1. Short answer questions
a. There are approximately $36 \times 10^{20}$ nucleons (protons and neutrons) in the earth. If we wanted to give each one a unique n-bit address, how many bits would it take?

$$2^{10} = 10^{3}$$

b. In a CMOS inverter with $R_{ON}=10k$ and $R_{OFF}=1M$ running from a 1V supply, what are the approximate output low/high voltage values $V_{OL}$, $V_{OH}$?

$$V_{OL} = 0.01V, V_{OH} = 0.99V$$

c. For that same CMOS inverter, if the input capacitance of each transistor is 0.1pF, what are the approximate rise and fall times if the inverter is driving one other inverter?

$$t_r = (10^4)(2 \times 10^{-16}) = 2 \times 10^{-12} = 2 ps$$

d. My neighbor's roof has solar panels with a total area of 30m$^2$. The panels are 10% efficient. In July, the peak solar flux is 1kW/m$^2$. What is the peak electrical power that she gets from her roof?

$$(30 m^2)(1 kW/m^2)(10\%) = 3 kW$$

e. My iphone has a 4Wh battery. If I charge it from a 500mW supply, how long will it take to fully charge the battery when it is empty?

$$\frac{4 Wh}{0.5 W} = 8 hr$$

f. In an electronic weighing scale, you use a strain gauge with a resistance of 10kΩ. The resistance change is 0.1% per kilogram of mass on the scale. You put the strain gauge in a Wheatstone bridge with 3 other resistors that are nominally 10kΩ and apply a bridge excitation voltage of 10V. What output voltage should you measure with 1kg on the scale?

$$V_{DD} \frac{1}{4} = 2.5 mV$$

h. What is the resistance of 100 resistors in parallel if each resistor is 1kΩ?

$$10 \Omega$$

j. What is the capacitance of 10 capacitors in series if each capacitor is 1F?

$$0.1 F$$
2. A sinusoidal voltage is applied across a 10Ω resistor. The RMS voltage is 1V. What is the zero-to-peak voltage? Peak-to-peak voltage? Average voltage? Average power?

\[ V_{\text{rms}} = 1V \]
\[ P_{\text{avg}} = \frac{V_{\text{rms}}^2}{R} \]

\[ \text{No partial credit +1} \]

| \( V_{0-P} \) | \( 1.4V \) or \( \sqrt{2} \) |
| \( V_{P-P} \) | \( 2.8V \) or \( 2\sqrt{2} \) |
| \( V_{\text{avg}} \) | \( 0V \) |
| \( P_{\text{avg}} \) | \( 0.1W \) or \( \frac{1}{10} \)

3. An RC low-pass filter has a pole frequency of 100rad/sec. Fill in the table with the magnitude of the transfer function \( H(j\omega) \), and phase of \( H(j\omega) \) must have BOTH \( |H(j\omega)| \) AND \( \angle H(j\omega) \) correct for a given frequency

| \( \omega \) | \( |H(j\omega)| \) | Angle \( \text{H}(j\omega) \) |
| --- | --- | --- |
| \( 10^0 \) | 1 | 0° or -0.6° |
| \( 10^1 \) | 1 | -6° |
| \( 10^2 \) | 0.7 | -45° |
| \( 10^3 \) | 0.1 | -84° or -135° |
| \( 10^4 \) | 0.01 | -90° or -89.4° |
| \( 10^5 \) | 0.001 | -90° |

NOTE: \( H(j\omega) \) must be very close to the solution.

a. If the currents are not in simplified form, -1 for \( |H(j\omega)| \) and +1 for \( \angle H(j\omega) \).
b. If forgot negative sign for the phase, -1 for all c. \( |H(j\omega)| \) in dB is fine

4. A police radar has an LC tank with a resonant frequency of approximately \( \omega_0 = 100\text{Grad/s} \).
Assuming that the inductor is 2nH, and has a series resistance of 20Ω,

a. What size is the capacitor?

\[ LC = \frac{1}{\omega_0^2} = 10^{-12} \]
\[ C = \frac{10^{-12}}{2 \pi \times 10^{12}} = 5 \times 10^{-4} \]

b. What is the complex impedance of the inductor at resonance?

\[ j\omega L = j \times 10^2 \times 10^{-9} = \frac{200j}{2} \]
\[ \text{either for } j\omega L \text{ or } 0.5 \times 10^{-12} \text{ for } 0.05 \text{ pf} \]

-1 for \( j\omega L \) (electric)

+2 for \( j\omega C \) (either)

\[ Q = \frac{V_0}{I} = \frac{1}{\omega_0 RC} \]

+1 for equation

d. What is the complex impedance of the capacitor at resonance?

\[ \frac{1}{j\omega C} = -j \times 10^2 \times 5 \times 10^{-14} = -j \times 200 \]

-1 for \( j \), take -1 off

+2 for \( j\omega C \)

e. What is the complex impedance of the tank at resonance?

\[ Q^2 \times 20 \Omega = 2000 \Omega \]

\[ Q = \frac{Q^2 \times \text{Re} \text{ of } Q \times \text{Im} \text{ of } Q}{\text{Re} \text{ of } Q} \]

+2 for \( Q^2 \times \text{Re} \text{ of } Q \times \text{Im} \text{ of } Q \)

\[ \frac{20}{\text{OR}} \]

\[ (j200 + 20) / (-j200) \]

\[ = 2000 - 3200 \]

f. What is the complex impedance of the tank at low frequency?
5. True/false questions (circle one)

a. In an ideal diode at room temperature, the current increases by a factor of 10 for every 60mV increase in forward voltage. TRUE □ FALSE □

b. Atoms in a conductor have more electrons than atoms in a semiconductor, which in turn have more electrons than atoms in an insulator. TRUE □ FALSE □

c. Pure silicon conducts electricity better at absolute zero than at room temperature. TRUE □ FALSE □

d. The Bohr model of the atom and the Pauli exclusion principle explain the formation of energy bands in semiconductors. TRUE □ FALSE □

e. The color of the light from an LED is determined primarily by the amount of current flowing through the LED. TRUE □ FALSE □

f. Electricity is usually carried in wires by the movement of positively charged protons. TRUE □ FALSE □

g. Modern transistors have dimensions measured in tens to hundreds of atoms. TRUE □ FALSE □

h. The number of boolean functions of n variables is 2^n, one row in the truth table for each function. TRUE □ FALSE □

i. The current in a capacitor can change instantaneously. TRUE □ FALSE □

j. The current in an inductor can change instantaneously. TRUE □ FALSE □

6. When I charge my car in the Hearst garage, the voltage (measured by the car) reads 206V before I start charging. When my car pulls 30A, the voltage reads 200V. Assume that the power source is ideal, and that my charging cable is not. What is the power delivered to my car, what is the resistance in my charging cable, what is the power dissipated in my charging cable?

\[ P_{\text{car}} = (200V)(30A) = 6000 \text{ W} \]

\[ R_{\text{cable}} = \frac{6V}{30A} = 0.2 \Omega \]

\[ P_{\text{cable}} = (30A)^2 (0.2) \]

2 pt. each minus 1 for right formula w/ wrong units minus 1 for incorrect math minus 1 for incorrect units
7. What are the DC voltages and currents in the following figure, and how much energy is stored and power dissipated in the inductor \((E_L\) and \(P_L)\), capacitor \((E_C\) and \(P_C)\), and resistor \(R_3\) \((E_3, P_3)\)\)? All resistors are \(1\) k\(\Omega\). The diode has a forward voltage of \(0.4\) V at \(1\) mA.

\[ I_1 \approx 10 \text{ mA} \quad V_i = 0.4 \text{ V} \]

\[ V_2 = 10 \text{ V} \quad V_3 = 0 \text{ V} \]

\[ E_L = \frac{1}{2} L \dot{I}_L^2 = \frac{1}{2} (10^{-2})^2 (10^{-6}) = \frac{1}{2} \times 10^{-10} = 50 \text{ pJ} \]

\[ P_L = (0 \text{ V})(10 \text{ mA}) = 0 \text{ W} \]

\[ E_C = \frac{1}{2} CV^2 = \frac{1}{2} (10^{-6})(10^2) = \frac{1}{2} \times 10^{-4} = 50 \text{ mJ} \]

\[ P_C = (10 \text{ V})(0 \text{ V}) = 0 \text{ W} \]

\[ E_3 = 0 \text{ J} \quad 10^{-2} \]

\[ P_3 = (10 \text{ V})(10 \text{ mA}) = 0.1 \text{ W} \]

\[ I_1 = \frac{10 \text{ V} - 0.46 \text{ V}}{1000 \Omega} = \frac{9.54 \text{ V}}{1000 \Omega} = 9.54 \text{ mA} \]

\[ I_1 = 9.54 \text{ mA} \]

\[ I_1 \text{ can't increase } V_d \text{ anymore} \]

\begin{table}
\begin{tabular}{|c|c|}
\hline
\textbf{V1} & 0.46 \text{ V} \\
\hline
\textbf{V2} & 10 \text{ V} \\
\hline
\textbf{V3} & 0 \text{ V} \\
\hline
\textbf{V4} & 10 \text{ V} \\
\hline
\textbf{I1} & 9.54 \text{ mA} \\
\hline
\textbf{I2} & 0 \text{ mA} \\
\hline
\textbf{I3} & 10 \text{ mA} = 10^{-2} \text{ A} \\
\hline
\textbf{I4} & 0 \text{ mA} \\
\hline
\textbf{E_L} & 50 \text{ pJ} = 0.5 \times 10^{-10} \text{ J} \\
\hline
\textbf{P_L} & 0 \text{ W} \\
\hline
\textbf{E_C} & 50 \text{ mJ} = 0.5 \times 10^{-3} \text{ J} \\
\hline
\textbf{P_C} & 0 \text{ W} \\
\hline
\textbf{P_3} & 0.1 \text{ W} \\
\hline
\end{tabular}
\end{table}
8. In the following switched capacitor circuit, calculate the Thevenin voltage and resistance of the equivalent source charging the capacitor before and after the switch changes position at t=0.

\[ V_x \]
\[ R_1 \]
\[ R_2 \]
\[ R_3 \]
\[ t=0 \]
\[ t>0 \]
\[ V_{\text{th}} \]
\[ R_{\text{th}} \]
\[ V_x \]
\[ V_x = \frac{R_2}{R_1 + R_2} V_x \]
\[ R_{\text{th}} = \frac{R_1 R_2}{R_1 + R_2} \]

9. If the Thevenin voltage and resistance in the circuit above is 10V and 1k\(\Omega\) respectively after t=0, what is the voltage on the capacitor at time t=0, 0.1ms, 1ms, 10ms?

\[ V_c(0) = 0V \]
\[ V_c(0.1ms) = 1V \]
\[ V_c(1ms) = 6xV \]
\[ V_c(10ms) = 10V \]

10. You design a register file in CMOS technology and find that it contains 10,000 gates. Your transistors have an OFF resistance of 10G\(\Omega\), and your gates have an average input capacitance of 10aF. The register file runs from a 1V supply, at 10GHz.

   a. What is the static leakage current and power?

\[ 1\mu A, 1\mu W \]

   b. What is the dynamic power assuming that each gate switches only every ten clock cycles on average?

\[ 10^{-4} = 100\mu W \]

   c. If the voltage drops from 1V to 0.5V, how does that change the static leakage current and power, and the dynamic power. For each, give an answer like “stays the same” or “increases by 10x”

<table>
<thead>
<tr>
<th>Static leakage current</th>
<th>↓ 2x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static leakage power</td>
<td>↓ 4x</td>
</tr>
<tr>
<td>Dynamic power</td>
<td>↓ 4x</td>
</tr>
</tbody>
</table>
11. In the datapath below, the program counter starts at 100. The contents of the instruction memory is given in the table. Initial contents of the registers is R0=10, R1=11, R2=12, R3=13

a. Write the values that appear on the ADDR, A, B, and C buses after the three rising edges below.

<table>
<thead>
<tr>
<th>ADDR</th>
<th>S_a</th>
<th>S_b</th>
<th>S_c</th>
<th>WE</th>
<th>S_ALU</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>1</td>
<td>A+B</td>
</tr>
<tr>
<td>101</td>
<td>2</td>
<td>12</td>
<td>20</td>
<td>1</td>
<td>A-R</td>
</tr>
<tr>
<td>102</td>
<td>3</td>
<td>13</td>
<td>-8</td>
<td>0</td>
<td>A-B</td>
</tr>
</tbody>
</table>

b. You want the instruction at memory location 8 to add the contents of registers 4 and 5 and store the result in register 7. Fill in the corresponding information in the table below.

<table>
<thead>
<tr>
<th>ADDR</th>
<th>S_a</th>
<th>S_b</th>
<th>S_c</th>
<th>WE</th>
<th>S_ALU</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>1</td>
<td>A+B</td>
</tr>
</tbody>
</table>

-1 for arithmetic mistake in calculating A-B or A+B
-0 if S_c (100) = S_b (101) but S_c (100) is wrong
-0 if S_c (101) = S_b (102) but S_c (101) is wrong
-0 if calculate arithmetic correct but one value is wrong only take off for wrong value not wrong arithmetic
12. You are designing a voice control system for a car. You have a microphone connected to an amplifier and an ADC that samples at 20kHz. You will add a filter in part f, as shown below.

Your software team is working with the frequencies from 100Hz to 5kHz. There is a noise source in the car at approximately 100kHz.

a. What is the Nyquist frequency of the ADC?

b. If the noise source has an amplitude of 100mV and a frequency of exactly 100kHz, what is the frequency and worst-case amplitude that the software will see at the output of the ADC?

\[ f_{\text{freq}} = 10 \text{kHz}, \quad \text{amplitude} = 100 \text{mV} \]

c. If the noise source has an amplitude of 100mV and a frequency of exactly 101kHz, what is the frequency and amplitude that the software will see at the output of the ADC?

\[ f_{\text{freq}} = 10 \text{kHz}, \quad \text{amplitude} = 100 \text{mV} \]

d. You decide to put an RC low-pass filter between the amplifier and the ADC. If you want to reduce the amplitude of the 100kHz signal by 10x, what pole frequency should you choose for the filter?

\[ f_{\text{pole}} = 1 \text{kHz} \]

e. Your boss tells you to put the filter pole at 5kHz, and to use a 1kΩ resistor. What size capacitor should you pick?

\[ f = \frac{1}{2\pi R C} \]

\[ C = \frac{2\pi}{f R} = \frac{2\pi}{5 \times 10^3 \times 10^3} = 25 \text{ mF} \]

f. Sketch your filter in the dashed box in the figure above.

g. Assuming that the filter pole is at 5kHz, and the output of the amplifier is \( V_{\text{amp}}(t) = 0.5V \sin(2\pi 100t) + 2V \sin(2\pi 5000t) + 100mV \sin(2\pi 100,000t) \), what is the output of the filter?

\[ 0.5V \sin(2\pi 100t + 0) + \frac{2}{V} \sin(2\pi 5000t - 45^\circ) + \frac{100mV}{20} \sin(2\pi 100,000t - 90^\circ) \]
13. The amplifier in the microphone circuit above needs to take an audio signal with a 1mV amplitude and generate an output with a 100mV amplitude.
   a. What is the magnitude of gain of the amplifier?
      \[ A_V = \frac{V_{out}}{V_{in}} = \frac{100\text{mV}}{1\text{mV}} = 100 \]
      
   b. If you need this to be a negative gain amplifier, sketch the op-amp circuit that you would use, and specify resistor values to achieve the desired gain.
   
   c. If you need this to be a positive gain amplifier, sketch the op-amp circuit that you would use, and specify resistor values to achieve the desired gain.
   
   d. If the output of a different microphone appears as a voltage difference between two output wires, and you need to amplify that difference by the same gain as above, sketch the op-amp circuit that you would use, and specify resistor values to achieve the desired gain.
14. If the Finite State Machine below starts in state 000, what are the next 4 states?

![Finite State Machine Diagram]

(4 pt)

1. One point each row is deducted, or two pts each column if they mess up the logic.

15. Given the following State Transition Diagram, fill in the truth table for the Output Function and the State Transition Function.

![State Transition Diagram]

<table>
<thead>
<tr>
<th>State</th>
<th>Q1</th>
<th>Q0</th>
<th>TT</th>
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<tbody>
<tr>
<td>Fred</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sue</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Bob</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ann</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Q1</th>
<th>Q0</th>
<th>P</th>
<th>Q</th>
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<tbody>
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<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

2/pt

8 pt

All or nothing if do it redundantly lose 1 pts.

2/pt

0.5 pt per row round up.

if they use meta expression and use it correct "x", just subtract 1 pt.

2/pt

if ( ) + we use state name - 2pt total.
16. You are building the FSM controller for a thermostat. The temperature sensor has two outputs, Low Threshold, LT, and High Threshold, HT. The heater has an input called FIRE. When the temperature falls below the Low Threshold (LT=0), the FSM should move to state HEAT, turn on the FIRE, and remain in state HEAT until the temperature goes above the High Threshold (HT=1). When the temperature goes above High Threshold, the FSM should move to state OFF.
   a. List the states, inputs, and outputs of your FSM.

   States: HEAT, OFF
   Inputs: LT, HT
   Outputs: FIRE

   b. Draw the state transition diagram.

17. Given a temperature sensor with an output of \( V_{\text{temp}}(T) = (10mV/C) \cdot T \), design an op-amp circuit to generate the HT and LT signals.

If they only draw on Ckt, the other.
You have two thresholds.

18. You have two ideal diodes of different sizes, which obey the expression \( I_D = I_S e^{VD/Vt} \) where \( V_D = kT/q \) and \( T \) is the absolute temperature in Kelvin. If you forward bias each diode with a constant current \( I_1 \) for one diode, and \( I_2 = 10I_1 \) for the other, calculate the voltage on each diode, and the voltage difference between the two diodes, \( V_{D2} - V_{D1} \). The voltage difference should be proportional to absolute temperature (PTAT). Simplify!

\[
\begin{align*}
I_1 &= I_S e^{V_{D1}/Vt} \\
10I_1 &= I_S e^{V_{D2}/Vt}
\end{align*}
\]

This is also okay.

\[
I_0 = \frac{I_S e^{V_{D2}/Vt}}{I_S} = \log \left( \frac{V_{D2}}{V_{D1}} \right)
\]

\[
V_{D2} - V_{D1} = V_{Th} \log \left( \frac{I_S e^{V_{D2}/Vt}}{I_S e^{V_{D1}/Vt}} \right) = \frac{kT}{q} \left( \log I_0 + \log \frac{I_S}{I_S} \right) = \frac{kT}{q} \log I_0
\]
19. Design the following figure down to NMOS and PMOS transistors. All wires carry single-bit quantities (they aren’t buses). The 3-LUTs and two MUXes are programmable – make sure that you show the programmability. (image from Wikipedia)

Design the 3-LUTs (programmable function of 3 variables) using DFF and MUXes. Design the MUXes, FA (full adder) and DFF using gates. Design the gates using transistors. Finally, sketch how the 3-LUTs and two programmable MUXes are wired up with $P_{\text{in}}$, $P_{\text{out}}$, and $P_{\text{CLK}}$.

This area is scratch and will not be graded. Put your answers on the following page.
3-LUT:
- 1 pt. for realizing it was an 8-1 MUX
- 1 pt. for showing how to make 8-1 MUX
- 1 pt. for attaching shift register below MUX
- 1 pt. for showing shift register implementation with DFFs

DFF:
- 2 points for having clocks in the right places
  - 1/2 pt. for each clock (rounded up)
- 2 points for general FF structure
  - (3/4 for drawing level-sensitive latch diagram without showing implementation)

FA:
1 pt. for correct input/output shown (A, B, C, Cout, S)
2 pts. for correct implementation
(1 pt. for getting close)

MUX:
- 1 pt. general 2-1 MUX structure
- 1 pt. for correct implementation

Gates:
- 1 pt. for using 1/2 adder without showing implementation
- 1 pt. for using 1/2 adder without showing implementation

Programming:
- 1 pt. for showing the effect of:

- 1 pt. for not or incorrectly implementing other gates you used