Arrakis: The Operating System is the Control Plane

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Problem: Building an OS for the Data Center

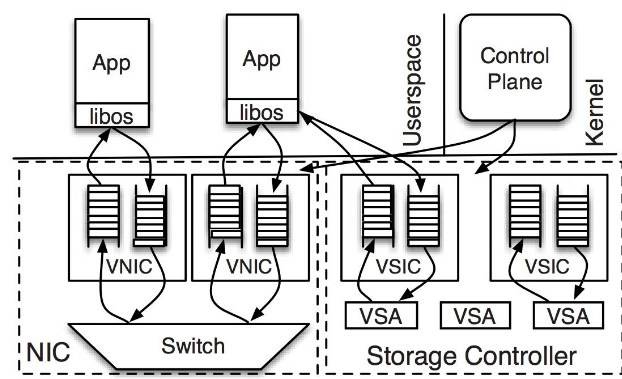
- Server I/O performance matters:
  - Key-value stores
  - Web & file servers
  - Lock managers
- Can we build an OS that would allow applications deliver performance close to that delivered by data center hardware technology?

  The hardware can help!

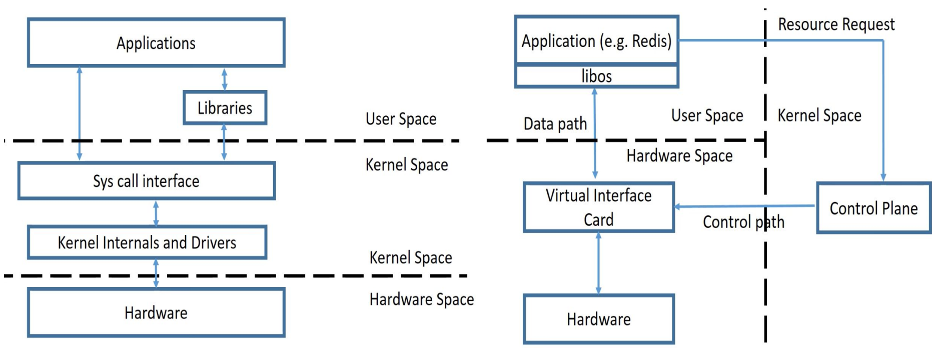
Arrakis Design Goals

- Minimize kernel involvement & deliver I/O directly to applications
  - Reduce OS overhead
- Transparency to the application programmer
  - No requirements for modifications to applications
- Appropriate OS/hardware abstraction
  - Keep classical server OS features
  - I/O protocol flexibility
  - Process protection
  - Global naming

Arrakis Architecture



Traditional OS Architecture   Arrakis Architecture



Source:https://www.youtube.com/watch?v=4NYpDad0f04

Skip the Kernel

- Kernel
  - API
  - Access Control
  - Copying
  - Global Naming
  - I/O Processing
  - I/O Scheduling
  - Multiplexing
  - Protection
  - Resource Limits
- Redis (Application)
- I/O Devices (Hardware)

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Kernel mediation is too heavyweight!

Skip the Kernel

Control Plane

- Kernel
  - Access Control
  - Global Naming
  - Resource Limits

Data Plane

- Application (Redis)
  - API
  - I/O Processing
- I/O Devices (Hardware)
  - I/O Scheduling
  - Multiplexing
  - Protection

- Copying: A native interface that supports true zero-copy I/O

Skip the Kernel

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Data Plane

- Redis (Application)
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  - I/O Processing

Data Path

- I/O Devices (Hardware)
  - I/O Scheduling
  - Multiplexing
  - Protection

Arrakis I/O Architecture

Arrakis I/O Architecture

Control Plane

- Kernel
  - Access Control
  - Global Naming
  - Resource Limits

Data Plane

- Redis (Application)
  - API
  - I/O Processing

Data Path

- I/O Devices (Hardware)
  - I/O Scheduling
  - Multiplexing
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Arrakis I/O Architecture

Arrakis Control Plane

- Access Control
  - Only do once when configuring the data plane
  - Enforced via NIC filters, logical disks
- Global Naming
  - Virtual file system still in kernel
  - Storage implementation in applications
- Resource Limits
  - Program hardware I/O schedulers

Global Naming

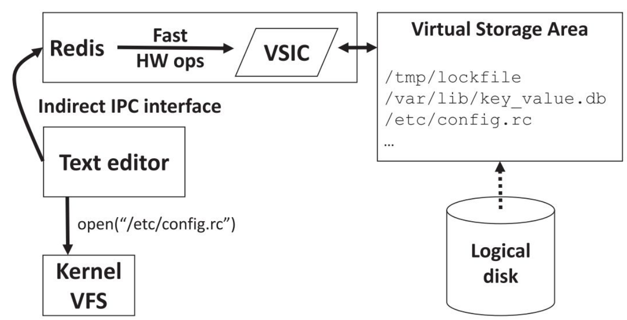

Fig. 6. Arrakis default file access example.

Arrakis I/O Architecture

Control Plane

- Kernel
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  - Global Naming
  - Resource Limits

Data Plane

- Redis (Application)
  - API
  - I/O Processing

Data Path

- I/O Devices (Hardware)
  - I/O Scheduling
  - Multiplexing
  - Protection

Storage Data Plane

- Persistent Data Structures
  - Examples: persistent log and queue data structures
- Benefits
  - Operations are immediately persistent.
  - The structure is robust versus crash failures.
  - Operations have minimal latency
- Drawbacks
  - A lack of backwards-compatibility to the POSIX API.

Arrakis I/O Architecture

Control Plane

- Kernel
  - Access Control
  - Global Naming
  - Resource Limits

Data Plane

- Redis (Application)
  - API
  - I/O Processing

Data Path

- I/O Devices (Hardware)
  - I/O Scheduling
  - Multiplexing
  - Protection

Hardware I/O Virtualization

- Standard on data center NIC, emerging on RAID
- I/O Scheduling
  - NIC rate limiter, packet schedulers
- Multiplexing
  - Single-Root I/O Virtualization (SR-IOV)
    - Support high-speed I/O for multiple virtual machines sharing a single physical machine.
    - Each virtual PCI device has its own register, queue etc.
- Protection
  - IOMMU
    - Restrict device access to only application virtual memory.
  - Packet filters, logical disks
    - Only allow eligible I/O.

Evaluation

- Arrakis was evaluated on four cloud application workloads
  - Read-heavy
  - Write-heavy
  - Http load balancer
  - IP-layer middlebox
- OS configurations used in the evaluation:
  - Ubuntu version 13.04 (kernel version 3.8)
    - Made some tunings and throughput performance improved by 10%
      - Installed latest ixgbe device driver
      - Disabled receive side scaling (RSS) when applications executed on one processor
  - Arrakis using the POSIX interface
  - Arrakis using its native interface

Server-side Packet Processing Performance

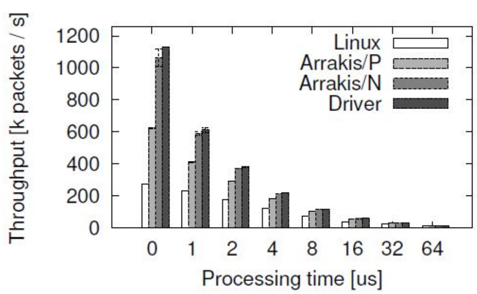
- UDP echo server
  - Other machines generated 1KB UDP packets at a fixed rate for 20 seconds in each experiment
  - the rate at which echoes arrived was recorded and used to compute server-side overhead
  - Arrakis eliminates scheduling and kernel crossing because packets are delivered directly to user space.

		Linux				Arrakis			
		Receiver running		CPU idle		Arrakis/P		Arrakis/N	
Network stack	in	1.26	(37.6%)	1.24	(20.0%)	0.32	(22.3%)	0.21	(55.3%)
	out	1.05	(31.3%)	1.42	(22.9%)	0.27	(18.7%)	0.17	(44.7%)
Scheduler		0.17	(5.0%)	2.40	(38.8%)	-		-	
Copy	in	0.24	(7.1%)	0.25	(4.0%)	0.27	(18.7%)	-	
	out	0.44	(13.2%)	0.55	(8.9%)	0.58	(40.3%)	-	
Kernel crossing	return	0.10	(2.9%)	0.20	(3.3%)	-		-	
	syscall	0.10	(2.9%)	0.13	(2.1%)	-		-	
Total		3.36	($\sigma = 0.66$)	6.19	($\sigma = 0.82$)	1.44	($\sigma < 0.01$)	0.38	($\sigma < 0.01$)

Table 1: Sources of packet processing overhead in Linux and Arrakis. All times are averages over 1,000 samples, given in μs (and standard deviation for totals). Arrakis/P uses the POSIX interface, Arrakis/N uses the native Arrakis interface.

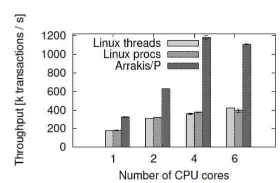
Server-side Packet Processing Performance

- Experiment repeated with delay added before echoing each UDP packet to simulate application-level processing time
- A minimal echo server was embedded directly into the NIC device driver to see how close to the maximum possible throughput Arrakis is able to achieve



Read-heavy load

- Memcached: is a general-purpose distributed memory caching system. It is often used to speed up dynamic database-driven websites by caching data and objects in RAM to reduce the number of times an external data source (such as a database or API) must be read[1].
- Setup:
  - Requests were sent at a constant rate via its binary UDP protocol
  - Workload pattern: 90% fetch and 10% store requests
  - Number of Memcached processes were varied to measure network stack scalability for multiple cores



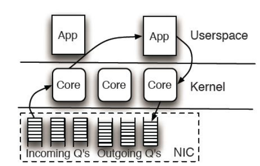
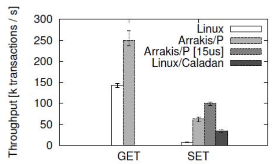


Figure 1: Linux networking architecture and workflow.

[1] Memcached. [online] Available: https://en.wikipedia.org/wiki/Memcached

Write-heavy load

- Redis: provides in-memory data structure stores, optionally persists each write via an operational log
  - AOF persistence logs every write operation received by the server
  - RDB persistence performs point-in-time snapshots of dataset at specified intervals [1]
- Log records were exchanged between Redis and Caladan
- Setup:
  - Benchmark tool distributed with Redis
  - Execute GET and SET requests in two separate benchmarks
  - Also ported Caladan to run on Linux
  - Simulated storage hardware with low write latency through a write-delaying RAM disk
- Results:
  - Write latency improves by 63%
  - Write throughput improves by 9X on Arrakis
  - Write throughput improves by 5X on Linux (w/ Caladan)



[1] Redis Persistence. [online] Available: http://redis.io/topics/persistence

Http Load Balancer

- Haproxy: high availability proxy, a popular open source software TCP/HTTP load balancer and proxying solution[1]
- Setup:
  - Deployed a static web page of 1024 bytes at five web server, which also served as workload generators
  - Distributed load in a round-robin fashion
  - Experiment was done with and without "speculative epoll" (SEPOLL) within the Linux kernel.
    - SEPOLL: uses knowledge about typical socket operation flows within Linux kernel to avoid calls to the epoll interface and optimize performance
    - Not implemented in Arrakis

- Haproxy inserts cookies into HTTP stream to remember connection assignments to web servers under client reconnections

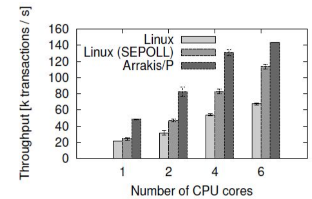
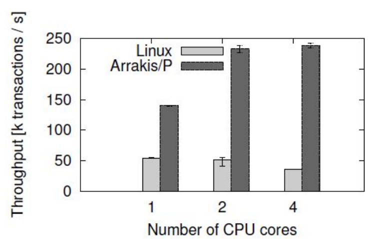


Figure 7: Average HTTP transaction throughput and scalability of haproxy.

[1] An Introduction to HAProxy and Load Balancing Concepts. [online] Available: https://www.digitalocean.com/community/tutorials/an-introduction-to-haproxy-and-load-balancing-concepts

IP-layer Middlebox

- IP-layer middleboxes: perform tasks such as firewalling, intrusion detection, network address translation, and load balancing.
- Setup:
  - Implemented a simple user-level load balancing middlebox using raw IP sockets. It simply rewrites source and destination IP addresses and TCP port numbers.
  - A hash table was used to remember existing connection assignment
  - Responses from back-end servers were intercepted and forwarded back to corresponding clients



Results and analysis:

- Load balancing middle box running either Linux or Arrakis experienced a higher throughput compared to Haproxy because of the simpler nature of the middlebox
- Linux implementation does not scale well because raw sockets carry no connection information → each middlebox instance has to look at each incoming packet to determine if it should handle it

Performance Isolation

- Wanted to know if it is possible to provide the same kind of QoS enforcement (rate limiting) in Arrakis as in Linux.
- Setup:
  - Simulated a simple multi-tenant scenario with 5 Memcached instances
  - Limit one tenant's sending rate to 100Mb/s
  - Used rate specifiers in Arrakis and queuing disciplines on Linux to limit the rate
  - Memcached experiment was repeated
- Conclusion
  - Arrakis is able to provide the same kind of rate limiting QoS enforcement as in Linux

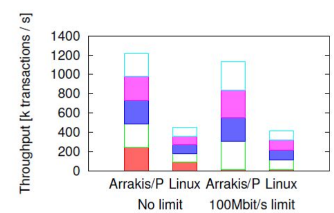


Figure 9: Memcached transaction throughput over 5 instances (colors), with and without rate limiting.

Discussions

Some applications of Arrakis:

- Make Arrakis as a virtualized guest
  - Moving the control plane into the virtual machine monitor (VMM)
  - Applications allocate virtual interfaces cards directly from VMM
- Virtualized Interprocessor Interrupts
  - Interprocessor signaling is inefficient because of kernel's involvement even though the sending and receiving threads are two threads of the same application
  - Kernel could be configure to allow an interrupt to be delivered to another processor given that the same application is running on that processor
  - Achieve similar cost as a cache miss

Improvements and Extension

- Throughput of Arrakis does not scale well beyond 4 cores based on the Memcached experiment
  - Reduce overhead caused by contention with Barrelfish system management processes
- Limited filtering support of the 82599 NIC (implementation)
  - Introduce software overhead: different MAC address for each VNIC