1. (30 points) Microcontroller MSP430 is using 32KHz crystal connected to LFXT1 Oscillator, 8MHz crystal connected to XT2 Oscillator, and 3V power supply. See Appendix (pages 5-9) for necessary information.

Datasheet specifications:
\[ \frac{f_{\text{Rsel}+1}}{f_{\text{Rsel}}} = 1.65, \quad \frac{f_{\text{DCO}+1}}{f_{\text{DCO}}} = 1.12, \quad \text{DCOR: use internal } R_{\text{osc}} \]

Set the following modes of operation (If the bit can be either 0 or 1, put X):

(a) (5 points) processor clock (MCLK) to 8MHz, ACLK to 8KHz, SMCLK to 750 KHz.

<table>
<thead>
<tr>
<th>BCSCTL1: 0x____</th>
<th>XT2Off</th>
<th>XTS</th>
<th>DIVA.1</th>
<th>DIVA.0</th>
<th>XT5V</th>
<th>Rsel2</th>
<th>Rsel1</th>
<th>Rsel0</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCSCTL2: 0x____</td>
<td>SELM.1</td>
<td>SELM.0</td>
<td>DIVM.1</td>
<td>DIVM.0</td>
<td>SELS</td>
<td>DIVS.1</td>
<td>DIVS.0</td>
<td>DCOR</td>
</tr>
<tr>
<td>DCOCTL: 0x____</td>
<td>DCO.2</td>
<td>DCO.1</td>
<td>DCO.0</td>
<td>MOD.4</td>
<td>MOD.3</td>
<td>MOD.2</td>
<td>MOD.1</td>
<td>MOD.0</td>
</tr>
</tbody>
</table>

(b) (5 points) processor clock to 840KHz, SMCLK to 420KHz, and ACLK to 32KHz.

<table>
<thead>
<tr>
<th>BCSCTL1: 0x____</th>
<th>XT2Off</th>
<th>XTS</th>
<th>DIVA.1</th>
<th>DIVA.0</th>
<th>XT5V</th>
<th>Rsel2</th>
<th>Rsel1</th>
<th>Rsel0</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCSCTL2: 0x____</td>
<td>SELM.1</td>
<td>SELM.0</td>
<td>DIVM.1</td>
<td>DIVM.0</td>
<td>SELS</td>
<td>DIVS.1</td>
<td>DIVS.0</td>
<td>DCOR</td>
</tr>
<tr>
<td>DCOCTL: 0x____</td>
<td>DCO.2</td>
<td>DCO.1</td>
<td>DCO.0</td>
<td>MOD.4</td>
<td>MOD.3</td>
<td>MOD.2</td>
<td>MOD.1</td>
<td>MOD.0</td>
</tr>
</tbody>
</table>
(c) (5 points) processor clock to 2MHz, ACLK to 32 KHz, SMCLK to 1MHz.

BCSCTL1: 0x_____

XT2Off XTS DIVA.1 DIVA.0 XT5V Rsel2 Rsel1 Rsel0

BCSCTL2: 0x_____

SELM.1 SELM.0 DIVM.1 DIVM.0 SELS DIVS.1 DIVS.0 DCOR

DCOCTL: 0x_____

DCO.2 DCO.1 DCO.0 MOD.4 MOD.3 MOD.2 MOD.1 MOD.0

(d) (5 points) processor clock and SMCLK to 787 KHz and ACLK to 32KHz.

BCSCTL1: 0x_____

XT2Off XTS DIVA.1 DIVA.0 XT5V Rsel2 Rsel1 Rsel0

BCSCTL2: 0x_____

SELM.1 SELM.0 DIVM.1 DIVM.0 SELS DIVS.1 DIVS.0 DCOR

DCOCTL: 0x_____

DCO.2 DCO.1 DCO.0 MOD.4 MOD.3 MOD.2 MOD.1 MOD.0

(e) (10 points) What should be the value of MOD if MCLK needs to be set to 1.5MHz for the system that doesn't use external oscillators (uses only DCO)? Give values for Rsel, DCO, and MOD. Show how you came up with the result. [Hint: use the formula T=((32-MOD)*T_{DCO} + MOD*T_{DCO+1})/32]
2. (30 points)
(a) (15 points) Write a C program that will output buffed clock signals MCLK, SMCLK, and ACLK to MSP430 port pins. Assume that clock inputs are as follows: ACLK = LFXT1 = 32768, MCLK = DCO Max, SMCLK = XT2. After initialization the main program should stay in an idle loop.

(b) (15 points) Write a C program that will toggle P2.1 using timed WDT interrupt service routine. Assume clock and connection as in EasyWeb2 development board. After the initialization the CPU should stay in LPM0 operating mode. Explain what happens when the MSP430 enters low-power mode.
3. (20 points) Your microcontroller system consist of an MSP430 microcontroller operating at 1MHz and an LCD display. System has following electrical characteristics:

<table>
<thead>
<tr>
<th></th>
<th>3 V</th>
<th>2.2 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcontroller active mode current</td>
<td>$I_{AM,3V} = 500 , \mu A$</td>
<td>$I_{AM,2.2V} = 300 , \mu A$</td>
</tr>
<tr>
<td>Microcontroller idle mode current</td>
<td>$I_{IM,3V} = 2 , \mu A$</td>
<td>$I_{IM,2.2V} = 1 , \mu A$</td>
</tr>
<tr>
<td>LCD display current</td>
<td>$I_{LCD,3V} = 20 \mu A$</td>
<td>$I_{LCD,2.2V} = 14 , \mu A$</td>
</tr>
</tbody>
</table>

Application running on your system is written so that microcontroller is active 20% of the cycle (on average). LCD is always active.

(a) (10 points) What is the expected system operation time for the basic system running at 3V, supplied from a battery pack with 720 mAh capacity?

(b) (10 points) You have two options for improvement:

- Change the system design, so that it can run at 2.2V, 720mAh battery pack.
- Improve the application, so that the microcontroller is active only 10% of the cycle (on average). Power supply is provided by a 3V battery pack with 720mAh capacity.

Which of these two options will give you longer operation time (battery life)? What is the difference (in hours) between these two improved version’s operating times and the basic system operation time?
4. **(20 points)** Microcontroller MSP430 operates with system frequency of 100 Hz (repeat the following sequence: a/d conversion, process data, real-time clock, idle). What is the expected system operation time if the system is supplied with 720mAh capacity battery? Power consumption of different components is:

- Analog interface circuit 2 mA, cycle operation time - 100 µs.
- Microcontroller in active mode 400 µA, cycle processing time:
  - 40 µs with probability 20%
  - 80 µs with probability 50%
  - 120 µs with probability 30%
- Microcontroller in idle mode 1.6 µA.
- Real Time Clock 350 µA, cycle operation time - 100 µs.
- LCD display 20 µA, always active.
Appendix

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>TEST CONDITIONS</th>
<th>MIN</th>
<th>NOM</th>
<th>MAX</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rsel = 0, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C</td>
<td>V_OC = 2.2 V</td>
<td>0.09</td>
<td>0.12</td>
<td>0.15</td>
<td>MHz</td>
</tr>
<tr>
<td>Rsel = 1, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C</td>
<td>V_OC = 2.2 V</td>
<td>0.14</td>
<td>0.19</td>
<td>0.23</td>
<td>MHz</td>
</tr>
<tr>
<td>Rsel = 2, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C</td>
<td>V_OC = 2.2 V</td>
<td>0.22</td>
<td>0.30</td>
<td>0.36</td>
<td>MHz</td>
</tr>
<tr>
<td>Rsel = 3, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C</td>
<td>V_OC = 2.2 V</td>
<td>0.37</td>
<td>0.49</td>
<td>0.59</td>
<td>MHz</td>
</tr>
<tr>
<td>Rsel = 4, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C</td>
<td>V_OC = 2.2 V</td>
<td>0.61</td>
<td>0.77</td>
<td>0.93</td>
<td>MHz</td>
</tr>
<tr>
<td>Rsel = 5, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C</td>
<td>V_OC = 2.2 V</td>
<td>1.2</td>
<td>1.5</td>
<td>1.5</td>
<td>MHz</td>
</tr>
<tr>
<td>Rsel = 6, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C</td>
<td>V_OC = 2.2 V</td>
<td>1.6</td>
<td>1.9</td>
<td>2.2</td>
<td>MHz</td>
</tr>
<tr>
<td>Rsel = 7, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C</td>
<td>V_OC = 2.2 V</td>
<td>2.4</td>
<td>2.0</td>
<td>3.4</td>
<td>MHz</td>
</tr>
<tr>
<td>Rsel = 8, DCO = 3, MOD = 0, DCOR = 0, T_A = 25°C</td>
<td>V_OC = 2.2 V</td>
<td>2.7</td>
<td>3.2</td>
<td>3.5</td>
<td>MHz</td>
</tr>
<tr>
<td>Rsel = 4, DCO = 7, MOD = 0, DCOR = 0, T_A = 25°C</td>
<td>V_OC = 2.2 V</td>
<td>1.35</td>
<td>1.05</td>
<td>2</td>
<td>MHz</td>
</tr>
<tr>
<td>Rsel = 5, DCO = 7, MOD = 0, DCOR = 0, T_A = 25°C</td>
<td>V_OC = 2.2 V</td>
<td>1.07</td>
<td>1.12</td>
<td>1.16</td>
<td>MHz</td>
</tr>
</tbody>
</table>

Temperature drift, Rsel = 4, DCO = 3, MOD = 0

Drift with V_OC variation, Rsel = 4, DCO = 3, MOD = 0

The DCO generator is connected to pin P2.5Rosc if DCOR control bit is set. The port pin P2.5Rosc is selected if DCOR control bit is reset (initial state).
7.5 Basic Clock Module Control Registers

The Basic Clock Module is configured using control registers DCOCTL, BCSCCTL1, and BCSCCTL2, and four bits from the CPU status register: SCG1, SCG0, OsCOff, and CPUOFF. User software can modify these control registers from their default condition at any time. The Basic Clock Module control registers are located in the byte-wide peripheral map and should be accessed with byte (.B) instructions.

<table>
<thead>
<tr>
<th>Register</th>
<th>Short Form</th>
<th>Register Type</th>
<th>Address</th>
<th>Initial State</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCO control register</td>
<td>DCOCTL</td>
<td>Read/write</td>
<td>056h</td>
<td>060h</td>
</tr>
<tr>
<td>Basic clock system control 1</td>
<td>BCSCCTL1</td>
<td>Read/write</td>
<td>057h</td>
<td>094h</td>
</tr>
<tr>
<td>Basic clock system control 1</td>
<td>BCSCCTL2</td>
<td>Read/write</td>
<td>059h</td>
<td>reset</td>
</tr>
</tbody>
</table>

7.5.1 Digitally-Controlled Oscillator (DCO) Clock-Frequency Control

DCOCTL is loaded with a value of 056h with a valid PUC condition.

\[
\begin{array}{cccccccc}
  & 7 & 6 & 5 & 4 & 3 & 2 & 1 & 0 \\
\hline
DCOCTL 056h & DCO.2 & DCO.1 & DCO.0 & MOD.4 & MOD.3 & MOD.2 & MOD.1 & MOD.0 \\
  \hline
  \text{rw} -0 & \text{rw} -1 & \text{rw} -1 & \text{rw} -0 & \text{rw} -0 & \text{rw} -0 & \text{rw} -0 & \text{rw} -0 & \text{rw} -0 \\
\end{array}
\]

MOD.0 .. MOD.4: The MOD constant defines how often the discrete frequency \( f_{DCO+1} \) is used within a period of 32 DCOCLK cycles. During the remaining clock cycles (32−MOD) the discrete frequency \( f_{DCO} \) is used. When the DCO constant is set to seven, no modulation is possible since the highest feasible frequency has then been selected.

DCO.0 .. DCO.2: The DCO constant defines which one of the eight discrete frequencies is selected. The frequency is defined by the current injected into the dco generator.
7.5.2 Oscillator and Clock Control Register

BCSCTL1 is affected by a valid PUC or POR condition.

<table>
<thead>
<tr>
<th>Bit</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>XT2Off</td>
</tr>
<tr>
<td>1</td>
<td>XT5V</td>
</tr>
<tr>
<td>2</td>
<td>DIVA.1</td>
</tr>
<tr>
<td>3</td>
<td>DIVA.0</td>
</tr>
<tr>
<td>4</td>
<td>XT5V</td>
</tr>
<tr>
<td>5</td>
<td>Rsel.2</td>
</tr>
<tr>
<td>6</td>
<td>Rsel.1</td>
</tr>
<tr>
<td>7</td>
<td>Rsel.0</td>
</tr>
</tbody>
</table>

Bit0 to Bit2: The internal resistor is selected in eight different steps.
Rsel.0 to Rsel.2: The value of the resistor defines the nominal frequency.
The lowest nominal frequency is selected by setting Rsel=0.

Bit3, XT5V: XT5V should always be reset.

Bit4 to Bit5: The selected source for ACLK is divided by:
- DIVA = 0: 1
- DIVA = 1: 2
- DIVA = 2: 4
- DIVA = 3: 8

Bit6, XT5: The LFXT1 oscillator operates with a low-frequency clock crystal or with a high-frequency crystal:
- XT5 = 0: The low-frequency oscillator is selected.
- XT5 = 1: The high-frequency oscillator is selected.

The oscillator selection must meet the external crystal’s operating condition.

Bit7, XT2Off: The XT2 oscillator is switched on or off:
- XT2Off = 0: The oscillator is on
- XT2Off = 1: The oscillator is off if it is not used for MCLK or SMCLK.

BCSCTL2 is affected by a valid PUC or POR condition.
Bit0, DOR: The DOR bit selects the resistor for injecting current into the dc generator. Based on this current, the oscillator operates if activated.
  DOR = 0: Internal resistor on, the oscillator can operate. The failsafe mode is on.
  DOR = 1: Internal resistor off, the current must be injected externally if the DCO output drives any clock using the DCOCLK.

Bit1, Bit2: The selected source for SMCLK is divided by:

- DIVS = 0: 1
- DIVS = 1: 2
- DIVS = 2: 4
- DIVS = 3: 8

Bit3, SELS: Selects the source for generating SMCLK:
- SELS = 0: Use the DCOCLK
- SELS = 1: Use the XT2CLK signal (in three-oscillator systems) or LFXT1CLK signal (in two-oscillator systems)

Bit4, Bit5: The selected source for MCLK is divided by:

- DIVM = 0: 1
- DIVM = 1: 2
- DIVM = 2: 4
- DIVM = 3: 8

Bit6, Bit7: Selects the source for generating MCLK:
- SELM = 0: Use the DCOCLK
- SELM = 1: Use the XT2CLK (x13x and x14x devices) or LFXT1CLK (x11xx and x12xx devices)
- SELM = 3: Use the LFXT1CLK