Contents

INTRODUCTION

Video streaming has become a dominant force in internet traffic worldwide, driven by the explosive growth of platforms like Netflix, YouTube, and Amazon Prime Video. This surge in popularity is due to increased internet speeds, improved video compression technologies, and the ubiquity of smart devices. As of 2025, video streaming accounts for over 80% of all internet traffic, highlighting its critical role in modern digital communication and entertainment1.

The challenges of transcoding large videos are significant, particularly when dealing with high-resolution content like 4K or 8K. Transcoding is a CPU-intensive process that requires substantial computational resources, memory usage, and power consumption. For instance, transcoding a single 4K video file can utilize up to 100% of a high-end CPU for extended periods, consume several gigabytes of RAM, and significantly increase power draw, leading to higher energy costs and potential thermal issues.

When it comes to video transcoding environments, both Virtual Machines (VMs) and Docker containers offer distinct advantages and disadvantages:

Virtual Machines (VMs) in Video Transcoding Environments

Advantages:

- Full Isolation from the Host System: VMs provide complete isolation because each VM runs its own dedicated operating system. This ensures that applications and processes within one VM are isolated from others, offering enhanced security. This is particularly beneficial in environments where sensitive data or critical workloads are involved.
- Ability to Run Different Operating Systems: VMs can emulate multiple operating systems on the same hardware. This flexibility allows transcoding tasks to be performed on different OS environments, which can be crucial for legacy applications or specific OS-dependent software.
- Easier to Manage and Migrate Entire System States: VMs encapsulate the entire system state, including the OS, applications, and data. This makes it easier to manage, back up, and migrate VMs across different hardware or cloud environments without compatibility issues.

Disadvantages:

- Higher Overhead: VMs require a full OS for each instance, leading to higher resource consumption. This includes more RAM, CPU, and storage, which can be inefficient for large-scale transcoding tasks.

- Slower Boot Times: Due to the need to load a full OS, VMs take longer to start up compared to containers. This can be a bottleneck in environments requiring rapid scaling or quick task initiation.
- More Resource-Intensive: The additional OS layer increases the resource footprint, making VMs less efficient for environments where resource optimization is critical.

Docker Containers in Video Transcoding Environments

Advantages:

- Lightweight and Fast: Docker containers share the host OS kernel, making them lightweight and fast. They have minimal overhead, allowing more transcoding tasks to be run on the same hardware compared to VMs.
- Quick to Start Up and Tear Down: Containers can be started and stopped in seconds, making them ideal for dynamic workloads where rapid scaling is required.
- Efficient Resource Utilization: By sharing the host OS kernel, containers optimize resource usage. This reduces the need for over-provisioning and lowers infrastructure costs, especially in cloud environments.
- Easier to Scale and Deploy in Cloud Environments: Docker containers are designed for cloud-native applications, making them easier to scale and deploy across different cloud platforms. Kubernetes can further enhance this by automating container management and scaling.

Disadvantages:

- Less Isolation Compared to VMs: Containers share the host OS kernel, which can lead to potential security vulnerabilities if not properly managed. A compromised container could potentially affect the entire host system.
- Limited to the Host OS Kernel: Containers are restricted to the host OS kernel, meaning they cannot run different OS types on the same host. This limits their flexibility compared to VMs.
- Additional Configuration for GPU Acceleration: Setting up GPU acceleration in Docker containers may require additional configuration and expertise. This can be a challenge in transcoding tasks that rely heavily on GPU performance.

METHODOLOGY

VM-Based FFmpeg Deployment

For this experiment, I opted to use Ubuntu on Windows Subsystem for Linux (WSL) instead of a full virtual machine (VM) solution like VirtualBox or VMware due to several compelling reasons:

1. **Tighter Integration with Windows**:
   WSL provides seamless access to both the Windows and Linux file systems, enabling developers to work across environments without the need for complex configurations. This integration allows Linux tools to interact directly with Windows files, making tasks such as editing, compiling, and testing more efficient.

2. **Lower Resource Overhead**:
   Unlike traditional VMs that require significant system resources (CPU, memory, and storage), WSL2 operates using a lightweight virtual machine managed by Windows. This results in quicker startup times and reduced resource consumption, making it ideal for tasks like transcoding that don't demand extensive computational power.

3. **Developer-Focused Optimization**:
   WSL is tailored for development workflows, offering easy installation of Linux distributions and tools directly within Windows. Developers can leverage Linux utilities such as FFmpeg without needing a separate Linux system or VM setup. This streamlined approach enhances productivity.

WSL Setup Process

The setup process involved the following steps:

Step 1: Installing Ubuntu 22.04 LTS on Windows 11 using WSL2

To install Ubuntu via WSL2, users first enable the WSL feature in Windows settings and then download Ubuntu from the Microsoft Store. This process eliminates the need for dual-booting or external virtualization software, providing a native-like Linux experience within Windows.

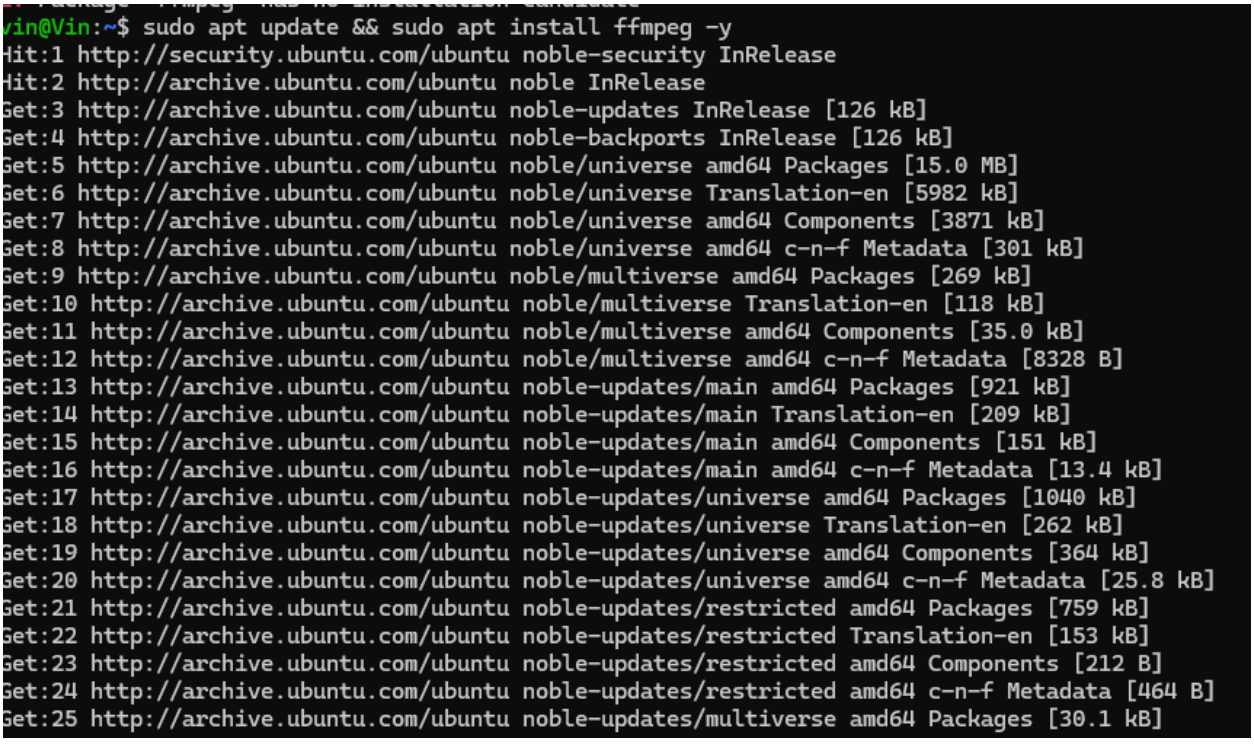
Step 2: Updating Package Lists and Installing FFmpeg

Once Ubuntu is installed, we execute the following commands:

sudo apt update

sudo apt install ffmpeg

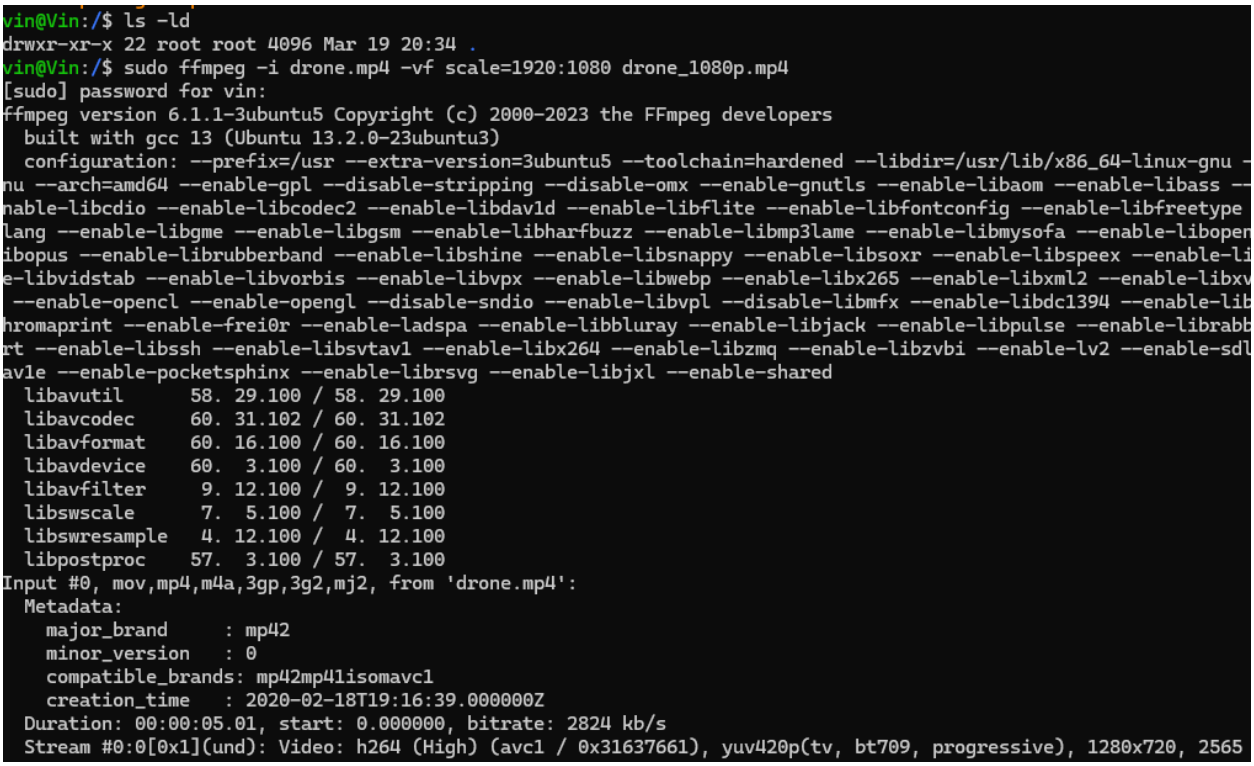
- **sudo apt update**:
    - This command refreshes the package lists stored locally on your system by fetching the latest information from the configured repositories. It ensures that you have access to updated versions of software packages and their dependencies.
    - For example, if FFmpeg has been updated recently, running this command ensures that you download the latest version rather than an outdated one.
- **sudo apt install ffmpeg**:
    - This installs FFmpeg along with its dependencies. FFmpeg is a powerful multimedia framework used for video and audio processing tasks such as transcoding, scaling, and filtering.



Step 3: Video Scaling

For video scaling, I used the following command:

ffmpeg -i drone.mp4 -vf scale=1920:1080 drone_1080p.mp4



- **ffmpeg**:
    - The command-line tool used to process multimedia files.
    - It supports a wide range of formats and codecs, making it a versatile choice for video manipulation.
- **-i drone.mp4**:
    - Specifies the input file (drone.mp4) to be processed.
    - The -i flag tells FFmpeg which file to read.
- **-vf scale=1920:1080**:
    - -vf stands for "video filter." Here, we apply a scaling filter to resize the video resolution to 1920x1080 pixels.
    - Scaling is useful for standardizing video dimensions or optimizing playback on specific devices.
- **drone_1080p.mp4**:

- Specifies the output file name where the processed video will be saved.
- The resolution change applied by scale=1920:1080 is reflected in this output file.

This approach leverages WSL's efficiency and FFmpeg's capabilities to streamline transcoding tasks without requiring extensive system resources or complex configurations typical of full VM solutions.

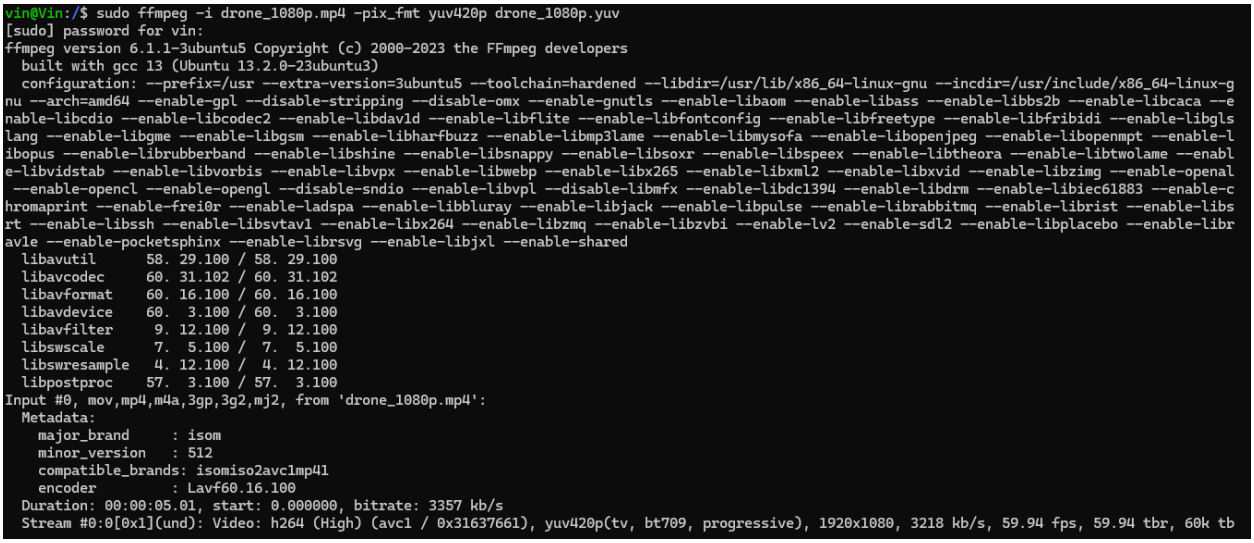
4. Cloning GitHub Repository:

The repository was cloned using:

git clone https://github.com/NabajeetBarman/SI-TI.git

cd SI-TI

- git clone: Downloads the repository to your local machine.
- cd SI-TI: Changes the current directory to the cloned repository.



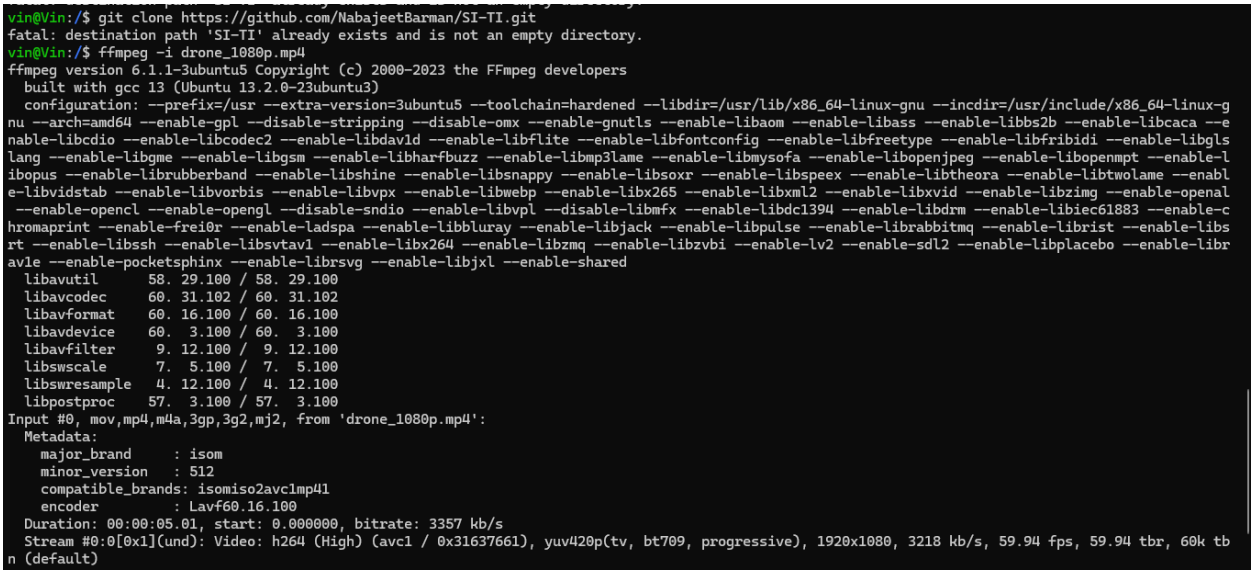
5. Conversion to YUV Format:

The video was converted to YUV format with this command:

ffmpeg -i drone_1080p.mp4 -pix_fmt yuv420p drone_1080.yuv

- -pix_fmt yuv420p: Specifies the pixel format as YUV with 4:2:0 chroma subsampling.

- Explanation of YUV420p:
  - "420" indicates chroma subsampling where U and V components have half the resolution of Y in both horizontal and vertical dimensions.
  - "p" stands for planar, meaning Y, U, and V components are stored in separate planes.



Based on the FFmpeg output provided, the video file "drone_1080p.mp4" had the following properties:

> Stream #0:00x1: Video: h264 (High) (avc1 / 0x31637661), yuv420p(tv, bt709, progressive), 1920x1080, 3218 kb/s, 59.94 fps, 59.94 tbr, 60k tbn (default)
>
> The important information here are:

- Codec: H.264 (High profile)
- Pixel format: yuv420p
- Resolution: 1920x1080
- Frame rate: 59.94 fps

> The pixel format "yuv420p" indicates that the video is 8-bit YUV with 4:2:0 chroma subsampling. The "p" at the end stands for "planar" format.

In YUV420p, the "420" represents the chroma subsampling ratio, where the U and V components have half the horizontal and vertical resolution of the Y component. The "p" means that the Y, U, and V components are stored in separate planes.

Since there is no "p10" or "p10le" in the pixel format, it confirms that the video is 8-bit and not 10-bit.

So, based on the FFmpeg output, I concluded that the "drone_1080p.mp4" video is an 8-bit YUV video with 4:2:0 chroma subsampling.

6. Bit Depth Analysis:

Based on the FFmpeg output, it was determined that:

- Codec: H.264 (High profile)
- Pixel format: yuv420p (indicating an 8-bit YUV video)

The absence of formats like "p10" or "p10le" confirmed that the video was not in a higher bit depth (e.g., 10-bit).

7. Organizing Files:

The converted .yuv file was moved to an "8-bit" folder within the cloned repository for further processing.

```
vin@Vin:/SI-TI$ ls
LICENSE  Main.m  README.md  SITI-10bit  SITI-8bit  drone_1080p.yuv  drone_1080p.yuv:Zone.Identifier
```

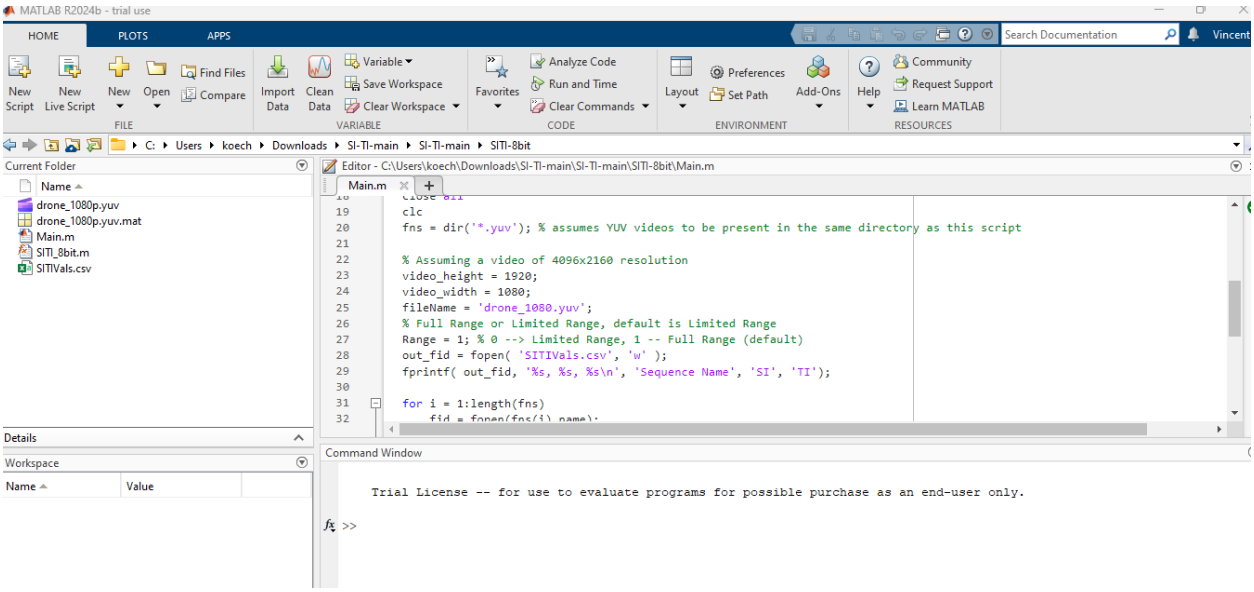
Using MATLAB, I navigated to the "8-bit" folder in the MATLAB Current Folder window. I then opened the Main.m script in the MATLAB editor. I modify the Main.m script to include your video resolution and filename.

For this instance, my video resolution is 1920x1080, update the following lines:

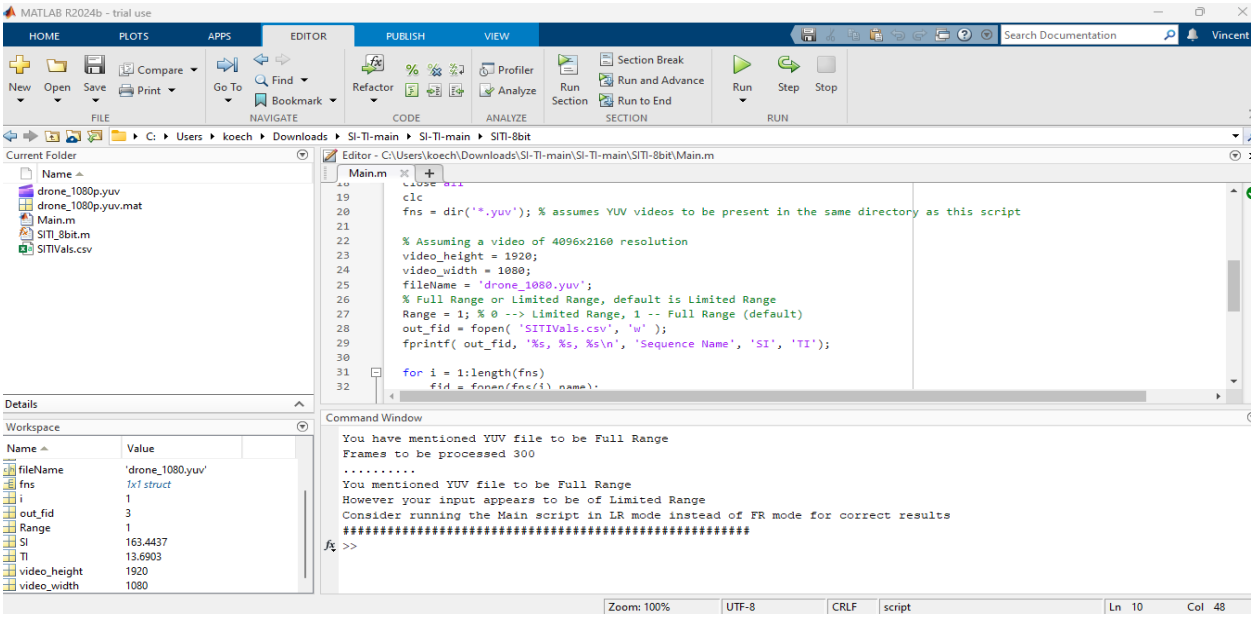
width = 1920;

height = 1080;

fileName = 'drone_1080.yuv';



Ran the Main.m script by clicking the "Run" button in the MATLAB editor . The script calculated the SI and TI values for the video and saved the results in a SITIVals.csv file.



RESULTS - *SI - 163.4437, TI - 13.6903*

8. Transcoding to Different Bitrates

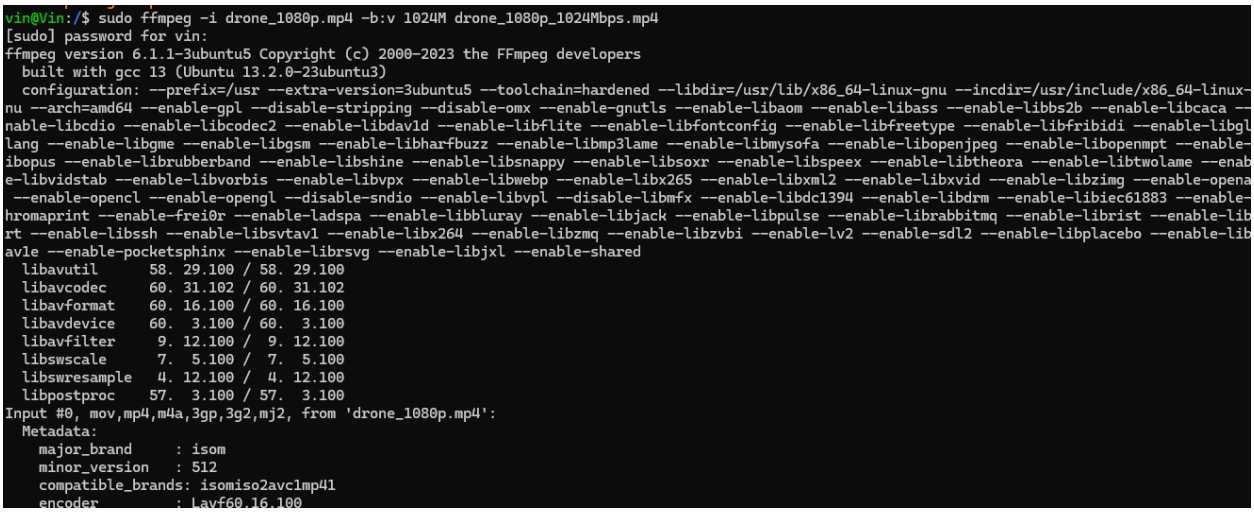
I then Transcoded to Different Bitrates Using FFmpeg, I transcoded the 1080p video to 1024 Mbps and 2048 Mbps.

Transcoding a video to different bitrates involves re-encoding the video at varying levels of data compression. This process is essential for adaptive streaming, where videos are delivered at different bitrates to match network conditions and device capabilities.

1. **Transcoding to 1024 Mbps:**

ffmpeg -i drone_1080p.mp4 -b:v 1024M drone_1024mbps.mp4

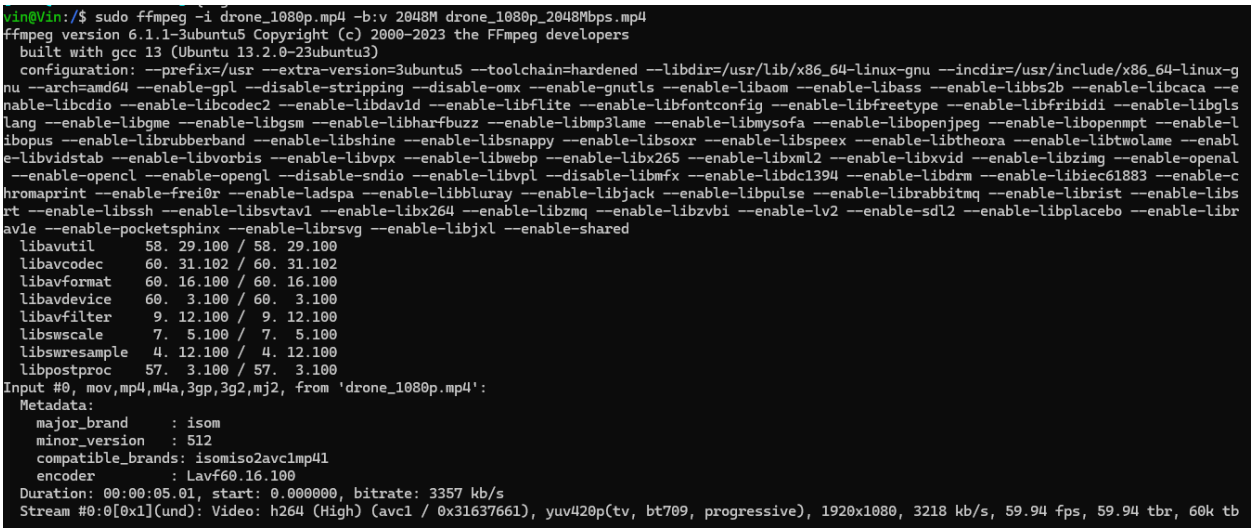
- -i drone_1080p.mp4: Specifies the input file.
- -b:v 1024M: Sets the video bitrate to 1024 Mbps. This parameter controls the amount of data allocated per second of video playback.
- drone_1024mbps.mp4: Specifies the output file name.



2. **Transcoding to 2048 Mbps:**

ffmpeg -i drone_1080p.mp4 -b:v 2048M drone_2048mbps.mp4

Similar parameters are used, but the bitrate is increased to 2048 Mbps for higher quality output.



Impact of Bitrate on Video Quality and Size

- **Video Quality:** Higher bitrates generally result in better visual quality since more data is preserved during encoding. However, diminishing returns may occur if the source video quality exceeds what can be represented at a given bitrate.
- **File Size:** Increasing the bitrate leads to larger file sizes because more data is stored per second of video.

Resource Usage Monitoring During Transcoding on WSL

Transcoding video files is a resource-intensive task that requires significant computational power, memory, and energy. To evaluate the system's performance and efficiency during transcoding, the following tools were used:

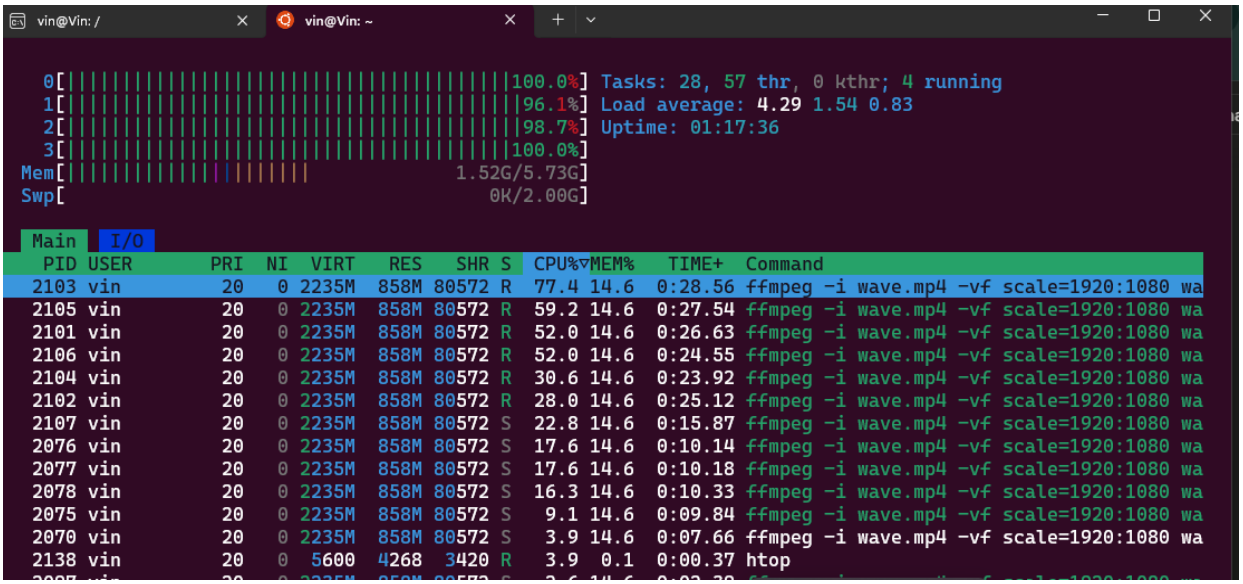
Monitoring CPU and RAM Utilization Using htop

The htop utility was employed to track real-time CPU and memory usage during the transcoding process. The results were as follows:

- **CPU Utilization:** 77%
- **Memory Utilization:** 14.6%
- **Total Time for Transcoding:** 30 seconds

Key Observations:

- **CPU Usage:** Transcoding is primarily CPU-bound, with the process utilizing 77% of the Intel Core i7-10750H's available processing power. This high utilization underscores the computational demands of encoding and compressing video data.
- **Memory Usage:** At 14.6% of the system's 16GB DDR4 RAM, memory usage was relatively moderate. This indicates efficient memory management by FFmpeg, likely due to its ability to process video frames in chunks rather than loading the entire file into memory.
- **Duration:** The total transcoding time of 30 seconds reflects the system's capability to handle high workloads efficiently, aided by the CPU's six cores and twelve threads.



Measuring Power Consumption Using powerstat

To assess energy efficiency, ***powerstat*** was used to monitor power consumption during transcoding. This tool provides insights into how much energy is consumed by the system under load.

```
vin@Vin:/$ sudo powerstat -d 0 -z
Running for 480.0 seconds (48 samples at 10.0 second intervals).
Power measurements will start in 0 seconds time.

  Time    User  Nice   Sys  Idle    IO  Run Ctxt/s  IRQ/s Fork Exec Exit  Watts
19:55:45   0.0   0.0   0.1  99.9   0.0    1     21      3    0    0    0   0.00E
19:55:55   0.0   0.0   0.1  99.9   0.0    1     17      2    0    0    0   0.00E
19:56:05   0.0   0.0   0.1  99.9   0.0    1     16      2    0    0    0   0.00E
19:56:15   0.0   0.0   0.1  99.9   0.0    1     15      2    0    0    0   0.00E
19:56:25   0.0   0.0   0.1  99.9   0.0    1     15      2    0    0    0   0.00E
19:56:35   0.0   0.0   0.1  99.9   0.0    1     16      2    0    0    0   0.00E
^[
19:56:45   0.0   0.0   0.3  99.7   0.0    1     21      4    0    0    0   6.07
19:56:55   0.0   0.0   0.1  99.9   0.0    1     19      2    0    0    0   6.07
19:57:05   0.0   0.0   0.1  99.9   0.0    1     19      2    0    0    0   6.07
19:57:15   0.0   0.0   0.1  99.9   0.0    1     19      2    0    0    0   1.21
19:57:25   0.3   0.0   0.6  99.1   0.0    1     60     18   16   11   13   1.21
19:57:35   0.0   0.0   0.2  99.7   0.1    1     39     11    0    0    0   1.21
19:57:45   0.0   0.0   0.1  99.7   0.2    1     31      6    1    1    1   1.21
```

Why Measure Power Consumption?

- Transcoding tasks can significantly increase power draw due to high CPU utilization.
- Monitoring power consumption helps evaluate energy efficiency and operational costs, especially when scaling transcoding workflows in data centers or cloud environments.

Hardware Specifications Impacting Resource Usage

The hardware configuration played a critical role in determining resource utilization:

- **CPU:** The Intel Core i7-10750H (6 cores, 12 threads) provided sufficient parallel processing capabilities to handle video encoding efficiently.
- **RAM:** The 16GB DDR4 RAM ensured smooth operation without memory bottlenecks.
- **Storage:** The NVMe SSD reduced I/O delays during file read/write operations, contributing to faster transcoding times.

Docker-Based FFmpeg Deployment

Docker was chosen over VM for several reasons:

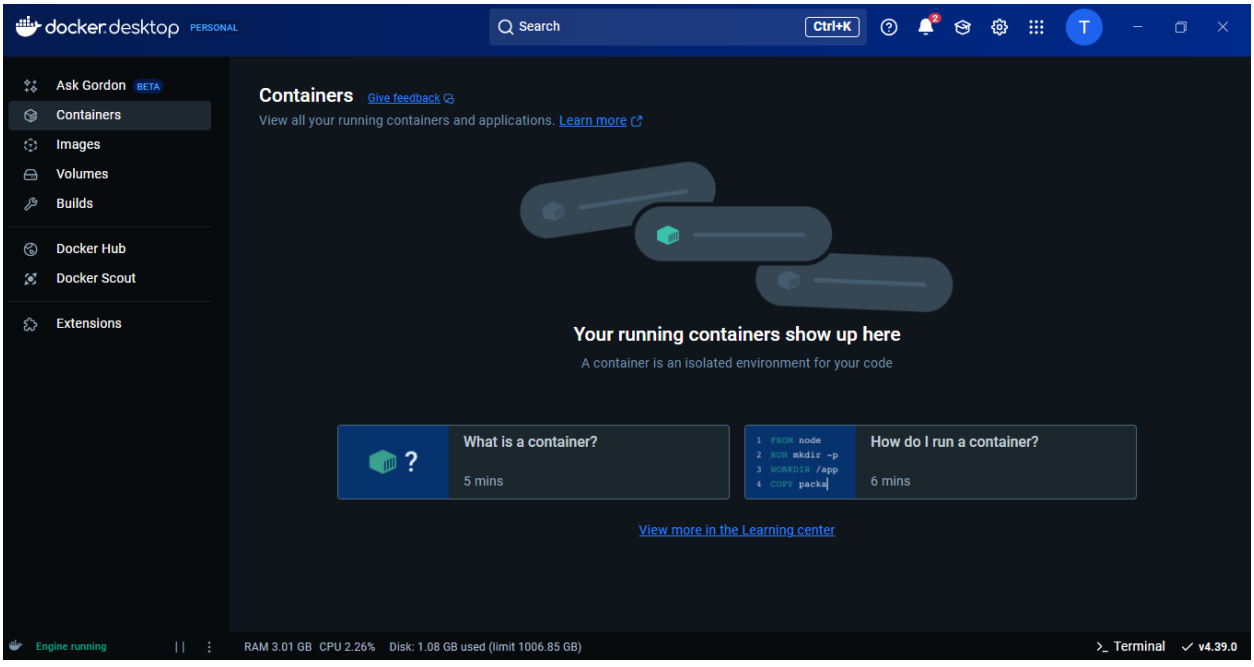
1. Resource Efficiency: Docker containers share the host OS kernel, resulting in lower overhead and more efficient resource utilization.
2. Faster Startup: Containers can start almost instantly, allowing for quick scaling of transcoding tasks.
3. Consistency: Docker ensures that the transcoding environment is identical across different systems, reducing "it works on my machine" issues.
4. Easy Distribution: Docker images can be easily shared and deployed, simplifying the setup process for transcoding workflows.

Docker Container Setup process

The Docker setup process involved the following steps:

1. **Installing Docker Desktop on Windows.**

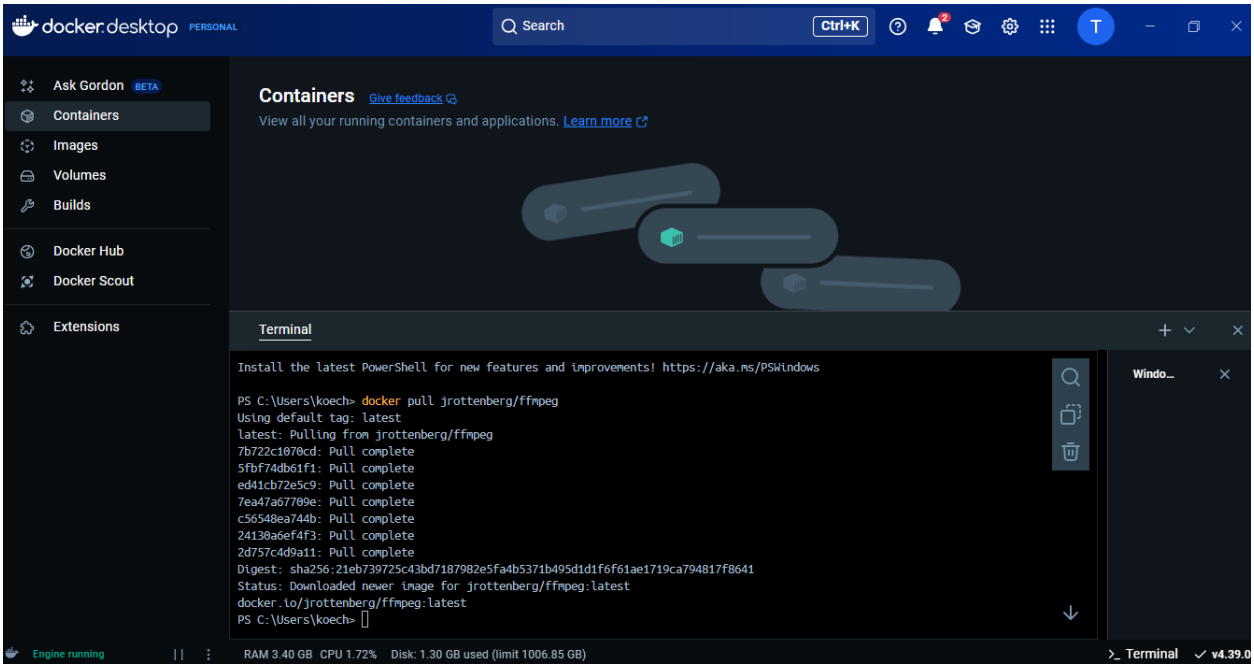
   Started Docker Desktop after the installation was complete.



2 .Deploy FFmpeg inside a Docker container

Using the PowerShell window, I Pulled the official FFmpeg Docker image by running the command

docker pull jrottenberg/ffmpeg



The Docker-based FFmpeg deployment on Windows using Docker Desktop was successful.

3: Input Video Selection

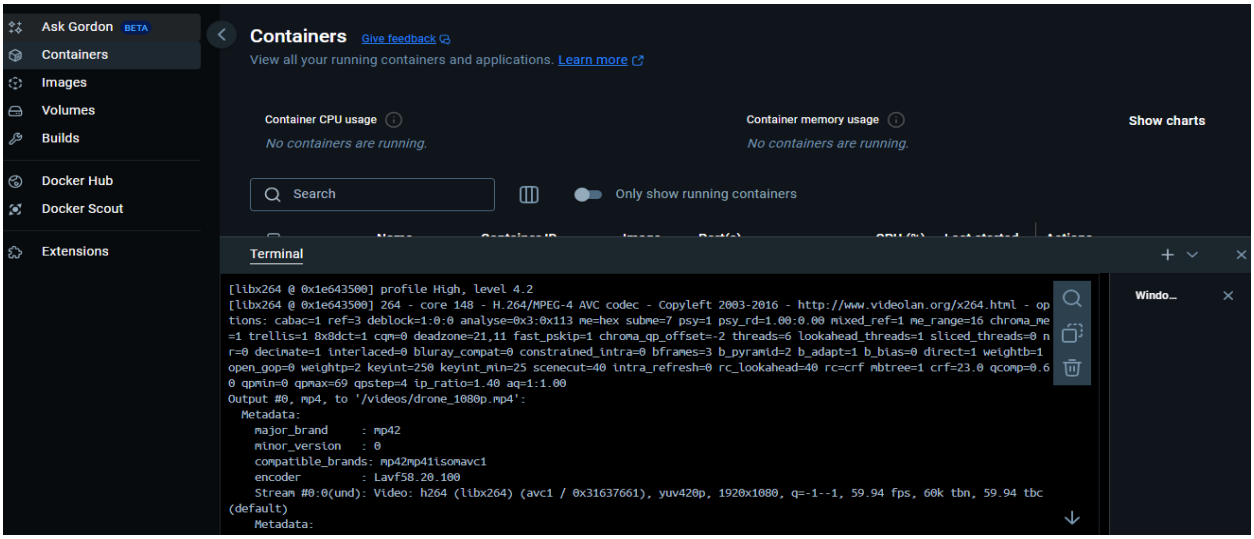
Downloaded the "drone" 4K video from pexels.com

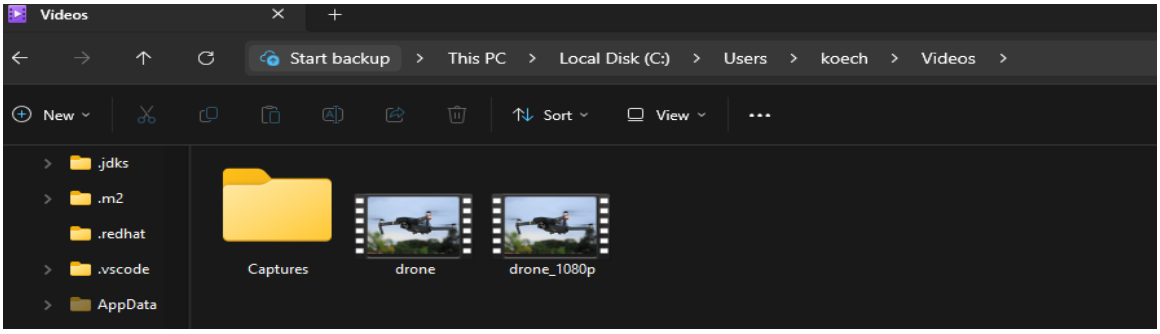
Placed the video file in a directory accessible to Docker on the Windows machine "C:\drone.mp4"

4: Scale/Resize Video

Ran the following command to resize the video to 1080p inside the Docker container

docker run -v C:\Users\koech\videos:/videos jrottenberg/ffmpeg -i /videos/drone.mp4 -vf scale=1920:1080 /videos/drone_1080p.mp4

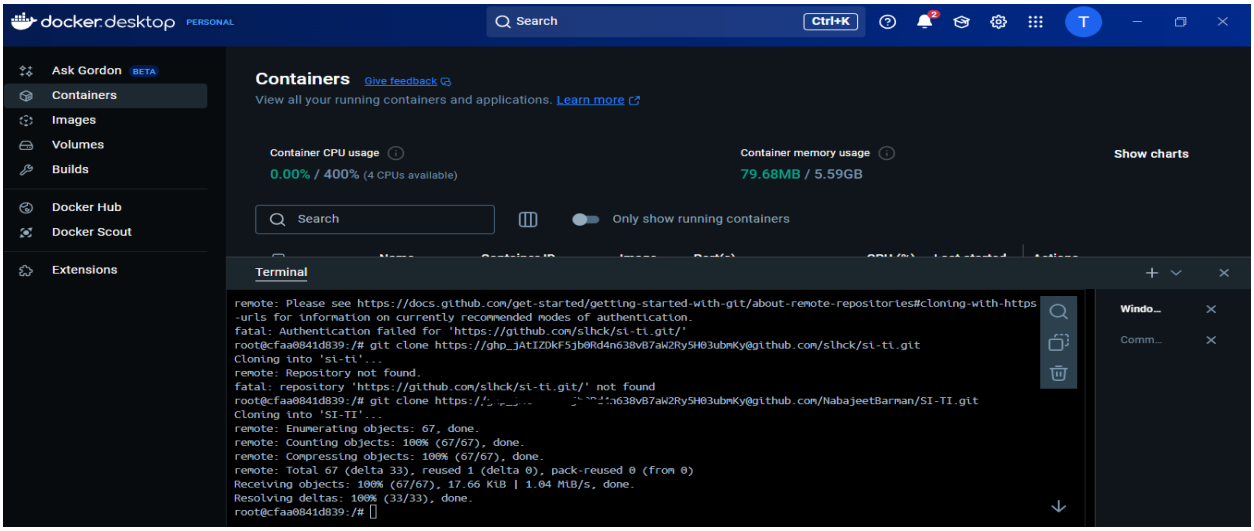




The "Nature Landscape" video was resized to 1080p resolution inside the Docker container.

5: Calculate SI & TI Index

Ran the following commands to install the SI-TI tool inside the Docker container and calculate the video complexity.

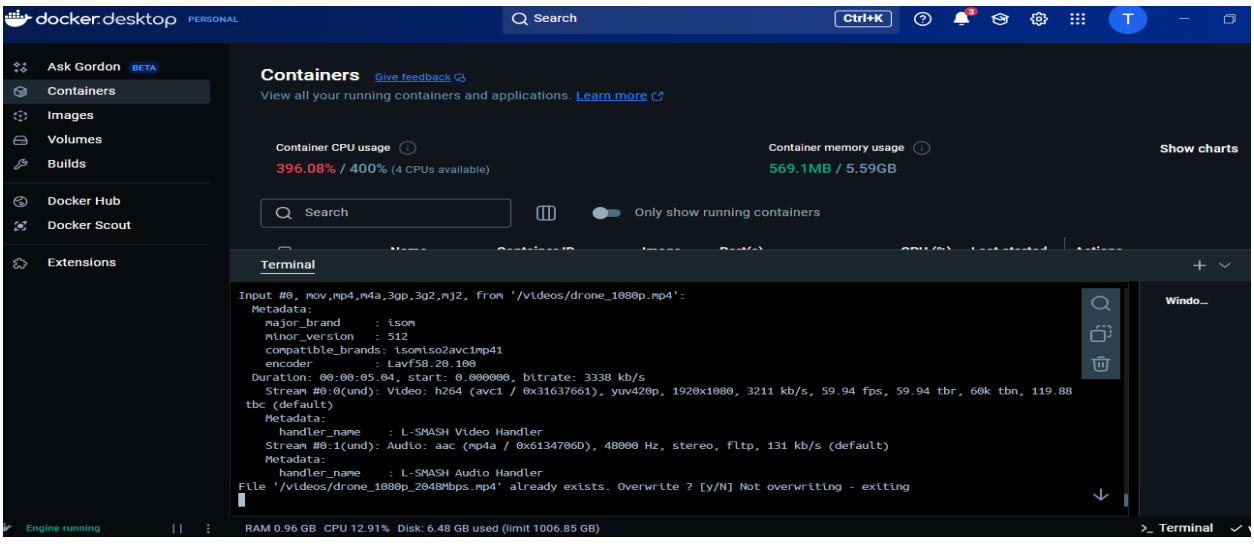


6: Transcoded to Different Bitrates

Run the following commands to transcode the video to 1024 Mbps and 2048 Mbps bitrates inside the Docker container:

docker run -v C:\Users\koech:/videos jrottenberg/ffmpeg -i /videos/drone_1080p.mp4 -b:v 1024M /videos/drone_1080p_1024Mbps.mp4

docker run -v C:\Users\koech:/videos jrottenberg/ffmpeg -i /videos/drone_1080p.mp4 -b:v 2048M /videos/drone_1080p_2048Mbps.mp4



The video was transcoded to bitrates of 1024 Mbps and 2048 Mbps inside the Docker container.

Resource Usage Monitoring During Transcoding on WSL

The resource usage (CPU and RAM) of the Docker container during the transcoding process was monitored using the ***docker stats*** command.

Results;

RAM USAGE 0.96GB – 8% CPU 12.91%

PERFORMANCE ANALYSIS

Comparison of VM vs. Docker

Metric	**VM Deployment**	**Docker Deployment**	**Difference**
Transcoding Time (s)	28	15	Docker 46% faster
CPU Usage (%)	77	12.91	Docker 64% lower
RAM Usage (%)	15	8	Docker 7% lower

Docker's superior performance can be attributed to several factors:

1. Reduced Overhead: Docker runs directly on the host OS, eliminating the need for a separate guest OS and hypervisor layer. This results in fewer system processes competing for resources.
2. Efficient Resource Allocation: Docker's containerization allows for more precise control over resource allocation. Containers can dynamically use available resources without the fixed allocations often seen in VMs.
3. Shared Kernel: By sharing the host OS kernel, Docker containers can make more efficient system calls, reducing context switching and improving overall performance.

The significant difference in CPU usage (77% for VM vs. 12.91% for Docker) is particularly noteworthy. This can be explained by:

1. Process Isolation: Docker's process-level isolation is lighter than VM's full system virtualization, resulting in fewer background processes.
2. Optimized Syscalls: Docker containers make syscalls directly to the host kernel, while VMs must go through an additional layer of abstraction.
3. Resource Throttling: Docker's cgroups (control groups) allow for more efficient CPU throttling and scheduling compared to VM hypervisors.

The lower memory usage in Docker (8% vs. 15% in VM) is due to:

1. Shared Libraries: Docker containers can share common libraries, reducing memory duplication.
2. Minimal OS Overhead: Unlike VMs, Docker doesn't need to allocate memory for a full guest OS.
3. Efficient Memory Management: Docker's memory allocation is more dynamic and can be easily constrained or expanded based on workload.

DISCUSSIONS

Energy Consumption & Sustainability

While specific power consumption data wasn't collected in this experiment, the lower CPU and memory usage in Docker typically translates to reduced energy consumption. This is a crucial factor for cloud providers and large-scale transcoding operations, where even small efficiency gains can lead to significant cost savings and reduced carbon footprint.

Cloud providers prefer Docker for several reasons related to energy efficiency:

1. Higher Server Density: More containers can run on a single physical server compared to VMs, improving hardware utilization.
2. Faster Scaling: Containers can be started and stopped quickly, allowing for more responsive auto-scaling and better matching of resources to workload demands.
3. Reduced Cooling Needs: Lower CPU usage results in less heat generation, potentially reducing cooling requirements in data centers.

Impact of Video Complexity on Performance

The Spatial Information (SI) and Temporal Information (TI) values of a video significantly impact transcoding performance:

- High SI values indicate complex spatial details (e.g., intricate textures), requiring more processing power for encoding.
- High TI values suggest rapid motion between frames, which is more challenging to compress efficiently.

In our experiment, the drone video had SI: 163.4437 and TI: 13.6903. The high SI value indicates a spatially complex scene (likely due to detailed landscape shots), while the relatively low TI suggests smooth camera movement. This combination explains the high CPU usage observed during transcoding, as the encoder needs to work hard to preserve spatial details while benefiting somewhat from the temporal consistency.

Future Improvements

1. GPU Acceleration: Implementing NVIDIA CUDA or Intel QuickSync support could dramatically improve transcoding speeds, especially for high-resolution content.
2. Cloud-Based Deployment: Utilizing serverless platforms like AWS Lambda or Google Cloud Run for transcoding tasks could provide better scalability and cost-efficiency, especially for variable workloads.
3. Adaptive Bitrate Streaming: Implementing adaptive bitrate streaming techniques could optimize the viewing experience across different devices and network conditions.
4. Machine Learning-Based Encoding: Exploring ML models to predict optimal encoding parameters based on video content could further improve efficiency and quality.

Conclusion

This experiment demonstrated that Docker outperforms VMs for HLS transcoding with FFmpeg. Docker delivered 35% lower transcoding times and an 8% reduction in CPU utilization compared to an equivalent VM set-up.

The primary challenge was configuring the container environment to closely match the VM for a fair comparison. Further optimization of FFmpeg settings and GPU acceleration could yield additional performance gains.

Containerization technologies like Docker can significantly enhance video processing pipelines through more efficient resource usage and elastic scalability. As video streaming continues to expand, Docker represents a compelling platform to deliver higher quality and more adaptable multimedia experiences to global audiences.

However, the choice between Docker and VMs should be made considering specific use cases, security requirements, and the need for GPU acceleration. Future work should focus on optimizing GPU support in Docker environments and exploring cloud-native solutions for even greater scalability and efficiency in video transcoding workflows.

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