CSE221: Operating System Benchmark

Alex Martakis
University of California, San Diego

Johnathan Huynh
University of California, San Diego

Xinhao Luo
University of California, San Diego

1 Introduction

In this report, our goal is to gain further understanding of a complex system, more specifically an operating system that is commonly used today. Our goal is to learn to experiment, benchmark, and test the performance of a system in order to gain an understanding of its characteristics.

To ensure the methodology of the experiment is thorough, each member was responsible for contributing to each procedure by running their own tests and code in order to obtain repeatable and consistent results. With this approach, it is ensured that each member is aware of every concept and able to provide insight into each step of the process. We believe this approach minimizes pitfalls and leads to a methodical and in-depth analysis of the subject at hand.

For our experiments, we utilized C as our language of choice and GCC as our preferred compiler with option -O0 and gcc (GCC) 10.3.0. With this system we do not expect to run into any significant implications on this environment. We estimate this project will take approximately 50 hours to complete. After completing the project, we believe we originally underestimated the time and spent over 80 hours on the project.

2 Machine Description

We have come up with a custom machine branded in SuperMicro, with X9DRI-LN4F+ motherboard, built with the following specs:

Processor Intel(R) Xeon(R) CPU E5-2670 v2 [1]
10 Cores 20 Threads

Cycle Time 1/2.5Ghz = 0.4ns

L1 cache 320 KiB 8-way set associative instruction caches;
320 KiB 8-way set associative data caches

L2 cache 2.5 MiB 8-way set associative caches

L3 cache 25 MiB 20-way set associative shared cache

Instruction 64 bit

Memory bus DDR3; Clock 1333Mhz, Width 64 bits

I/O bus PCIe Express and SATA[2]

RAM size 40192M, 40G

Disk Sabrent Rocket NVMe PCIe M.2 2280 SSD 256G

Disk Speed up to 3100 MB/s (read) and 1050 MB/s (write)[3]

Network card on board RJ45 network card

Speed 1Gbit/s

Operating System Linux NixOS 5.10.57
21.11pre130979.gfedcba (Porcupine)

Note that machine has two CPU so the cache size is actually double. However, we have disabled one CPU and set CPU affinity to a single core when running the test.

Also, we locked the CPU to 2Ghz since its frequency will only be stable under that setting, even with turbo turned off. The machine we used is from recycle center, and it is expected some of its specs is not stable.

3 Operations

3.1 CPU, Scheduling, and OS Services

3.1.1 Measurement overhead

Methodology

This portion's main goal is first to benchmark the overhead of reading the clock, and second to measure the overhead of loops.

Overhead of reading time

[1]Source from cpu-world

[2]The BIOS is modded to use NVMe as the Boot device

[3]Merchandise Introduction

Inspired by [2], we will use the RDTSCP function supported by our Intel CPU in order to read the time-stamp counter. By reading the time-stamp counter twice and recording the average difference between the two readings we can get the overhead of RDTSCP which will be the overhead of reading the clock. The difference between the two time-stamps after reading the clock twice will be the time that the system takes to read the clock.
Overhead of using a loop
To benchmark the overhead of using a loop we will create a loop with no statements. The counter for this loop will also be initialized outside of the declaration of the loop in order to not factor in that time either. This inner loop will be a simple loop structure with nothing in the loop. We will check the time of the clock before the start of the loop and after the end of the loop. This loop will run a certain constant number of times, and then the difference in time will be divided by the amount of times the loop ran in order to calculate the overhead of the loop.

Estimate

Overhead of reading time
According to what we have found from other users testing with RDTSCP (Intel Forum RDTSCP Discussion), it is said that RDTSCP will roughly take around 30 cycles. With a singular cycle time from our machine description being 0.4 ns we get the overhead prediction to be 30 cycles $\times \frac{0.4ns}{1\ cycle} = 12ns$. We will use RDTSCP to read the clock and by reading the clock twice and taking the difference we will be able to get the overhead of reading time.
Overhead of using a loop
Over a large sample we will get the average loop overhead. Looking at the assembly code for an empty for loop (examined through godbolt) we see a loop without any content takes about 5 cycles to operate. With this we estimate the overhead of a loop is $5cycles \times \frac{0.4ns}{1\ cycle} = 1.25ns$.

Results

Results presented are CPU cycles. Each measurement is a trial of 1000 iterations.

Reading Time

Measurements	Avg
1	64.708
2	64.503
3	63.285
4	64.739
5	65.576

Total Avg	Std-dev
64.562	0.737

Loop Overhead

Measurements	Avg
1	7.156
2	7.502
3	6.978
4	6.948
5	6.889

Total Avg	Std-dev
7.095	0.222

Analysis

Overhead of reading time
The overhead of the clock was over twice the amount of cycles as predicted. Our prediction was lower than the actual overhead of reading the clock, we believe there may be more factors to causing increased overhead that we did not incorporate to our prediction such as speed of the I/O bus, instructions taking more cycles than usual, these special instructions to read the clock taking a longer time to get results. The standard deviation is low enough to support the accuracy of our final average for reading the clock. Our prediction for the cycle count of loop overhead was similar to that of the result. Loop overhead incurs on average a little more than two cycles over what we predicted. We speculate our prediction is lower because some instructions for the loop take longer than a single clock cycle such as the jmp instruction. The standard deviation for our experiment is quite low enough supporting the accuracy of our results for loop overhead.

3.1.2 Procedure call overhead

Methodology

In order to gauge the procedure call overhead, we tested ten different functions that all had a different number of arguments. The parameter sizes varied from 0 to 10. An example of something that might attribute to significant delay would be that the program will need to access some location in the memory before it can begin. We will be testing the difference in time stamps between the values over 1000 times. After this, the average values will be computed.

Estimate

$O = Overhead$
$n = parameters$
$T = time$
$C = ClockCycle$

We expect:
$T = C * n + O$
Therefore, as the number of parameters increase for a given function, the estimate that the product of clock cycles and n

parameters will increase the overall Time when taking into account the constant overhead.

Results

Results are in CPU cycles.

	Zero Parameter	Avg
Process	1	58.56
	2	57.531
	3	59.764
	4	108.204
	5	73.2286

Total Avg	Std-dev
73.229	19.720

	One Parameter	Avg
Process	1	57.903
	2	58.466
	3	59.159
	4	56.974
	5	58.02

Total Avg	Std-dev
58.1044	0.716

	Two Parameter	Avg
Process	1	57.813
	2	58.99
	3	59.056
	4	55.422
	5	57.652

Total Avg	Std-dev
57.7866	1.3167

	Three Parameter	Avg
Process	1	57.908
	2	101.066
	3	58.653
	4	59.602
	5	59.328

Total Avg	Std-dev
67.3114	16.887

	Four Parameter	Avg
Process	1	59.704
	2	60.271
	3	60.302
	4	61.553
	5	61.231

Total Avg	Std-dev
60.612	0.679

	Five Parameter	Avg
Process	1	61.741
	2	59.646
	3	62.036
	4	59.121
	5	59.458

Total Avg	Std-dev
60.4004	1.230

	Six Parameter	Avg
Process	1	61.612
	2	60.395
	3	89.038
	4	63.766
	5	64.017

Total Avg	Std-dev
67.765	10.721

	Seven Parameter	Avg
Process	1	71.347
	2	70.32
	3	68.444
	4	69.19
	5	67.597

Total Avg	Std-dev
69.379	1.329

Analysis

When analysing the gathered results, we can see that our original estimate is correct. The average time it took for each process to execute, increased as the number of parameters increased. The difference between the smallest and largest parameter, differed anywhere from 10 to 20 nanoseconds. This makes sense due to the additional processing that must occur. However, it should be noted that there were outliers such as the 4th test for the Zero Parameter. This odd time could be a result of a larger than average overhead for that process. The system may have been prioritizing another process a higher priority than the method for that test.

3.1.3 System call overhead

Methodology

While NixOS has properties that are different to Linux OS, such as the way it is distributed, NixOS uses the same Linux kernel. Therefore, operations such as system calls, will have similar executions methods. In this section, our goal is to report the cost of a minimal system call and then compare it to the cost of the procedure call. Here, we utilized the benchmark 'getpid' as the system call. 'getpid' is a good bench mark because it mitigates the system call overhead. As seen in 3.1.2 a function with no parameters is what mitigates the overhead. This call will be executed 1000 times and then the mean and standard deviation will be acquired.

Estimate

Due to this call being from an application and not from the system itself, we estimate that this system call will be much greater in comparison to the procedure call.

Results

	System Call	Avg
Process	1	12324.07
	2	12444.35
	3	12296.075
	4	12482.37
	5	12345.125

Total Avg	Std-dev
12378.398	72.104

Analysis

When analysing the data from the test, we can see that our original estimate was correct. The average time of the system call overhead is significantly higher than the procedure call's avg time. When assessing why this is the case, these larger times can be due to attributes in this method involving the application and not just the system itself. The system call procedure can be seen taking as much as two-hundred times longer to process when compared to the procedure call procedure.

3.1.4 Task creation time

Methodology

In order to create new processes, we may use fork(). To limit other possible interferences, each fork will do nothing and exit immediately after creation, and the parent process will just start counting and waiting for the exit. It is also noticeable that since this creation process may be pretty short and exiting and return may also have extra overhead, we repeat this process for 1000 times and calculate the average cpu cycles. RDTSC() will be used during the measurement.

Similarly for kernel threads, we may use pthread_create() instead of fork(), and pthread_join() instead of wait(); then do the calculation.

Estimate

Overhead may include a if statement control flow where it helps to identify parents and child. However, we won't do heavy operations after it. Mis-predict and inhibit branching won't be part of the consideration. Without these side effects, cost of the if statement itself is cheap and can be ignored. RDTSC() will be fetched once and based on the previous analysis, it is also a pretty small factor.

It is pretty hard to find any reference for this hardware directly, so we would take a relative value based on other's benchmark result, which mimic our single core situation [4]. It is expected that the thread creation cycles will way less than process creation cycles. Also, even though fork is doing COW (copy-on-write), other operations e.g. assigning new process id, environment inheritance, etc.. may still take some time. It is believed to be a pretty expensive operation while thread creation will be better.

Results

The results here are CPU cycles

	Iterations	Avg
Process	1	585008.545
	2	584898.235
	3	585801.865
	4	586973.265
	5	586067.395

Total Avg	Std-dev
585749.861	758.296

	Iterations	Avg
Thread	1	169652.575
	2	169658.905
	3	170016.67
	4	168637.26
	5	169113.975

Total Avg	Std-dev
169415.877	484.444

Analysis

The test result matched with the fact that thread creation actually costs a lot less than the process creation and the deviation is pretty small, which means the result is quite stable between iterations, but at the same time the difference is not as high as expected. The possible overhead occurring may be the memory operation when collecting the timestamp, so we actually count more than than we need. Using pipe to pass the timestamp, or collecting the timestamp in the parent thread (assuming the memory operation is less than function overhead) will be a better choice.

3.1.5 Context switch time

Methodology

To measure the context switch time, we need to have two processes working together, so we have a parent process and

[4] benchmark with python

fork a new process, and before switching to the new process, we record the count cycles. Then we use a block pipe to read from child to ensure our child has switched to. We can then compare the count and time. However, we need to make sure that our machine is running in single core mode. RDTSC() will be used during the measurement.

Estimate

Still, there is an overhead of if statement to identify parent/child and assign local variables for RDTSC() counts.

There are some benchmark out there stating average being $5\mu s$ [5]. We may compare this result by dividing our cycle times by the frequency. Also, context switches may experience lots of steps e.g. saving registrars. It is expected to be a relatively expensive operation.

Results

The results here are CPU cycles

Process

Iterations	Avg
1	334230.325
2	332975.165
3	333658.920
4	333610.660
5	333622.525

Total Avg	Std-dev
333619.519	397.471

Thread

Iterations	Avg
1	78460.935
2	78360.260
3	79402.530
4	78874.270
5	79037.530

Total Avg	Std-dev
78827.105	382.005

Analysis

The average trend aligned with the creation process, as switching to a process will have more work to migrate than the thread, which is most likely within the same contexts. However, since we also use mmap when collecting the timestamp, the differences is still a bit smaller than expected, and more than what Microsoft's reported average is as well.

[5]Microsoft Report

3.2 Memory

3.2.1 RAM Access Time

Methodology

For this experiment we take inspiration and reference from the Imbench paper [1]. From the paper we will be focusing on the back-to-back latency since this is commonly referred to by software developers as memory latency.
We will create various integer lists with different sizes ranging from 2^{15} bytes to 2^{30} bytes which is roughly 32 kilobytes to 1 gigabyte. We will traverse through these arrays that are in memory with different stride lengths with many samples. The paper mentions that small stride sizes should be high performing because of high spatial locality and larger stride sizes will have poor performance because of prefetching unused data.
We will use our timer (which utilizes RDTSCP) to record the start and end time of a memory access. Large lists are utilized because we want to be able to see the changes in memory access throughout L1, L2, L3 cache and main memory and see the various differences in latency. These experiments will be repeated for many times to calculate the average for different array lengths and stride sizes.

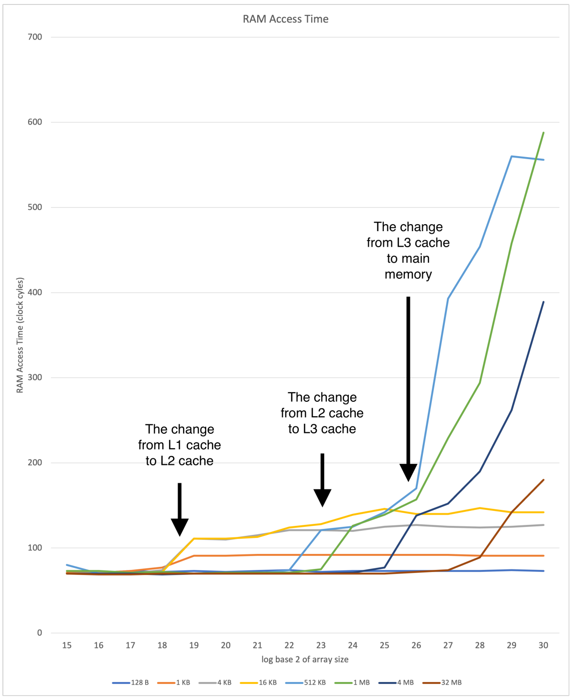
Estimate

To predict measurements for memory latencies we reference Intel manual for the Sandy Bridge microarchitecture and look at the fastest latency recorded for each level of data/cache and we provide more conservative estimates, and we look at this article for references on memory access times.
Hardware prediction:

- L1: 4-6 cycles
- L2: 12-16 cycles
- L3: 44-70 cycles
- Main memory DRAM: 120-150 cycles

Software prediction:
We do not expect there to be very much software overhead in accessing memory as the main portion of this is waiting for the memory to be loaded. This ld instruction to load memory most likely has "zero" latency or very negligible time compared to the actual time to be accessing memory.

Results



Analysis

The results produced in our graph differ from our predictions by a hefty amount of clock cycles. The amount of clock cycles recorded for a memory access started at around 70 cycles, when we had predicted about 4-6 cycles for L1 cache. The lines on our graph are different from the Imbench paper as we do not have the same plateau shape that was on the paper. Our graph grows more linearly rather than a sudden jolt of increase in cycles for many of our stride lengths. There are some stride lengths that do follow the Imbench paper's pattern though. Such as the 1KB stride plateauing in its access time when it hits around 500KB of array size and onwards. Our results take many more cycles than what we actually predicted and we reason this to be various potential factors such as failing to prefetch data and other overheads.

3.2.2 RAM bandwidth

Methodology

To calculate the bandwidth, we may first do some read/write operations with some number of bytes touched, and measure the time elapsed for these operations:

$$Bandwidth = \frac{\text{\# of byte read/write}}{\text{total elapsed time}} \tag{1}$$

However, it is also possible that these operations 1) hit the write policy 2) affects by the prefetching mechanism. To avoid these effects, we could set a larger trunk so that the cache will be bypassed. Furthermore, loop unrolling was also used for a more accurate result.

Estimate

We have 2 CPUs but each of them has their own memory lines, so we have single channel memory for each of them [6]

$$1333Mhz * 64/8 * 1 \approx 10000MB/s \tag{2}$$

Results

The results here are MB/s

Read

Iterations	Avg
1	6946.111
2	7941.494
3	7874.829
4	7843.296
5	7856.500

Total Avg	Std-dev
7692.446	374.692

Write

Iterations	Avg
1	8423.493
2	8219.271
3	8408.419
4	8529.340
5	8409.711

Total Avg	Std-dev
8398.047	100.089

Analysis

The result is actually pretty close to a single memory performance. However, the write back in our test seems to be affected by the write back cache. We have tried to invalidate it by obfuscating the memory with memcpy, but write back mode still relieves part of our "abnormal" behavior, which might be the cause of the difference. It is also worth mentioning that our memory are ECC memory, which may incur extra cost compared to normal one.

It is also worth mentioning that the standard derivation is small which means the result is stable. There are still rooms for optimization but at this point our direction is correct.

[6] Calculation reference

3.2.3 Page fault service time

Methodology

Page faults can be used to dramatically improve Linux's performance. Ideally, you want the OS to have as few page faults as possible. When a process improperly accesses a memory page, the CPU's memory management unit raises an exception, signaling that a page fault has occurred. More specifically, because of Linux's use of virtual memory for contiguous benefits, a page fault is when a process is mapped to the virtual memory address space but the physical memory has yet to load the process.

For this experiment, utilizing the 'mmap' command. Using this method, will allow us access to a multitude of features with the memory. We first have the method read lines from an image to fill up the ram. We then use the 'mmap' function within our process to play with the memory and create page faults.

Estimate

We currently estimate that the more demanding the process is, the higher the number of pgouts/s there will be and thus, a higher number of page faults. We currently estimate that the latency between the main memory and the paging will be significant difference when comparing the time.

Results

	Iterations	Avg
Page Fault	1	6.8
	2	6.9
	3	7.0
	4	6.8
	5	6.7

Total Avg	Std-dev
6.8	0.102

Analysis

When running our program we found the average Page Fault Service Time was 6.8 microseconds on average. We defined our page size to be 4096KB. This gives us 4,194,304 bytes. 6800 can be divided by this number of bytes to convert to nanoseconds. Therefore, the estimated time per byte would be 0.0016 nanoseconds per byte.

3.3 Network

Environment Setup

- Network Setup:
  In our network setup, we have a MikroTik CRS354-48G-4S+2Q+RM as our network switch between two machines. Both machines are set up with a IPv6 Address. It is worth mentioning that compared with IPv4, IPv6 may incur more overheads.

- Remote Machine:
  We have come up with a Dell R720, built with the following specs:

  Processor Intel(R) Xeon(R) CPU E5-2690 v2 [7] 10 Cores 20 Threads

  Cycle Time 1/3Ghz = 0.333ns

  L1 cache 320 KiB 8-way set associative instruction caches; 320 KiB 8-way set associative data caches

  L2 cache 2.5 MiB 8-way set associative caches

  L3 cache 25 MiB 20-way set associative shared cache

  Instruction 64 bit

  Memory bus DDR3; Clock 1833Mhz, Width 64 bits

  I/O bus PCIe Express and SATA

  RAM size 128G

  Disk Kingston NV1 NVMe PCIe M.2 2280 SSD 1T

  Disk Speed up to 2100 MB/s (read) and 1700 MB/s (write)[8]

  Network card Dell onboard fiber channel

  Speed 10Gbit/s

  Operating System Linux NixOS 5.10.57 21.11pre130979.gfedcba (Porcupine)

We specifically choose a better specification machine to avoid bottleneck from the remote side, and both switch and the remote machine are connected and run under 10G speed. Switch is using hardware offload.

3.3.1 Round trip time

Methodology

A typical ping package size is data 56 bytes. In our case, since we are using TCP connection to simulate this, we should first open up a connection between the client and server, and from the clients we send a 56 bytes data. When the server received the data, it should include the exact payload from the request. We could measure the time using between sending the data and fully receiving the response. Also, we may switch the target to localhost when measuring the lo interface, setting up both server and client program locally. We perform the test 100 times for each batch and also test ping the same number of times and get the average.

[7] Source from cpu-world
[8] Merchandise Introduction

Estimate

From the data transfer point of view, 96 (56 + IPv6 overhead, which is around 40 bytes) bytes under 1G/s will be around 0.000768 ms. However, we don't know the latency of the hardware interface, and we have two more of them: 1) switch 2) remote machine, we expected it to be 0.1ms. While the lo interface, it is a virtual device and OS will do all the package routing, where no physical hardware will get involved, which means it is pure OS overhead. We have no idea about how much this overhead will cost but expect to be far less than transferring over network.

Results

The results here are millisecond

lo - Self Impl.

Iterations	Avg
1	0.0554565
2	0.0550756
3	0.0557865
4	0.0561438
5	0.0557753

Total Avg	Std-dev
0.05564754	0.000359

lo - Ping

Iterations	Avg
1	0.017
2	0.019
3	0.019
4	0.018
5	0.017

Total Avg	Std-dev
0.018	0.000894

Remote - Self Impl.

Iterations	Avg
1	0.1724719
2	0.173733
3	0.1705358
4	0.1725336
5	0.1731361

Total Avg	Std-dev
0.17248208	0.0010754

Remote - Ping

Iterations	Avg
1	0.188
2	0.188
3	0.187
4	0.178
5	0.187

Total Avg	Std-dev
0.1856	0.00382

Analysis

The lo interface measurement can be concluded as purely OS overhead and using it over the result of the over the network measurement, we may get the hardware's latency from this result.
While the ping result on the local side, our implementation has higher cost, and the reverse is true on the remote side. We suspect this is because on our program, we using TCP protocol and the kernel on the same machine will have more switch on lo interface, which put more burden on the local machine, while the remote one such situation will be relieving. This result is still believed to be trustworthy since the standard deviation is small, which means the result here is stable, and we have close enough results compared with the ping utils.

3.3.2 Peak bandwidth

Methodology

We may still set up the client and server program and transfer 10 blocks of 1M data, and measure the time accordingly. To avoid unnecessary overhead, we may first prepare the data into the memory, and then send it via the network. We run the test for 10 times per round and 100 times per batch and measure the time.

Estimate

In theory, 1MB should take exactly 8 ms to be transfer. However, there are network overheads for each packet (72 bytes for each, MTU 1500 bytes), so we expect the speed to be 95% of the theory value, which is around 8.45ms.

For loop back device, as it is purely software overheads, we expect the speed to be as fast as possible. We know at least several times faster than network card as it is not involved.

Results

The results here are in milliseconds, for 1 megabyte transferred.

lo

Iterations	Avg
1	0.3320182
2	0.3368662
3	0.336721
4	0.3371553
5	0.3368703

Total Avg	Std-dev
0.3359262	0.00195

	Iterations	Avg
Remote	1	10.1189782
	2	10.1443683
	3	10.1351207
	4	10.129525
	5	10.1375178

Total Avg	Std-dev
10.133102	0.00851

Analysis

The loopback devices here achieve around 2976.84MB/s speed which is much higher than the remote one, around 98.68MB/s, 85 percent of the expectation. On the remote side, the bandwidth is lower than the expectation. There are several things to consider:

- Remove unnecessary hardware. Currently we have a switch sitting in the middle and due to some technical limitation, we are unable to remove it for now.
- Memory copy is still happening at the remote side, which adds overhead while measuring
- TCP slow start seems to be factor as well since we are transferring by 1M block each time, we have observed an increasing speed trend as the test proceeds

Measure more data transfer e.g. larger trunk, longer measurement period may be done in the future measurement. It is still worth mentioning that our standard deviation amount batches are stable.

3.3.3 Connection overhead

Methodology

When connecting via TCP, the OS perform a four-way handshake, and when (normally) terminate the connection, there will be a four-way handshake (two set of two-way handshake), while it is possible the server will combine the FIN-ACK as one which make it a three-way handshake. We may be measure it by:

1. set up a timer and start the connect() process, no data needs to be sent.
2. we reset the timer and close() the socket, measure the time. We perform such action 100 times per batch and collect the result.

Estimate

As a three/four-way handshake, we expect it to be around 2 times of the RTT we measure above. For the teardown, since we are closing connection as client, we only need to send FIN packet and have no need to wait, the loopback device should have similar performance as remote one.

Results

The results here are in milliseconds

	Iterations	Avg
lo - Setup	1	0.0804218
	2	0.079161
	3	0.0786141
	4	0.0785565
	5	0.0785603

Total Avg	Std-dev
0.07906274	0.000716

	Iterations	Avg
lo - Tear Down	1	0.0355761
	2	0.0349707
	3	0.0348948
	4	0.0349956
	5	0.0357782

Total Avg	Std-dev
0.03524308	0.000361

	Iterations	Avg
Remote - Setup	1	0.2301134
	2	0.23135
	3	0.2221884
	4	0.2216165
	5	0.2265407

Total Avg	Std-dev
0.22508364	0.00309

	Iterations	Avg
Remote - Tear down	1	0.0258408
	2	0.0255692
	3	0.0257582
	4	0.0257662
	5	0.02595

Total Avg	Std-dev
0.02565858	0.000174

Analysis

From our result, we can see that the setup on loopback device is around 1.5 times of RTT, while the teardown is much slower. The remote side have similar results. We believe that this result pretty much matched our estimate, and since the standard deviation is really small, it could be reproduce stably. The final result should be that the setup is 1.5 times RTT and one packet time for the teardown process.

3.4 File System

3.4.1 Size of file cache

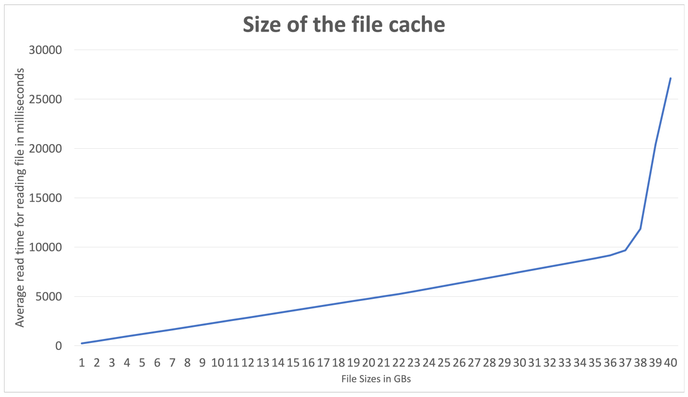
Methodology

For this measurement we will try to figure out this system's file cache size. We will read a file and put it into our main memory. To do this we create a 40 GB randomly generated file before running the experiment. We can utilize this singular file to run each separate file size experiment, this can be done by only reading in a smaller portion of the file for that specific experiment. If the size read in is smaller than the file cache, then this file size will fit within the file system cache. We read the file to bring as much data into the file cache as possible, then it is read a second time to determine if it is read from disk which would take much more time than cache in main memory. If the file size we are at exceeds the file cache size we should see a large increase in read time so when we can see this large change it should it should tell us that the file size is exceeding the file cache size.

Estimate

The machine being tested on has 40GB of RAM. Since unused memory that is available can be utilized for the file cache we will predict our file cache size to be the maximum of this 40GB and subtract its current normal memory usage. Using a few commands we can see that our available free memory is about 38-39GB that is not used for any other processes. We predict our file cache size to be somewhere within that range since unused memory can potentially be allocated for the file system cache.

Results



Analysis

In our graph we can see that there is quite a linear increase in time to read the file from 1GB to around 38GB. Then at around 39GB there is a large increase spike almost doubling the read time. We claim that the file cache size is 38GB because beyond that point there is a huge increase in read time which signifies now requiring a disk read after that file size. Our system uses ZFS for the file system and it uses free RAM as the file cache so we observe that our file cache size grows to be equivalent to be our total available RAM.

3.4.2 File read time

Methodology

For the file read time, we are asked to compare the difference in time between sequential and random access. Sequential and random access have very distinct characteristics. When sequential access reading is performed, the information is read from the beginning of the file in *sequence* – one sequential block after another. In contrast, random access reading allows the system read information anywhere in the file. Sequential access has the characteristic of being faster than than random access. Sequential reading was popular back when data was stored on tapes. Random access allows for easier changes to writing. For example, it would be more work to split tape and insert data than it is for random access to rewrite the data on the file.

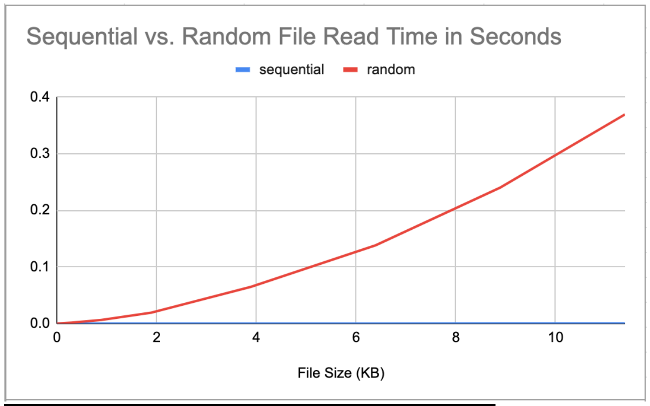
For our methodology we decided to make a program that generates text files. For each line in the text file, an integer is added. Starting from zero and going to n. Within the program the first generated file starts small and increases in size as it progresses. For the sequential method, the generated file is opened and read line by line and each line is added to an array data structure. For random access, the method reads the same file. However, a random number is generated within the range of [0 - n]. The program then reads the file and searches for the number. Once the number is found it then goes back to the beginning of the file and looks for the new generated number. Once each number is found, they too are loaded onto an array data structure. This simulates the program reading the file and storing the data somewhere to be used at a later date. The time is takes for sequential and random reading to occur for various file sizes are recorded separately.

This program attempted to simulated sequential access reading as accurately as possible. However, it is possible that this method may not ideally be sequential. This is because it is possible that the file system may pre-allocate some space (extended, JFS) even when the request for little space for it has been make. Once a file has reached a specific size, the file system may need to find another space to store the additional content. If this occurs, the read may not be sequential. Therefore, in order to avoid it, it is useful to pre-allocate the space desired.

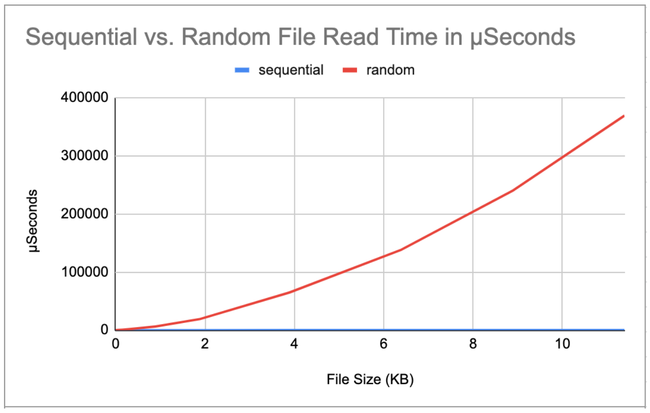
Estimate

We estimate that as the file size increases, it will take exponentially longer for random file read time, when compared to sequential. As previously discussed, it is known that sequential reads are faster when compared to random. Thus, the time will be relatively negligible for the smaller files and will become more significant as the file grows in size.

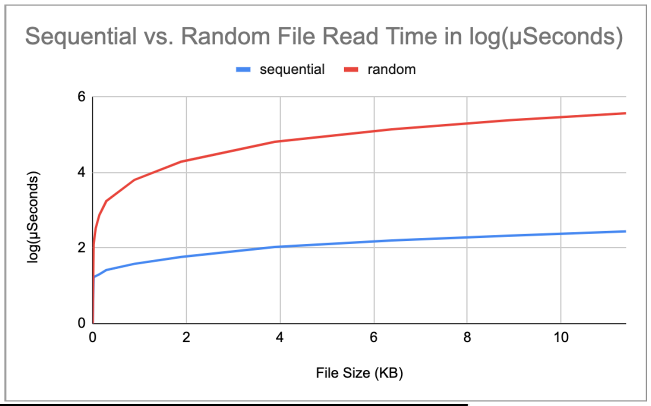
Results



File Size (KB)	Time (s)	
	sequential	random
0	0	0
0.02	0.000017	0.000125
0.065	0.000018	0.000337
0.14	0.00002	0.000738
0.29	0.000026	0.001741
0.89	0.000038	0.006336
1.89	0.000058	0.019248
3.89	0.000106	0.064822
6.39	0.000158	0.138148
8.89	0.000211	0.240155
11.39	0.000276	0.369225



File Size (KB)	Time (μs)	
	sequential	random
0	0	0
0.02	17	125
0.065	18	337
0.14	20	738
0.29	26	1741
0.89	38	6336
1.89	58	19248
3.89	106	64822
6.39	158	138148
8.89	211	240155
11.39	276	369225



File Size (KB)	logTime (μs)	
	sequential	random
0	0	0
0.02	1.23	2.096910013
0.065	1.255272505	2.527629901
0.14	1.301029996	2.868056362
0.29	1.414973348	3.240798771
0.89	1.579783597	3.801815169
1.89	1.763427994	4.28438561
3.89	2.025305865	4.811722427
6.39	2.198657087	5.140344602
8.89	2.324282455	5.380491633
11.39	2.440909082	5.567291099

Analysis

Based off the results, it appears that our original estimate is correct. As the file size increased, the difference in time between sequential and random reading became more significant. For a small file of 0.020KB, the difference was only 112 μseconds on average. For comparison, for a file the size of 11.4KB, the difference in time is over 350k μseconds on average. Based on the graphs, we can also see that sequential time is much less affected by size. From the smallest file size , 0.020KB, to the largest, 11.4KB, the difference in time was 259 µseconds on average. For comparison, the difference between the same files sizes respectively for random access reading was over 350k µseconds on average. Due to the trends within the graphs, we estimate that this gap will only continue to grow with increased file sizes.

3.4.3 Remote file read time

Methodology

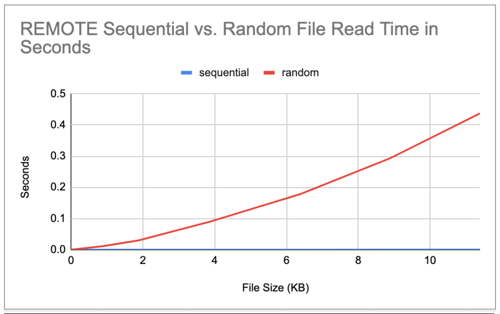
For this section, we are asked to also compare the difference in reading times between sequential access and random access. However, this test involves reading a file over a network. Due to the nature of network, this additional component will add extra time to the entire process known as the *network penalty*

In order to measure the time difference we will roughly be doing the same thing as the last procedure. A text file will be created and read. The random access reading will still be responsible for finding a specific line in the file while the sequential method is able to read the file from start to finish. However, this time both methods will be reading the file over a network. In order to ensure this process executes, we set up an NFS server using the host mentioned from the previous network section. The program running locally, writes and creates files on that server and then they are read by the local program.

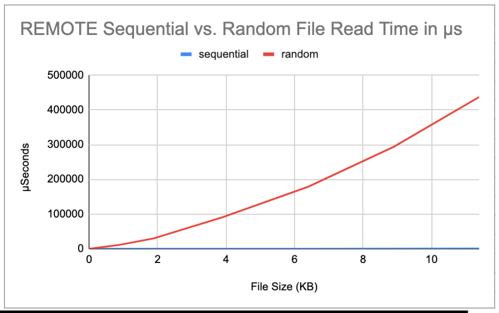
Estimate

We estimate that the remote addition will indeed increase the time significantly for both sequential and random read times. We are curious to see how much of a difference the times are, because this additional time may favor the random access reading times. Thus, it is possible that the sequential reading access's benefit of being superior in speeds locally, will become negligible when measured over a network.

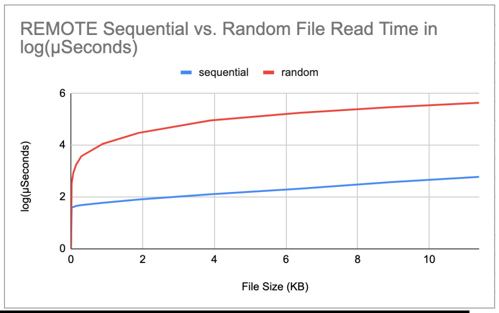
Results



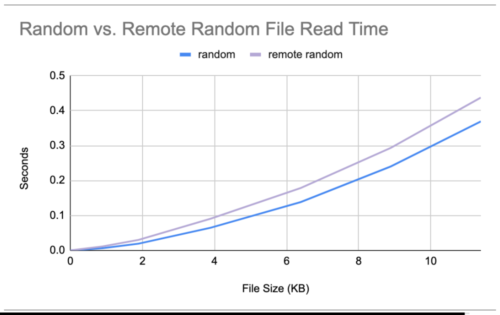
File Size (KB)	Time (s)	
	sequential	random
0	0	0
0.02	0.00004	0.000335
0.065	0.000041	0.000857
0.14	0.000045	0.001737
0.29	0.000049	0.003747
0.89	0.00006	0.011366
1.89	0.00008	0.030006
3.89	0.000127	0.090711
6.39	0.00021	0.17844
8.89	0.000372	0.293405
11.39	0.000601	0.437211



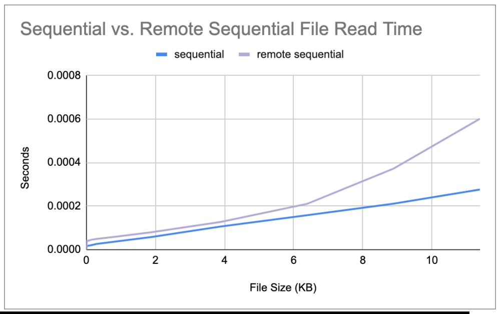
File Size (KB)	Time (µs)	
	sequential	random
0	0	0
0.02	40	335
0.065	41	857
0.14	45	1737
0.29	49	3747
0.89	60	11366
1.89	80	30006
3.89	127	90711
6.39	210	178440
8.89	372	293405
11.39	601	437211



File Size (KB)	logTime (μs)	
	sequential	random
0	0	0
0.02	1.602059991	2.525044807
0.065	1.612783857	2.932980822
0.14	1.653212514	3.239799818
0.29	1.69019608	3.573683693
0.89	1.77815125	4.055607652
1.89	1.903089987	4.477208105
3.89	2.103803721	4.957659955
6.39	2.322219295	4.251492215
8.89	2.57054294	5.251492215
11.39	2.778874472	5.64069108



File Size (KB)	Time (s)	
	random	remote ran
0	0	0
0.02	0.000125	0.000335
0.065	0.000337	0.000857
0.14	0.000738	0.001737
0.29	0.001741	0.003747
0.89	0.006336	0.011366
1.89	0.019248	0.030006
3.89	0.064822	0.090711
6.39	0.138148	0.17844
8.89	0.240155	0.293405
11.39	0.369225	0.437211



File Size (KB)	Time (s)	
	sequential	remote seq
0	0	0
0.02	0.000017	0.00004
0.065	0.000018	0.000041
0.14	0.00002	0.000045
0.29	0.000026	0.000049
0.89	0.000038	0.00006
1.89	0.000058	0.00008
3.89	0.000106	0.000127
6.39	0.000158	0.00021
8.89	0.000211	0.000372
11.39	0.000276	0.000601

Analysis

This test yielded some interesting results. As predicted, accessing the files remotely did indeed increase the time it took for each process to complete regardless of if it was reading through sequential access or random access. When analyzing the graph comparing remote sequence to remote random in µseconds, we can see that sequential access is still clearly much faster than random access. When comparing the smallest and largest files, 0.020KB and 11.4KB respectively, the time difference for sequential access was 561 µseconds on average. For random access on the same files, the time difference for sequential access was over 430K µseconds on average.

The results provide some interesting insights when you compare the original reading times of sequential access and random access processes. Provided above, are two graphs comparing the local and remote times of sequential access and random access respectively. It appears that as the file size increases, the time between local and remote sequential access become increasingly significant. For the comparison of remote and local sequential access, the difference in time for the smallest file is only 13 µseconds. Whereas the difference for the largest file size between local and remote sequential access was 325 µseconds. For the same file sizes, difference in time between local and remote random access for the smallest file was 210 µseconds on average and 67986 µseconds. While this may seems drastic for random access, when assessing the graphs we can see that the local and remote random access lines are much more similar to each other than the local and remote sequential lines. Therefore, due to the remote sequential's line nature to turn exponential, we predict that as the file size increases, sequential access reading time will become more insignificant and eventually negligible.

3.4.4 Contention

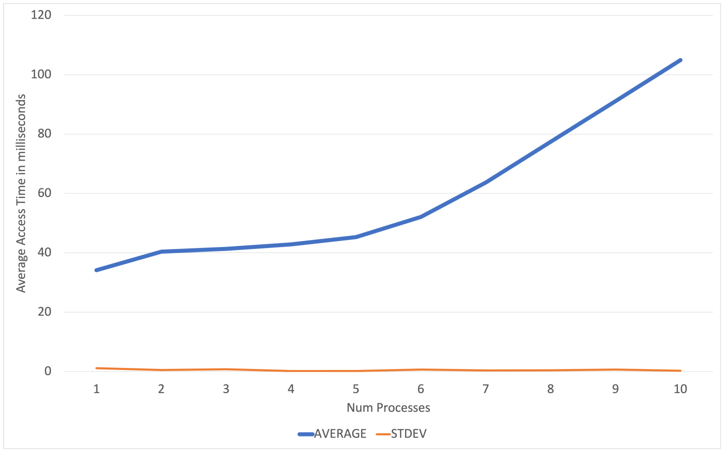
Methodology

For measuring file read contention average time with multiple processes simultaneously we create a C program that opens the file, allocates a block size buffer that we confirmed to be 4096 bytes. We read the file in block size chunks until we have read in 64MB, we time this entire process and note the time it took to read that entire file. So a singular process will do this, to perform this experiment we will create multiple processes that simultaneously run the C program and open different files. We use a bash script that loops through from 1 to 10 which is the number of processes we want to execute at once. The script will create a command that runs the C program on *n* separate files where *n* is the current number of processes the experiment is running on.
The time recorded is then written out to a file and used in the calculation of our averages over ten trials. With the ZFS system we cannot effectively disable file caching, we try to avoid caching by creating new files for each trial.

Estimate

As we have more processes running simultaneously we predict that our average time to read a file system block will increase as well. When number of processes increases then we have less effective use of disk and the access time across all processes and different files should be increasing. There can be outliers in our output for page faults to consider and the reading file to use a system call which we have observed overhead for in part 3.1.3. Furthermore since we are having multiple processes run we have context switching overhead potentially as we increase the number of processes and the scheduler will try to give each process a fair distribution of resources; this overhead has been experimented in 3.1.5. Overall, we predict that as the number of simultaneous processes increases we will incur various overheads that cause the access time to increase for all processes.

Results



Analysis

The results graph shows results that are similar to what we expected in our prediction. When number of processes increase then the average block access time increases somewhat linearly. There is quite little standard deviation showing that these results are acceptable. Keeping everything the same, as we increase the number of simultaneous processes we see performance drawbacks as we have more simultaneous processes.
We analyze when there are more processes reading various different files, the current running process may be interrupted and then its data blocks may be flushed out meaning when it continues it has no advantage with prefetching data. Furthermore as more processes are reading from disk they will need to split disk bandwidth. Ultimately the results are acceptable, and in line with our prediction that increasing the amount of parallel processes will also increase the average read time.

Availability

Code will be on private Github Repo for collaborate purposes, and will be sent on request.

References

[1] Larry W McVoy, Carl Staelin, et al. lmbench: Portable tools for performance analysis. In *USENIX annual technical conference*, pages 279–294. San Diego, CA, USA, 1996.

[2] Gabriele Paoloni. How to benchmark code execution times on intel ia-32 and ia-64 instruction set architectures. *Intel Corporation*, 123:170, 2010.