University of Pennsylvania
Department of Electrical and System Engineering
Digital Audio Basics

ESE150, Spring 2022 | Midterm | Monday, Feb 28

- Exam ends at 12:55PM; begin as instructed (target 12:05PM)
- Do not open exam until instructed to begin exam.
- Problems weighted as shown.
- Calculators allowed.
- Closed book = No text or notes allowed.
- Provided reference materials on next to last page.
- Show work for partial credit consideration.
- Unless otherwise noted, answers to two significant figures are sufficient.
- Sign Code of Academic Integrity statement (see last page for code).

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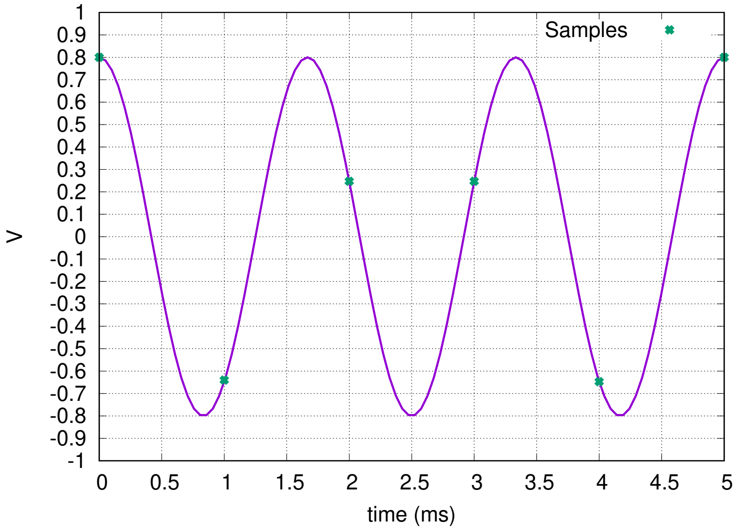
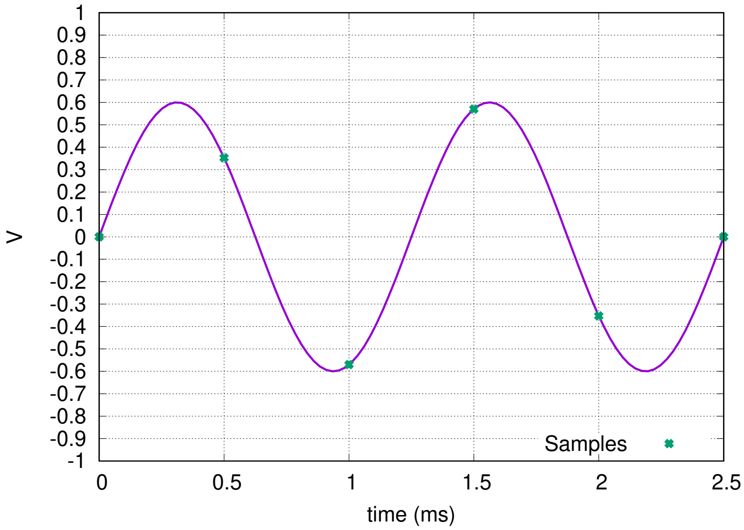
I certify that I have complied with the University of Pennsylvania's Code of Academic Integrity in completing this exam.

Name: Solution

1	2			3					4		5		
	a	b	c	a	b	c	d	e	a	b	a	b	c
16	5	5	10	2	2	4	9	4	14	8	5	7	9

1. Consider the following sampling cases, complete the table entries.

Waveform and Sample	Waveform Frequency (Hz)	Sample Frequency (Hz)	Inferred Frequency (Hz) from Samples	Properly Sampled?
	600	1000	400	No
	800	2000	800	Yes

2. Consider PCM sampling at 12KHz with 10b quantization.

   (a) What is the maximum frequency this PCM sampling can correctly capture?
   6KHz

   (b) How many bits per second does the PCM sampling require?
   $12000 \times 10 = 120{,}000$ b/s

   (c) Using a 25 ms window, this sample rate can identify 150 frequencies. Assuming there are a most 3 frequencies to encode per human cirtical band, you can still use 10b amplitude per frequency, and you operate on 25 ms sound frames, how many bits per second to encode this frequency time-window representation?
   20 critical bands (bands 21–24 are above 6KHz)
   3 frequencies per band
   18b for (freq,amplitude pair) $= \log_2(150)+10$
   $20 \times 3 \times 18/0.025 = 43{,}200$ b/s

3. Consider the following quote from Benjamin Franklin:

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
e	n	e	r	g	y		a	n	d		p	e	r	s	i	s	t	e	n	c	e

22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
	c	o	n	q	u	e	r		a	l	l		t	h	i	n	g	s

This has 41 symbols from a set of 18 unique symbols.

symbol		a	c	d	e	g	h	i	l	n	o	p	q	r	s	t	u	y	**sum**
count	5	2	2	1	6	2	1	2	2	5	1	1	1	3	3	2	1	1	41

(a) How many bits to encode this using a uniform encoding where each symbol is encoded using the same number of bits?

$41 \times \lceil \log_2(18) \rceil = 41 \times 5 = 205$

(b) What property or properties of this quote make it amenable to lossless compression?

Symbols occur with different frequencies. Some symbols occur more often than others; we can give short encodings to the more frequently occuring symbols.

(c) What is the Shannon Entropy lower bound for encoding this entire quote?

$$\text{Lower Bound} = -\sum_i \log_2(P(c[i])) \tag{1}$$

Hint: there are only 5 different counts, so 5 different P(c[i]) values to calculate.

$6 \times \log_2(6/41) + 10 \times \log_2(5/41) + 6 \times \log_2(3/41) + 12 \times \log_2(2/41) + 7 \times \log_2(1/41) = 159.4 \approx 160$

(d) Consider the following set of variable-length binary encodings. Assign each symbol to an encoding to minimize the encoded length.

encode	110	100	011	1110	1011	1010	0100	0001	0000
symbol	e	space	n	r	s	a	c	i	l
encode	**11111**	**11110**	**01010**	**00111**	**00110**	**00101**	**00100**	**010111**	**010110**
symbol	t	g	d	h	o	p	q	u	y

Within encodings of the same length, the assignment of symbols of the same frequency is not important. E.g. e could be encoded with any of 110, 110, 011.

(e) For the above assignment, how many bits are required to encode the quote?

$6 \times 3 + 10 \times 3 + 6 \times 4 + 8 \times 4 + 4 \times 5 + 5 \times 5 + 2 \times 6 = 161$

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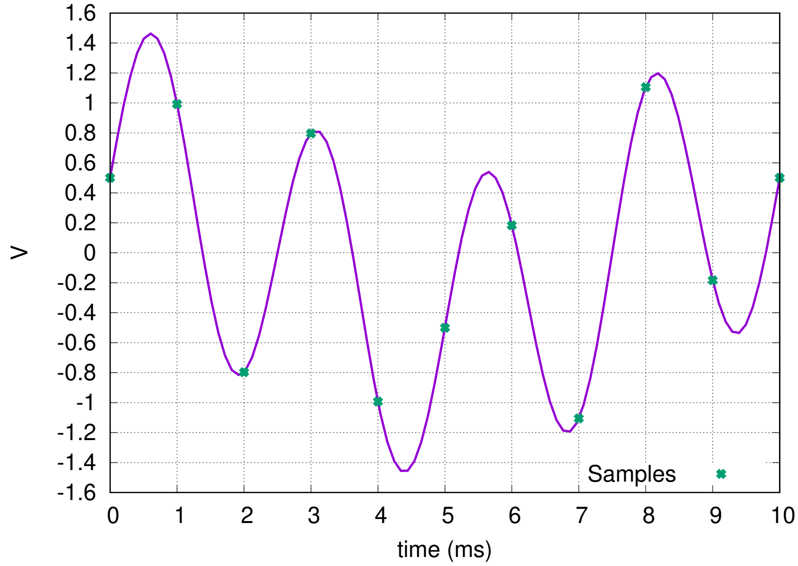
4. Given the following waveform and associated samples at 1000Hz, identify the frequencies present.



Time (t)	0 ms	1 ms	2 ms	3 ms	4 ms	5 ms	6 ms	7 ms	8 ms	9 ms
Sample Value	0.5	1.0	-0.8	0.8	-1.0	-0.5	0.18	-1.1	1.1	-0.18

(a) Which of the following frequencies are present in the waveform:

Frequency	100	200
Present?	Y	N

(given the limited precision of the samples and sine/cosine values below; treat final values between 0.1 and -0.1 to zero.)

Perform dot products with sine and cosines below, get:

term	dot product with samples
$\cos(2\pi 100t)$	3
$\sin(2\pi 100t)$	0
$\cos(2\pi 100t)$	0
$\sin(2\pi 100t)$	0

This shows 100 Hz is present and 200 Hz is not.

(b) Are there any other frequencies present? How do you know?

Yes.

We can reason from the main oscillation, where we have 4 complete cycles in the 10 ms period, suggesting a 400 Hz component.

Alternately, we can observe that the signal goes from high to low in a little over 1 ms. For the signal to change this fast, there must be a frequency a little lower than 500 Hz (which goes from high to low in 1 ms).

t	0 ms	1 ms	2 ms	3 ms	4 ms	5 ms	6 ms	7 ms	8 ms	9 ms
$\cos(2\pi 100t)$	1.0	0.81	0.31	-0.31	-0.81	-1.0	-0.81	-0.31	0.31	0.81
$\sin(2\pi 100t)$	0.0	0.59	0.95	0.95	0.59	0.0	-0.59	-0.95	-0.95	-0.59
$\cos(2\pi 200t)$	1.0	0.31	-0.81	-0.81	0.31	1.0	0.31	-0.81	-0.81	0.31
$\sin(2\pi 200t)$	0.0	0.95	0.59	-0.59	-0.95	0.0	0.95	0.59	-0.59	-0.95

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5. Consider an alien first-encounter situation. When the aliens go to speak, you hear nothing. However, nearby dogs bark back in response to the aliens.

   (a) Why is it likely the dogs can hear them but you cannot?

   The aliens are likely communicating in frequencies above human hearing (22 KHz) but, at least partially, within range of dog hearing (up to 65 KHz).

   (b) If you listened to the aliens through a PCM transmission, you also hear nothing. What would likely happen if you removed the anti-alias filter prior to time-domain sampling at 44 KHz for the PCM recording?

   Without the ant-aliasing filter, we will get aliasing and the high frequencies fold, so their aliased version shows up below 22 KHz, in the range audible to humans. So, the humans will be able to hear the speech, but it may be in bands where humans have less selectivity and multiple original frequencies may end up mapped to the same frequency, possibly making fine discernment a challenge.

   (c) Assuming the aliens do communicate entirely with sound waves, describe a better way to determine (i) what you need to do to fully capture alien communication and (ii) render it in a form humans can hear.

   (i) Sample at a much higher rate and convert that high sampling to the frequency domain to see what frequencies are present. Given that the dog can hear it, sampling at $2\times 6\,5$KHz=130 KHz might be a start. However, there is no guarantee the dog can hear the full range, so it is worthwhile to keep sampling at even higher frequencies until it appears there are no higher frequencies present.

   (ii) Once you have a good idea of the upper range, convert the frequencies down to the human hearing range. The simplest might be to divide the frequency by the ratio of (highest alien frequency)/22 KHz, to render the entire alien range in the human range. Since humans have poor hearing near 22 KHz, and many humands have hearing loss before that, it may make sense to aim for a 100 Hz to 10 KHz range target instead of 0 to 22 KHz. The shifted frequencies can then be converted back to the time domain to render for humans. This compression may map some frequencies that need to be differentiate to frequencies too closer together for human differentiate. That may require additional care to spread out important frequencies in key critical bands.

Human auditory critical bands:

Band Number	Low	High
1	20	100
2	100	200
3	200	300
4	300	400
5	400	510
6	510	630
7	630	720
8	720	920
9	920	1080
10	1080	1370
11	1270	1480
12	1480	1720
13	1720	2000
14	2000	2320
15	2320	2700
16	2700	3150
17	3150	3700
18	3700	4400
19	4400	5300
20	5300	6400
21	6400	7700
22	7700	9500
23	9500	12000
24	12000	15500

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B. Plagiarism Using the ideas, data, or language of another without specific or proper acknowledgment. Example: copying another person's paper, article, or computer work and submitting it for an assignment, cloning someone else's ideas without attribution, failing to use quotation marks where appropriate, etc.

C. Fabrication Submitting contrived or altered information in any academic exercise. Example: making up data for an experiment, fudging data, citing nonexistent articles, contriving sources, etc.

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E. Misrepresentation of academic records Misrepresentation of academic records: misrepresenting or tampering with or attempting to tamper with any portion of a student's transcripts or academic record, either before or after coming to the University of Pennsylvania. Example: forging a change of grade slip, tampering with computer records, falsifying academic information on one's resume, etc.

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