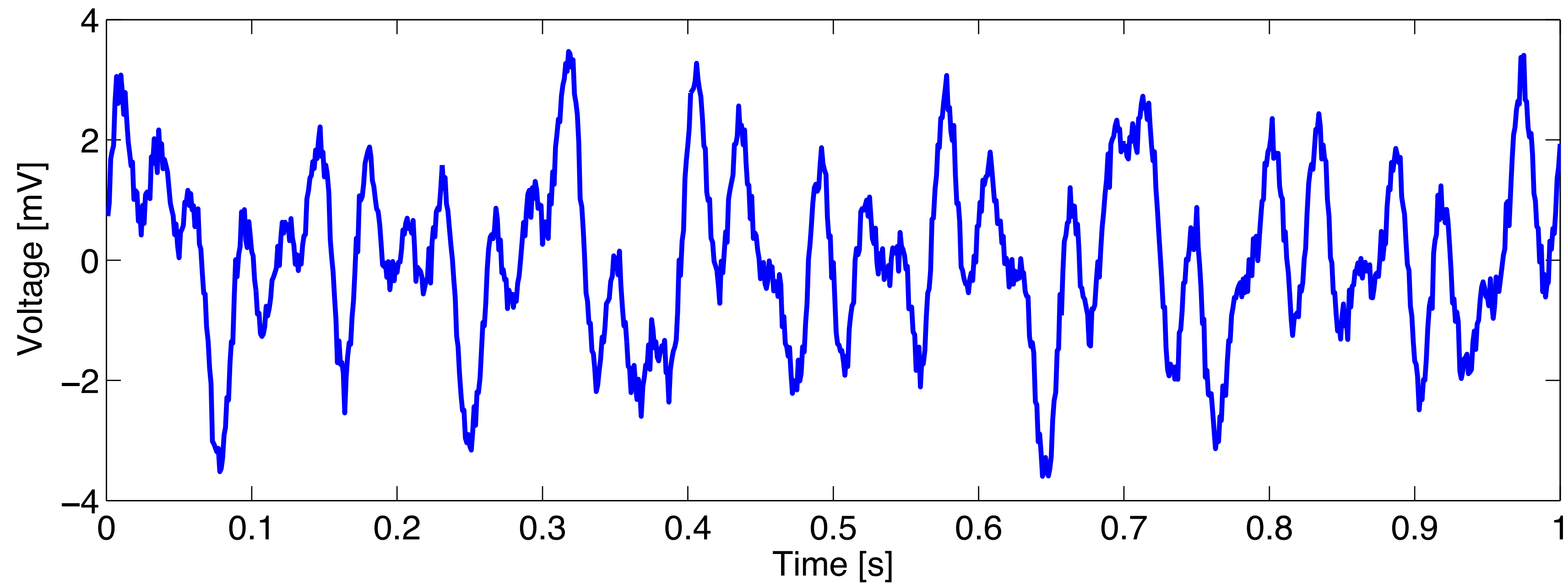


Note: The peaks correspond to the dominant rhythms

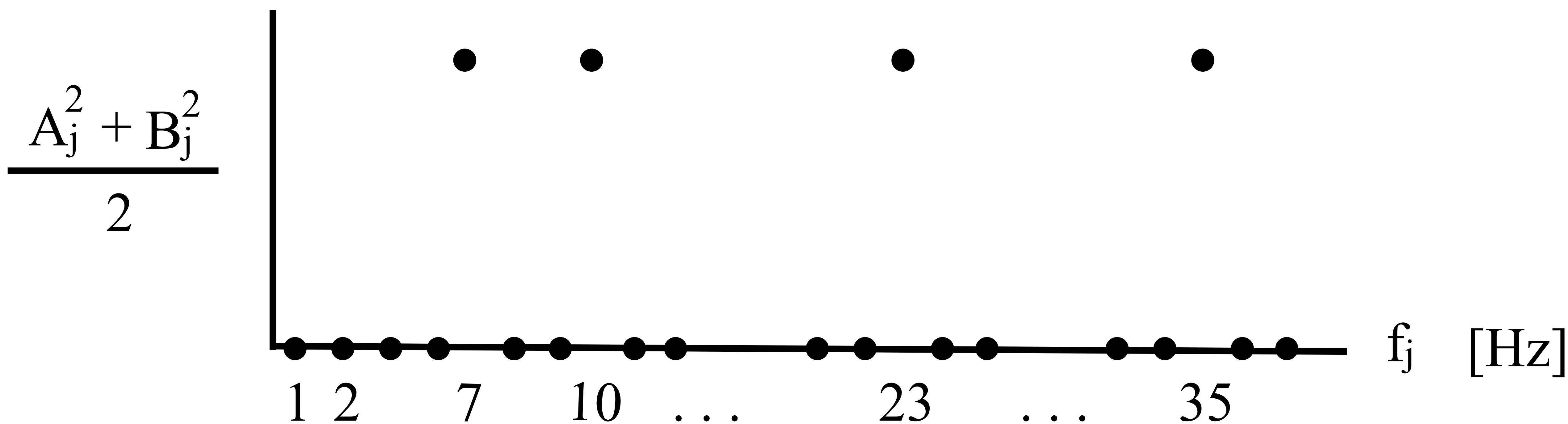
Example: rhythmic signal

Ex.

$V =$



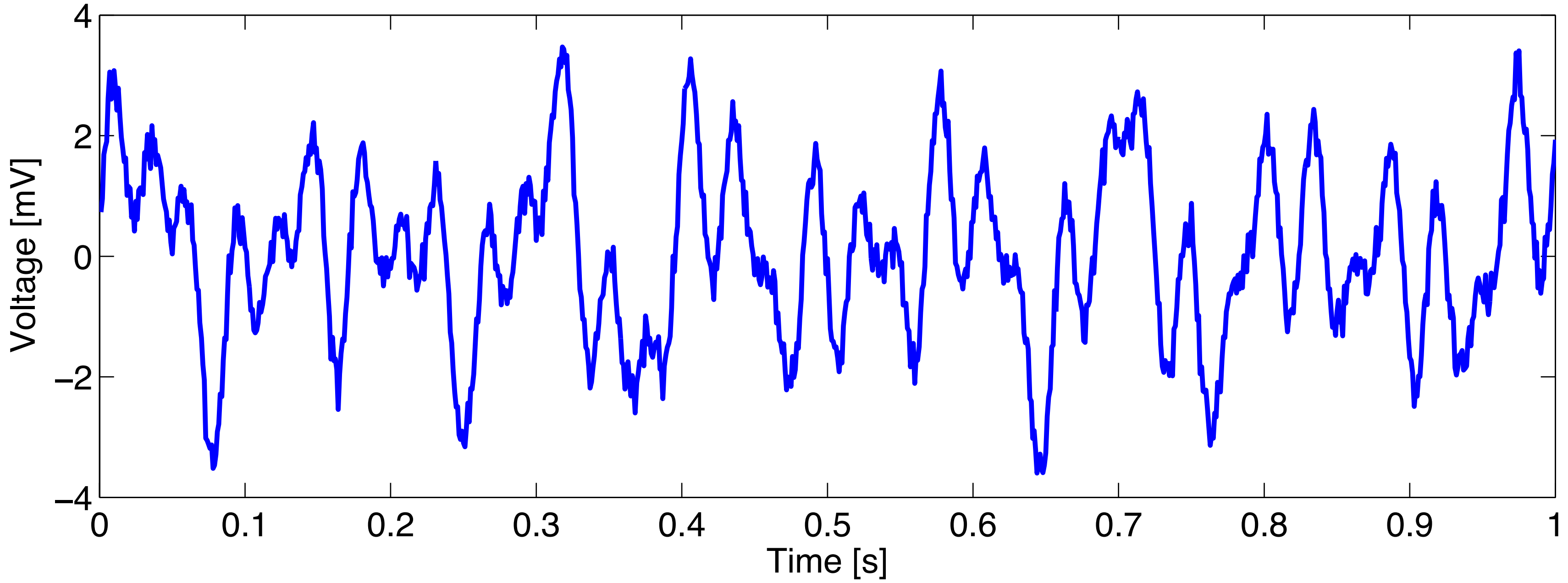
Note: It's complicated   Plot the spectrum:



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:

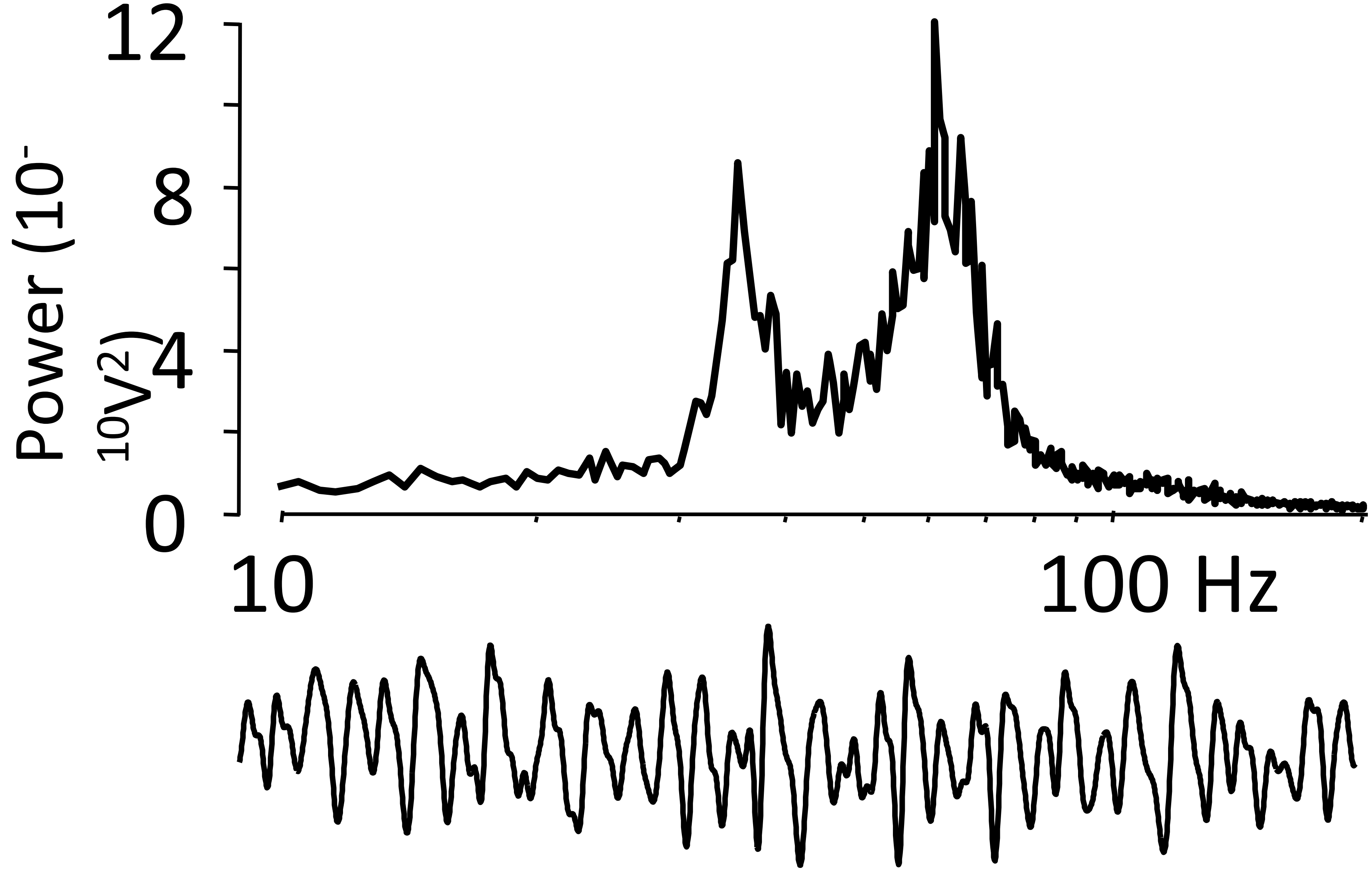
7 Hz, 10 Hz, 23 Hz, and 35 Hz

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

Python

Practical notions …

(**later?**) A simple answer to one big rhythm question …