Question 1

As per https://ark.intel.com/content/www/us/en/ark/products/191045/intel-core-i79750h-processor-12m-cache-up-to-4-50-ghz.html and https://www.cpu-monkey.com/en/cpu-intel_core_i7_9750h

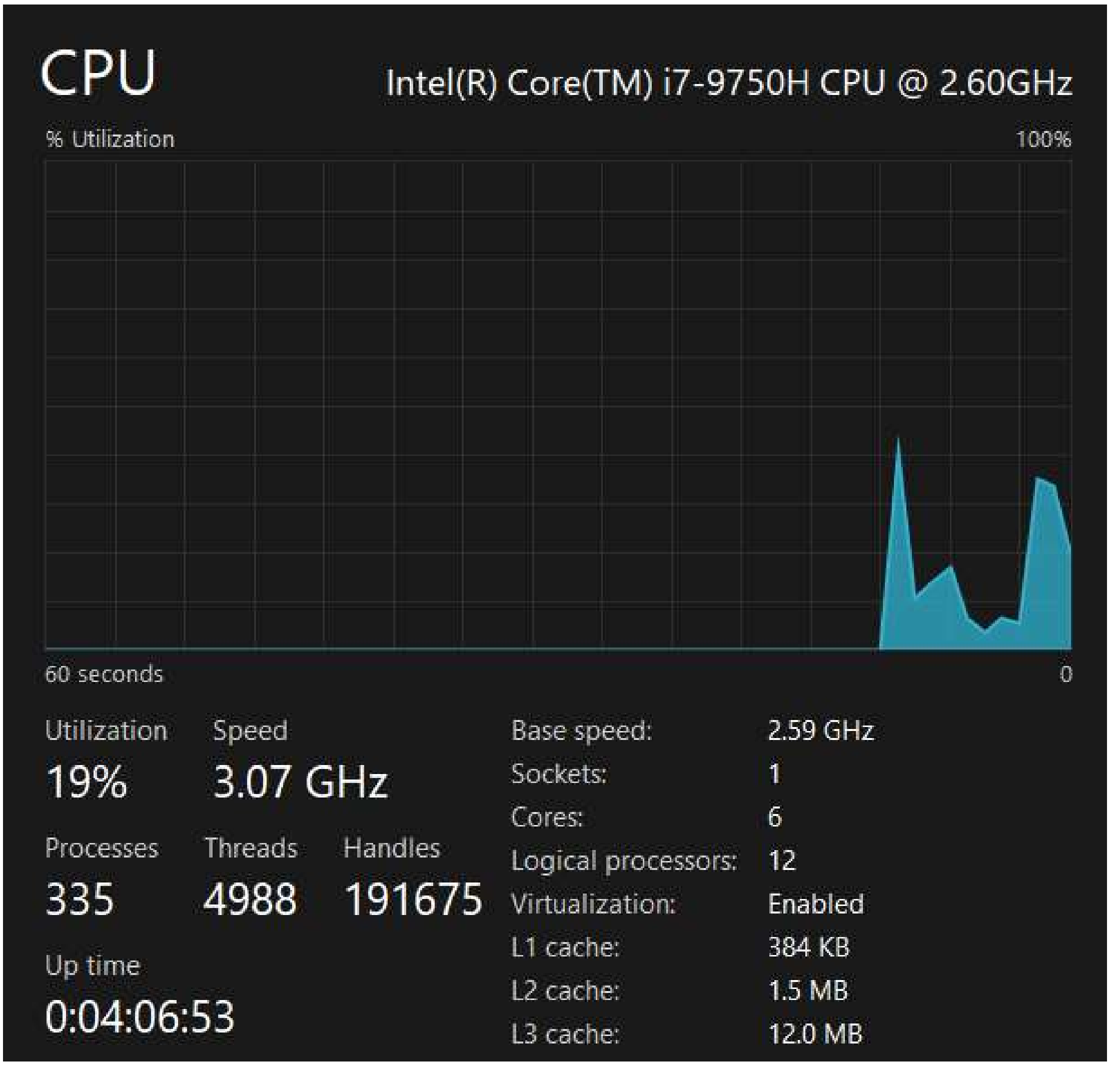
- CPU Make: Intel(R) Core(TM) i7-9750H
- Number of Physical Cores: 6
- Base Frequency: 2.60 GHz
- Turbo (Maximum) Frequency: 4.50 GHz (1 core), 3.20 GHz (6 core)

References:

1. https://ark.intel.com/content/www/us/en/ark/products/191045/intel-core-i79750h-processor-12m-cache-up-to-4-50-ghz.html
2. https://psref.lenovo.com/syspool/Sys/PDF/Legion/Lenovo_Legion_Y740_15IRHg/Lenovo_
3. https://www.intel.com/content/www/us/en/products/docs/processors/core/8th-gen-core-family-datasheet-vol-1.html
4. https://www.intel.com/content/www/us/en/products/docs/processors/core/8th-gen-core-family-datasheet-vol-2.html
5. https://www.cpu-monkey.com/en/cpu-intel_core_i7_9750h
6. https://setiathome.berkeley.edu/cpu_list.php
7. https://www.intel.in/content/www/in/en/support/articles/000056722/processors/intel-core-processors.html

Question 2

As per Performance GUI of Windows Task Manager



- L1 Cache Size: 384kB = 6 * 64 kB
- L2 Cache Size: 1.5 MB = 6 * 256 kB
- L3 Cache Size: 12.0 MB

Sharing of the caches

As per the https://www.intel.com/content/www/us/en/products/docs/processors/core/8th-gen-core-family-datasheet-vol-1.html

> Each execution core has an instruction cache, data cache, and 256-KB L2 cache. All execution cores share the LLC (L3 cache).

- Thus each core has its own 32kB L1 instruction and 32 kB L1 data cache, L2 cache
- The L3 cache is shared among all the six cores

Question 3

As per https://ark.intel.com/content/www/us/en/ark/products/191045/intel-core-i79750h-processor-12m-cache-up-to-4-50-ghz.html

- Max Memory Bandwidth: 41.8 GB/s for DDR4 onchip RAM

As per https://setiathome.berkeley.edu/cpu_list.php for i7-9750H

- peak GFLOPS per computer: 49.34
- peak GFLOPS per core: = 4.11

Question 4

As per https://ark.intel.com/content/www/us/en/ark/products/191045/intel-core-i79750h-processor-12m-cache-up-to-4-50-ghz.html

- Bus Speed: 8 GT/s (Giga transfers per second)

Question 5

In [ ]:
```
import time
import numpy as np
import numba
import matplotlib.pyplot as plt
from tqdm import tqdm
```

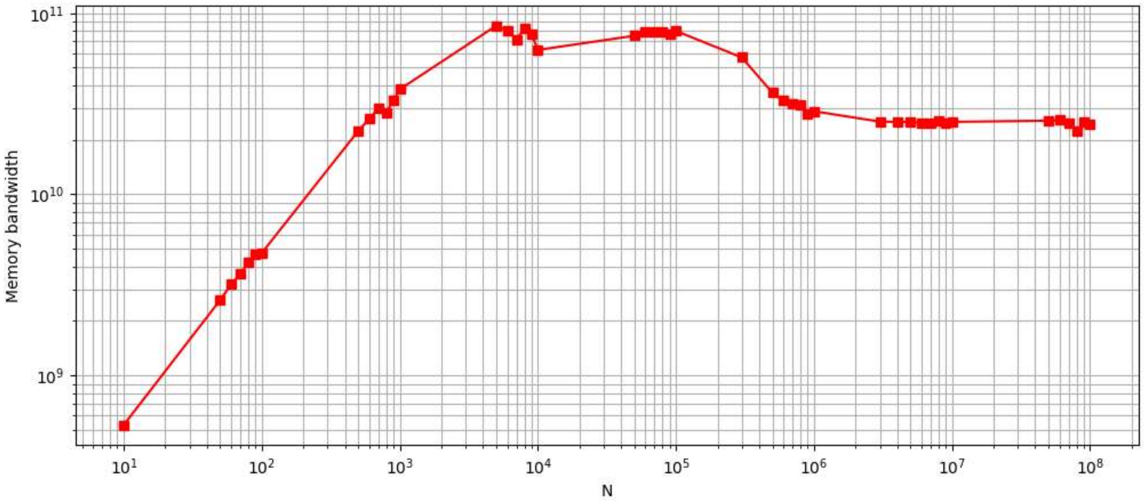
In [ ]:
```
@numba.njit
def benchmarker(y, a, b, x):
    # performs 3 loads and 1 store
    # assuming 1 store is same as 2 loads
    # hence 5 word data traffic per iteration
    for i in range(y.shape[0]):
        y[i] = a[i]*x[i] + b[i]


@numba.njit
def make_data(N):
    a,b,x = np.random.random((3,N))
    y = np.zeros(N)
    return a,b,x,y


def memory_bandwidth(N):
    times = []
    a, b, x, y = make_data(N)
    for _ in range(5):
        # for five times perform
        main_time = 0
        niters = 0
        while (main_time < 0.1):
            # perform as many benchmarks as possible in 0.1 seconds
            t = time.perf_counter()
            benchmarker(y, a, b, x)
            t = time.perf_counter() - t
            niters += 1
            main_time += t
        # store the time taken for niter benchmarks
        times.append((main_time, niters))
    # take the minimum time and its corresponding niters
    t = min(times)
    # float is 8 bytes, N is array size, 5 words is data traffic
```

```
    # t[0] is the time taken and t[1] is the number of iterations
    mem_bw = (N * t[1] * 8 * 5)/t[0]
    return mem_bw
```

In [ ]:
```
nvals = np.array([10, 50, 60, 70, 80, 90, 100, 500, 600, 700, 800, 900, 1000, 50
                  50000, 60000, 70000, 80000, 90000, 100000, 300000, 500000, 600
                  3000000, 4000000, 5000000, 6000000, 7000000, 8000000, 9000000,
                  10000000, 50000000, 60000000, 70000000, 80000000, 90000000, 10
memory_bandwidths = []

# dummy calls to warm up numba
a,b,x,y = make_data(100)
benchmarker(y,a,b,x)

# benchmarking memory bandwidth for various values of nvals
for i in tqdm(range(nvals.shape[0])):
    memory_bandwidths.append(memory_bandwidth(nvals[i]))

memory_bandwidths = np.array(memory_bandwidths)
```

```
100%|██████████| 46/46 [00:39<00:00,  1.17it/s]
```

In [ ]:
```
plt.rcParams["figure.figsize"] = (12,5)
plt.loglog(nvals, memory_bandwidths, 'rs-')
plt.xlabel("N")
plt.ylabel("Memory bandwidth")
plt.grid(True, which='both', ls='-')
plt.show()
```



Question 6

In [ ]:
```
@numba.njit
def flop_72_benchmarker(y, a, x, b):
     for i in range(y.shape[0]):
        ai = a[i]
        bi = b[i]
        xi = x[i]
        tmp1 = (ai*xi + bi)*(ai + bi)*(ai - bi)*(bi - xi)
        tmp2 = (ai*xi - bi)*(ai - bi)*(ai + bi)*(bi + xi)
        tmp3 = (ai*xi - bi)*(bi - xi)*(ai + xi)*(ai + xi)
        tmp4 = (ai*xi + bi)*(ai + bi)*(ai - bi)*(bi - xi)
        tmp5 = (ai*xi - bi)*(ai - bi)*(xi + bi)*(bi + xi)
```

```
        tmp6 = (ai*xi - bi)*(bi + ai)*(xi + xi)*(ai + xi)
        tmp7 = (ai*bi - xi)*(bi - xi)*(xi + ai)*(xi - bi)
        tmp8 = (ai*bi + xi)*(bi + xi)*(xi - ai)*(xi + bi)
        y[i] = ((tmp8*tmp6 + tmp7*tmp5 + bi*tmp4 - tmp3) + tmp2)*tmp1


@numba.njit
def flop_64_benchmarker(y, a, x, b):
     for i in range(y.shape[0]):
        ai = a[i]
        bi = b[i]
        xi = x[i]
        tmp1 = (ai*xi + bi)*(ai + bi)*(ai - bi)*(bi - xi)
        tmp2 = (ai*xi - bi)*(ai - bi)*(ai + bi)*(bi + xi)
        tmp3 = (ai*xi - bi)*(bi - xi)*(ai + xi)*(ai + xi)
        tmp4 = (ai*xi + bi)*(ai + bi)*(ai - bi)*(bi - xi)
        tmp5 = (ai*xi - bi)*(ai - bi)*(xi + bi)*(bi + xi)
        tmp6 = (ai*xi - bi)*(bi + ai)*(xi + xi)*(ai + xi)
        tmp7 = (ai*bi - xi)*(bi - xi)*(xi + ai)*(xi - bi)
        y[i] = ((ai*tmp6 + tmp7*tmp5 + bi*tmp4 - tmp3) + tmp2)*tmp1


@numba.njit
def flop_32_benchmarker(y, a, b, x):
    for i in range(y.shape[0]):
        ai = a[i]
        bi = b[i]
        xi = x[i]
        tmp1 = (ai*xi + bi)*(ai + bi)*(ai - bi)*(bi - xi)
        tmp2 = (ai*xi - bi)*(ai - bi)*(ai + bi)*(bi + xi)
        tmp3 = (ai*xi - bi)*(bi - xi)*(ai + xi)*(ai + xi)
        y[i] = ((ai*ai + xi*xi + bi*bi - tmp3) + tmp2)*tmp1


@numba.njit
def flop_24_benchmarker(y, a, b, x):
    for i in range(y.shape[0]):
        ai = a[i]
        bi = b[i]
        xi = x[i]
        tmp1 = (ai*xi + bi)*(ai + bi)*(ai - bi)*(bi - xi)
        tmp2 = (ai*xi - bi)*(ai - bi)*(ai + bi)*(bi + xi)
        y[i] = ((ai*ai + xi*xi + bi*bi - tmp1) + tmp2)*tmp1


@numba.njit
def flop_16_benchmarker(y, a, b, x):
    for i in range(y.shape[0]):
        ai = a[i]
        bi = b[i]
        xi = x[i]
        tmp = (ai*xi + bi)*(ai + bi)*(ai - bi)*(bi - xi)
        y[i] = ((ai*ai + xi*xi + bi*bi - tmp) + tmp)*tmp


@numba.njit
def flop_4_benchmarker(y, a, b, x):
    for i in range(y.shape[0]):
        y[i] = (((a[i] + b[i])*x[i]) + b[i])*a[i]
```

```
@numba.njit
def flop_8_benchmarker(y, a, b, x):
    for i in range(y.shape[0]):
        ai = a[i]
        bi = b[i]
        xi = x[i]
        y[i] = ((ai*ai + xi*xi + bi*bi - 3.14) + 3.14)*3.14


def flops(N, k, benchmarker):
    times = []
    a, b, x, y = make_data(N)
    for _ in range(5):
        main_time = 0
        niters = 0
        while (main_time < 0.1):
            t = time.perf_counter()
            benchmarker(y, a, b, x)
            t = time.perf_counter() - t
            niters += 1
            main_time += t
        times.append((main_time, niters))
    t = min(times)
    flops = (N * t[1] * k)/t[0]
    return flops
```

In [ ]:

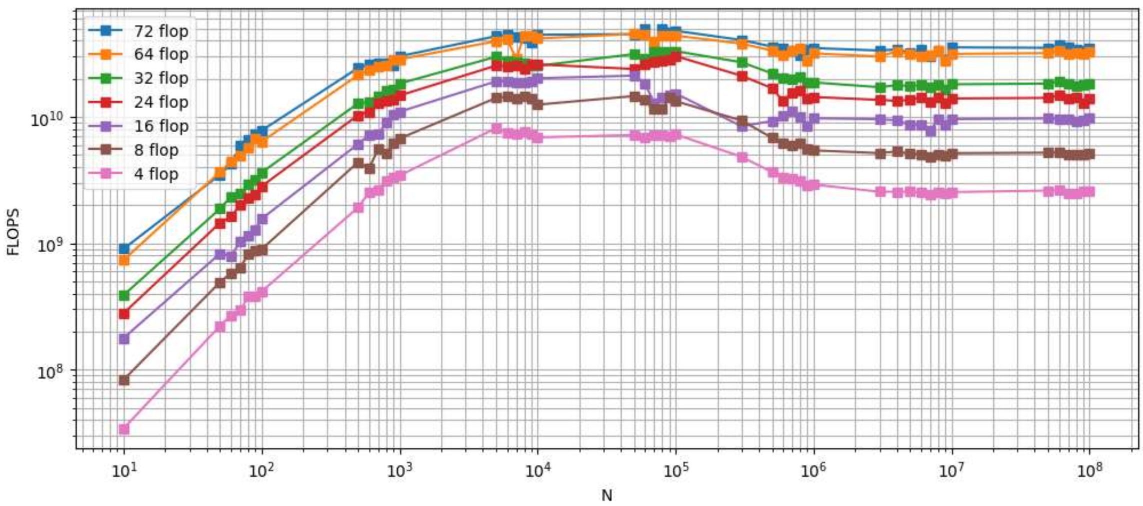
```
nvals = np.array([10, 50, 60, 70, 80, 90, 100, 500, 600, 700, 800, 900, 1000, 50
                  50000, 60000, 70000, 80000, 90000, 100000, 300000, 500000, 600
                  3000000, 4000000, 5000000, 6000000, 7000000, 8000000, 9000000,
                  10000000, 50000000, 60000000, 70000000, 80000000, 90000000, 10

flops_72 = []
flops_64 = []
flops_32 = []
flops_24 = []
flops_16 = []
flops_8 = []
flops_4 = []

# dummy calls to warm up numba
a,b,x,y = make_data(100)
flop_72_benchmarker(y, a, x, b)
flop_64_benchmarker(y, a, x, b)
flop_32_benchmarker(y, a, x, b)
flop_24_benchmarker(y, a, x, b)
flop_16_benchmarker(y, a, x, b)
flop_8_benchmarker(y, a, x, b)
flop_4_benchmarker(y, a, x, b)


# benchmarking performance for different values of array size for 72 flops code
for i in tqdm(range(nvals.shape[0])):
    flops_72.append(flops(nvals[i], 72, flop_72_benchmarker))

# benchmarking performance for different values of array size for 64 flops code
for i in tqdm(range(nvals.shape[0])):
    flops_64.append(flops(nvals[i], 64, flop_64_benchmarker))

# benchmarking performance for different values of array size for 32 flops code
```

```
for i in tqdm(range(nvals.shape[0])):
    flops_32.append(flops(nvals[i], 32, flop_32_benchmarker))

# benchmarking performance for different values of array size for 24 flops code
for i in tqdm(range(nvals.shape[0])):
    flops_24.append(flops(nvals[i], 24, flop_24_benchmarker))

# benchmarking performance for different values of array size for 16 flops code
for i in tqdm(range(nvals.shape[0])):
    flops_16.append(flops(nvals[i], 16, flop_16_benchmarker))

# benchmarking performance for different values of array size for 8 flops code
for i in tqdm(range(nvals.shape[0])):
    flops_8.append(flops(nvals[i], 8, flop_8_benchmarker))

# benchmarking performance for different values of array size for 4 flops code
for i in tqdm(range(nvals.shape[0])):
    flops_4.append(flops(nvals[i], 4, flop_4_benchmarker))

flops_72 = np.array(flops_72)
flops_64 = np.array(flops_64)
flops_32 = np.array(flops_32)
flops_24 = np.array(flops_24)
flops_16 = np.array(flops_16)
flops_8 = np.array(flops_8)
flops_4 = np.array(flops_4)
```

```
100%|██████████| 46/46 [00:39<00:00,  1.16it/s]
100%|██████████| 46/46 [00:39<00:00,  1.16it/s]
100%|██████████| 46/46 [00:39<00:00,  1.16it/s]
100%|██████████| 46/46 [00:40<00:00,  1.13it/s]
100%|██████████| 46/46 [00:39<00:00,  1.16it/s]
100%|██████████| 46/46 [00:39<00:00,  1.16it/s]
100%|██████████| 46/46 [00:39<00:00,  1.16it/s]
```

In [ ]:

```
plt.rcParams["figure.figsize"] = (12,5)
plt.loglog(nvals, flops_72, 's-', label='72 flop')
plt.loglog(nvals, flops_64, 's-', label='64 flop')
plt.loglog(nvals, flops_32, 's-', label='32 flop')
plt.loglog(nvals, flops_24, 's-', label='24 flop')
plt.loglog(nvals, flops_16, 's-', label='16 flop')
plt.loglog(nvals, flops_8, 's-', label='8 flop')
plt.loglog(nvals, flops_4, 's-', label='4 flop')
plt.xlabel("N")
plt.ylabel("FLOPS")
plt.legend()
plt.grid(True, which='both', ls='-')
plt.show()
```



In [ ]:

```
print("Max GFLOPS for 72 FLOP benchmark code", max(flops_72)/1e9)
print("Max GFLOPS for 64 FLOP benchmark code", max(flops_64)/1e9)
print("Max GFLOPS for 32 FLOP benchmark code", max(flops_32)/1e9)
print("Max GFLOPS for 24 FLOP benchmark code", max(flops_24)/1e9)
print("Max GFLOPS for 16 FLOP benchmark code", max(flops_16)/1e9)
print("Max GFLOPS for 8 FLOP benchmark code", max(flops_8)/1e9)
print("Max GFLOPS for 4 FLOP benchmark code", max(flops_4)/1e9)
```

```
Max GFLOPS for 72 FLOP benchmark code 50.104484325535964
Max GFLOPS for 64 FLOP benchmark code 45.31127503451943
Max GFLOPS for 32 FLOP benchmark code 33.114403665813434
Max GFLOPS for 24 FLOP benchmark code 30.263606579917468
Max GFLOPS for 16 FLOP benchmark code 21.199406412794712
Max GFLOPS for 8 FLOP benchmark code 14.61850890866153
Max GFLOPS for 4 FLOP benchmark code 8.145734810036641
```

Thus we see that the maximum GFLOPS for our benchmark is 50.10 GFLOPS, which is about the same order as suggested by the reference which said 49.34 GFLOPS.