Title: Signals, Noise and Decoherence

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Abstract: <p> It is well known - to those who know it - that noise and randomness can enhance signal resolution. I'll present an easy-to-follow example from digital audio that illustrates the way in which adding noise ("dither") prior to measurement enhances the accuracy with which we are able to distinguish the features of the sound or image. I will then explore the way in which the environmental interactions prior to measurement ordinarily characterized as environment-induced decoherence may play a similar role. The paradoxical conclusion is that the quasiclassical behavior associated with such systems may be a more accurate representation of the quantum world than what we think of as fully "quantum" behavior, which may in turn be artifactual, the result of errors similar to those introduced by the discretization (also known as "quantization") of data in digital audio and imaging.</p>

# Talk Overview

- Noise & Decoherence
- Dithering to mitigate quantization error: examples from digital signal processing
- Noisy environments and quantum systems

# Noise

Noise - random fluctuations impinging on a signal - can not only degrade signal resolution, but in many cases enhance it.

*Stochastic resonance* phenomena are among those in which noise plays a constructive role.

The use of *dither* in digital signal processing is a kind of stochastic resonance phenomenon. Dither is noise added to an audio signal or visual image prior to quantization which paradoxically improves the resolution of the quantized image.

# Decoherence

The environmental interactions associated with decoherence in quantum systems may be viewed in a similar light.  That is, they cumulatively induce random fluctuations in the phase relationships between elements of a superposition.

The quasi-classical behaviour associated with systems undergoing decoherence is usually associated with a loss of information about the system of interest.   But if the analogy holds, systems undergoing decoherence may actually behave in a way that more accurately reflects the underlying state of the system.

# Digital Audio: Sampling

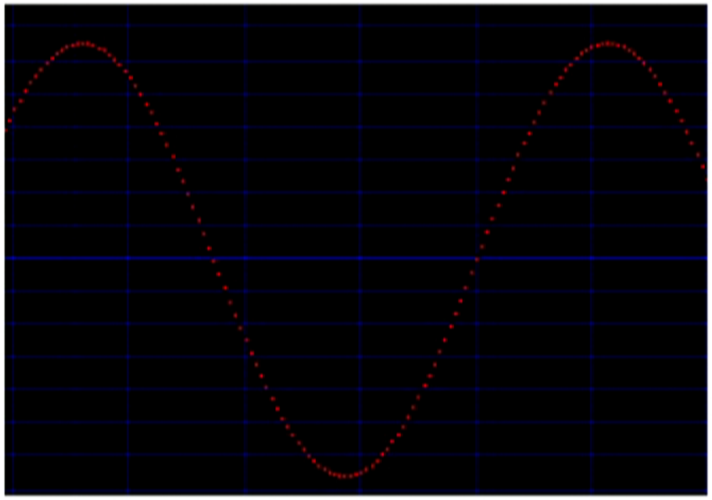
- Digital audio is based on the observation by Nyquist and Shannon that a bandlimited signal can be encoded without loss by sampling the amplitude of the signal at a frequency of at least twice the bandwidth. This sampling frequency is known as the Nyquist rate.

- The CD standard is 44.1 kHz, which is a little more than twice the maximum frequency humans can perceive.

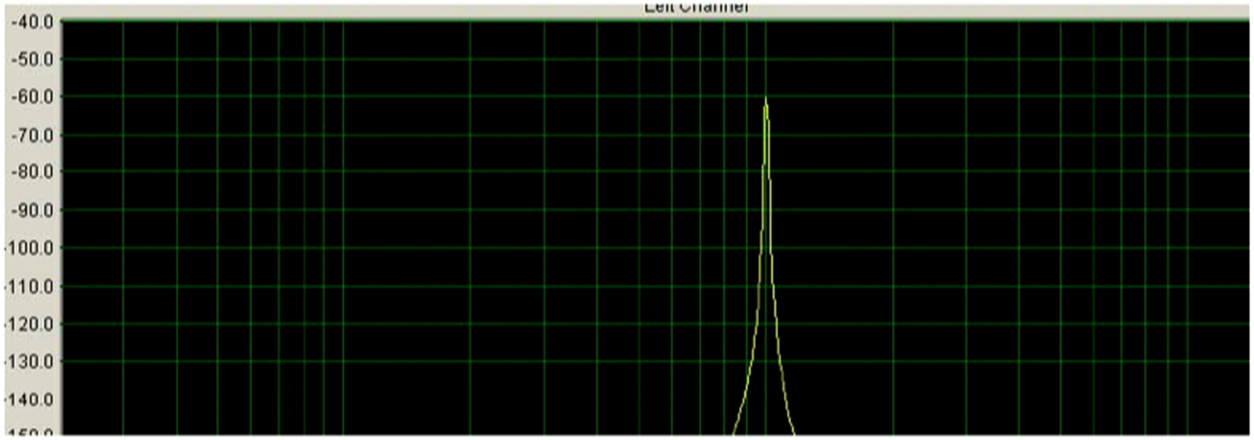
# Finite precision

- In the real world, the amplitude of the signal cannot be either measured or stored with arbitrary precision.

- Modern recording is typically done at a *bit depth* of 24. With this level of precision, the *quantization error* — the difference between the real value and the recorded value — is inaudible.



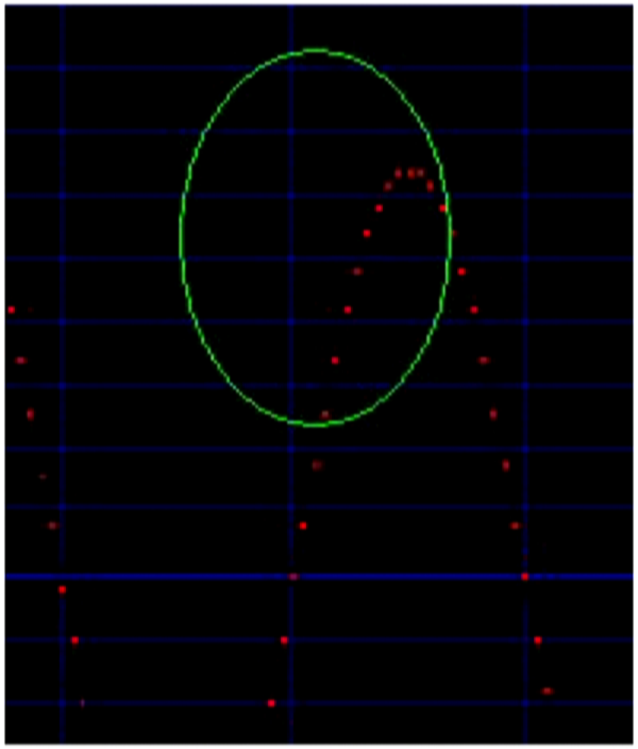
# Spectrum 1



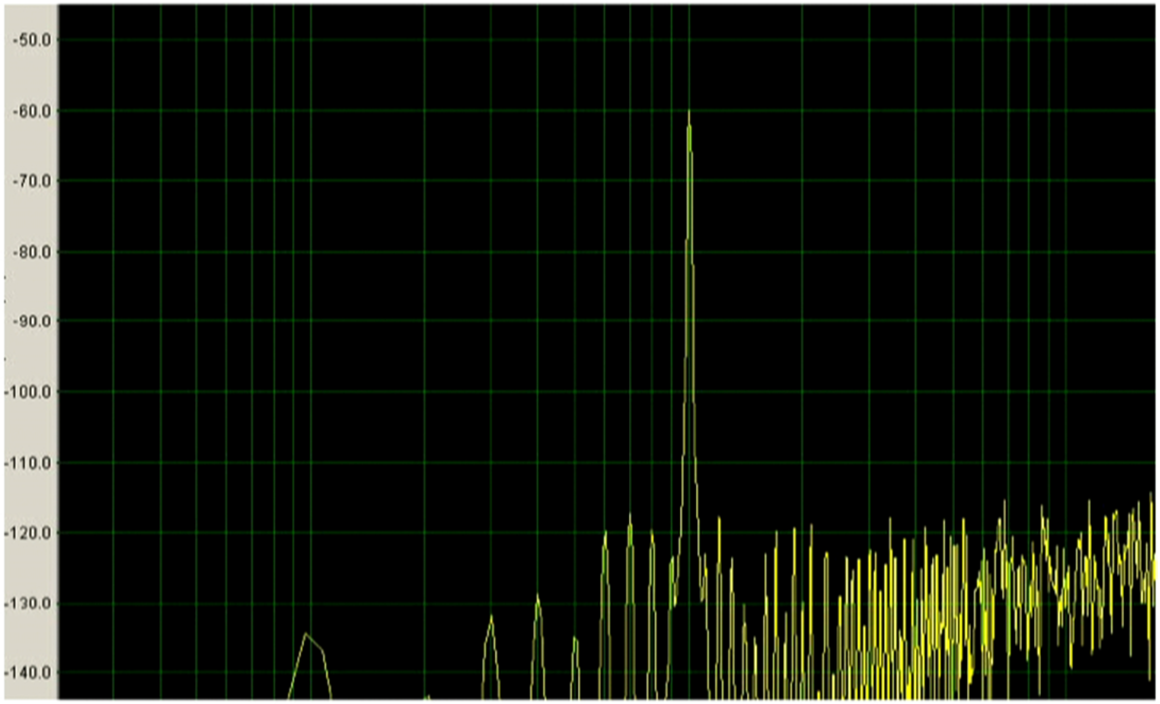

Fourier transform of 1 kHz pure tone recorded at 24 bit depth

# Bit depth reduction

- CDs are encoded with a bit depth of 16, not 24.
- If you record at 24 bits and then truncate the last 8 bits, you get further quantization error, beginning to be visible here.



# Spectrum 2



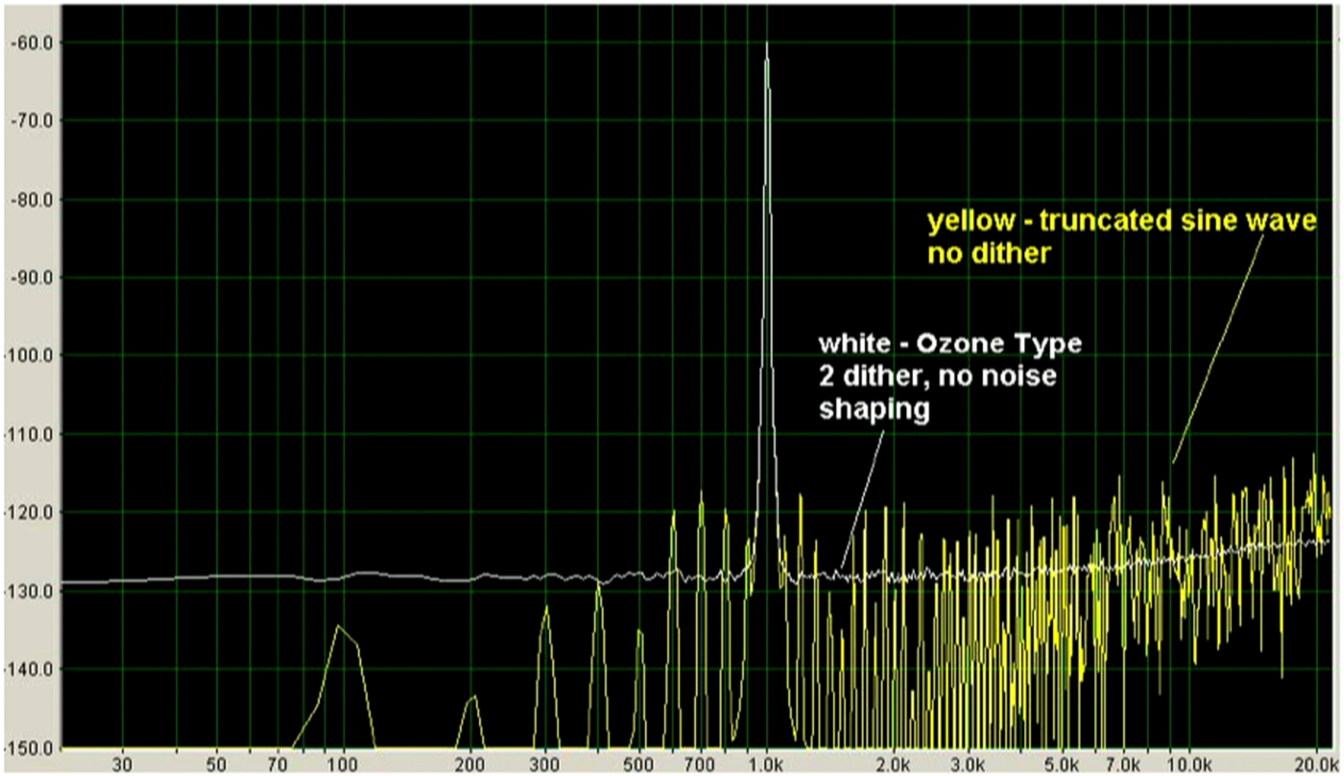

Here's the Fourier transform of the same 1 kHz tone, represented with 16 bits per sample.

# Dithering: Bring the Noise!

- *Dithering* is the addition of noise (white or otherwise) to a signal before it is quantized, or before it is re-quantized (say, from 24 bits to 16 bits).

- Dithering adds noise, but largely eliminates the artifacts of quantization.

# Spectrum 3



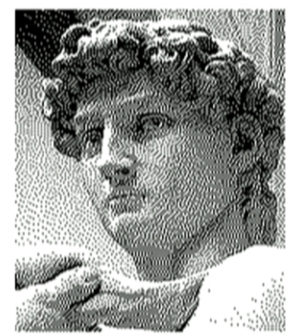

Fourier transform of 16 bit representation of 1 kHz signal, with and without dither. (Thanks to *Izotope*.)

# Dithering from 24 to 16 bits

- Dithering is adding noise.
- In this case, the noise is a random number between 0000 0000 0000 0000 0000 0000 and 0000 0000 0000 0000 1111 1111.
- Adding this to the signal xxxx xxxx xxxx xxxx xxxx xxxx has the effect of bringing some of the information in the 8 least significant bits into the 16 remaining bits, while at the same time ensuring that the quantization error is decorrelated from the signal.

# Dithering visual images

- Dither is also routinely used when reducing the bit depth of images.
- The middle image is a two-bit truncation of the upper left image, while the image on the lower right is dithered with the same bit depth.



# Coherence

- Consider the two-slit experiment for individual electrons or photons. A particle of roughly determinate momentum is aimed at a barrier with two slits, the result of which is represented quantum-mechanically as a coherent superposition of waves emanating from each slit.

- "Coherence" means that the relative phase of one wave relative to the other is fixed. It is this that gives rise to the interference pattern which builds up at the detection screen.

# Decoherence

- If the particles undergo interaction with dust or some other medium on the way to the screen, the interference pattern does not appear.

- Quantum mechanics accounts for this by positing that the interactions modify the phase of the particle's wavefunction.  Assuming that the quantum state of the environment in one region is uncorrelated with that in another region, the phase relationship between the two elements of the superposition will be decorrelated.

- Coherence is lost, and so is the interference pattern.

# Interference as artifact

- What corresponds to a system which is protected from a noisy environment prior to measurement?
- In this case, we might expect that the “signal” is confounded by distortion (e.g., harmonic distortion) resulting from the coarse-graining error introduced by measurement.
- Whatever form it takes, the distortion is not random, and it depends on the signal. It may be the case that quantum-mechanical interference is a kind of distortion induced by the finite resolution of the measurement process.

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# Wrap-up

- Paradoxically, the presence of noise can enhance signal detection.
- This happens when one has a threshold below which the high-resolution signal cannot be resolved.
- Noisy environments associated with quantum-mechanical decoherence may actually be acting to enhance our ability to extract information about the state of the system being observed.
- Measurements of systems that do not undergo decoherence may display artifacts of the finite resolution of the measurement process.