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

ESE150, Spring 2019 Final Monday, May 6

- Exam ends at 5:00PM; begin as instructed (target 3:00PM)
- 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).

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					
a	b	c.i	c.ii	d.i	d.ii	a	b	c	d		a	b.i	b.ii	c.i	c.ii	c.iii
1	4	3	2	2	3	1	1	8	5	10	5	2	2	2	2	2

5					6						7					**Total**
a	b	c	d	e	a	b	c	d	e	f	a	b.i	b.ii	b.iiii	b.iv	
3	3	3	3	3	2	2	2	1	5	3	7	2	2	2	2	100

Hypothetical cat auditory critical bands:

Band Number	Low	High
1	45	100
2	100	200
3	200	300
4	300	400
5	400	500
6	500	600
7	600	800
8	800	1200
9	1200	1500
10	1500	2000
11	2000	2500
12	2500	3000
13	3000	4000
14	4000	5000
15	5000	6000
16	7000	8500
17	8500	10000
18	10000	12000
19	12000	15000
20	15000	18000
21	18000	22000
22	22000	25000
23	25000	30000
24	30000	35000
25	35000	42000
26	42000	46000
27	46000	50000
28	50000	56000
29	56000	60000
30	60000	64000

While the cat auditory range to 64,000 Hz is real. This auditory band structure is a synthetic construct generated just for this problem and likely does not represent reality.

1. Continuing our cat audio compression from the midterm, we again consider that a cat can hear up to 64KHz and likely has similar critical band limitations to humans. Consider the hypothetical band structure shown on the facing page, and make the simplifying assumption that we only need to represent the strongest 4 frequencies in each band over a 25 ms time window to 4 Hz resolution. Assume 16b amplitude quantization for each frequency. What bandwidth do we need to continuously send compressed cat audio in real time (send compressed data for 25 ms of sound in 25 ms)?

   (a) Exploiting this structure, what do you store for each 25 ms window and how many bits does this require?

   Same as midterm.

   Store 4 (frequency, amplitude) pairs in each band, for a total of $4 \times 30 = 120$ frequencies.

   Since we only want 4 Hz resolution, we need $\log_2\left(\frac{64{,}000}{4}\right) = 14$b to represent each frequency.

   Total: $120 \times (14 + 16) = 3600$

   As noted on midterm solutions, we can tighten this, using fewer bits to select frequencies in each band.

   (b) What raw bandwidth does this require? [state in bits/second]

   3600b / 25 ms = 144,000 b/s

   (c) Assume we form one TCP/IP over ethernet packet for every 25 ms window. Each packet has a header and checksum that occupies 40 Bytes along with the compressed payload data for one 25 ms window.

      i. What total bandwidth is required including the packet header and checksum? [state in bits/second]

      (3600b+40 × 8b) / 25 ms = 156,800 b/s ≈ 160Kb/s

ii. List at least 3 data fields that exist in the packet header (not including the checksum):
source port, source IP, destination port, destination IP, sequence number, packet length

(d) Given that the maximum payload size for TCP/IP over ethernet is 1500 Bytes:

i. How many 25 ms frames can you pack into one TCP/IP packet?
$\left\lceil \frac{1500 \times 8}{3600} \right\rceil = 3$

ii. What is the total bandwidth requirement to achieve real-time transmission when you pack this many 25 ms frames into one TCP/IP packet? [state in bits/second]
$(3 \times 3600\text{b} + 40 \times 8\text{b}) \ / \ (3 \times 25)\,\text{ms} = 148.267\ \text{b/s} \approx 150\text{Kb/s}$

2. Continuing with the compressed cat audio from the previous question, we want to understand the computational requirements for decoding cat audio. At the receiving end, we will need to decode the data. Consider the following code:

```
   // some headers and definitions omitted
#define REC_LENGTH 2
#define FREQUENCY_OFFSET 1
#define AMPLITUDE_OFFSET 0
void decode(uint16_t *freq, uint16_t *pcm25ms)
{
  for (int i=0;i<PCM_SAMPLES_IN_WINDOW;i++) { // contributes 3 instructions
                                              // per loop iteration
    uint16_t v=0;// 1 instruction
    for (int j=0;j<FREQS;j++) { // contributes 3 instructions per loop iteration
      int f=(freq[j*REC_LENGTH+FREQUENCY_OFFSET])<<2;  // 4 instructions
      uint16_t cycles=((int)(f*i<<16)/SAMPLE_INTERVAL)%(1<<16); // 4 instructions
      uint16_t sine_index=2*PI*cycles; // 1 instruction
      int a=freq[j*REC_LENGTH+AMPLITUDE_OFFSET]; // 2 instruction
      v+=a*SINE_TABLE[sine_index]; // 3 instructions
      }
    pcm25ms[i]=v; // 1 instruction
  }
}
```

(a) Assuming we sample at the Nyquist rate to capture frequencies up to 64KHz, what is PC_SAMPLES_IN_WINDOW for the 25 ms window?

Sample at Nyquist rate $= 2 \times 64$ KHz.
Samples in one 25 ms window is (128000×0.025)=3200 samples.

(b) From Problem 1, what is FREQS?

120

(c) Based on the instruction annotations and your answers to (a) and (b), how many instructions are required for one call to `decode` (equivalently for decoding on 25 ms frame of cat audio)?

$5 \times 3200 + 3200 \times 120 \times 17$=6,544,000≈6.5M

(d) How fast must a processor run to decode the cat audio in real-time? Specifically, to decode one 25 ms window in 25 ms? [instructions/second]

6,544,000/(0.025 s)≈260M instructions/second

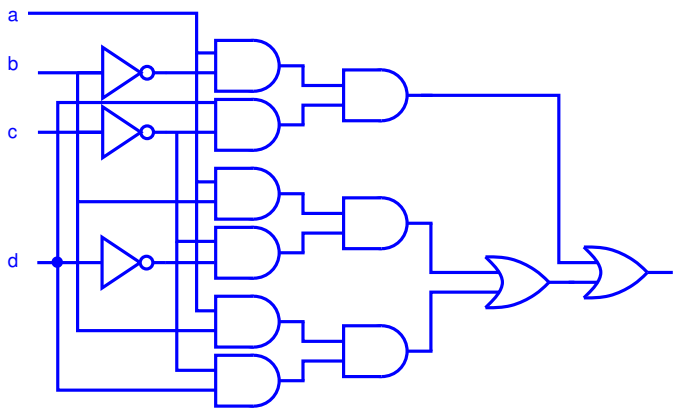
3. Implement the following truth table using inverters and 2-input AND and OR gates.

a	b	c	d	out	
0	0	0	0	0	
0	0	0	1	0	
0	0	1	0	0	
0	0	1	1	0	
0	1	0	0	0	
0	1	0	1	0	
0	1	1	0	0	
0	1	1	1	0	
1	0	0	0	0	
1	0	0	1	1	$a \cdot /b \cdot /c \cdot d$
1	0	1	0	0	
1	0	1	1	0	
1	1	0	0	1	$a \cdot b \cdot /c \cdot /d$
1	1	0	1	1	$a \cdot b \cdot /c \cdot d$
1	1	1	0	0	
1	1	1	1	0	

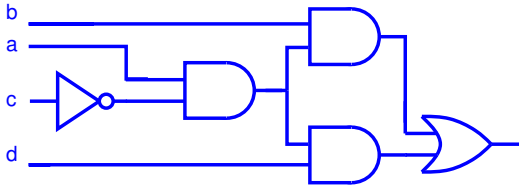
$y = a \cdot /b \cdot /c \cdot d + a \cdot b \cdot /c \cdot /d + a \cdot b \cdot /c \cdot d$

Can optimize to (not required for ESE150): $a \cdot /c \cdot d + a \cdot b \cdot /c$

No Optimization



Optimized



4. For the midterm, you sketched a design to translate cat-audible sounds (0 to 64KHz) down to human-audible sounds (0-22KHz).

   (a) Give one reason why the sketch you turned in for the exam would likely not be patentable?

   - not reduced to practice
   - frequency shifting hearing aids a prior art? this is not a non-obvious extension?
   - not first to file?
   - didn't identify need (exam or engineer hypothesized in the exam did); would need to include that engineer in filing.

   (b) Assuming you wrote your own code from scratch to implement the translator:

   i. How would that help in potentially patenting a translator?
   Would represent reducing the idea to practice.

   ii. Can you copyright your code? (explain why or why not)
   Yes. Software is considered an expression which is copyrightable.

   (c) After writing your code as an App for a popular smart phone, you discover that the audio input to the Analog-to-digital converter in the phone has low-pass filters that only allow frequencies below 22 KHz to be seen by the Analog-to-digital converter. Based on this, you decide it may be better to build your own hardware device to perform the cat-audible to human-audible sound conversion.

   i. Why did the smart phone have this low-pass filter?
   Most humans can only hear up to 22 KHz, and MP3s only encode ulp to 22 KHz. Need to filter out higher frequencies before sampling to avoid aliasing.

   ii. How does audio capture for your hardware design need to differ from the smart phone audio capture?
   Change the low-pass filter to allow frequencies up to 64 KHz.

   iii. Compare the patentability of the hardware device converter versus the software-only App converter?
   Pure software is not typically patentable. A machine or hardware that includes software is. So, you would be patenting the full hardware system including the design of the low-pass filter.

5. An engineer decides to create a c(h)at (a cat-audio version of skype or face time) for computer-to-computer cat audio conferences. Being concerned about bandwidth requirements and quality, she generalizes the cat-audio compression from Problem 1. It now has 3 parameters:

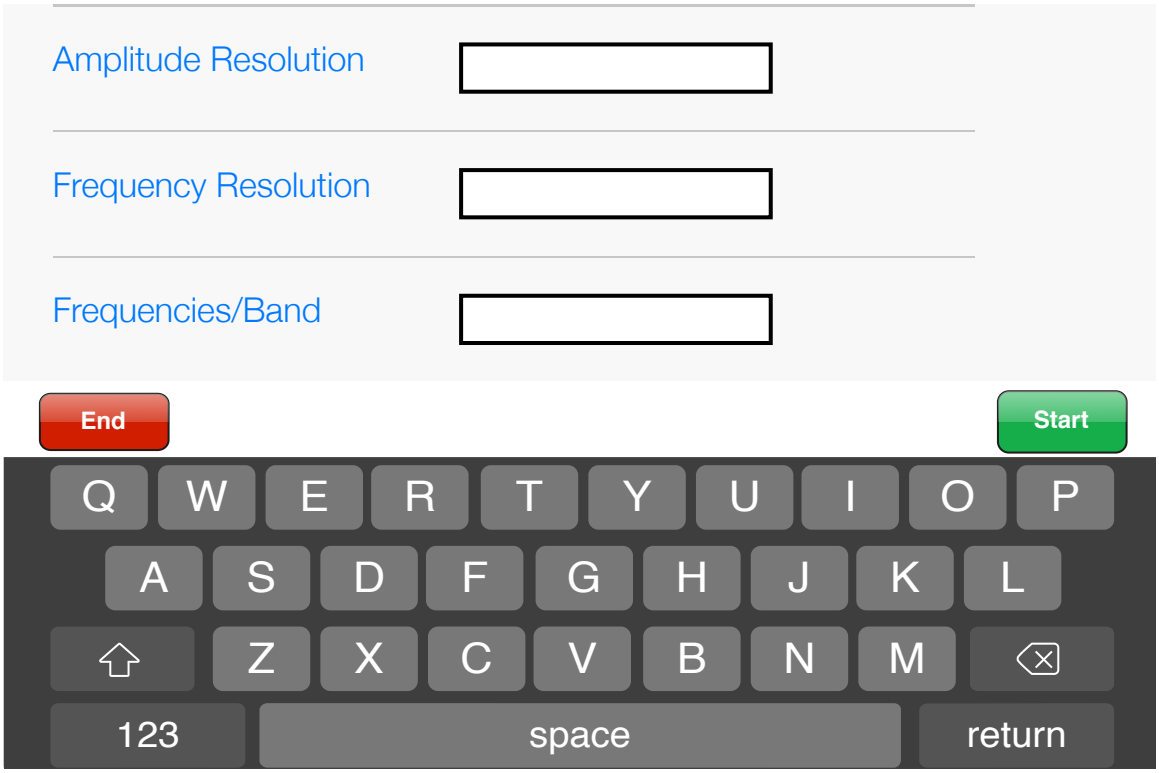
   (a) amplitude quantization

   (b) frequency resolution (quantization)

   (c) number of frequencies to keep per critical band

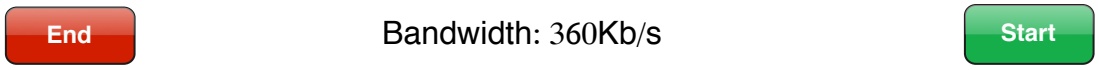
   The c(h)at compressor takes these 3 arguments and compresses sound accordingly, packetizing it for communication over a network (as in Problem 1). The idea is that users will adjust the parameters based on the bandwidth available to them. For each of the following User Interfaces for this task: (a) rank their ease-of-use from (1) easiest to (5) hardest to use; (b) Identify strengths and weaknesses (at least one of each) [hint: general, cat-owning users are unlikely to be familiar with concepts like critical bands and only dimly aware of bandwidth.]:

(a) 3 text boxes that allow you to type any text for the 3 parameters and a start button to indicate you have set the values and are ready to start the c(h)at. When any of the values in the text box are invalid, prints an error message "invalid parameters". When the configuration exceeds the bandwidth available on the link, it drops packets silently (without showing any indication about dropped packets).



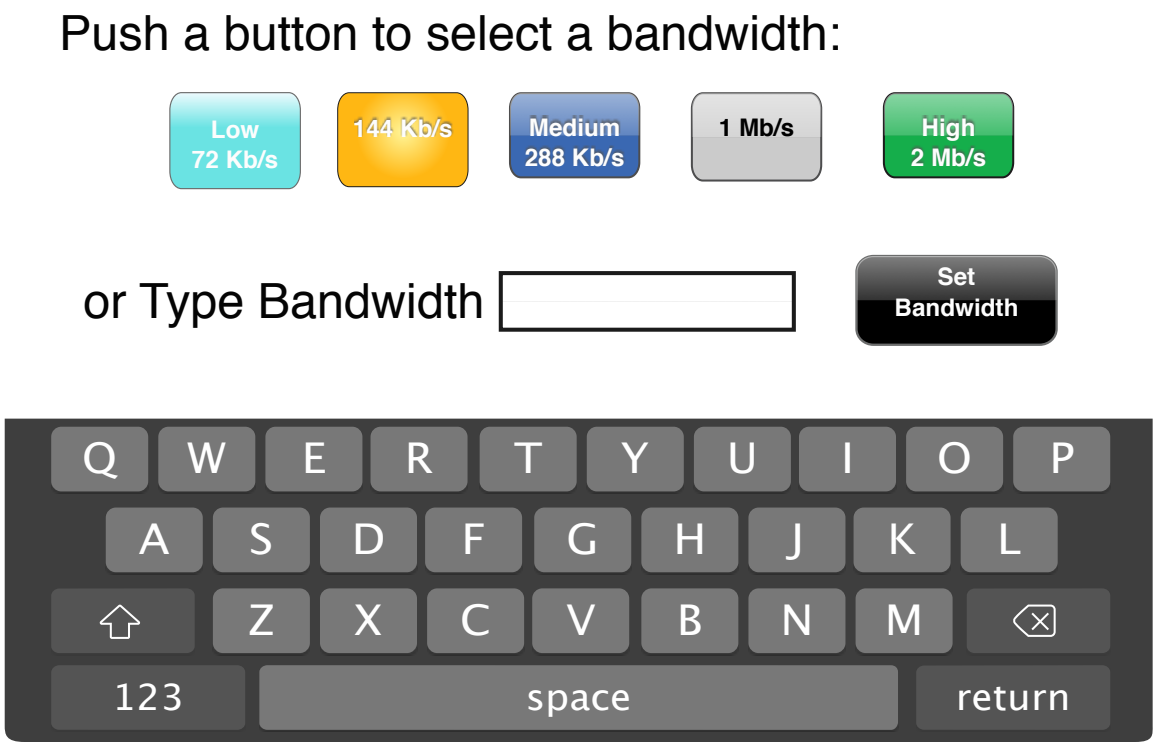
Ease-of-Use Rank	5
Strength	(almost none)
	All input on one screen
Weakness	Exposes low level parameters user typically won't understand
	Doesn't constrain inputs to sensible values
	Provides no useful feedback on how to fix invalid parameters
	Even when user puts in valid numbers, gives no hint about bandwidth requirements
	Doesn't give visibility into what's happening when drops packets

(b) Program has a start button. The program measures the bandwidth on the link, internally determines the values for the 3 parameters to not exceed 80% of the measured link bandwidth, and uses those. When packets are dropped, it remeasures link bandwidth, updates the parameters accordingly, and reports the current bandwidth in use to a status bar at the bottom of the c(h)at window.



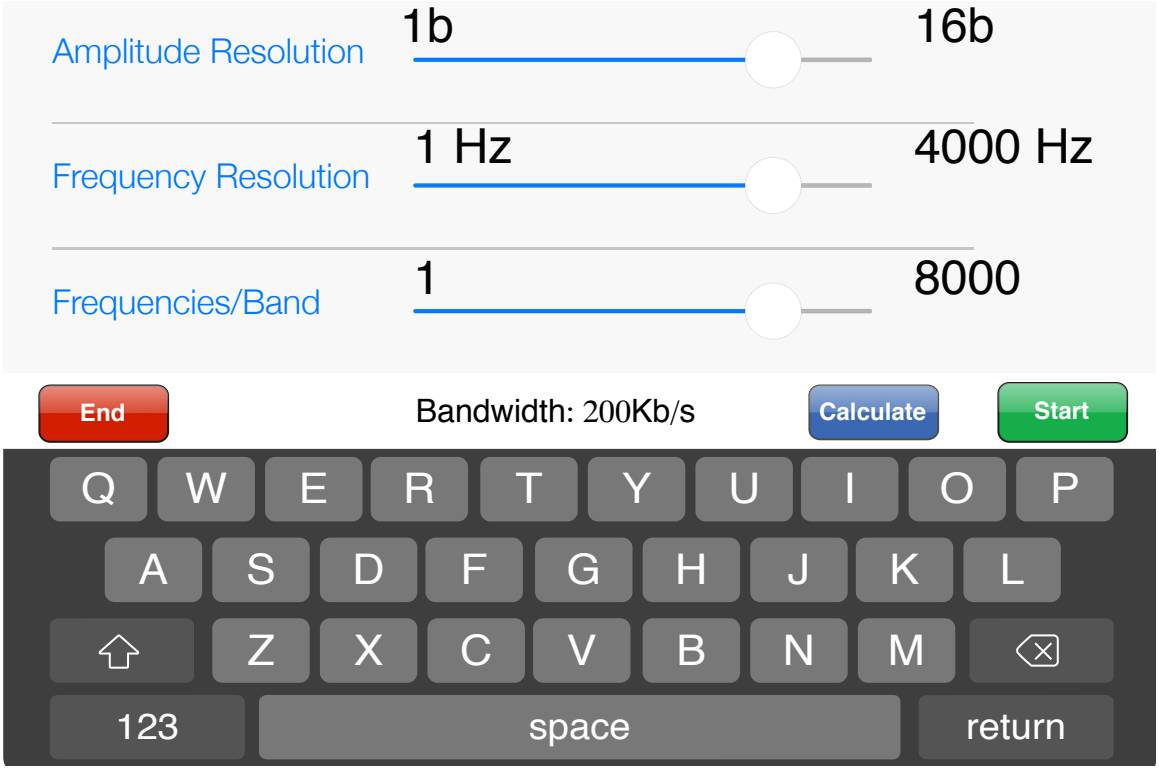
Ease-of-Use Rank	1
Strength	Takes care of selecting bandwidth and parameters for user
	Visibly reports bandwidth state
	Gets started with minimal, single button click
	Re-adjusts parameters as needed without user request
Weakness	As stated, never increases bandwidth when more bandwidth becomes available; only degrades
	User doesn't have control of how bandwidth allocated
	Not able to limit bandwidth lower than 80% of link availability

(c) Five buttons to select common bandwidth choices, an optional text box, and a sixth button to set the bandwidth to the value provided in the optional text box. Each of the six buttons start the transfer. When the configuration exceeds the bandwidth available on the link, it: (a) drops to the next smallest common bandwidth, if configured to a common bandwidth, or (b) drops the bandwidth by 10% if the bandwidth was specified in the text box.



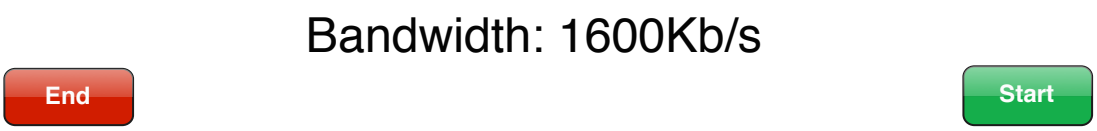
Ease-of-Use Rank	2
Strength	In common case, can start with a single button click
	Also supports broader choices on same screen
	Updates parameters to adjust to bandwidth available automatically
	Simplifies choice to bandwidth; hides internal parameters
Weakness	Doesn't constrain typed input for bandwidth
	As described, doesn't show what's happening as bandwidth is reduced

(d) 3 sliders that allow you to select choices within the allowed range of values for each of the 3 parameters, a calculate button, and a start button. When the calculate or start button is selected, the application will calculate and report the bandwidth required to support the specified parameters. When the configuration exceeds the bandwidth available on the link, it drops packets and prints "packets dropped" in a status bar at the bottom of the c(h)at window.



Ease-of-Use Rank	4
Strength	Limits inputs to legal values
	Performs bandwidth calculation for user
	Provides some feedback about dropped packets
Weakness	Exposes internal parameters user may not understand
	Forces user to set bandwidth
	Provides no feedback on bandwidth available
	Packet dropped feedback doesn't give user a sense of how much over bandwidth they are
	User must restart to change configuration

(e) One slider to specify the target bandwidth and a start button. The program internally determines a value for the 3 parameters and uses those. When the configuration exceeds the bandwidth available on the link, it drops packets and reports the packet drop rate on the screen.



Ease-of-Use Rank	3
Strength	Simple with single slider
	Hides internal parameters
	Gives useful information about how much over bandwidth the configuration is
Weakness	Burden is on user to chose bandwidth
	User must restart to change configuration

6. Consider an Internet-of-Things cat collar with a microphone, an analog-to-digital converter, a small processor, a wireless transmitter, and small battery. We want to use this to record compressed cat audio onto a server. To maximize battery life, where should we perform compression on the data? Assume:

   - Capture 64KHz cat audio.
   - Compress using the scheme from Problem 1.
   - Sending one bit over wireless costs 1 μJ (10^{-6} J).
   - Executing one instruction on the processor costs 1 nJ ($10^{-9}J$) per instruction.
   - The dominant cost in compression is the Fourier Transform to convert to frequencies. Performing an efficient FFT takes 200 instructions per sample point.
   - Detection applies a threshold to the frequencies in the frame. If all frequencies are below an identified threshold, the frame is considered silent and does not need to be stored.
     - Assume detection takes one additional instruction per sample when already doing compression.
     - Detection for uncompressed data requires 5 instructions per sample.
   - On average 95% of frames will be classified as silent.
   - You may ignore the overhead of packet headers for the calculations in this problem.
   - Uncompressed PCM samples 16b each.

   (a) How much energy to send each uncompressed 25 ms frame? [Joules]
   $3200 \times 16 \times 10^{-6}\text{J} = 0.0512\text{J}$

   (b) How much energy to send each compressed 25 ms frame? [Joules]
   $3600 \times 10^{-6}\text{J} = 0.0036\text{J}$

   (c) How much energy to compress a 25 ms frame (without detection)? [Joules]
   $3200 \times 200 \times 10^{-9}\text{J}$=0.00064J

(d) How much energy to detect if a frame has data? [Joules]

i. on uncompressed data? $3200 \times 5 \times 10^{-9}$=$16 \times 10^{-6}$J

ii. on compressed data? $3200 \times 1 \times 10^{-9}$=$3.2 \times 10^{-6}$J

(e) What strategy maximizes the battery life? (detail what computation you perform on the collar processor and what data you send out of the collar processor.)

- Compress data on collar and detect if above threshold.
- Send out compressed data when exceeds threshold.

Better solution. Instructor didn't figure out until a week later preparing solutions. Will take both.

- Detect if above threshold on uncompressed
- When above threshold
  - Compress data
  - Send out compressed data

(f) For this strategy, what is the average energy required per hour of operation? [Joules]

Compress before detect: $(0.0036 \times 0.05 + 0.00064 + 0.0000032) \times 40 \times 3600 = 118.54 \approx 120$J

Detect before compress $(0.0036 \times 0.05 + 0.00064 \times 0.05 + 0.000016) \times 40 \times 3600 = 32{,}823 \approx 33$J

Common case is don't have to compress. So, ok to spend larger energy to detect to avoid spending energy to compress most of the time.

A coin-sized battery (e.g. CR2032) holds 720J. A 9V battery holds about 20,000J.

7. As discussed in class, a computer with multiple links can help route packets. If it receives a packet that isn't destined for itself, it can send it out along a link that gets the packet closer to the destination. Consider a computer:

   - one input link and two output links
   - packet length 1000 Bytes (as simplification for exam, assume all packets fixed-size at this length)
   - processor spends 100,000 cycles processing each forwarded packet
   - the processor on the computer executes 3 Billion (3×10^9) cycles per second.

   (a) What fraction of the processor's cycles are spent on routing when supporting 100 Megabit/second network links.

   $\frac{\frac{10^8}{8\times1000}\times10^5}{3\times10^9}$=0.41

   (b) If the computer also kept a record of the IP (IPv4) address of every computer that sent messages through it in a day:

   i. maximum number of sources?
   $\frac{10^8}{8\times1000} \times 24 \times 3600 = 1.08 \times 10^9 \approx 1$ Billion

   ii. Uncompressed space to store those sources?
   4×1 Billion $= 4$GB

   iii. How much are you likely to be able to compress the list of sources if you Huffman code the list of sources and the computer typically only sees 1000 different sources per hour.
   Assume the 1000 sources occurr equally frequently (worst=least compression) case. Need 10b to represent those cases. So, store about 10b per packet rather than 32b. So, compress to 1/3 (about 10/32≈31%) of the uncompressed case.

   iv. How else might you compress a day's worth of source data? and what compression would you get if you only saw 1000 different sources per hour?

   - Only keep track of unique sources. So only store each source once.
   - At most 24×1000=24,000 sources in a day.
   - $10^9 / (24 \times 10^3)$ ≈42,000× compression, or 2.4×10^{-5} of the worst-case, uncompressed data.

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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