Elasticizing Linux via Joint Disaggregation of Memory and Computation

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Abstract
In this paper, we propose a set of operating system primitives which provides a scaling abstraction to cloud applications in which they can transparently be enabled to support scaled execution across multiple physical nodes as resource needs go beyond that available on a single machine. These primitives include \textit{stretch}, to extend the address space of an application to a new node, \textit{push} and \textit{pull}, to move pages between nodes as needed for execution and optimization, and \textit{jump}, to transfer execution in a very lightweight manner between nodes. This joint disaggregation of memory and computing allows for transparent elasticity, improving an application’s performance by capitalizing on the underlying dynamic infrastructure without needing an application re-write. We have implemented these primitives in a Linux 2.6 kernel, collectively calling the extended operating system, ElasticOS. Our evaluation across a variety of algorithms shows up to 10x improvement in performance over standard network swap.

1 Introduction
We are in the midst of a significant transition in computing, where we are consuming infrastructure rather than building it. This means that applications have the power of a dynamic infrastructure underlying them, but many applications struggle to leverage that flexibility. In this paper, we propose supporting this at the operating system level with new primitives to support scaling.

To gain some context on the challenge with scaling, we first discuss how it is predominantly handled today. The most straightforward option, which required no changes to applications, is to simply get a bigger (virtual) machine as load for an application increases. Cloud providers, such as Amazon\cite{3}, offer a wide range of machine sizes which cost anywhere from less than a penny per hour to a few dollars per hour. For cost efficiency, companies wish to use the “right” size machine, which might change over time. But, transitioning from one VM size to another can pose challenges. In some cases, we can take snapshots (e.g., with CRIU \cite{8}) and migrate the application to a bigger/smaller VM, but this can be disruptive, and the management of the application needs scripts and other infrastructure to trigger scaling.

An alternative is to re-write the applications with scaling in mind. To leverage the scaling, commonly applications are built around frameworks such as Hadoop\cite{12}, Apache Spark\cite{26}, MPI\cite{7} or PGAS\cite{1}. These frameworks are designed with the flexibility of being able to execute tasks on a varying amount of distributed resources available. The problem here is two-fold. First, to leverage this, the application needs to be built for this – a significant challenge (requiring a re-write) for any existing application, and forcing application developers to evaluate and become fluent in the latest frameworks and potentially adapt the application as the frameworks change. Second, and perhaps more challenging, is that not every application fits into one of these frameworks.

Another approach to scaling is to replicate VMs/containers when an application becomes popular and requires more resources. This too introduces burdens on the programmer in order to synchronize shared data and state across multiple replicas, as well as to script their applications to spawn/delete replicas depending on load.

In short, in each case, the burden of scaling is placed on programmers. We argue that developers shouldn’t need to be experts in cloud management and other frameworks, in addition to also needing to be fluent in programming and their application domain. Instead, the operating system should provide more support. Broadly speaking, the job of an operating system is to make the life of an application developer easier (through abstraction). A modern OS provides virtual memory abstractions, so developers do not have to coordinate memory use among applications, network socket abstractions, so
developers can send messages without needing to be intimately familiar with the underlying network protocols, and many other abstractions (file system, device, multitasking) all to support developers. We propose that scaling should be an OS abstraction.

Related Work: We are not the first to propose that operating systems should support scaling. Scaling of memory approaches are popular and include efforts such as RAMCloud [22], which requires refactoring in user space to utilize its memory scaling capabilities. An early approach to sharing memory called DSM [21] [12] [17] [16][14][6] suffered from scaling issues, but more recently disaggregation-based approaches towards memory have emerged that are centered around transparent scaling of memory behind the swap interface, such as NSwap, Infiniswap, X-Swap and Memx [20] [10] [29] [4]. Scaling of computation approaches include process migration to machines with more resources [8] [13][8][25][18][27], in addition to the scaling frameworks and replication methods mentioned previously. Approaches to accelerate process migration [24][15] have been proposed to hide the latency of migration by copying most of the process state in the background and only copying a small delta to the new machine after halting the process. Single system image (SSI) OSs such as Kerrighed, MOSIX, Sprite and Amoeba [15][8][5][28] have been created to support operation across a distributed cluster of machines. These approaches typically employ a process migration model to move computation around cluster nodes and require applications to be recompiled for these specialized OSs.

These prior efforts in OS scaling suffer from a variety of limitations. Network swap-based approaches, while being a step in the right direction of disaggregation in the data center, miss the opportunity to exploit joint disaggregation of computation and memory for improved performance. Execution is typically assumed to be pinned on one machine, while memory pages are swapped back and forth remotely across the network. This can result in excessive swapping of pages over the network. In these cases, movement of computation to a remote machine towards a cluster of locality stored in the remote machine’s memory would result in substantially faster execution and lower network overhead, as we will show later.

Combining current network swap approaches with existing process migration techniques to alleviate excessive network swapping overhead would suffer two major limitations. First, each decision to move computation would incur the overhead of copying the entire address space. This is a significant amount of overhead to impose on the network. Second, even with accelerated process migration, there is a substantial delay between the time the decision is made to migrate and when that is completed, at which time the conditions that triggered the original migration decision may be obsolete due to the length of time needed to copy all the state.

Introducing ElasticOS: In response to these shortcomings, we introduce four primitives to realize the scaling OS abstraction - stretch, jump, push, and pull. These scaling abstractions are designed to be transparent, efficient, and practically useful. Our approach is inspired by an early work that hypothesized elasticizing operating systems as a hot research topic, but did not build a working implementation of the proposed concept [11]. Stretch is used when an application becomes overloaded (e.g., a lot of thrashing to disk is occurring), so the operating system stretches the application’s address space to another machine – extending the amount of memory available to the application. Push and pull allow memory pages to be transferred between machines which the application has been stretched to, whether proactively to optimize placement, or reactively to make it so the data is available where it is needed. Jump allows program execution to transfer to a machine which the application has been stretched to. Unlike heavyweight process migration, our jump primitive is a lightweight transfer of execution that only copies the small amount of state needed to begin execution immediately on the remote machine, such as register state and the top of the stack. Any additional state that is needed is faulted in using pulls from the rest of the distributed address space. Having both jumping and push/pull allows for the OS to choose between moving the data to be where the execution needs it, and moving the execution to be where the data is. This supports the natural, but not necessarily perfect locality that exists in applications.

To demonstrate the feasibility of this scaling approach, we extended the Linux kernel with these four primitives, and call the extended Linux, ElasticOS. Figure 1 provides a high level view of ElasticOS. We see that an instance of ElasticOS is capable of spanning a number of nodes in the data center, and that the number of spanned nodes can elastically scale up or down depending upon application demand. The application is executed within ElasticOS, and the scaling primitives are used to support this execution across a distributed collection of resources.
To demonstrate the desirability of these four primitives, we evaluated a set of applications with large memory footprints and compared against network swap, which supports the pull and push primitives, and itself has shown performance improvements of being able to scale memory resources transparently across multiple machines. We illustrate the additional benefit of also transparently scaling computing resources across multiple machines, forming a system with joint disaggregation of memory and computation. Our evaluation shows up to 10x speedup over network swap, as well as a reduction of network overhead by 2x and 5x.

In summary, we make the following contributions.

- Introduce scaling as a new OS abstraction, specifically with four primitives: stretch, push, pull, and jump.
- Provide an architecture and implementation of these abstractions in Linux.
- Demonstrate through an evaluation on Emulab servers that ElasticOS achieves up to 10x speedup over network swap across a range of applications, and up to 5X reduction in network overhead.

2 ElasticOS Primitives in Action

In this section, we describe the four primitives through an illustration of a running program. Figure 2 graphically presents each of the primitives. In this figure, we can see nodes 1 and 2, with pages inside of each node – this represents the physical memory and whether a given page is used (shaded) or unused (unshaded) in physical memory. As a starting point, an application is running on a single machine. Over time, this application grows in memory use to nearly the size of the amount of memory in the entire node (label 0 in the figure). This is when ElasticOS decides to stretch the process, that is to scale out by using memory on a second node (label 1). At this point, the memory available to the application has grown (doubled in the figure, since it is now on two nodes with equal memory, which is not required in ElasticOS). ElasticOS can choose to balance the pages at this point, to transfer pages to the (new) remote node (label 2). These can be chosen by a means, such as least recently used.

Once the process is stretched, this means that the process is effectively running on multiple machines, but each node only hosts some of the pages. At this point, execution continues on the original machine. As not all of the pages are on this machine (which would have naturally happened over time, even if we didn’t balance pages), when the process tries to access a page, it might trigger a page fault. In ElasticOS, the page fault handler is modified to handle this situation. At this point, we perform a pull, where a page from a remote machine (that caused the fault), is transferred to the local machine and the process is resumed. The process will be able to make progress, as the page that is being accessed (and caused a fault) is now local.

If space is needed to perform a pull, we can perform a push to free up memory for the incoming page by transferring a page to a remote node (that we have stretched the application to). Push (and pull) is more versatile, as they can be performed proactively as well – moving pages around, in the background, to optimize the placement for locality (label 3).

The idea of locality is important, especially in regards to our final primitive, jump. Assuming that programs have locality, there is a certain point at which, when we transition into a new pocket of locality, that the amount...
of data that forms that locality is high. It is therefore advantageous to jump execution to the data, rather than pull it all into the local node (as is done in network swap).

In the figure, in steps (4 and 6), the area highlighted in red represents an island of locality that would be more advantageous to jump to rather than pulling the entire group of pages to the local machine. When to jump is an important decision – jumping too much can hurt performance (constantly transferring execution, without making progress), but not jumping enough can also hurt performance (transferring lots of data back and forth between machines). As such, we created an initial algorithm, and implemented it as a flexible module within which new decision making algorithms can be integrated seamlessly.

3 ElasticOS Architecture

In this section, we describe the main components of the ElasticOS architecture. ElasticOS can be built as a service integrated into existing and commercially-available operating systems. Figure 3 illustrates the main functional elements that enable a process (e.g., a.out) to be stretched for distributed execution over two ElasticOS nodes. For clarity purposes, we depict the perspective of pushing and pulling from the perspective of node 1, but in reality all nodes have symmetric capabilities to enable pushing, pulling, and jumping in all directions.

In the remainder of this section, we will provide a more detailed architectural overview focusing on mechanisms that are roughly OS-independent in order to achieve stretching (3.1), pushing (3.2), pulling (3.3), and jumping (3.4). The discussion of OS-dependent elements specific to the Linux implementation is reserved for Section 4.

3.1 Stretching

Stretching is responsible for enabling a process to span multiple nodes. This consists of an initial stretch operation, as well as on going synchronization.

**Initial stretch operation:** In order for a process to span multiple nodes, it needs a process shell on each machine. In this way, stretching resembles previous Checkpoint/Restore (C/R) works [8, 3], except that less information needs to be written into the checkpoint. Here we will need to create a process shell that will remain in a suspended state rather than wholly-independent runnable replica. This makes stretching faster than standard C/R. It requires kernel-space process meta-data. These include virtual memory mappings (mmaps), the file descriptor table, scheduling class, and any other meta-data which is not updated frequently. Other information that is typically modified at a high rate such as pending signals, register state, and stack frames need not be in the checkpoint and will be carried over from the running process whenever it jumps (3.4).

As shown in Figure 4, stretching is triggered by the EOS manager, which continuously monitors process’ memory usage and issues a newly-created signal (SIGSTRETCH) whenever it detects a process that is too big to fit into the node where it is running. Our special kernel-space handler (eos_sig_handler) intercepts the signal and instructs the process-export module (p_export) to send the checkpoint using a pre-created TCP socket to a process-import module (p_import) waiting in the other node. The latter will, then, create a shell process by allocating the necessary kernel-space structures and filling them in with checkpoint data.

**State Synchronization:** After the process has been stretched, and its replica has been created on another machine, additional changes in process state on the first machine will need to be propagated to the replica. This is handled in two ways. Rapid changes in state are handled using the jumping mechanism, as explained later. Changes in state at a more intermediate time scale such as mapping new memory regions and opening or closing files are handled using multicast sockets to listeners on each participating node.

One of the pitfalls to avoid here is that the operating
system scheduler may delay flushing all such synchronization messages until after a jump is performed. If this happens, the system may arrive at an incorrect state or even crash. So, it is crucial to flush all synchronization message before a jump is performed.

3.2 Pushing

Now that the process has presence on more than one machine, its memory pages are pushed between nodes in order to balance the load among participating nodes. Our page pusher piggybacks on existing OS’s swap management (See Figure 5).

Typically, the swap daemon scans least-recently used (LRU) lists to select least recently used page frames for swapping. Our page balancer modifies this page scanner in order to identify pages mapped by elasticized processes (shaded pages in Figure 5) using reverse mapping information associated with the page. These are then sent to a virtual block device client (VBD), similar to the one described in [10], after updating the respective page table entries (PTEs) in the elastic page table. The VBD then forwards the page along with relevant information such as process ID, and the page’s virtual starting address to the page injection module (pg_inject) on the node, which will then allocate a new page, fill it with the proper content, and update the replicas elastic page table.

Maintaining accurate information in the elastic page tables when pushing pages is very crucial to correct execution. As we will see later, jumping depends on this information for locating pages in the system.

3.3 Pulling

Partitioning the process’s memory footprint will, inevitably, result in references to remote pages. These are handled by our modified page fault handler (Figure 6). On a page fault, the handler will consult the elastic page table to identify the page’s location. If it happened to be on a remote node, the page’s starting virtual address and process ID is forwarded to the VBD, which will then contact the page extraction module (pg_extract) on the respective node to pull the page. Once it receives the page’s content, the VBD client, then restores the process’s access to the page.

Whenever a remote page fault is handled as described above, page fault counters are updated. This is required by ElasticOS’s jumping policy (Section 3.4), which will always try to co-locate execution with its most-referenced memory.

3.4 Jumping

Jumping is the act of transferring execution from one node to another. For this, there is both a jumping mechanism that performs a lightweight process migration, and the jumping policy to determine when to jump.

Jumping mechanism: Jumping is a lightweight mechanism similar to checkpoint/restore systems. In contrast to stretching, with jumping, the process does actually transfer execution, and only carries in the checkpoint the information that changes at a high rate. This includes CPU state, the top stack frames, pending signals, auditing information, and I/O context. The overall size of jumping checkpoint data is dominated by the stack frames, so it is very important to include only the top-
most stack memory pages that are necessary for correct execution.

As shown in Figure 7, whenever a jump is deemed necessary by the jumping policy in the EOS Manager, it sends a special signal (SIGJUMP) to the process, which is then routed to the eos_sig_handler which will then instruct the p_export module to checkpoint the process and send the information to the other node’s p_import module. The latter will fill in the appropriate kernel-space structures and set the process’s state to runnable. Notice here that when jumping, no new structures need to be allocated since the process has been already stretched to the target node. Also, notice that the process at the source node will remain in a suspended state. In essence, jumping resembles rescheduling a process from one CPU to another across the boundaries of a single machine.

Jumping Policy Algorithm: Maximizing locality is crucially important to the application’s performance. A naive approach to moving execution and memory pages around in the system will, inevitably, increase the rate of remote page faults leading to poor performance. Thus, a good policy for moving processes close to their most frequently used memory is of critical importance. ElasticOS can achieve this goal by overcoming two challenges, namely having a good sense of how to group interdependent memory pages together on the same node, and detecting which of those groups is the most frequently accessed one.

The first challenge can be overcome by taking advantage of the natural groupings memory pages belonging to an application tend to form due to recency of reference. This property is already evident in the wide adoption of the LRU algorithm for page replacement in most modern OSs. Thus, we can extend LRU algorithms to work in a multi-node system, where pages evicted from one node’s RAM are immediately shipped to another node via our pushing mechanism.

The second challenge can be addressed by implementing a jumping policy that: 1) monitors the process’s page accesses to find the “preferred” node, and 2) reschedules the process to the preferred node if it is running on any of the other ones.

Bear in mind that accurately tracking memory references for a particular process can be a challenging task since CPUs do not report every memory access to the OS for performance reasons. This leaves us with options that provide the “next best thing”, such as counting the number of time the CPU sets PG_ACCESSED flag for a particular page frame when it is accessed in the X86_64 architecture or tracking handled page faults.

4 ElasticOS Implementation

We implemented ElasticOS as a fork of the Linux kernel v2.6.38.8. We chose the 2.6 kernel because it contains the key features that we needed to demonstrate elasticity, e.g. support for 64-bit x86 architectures and a reasonably featured virtual memory manager, while avoiding unnecessary complexity and instability in later kernels.

System Startup: Whenever a machine starts, it sends a message on a pre-configured port announcing its readiness to share its resources. The message includes two groups of information. First, connectivity parameters such as IP addresses and port numbers. Second, information noting the machine’s available resources, which includes total and free RAM. Next, each participating node records the information received about the newly-available node and initiates network connections for the various clients. Finally, EOS manager is started, which will periodically scan processes and examines their memory usage searching for opportunities for elasticity.

Identifying such opportunities can be achieved by examining the per-process counters Linux maintains to keep track of memory usage. They include: 1) task_size inside each process’s memory descriptor (i.e., struct mm_struct) which keeps track of the size of mapped virtual memory, 2) total_vm inside the same structure to track the process’s mapped RAM pages, 3) rss_stat of type struct mm_rss_stat which contains an array of counters that further breaks down task_size into different categories (i.e., anonymous and file-mapped RAM pages used, and swap entries), and 4) maj_flt variable inside the struct task_struct which counts the number of swap-ins triggered by the process.

Linux also maintains memory utilization indicators called watermarks. There are three levels of watermarks: min, low, and high. These levels drive the kernel swap daemon’s (kswapd) activity. When memory usage reaches the high watermark, page reclaim starts, and when it goes down to low watermark, page reclaim stops.

ElasticOS leverages these watermarks and the level of kswapd’s activity to detect periods of memory pressure. Further, it identifies specific memory-intensive processes using the counters mentioned above and marks them for elasticity.

Stretching Implementation: The Linux kernel forces each process to handle pending signals upon entering the CPU. This is when our in-kernel signal handler, the p_export module, checks for pending ElasticOS-specific signals. This design choice of checkpoint creation logic placement gives us access to register state, while preventing the process from updating its own memory while a checkpoint is in progress.
The handler, then, accesses the process information while writing them to a socket initialized during system startup. At the other end of the socket, the p_import module collects the information and uses it to create the new shell process.

The key items that are included in this checkpoint consist of: contents of the process descriptor (struct task_struct), memory descriptor and (struct mm_struct) virtual memory mappings (struct vm_area_struct), open files information (struct files_struct), scheduling class information (struct sched_class), signal handling information (struct sighandler_struct), and few others. The overall size of the this checkpoint in our experiments averages around nine kilobytes, which are dominated by the size of the process’s data segment which is also included in the checkpoint.

Note, that we do not need to copy memory pages containing the code, since our implementation assumes that the same file system is available on all participating nodes. Instead, we carry over with the checkpoint data the mapped file names. Our p_import module will locate and map the same files at the appropriate starting addresses.

P_import handle the process creation the same way as if it were forked locally while substituting missing values with others from the local machine. For example, it assigns the newly created process a "baby sitter" to replace the real parent from the home node.

Finally, the p_import module leaves the newly created process in a suspended state and informs the p_export module that it can allow the original process in the source node to resume execution.

**Pushing and Pulling Implementation:** We extend Linux’s second-chance LRU page replacement algorithm by adding multi-node page distribution awareness to it. In this version, pages selected for swapping out belong to elasticized processes and are pushed to another node and injected into the address space of the process duplicate there. Second-chance LRU groups pages in reference-based chronological order within the pages list. So, it is most likely that pages at the rear of the queue, which are typically considered for eviction, are related in terms of locality of reference.

One challenge that needed to be solved to implement page balancing is identifying pages belonging to an elasticized process and what virtual address they are mapped to. Luckily, Linux maintains a functionality called reverse mapping, which links anonymous pages to their respective virtual area map. By walking this chain of pointers and then finding which process owns that map, we can tell them apart from other pages owned by other processes in the system. Then, with simple calculations we can find the starting virtual address of that page. As for moving pages from one machine to another, we created a virtual block device (VBD) that sends page contents using a socket connected to a page server on the other machine (VBD Server) rather than storing it to a storage medium. This was shown in Figure 6. This virtual block device is added to the system as a swap device. All pages belonging to an elasticized process sent to the other machine are allocated swap entries from this device. This swap entry is inserted into the page table of the elasticized process where the page is mapped. As a result, if that page needs to be faulted in later on, the swap entry will route the page fault to our VBD. This design choice allows us to reuse Linux’s page eviction and faulting code.

**Jumping:** Whenever a remote page fault occurs, a remote page counter is incremented. We keep track of the number of remote page faults to use it later on for jumping. As the page remote fault counter builds up, it will show the tendency of where page faults are "going". If the remote faults count value hits a predetermined threshold, then the system could determine that the process would better exploit locality of reference if it jumps to the remote node. Jumping starts by sending a special signal to the target process, which is handled by an in-kernel checkpoint module. This module will, then, copy only the necessary information for the process to resume on the other node. This information includes: 1) the thread context, which contains the register state and other flags, 2) pending signals (i.e., struct sigpending contents inside struct task_struct), 3) auditing counters, and 4) the stack page frames (i.e., RAM pages mapped inside struct task_struct), with the flag VM_GROWSDOWN set). In our tests, the checkpoint size was roughly 9KBs and was dominated by the two stack page frames (4KBs each). Other information about the process will be synchronized using a special module described next. These pieces of information are sent to the restart module in the remote node via a pre-established TCP connection. In its turn, the restart module updates the process information with the checkpoint data, and sends a (SIGCONT) to the process. This will inform the scheduler that it is ready to run again. The process on the source machine will remain in an interruptible wait state (i.e., suspended). This will guarantee that only one clone of the process is running at any given instance.

**State Synchronization:** The state synchronization component is built as a collection of user-space programs and a kernel module. The user space portion simply sets up the network connections and then passes their socket descriptors to the kernel module, which exposes hook functions to the main kernel.

When an elasticized process issues a system call that modifies its in-kernel data structures (e.g., mmap), the appropriate kernel module hook function is called (e.g.,
Table 1: Tested algorithms and their memory footprints.

| Algorithm       | Memory Footprint          |
|-----------------|---------------------------|
| Depth First Search | 330 million nodes (15 GB) |
| Linear Search   | 2 billion long int (15 GB) |
| Dijkstra        | 3.5 billion int weights (14 GB) |
| Block Sort      | 1.8 billion long int (13 GB) |
| Heap Sort       | 1.8 billion long int (14 GB) |
| Count Sort      | 1.8 billion long int (14 GB) |

sync new mmap), which will then multi-cast a message to all participating nodes. The message will contain all necessary information (e.g., region’s starting address, its length, mapping flags, and file name) to apply the same operation on all process replicas. Multi-cast listeners, then, relay the message to the appropriate hook functions, who will apply the change (i.e., call mmap on the process replica).

5 Performance Evaluation

In this section, we focus on evaluation of the performance of ElasticOS. Specifically, we look to quantify the benefit of joint disaggregation (memory and computation) by comparing against network swap, which is a one dimensional (scaling memory), which has previously been shown to have performance benefits over not scaling memory [20, 10]. We note that we do not explicitly compare against just process migration, as the use cases are different, where process/VM migration is commonly used to move execution permanently and triggered by contention for resources or for other operational reasons (e.g., planned maintenance) – making it heavier weight and not well suited for comparison.

5.1 Experimental Setup

We evaluated ElasticOS on the Emulab testbed [9]. We used Emulab D710 nodes with 64-bit Quad Core Xeon processor, 12 gigabytes RAM, and a gigabit NIC. We choose Emulab D710 nodes because they support Linux kernel 2.6. Our experimental setup for each experiment consists of two nodes connected via gigabit Ethernet ports, transported through a network switch.

To evaluate, we ran tests on a variety of algorithms representing the type of processing that would be a target use case for ElasticOS – large graphs or lists to be processed. Shown in Table [1] is a summary of these applications, and the footprint of each application – note that the footprint goes beyond the limits of a single node in Emulab. Specifically, these algorithms typically use 11GB of memory on the first machine, and stretch to a remote machine for the additional memory.

Table 2: Micro-benchmarks of ElasticOS primitives.

| Primitive | Latency | Network Transfer |
|-----------|---------|------------------|
| Stretch   | 2.2ms   | 9KB              |
| Push      | 30-35us | 4KB              |
| Pull      | 30-35us | 4KB              |
| Jump      | 45-55us | 9KB              |

In our experimental setup, we employed a basic jumping algorithm to trigger transfer of execution. A simple remote page fault counter is updated for each remote pull, and whenever a counter threshold value is reached, then a process will jump its execution to the remote machine. In addition, the counter is then reset. We tested the algorithms with different counter threshold values (32 up to 4M).

For each algorithm, we measure its execution time as well as network traffic generated, and compare results of ElasticOS and network swap. To provide a comparison with network swap, hereafter termed Nswap, in a manner which isolated the gains to simply the benefit of jumping and not any implementation differences, we use ElasticOS code, but disable jumping. In this way, Nswap tests pin a process on one machine, but use the memory of a remote machine as a swap space. In our experiments, both ElasticOS and Nswap spanned two machines. Emulab provides isolation of networking and execution in the testbed from external disturbances.

5.2 Micro-benchmarks

An important metric when evaluating ElasticOS is the performance of each individual primitive. These are summarized in Table 2 based on our measurements on Emulab D710 nodes. We’ll note that jumping is very fast, taking only 45-55 microseconds. This is substantially lower than reported numbers for process or VM migration, which are measured in seconds (e.g., one benchmark states CRIU’s downtime is roughly 3 seconds [23]). Stretching is also only performed once – when a decision is made that this process would benefit from scaling in the future.

We measured pushing and pulling to be between 30-35 microseconds – roughly the time to submit the request and transfer a page (4KB) of data across a network. For jumping to be effective in speeding up execution in ElasticOS, there must be locality. That is, the time for a single jump must be less than the time for the number of remote page pulls that would be saved by jumping. For our performance microbenchmarks, for jumping to be efficient, the process should save at least two remote page pulls. As we show next, the locality is much greater than this, resulting in substantial speedups.
5.3 Execution Time and Network Traffic

There are two key metrics to consider when comparing ElasticOS (with jumping, pulling and pushing), to network swap (just pulling and pushing). The first is overall execution time. Here, the key premise behind jumping is that to exploit locality, we should transfer execution to where the data is, rather than pull in the data to where the execution is. The second is the amount of network traffic – jumping needs to transfer context (e.g., the current stack), and pulling/pushing transfers pages.

In Figure 8, we show our measured average execution time for both Nswap and ElasticOS for each of the algorithms we have evaluated. These execution times are averaged over four runs using the threshold that achieves the most improvement. We observe that in the best case, ElasticOS shows substantial performance benefits for most algorithms. For example, Linear Search experienced about an order of magnitude speedup in execution performance, Depth First Search (DFS) achieved about 1.5X delay improvement, while Dijkstra’s algorithm achieved no speedup.

Table 3 describes the specific threshold values where best performance was achieved in ElasticOS for each algorithm. It also lists the total number of jumps at that threshold as well as the frequency of jumping for each algorithm at that threshold. The jumping rate ranges from less than once per second to hundreds of times per second.

While Figure 8 represents the best case, we were also interested in understanding whether we could find universal threshold values that achieve performance improvements - perhaps not the best - regardless of the algorithm. Our analysis found that, regardless of the algorithm, using any threshold value above 128, Elastic OS performs better than Nswap for any algorithm, either in delay, network overhead or both.

The use of jumping to exploit locality improves the execution time by enabling more local pages to be accessed, rather than needing to go across a network (which is orders of magnitude slower). This also reduces the amount of network traffic, even taking into account the data transfer needed to perform a jump. Shown in Figure 9 are our measured results for each of the algorithms tested. We can see that ElasticOS reduces the amount of traffic on the network for all algorithms tested by a significant amount – from a 5X reduction for Linear Search to about 2X reduction for DFS. By avoiding the process of swapping in and out to remote machines through lightweight jumping, we save a large amount of data and control traffic associated with avoidable remote page faults. Also, even if we did not achieve any delay improvements running ElasticOS, we still can obtain network traffic reduction. For example, Dijkstra’s algorithm did not achieve any delay improvement, even though Table 3 shows that Dijkstra had 520 jumps, but these jumps helped reducing its network overhead by 70%. In examining the behavior of Dijkstra’s, its initial set of jumps before settling down to execution on one machine resulted in substantial overhead savings.

5.4 Understanding Application Specific Behavior

We previously showed that each algorithm has a varying degree of improvements. While the simple reasoning is that it is due to locality, here we examine three of the algorithms in detail to really understand this behavior.
5.4.1 Linear Search

For Linear Search, the memory access pattern is simple and predictable, namely the memory address space is accessed in a linear fashion. As a result, consecutive memory pages tend to age in LRU lists together, and end up being swapped to the remote machine together. When a process jumps towards a remote page, it is very likely for the process to find a chunk of consecutive pages to access, exploiting locality of these pages, which saves the process a significant amount of time by avoiding swap overhead. Figure 10 shows delay improvements on Linear Search with respect to jumping threshold. Linear Search tends to perform better when the counter threshold is smaller, hence jumping early is better when accessing the address space in a linear fashion. Table 3 shows the highest frequency of jumping for linear search, as well as the lowest threshold value used. We also observe that as the threshold for jumping increases, jumping will occur less often and eventually not at all, hence explaining why the delay curve for ElasticOS converges to Nswap.

Figure 10: Linear Search Execution Time.

5.4.2 Depth First Search

On the other hand, Depth First Search has a non linear memory access pattern. When the algorithm starts a depth first search, the search starts at the root node, and traverses the graph branch by branch, from root to the end (depth) of the branch. While the graph nodes are laid out in a certain order in the memory space, the access pattern of DFS does not match this layout. This increased randomness of access to pages means that there is less locality to exploit on each jump than occurred for Linear Search, and hence less gain versus Nswap compared to Linear Search. Figure 11 shows different execution times of DFS for various counter threshold sizes. ElasticOS achieves at best about a 1.5x improvement in delay over Nswap across a wide range of counter thresholds, namely larger than 64. However, for very small values of threshold less than or equal to 64, DFS performs worse. Figure 12 shows that when the threshold value is very small, DFS experiences a large number of jumps. Also, our tests showed that DFS’s best performance happens when the threshold value is large compared to other algorithms as shown in Table 3.

Figure 11: Depth First Search Execution Time.

Figure 12: Depth First Search Number of Jumps.

The shape of the graph in DFS can also impact the memory access pattern. For example increasing the depth of the graph would make branches longer, resulting in a longer branch that occupies more memory pages, increasing the chance of a single branch having pages located both on local and remote machines. This would increase the chances of jumping more and performing poorly. Figure 13 shows DFS performance on ElasticOS for different graph depths with a fixed jumping counter size of 512. Increasing the graph depth eventually results in poorer performance. Figure 14 shows that this poorer performance occurs when there is excessive jumping for deep graphs. To make ElasticOS perform better on such graph depth we need to increase the jumping counter size to values larger than 512, to avoid jumping too much.

5.4.3 Dijkstra’s Algorithm

ElasticOS achieved very little gain when executing Dijkstra’s algorithm when compared to Nswap. Dijkstra’s algorithm scans through an adjacency matrix, then learns and stores information about the shortest path in a separate array. However, Dijkstra does not necessarily access all nodes in the adjacency matrix, because some nodes are not connected, or one of the paths was excluded for being too long. Since Dijkstra’s algorithm keeps track
of the shortest path nodes in a separate array, it only accesses the adjacency matrix nodes once, and keeps useful information in the shortest path array. Based on how Dijkstra’s algorithm works, it does not access memory frequently, and only accesses part of the allocated memory. Therefore, most of Dijkstra’s execution time does not involve many remote page faults. Since jumping saves time wasted on remote page faults, Dijkstra does not gain much delay improvement, because it does not jump due to very small number of remote page faults. Figure 15 confirms that Dijkstra’s algorithm spends most of its execution time on one machine without jumping. Our experiments showed that only a relatively small set of jumps happened at the beginning, and the rest of the time execution stayed on one machine.

6 Discussion and Future Work

We intend to upgrade ElasticOS to a newer version of Linux. We plan to investigate improved jumping algorithms that better exploit locality by actively learning about elasticized process’ memory access patterns during run time and employing adaptive jumping thresholds. Probabilistic models will be investigated. In addition, we will explore whether incorporating into the jumping decision the burstiness of remote page faulting brings any benefit. Also, we are considering a more proactive approach to controlling the swap out operation for elasticized processes by modifying kswapd. If we selectively swap out pages to remote machines, we might be able to create islands of locality on remote machines, thus, making jumping more efficient. We also can pin memory pages, and prevent them from being swapped, which would allow us to control how the memory address space is distributed across participating machines. We plan to test a wider variety of algorithms, including SQL-like database operations. We intend to expand testing to more than two nodes.

7 Conclusion

In this paper, we have implemented within Linux four new primitives, namely stretch, push, pull, and jump, to support scaling as an OS abstraction. This extended Linux system is called ElasticOS. These primitives transparently achieve joint disaggregation of computation and memory, enabling both data to move towards execution, as well as execution to move towards data within a stretched address space spanning multiple nodes in a data center. Our evaluation results were obtained from Emulab deployments of ElasticOS testing a variety of different application algorithms, and indicate that such joint disaggregation achieves up to 10X speedup in execution time over network swap, as well as 2-5X reductions in network overhead.

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