**Part A:**

**N.B:** Our results shown in our attached notebook can only be replicated using a machine with 8 cores.

Quite unsurprisingly, and illustrating the rationale for implementing more than one core, we note that generally speaking increasing the number of cores reduces the time taken for our machines to perform calculations. What did strike us as surprising however, was the marginal increase in performance (i.e. reducing time) to which adding each additional core made. Initially, adding extra cores led to significant increases in performance. For instance, utilising two cores instead of one came close to halving runtime. However, diminishing marginal returns quickly set in and we often saw no increase in performance (sometimes adding an extra core even resulted in a longer computation). Ultimately, this leads us to the conclusion that, unless performing extremely complicated calculations that could be run on separate cores, additional resource allocation [the added cost (both financial and computational)] is not worth the slight uptick in performance.

It is worth framing the results we observed in the context of the type of calculations that were being performed. As it was largely a CPU bound program (it was simply conducting a large number of comparisons), as opposed to I/O bound, we would expect multiprocessing, instead of multithreading, to speed up the calculations. With a single core, python cannot calculate any of the required comparisons concurrently, however splitting the workload between multiple cores enables quicker execution, unlike in a I/O dominated program where multithreading would lead to efficiencies while I/O operations were being performed and the CPU was idle.

**Python Global Interpreter Lock (**[**GIL**](https://realpython.com/python-gil/)**)**

By default, Python does not utilise more than one core at once. Interestingly, it is actually the GIL that both contributed to the rise and dominance of Python as a mainstream programming language, and means that only one thread can control the Python interpreter at any one time. The GIL is basically a lock on the interpreter that requires acquisition to conduct code execution. Around the time of Python’s widespread adoption, the GIL was a simple solution to prevent inconsistencies with the integration of C libraries that are not thread safe. For many other reasons, such as maintaining backwards compatibility, maintaining performance for single threaded implementations and others, the GIL has remained apart of Python.

Although other solutions to thread-safe memory management (such as garbage collection using which multiple threads can be created) have been implemented in other languages, Python’s approach allows for the performance benefits that accompany single threaded implementations, such as the avoidance of repeated acquisition and release of locks and the enablement of higher clock speeds.

**Performance Improvements using Multithreading**

Understanding the mechanism for the GIL is crucial to understanding why implementing multiprocessing as opposed to multithreading (which is still possible in Python) leads to performance increases. If instead we had initialised a single process with say 8 threads, each thread would have to wait on the one above it to execute before it could access the CPU. With no I/O operations there does not come a point whereby a thread can take over the GIL while another waits for I/O. A logical follow-on therefore would be that creating many instances of the interpreter which themselves have a single mutex may enable enhanced performance for CPU-bound processes.

As alluded to, with the requirement for the acquisition of the mutex, Python only allows one thread to be in execution at any one time. For CPU-bound programs such as ours this obviously leads to bottlenecks in performance, as although there is not a point in which the one thread holding the lock is not in execution, there is only one instance of the Python interpreter, meaning only one core in use.

The Multiprocessing library that we used navigates around the GIL issue by instantiating more than one operating system processes for the tasks to be carried out. In essence this gives each process a Python interpreter of its own, meaning a scenario whereby there are as many GILs as there are new processes. In this way, the new processes are executed separately and crucially, concurrently, in different cores and subsequently regrouped once all processes have executed.

The effects of this are striking, and explored in depth in our accompanying notebook. Proving how computationally intensive (and therefore CPU-bound) the program is, we see a near 50% reduction in performance time when analysing the same set of primes using 2 cores instead of 1.

There was also an interesting observation in that the marginal uptick in execution for each additional core is far from linear and is more convex in nature. Indeed, for some of our tests we sometimes saw an increase in performance time, however we theorise this is due to external factors, such as other processes on our machines taking over a core (particularly as it does not happen all the time, nor does it happen in the average run time tests). Still, it is intuitive why the increases in performance are not distributed evenly for each extra core. Recalling what is actually occurring when we make a call for one more core, Python must create an extra process which is in itself computationally expensive and introduces I/O overhead. These overheads are what seem to be the reason for increasingly smaller amounts of performance optimisation through adding additional cores.

It would be quite interesting to conduct the same experiments on a machine with cores far in excess of the 8 we used, to see if the performance time continued to flat-line, or if we actually saw increased times due to the overheads created when spawning new processes. We also believe it would be interesting to explore combining multiprocessing with multithreading. Given that the creation of additional processes introduces process management [I/O] overhead, and it is largely the creation of these processes that cause the flatline in performance as the cores are increased, it may be the case that creating additional threads to handle this, and the additional processes to handle the CPU-bound work, leads to a more linear relationship.

* Getting data to cores etc, more meaningful with more complex computations
* Talk about reason for marginal decrease due to overhead in creating multiprocessing processes – heavier than threads etc
* Could be interesting to see if time increases due to creation of extra processes when it is simplistic
* <https://www.linuxjournal.com/content/multiprocessing-python>
* https://www.quantstart.com/articles/Parallelising-Python-with-Threading-and-Multiprocessing/

LESSONS

**Part B:**

For the second task of this assignment, initially we considered downloading images, however, after further research we discovered that downloading is primarily an I/O bound task, since there is a wait time for the images to download. Therefore, to follow the assignment requirements we decided image processing was a more appropriate task as it is predominantly a CPU bound task.

We utilised the Pillow Python library to do some image processing (adding a Gaussian blur) on the pre-downloaded images. The `normal\_image\_process` and `multiprocessing\_image\_process` functions simply open the image, apply the filter and thumbnail size and then save the image to the appropriate location. The functions are identical apart from the location where the processed images are saved. It would have been preferable to merge this into one function which takes the folder route as an additional parameter, but the pool process function does not permit this as the function it takes as an argument, must itself only take one argument.

The results obtained in this part of the project were similar those seen in Part A. As can been seen in the accompanying notebook, it took \_\_ seconds to process the 15 images using only 1 core. When 8 cores were used the time took to process the images was \_\_ seconds. This increase in core utilisation lead to a \_\_% decrease in processing time. This is a significant drop in time and highlights how multiprocessing can greatly reduce the time necessary to perform CPU intensive tasks. As discussed in Part A, it was also found that adding the first few additional cores greatly reduced processing times however, after a certain point diminishing marginal returns (caused by the increase in process management overhead) quickly set in leading to only minor reductions in processing times.