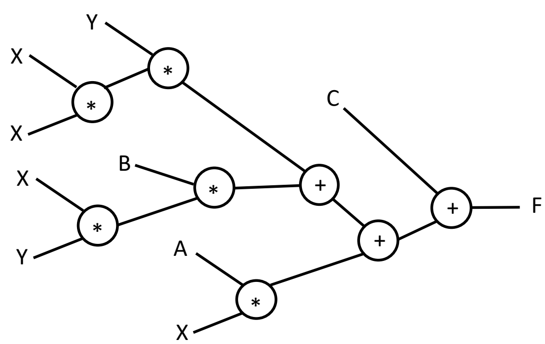
Problem 1. Tree Height Reduction (15 points)

One implementation for an arithmetic expression is shown below, using 2-input adder and multiplier modules.



(a) Write an equation for this expression which takes the least number of cycles.

XYB + XXY + XA + C
XY(X+B) + XA + C
3 cycle implementation

(b) If the energy required to perform an addition is E, and that required for a multiplication is 4E, what is the energy required for:

(i) the original implementation

23E

(ii) your implementation in (a)?

15E

(c) Write an equation that requires the minimum energy for the computation of the original expression, and which takes no more time than the original implementation.

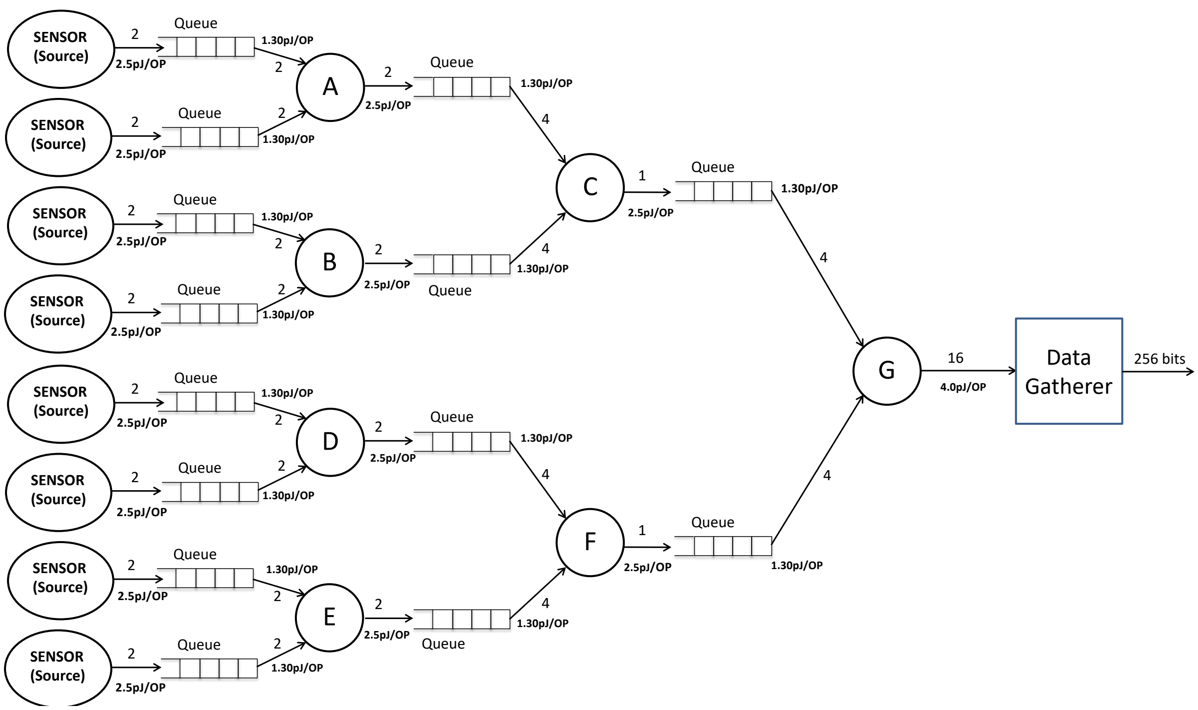
X(Y(X+B) + A) + C
5 cycles
11E

Problem 2. SDF Power Analysis (35 points)

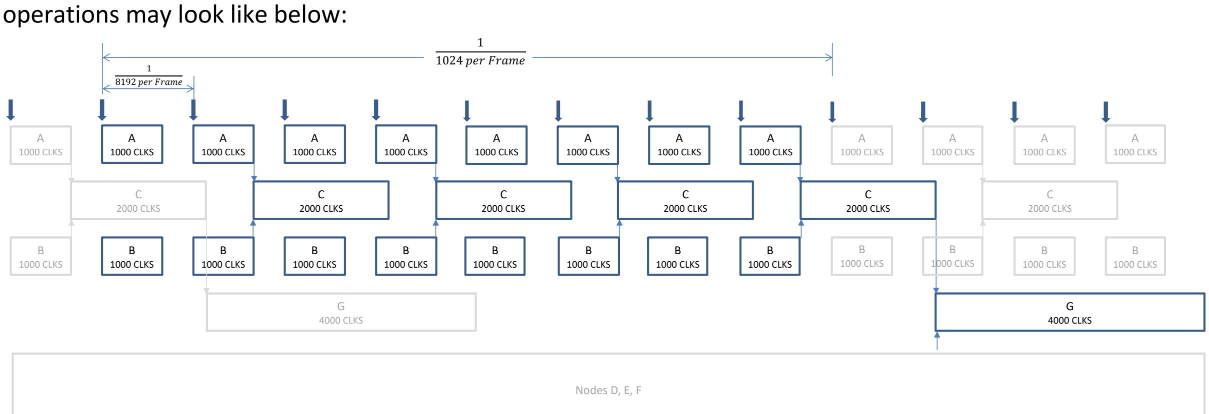
The following circuit executes a spectral imaging sensor fusing algorithm. There are eight sensors and seven SDF processing elements. Each sensor produces two new tokens 8192 times per frame. Each token is two-bytes wide. Node-G produce 16 tokens each operation.

Energy consumption:

- A single write operation to a queue consumes: 2.50 pJ/Op
- A single read operation from a queue consumes: 1.30 pJ/Op
- Sensor evaluation: 45.0 pJ/Op
- Nodes A, B, D, E each consume: 2.0 pJ/clock and require 1000 clocks to complete the “Firing”
- Nodes C, F each consume 3.0 pJ/clock and require 2000 clocks to complete the “Firing”
- Node G consumes 4.0 pJ/clock and require 4000 clocks to complete the “Firing”
- A single token-write to the Data Gathering Unit consumes 4.0 pJ/Op
- A single 256-bit write from the Data Gathering Unit to the Dual-Port memory 2.56nJ



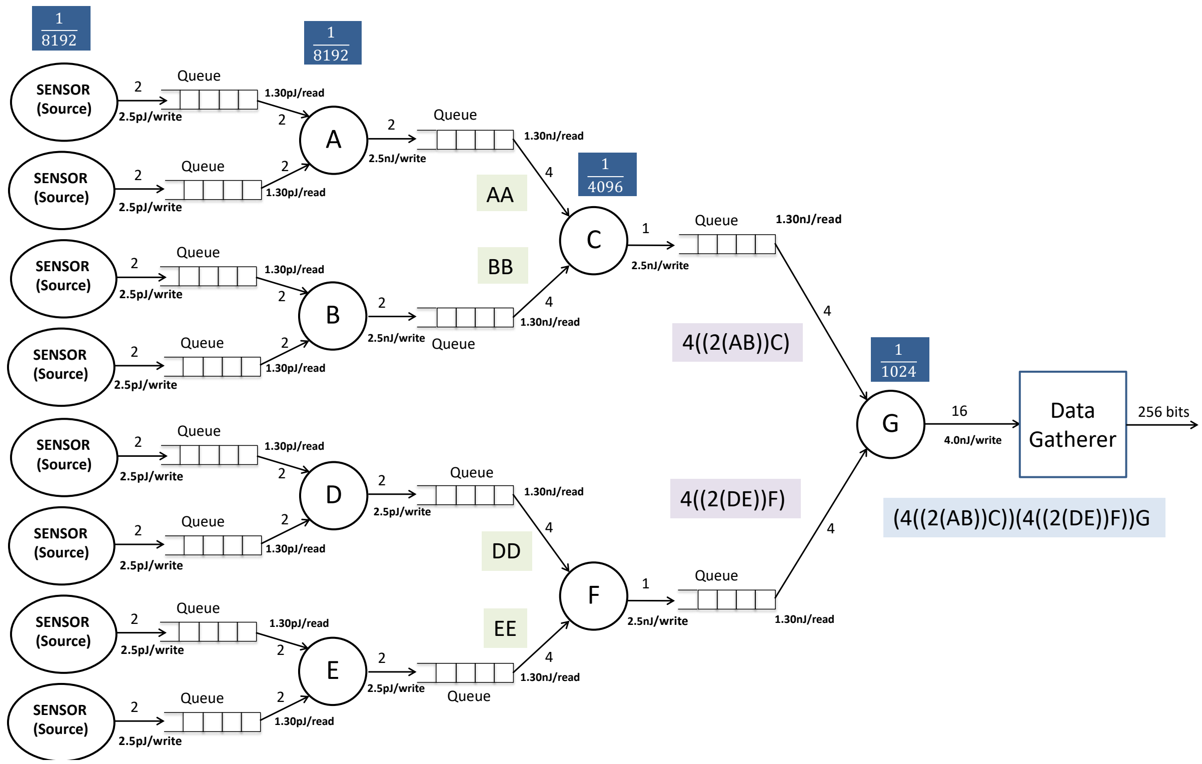
The display image is 128 x 128 16-bit pixels. The display rate is 20 frames/second. A typical schedule of operations may look like below:



Note: only nodes A, B, C & G are shown, D, E, & F are mirror images of A, B & C

QUESTIONS:

a) What is the periodic schedule for Node-G ?



(4((2(AB))C))(4((2(DE))F))G

b) How many bytes of data are generated each frame by Node-G?

Node-G fires 1024 times per frame ∴ 1024 * 32 bytes = 32768 bytes/frame

Recall display frame size: 128 pixels x 128 pixels x 2 bytes/pixel = 32768 bytes

c) Calculate the amount of energy consumed per frame? Use the back of this sheet to show your work.

Sensor (one OP per 2 tokens)			
OP	1	45	45.00
Writes	2	2.5	5.00
		SUM	50.00

One NODE A Firing			
OP	1	2000	2000.00
Reads	4	1.3	5.20
Write	2	2.5	5.00
			2010.20

One NODE B Firing			
OP	1	2000	2000.00
Reads	4	1.3	5.20
Write	2	2.5	5.00
			2010.20

One NODE D Firing			
OP	1	2000	2000.00
Reads	4	1.3	5.20
Write	2	2.5	5.00
			2010.20

One NODE E Firing			
OP	1	2000	2000
Reads	4	1.3	5.2
Write (sir	2	2.5	5
			2010.2

One NODE C Firing			
OP	1	6000	6000.00
Reads	8	1.3	10.40
Write	1	2.5	2.50
			6012.90

One NODE F Firing			
OP	1	6000	6000.00
Reads	8	1.3	10.40
Write	1	2.5	2.50
			6012.90

One NODE G Firing			
OP	1	16000	16000.00
Reads	8	1.3	10.40
Write	16	2.5	40.00
			16050.40

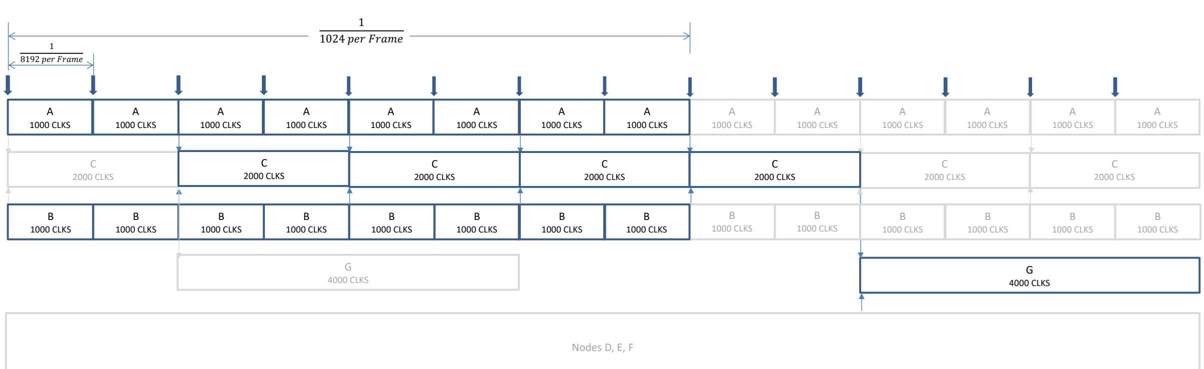
	Number of Firings	Energy per firing	Total Energy (pJ)
Sensor	8192	50.00	409600.00
Node A	8192	2010.20	16467558.40
Node B	8192	2010.20	16467558.40
Node D	8192	2010.20	16467558.40
Node E	8192	2010.20	16467558.40
Node C	4096	6012.90	24628838.40
Node F	4096	6012.90	24628838.40
Node G	1024	16050.40	16435609.60
Writes to DP Memory	1024	2500	2560000.00
			134533120.00

	# CLKS	pJ/CLK	Total Energy
Node A	1000	2	2000
Node B	1000	2	2000
Node D	1000	2	2000
Node E	1000	2	2000
Node C	2000	3	6000
Node F	2000	3	6000
Node G	4000	4	16000

d) What is the slowest frequency that the SDF can run at without impacting the results of the calculations?

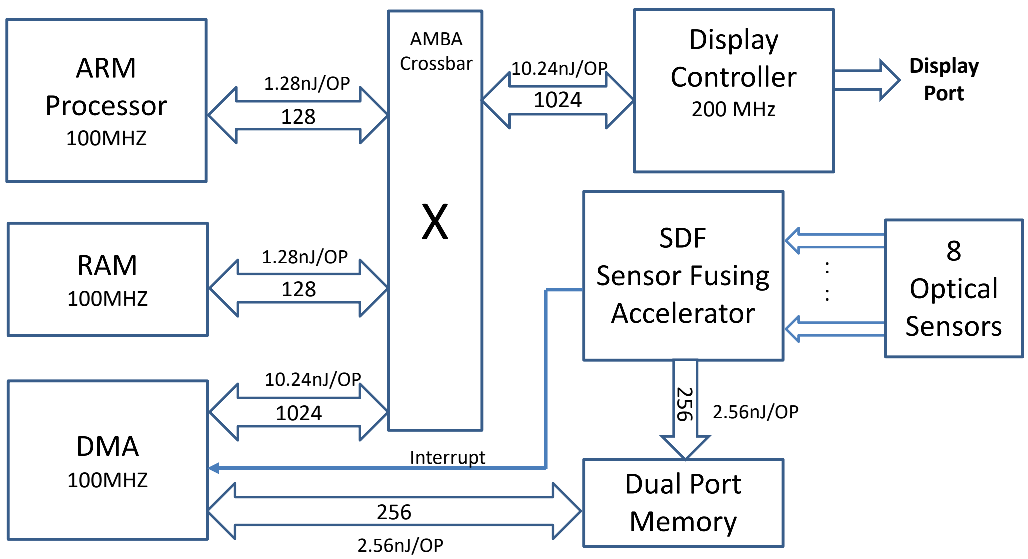
8000 clocks x 1024 firings x 20 frames = 163.840 MHz

e) Draw the schedule of operations for the slowest frequency that the SDF can run at.



Problem 3. System Power Analysis (50 Points)

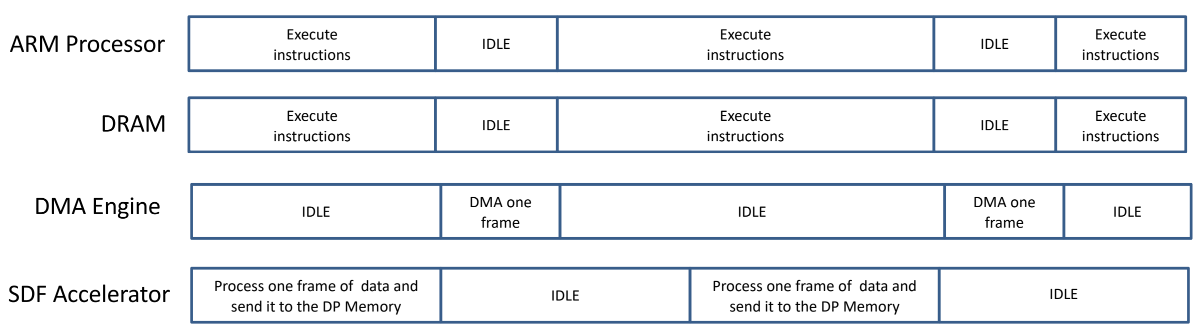
This problem determines the energy of the system topology below. All transactions will be specified in Joules/OP or Joules/clk. Your task is to determine amount of energy consumed by the system and determine how long a 2550 ma-Hour battery will last.



Basic operation

The SDF Sensor Fusing Accelerator (from question #2) produces frame data for the Display Controller by fusing data from 8 optical sensors. When the fusing is complete for each frame, an interrupt is generated to the DMA Unit. The frame data is buffered in a dual-port memory. The DMA transfers the frame data to the Display Controller at a frame rate that is determined by the SDF Sensor Fusing Accelerator.

A rudimentary timing schedule is shown below:



(Not to scale ☺)

As noted above this schedule needs to be analyzed to determine if it can execute correctly. Note the Display Controller timing schedule is missing.

ARM Processor

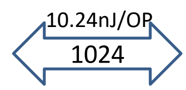
The ARM processor executes 1 IPC and runs at 100MHz. All instructions are 4-bytes wide. The processor executes all instructions from RAM. Memory. The ARM processor stalls when the DMA unit is active. The processor consumes 40pJ/clk when it is not stalled. It consumes 10pJ/clk when it is stalled.

Processor RAM

The processor RAM runs at 100MHz and consumes 10pJ/clk when it is active and 1pJ/clk when it is inactive.

AMBA Crossbar

The AMBA Crossbar Bus transfers data at the same clock speed as the processor. The AMBA Crossbar Bus can transfer data widths of 32, 128, 256, 512 & 1024. All transactions on the AMBA Crossbar Bus consumes an average of 0.01nJ/bit. This energy consumption covers all energy used in the crossbar itself and the interconnect to the components attached to the AMBA Bus. The energy values are shown next to bus symbol as shown on the right:



DMA Engine

The DMA Engine runs at 100MHz and is like the one we have used in the labs this semester. It reads four 256-bit wide values from the DP Memory and then writes a 1024-bit wide value to the Display Controller. There is a startup arbitration phase which requires 20 clocks to arbitrate for the AMBA bus at the beginning of the frame data transfer. Each transaction requires 10 clocks: 4 clocks to read the data from the DP Memory, 2 clocks to gather the four 256-bit words into a single 1024-bit word, and another 2 clocks to write the data to the Display Controller. The DMA unit consumes 2.5pJ/clk when it is active and 1pJ/clk when it is inactive

Dual-Port Memory

The Dual-Port memory runs continuously at 100MHz and consumes 10pJ/clk.

Display Controller

The Display Controller runs continuously at 200MHz and consumes 20pJ/clk.

Energy Consumption Details

Component	Energy/clk (Active)	Energy/clk (Inactive)
ARM Processor (100 MHz)	40pJ/clk	10pJ/clk
Processor RAM (100MHz)	10pJ/clk	1pJ/clk
DMA Engine (100 MHz)	2.5pJ/clk	1pJ/clk
Display Controller (200 MHz)	20pJ/clk	2pJ/clk
Dual Ported Memory (100 MHZ)	10pJ/clk	1pJ/clk

Note: The energy/OP for the SDF Sensor Fusing Accelerator is determined in Problem #2.

Questions:

a) How many bytes of data are sent to the Display Controller per second?

20 Frames/second

1024 * 32 bytes = 32768 bytes/frame (128 x 128 x 2 = 32768)

32768 * 20 = 655,360 bytes per second

b) How many clocks are required for the DMA Unit to send a frame to the Display Controller?

20 Clocks for Arbitration

10 Clocks per DMA Transaction

Each DMA Transaction sends 128 bytes

32768 bytes per frame requires 256 DMA Transactions

Total number of 100 MHZ clocks = 20 + 10 * 256 = 2580 clocks (25.8 uSecs)

c) How many instructions can the ARM processor execute each frame?

20 Frames/second

100 MHz/20 frames = 5e+6 clocks/frame

DMA takes 2580 clocks; ARM processor can execute 5e+6 – 2580 = 4.99742e+6 instructions

d) How much energy is required to do a move a frame of data from the DP Memory to the Display Controller? This includes only the AMBA Crossbar read and write cycles. The DP Memory and the Display Controller will be calculated separately.

Display is 128 x 128 = 16,384 pixels at 2 bytes/pixel = 32768 bytes /frame

Each DMA transfer sends 128 bytes (1024 bits) to the Display Controller. This will require 32768/128 = 256 transfers

Each transfer: 4 reads of the DP-Memory @ 2.56nJ/read = 10.24nJ
1 write to the Display Controller @ 10.24nJ/write = 10.24nJ
1 write to the AMBA Crossbar @ 10.24nJ/write = 10.24nJ

Energy per frame = 256 x 30.72nJ = 5,242nJ = 7.864uJ

e) How much energy does the ARM processor consume per frame?

The ARM executes 4.99742e+6 clocks @ 40pJ/clk = 199.896uJ
2580 clocks at 10pJ/clk = 25.800nJ
Total = 199.922uJ

f) How much energy does the Processor RAM consume per frame?

The RAM executes 4.99742e+6 clocks @ 10pJ/clk = 49.974uJ
2580 clocks at 1pJ/clk = 2.580nJ
Total = 49.976uJ

g) How much energy does it take to fetch instructions from the Processor RAM?

The ARM processor fetches four 32-bit instructions per AMBA bus cycle
So, there are 4.99742e+6/4 = 1.249355e+6 128-bit instruction fetches to the RAM.

ARM <-> Crossbar: 1.249355e+6 * 1.28nJ = 1599uJ
Crossbar <-> RAM: 1.249355e+6 * 1.28nJ = 1599uJ
Total = 3198uJ

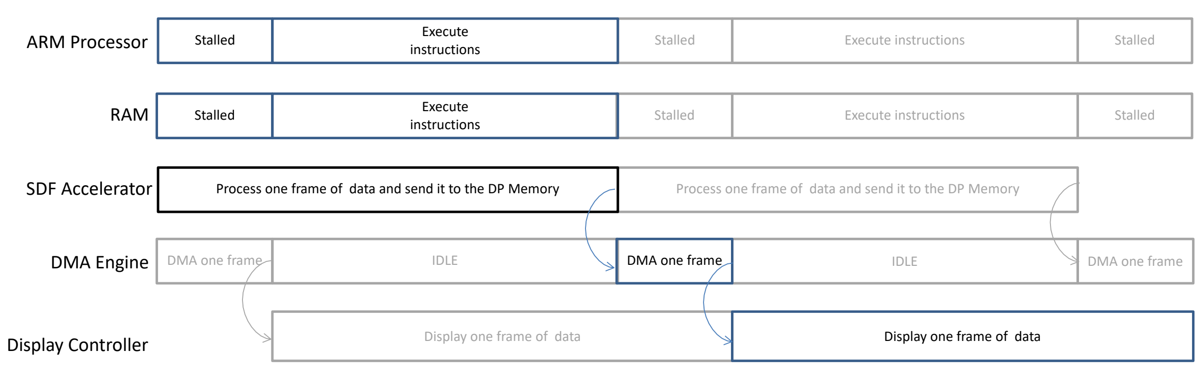
h) How much energy does the Display Controller consume per frame?

There are 10e+6 clocks per frame for the Display Controller @ 20pJ/clk = 200uJ

i) How much energy does the Dual-Ported Memory consume per frame?

There are 5e+6 clocks per frame for the Dual-Ported Memory @ 10pJ/clk = 50uJ

j) Draw the optimal timing schedule.



k) You are given a NiMH battery (1.2V) with 2550 mA-hour capacity which translates to 127.5 ma for 20 hours. NOTE: 3600 Joule = 1 WATT-HOUR. How long will the battery provide energy for this system?

Total energy consumed per frame = 3840.31 uJ

	u-J
DMA AMBA Bus Enegry	7.90
ARM AMBA Bus Energy	3198.00
ARM Processor	199.90
Processor RAM	49.97
Display Contoller	200.00
Dual-Port Memory	50.00
SDF	134.54
	3840.31

The NiMH battery can provide 1.2V x 2.55A-Hour x 3600 = 11,016 Joules

Total number of frames that can be displayed are: 11,016 / 3840.31e-6 = 2.8668e+6 frames

At 20 frames per second, we get 2.868e+6/20 = 143,425 seconds which is ~39.84 hours