Reducing The Cost of Containing:

ContainerFS, A gVisor File System for Performance

Ethan G. Young, Shenghao Zou, Pengfei Zhu, Tyler Caraza-Harter, Andrea C. Arpaci-Dusseau, Remzi H. Arpaci-Dusseau

University of Wisconsin-Madison
December 5, 2019

gVisor

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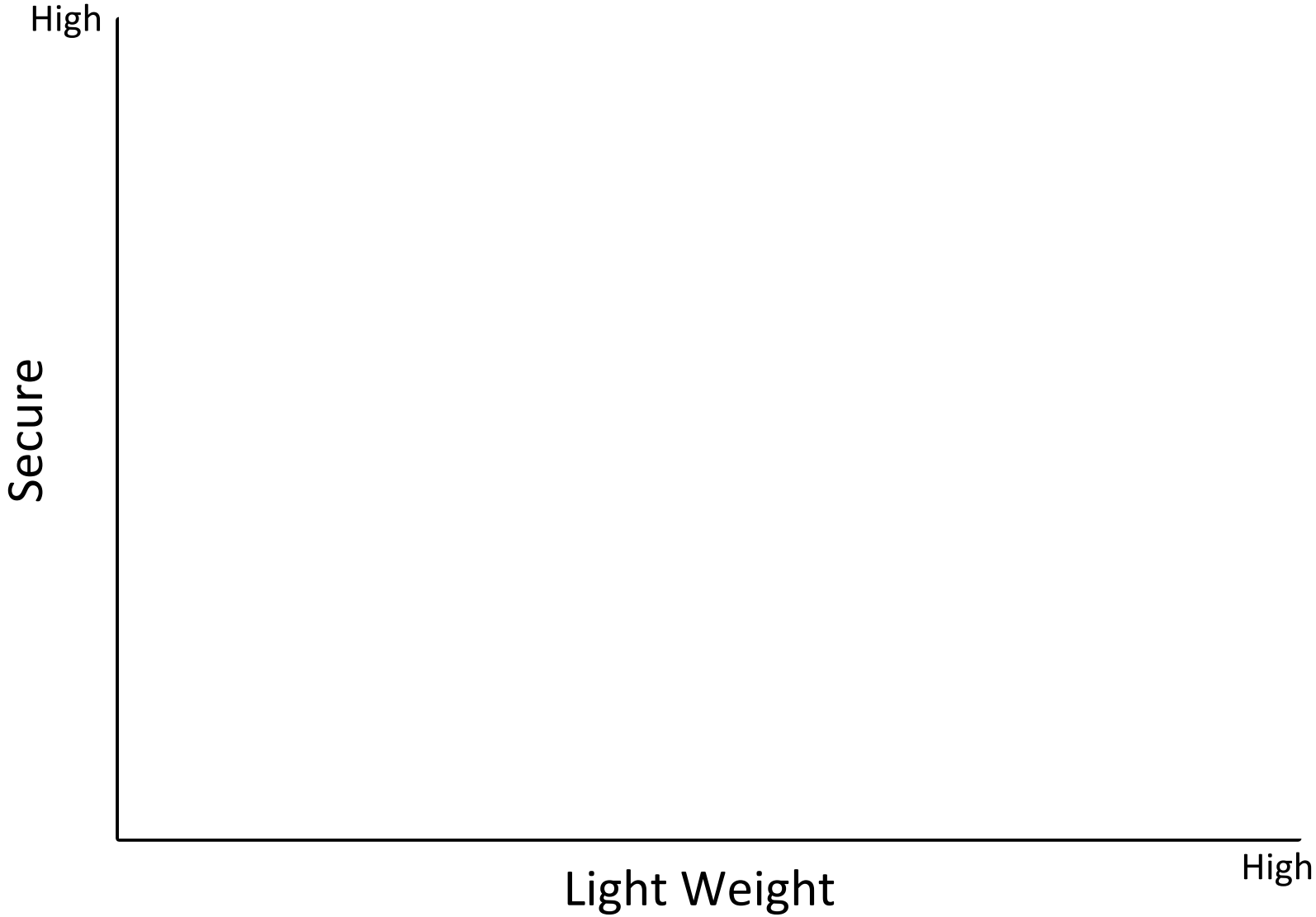

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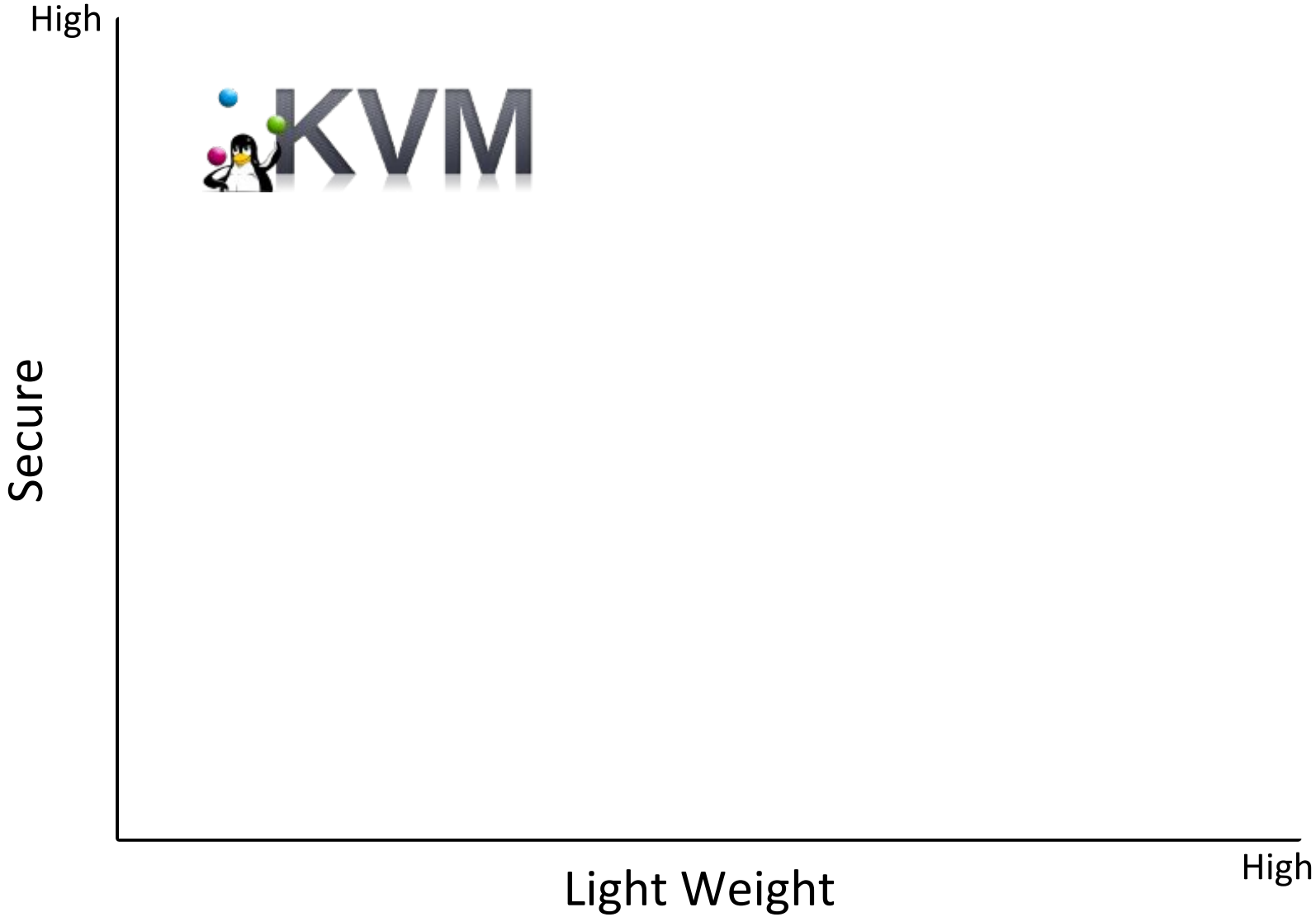

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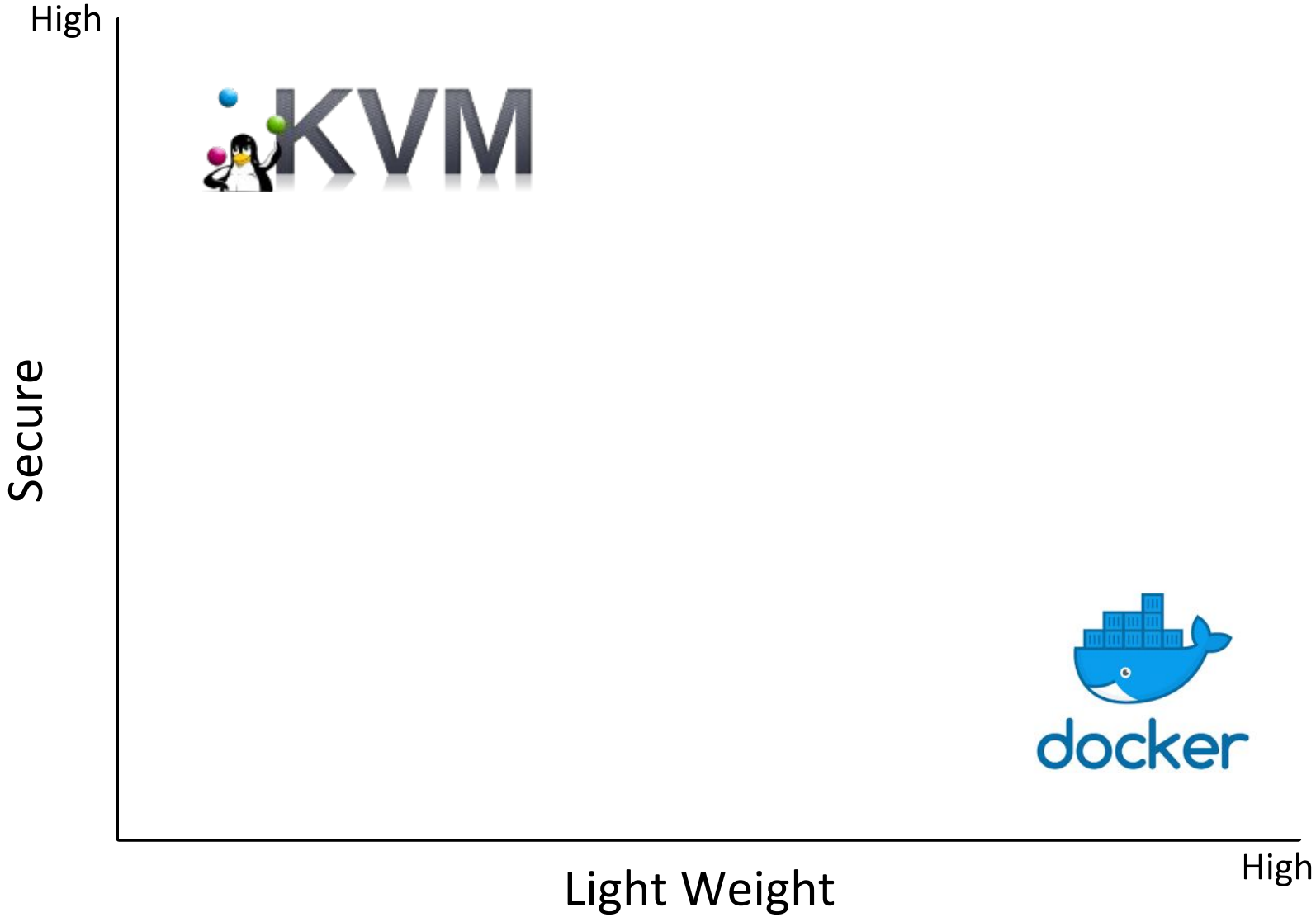

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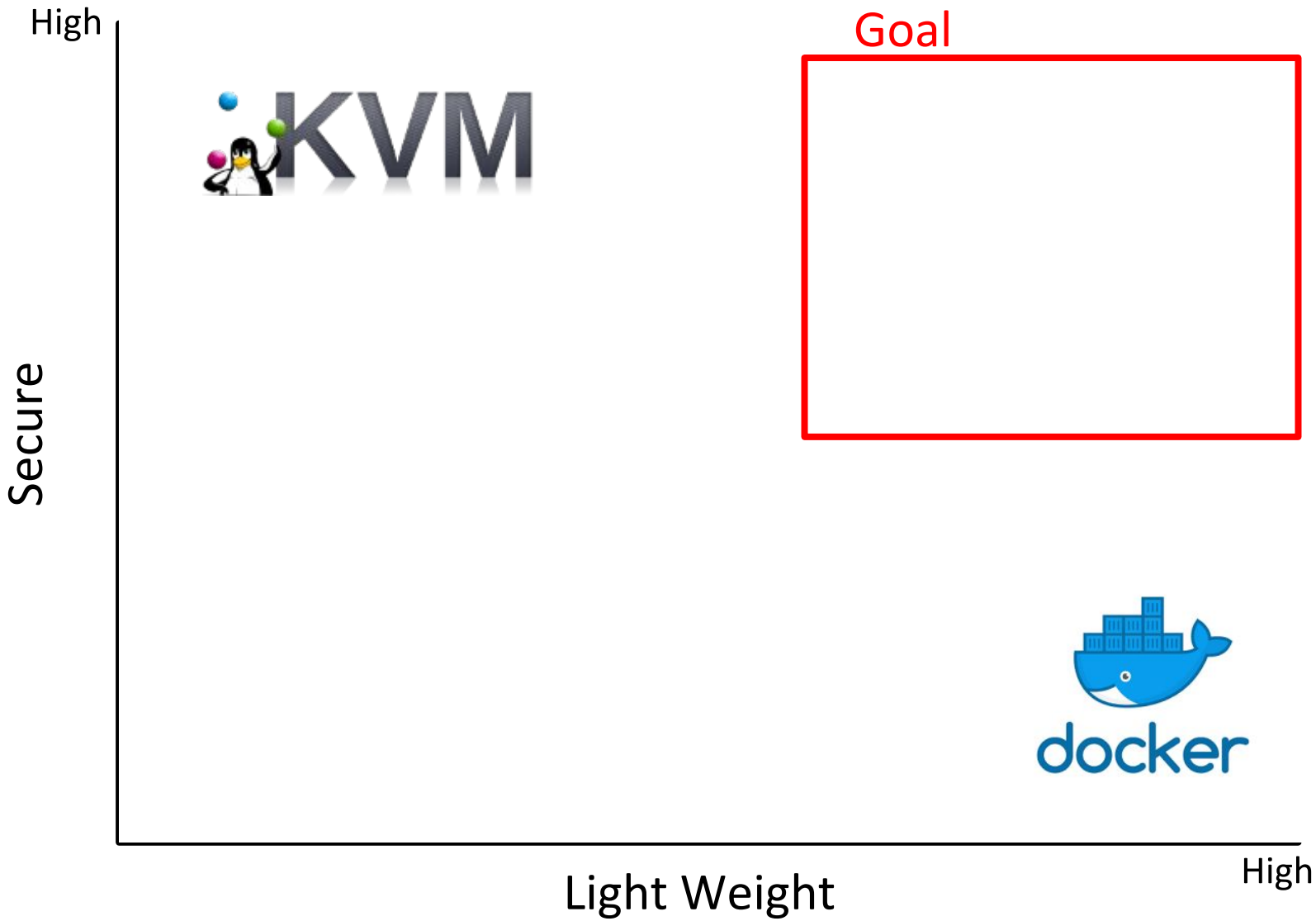

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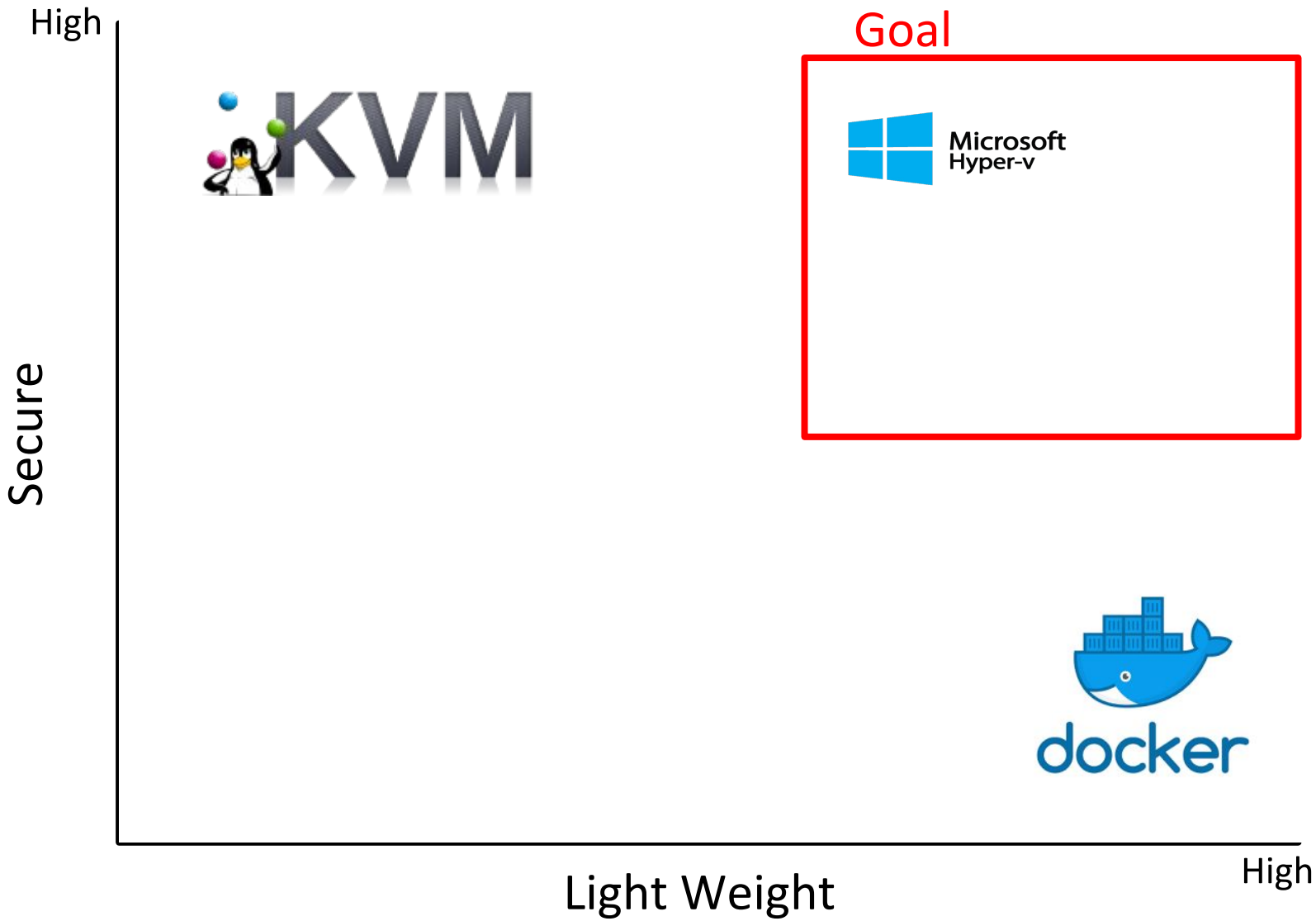

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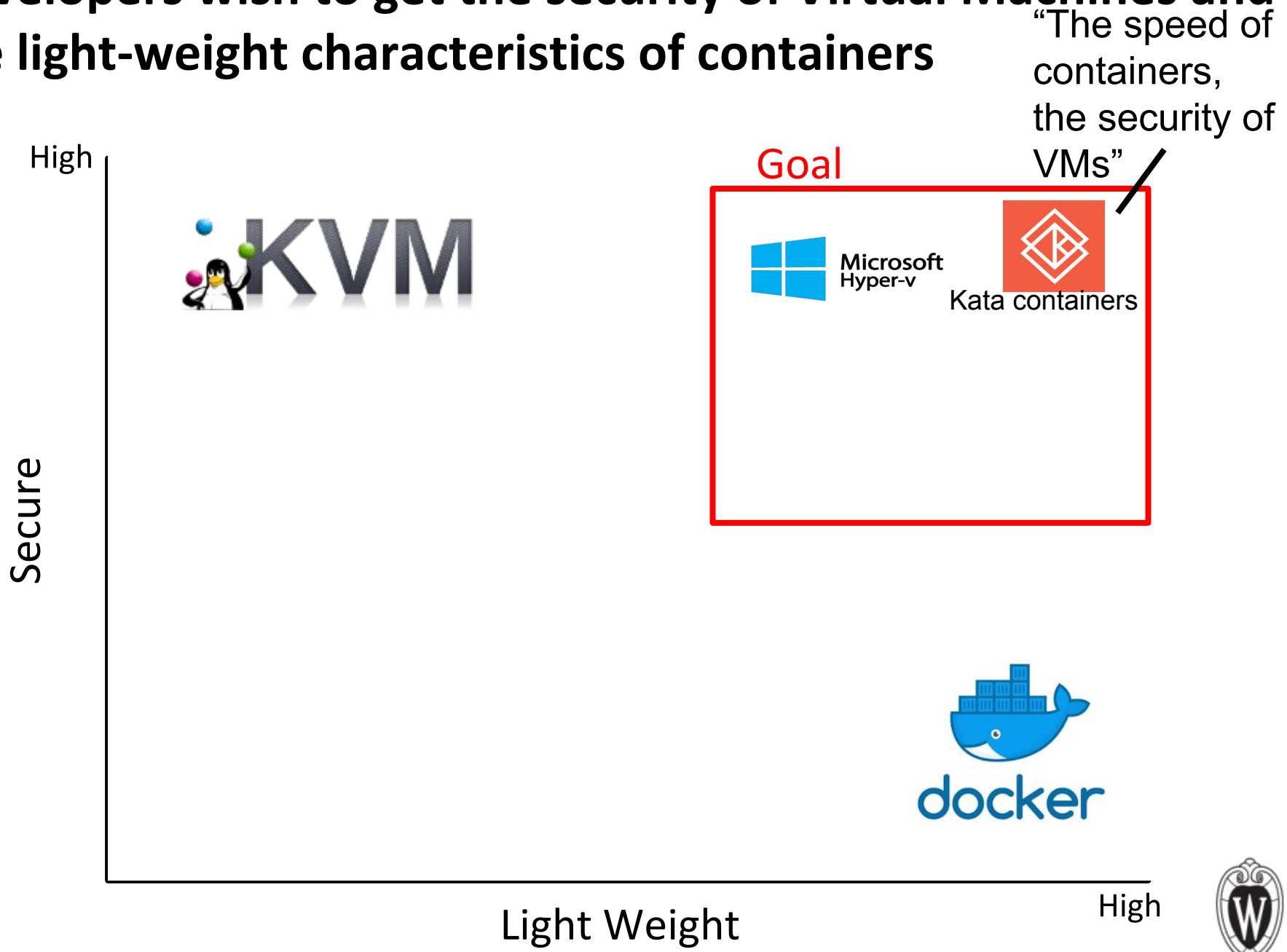

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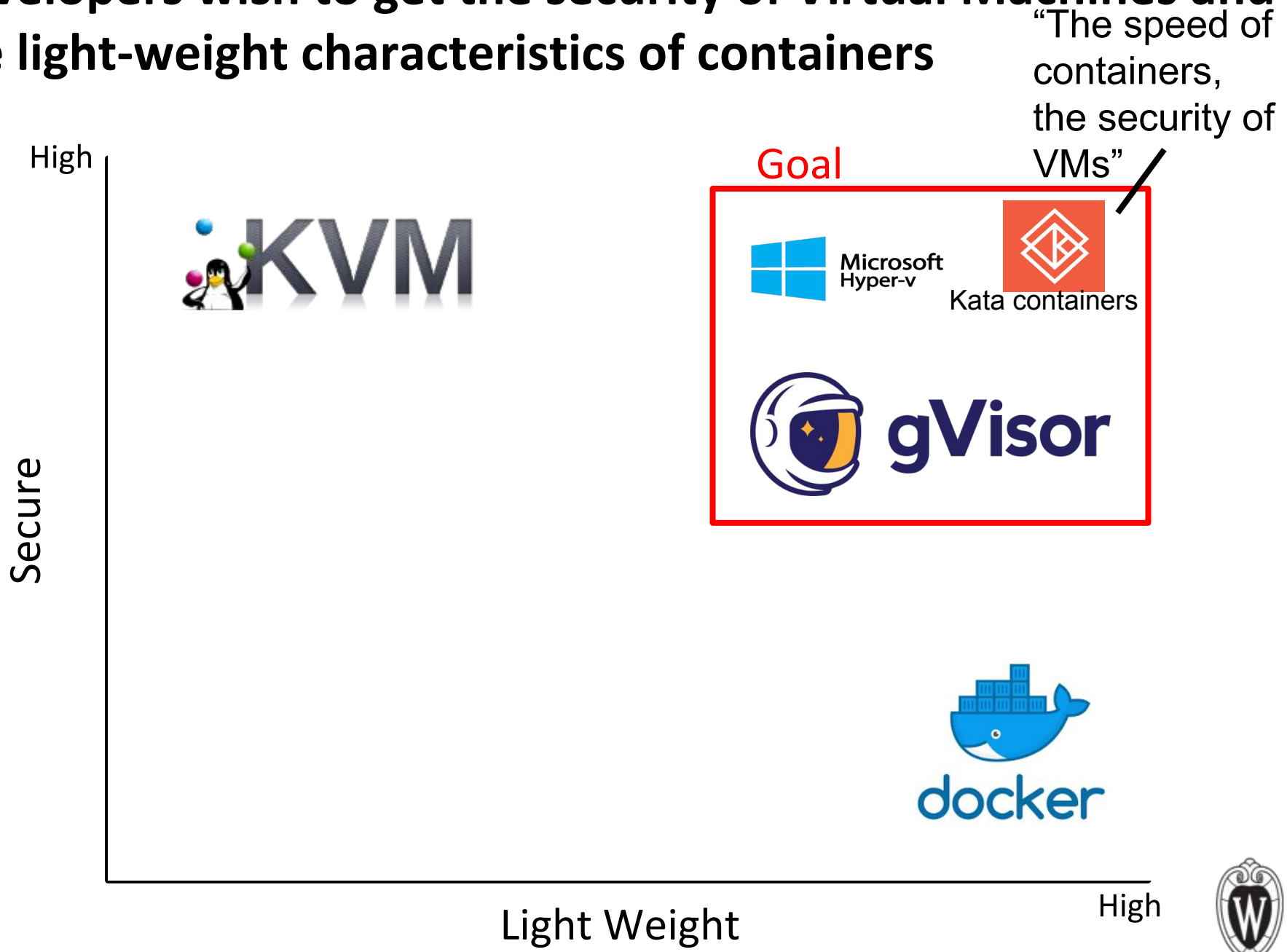

gVisor is an interesting case study because it backs Google's serverless platform and is open-source

gVisor

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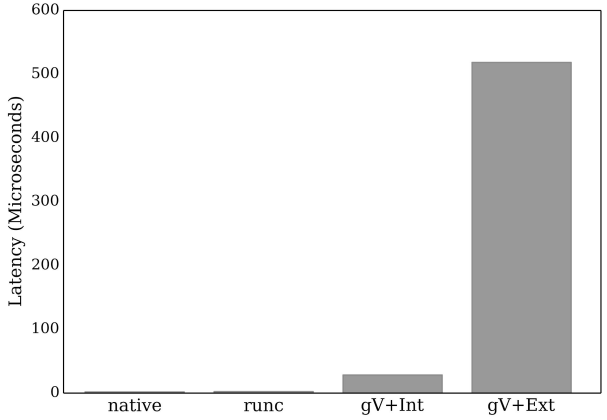
gVisor

gVisor Architecture



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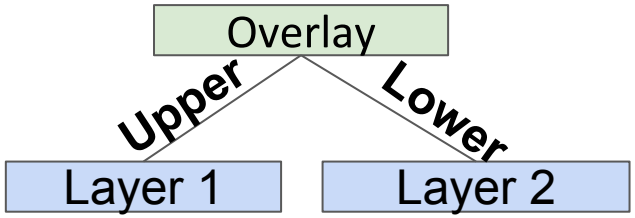

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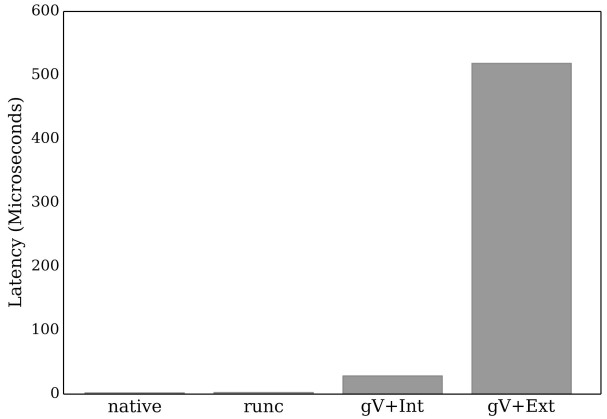

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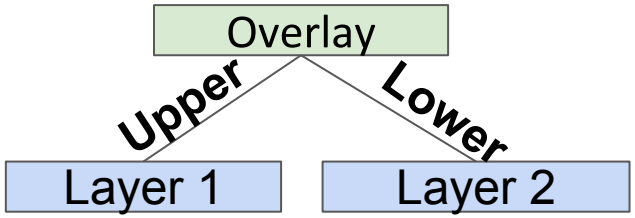
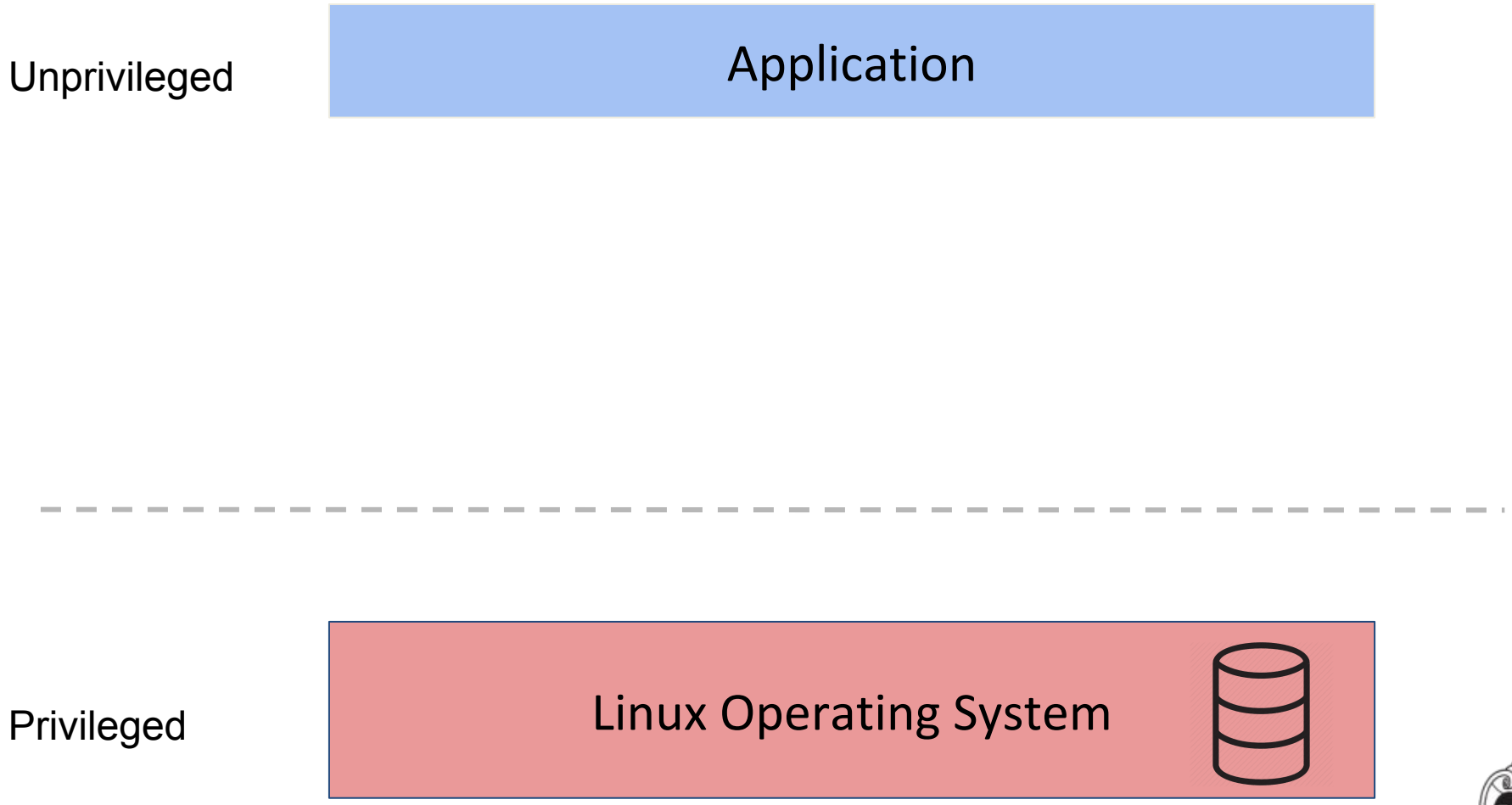


ContainerFS Overview

Even in a container, applications typically have direct access to the entire Linux system call interface



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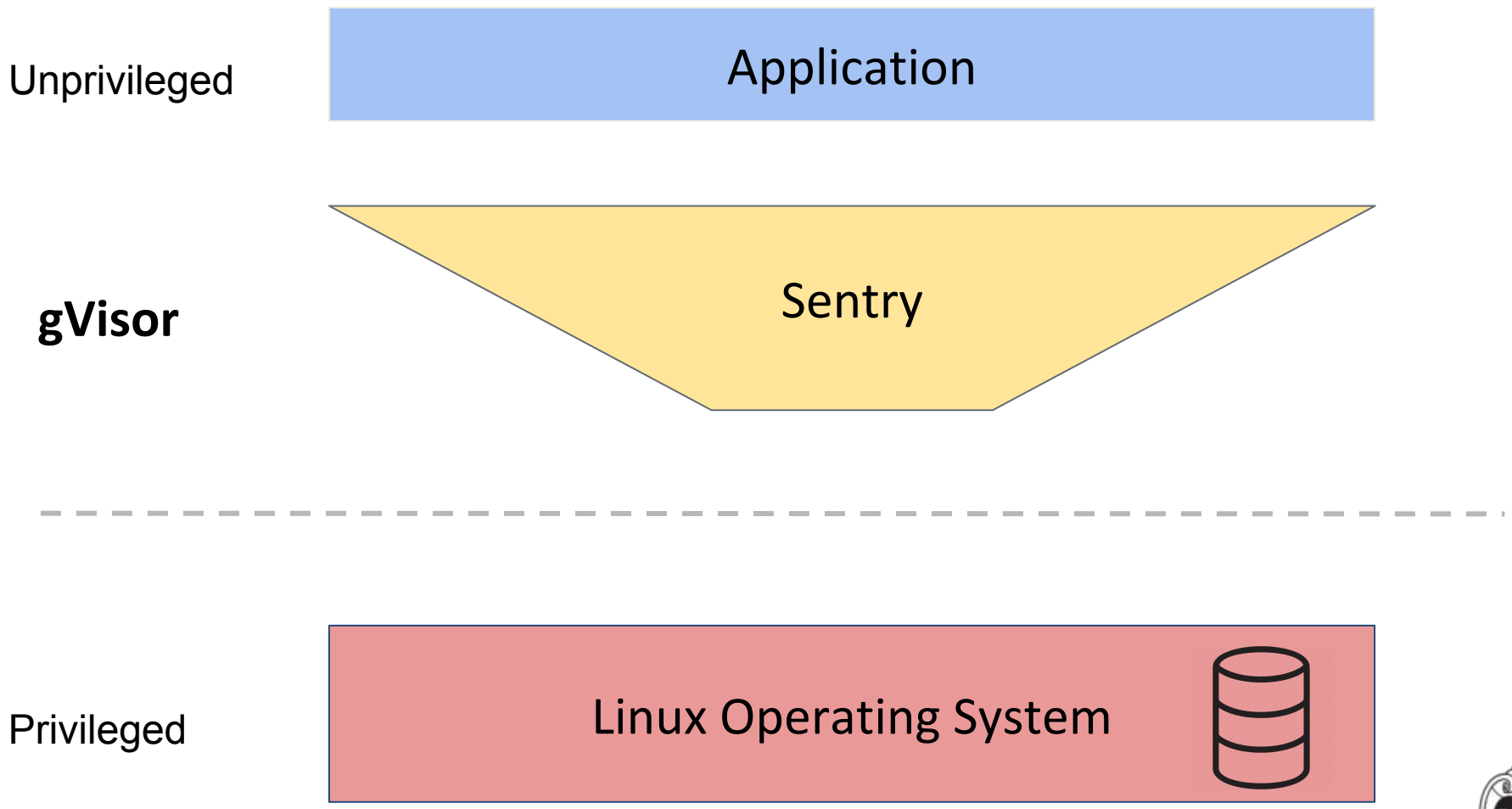

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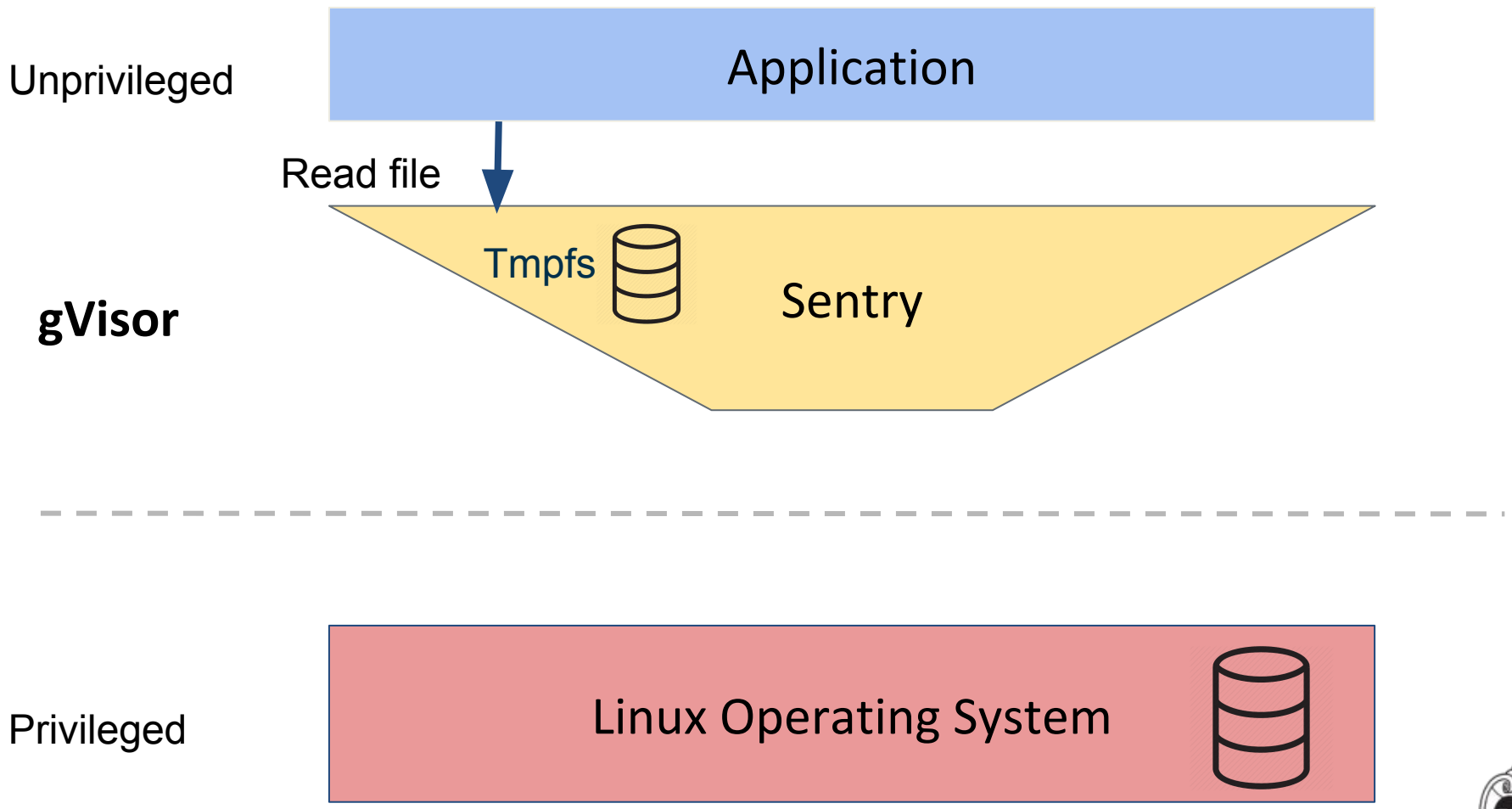

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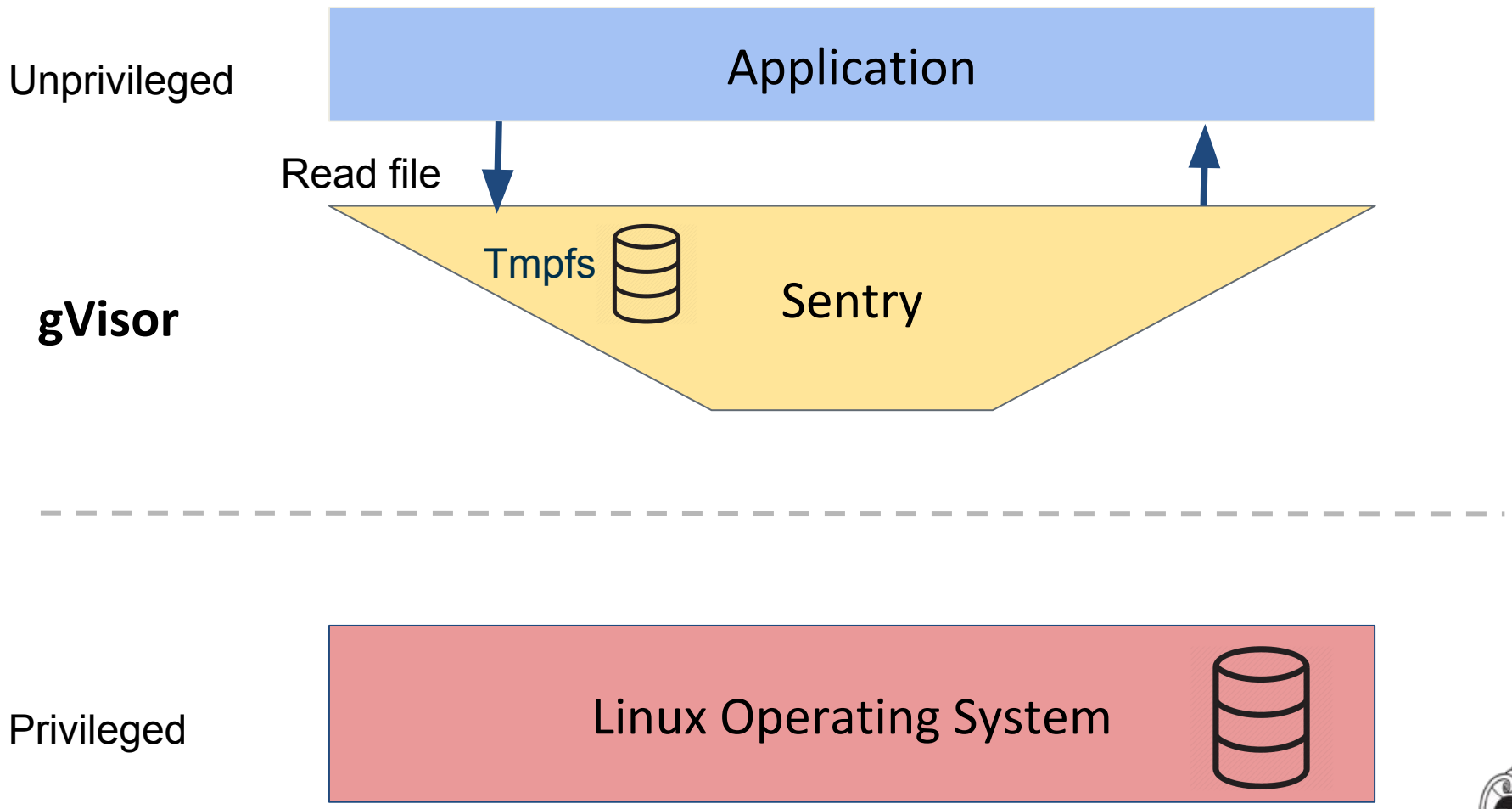

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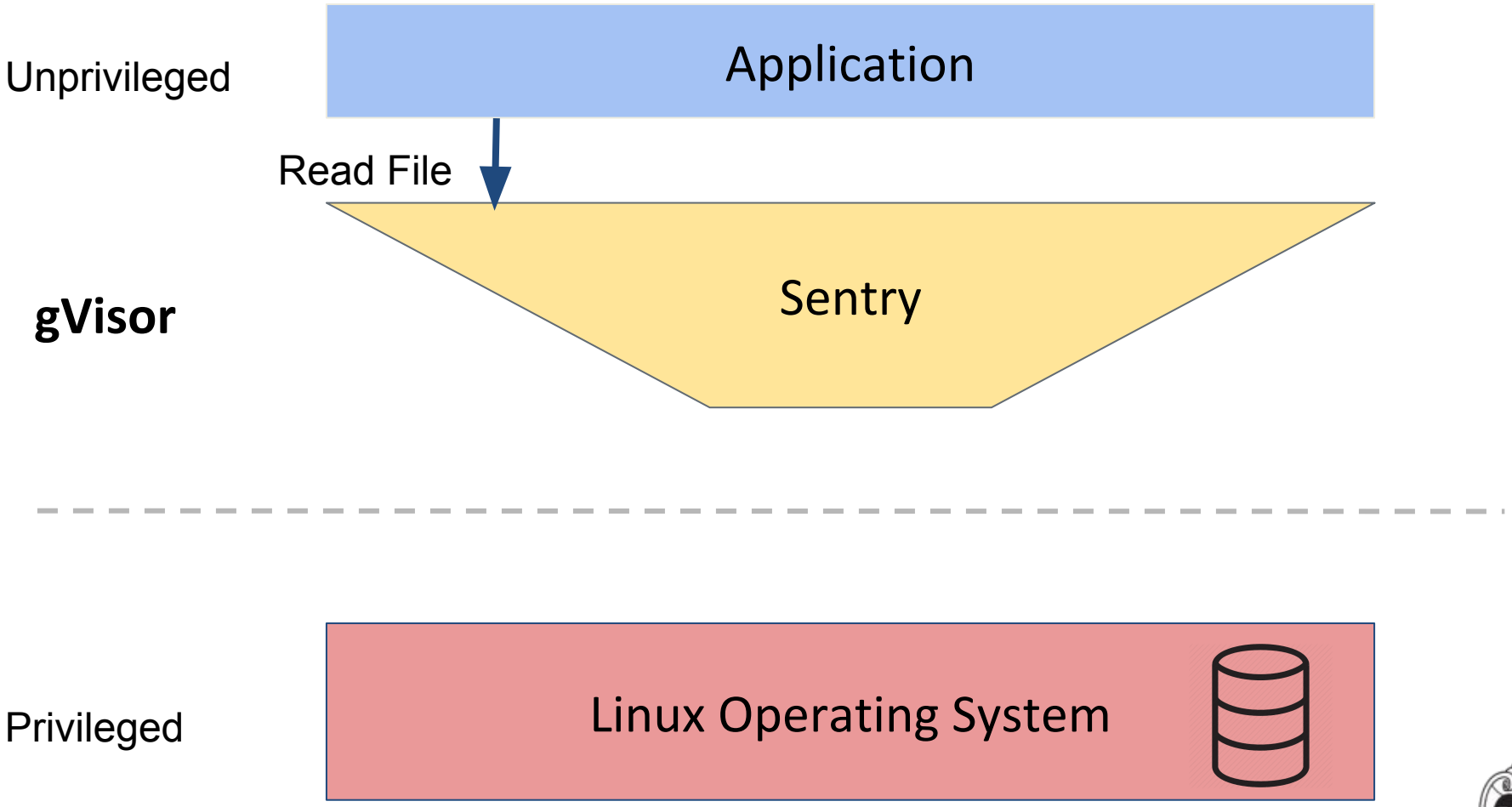

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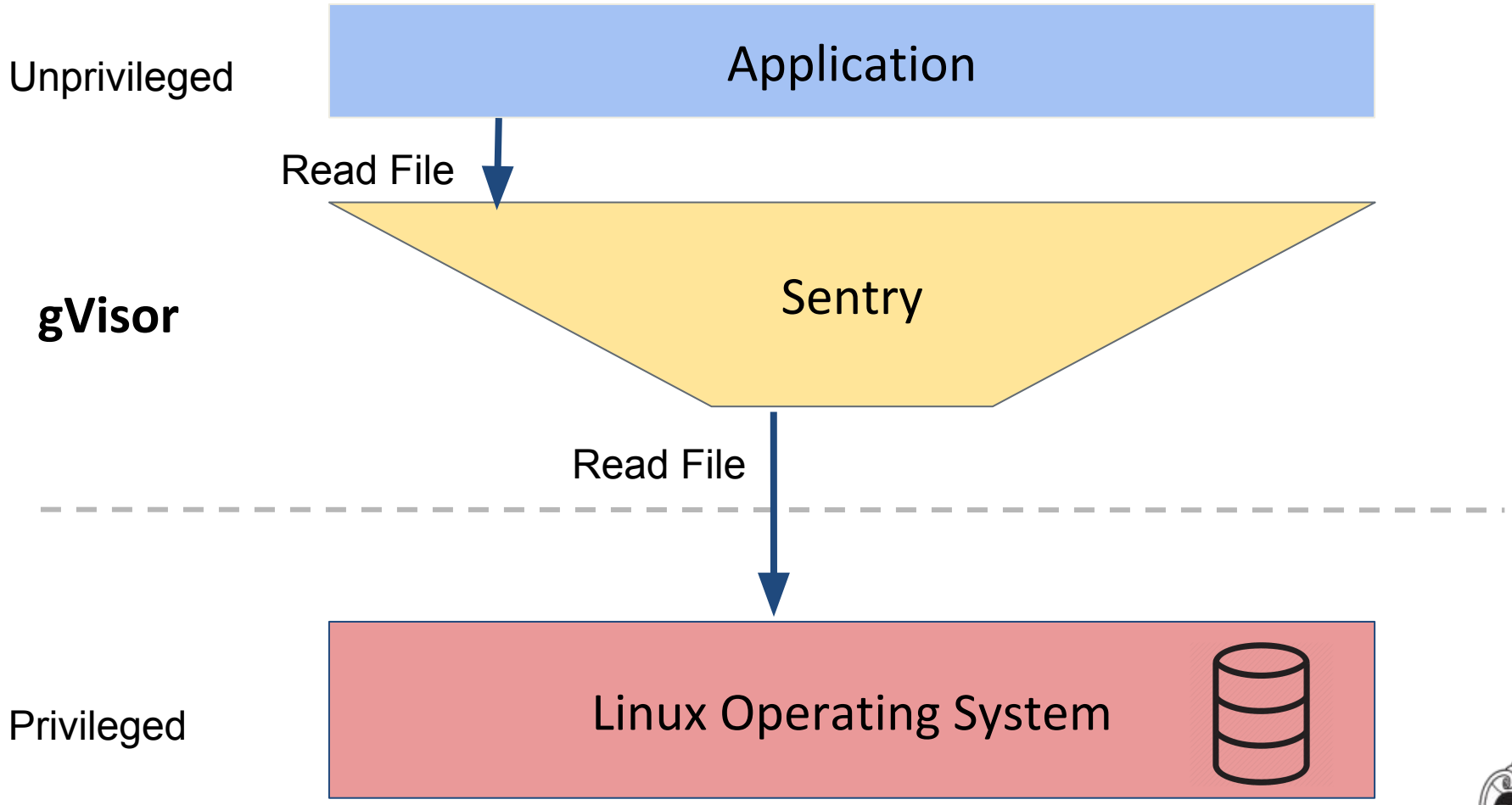

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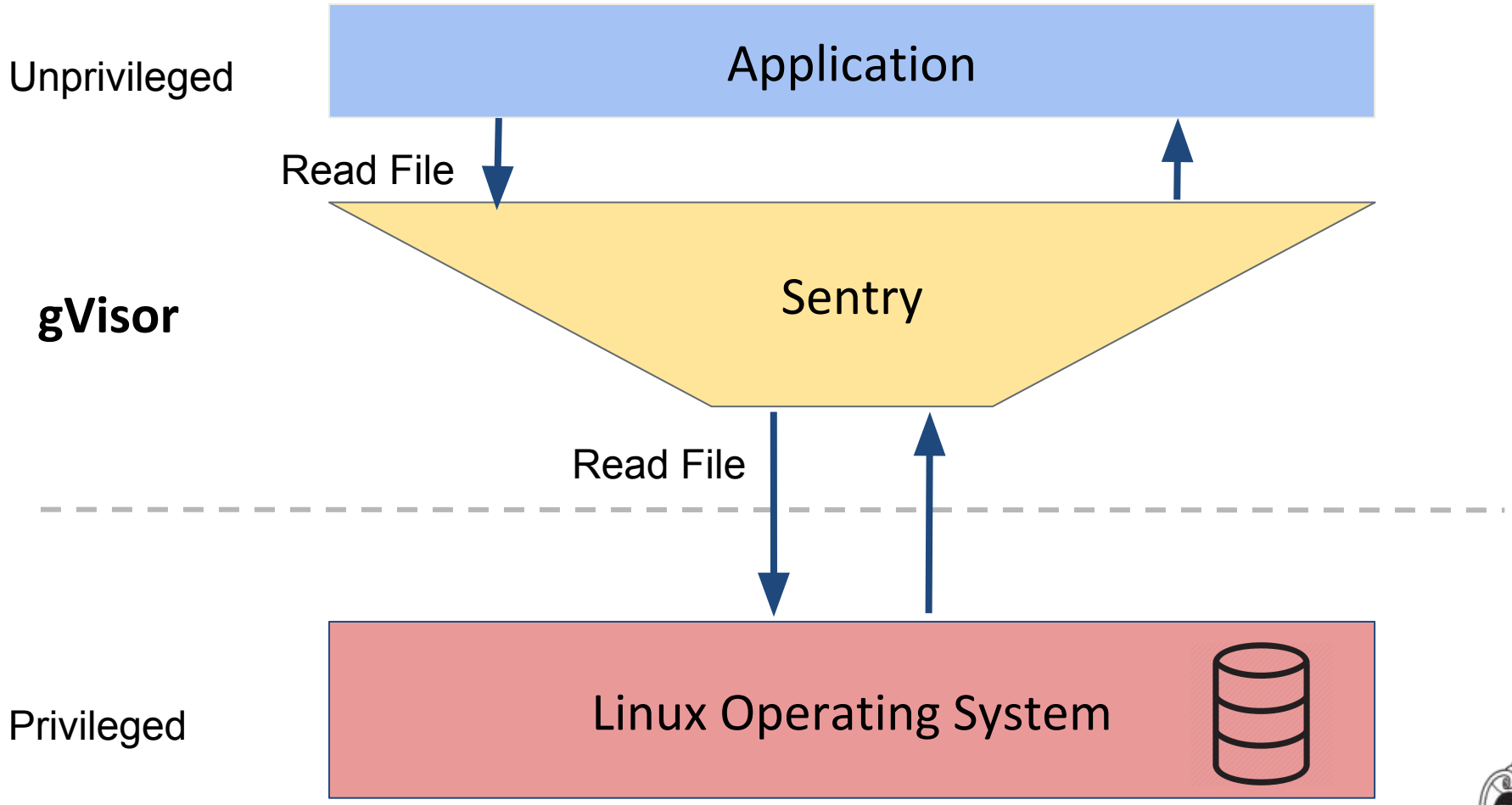
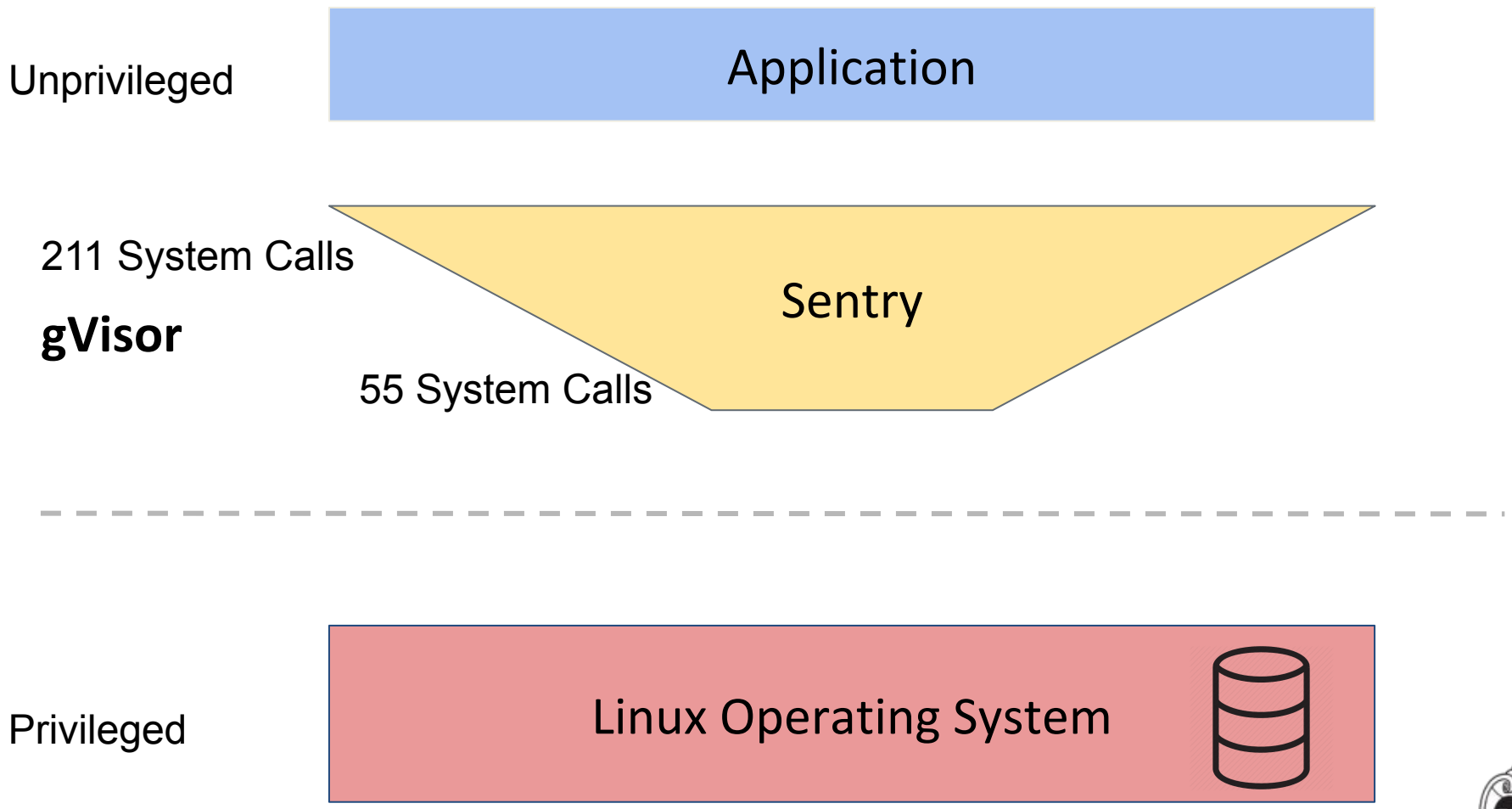


gVisor drastically reduces the attack surface of an application to the host operating system



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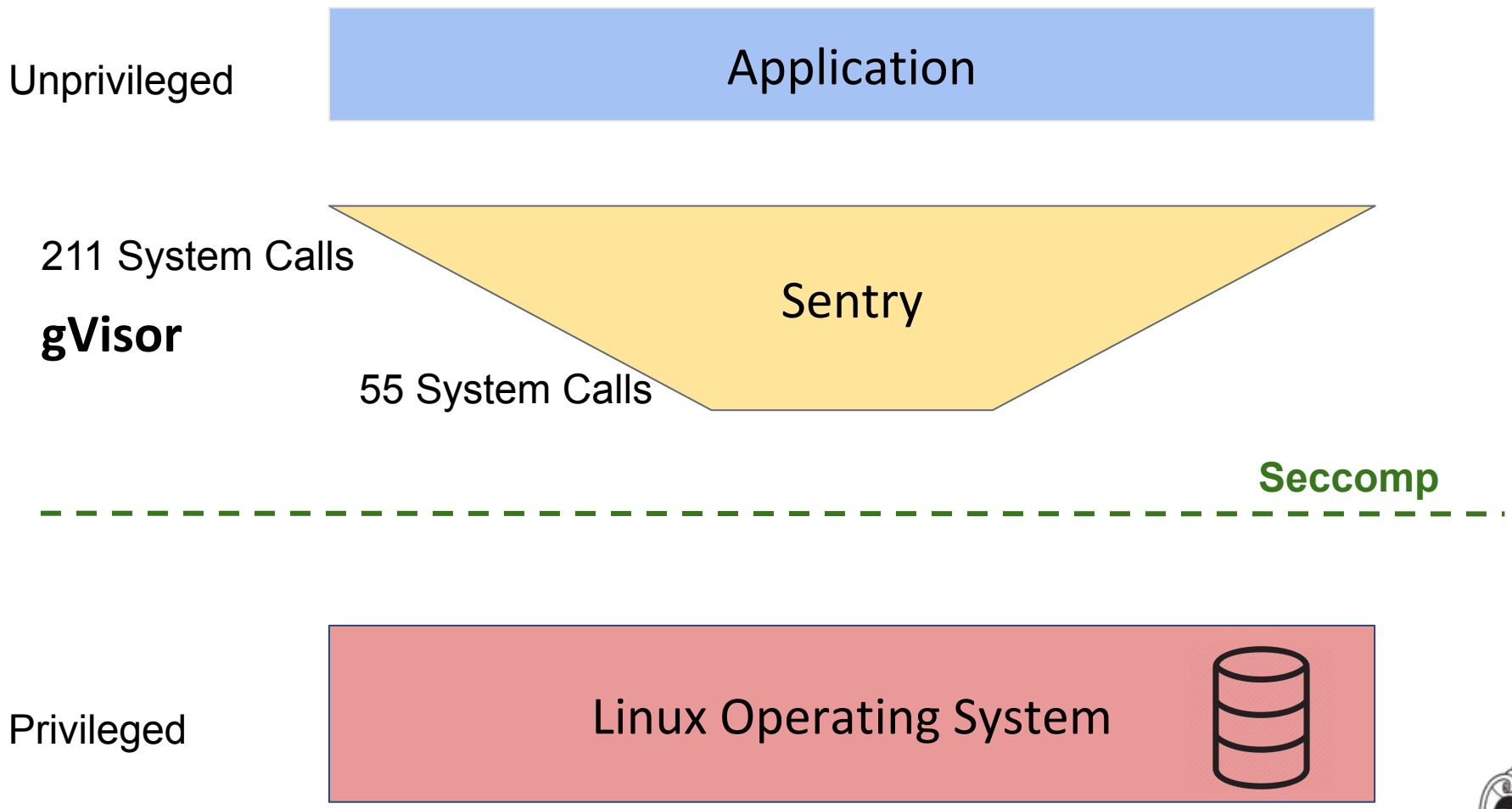

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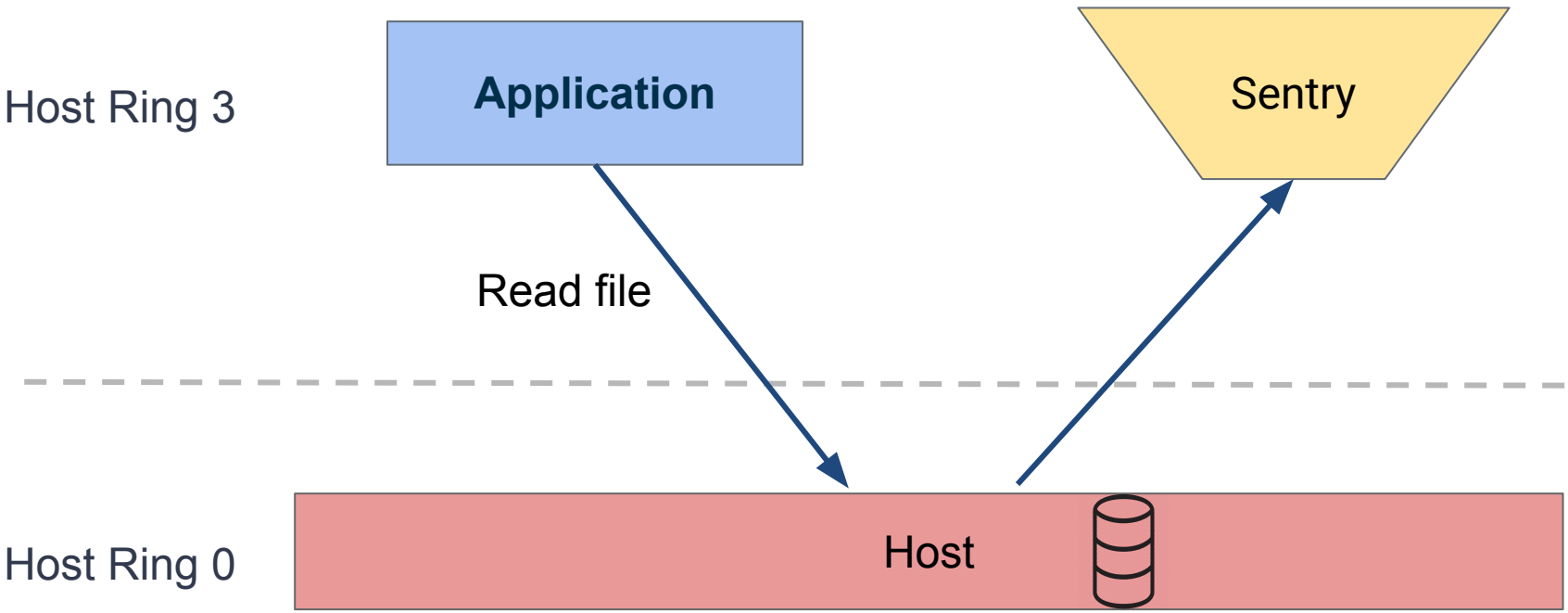

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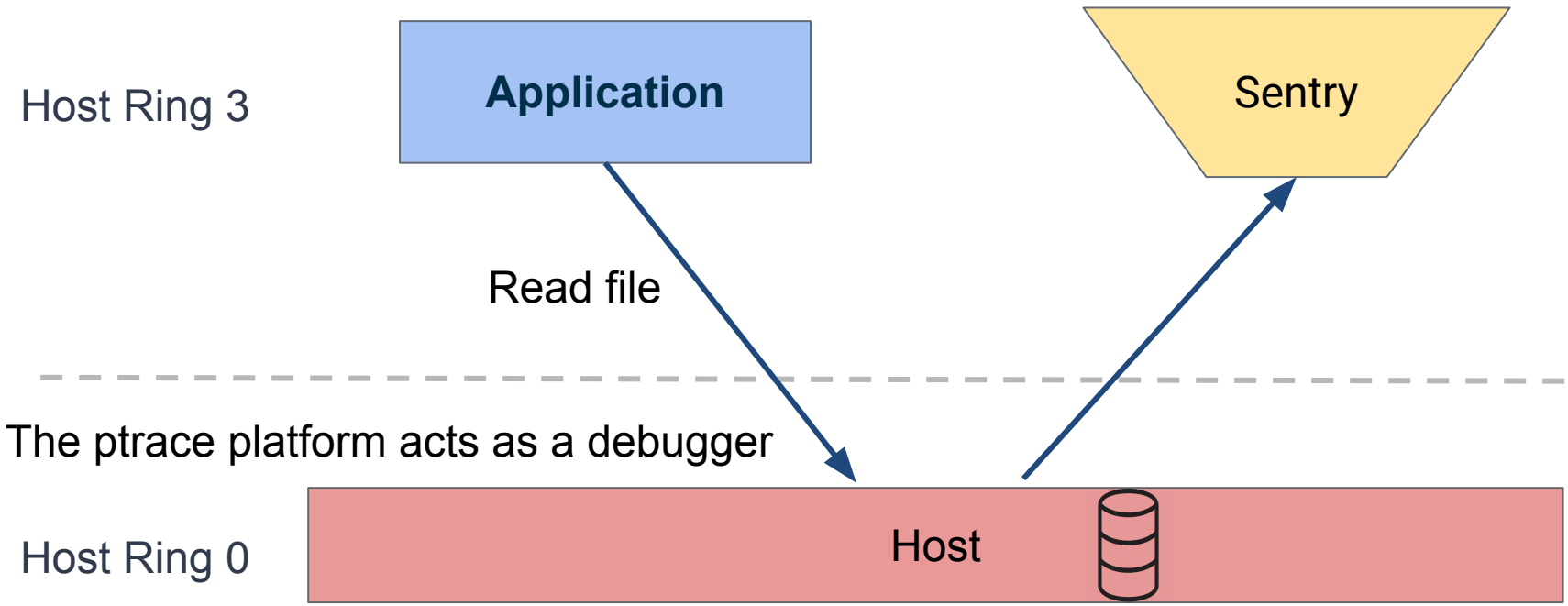
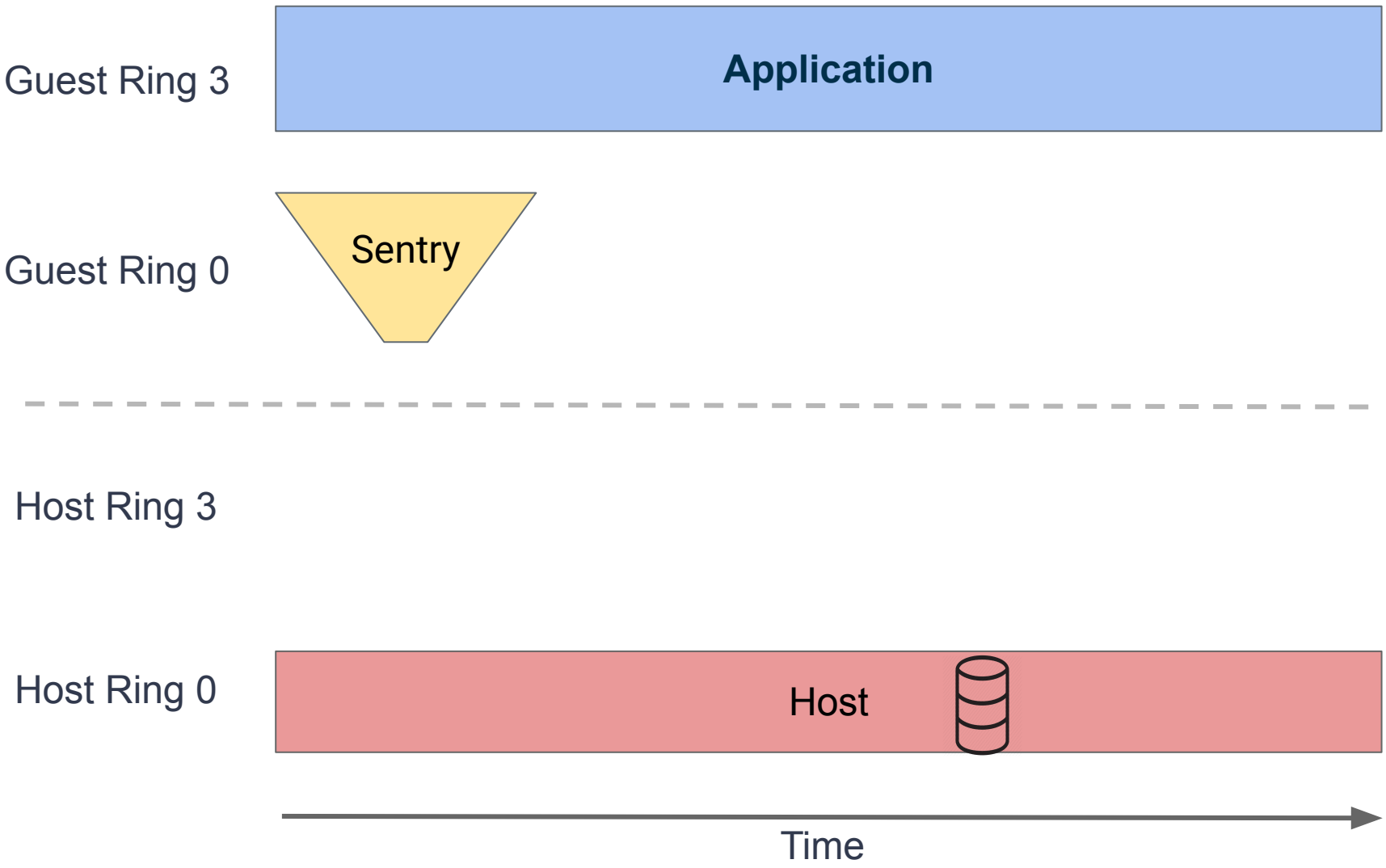


Issuing a system call to the host requires the sentry to switch from non-root ring0 to root ring3 in KVM mode



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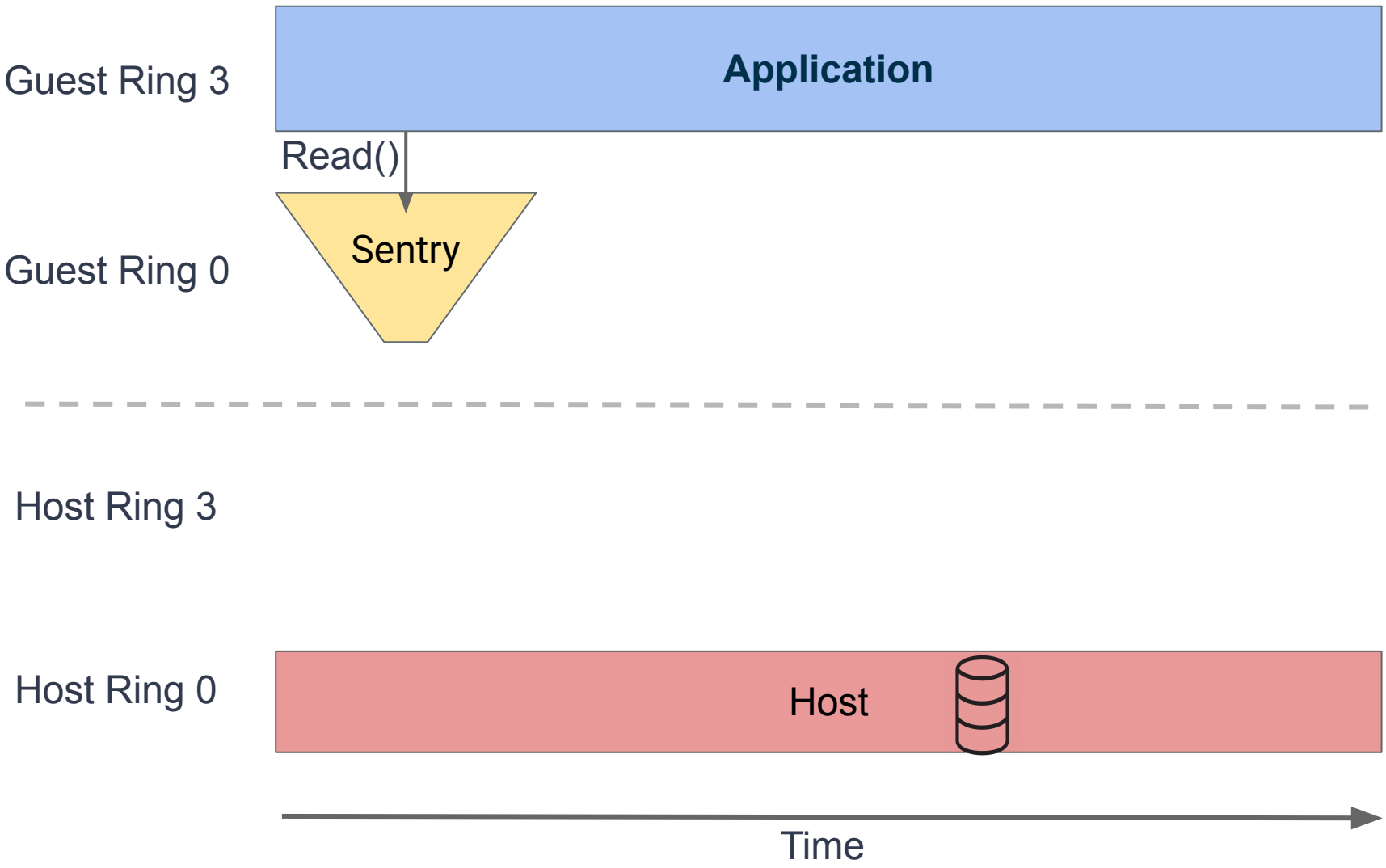

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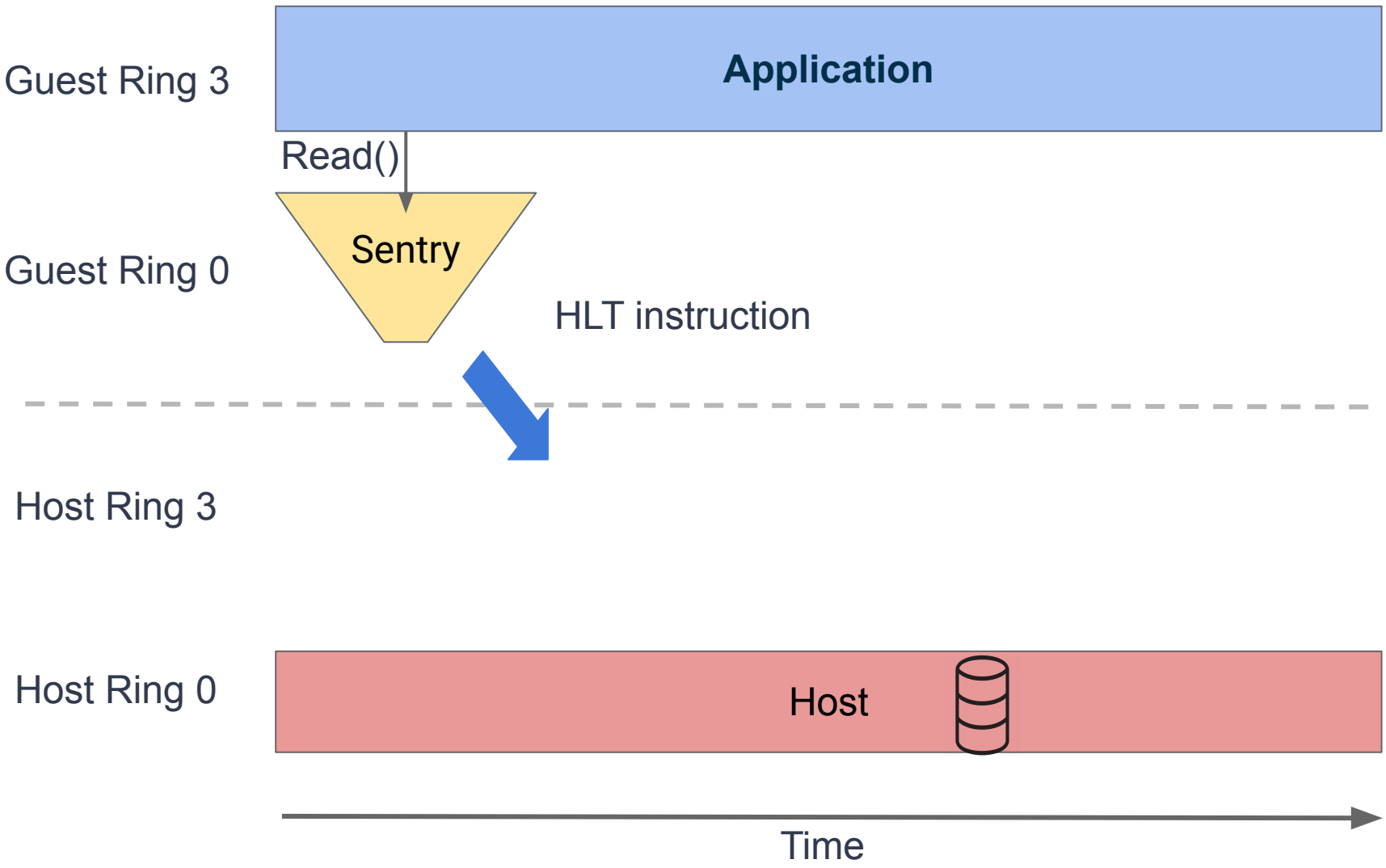

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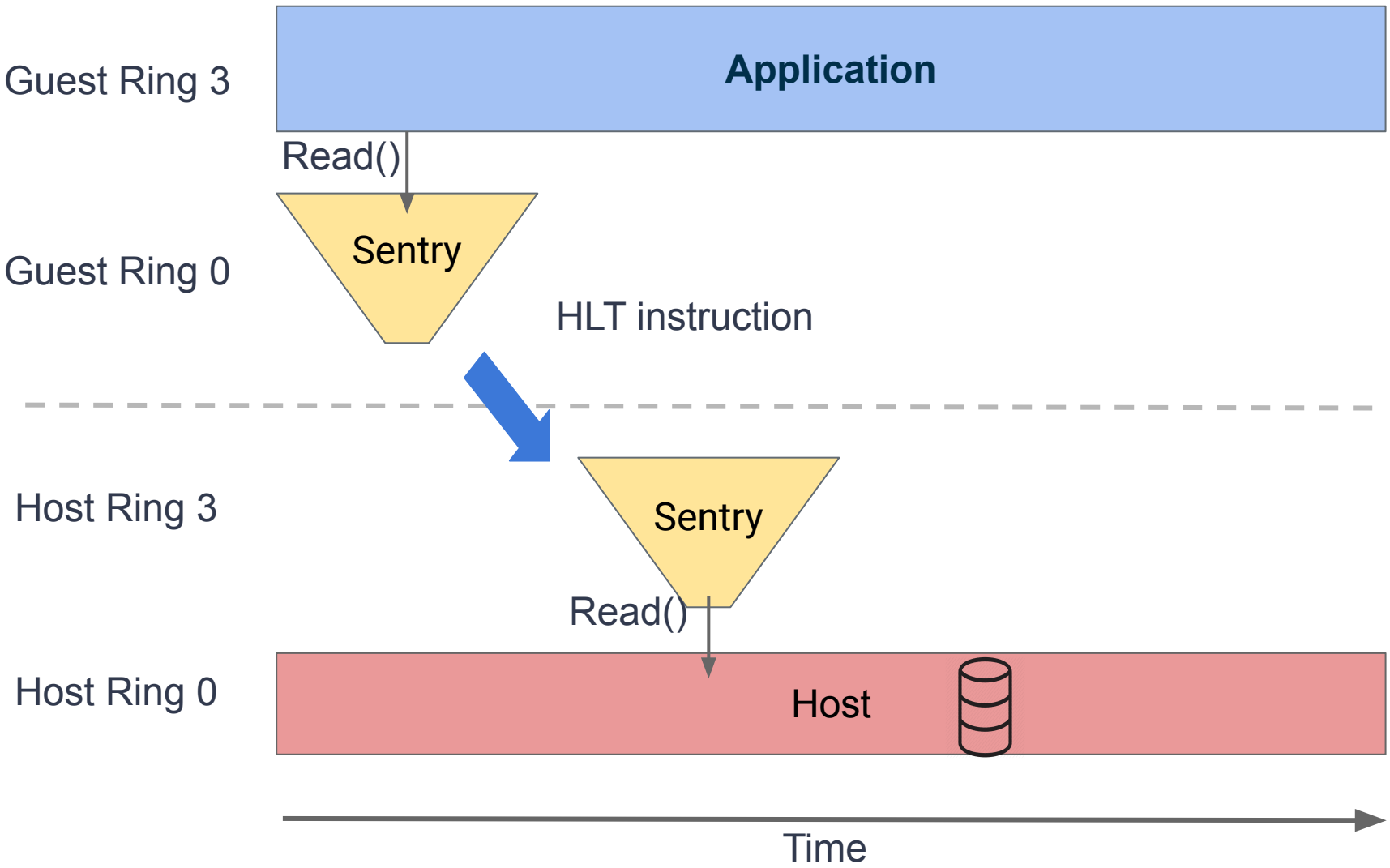

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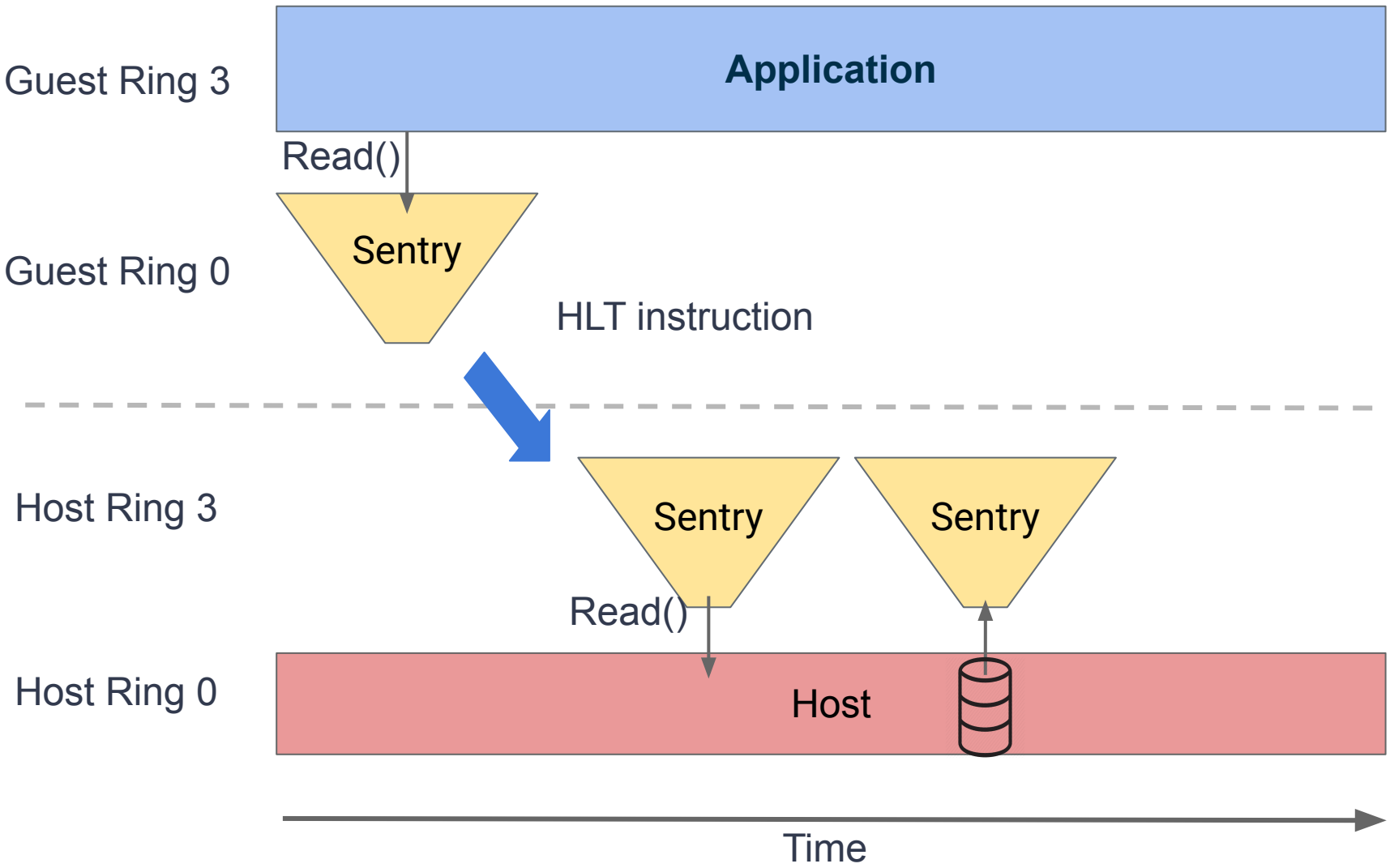

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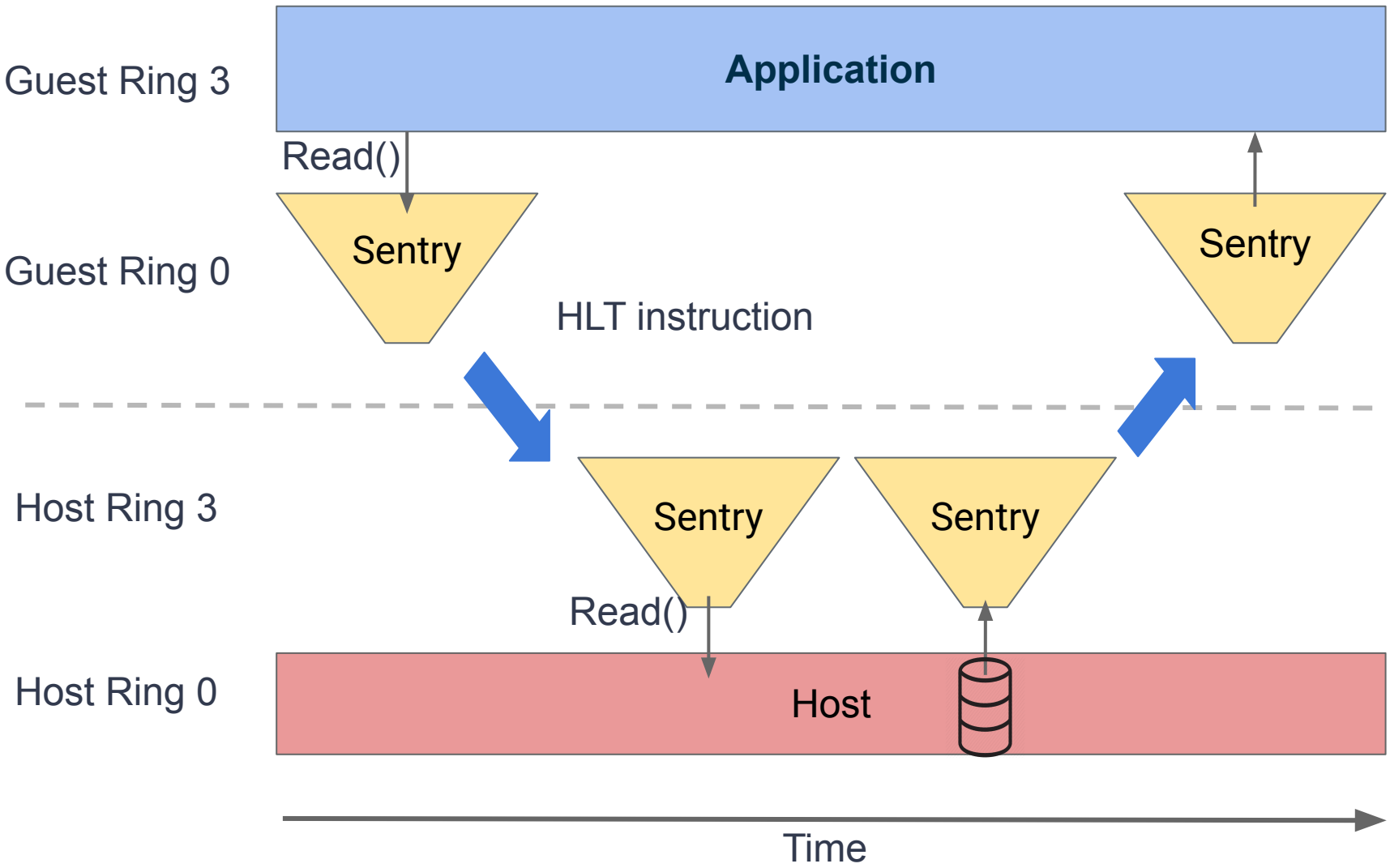

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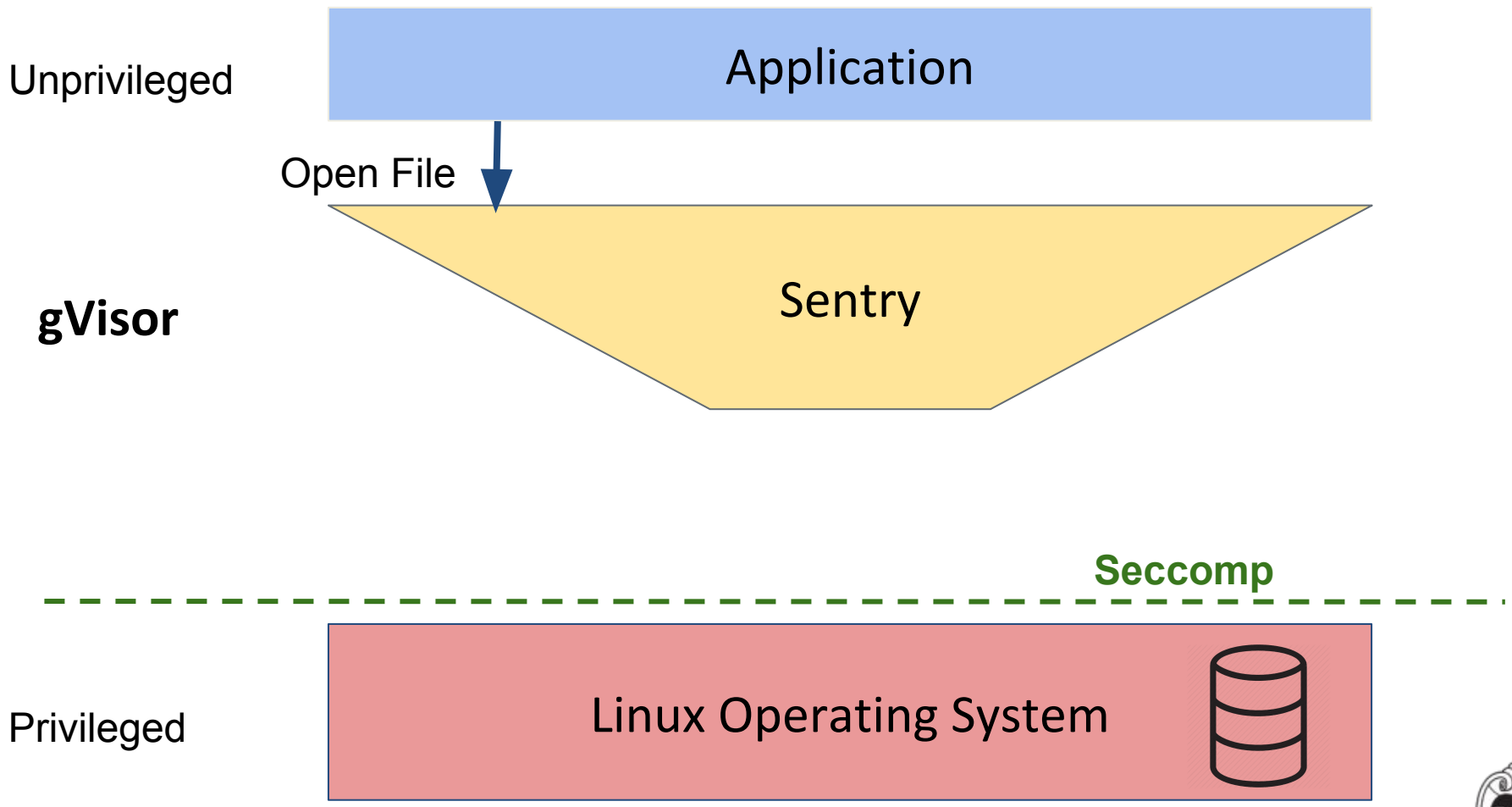

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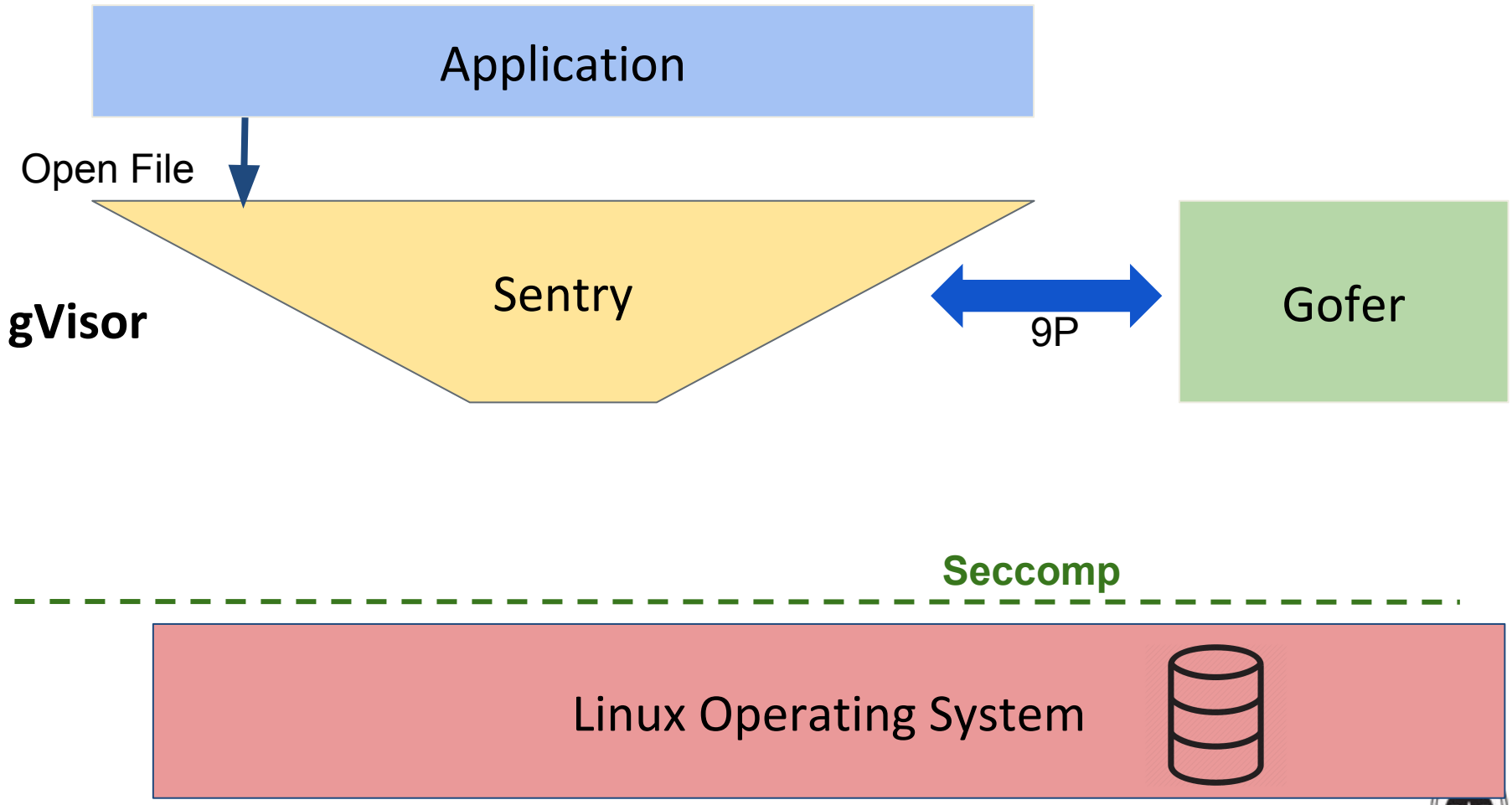

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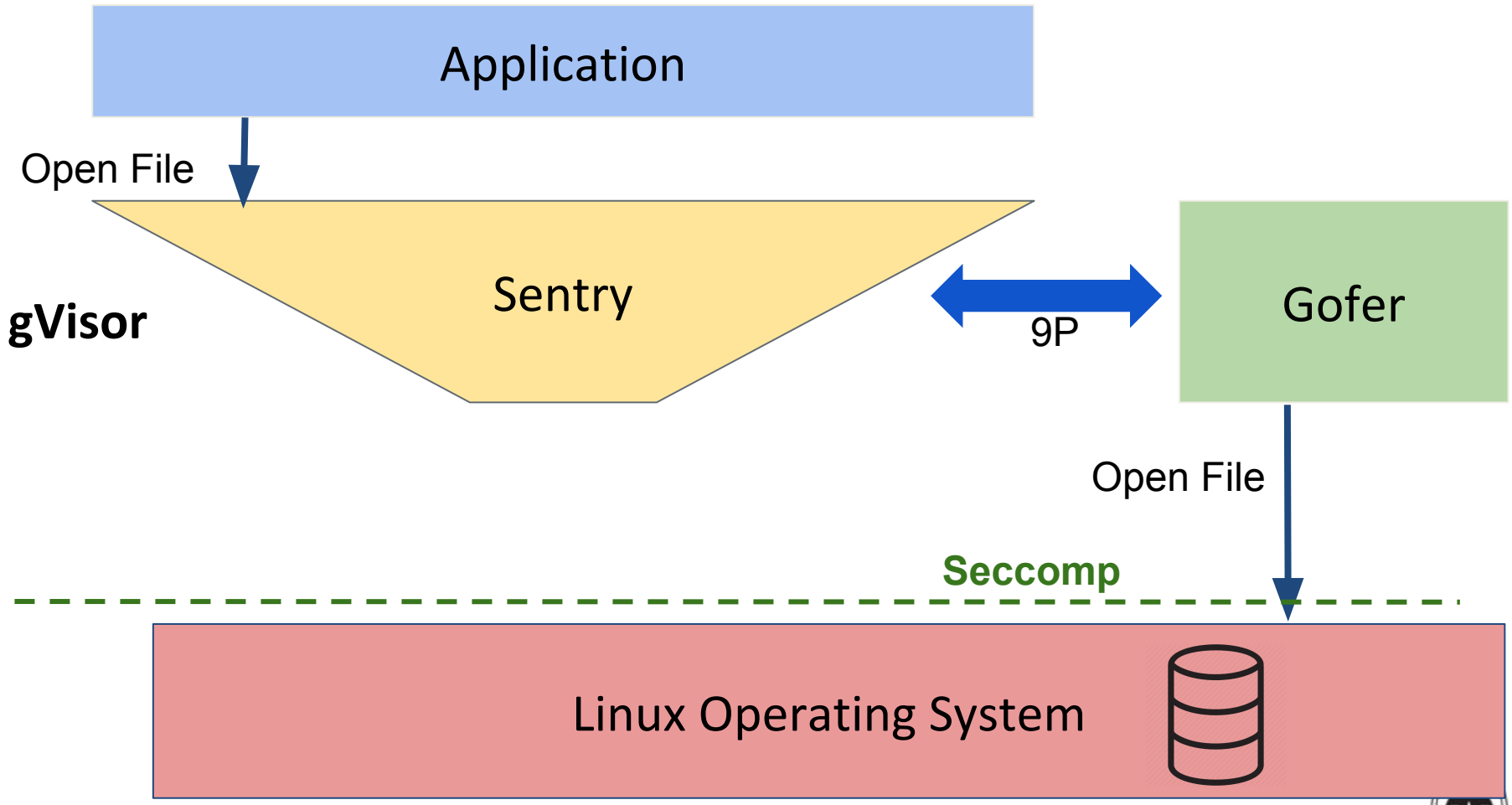

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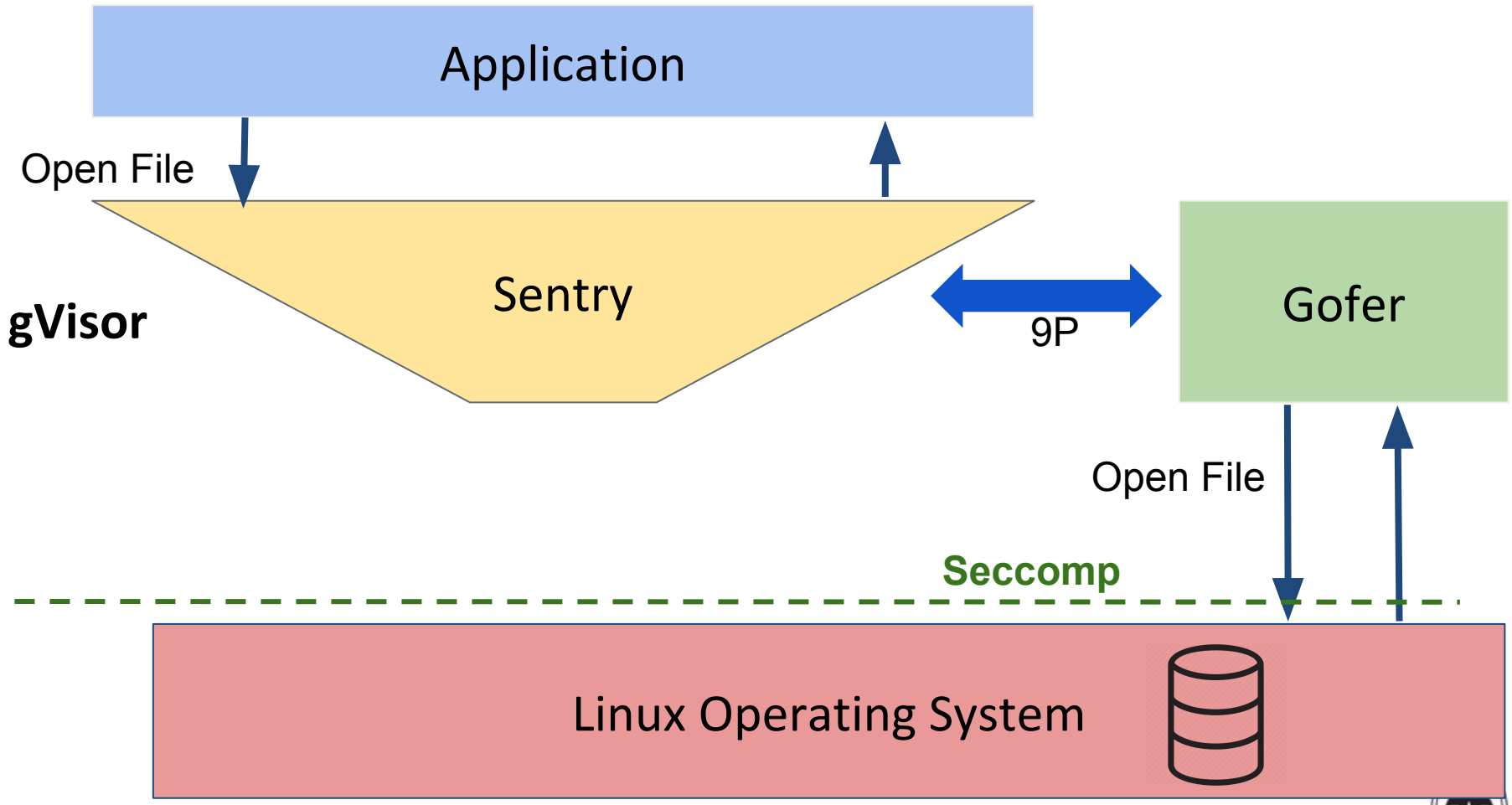

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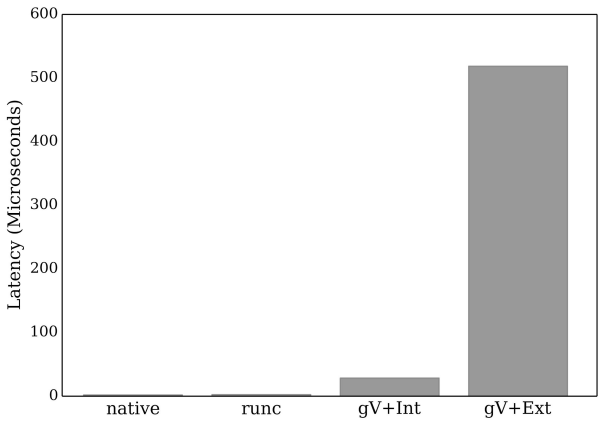

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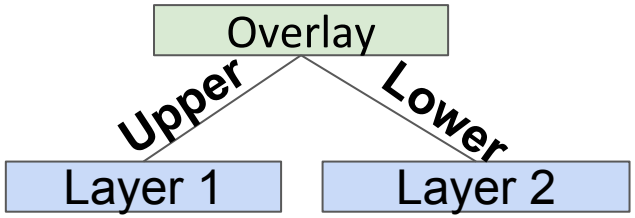

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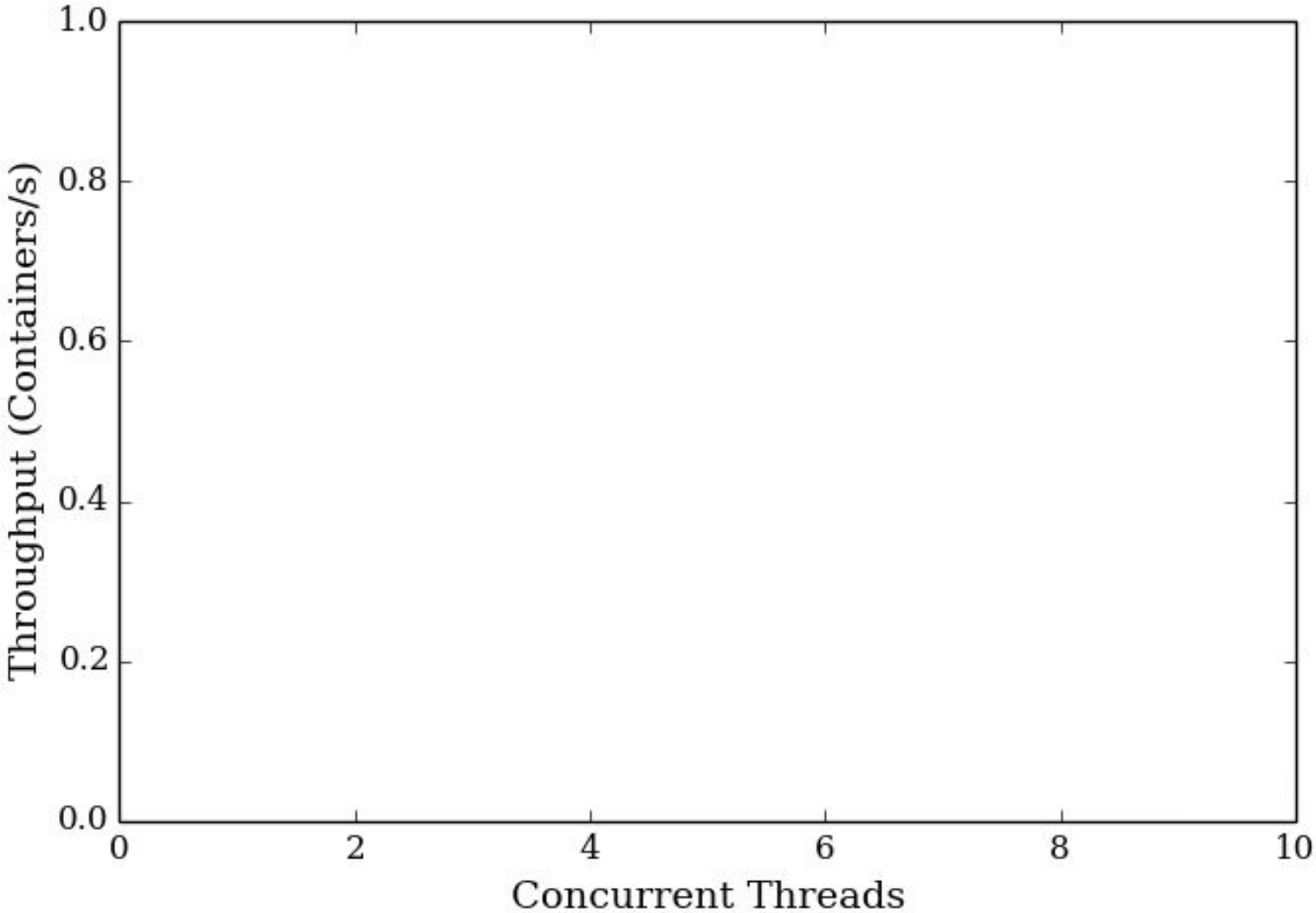

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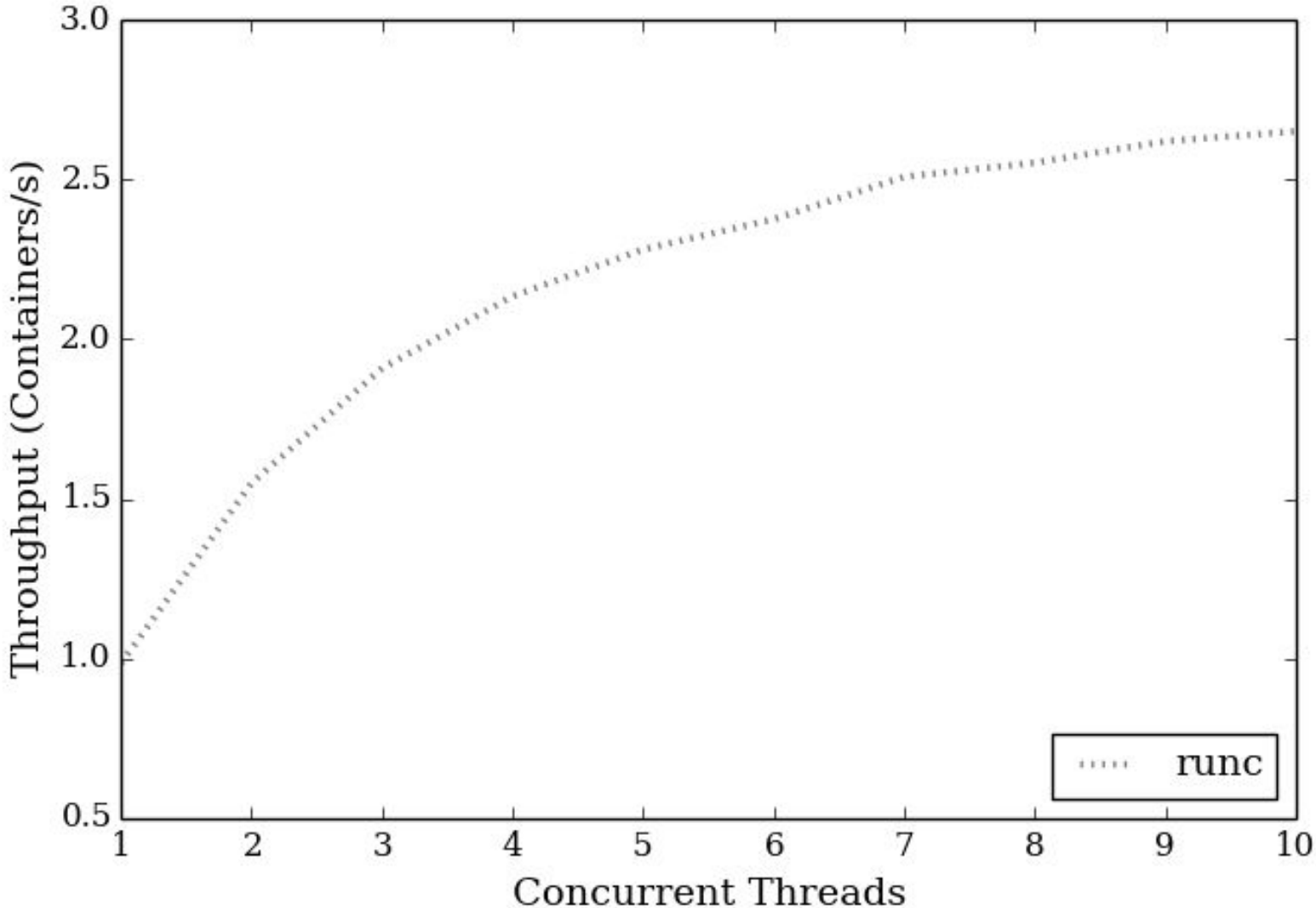

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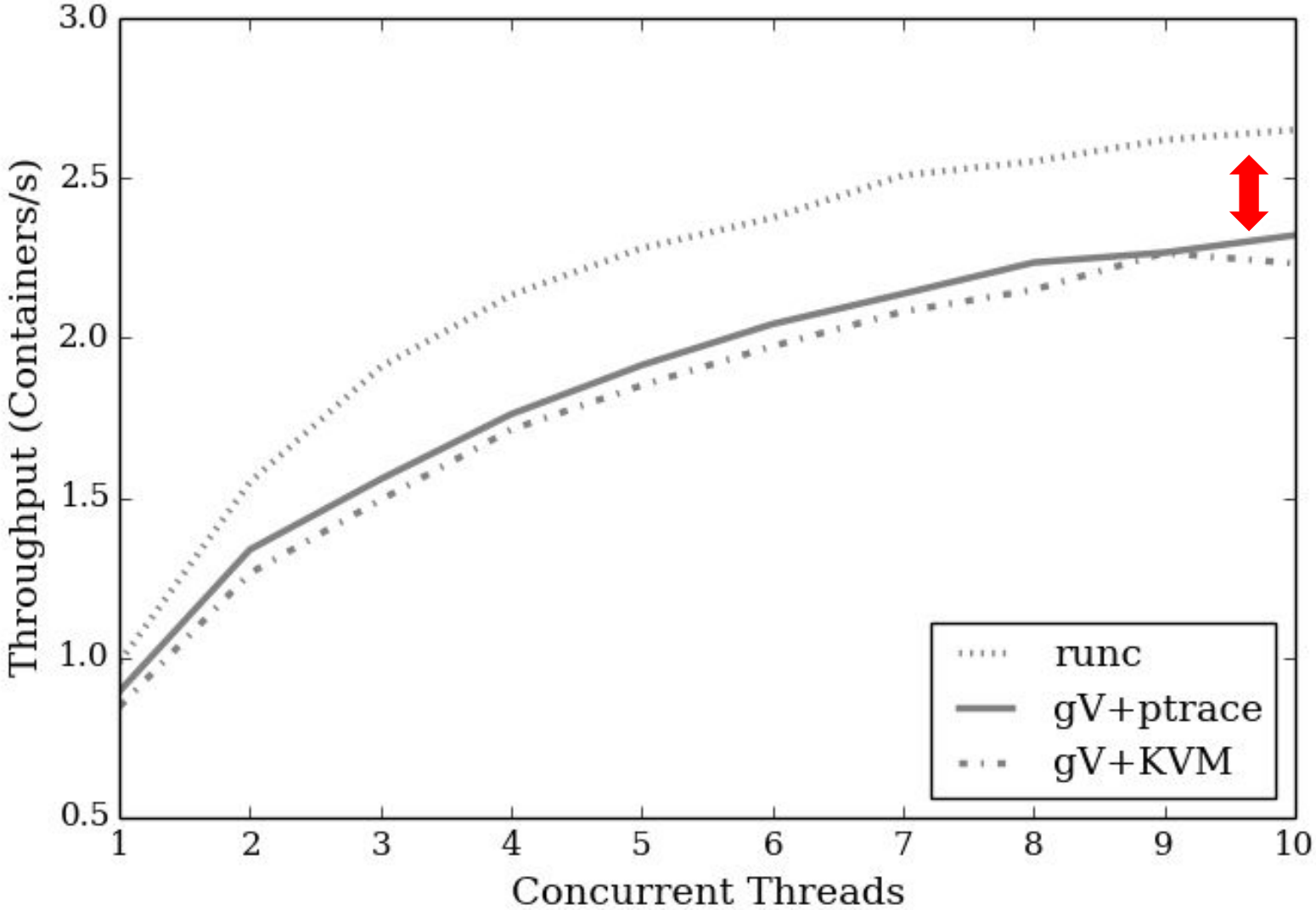

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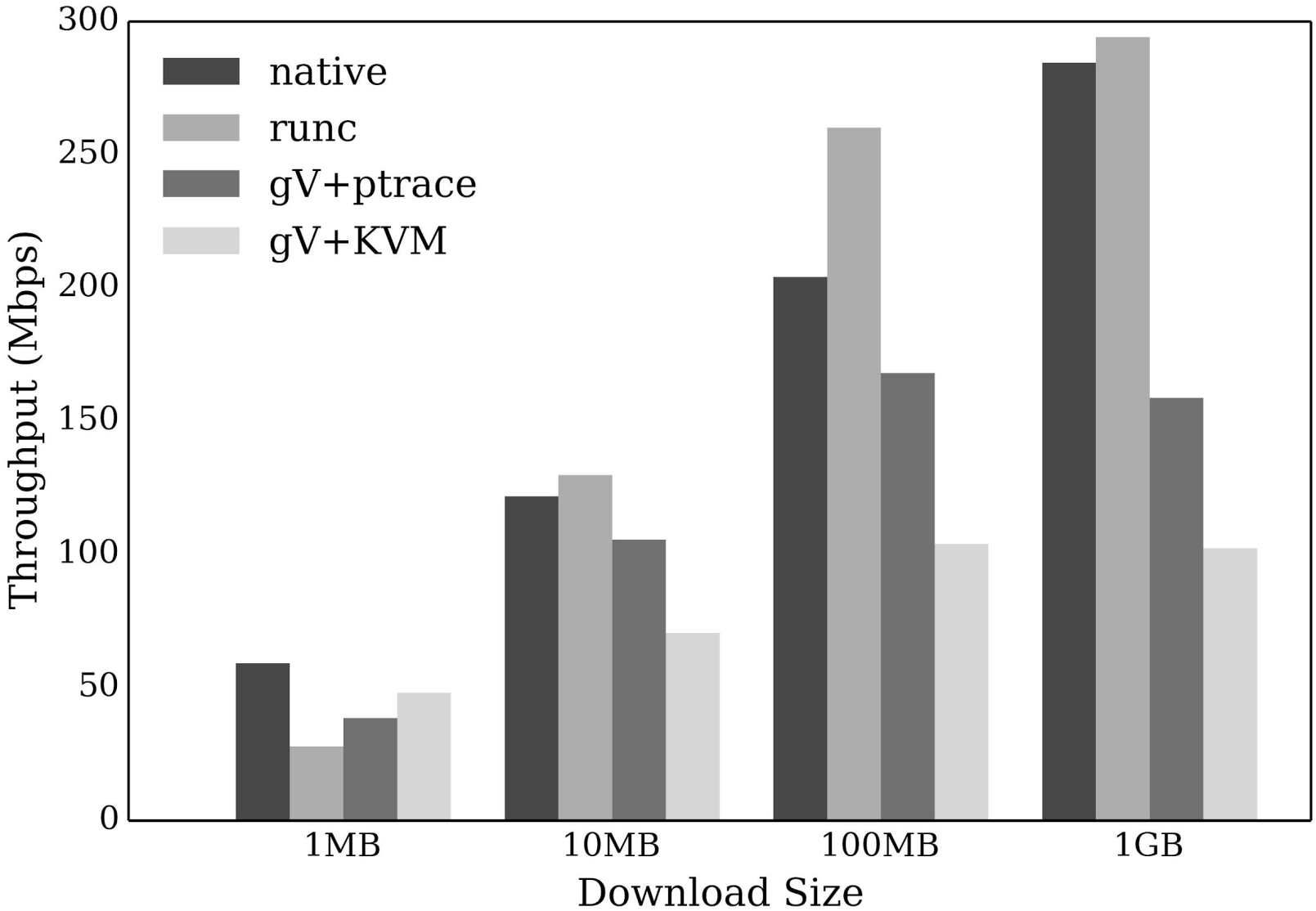
gVisor+KVM achieves 34% of the other system's performance but is competitive at small download sizes



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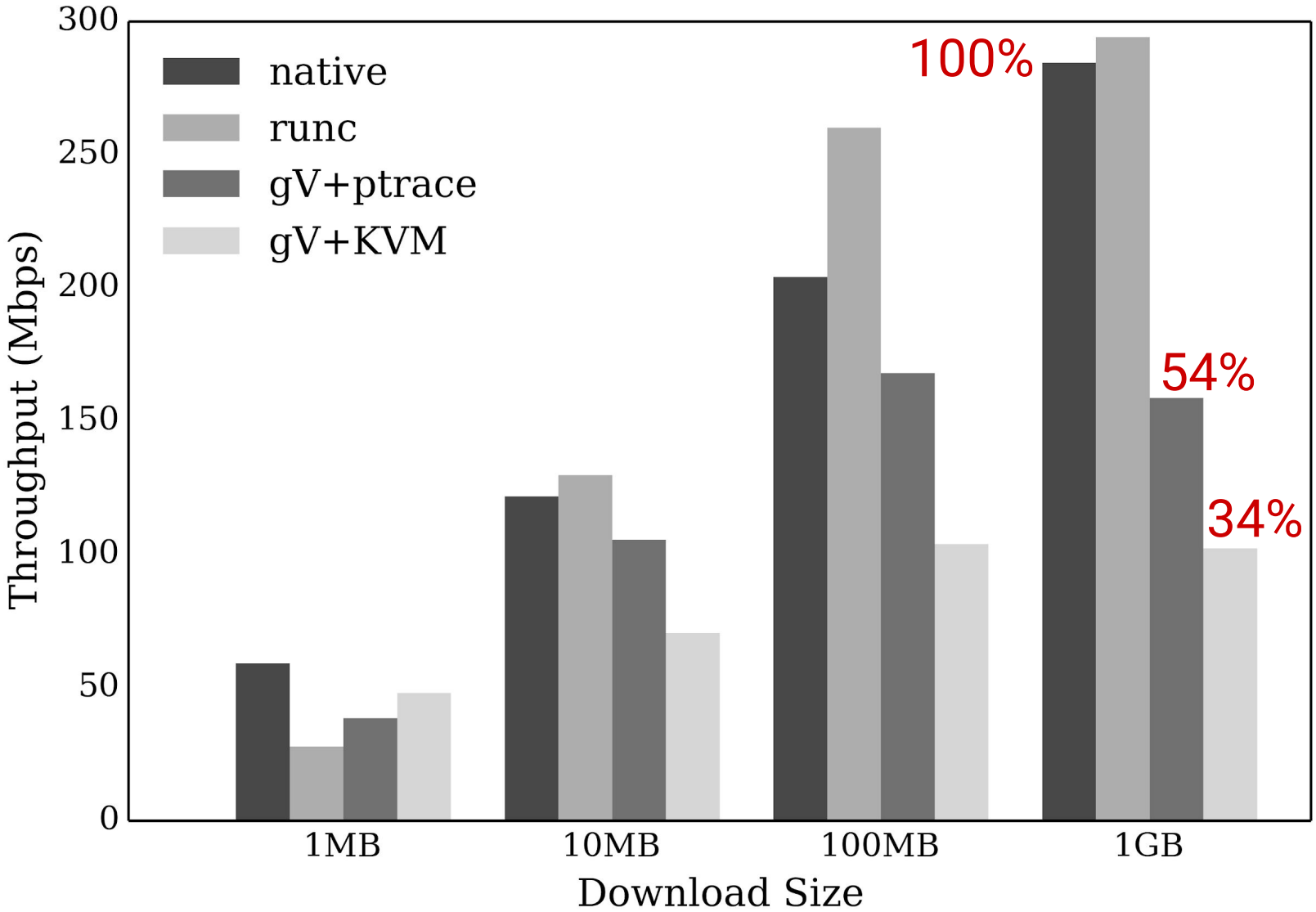

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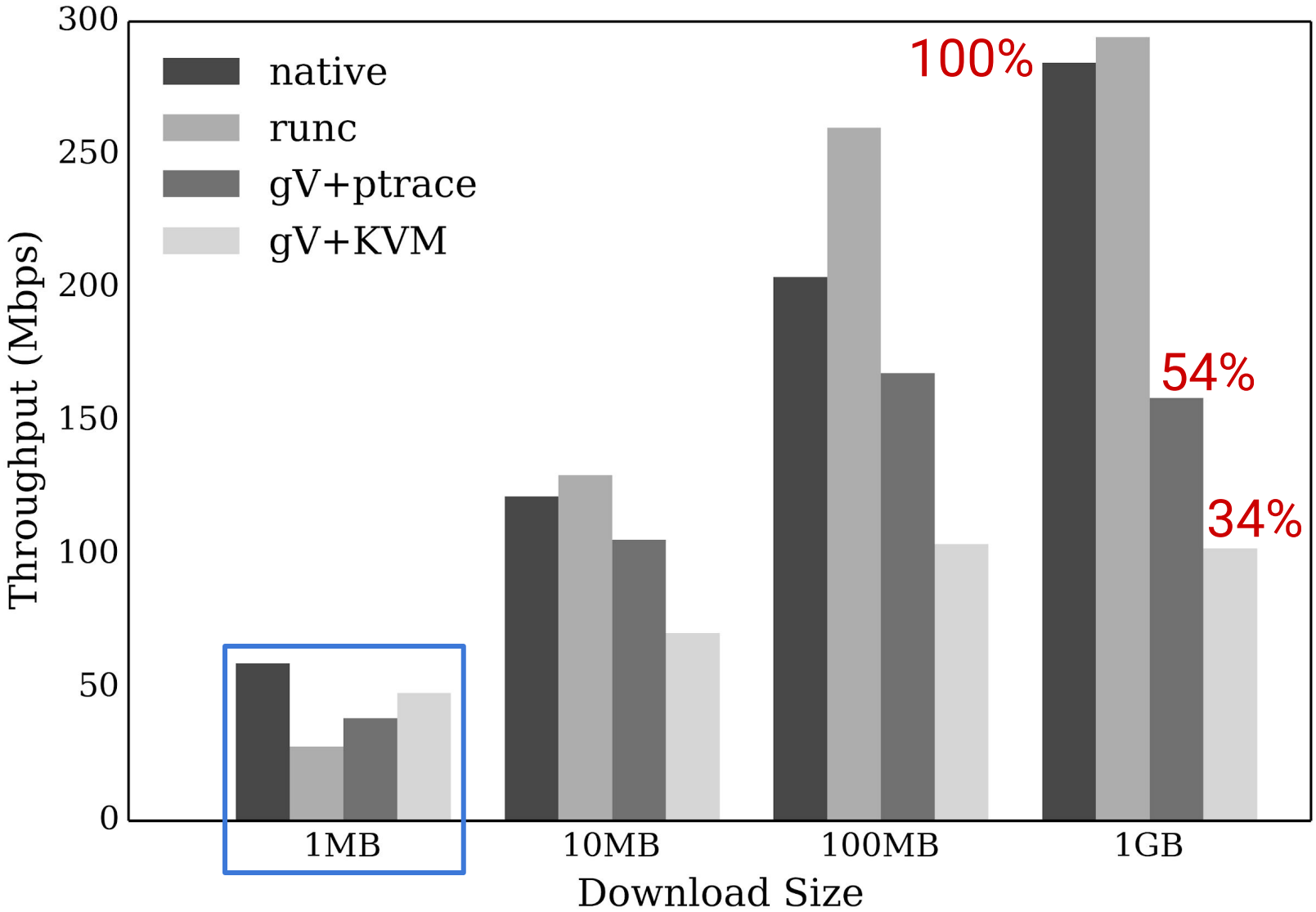

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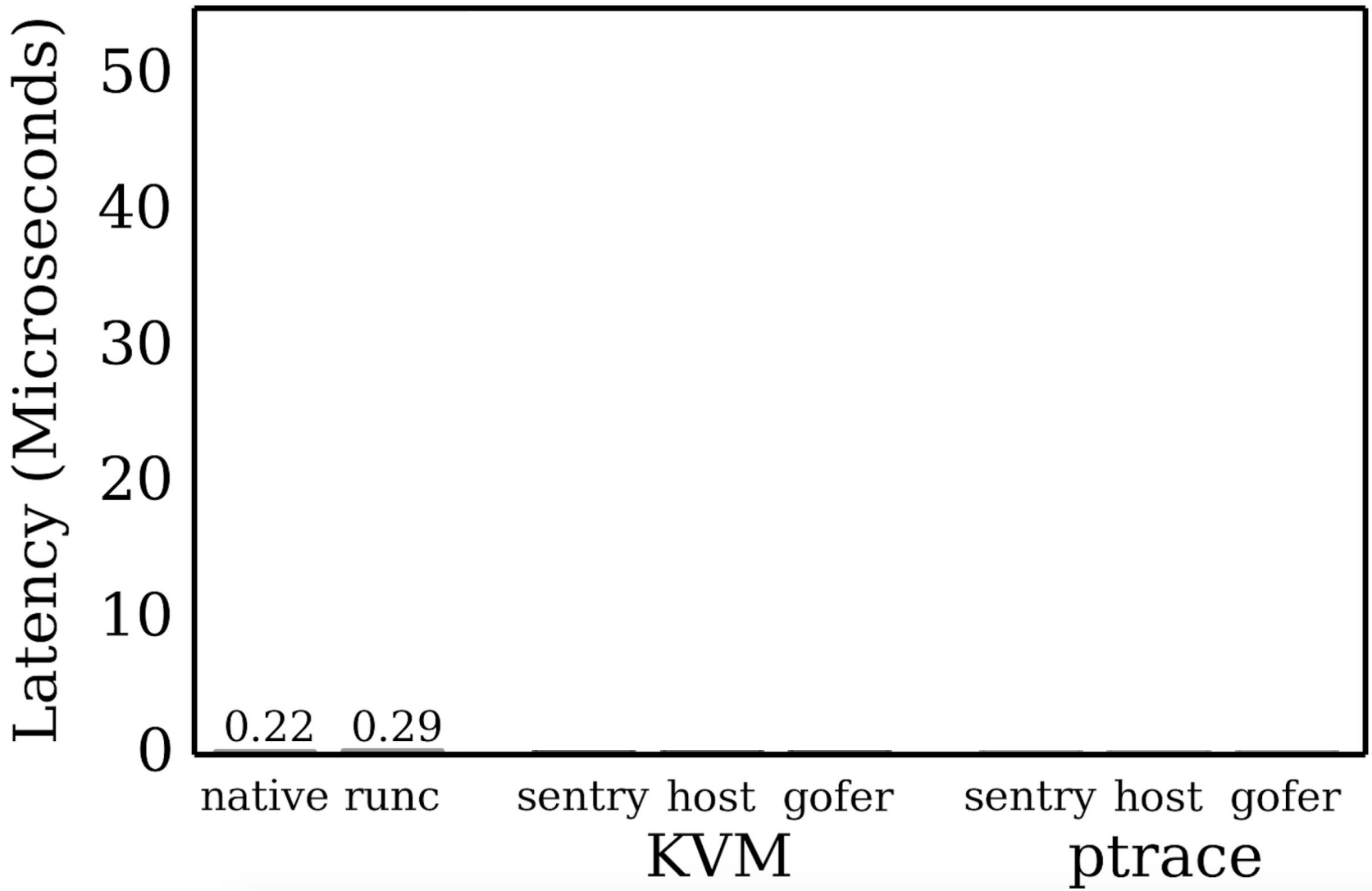
- What are the overheads of servicing system calls?

Handling system calls incurs high latencies on both the ptrace and KVM platforms, especially when using the gofer



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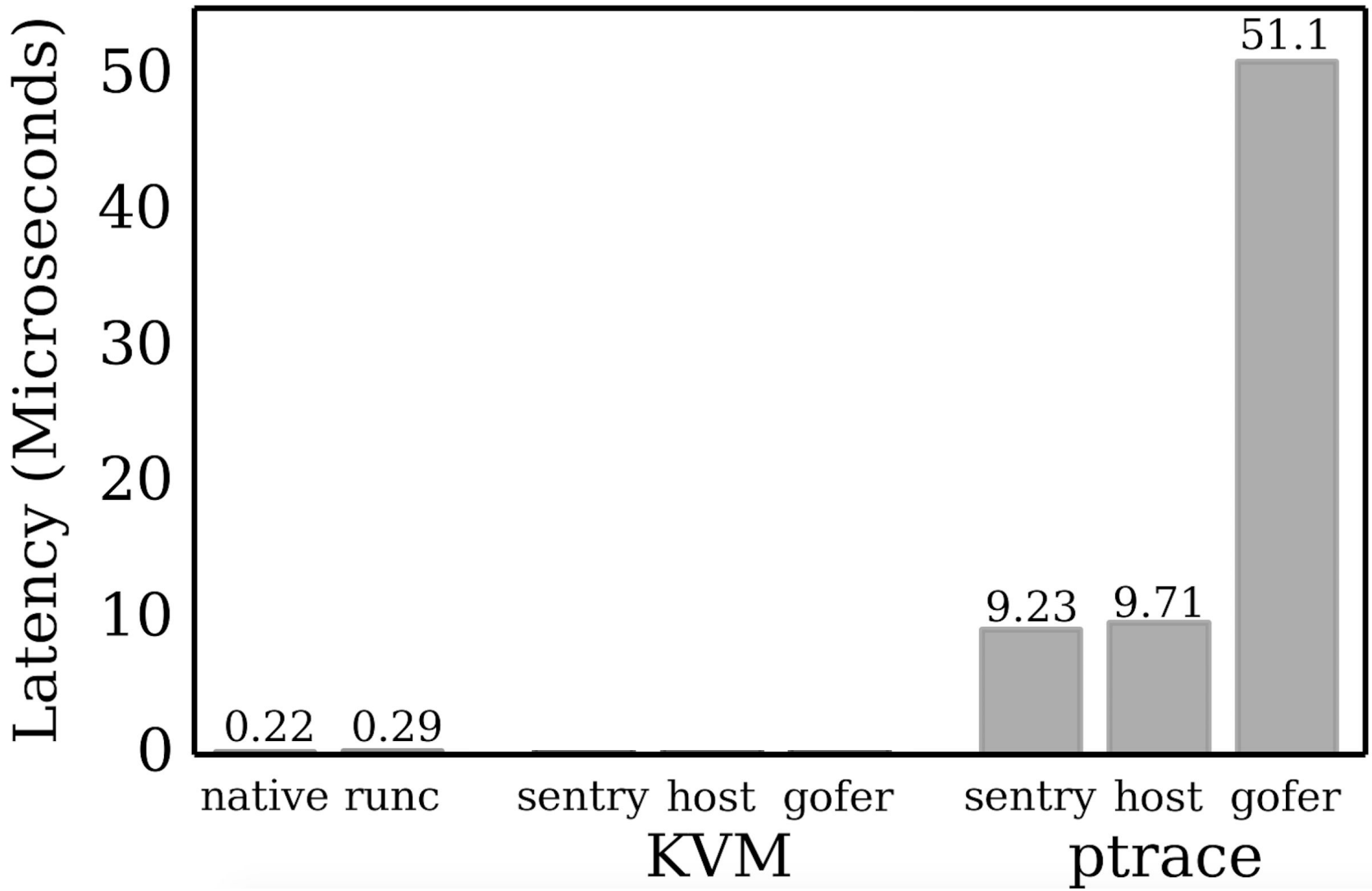

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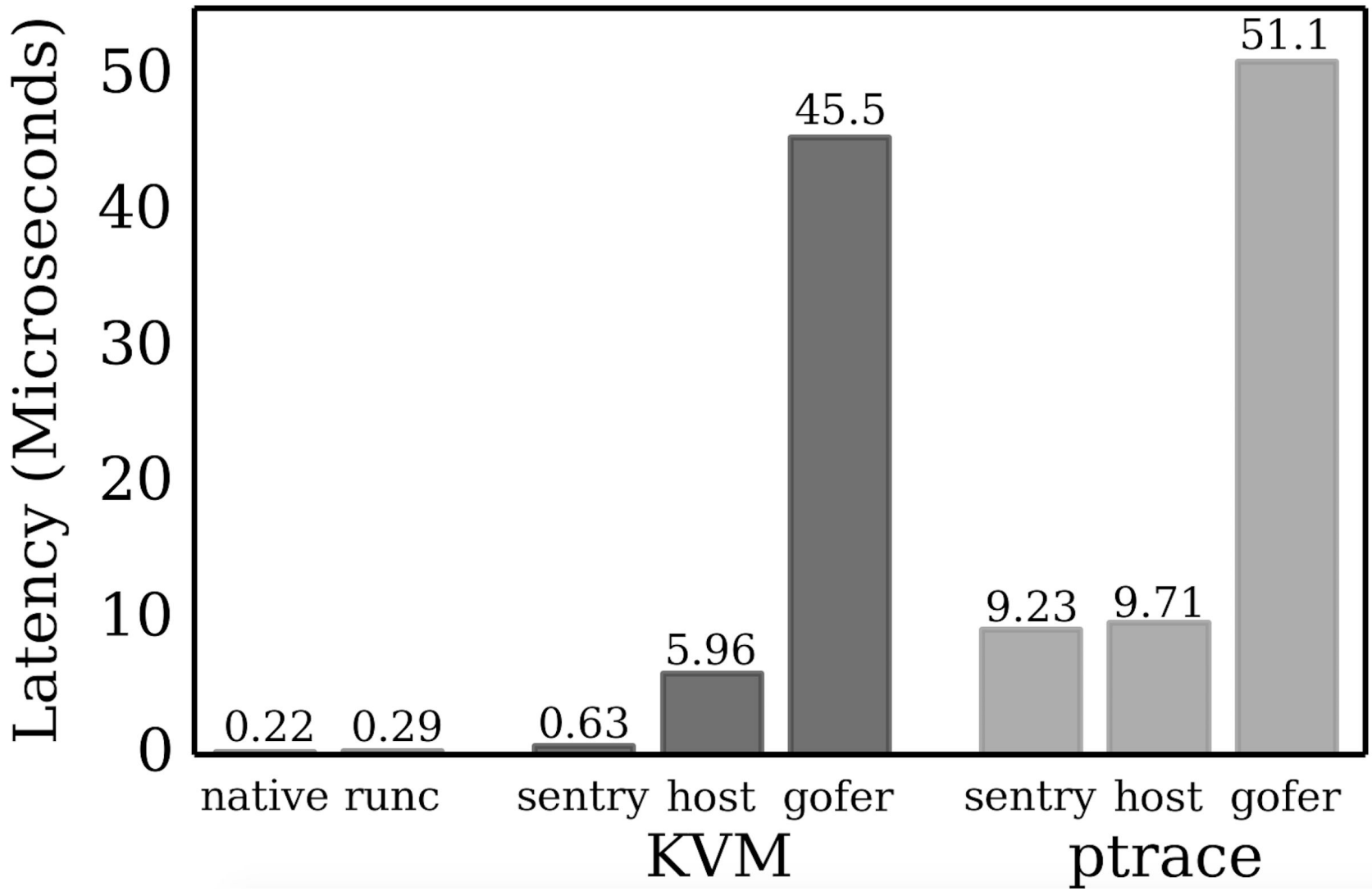

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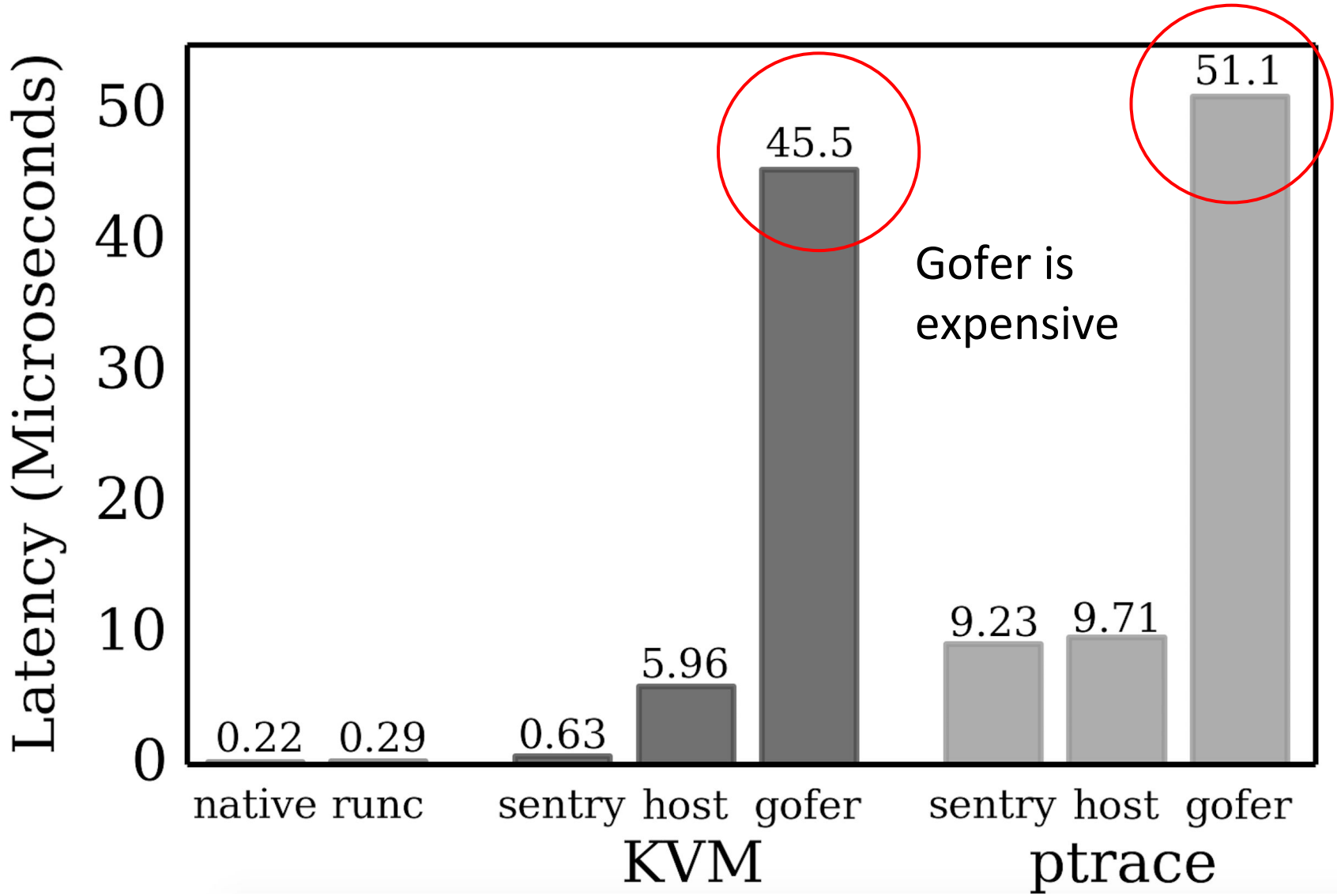

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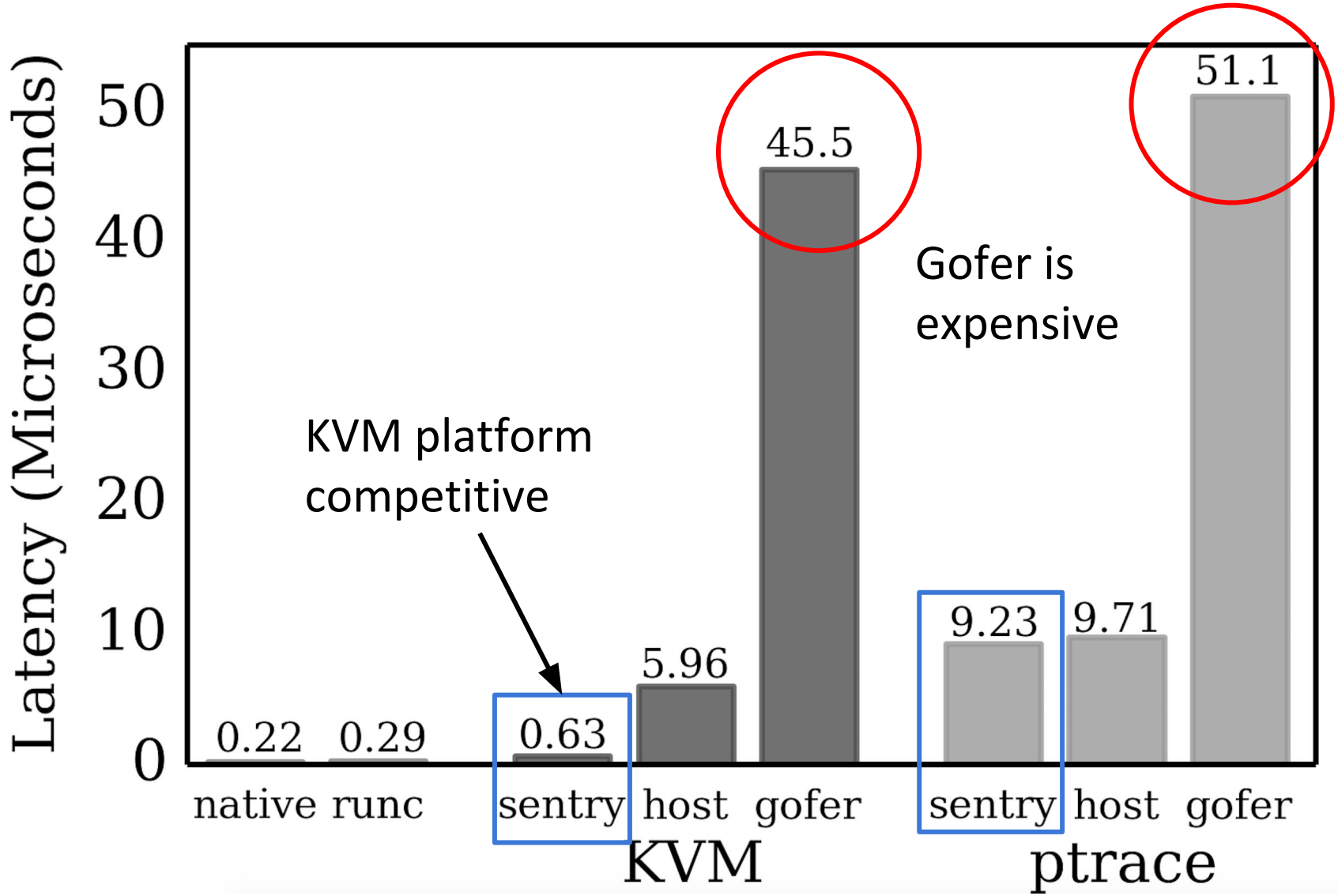

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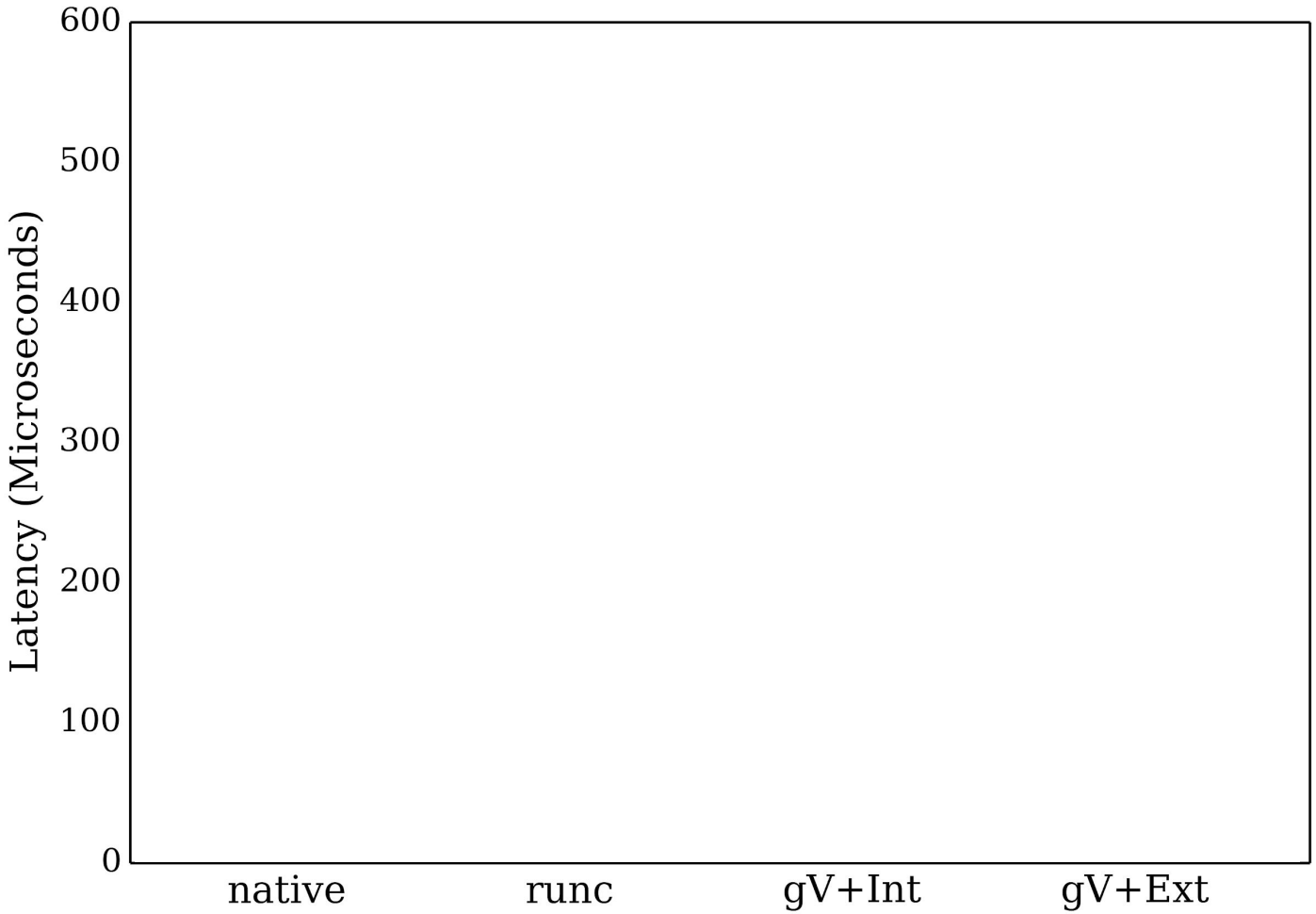

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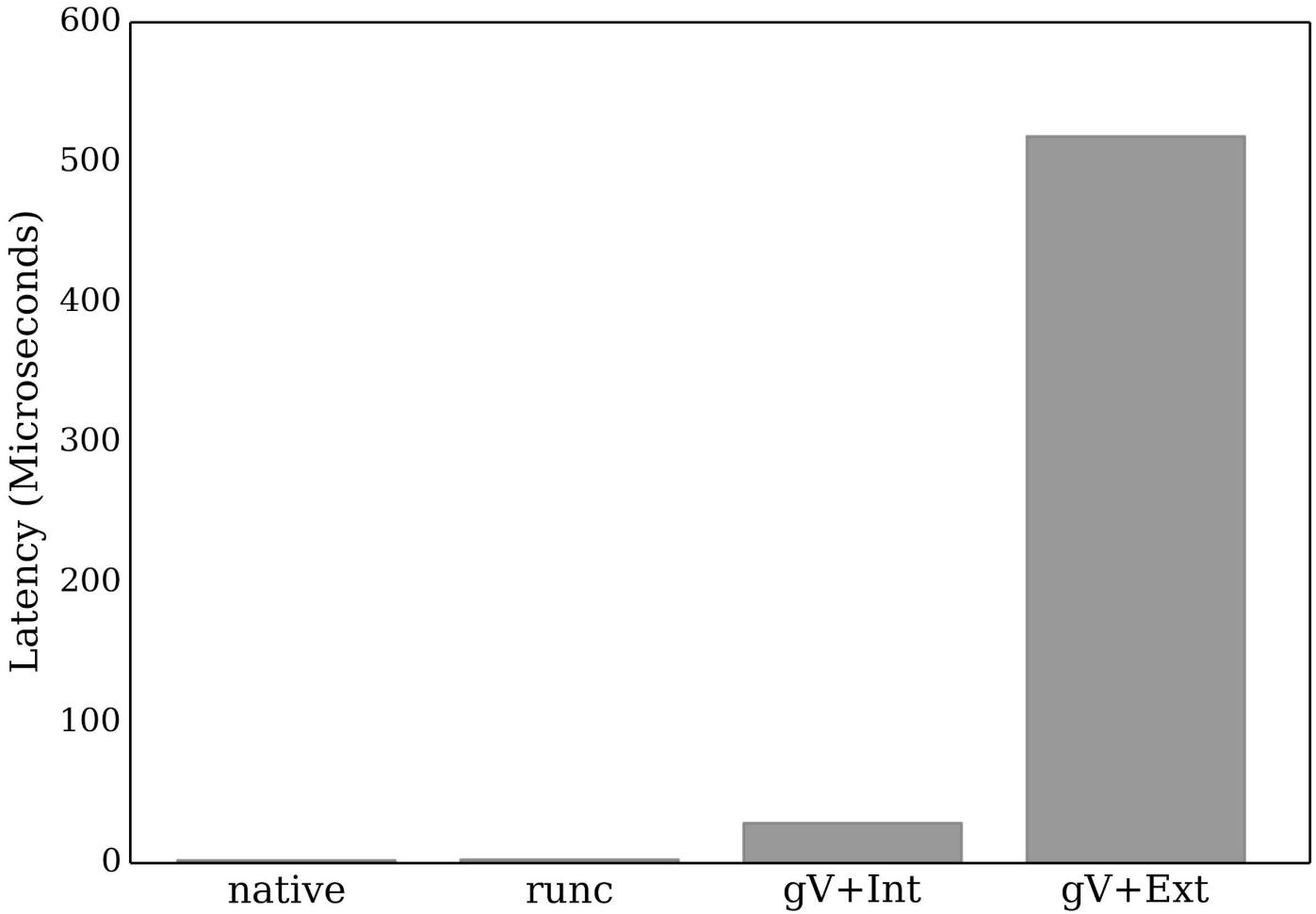

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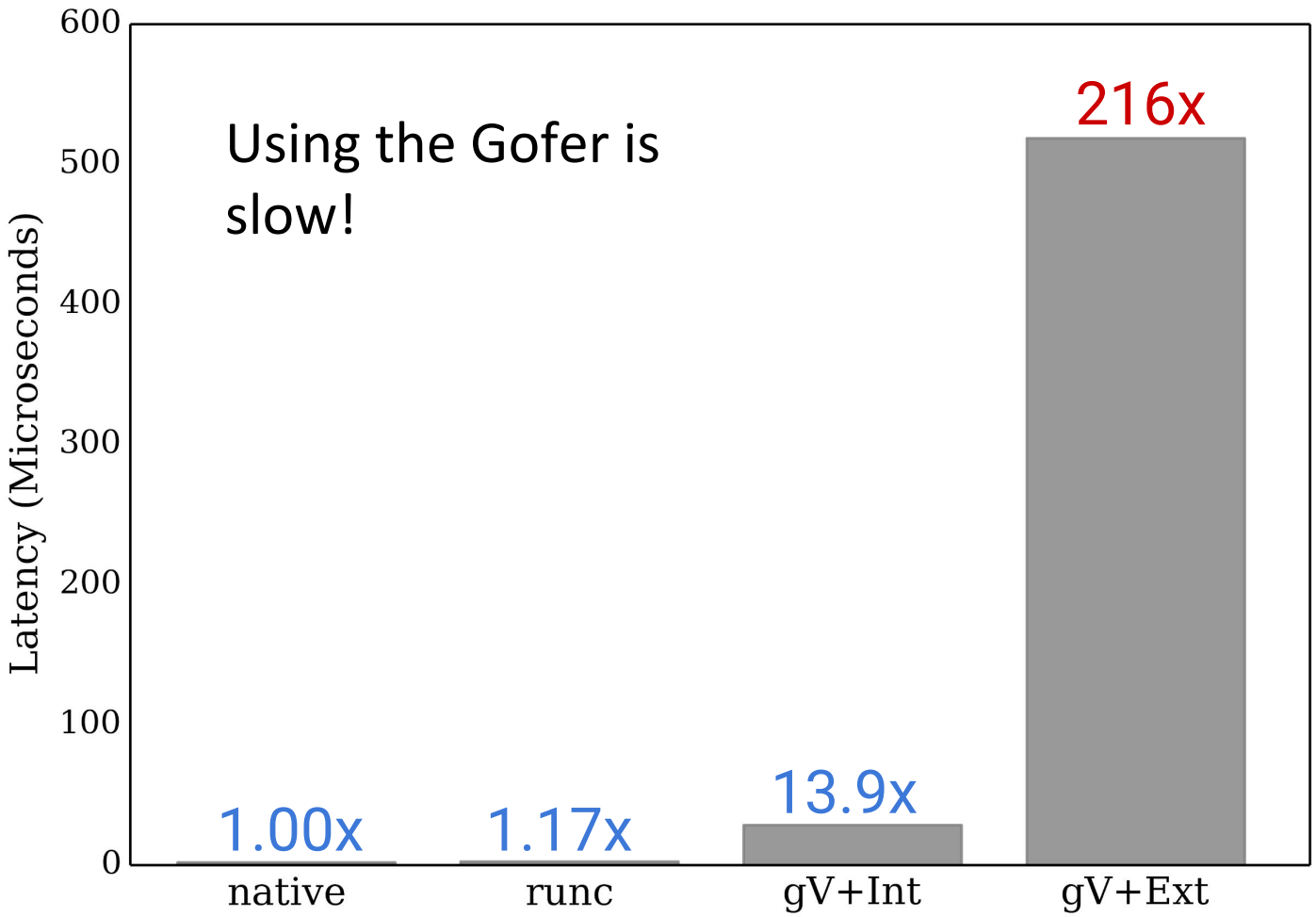

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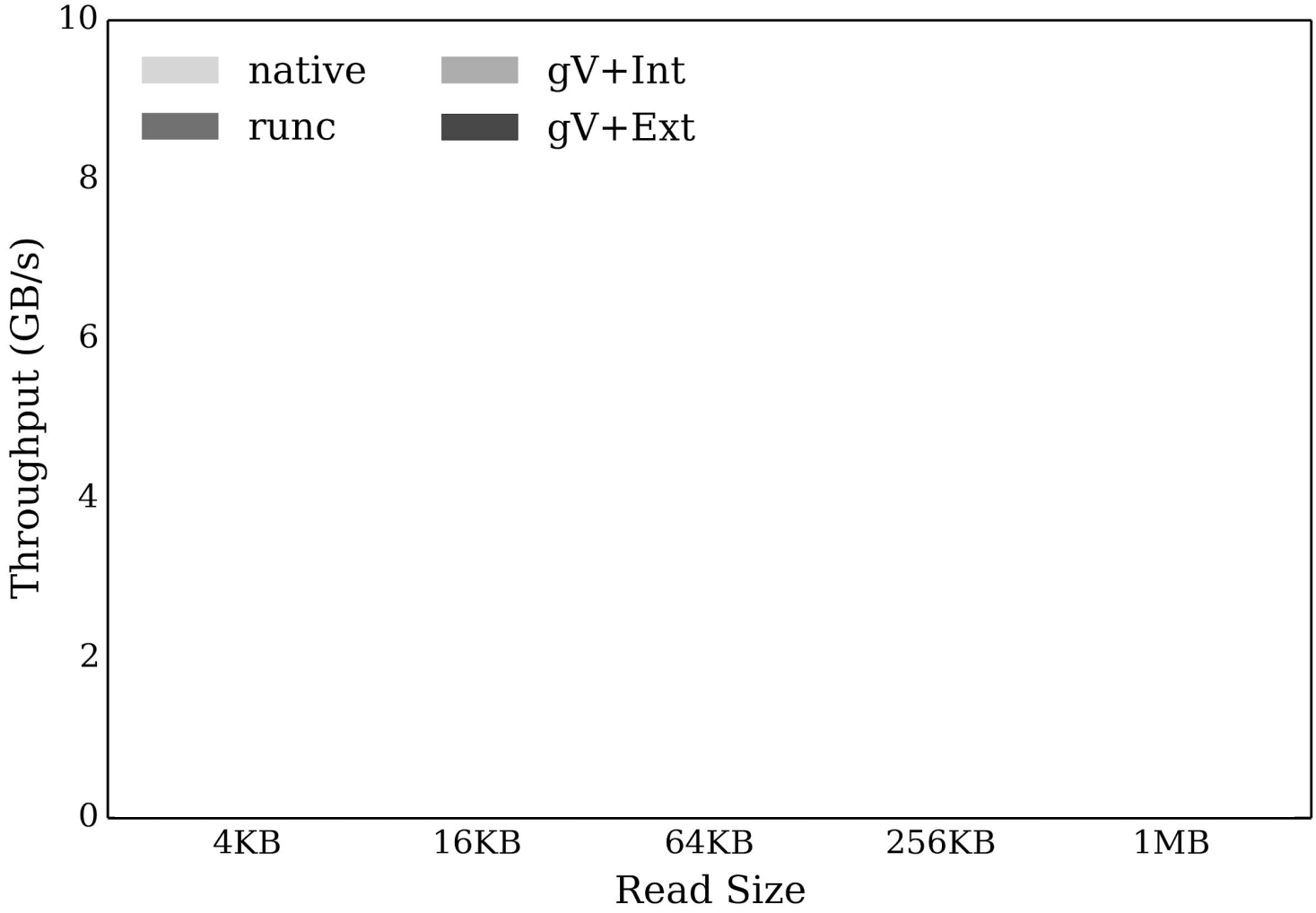

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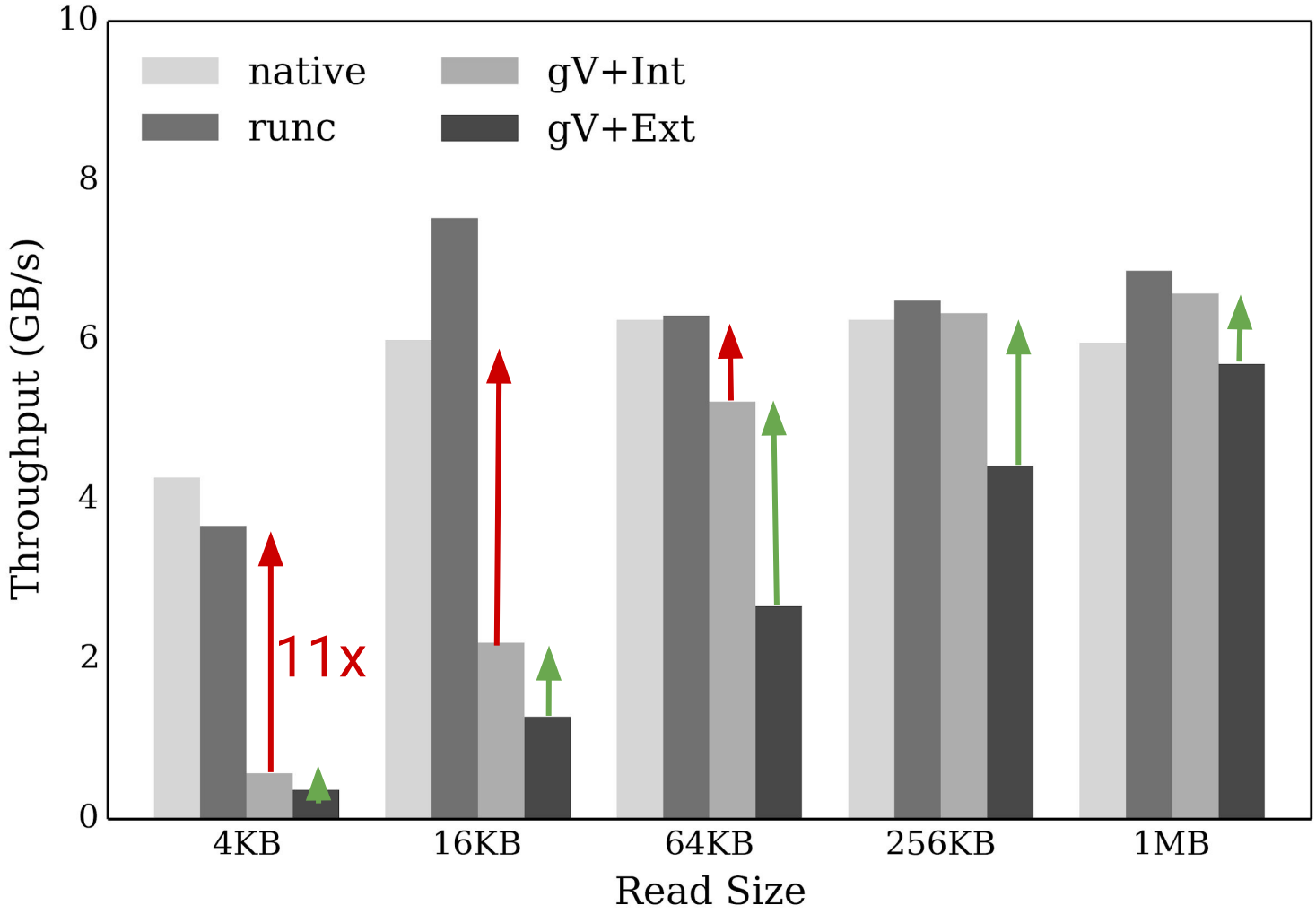

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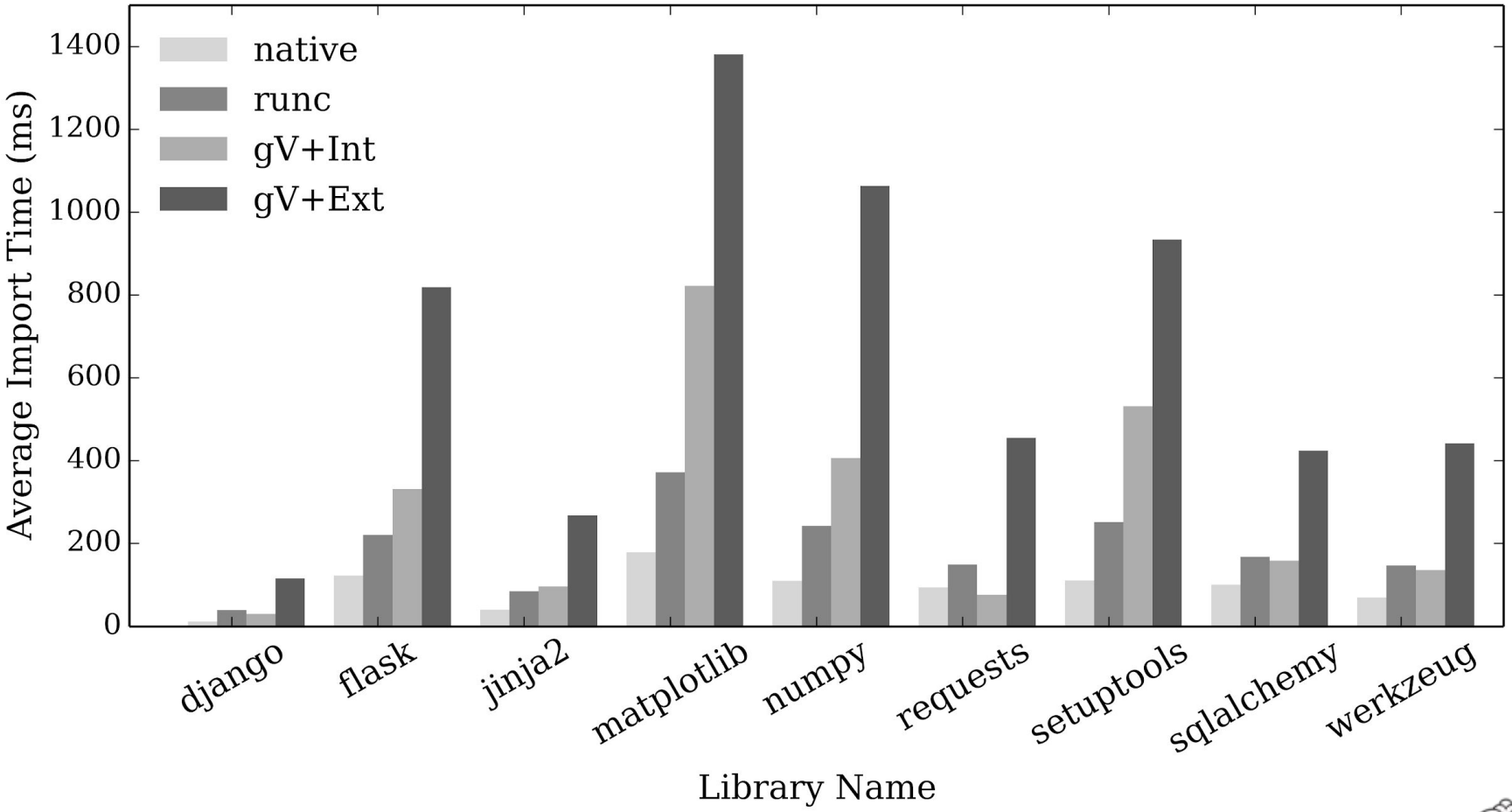

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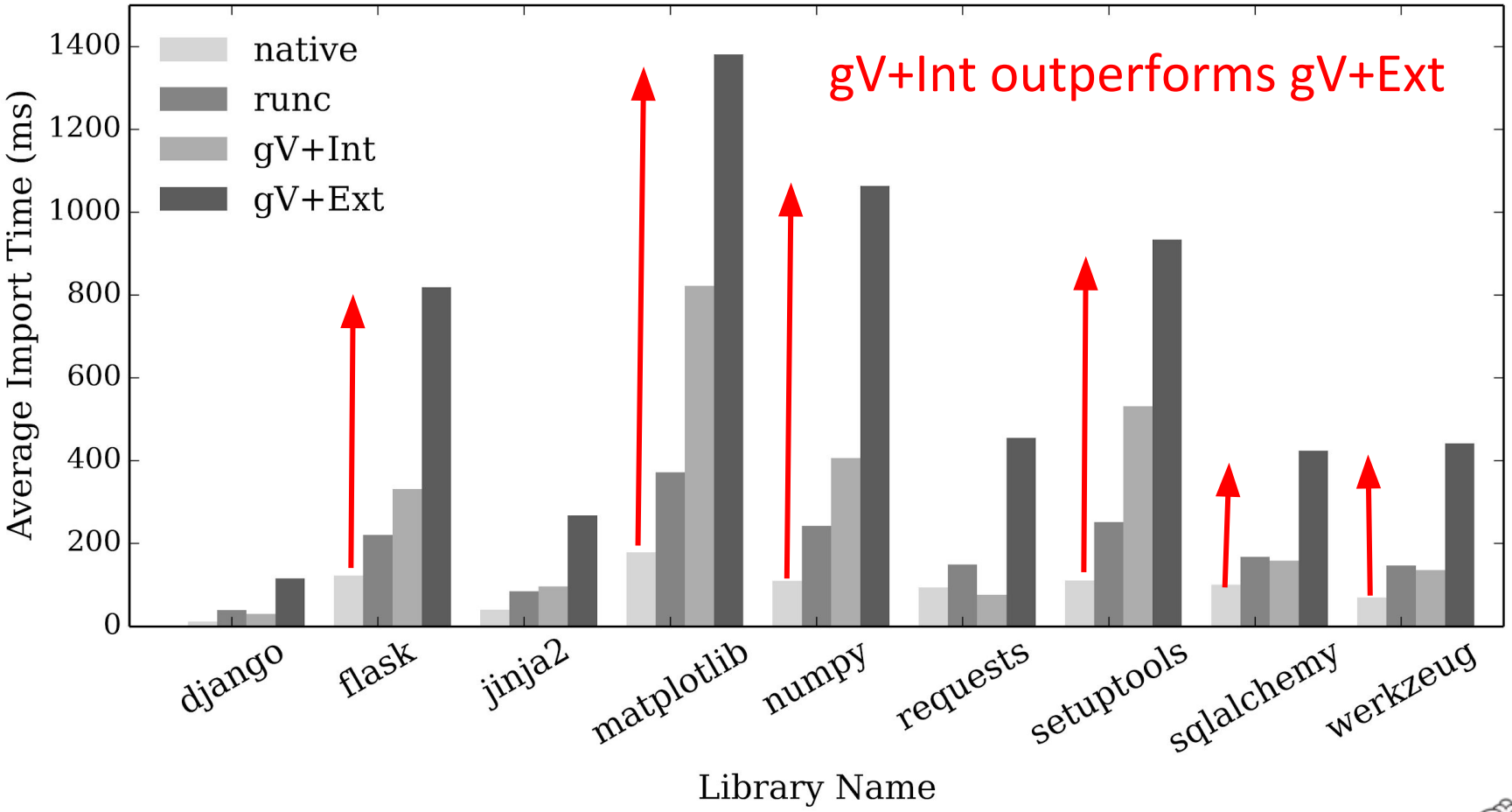

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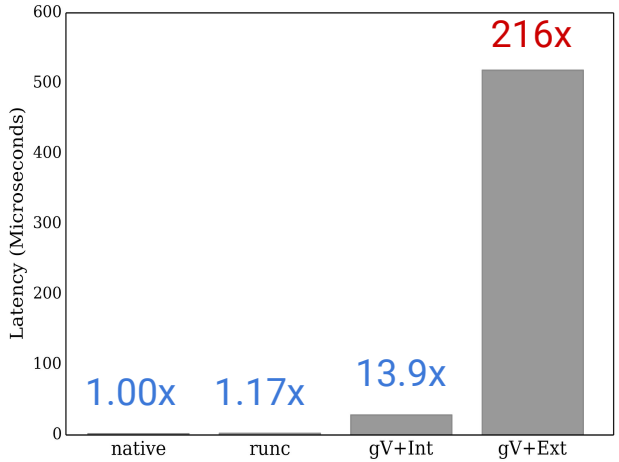

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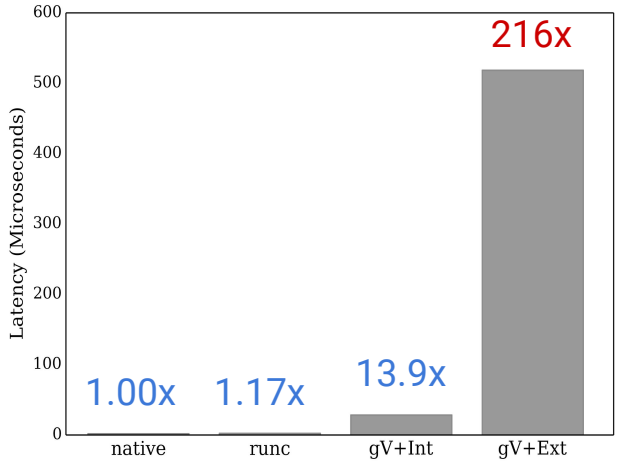

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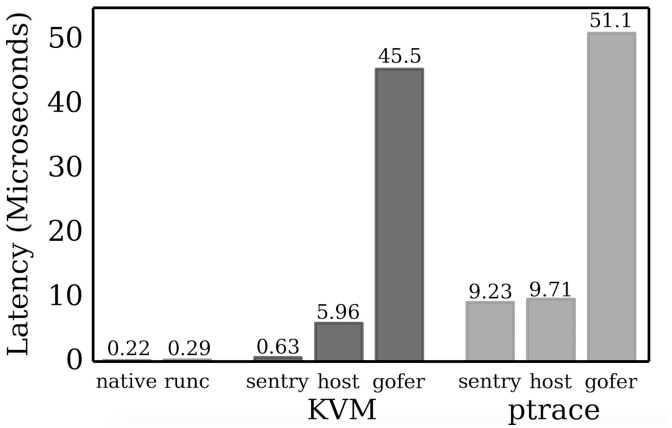

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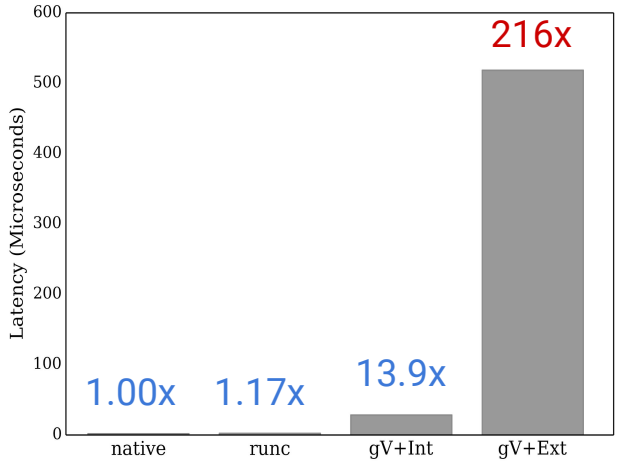

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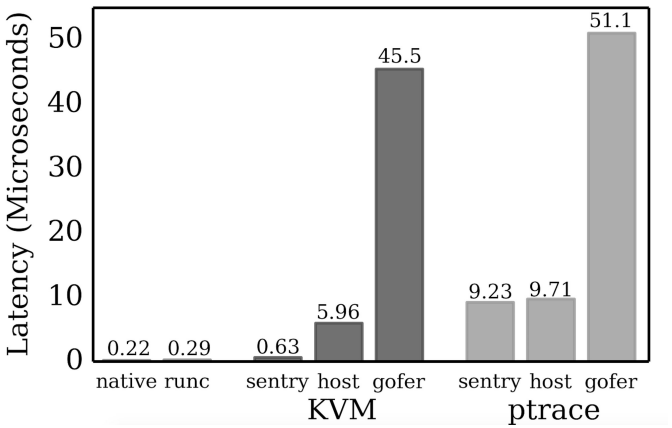

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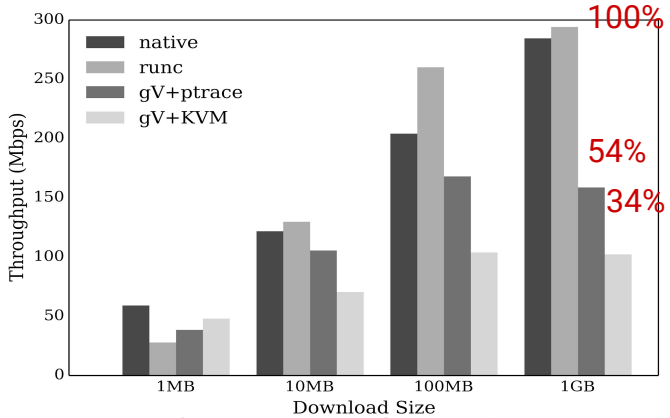

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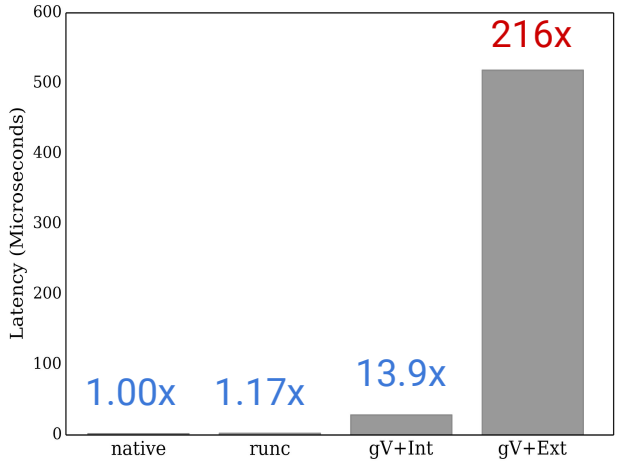

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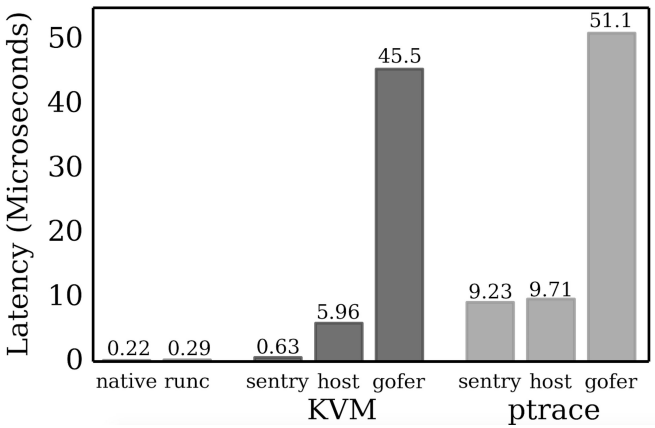
Focus



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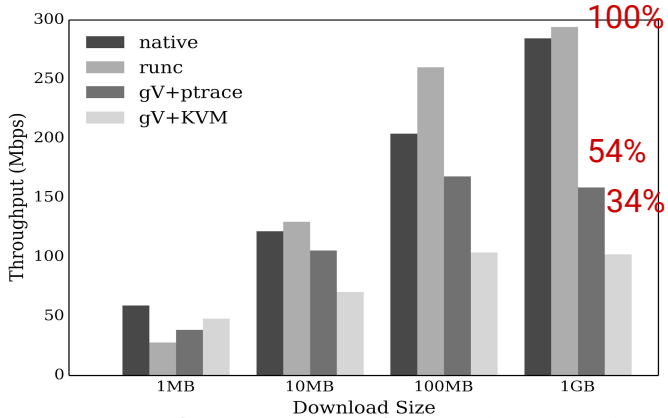

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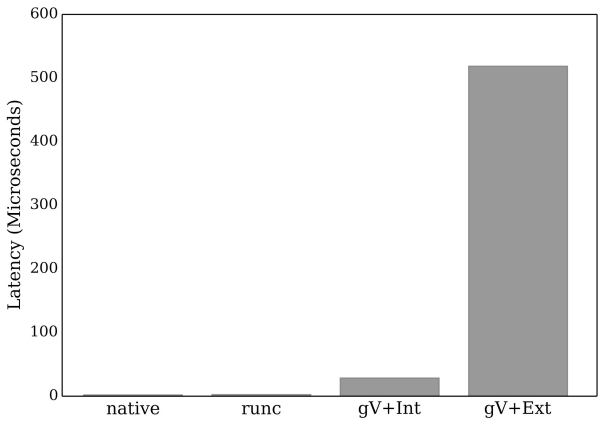
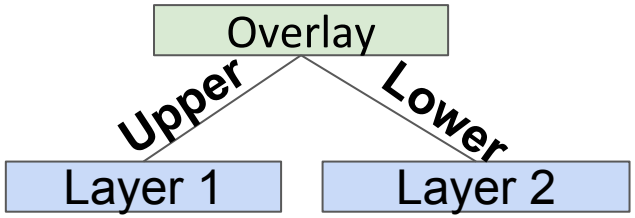
This talk analyzes gVisor, the platform backing Google Cloud Functions, and offers a file system to improve performance

gVisor

gVisor Architecture

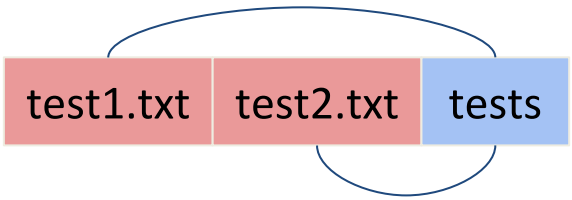


gVisor Performance Analysis



ContainerFS Overview

The second half of this talk explores the architecture of ContainerFS, a gVisor file system for performance



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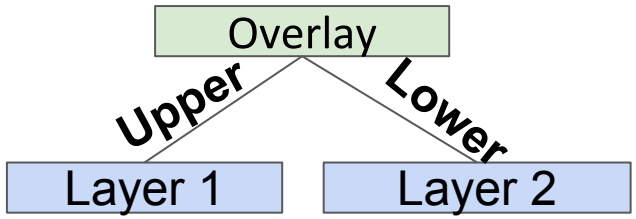

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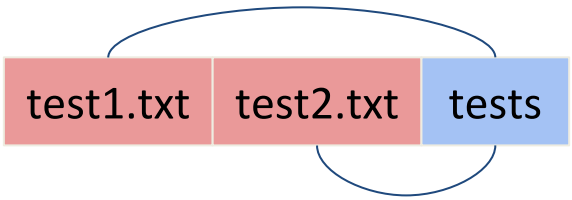

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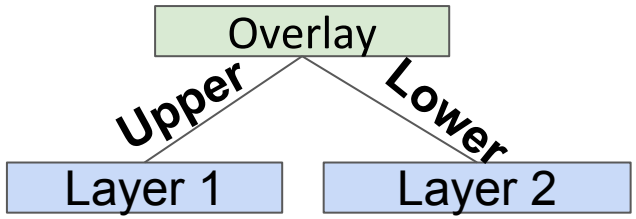

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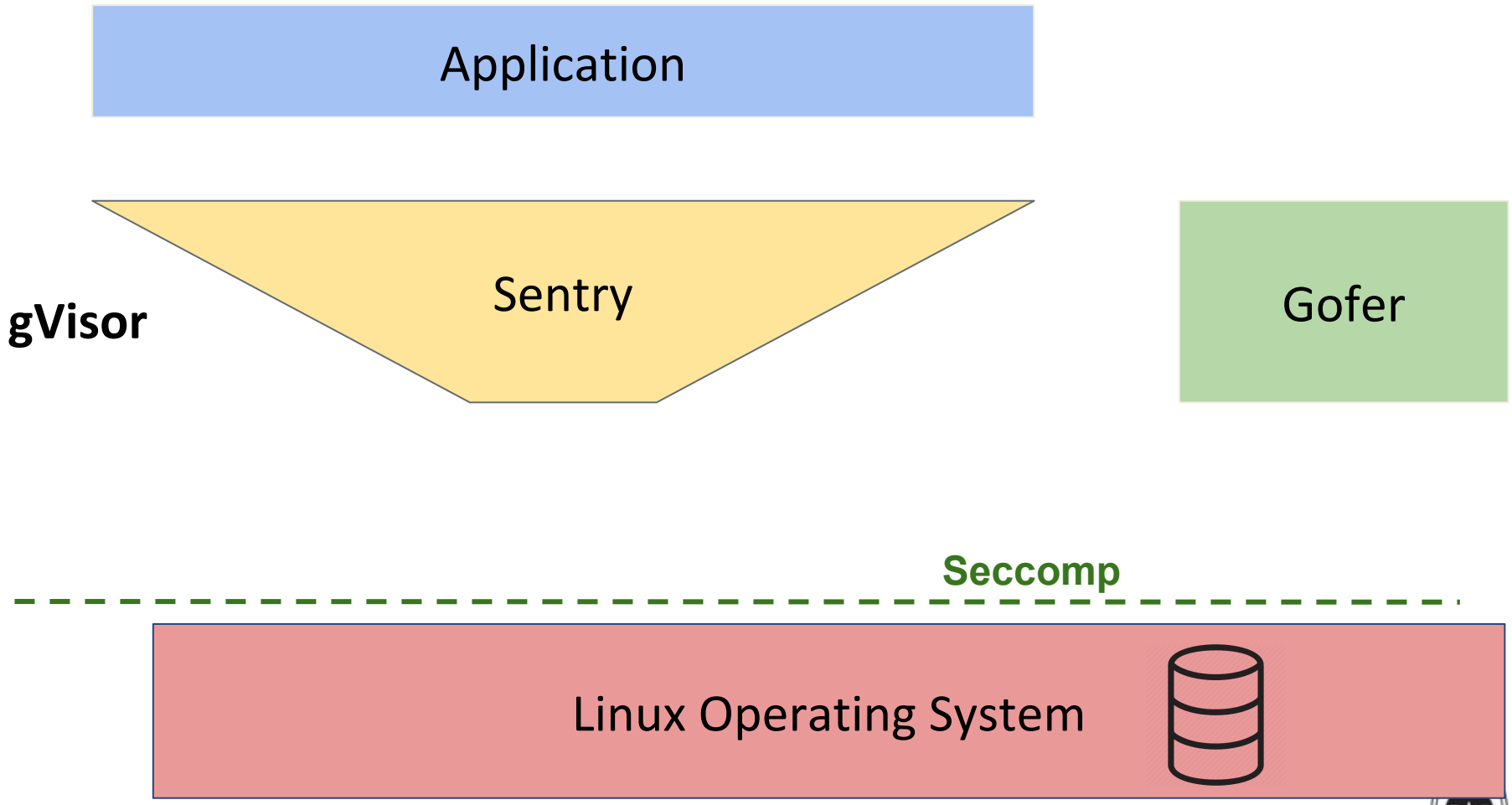

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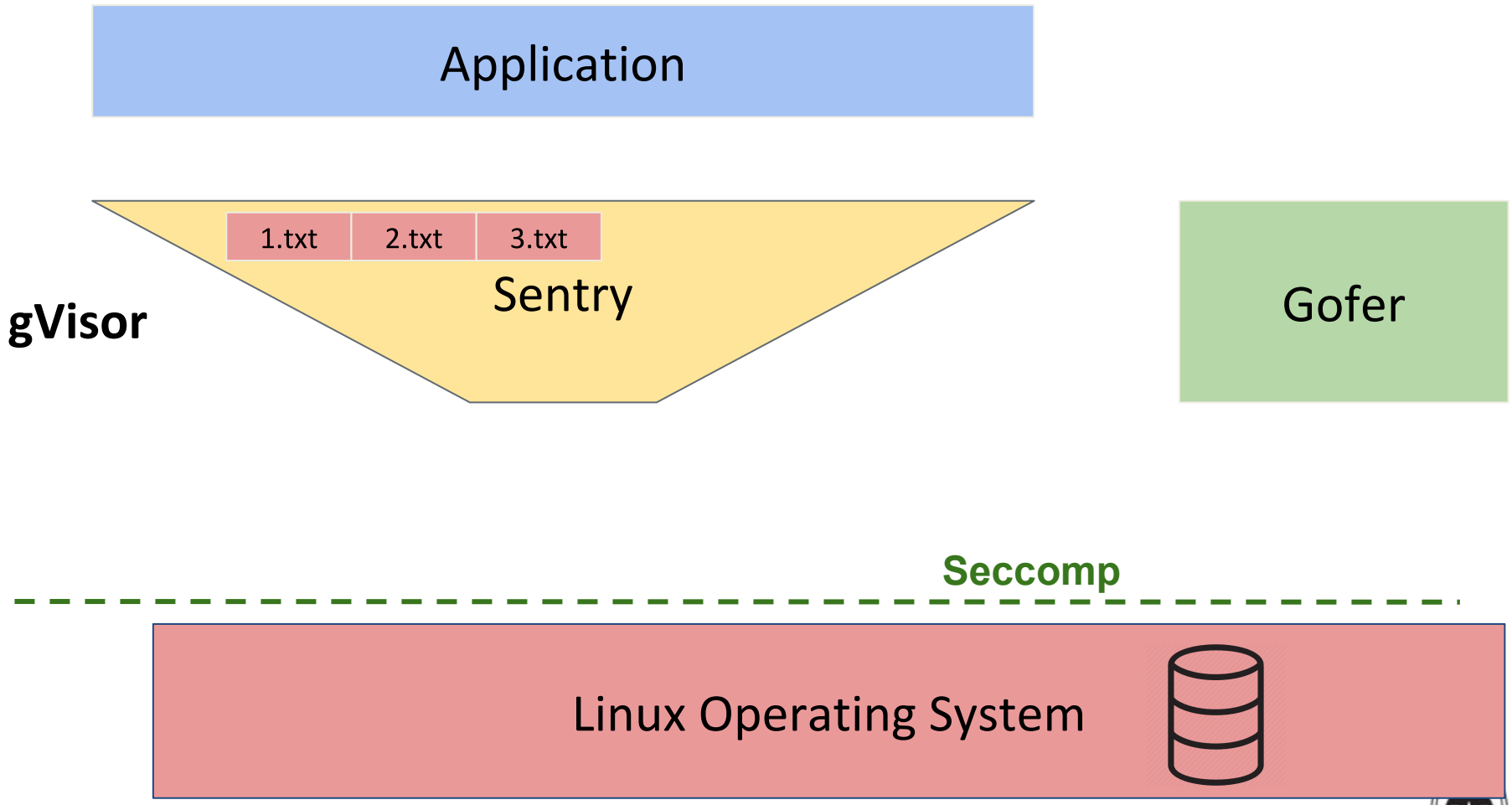

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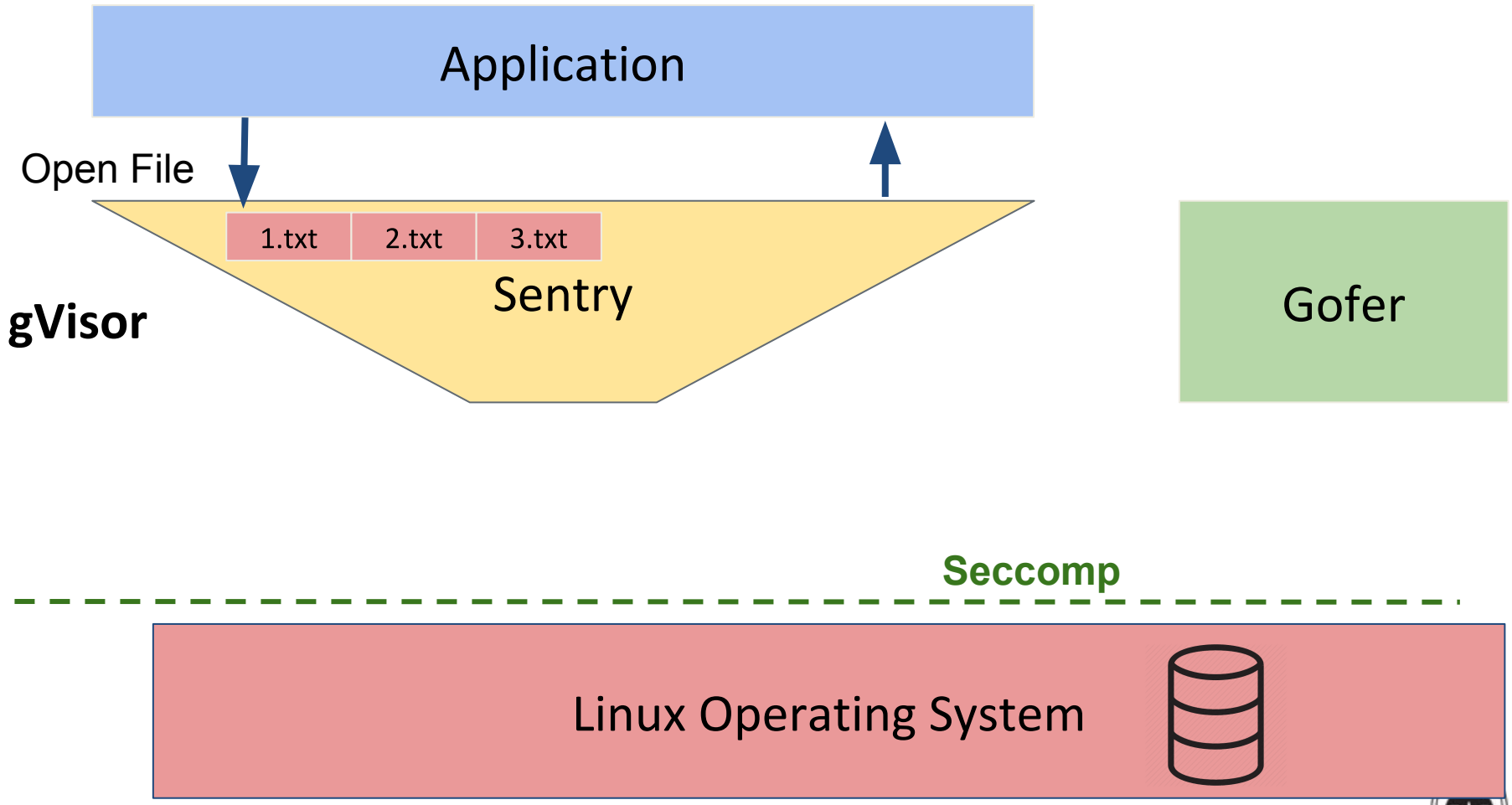

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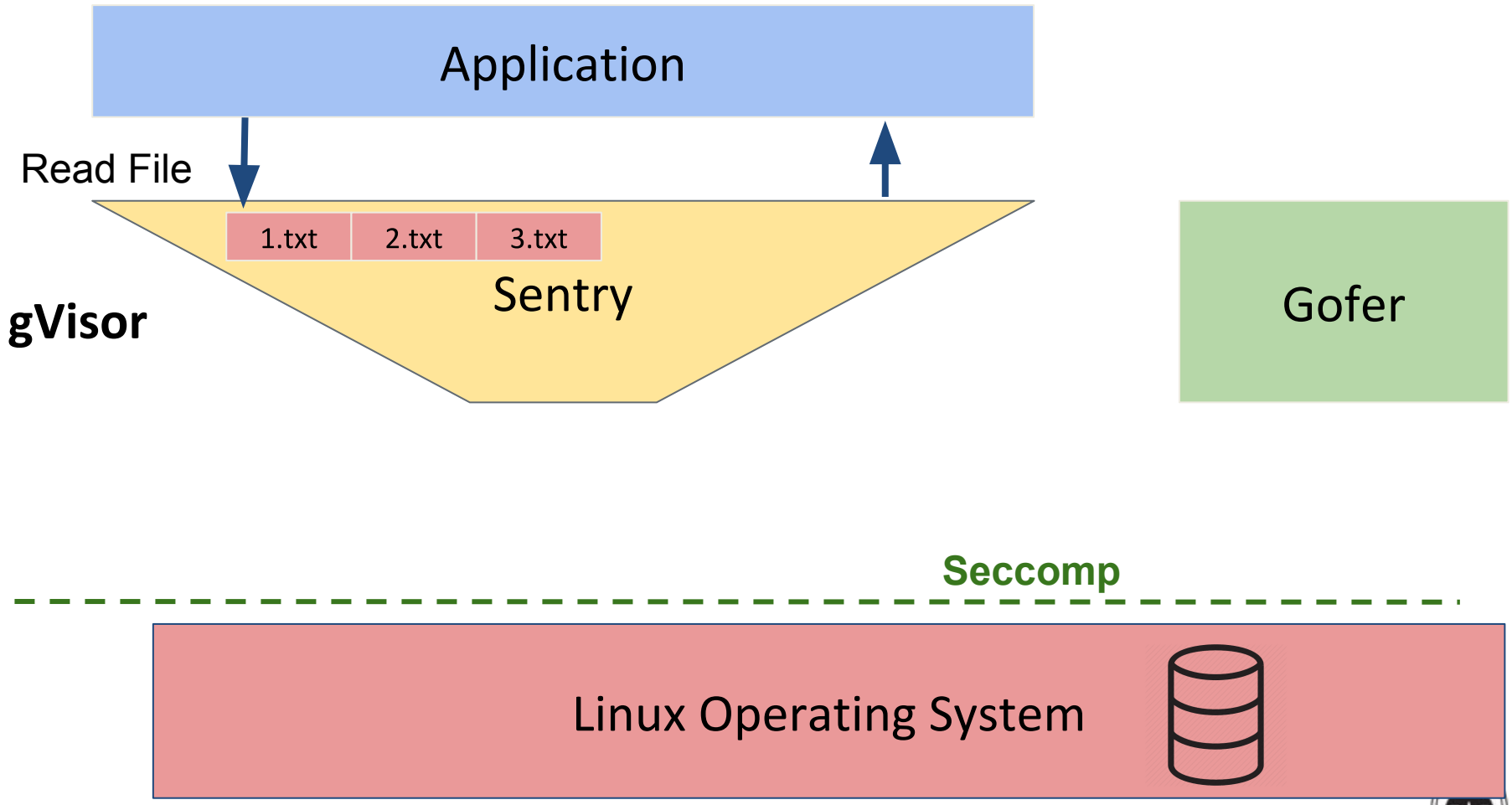

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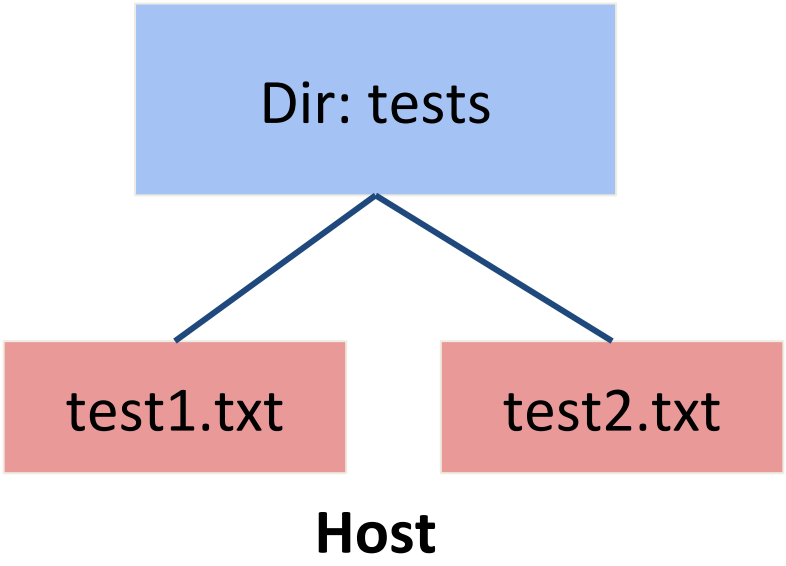

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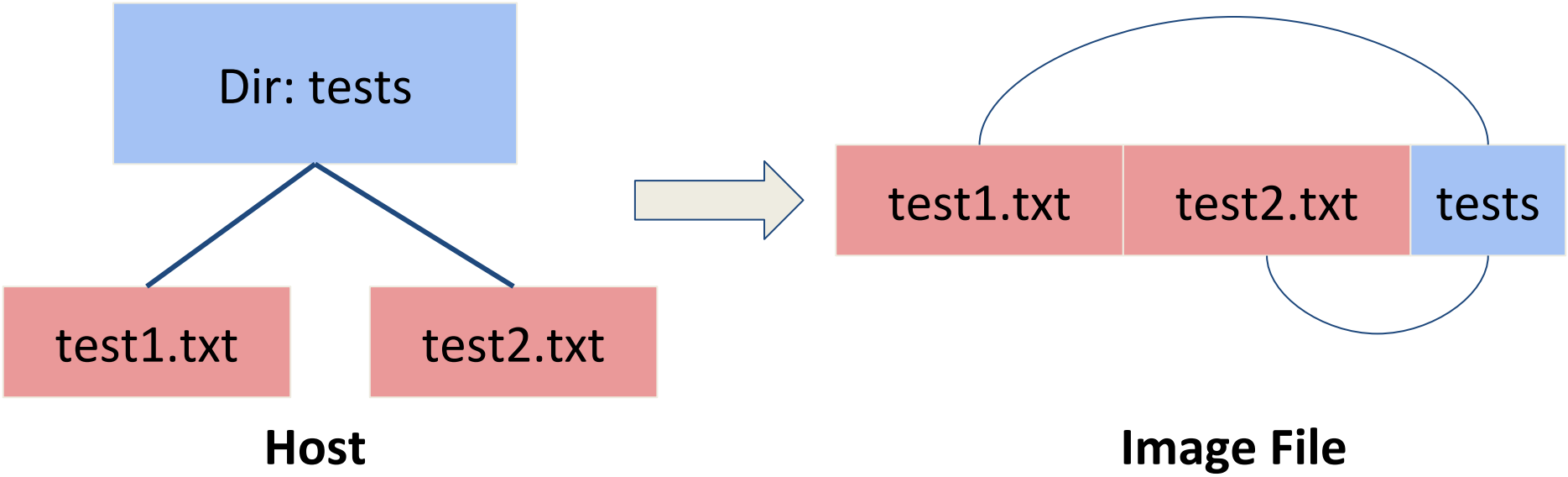

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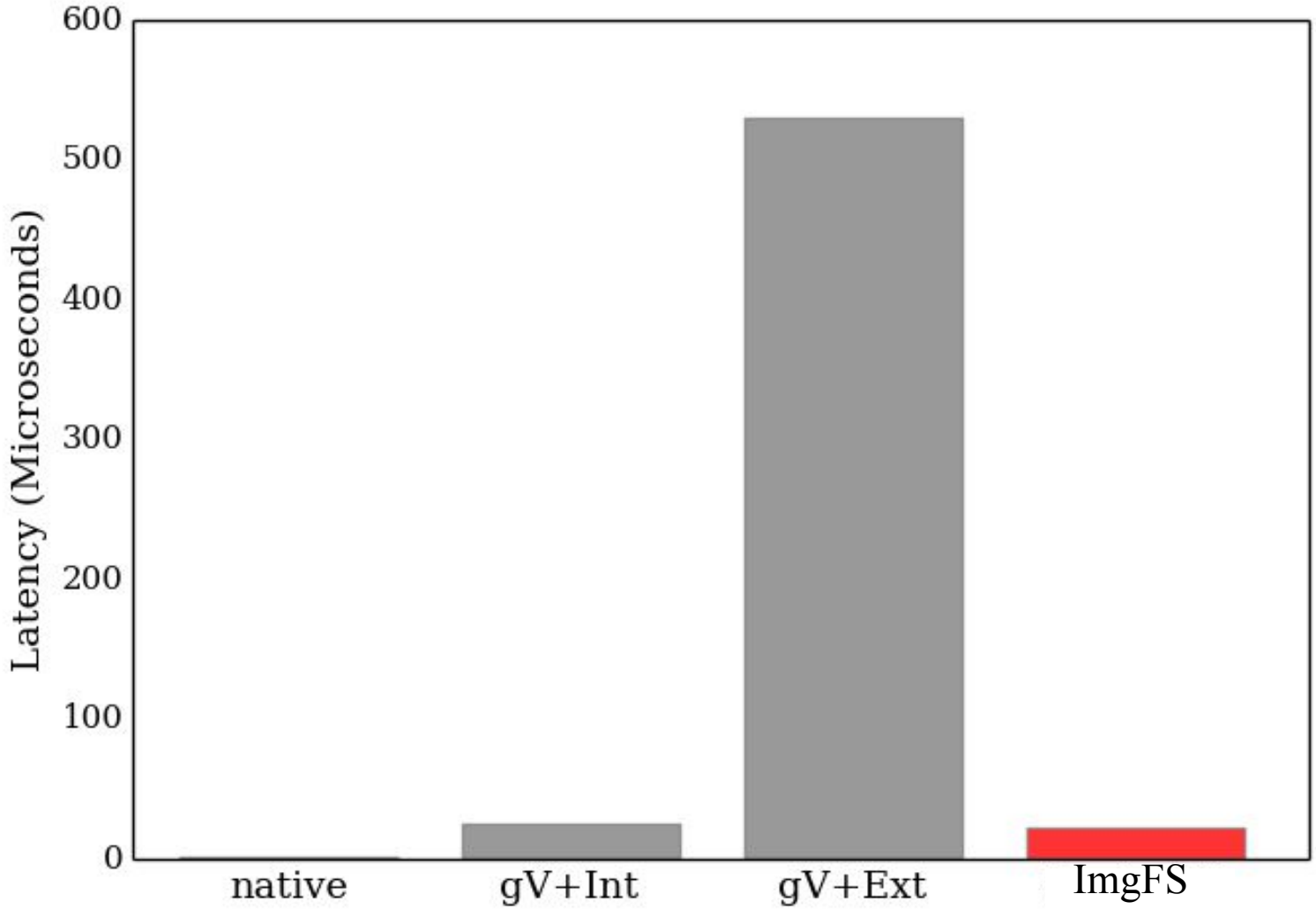

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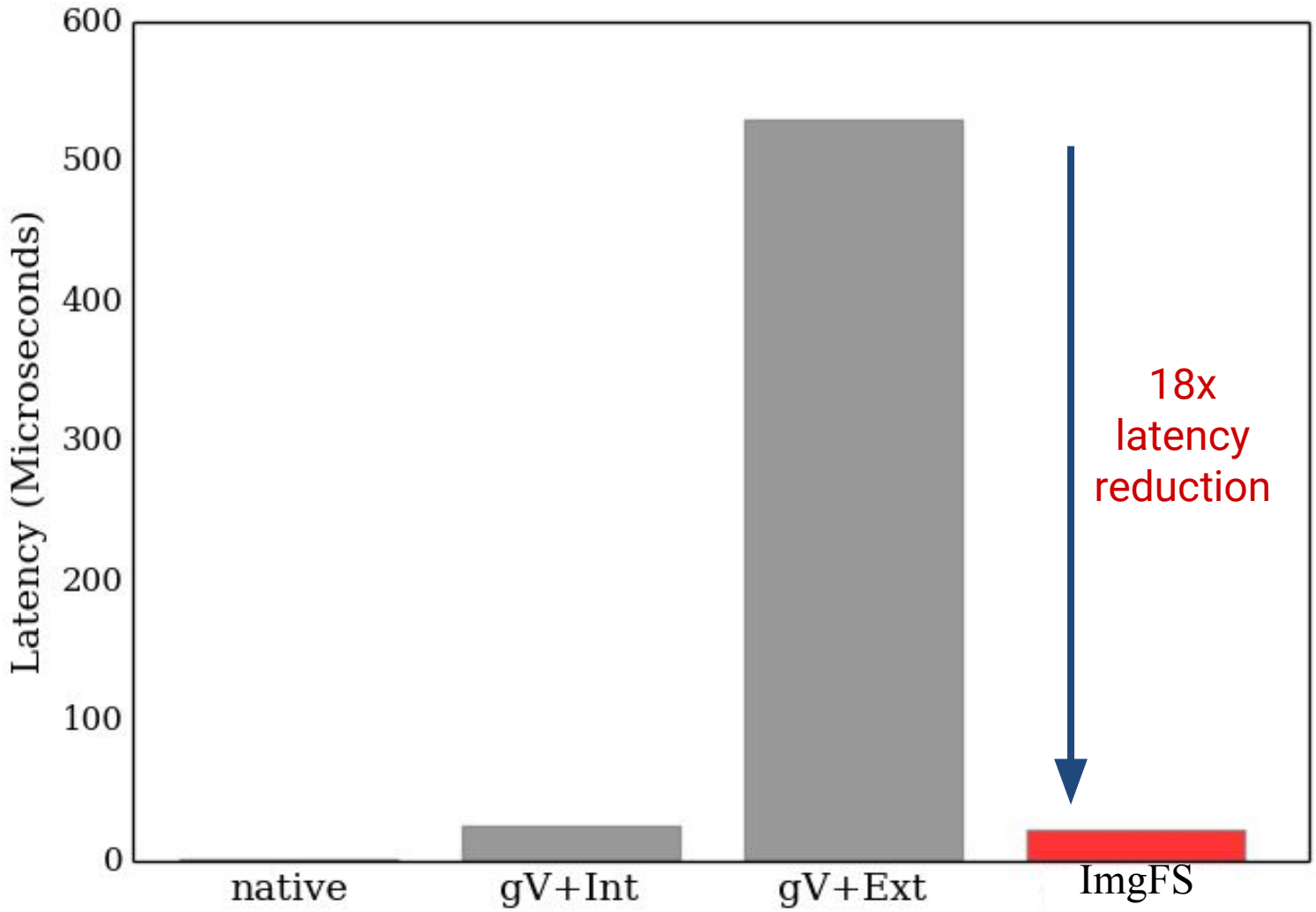

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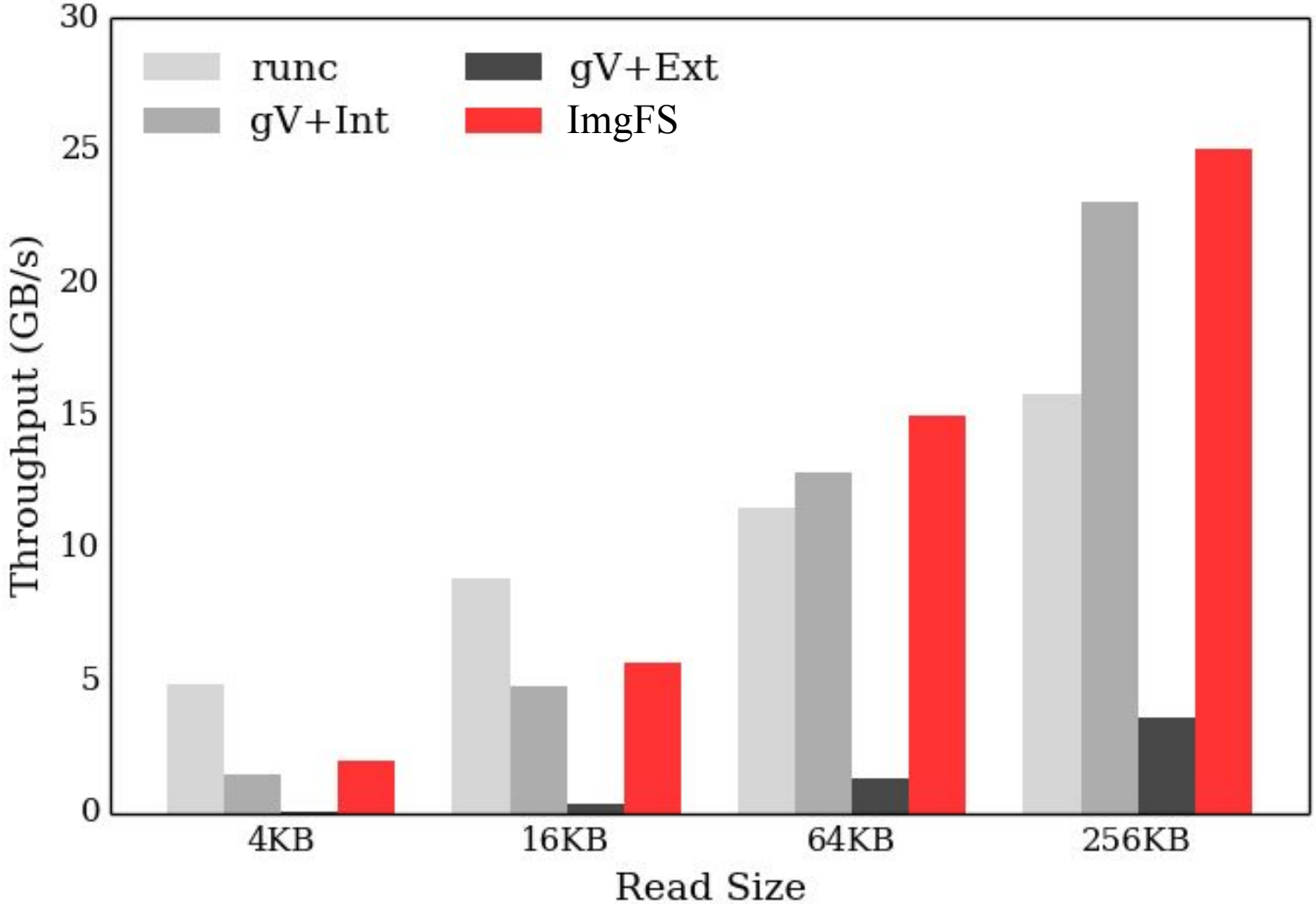

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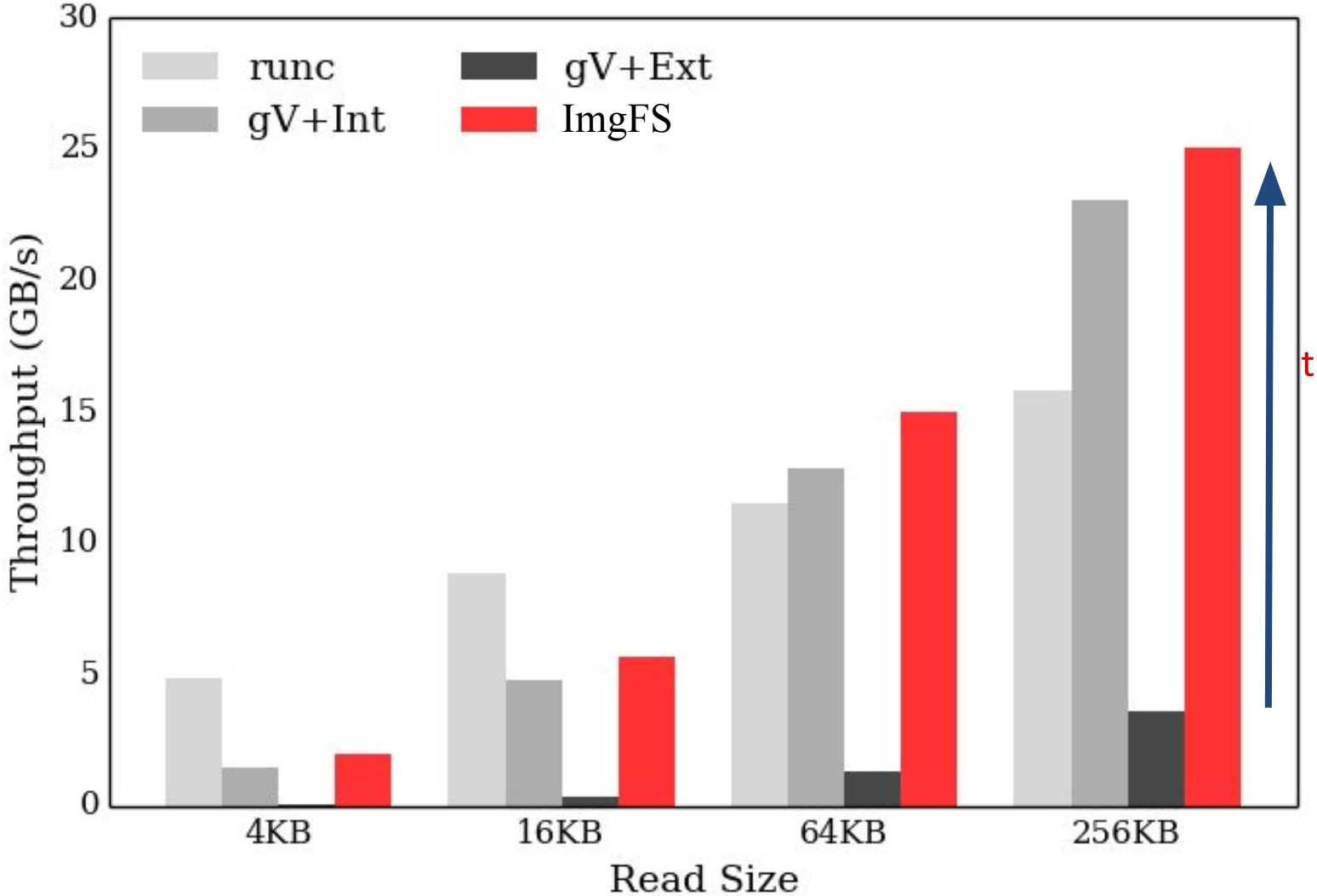

22x throughput increase

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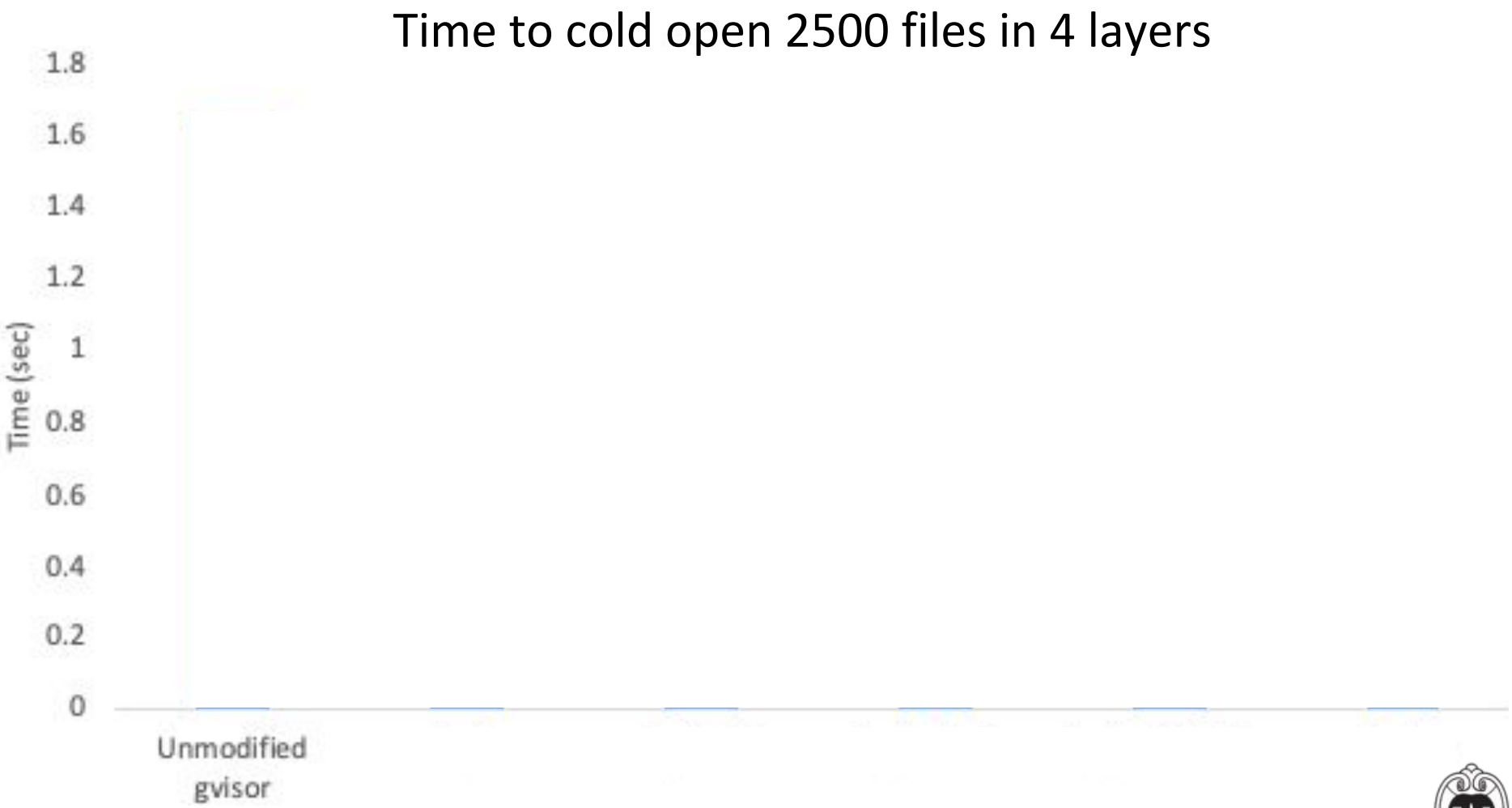

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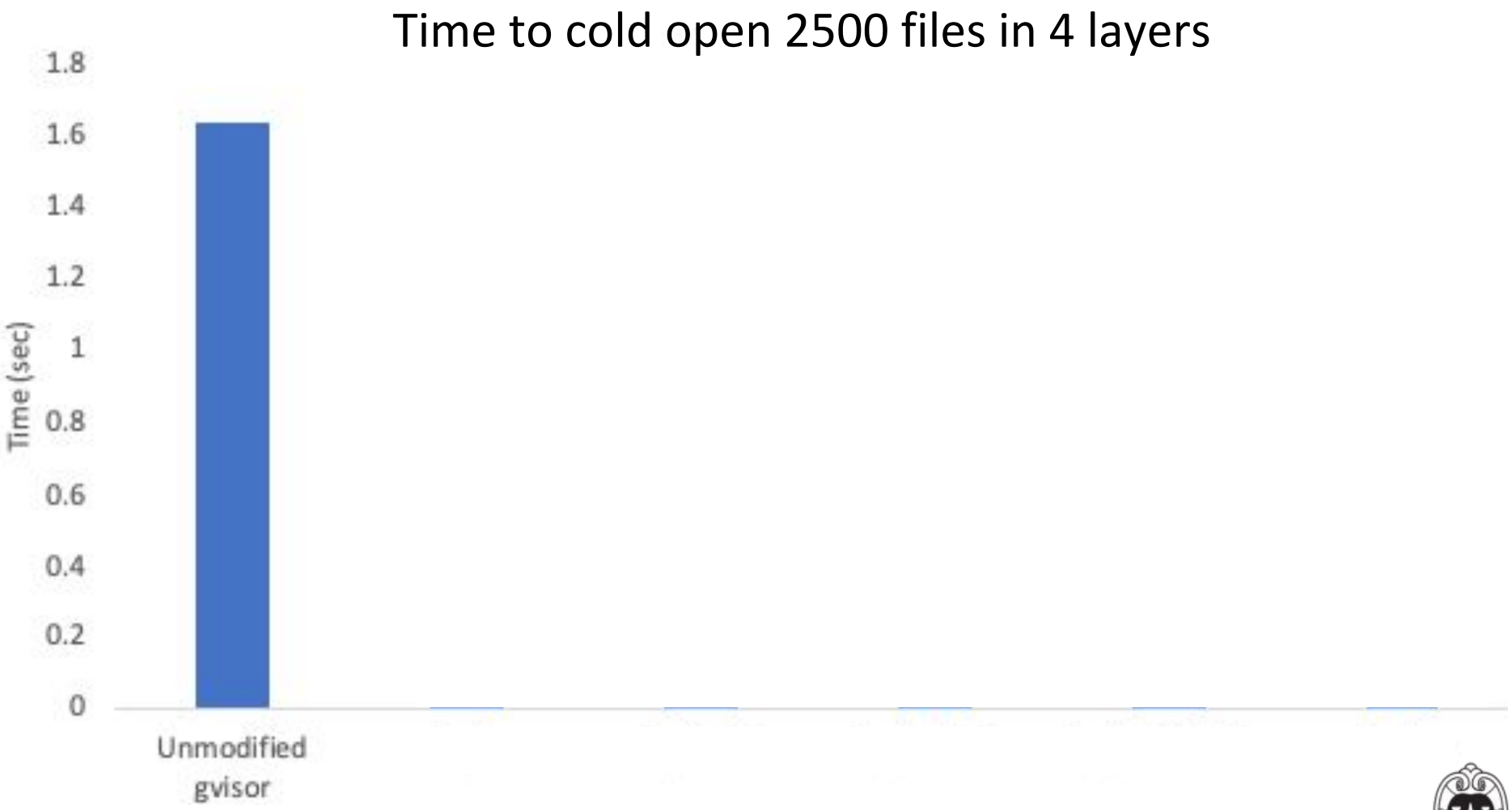

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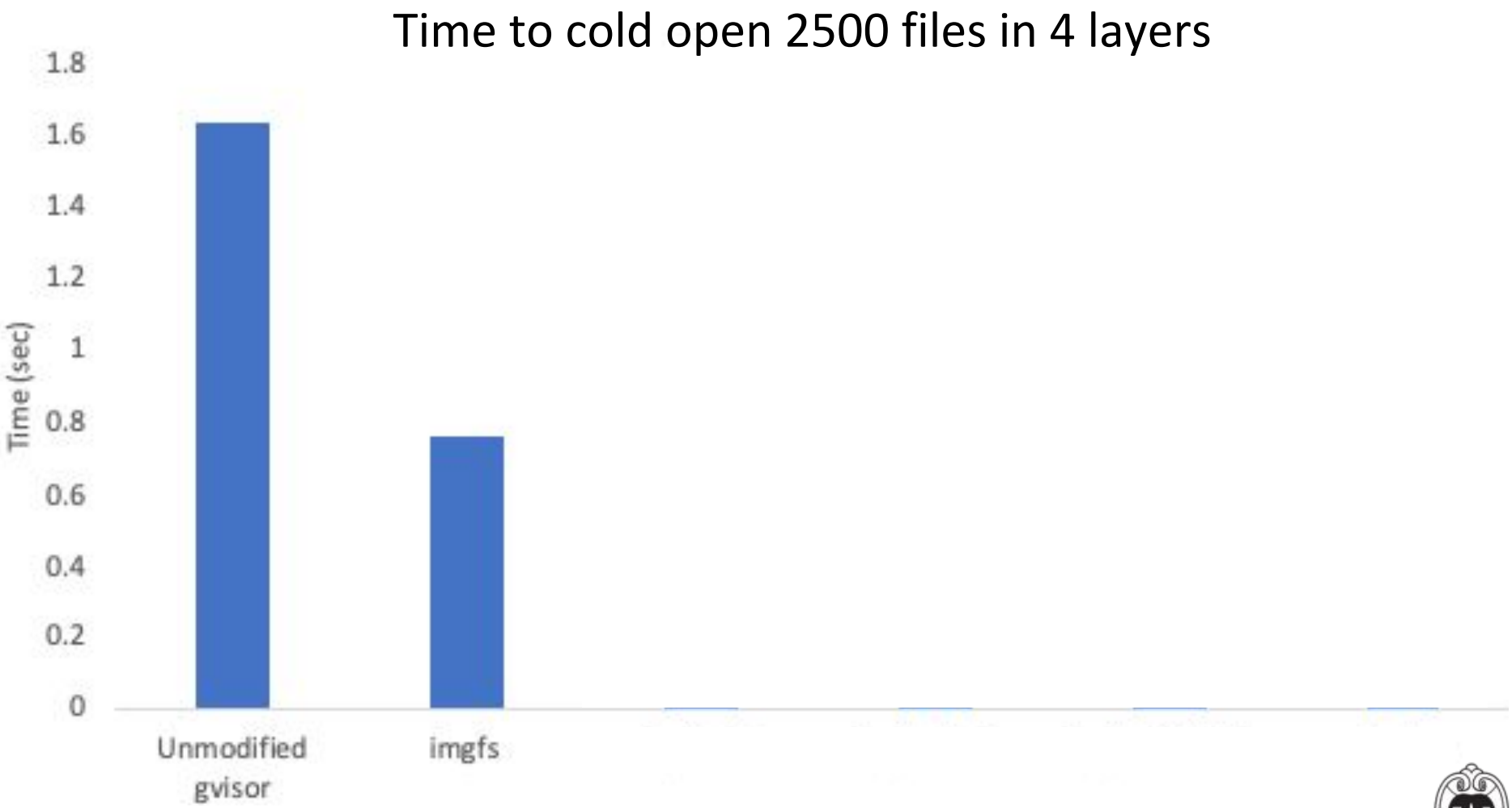

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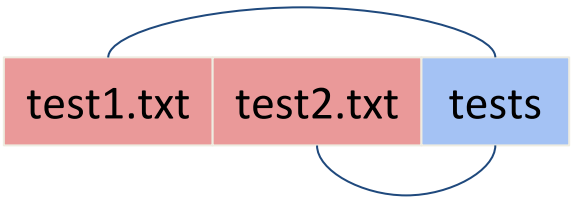

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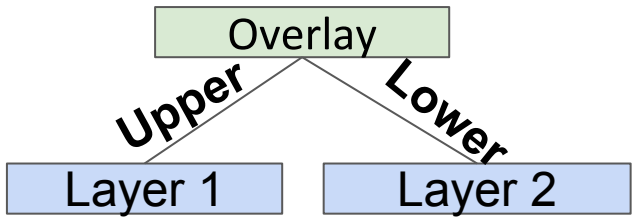

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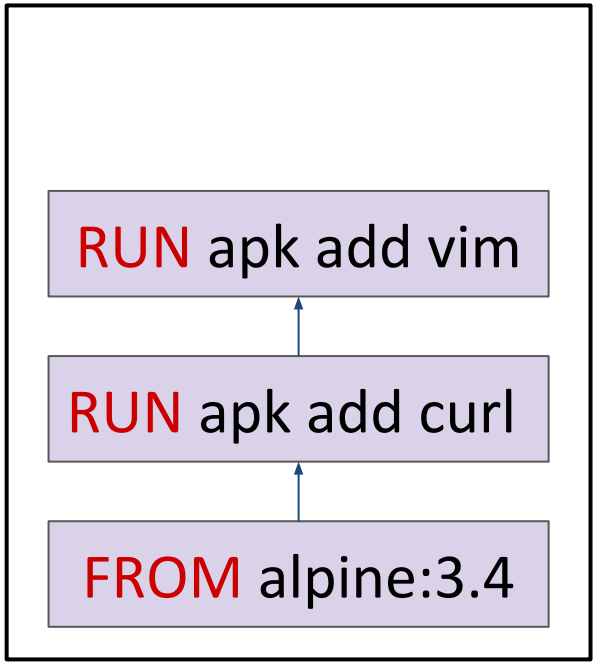
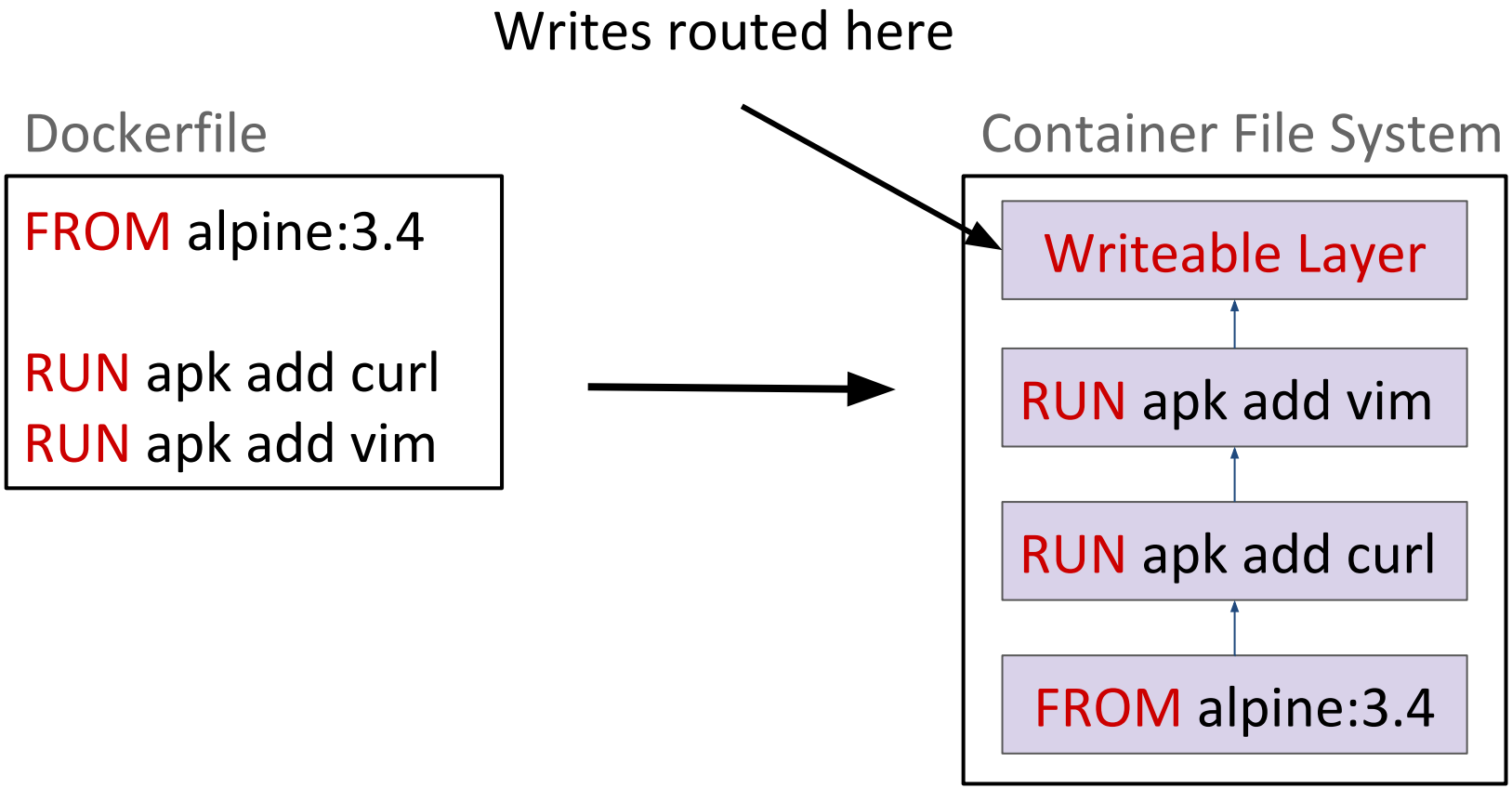


Docker images are a stacked collection of file system layers made available to the container



Linux' OverlayFS provides a mechanism creating a merged view of different file systems

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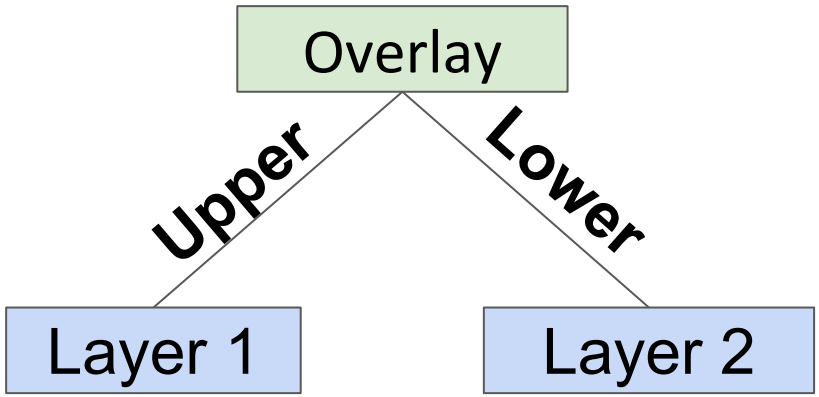
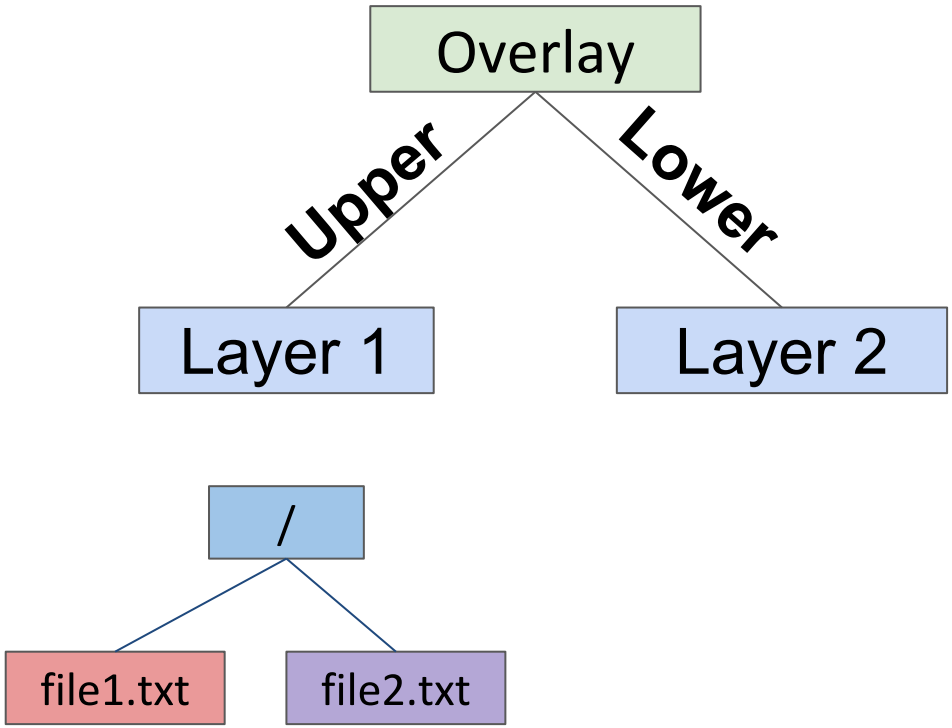
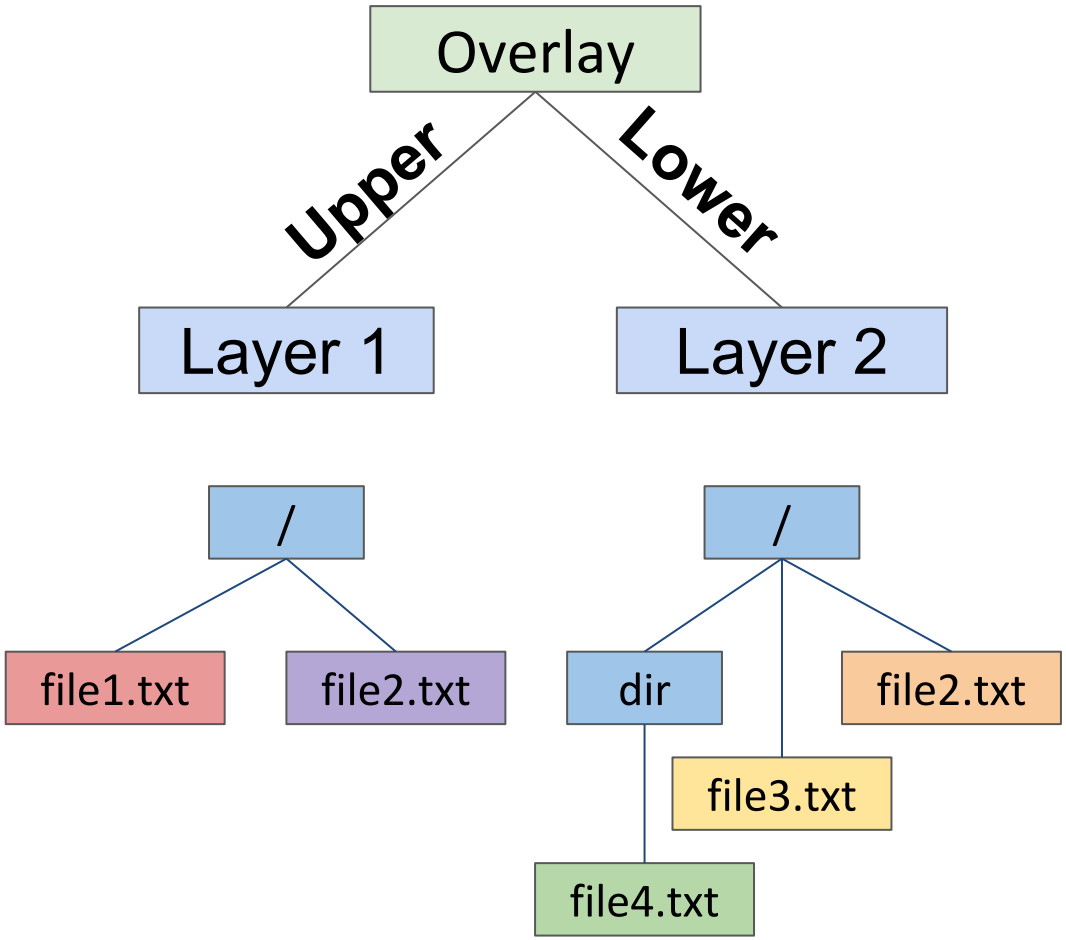


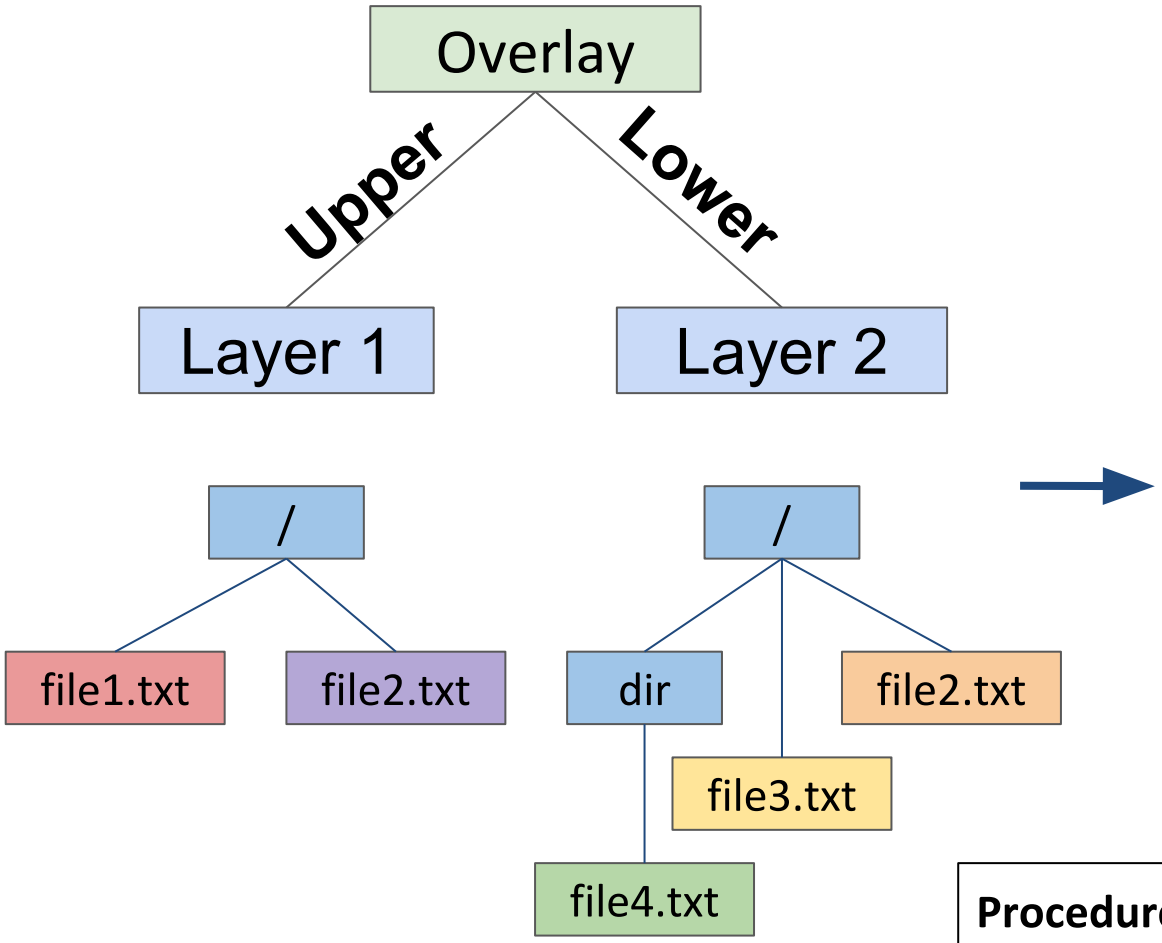
Linux' OverlayFS provides a mechanism creating a merged view of different file systems



Linux' OverlayFS provides a mechanism creating a merged view of different file systems



Linux' OverlayFS provides a mechanism creating a merged view of different file systems

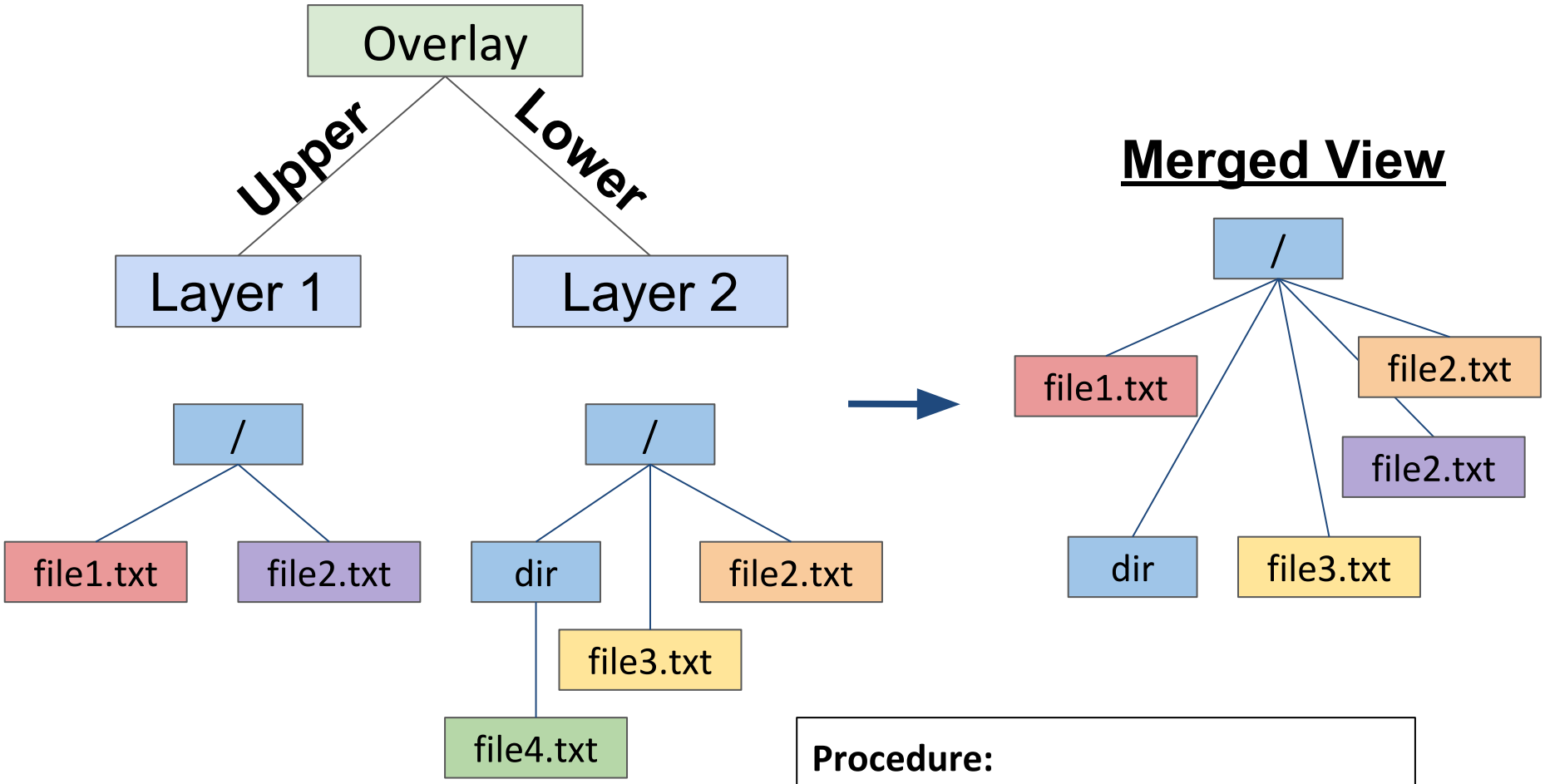


Merged View

Procedure:

- Recursively merge directory contents

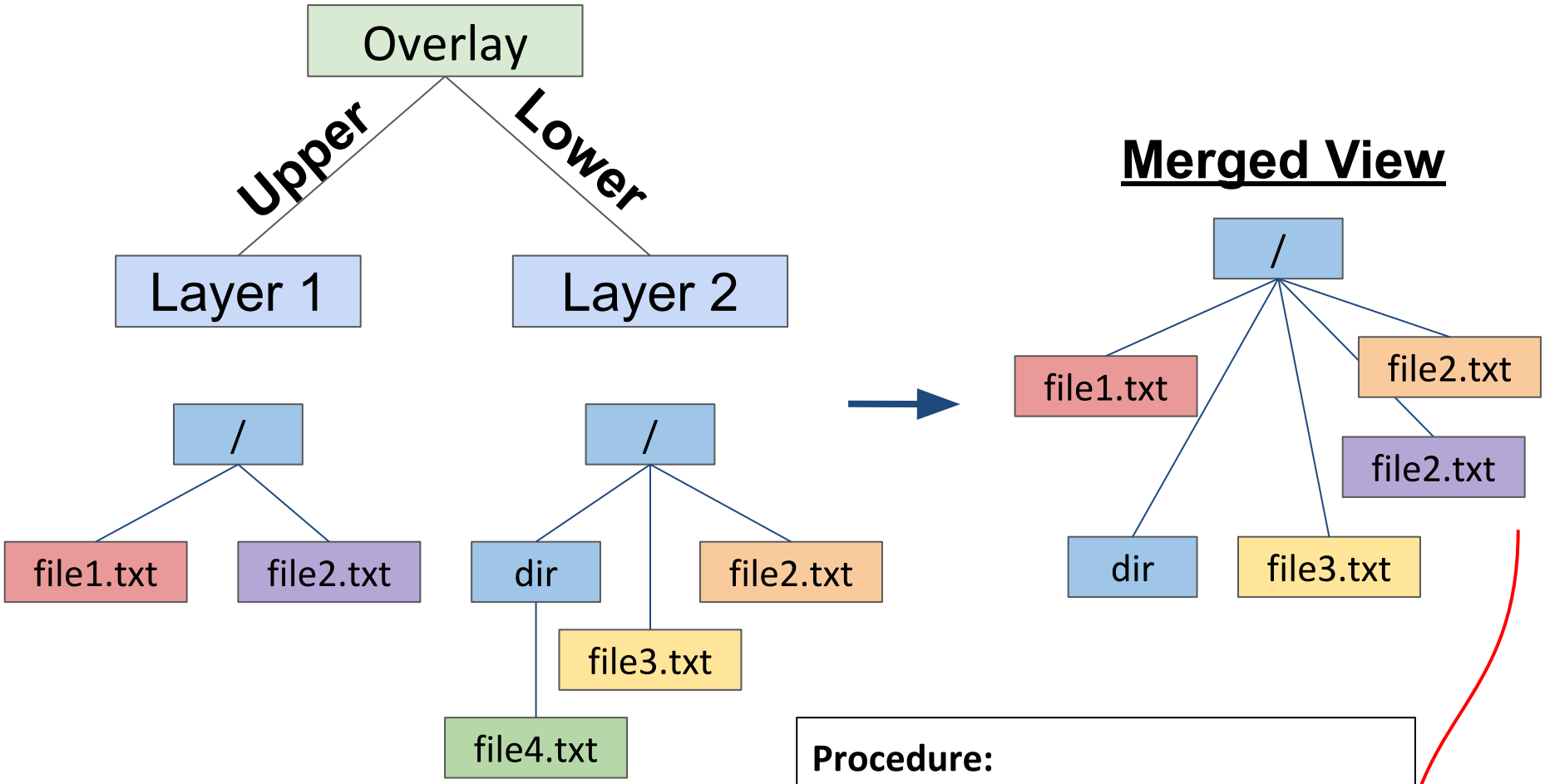
Linux' OverlayFS provides a mechanism creating a merged view of different file systems



Procedure:

- Recursively merge directory contents

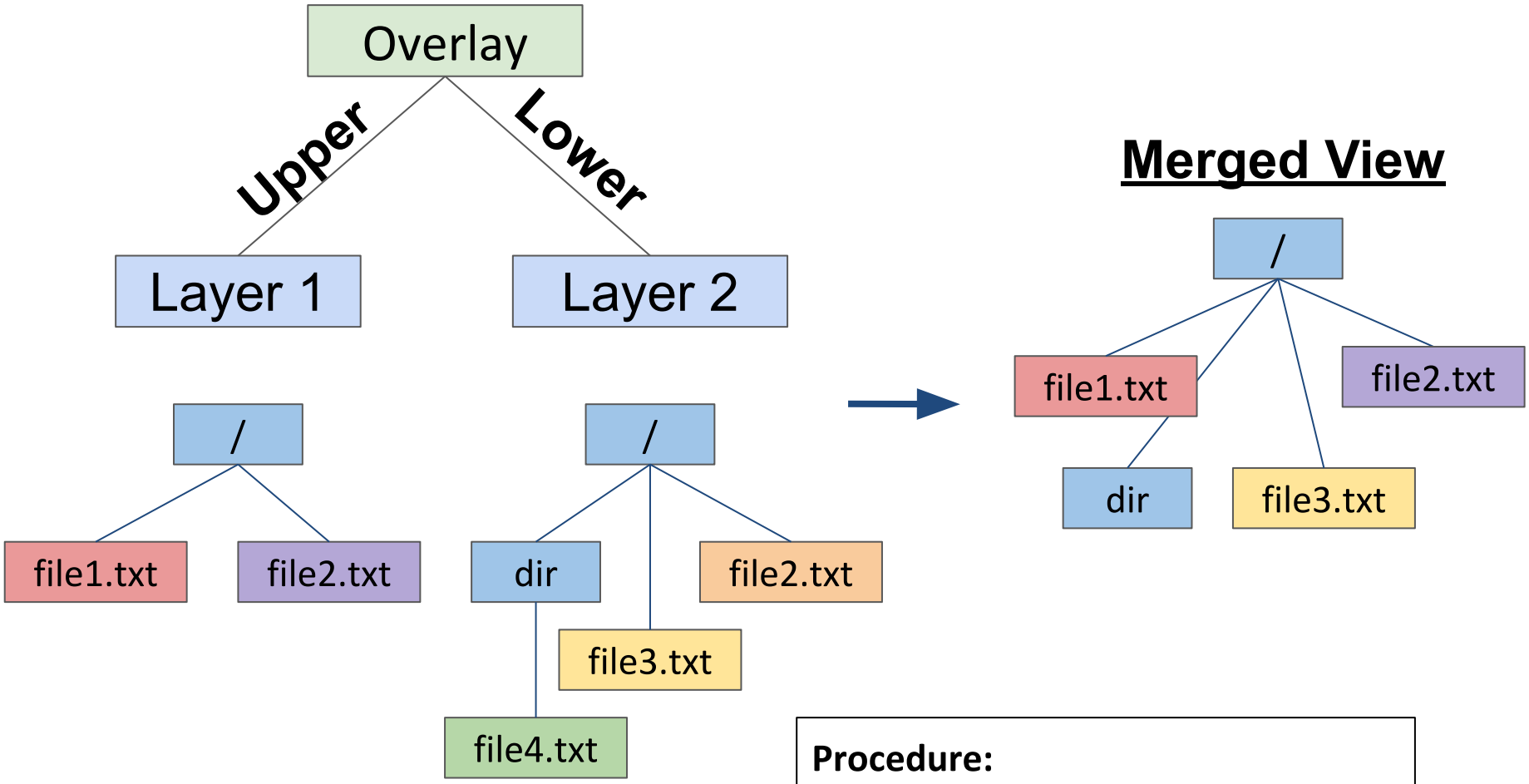
Linux' OverlayFS provides a mechanism creating a merged view of different file systems



Procedure:

- Recursively merge directory contents
- If same file in both, take upper

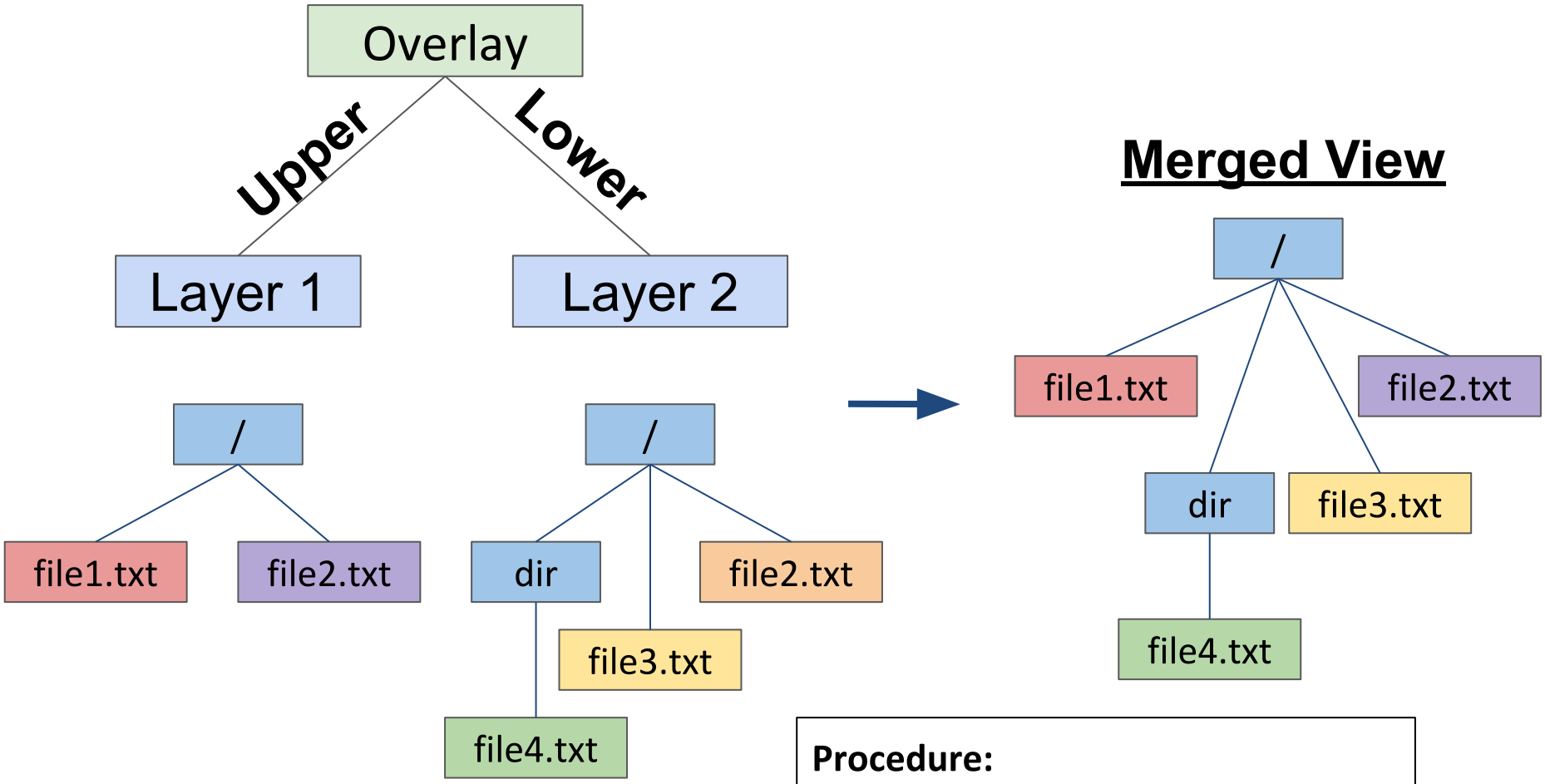
Linux' OverlayFS provides a mechanism creating a merged view of different file systems



Procedure:

- Recursively merge directory contents
- If same file in both, take upper

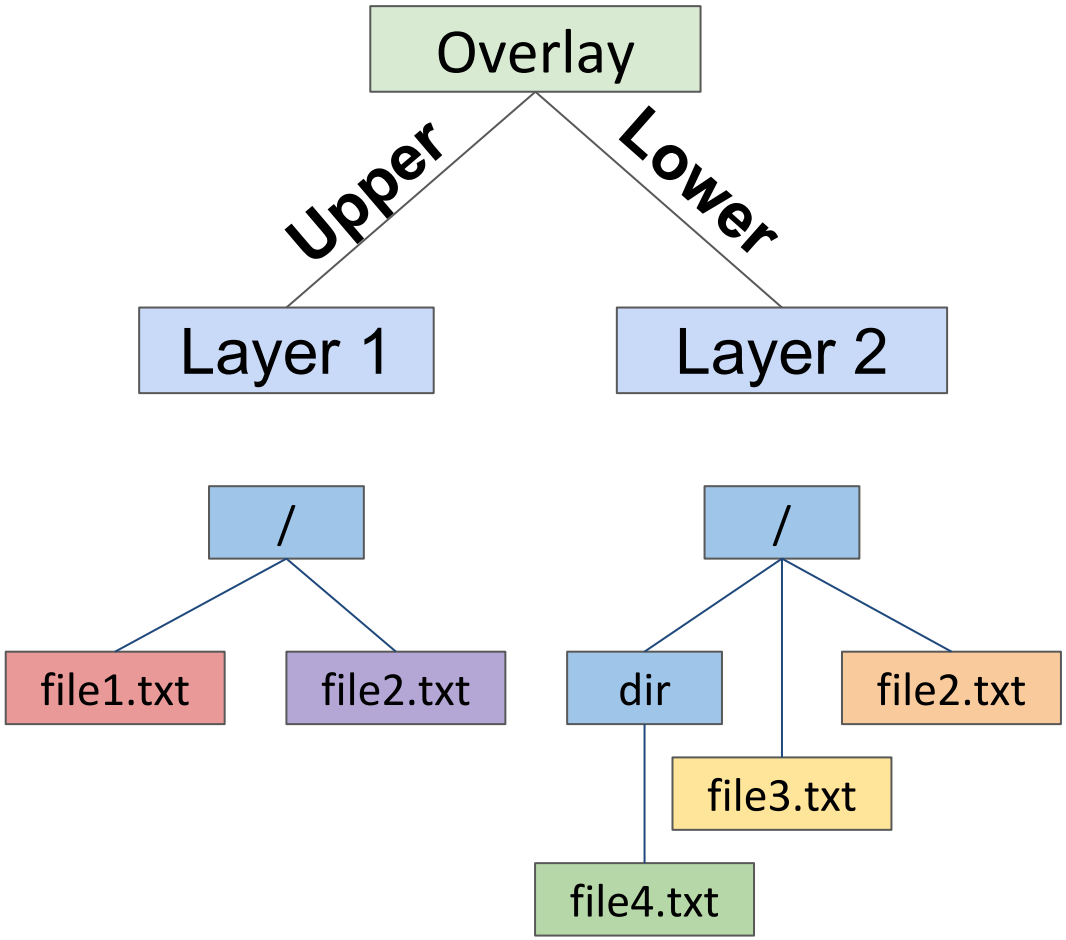
Linux' OverlayFS provides a mechanism creating a merged view of different file systems



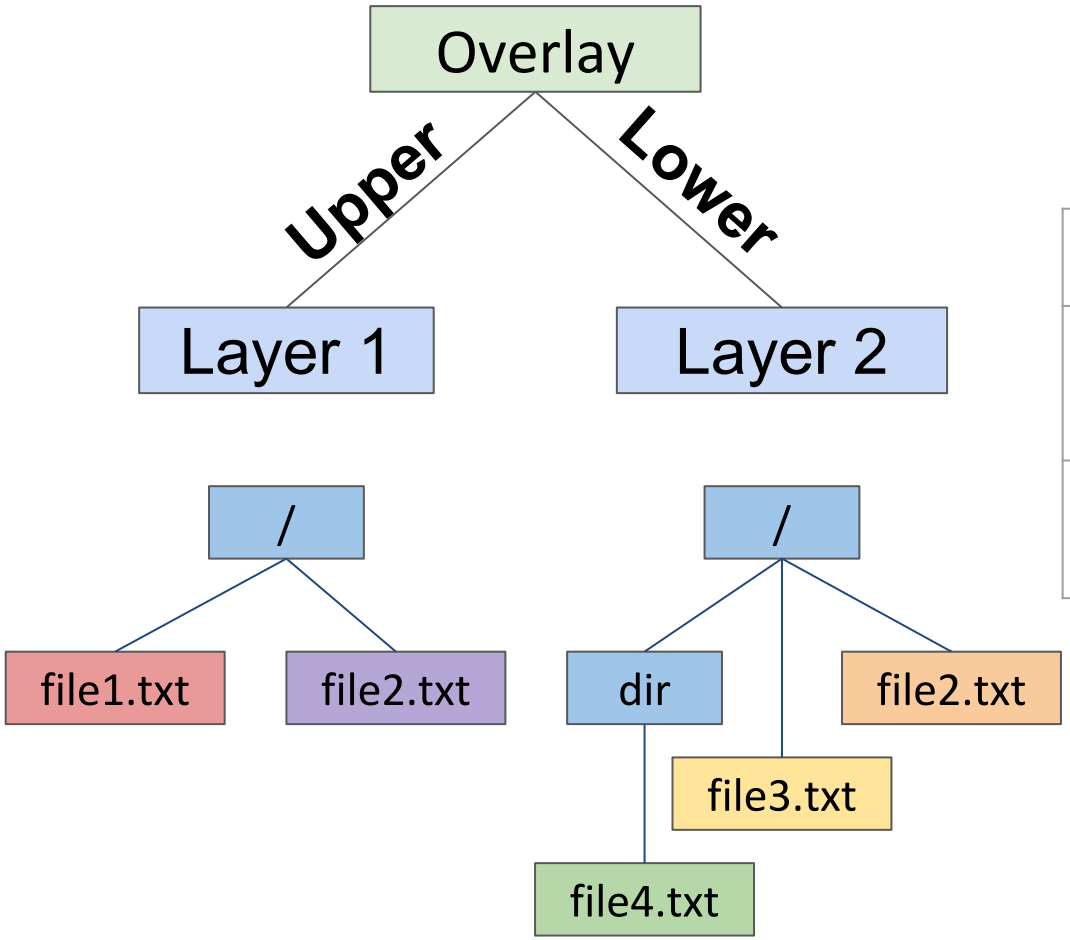
Procedure:

- Recursively merge directory contents
- If same file in both, take upper

OverlayFS resolves the path component by component in the upper FS then the lower FS

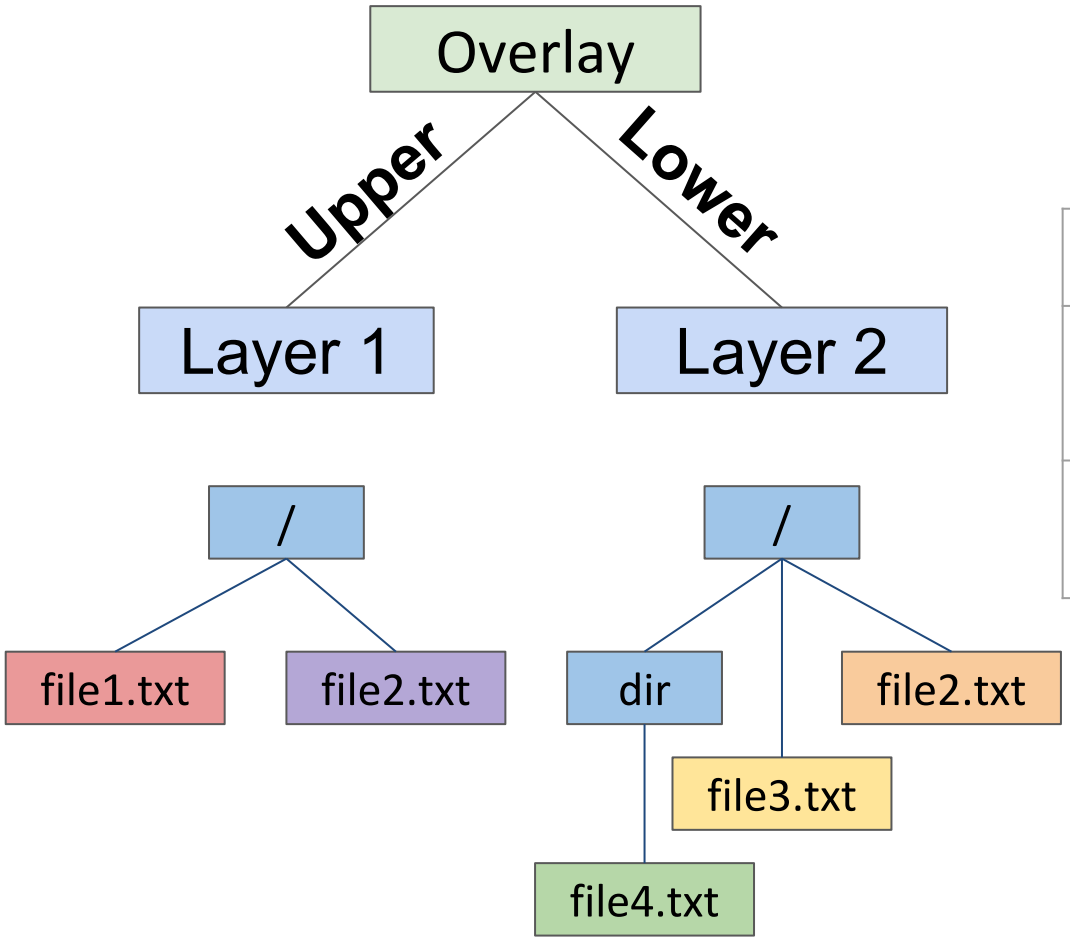


OverlayFS resolves the path component by component in the upper FS then the lower FS



Layer	/	dir/	file4.txt
Layer 1			
Layer 2			

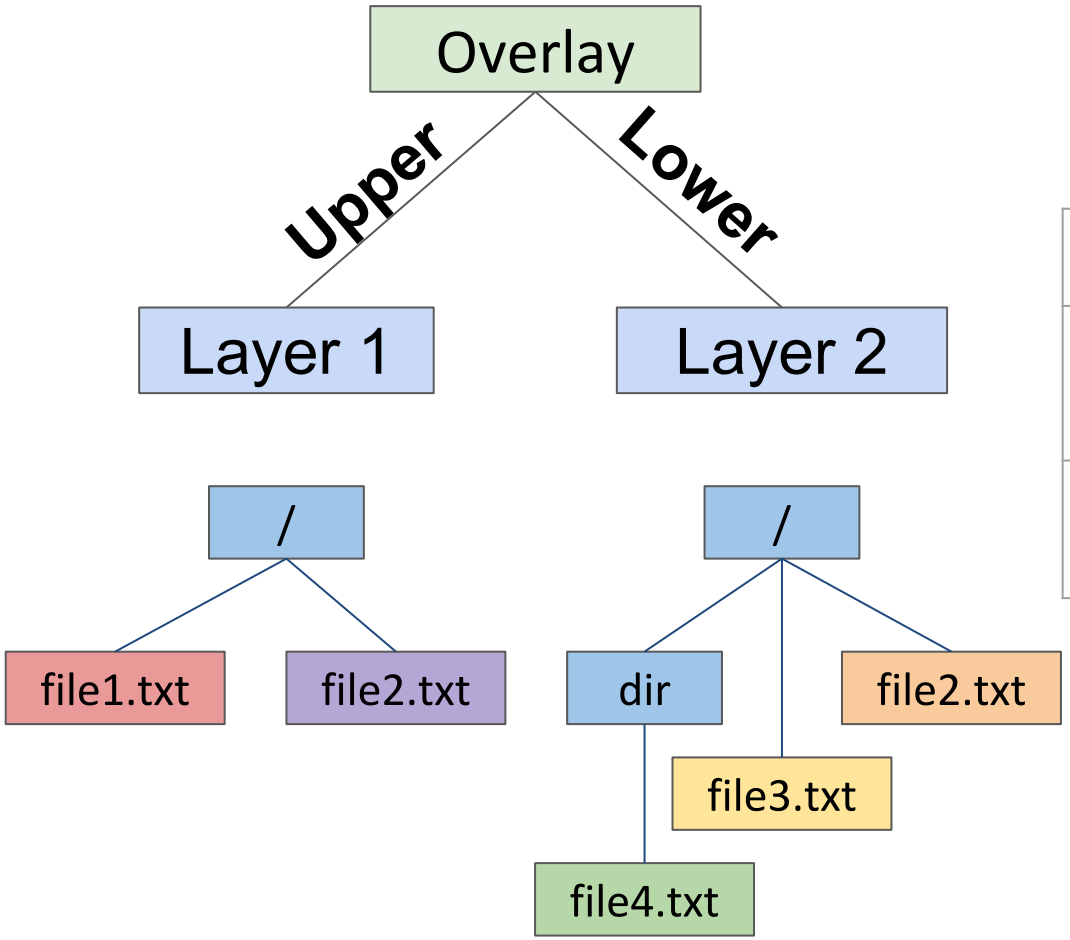
OverlayFS resolves the path component by component in the upper FS then the lower FS



Checking in '/' if 'dir/' exists

Layer	/	dir/	file4.txt
Layer 1			
Layer 2			

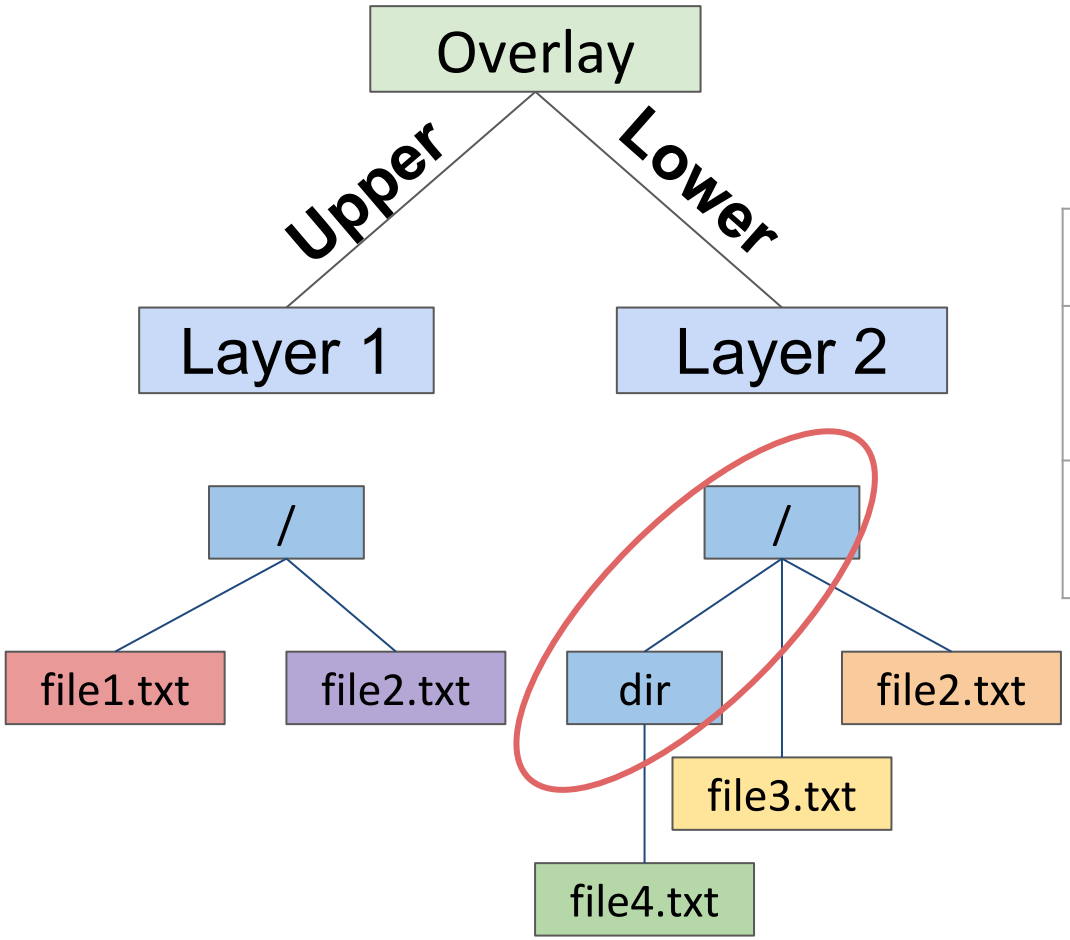
OverlayFS resolves the path component by component in the upper FS then the lower FS



Checking in '/' if 'dir/' exists

Layer	/	dir/	file4.txt
Layer 1	1		
Layer 2			

OverlayFS resolves the path component by component in the upper FS then the lower FS

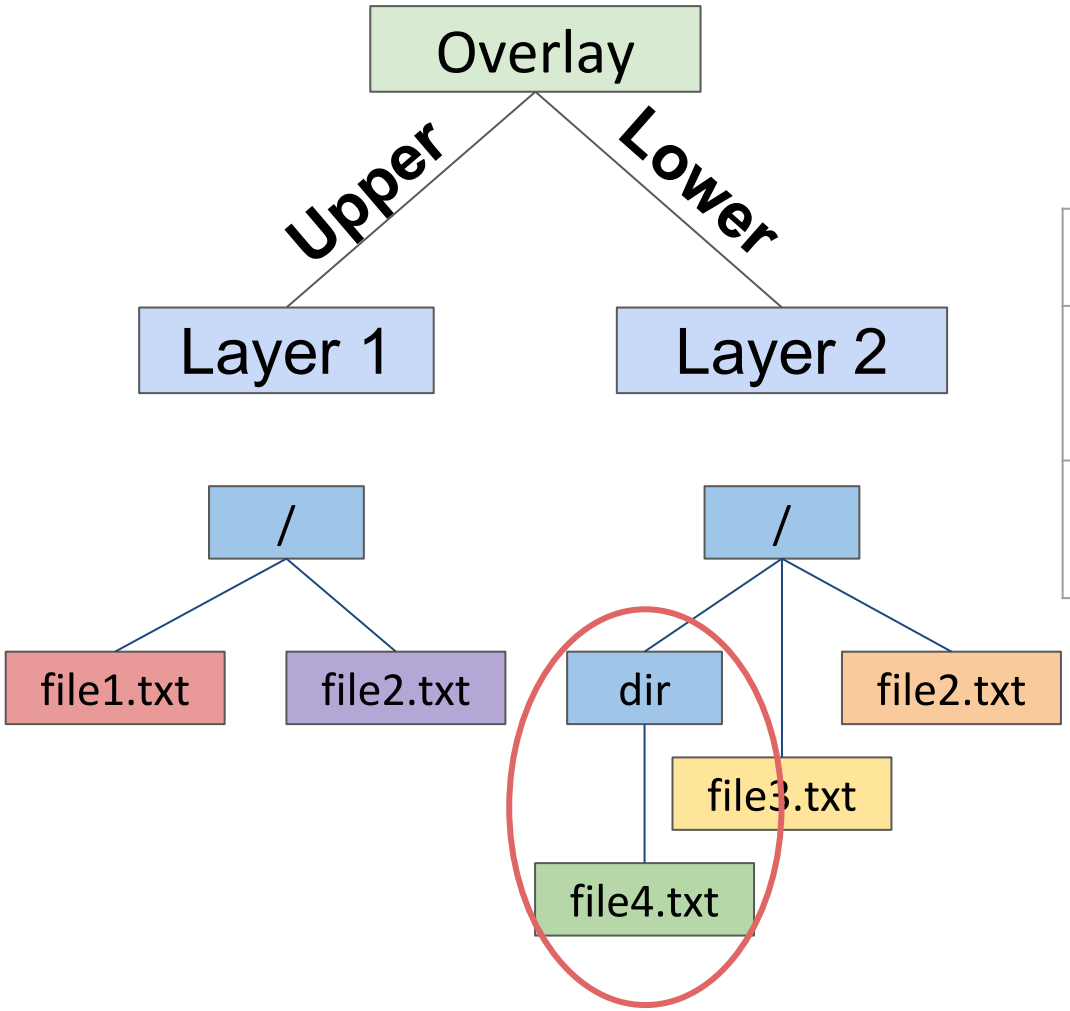


Checking in '/' if 'dir/' exists

Layer	/	dir/	file4.txt
Layer 1	1		
Layer 2	<u>2</u>		

Underlined means success and bold means file found

OverlayFS resolves the path component by component in the upper FS then the lower FS

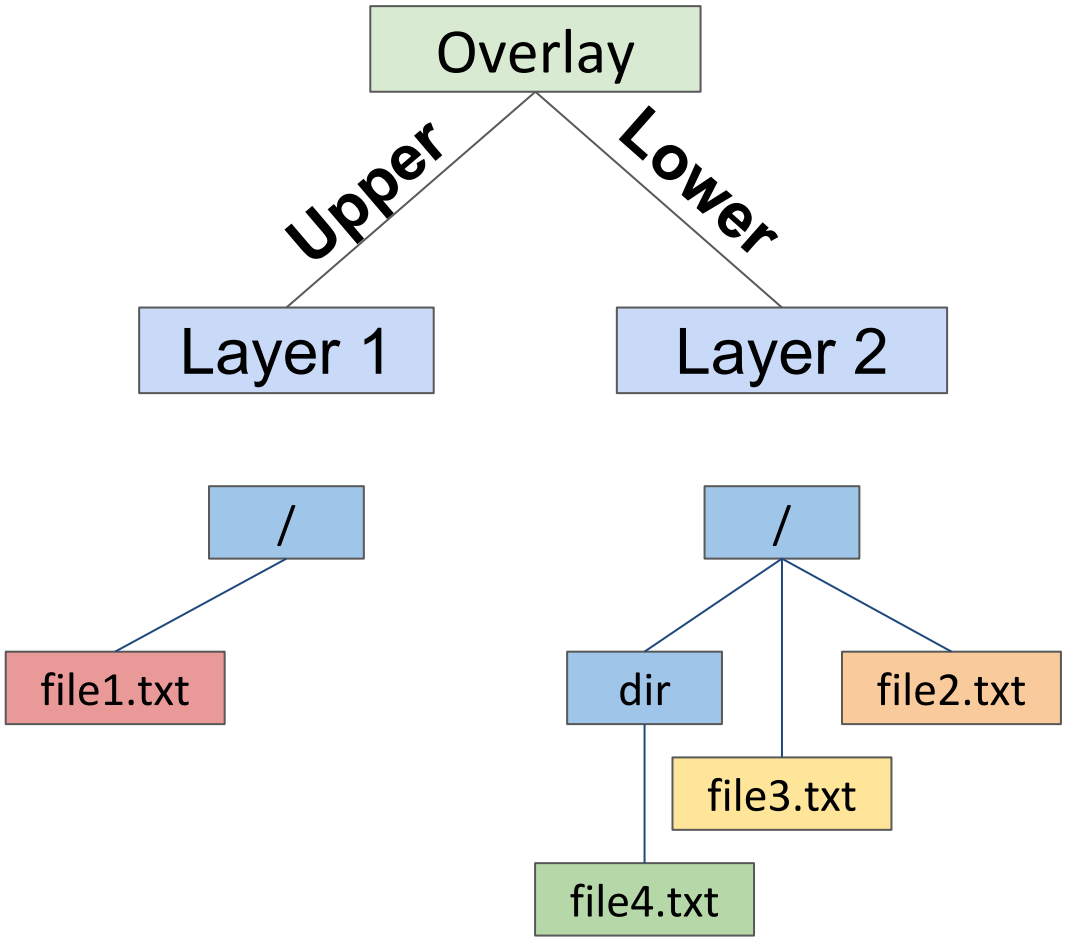


Checking in '/' if 'dir/' exists

Layer	/	dir/	file4.txt
Layer 1	1		
Layer 2	<u>2</u>	<u>**3**</u>	Used

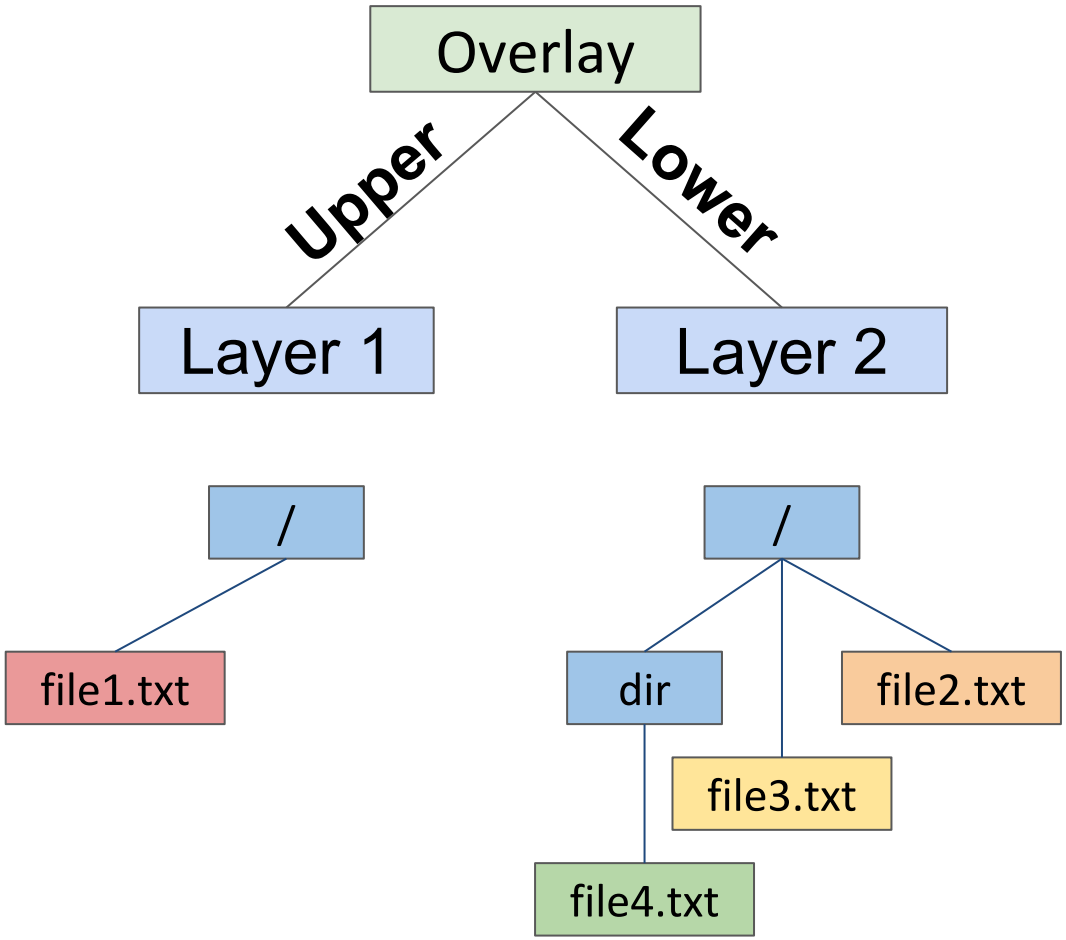
Underlined means success and bold means file found

File writes can only occur in the upper FS, thus file contents in lower FS must be "copied up"



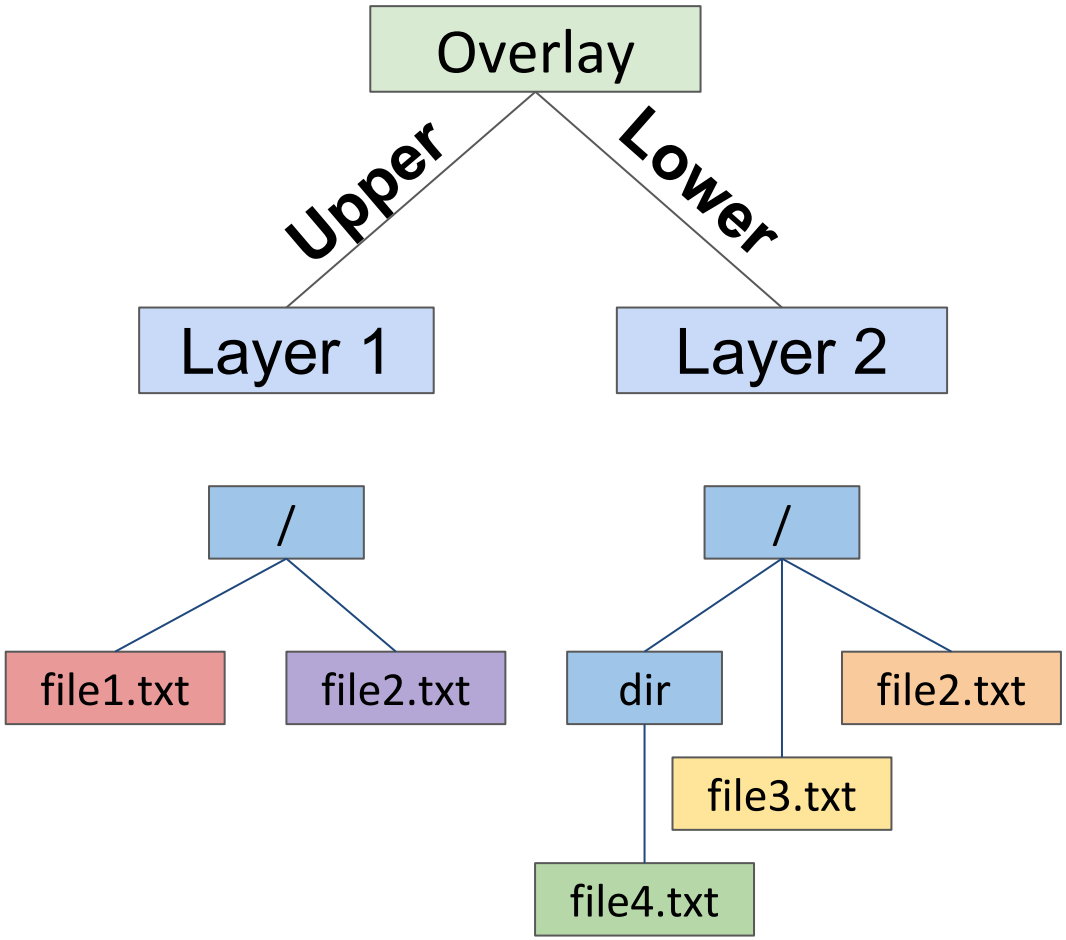
1) Write to /file2.txt

File writes can only occur in the upper FS, thus file contents in lower FS must be "copied up"



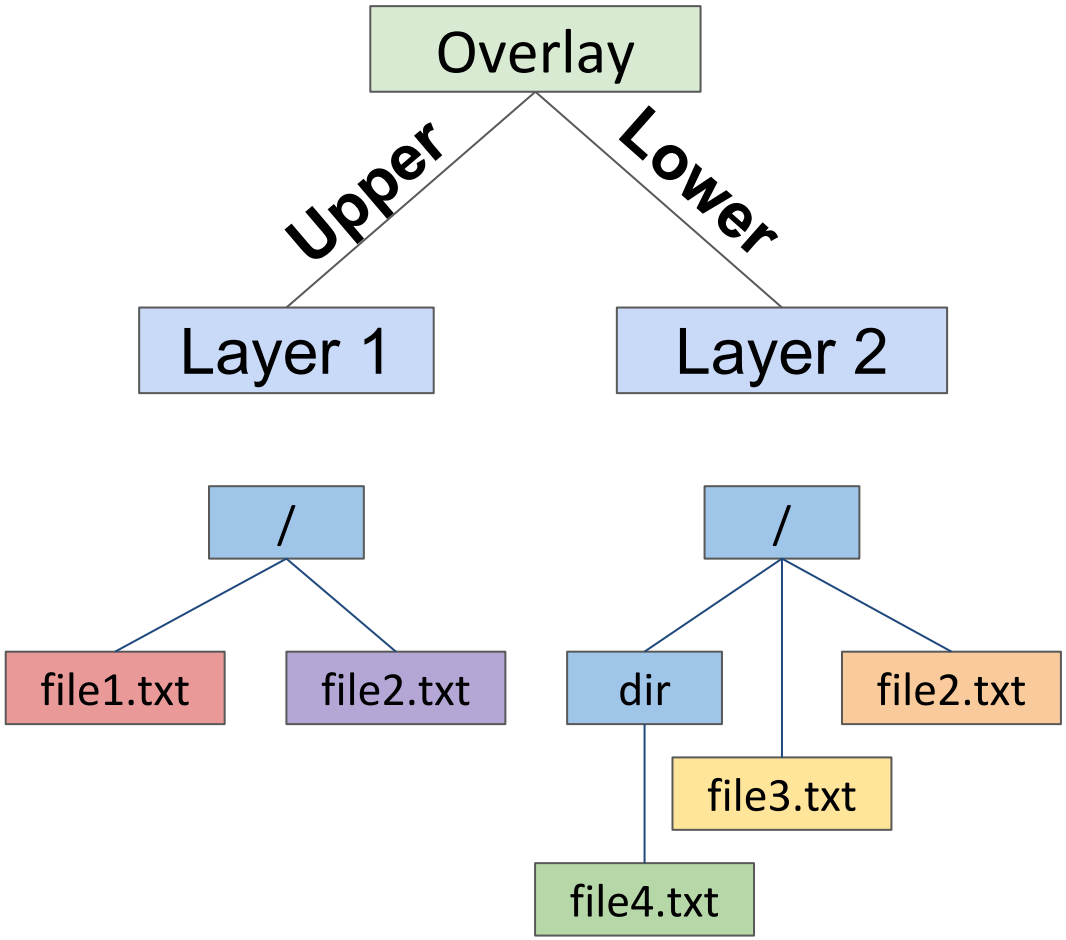
1) Write to /file2.txt
2) Resolve path

File writes can only occur in the upper FS, thus file contents in lower FS must be "copied up"



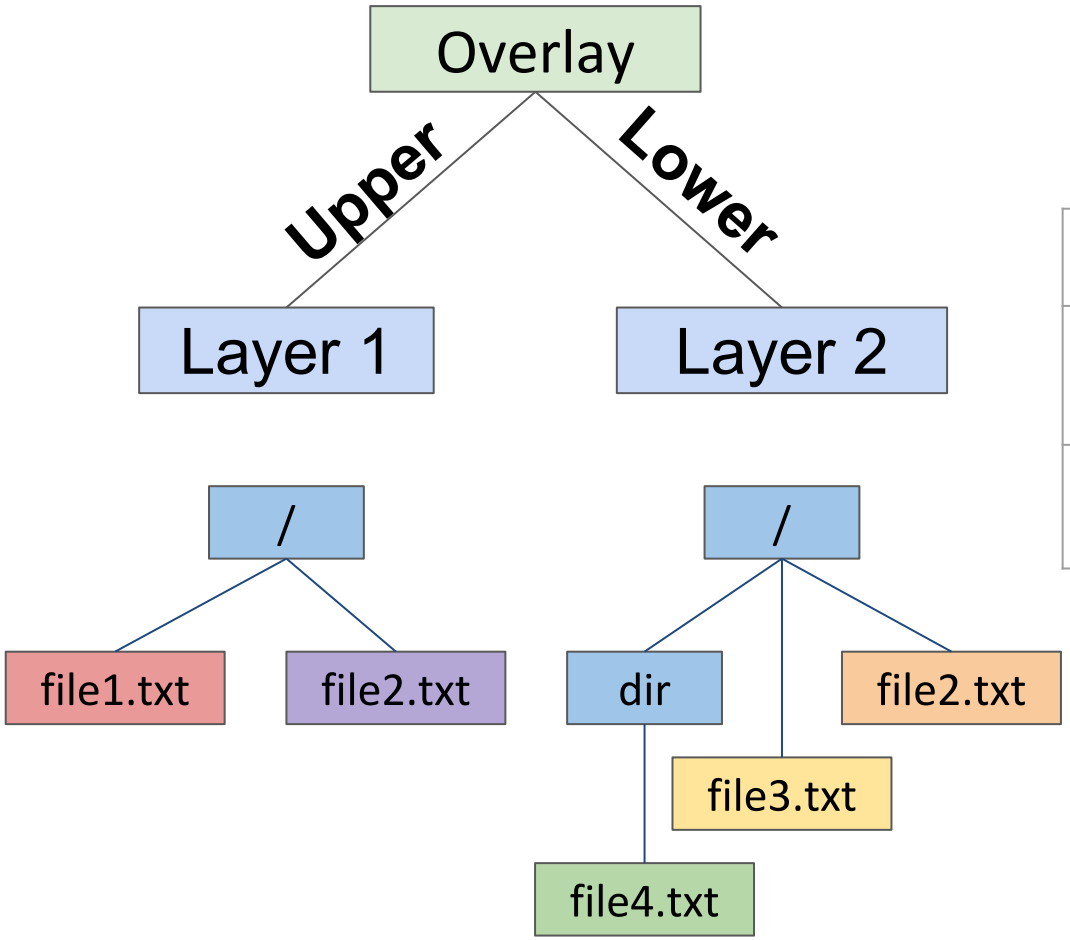
1) Write to /file2.txt
2) Resolve path
3) Copy up

File writes can only occur in the upper FS, thus file contents in lower FS must be "copied up"



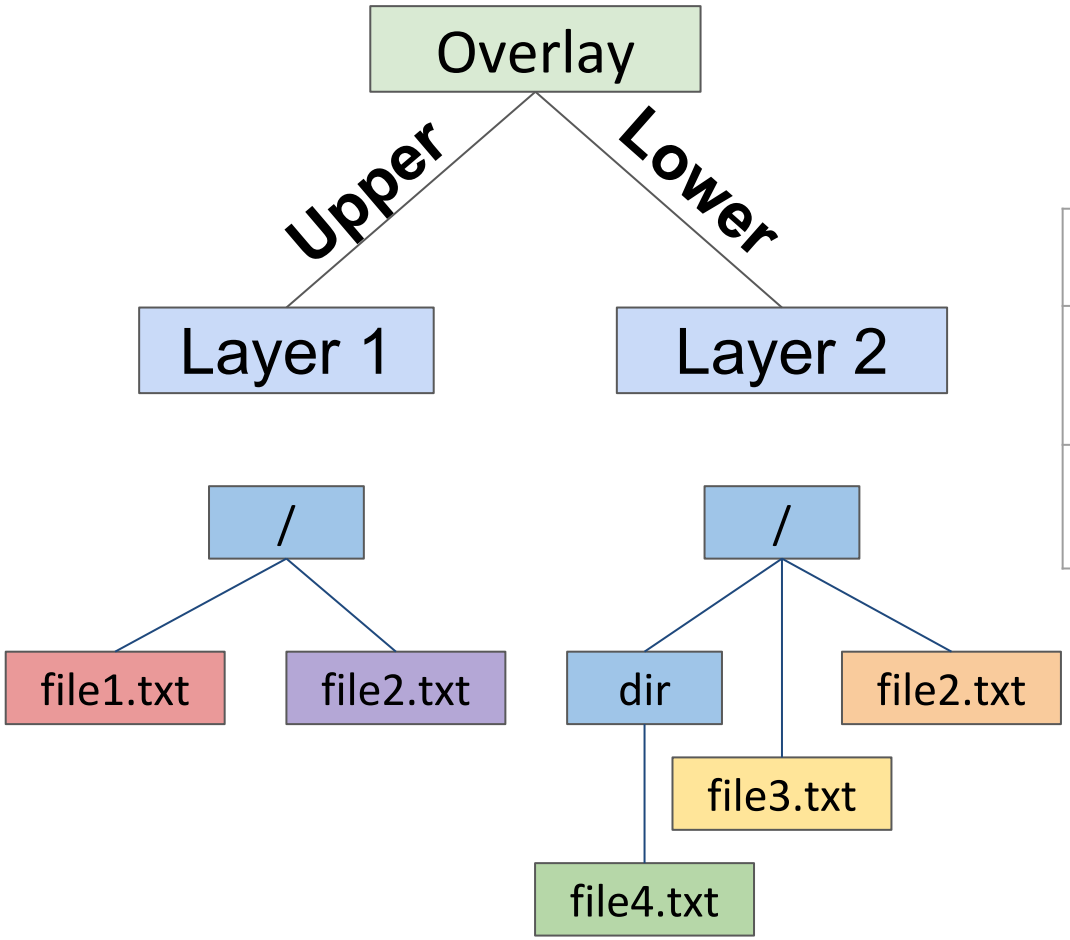
1) Write to /file2.txt
2) Resolve path
3) Copy up
4) Write to /file2.txt in upper

If a file exists in both upper (initially empty) and lower, we must retrieve the inode number from the lower



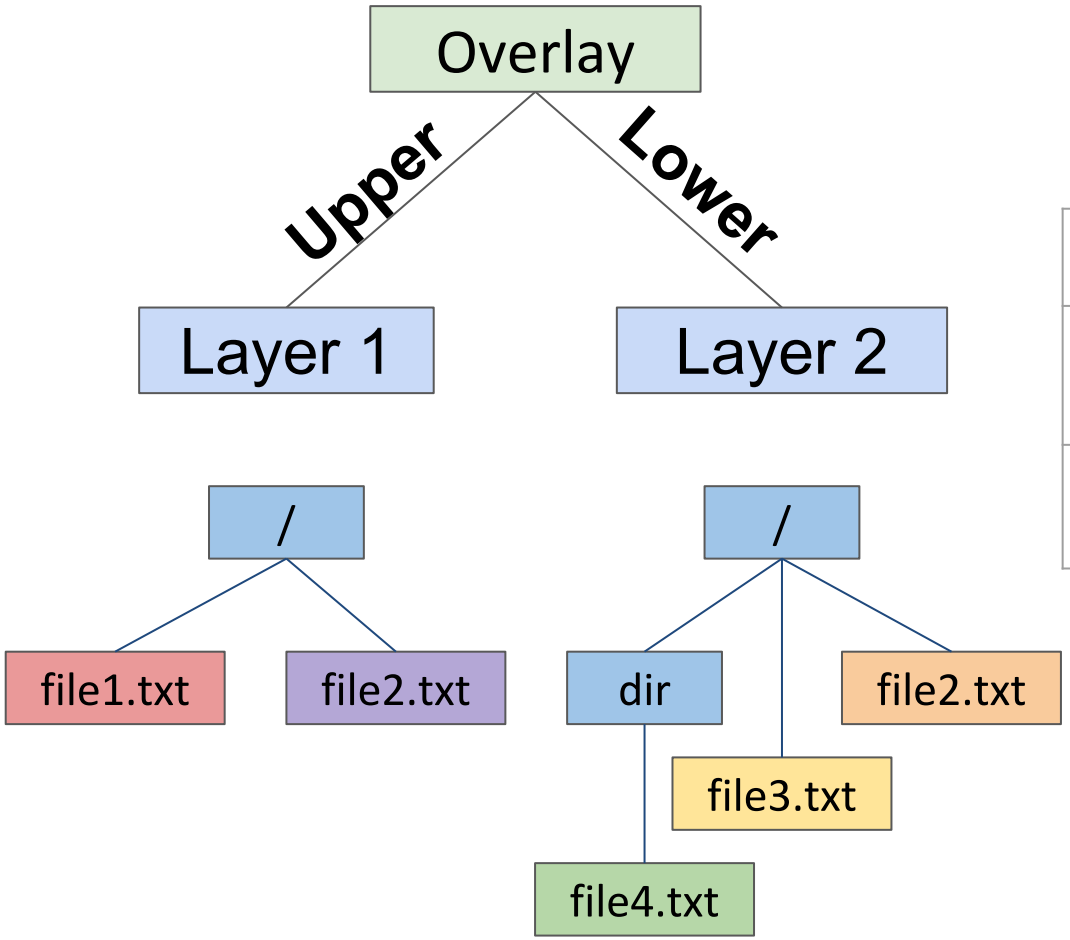
Layer	/	file2.txt
Layer 1		
Layer 2		

If a file exists in both upper (initially empty) and lower, we must retrieve the inode number from the lower



Layer	/	file2.txt
Layer 1	**1**	Used
Layer 2	**2**	

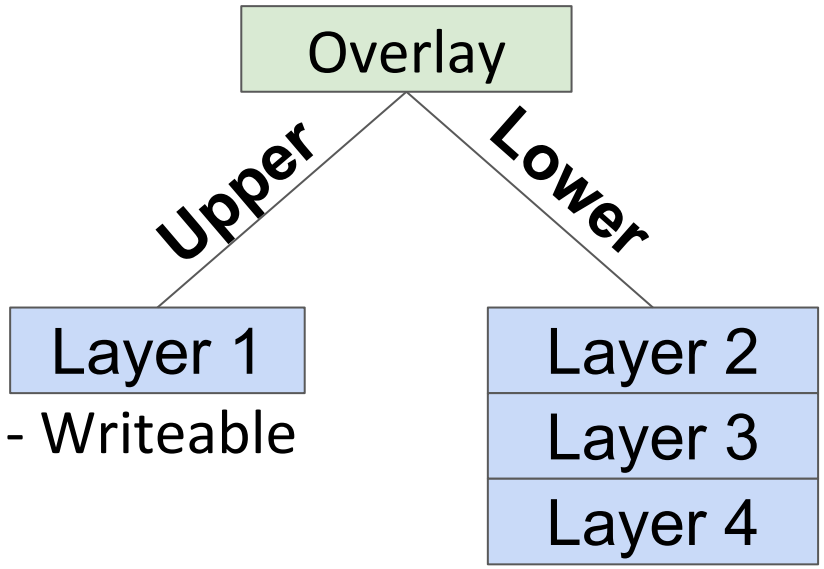
If a file exists in both upper (initially empty) and lower, we must retrieve the inode number from the lower



Layer	/	file2.txt
Layer 1	**1**	Used
Layer 2	**2**	

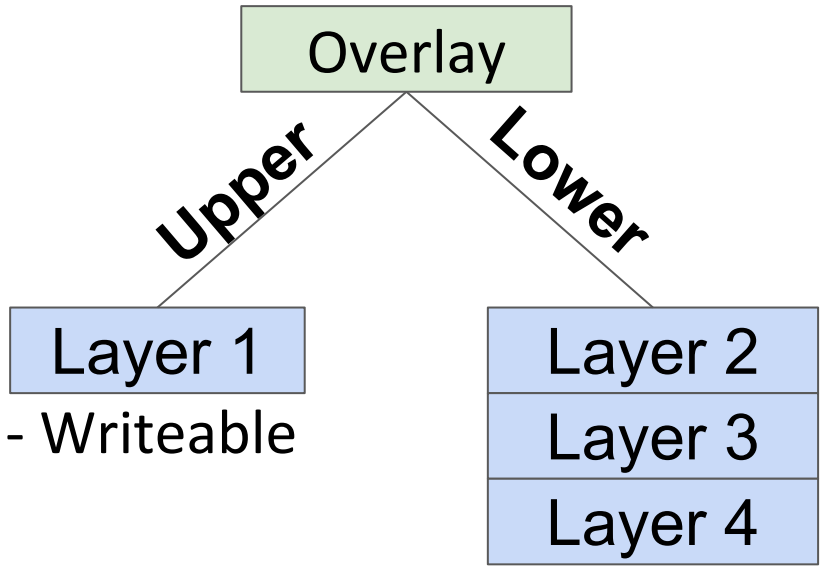
Retrieves inode number from lower because upper writeable

OverlayFS allows for multiple read-only lower layers, which are traversed from top to bottom



Layer	/	dir/	file4.txt
Layer 1			
Layer 2			
Layer 3			
Layer 4			

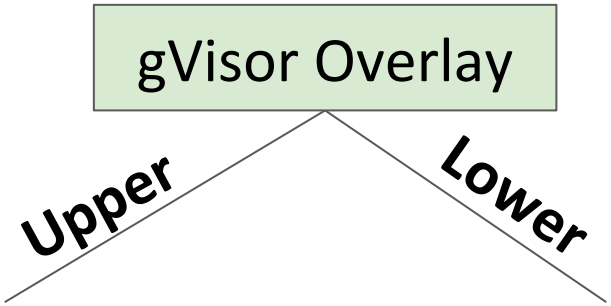
OverlayFS allows for multiple read-only lower layers, which are traversed from top to bottom



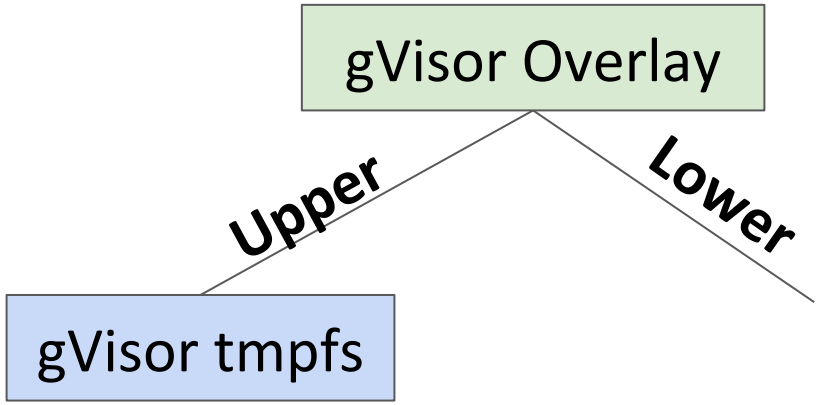
Layer	/	dir/	file4.txt
Layer 1	1	5	
Layer 2	2	6	
Layer 3	3	7	
Layer 4	4	**8**	Used

gVisor uses a combination of an internal Overlay and Linux' OverlayFS to access files in image layers

gVisor uses a combination of an internal Overlay and Linux' OverlayFS to access files in image layers

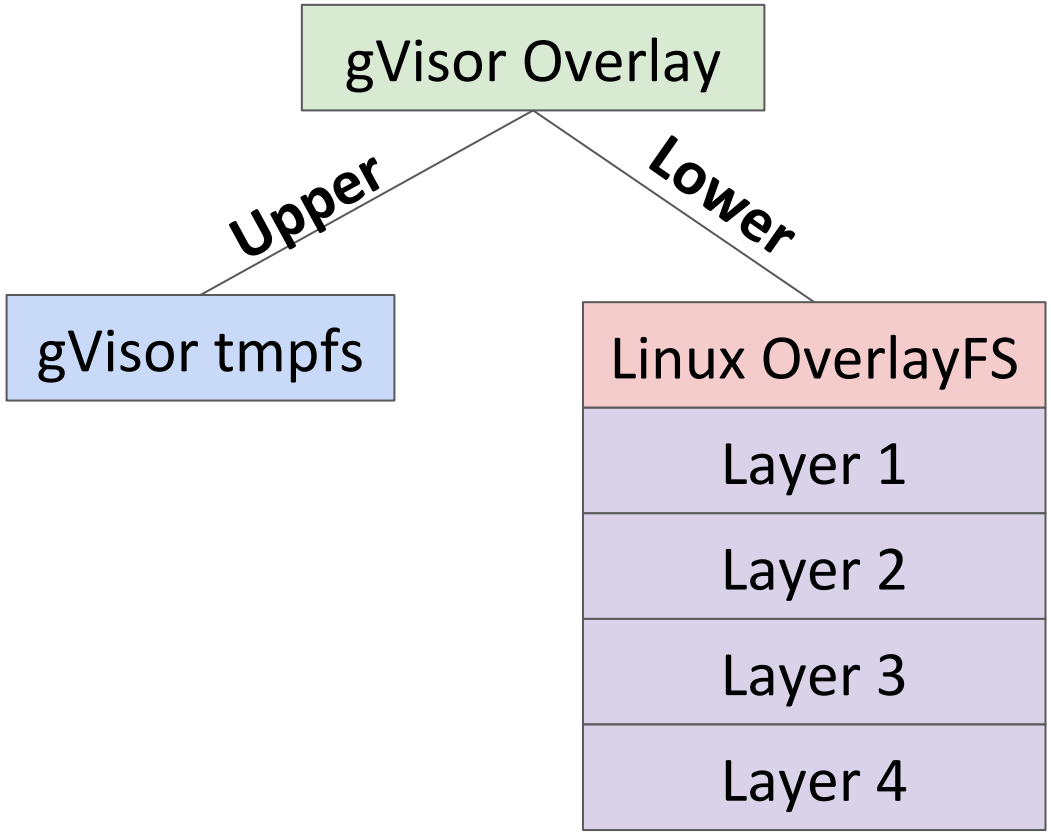


gVisor uses a combination of an internal Overlay and Linux' OverlayFS to access files in image layers



- Writeable
- Initially empty

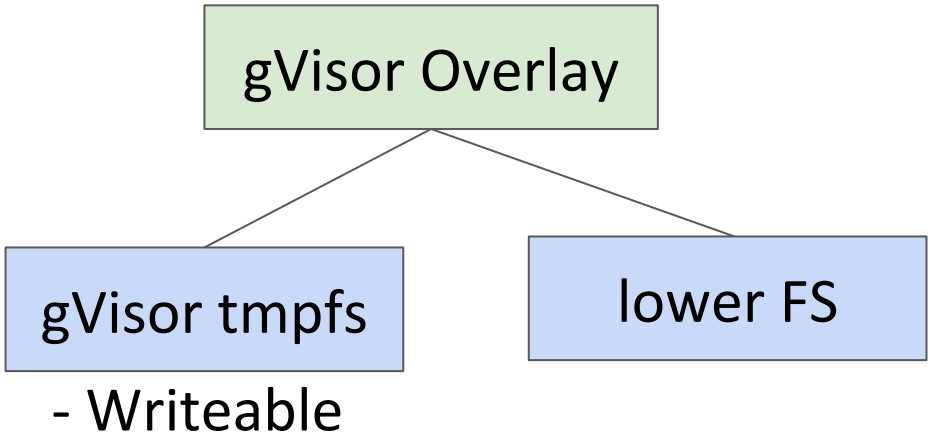
gVisor uses a combination of an internal Overlay and Linux' OverlayFS to access files in image layers

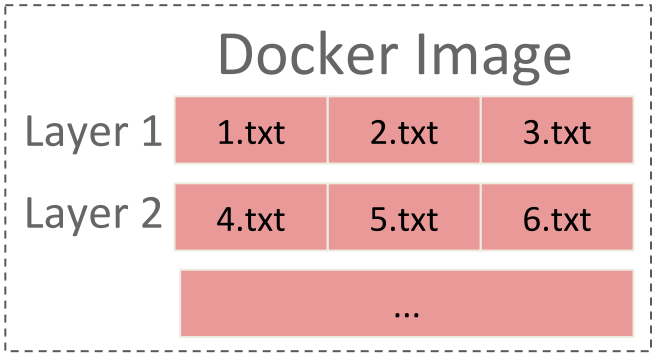


- Writeable
- Initially empty

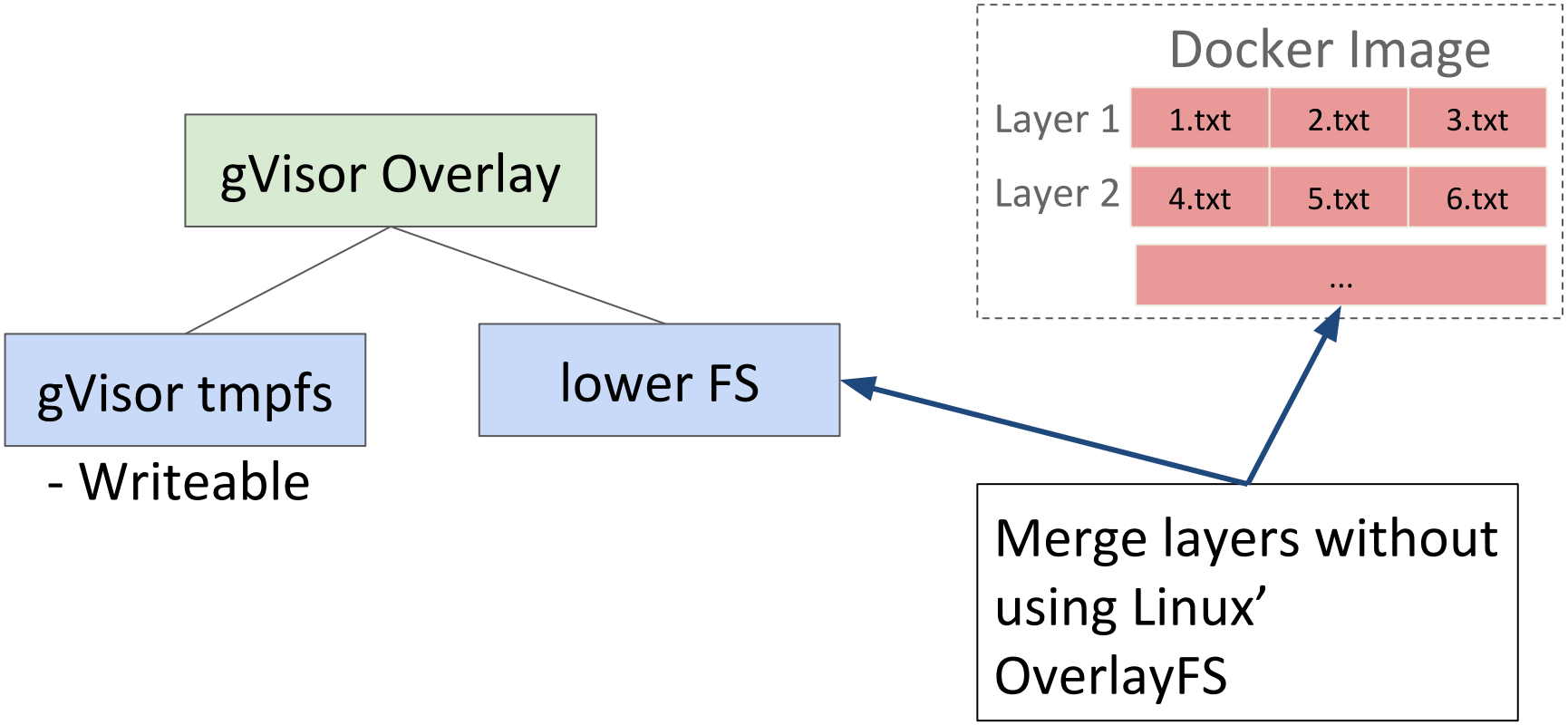
- Accessed via Gofer

In ContainerFS, Docker image layers are converted to image files and mounted within gVisor

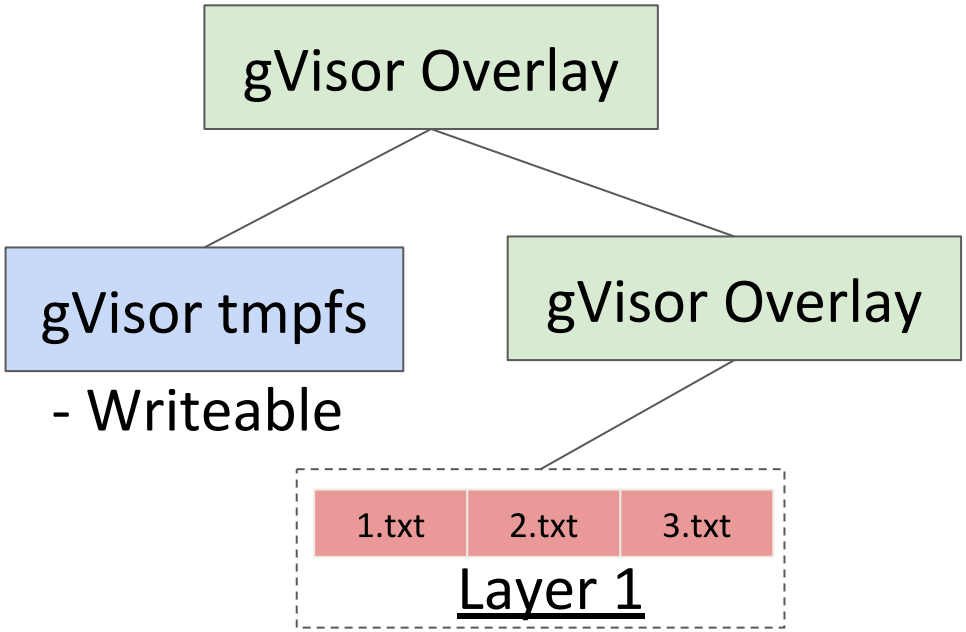


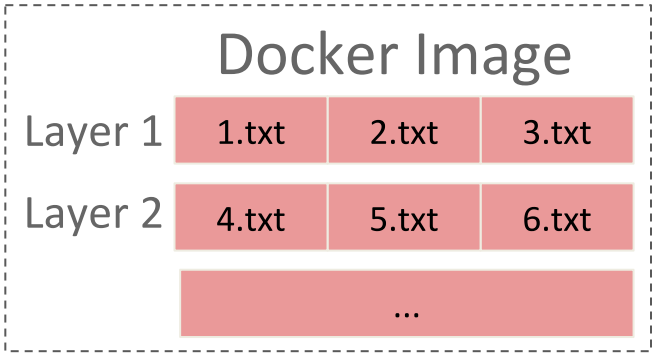


In ContainerFS, Docker image layers are converted to image files and mounted within gVisor

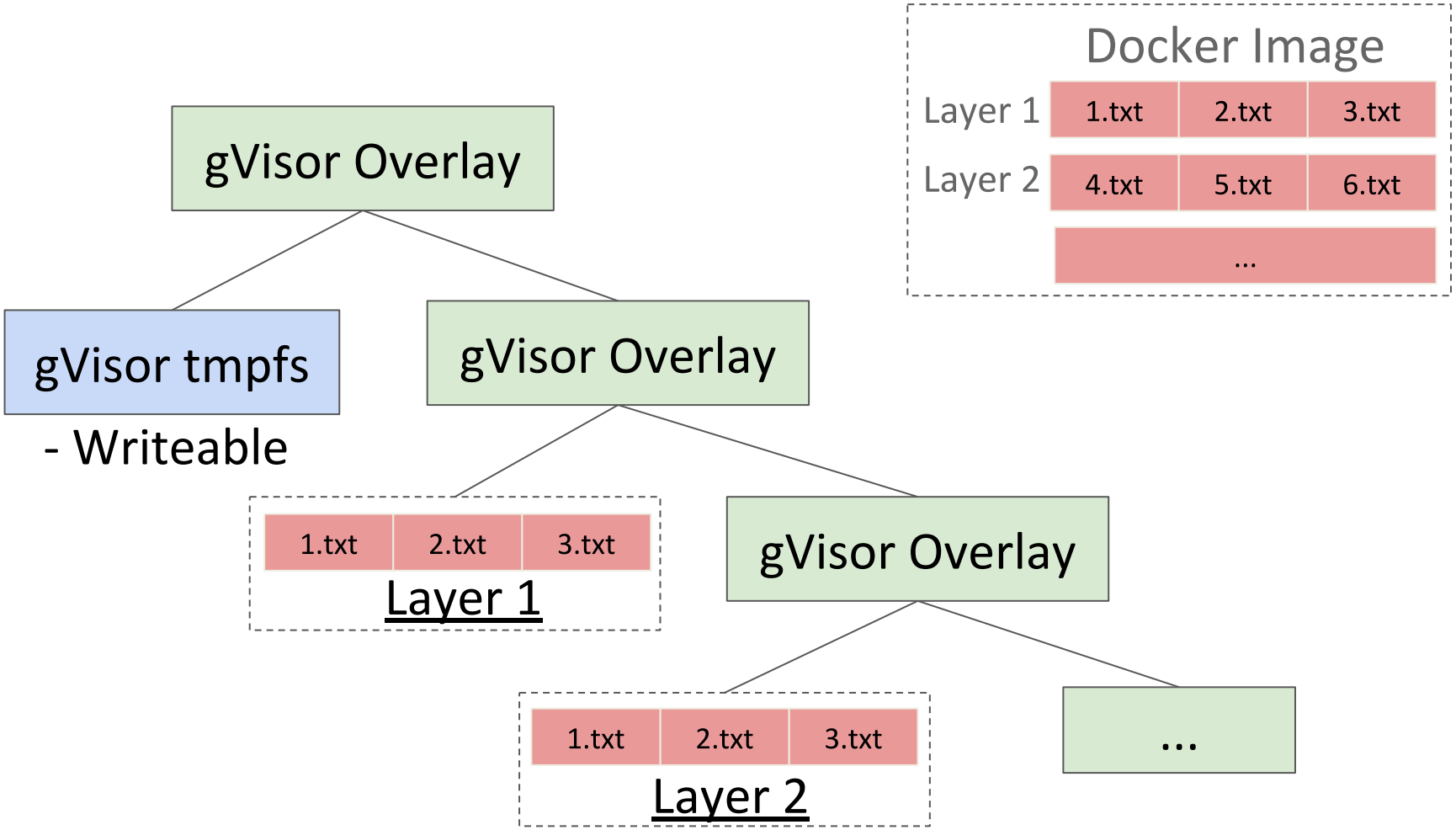


In ContainerFS, Docker image layers are converted to image files and mounted within gVisor





In ContainerFS, Docker image layers are converted to image files and mounted within gVisor



ContainerFS' Overlay tree is traversed identically to OverlayFS with multiple lower layers

Linux Overlay

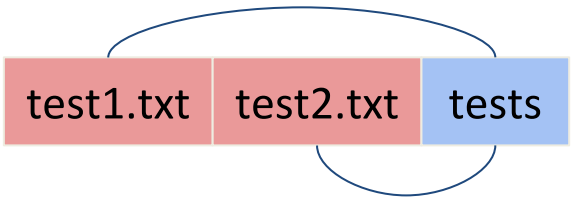
Layer	/	dir1	dir2	file.txt
img8	1	10	19	
img7	2	11	20	
img6	3	12	21	
img5	4	13	22	
img4	5	14	23	
img3	6	15	24	
img2	7	16	25	
img1	8	17	26	
img0	9	18	**27**	Used

→

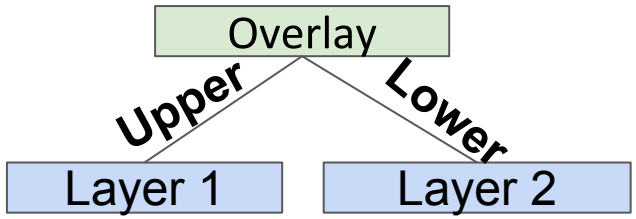
ContainerFS

Layer	/	dir1	dir2	file.txt
img8	1	10	19	
img7	2	11	20	
img6	3	12	21	
img5	4	13	22	
img4	5	14	23	
img3	6	15	24	
img2	7	16	25	
img1	8	17	26	
img0	9	18	**27**	Used

The second half of this talk explores the architecture of ImgFS, a gVisor file system for performance



ImgFS Architecture

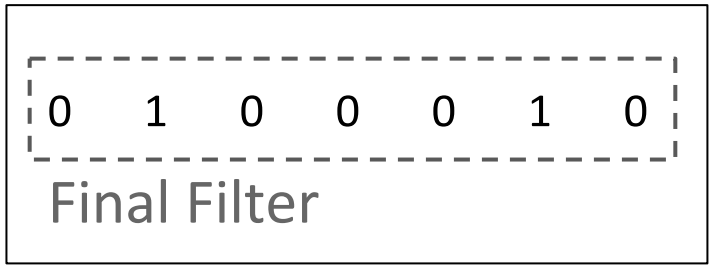


Mounting ImgFS Layers

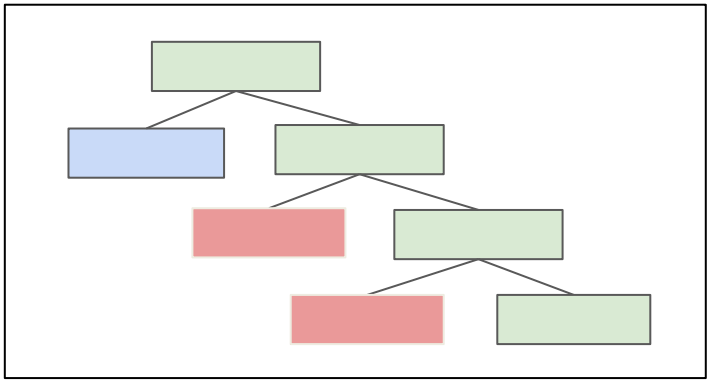
Layer	/	file2.txt
Layer 1	1	Used
Layer 2	2	

ContainerFS Traversal Algorithms

ContainerFS traverses the layers using two methods: Bloom Filter Traversal and Horizontal Traversal

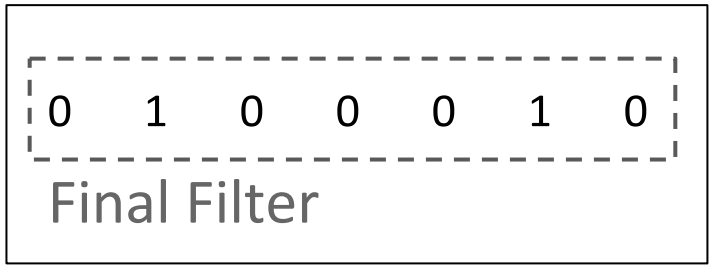


Bloom Filter Traversal

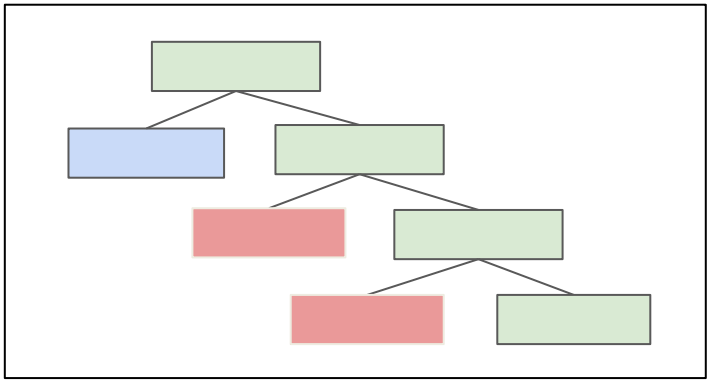


Horizontal Traversal

ContainerFS traverses the layers using two methods: Bloom Filter Traversal and Horizontal Traversal



Bloom Filter Traversal



Horizontal Traversal

A Bloom Filter is a probabilistic method for testing if an element definitely does not exist in a set

<u>Example</u>: Add element “test”

0	0	0	0	0	0	0

Initial Filter

A Bloom Filter is a probabilistic method for testing if an element definitely does not exist in a set

<u>Example</u>: Add element “test”

Set one bit from each hash

hash(“test”)
hash(“test”)
…

0	0	0	0	0	0	0

Initial Filter

0	1	0	0	0	1	0

Final Filter

A Bloom Filter is a probabilistic method for testing if an element definitely does not exist in a set

<u>Example</u>: Add element "test"

Set one bit from each hash

hash("test")
hash("test")
...

0	0	0	0	0	0	0

Initial Filter

0	1	0	0	0	1	0

Final Filter

<u>Example</u>: Test element <u>"init"</u>

0	0	0	0	0	0	0

Initial Filter

A Bloom Filter is a probabilistic method for testing if an element definitely does not exist in a set

Example: Add element "test"

Set one bit from each hash

hash("test")
hash("test")
...

0	0	0	0	0	0	0

Initial Filter

0	1	0	0	0	1	0

Final Filter

Example: Test element "init"

hash("init")
hash("init")
...

0	0	0	0	0	0	0

Initial Filter

0	1	0	1	0	0	0

Final Filter

A Bloom Filter is a probabilistic method for testing if an element definitely does not exist in a set

<u>Example</u>: Add element "test"

Set one bit from each hash

hash("test")
hash("test")
...

0 0 0 0 0 0 0

Initial Filter

0 1 0 0 0 1 0

Final Filter

Not matching, so definitely not in filter

<u>Example</u>: Test element "init"

hash("init")
hash("init")
...

0 0 0 0 0 0 0

Initial Filter

0 1 0 1 0 0 0

Final Filter

A Bloom Filter is a probabilistic method for testing if an element definitely does not exist in a set

<u>Example</u>: Add element “test”

Set one bit from each hash

hash(“test”)
hash(“test”)
…

0	0	0	0	0	0	0

Initial Filter

0	1	0	0	0	1	0

Final Filter

<u>Example</u>: Test element <u>“file”</u>

0	0	0	0	0	0	0

Initial Filter

A Bloom Filter is a probabilistic method for testing if an element definitely does not exist in a set

Example: Add element "test"

Set one bit from each hash

hash("test")
hash("test")
...

0	0	0	0	0	0	0

Initial Filter

0	1	0	0	0	1	0

Final Filter

Example: Test element "file"

hash("file")
hash("file")
...

0	0	0	0	0	0	0

Initial Filter

0	1	0	0	0	1	0

Final Filter

A Bloom Filter is a probabilistic method for testing if an element definitely does not exist in a set

<u>Example</u>: Add element "test"

Set one bit from each hash

hash("test")
hash("test")
...

0 0 0 0 0 0 0

Initial Filter

0 1 0 0 0 1 0

Final Filter

Matching, so maybe element in filter

<u>Example</u>: Test element <u>"file"</u>

hash("file")
hash("file")
...

0 0 0 0 0 0 0

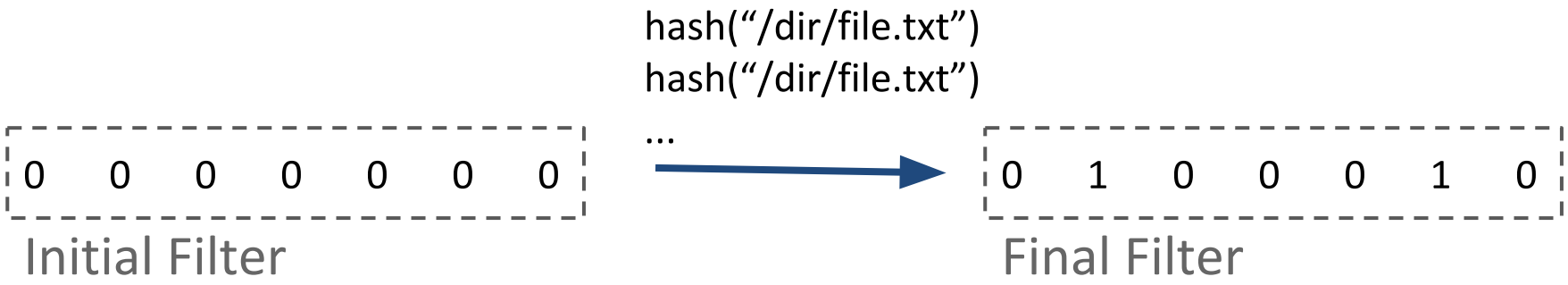
Initial Filter

0 1 0 0 0 1 0

Final Filter

Bloom Filters can be used to determine if a path exists in a layer

<u>Example</u>: Add element “/dir/file.txt”



Bloom Filters can be used to determine if a path exists in a layer

Example: Add element "/dir/file.txt"

hash("/dir/file.txt")
hash("/dir/file.txt")
...

0	0	0	0	0	0	0

Initial Filter

0	1	0	0	0	1	0

Final Filter

Example: Test element "/file.txt"

hash("/file.txt")
hash("/file.txt")
...

0	0	0	0	0	0	0

Initial Filter

0	1	0	1	0	0	0

Final Filter

Bloom Filters can be used to determine if a path exists in a layer

Example: Add element "/dir/file.txt"

hash("/dir/file.txt")
hash("/dir/file.txt")
...

0 0 0 0 0 0 0 → 0 1 0 0 0 1 0

Initial Filter Final Filter

Not matching, so path not in filter

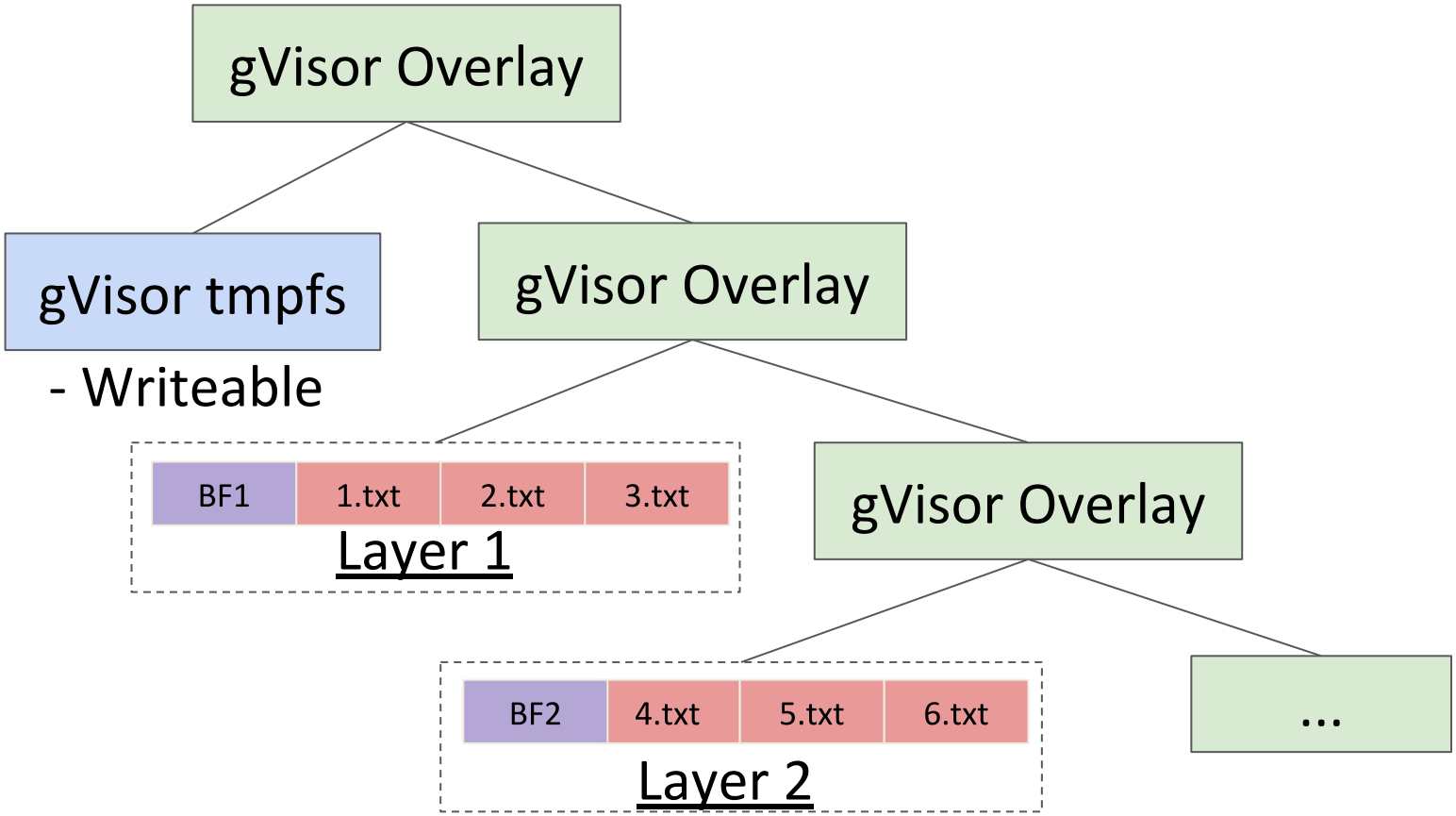
Example: Test element "/file.txt"

hash("/file.txt")
hash("/file.txt")
...

0 0 0 0 0 0 0 → 0 1 0 1 0 0 0

Initial Filter Final Filter

ContainerFS uses Bloom Filters preloaded with the absolute paths of all files and directories in layer



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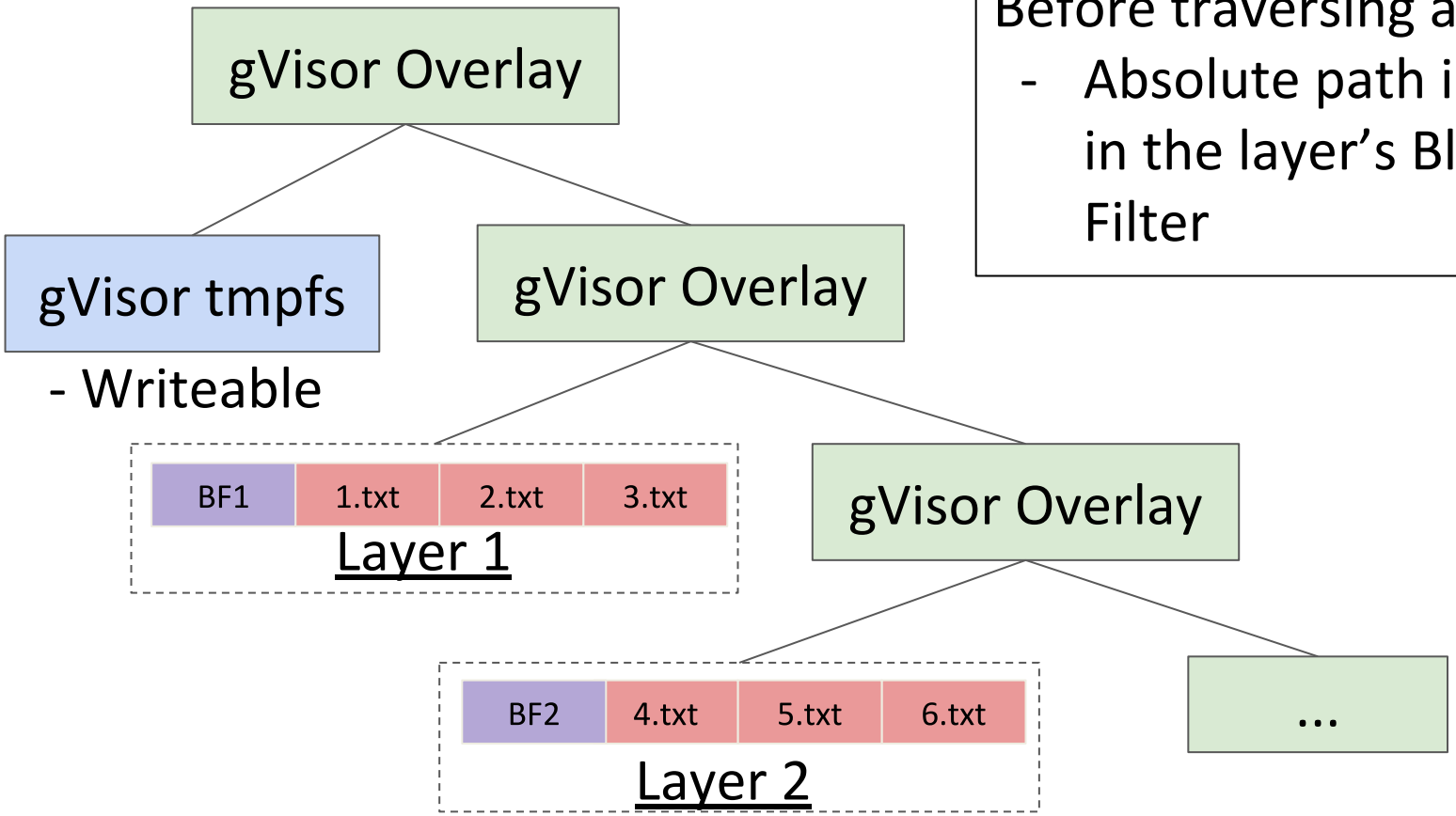

Before traversing a layer…
- Absolute path is tested in the layer's Bloom Filter

Bloom Filters eliminate unnecessary lookups in high layers

Without BF

Layer	/	dir1	dir2	file.txt
img8	1	10	19	
img7	2	11	20	
img6	3	12	21	
img5	4	13	22	
img4	5	14	23	
img3	6	15	24	
img2	7	16	25	
img1	8	17	26	
img0	9	18	**27**	Used

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Without BF

Layer	/	dir1	dir2	file.txt
img8	1	10	19	
img7	2	11	20	
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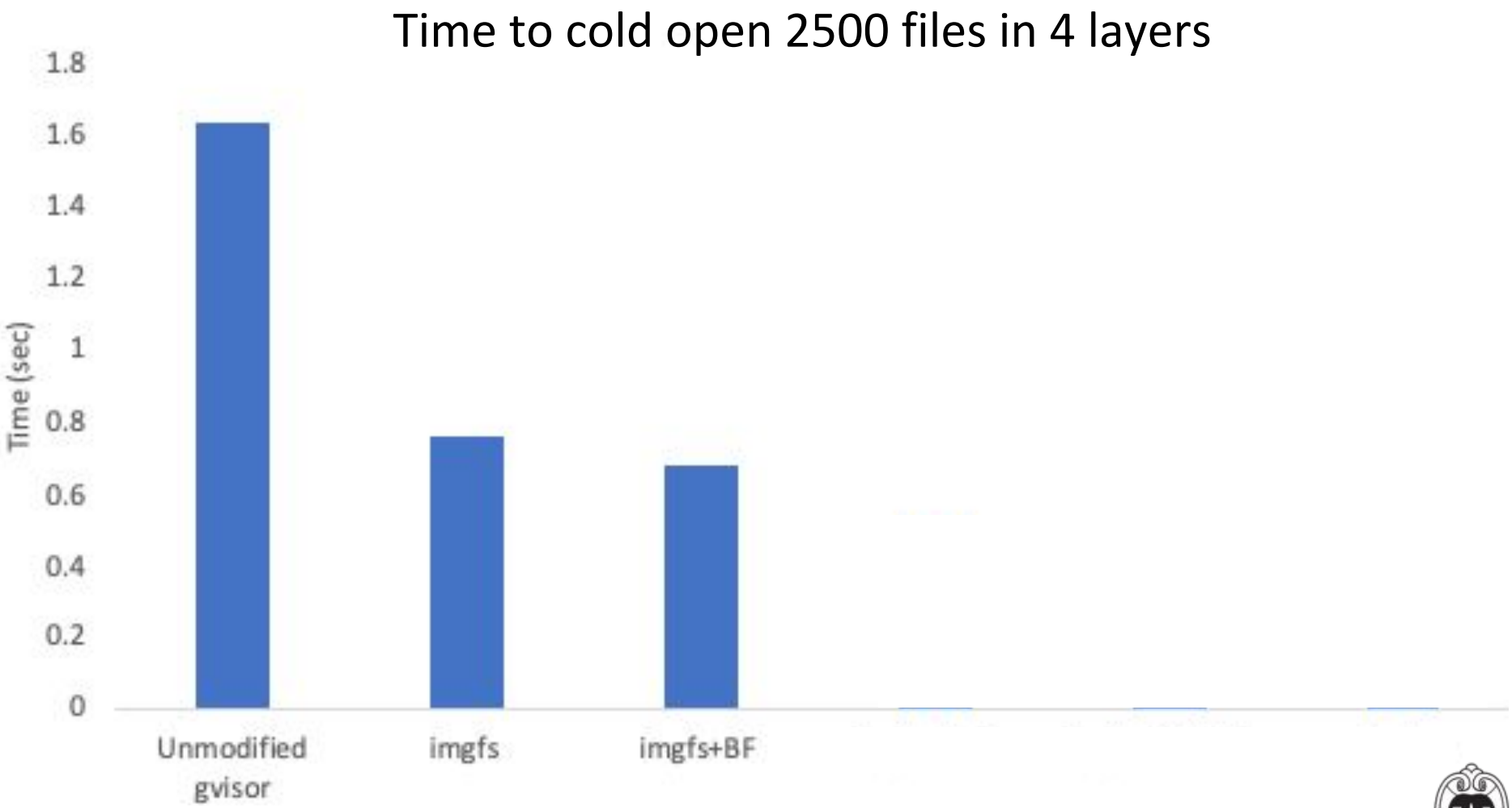
img5	4	13	22	
img4	5	14	23	
img3	6	15	24	
img2	7	16	25	
img1	8	17	26	
img0	9	18	**27**	Used

→

With BF

Layer	BF	/	dir1	dir2	file.txt
img8	1				
img7	2				
img6	3				
img5	4				
img4	5				
img3	6				
img2	7				
img1	8				
img0	9	11	12	**13**	Used

Bloom Filters increase ContainerFS' performance, but it is costly to check each layer for each path



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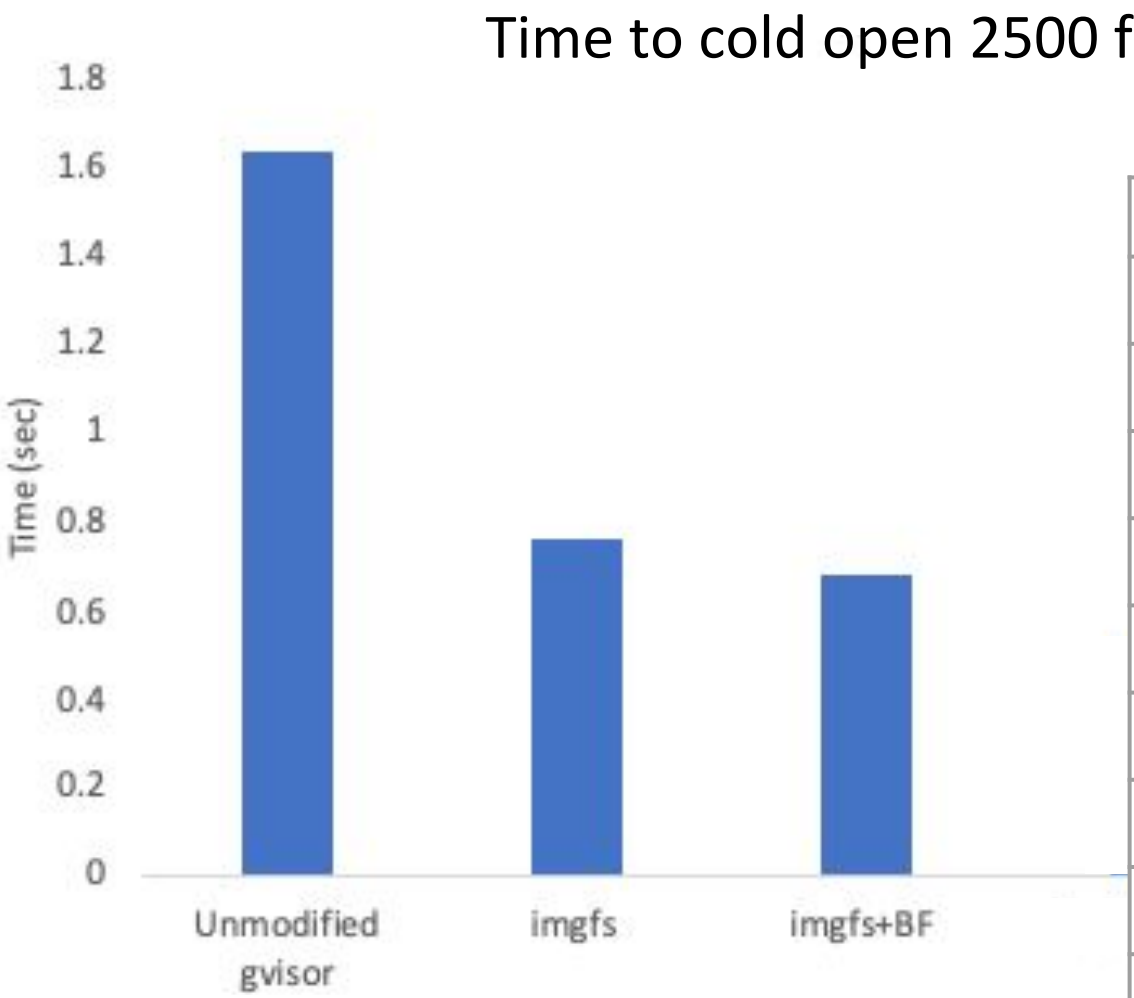

Layer	BF	/	dir1	dir2	file.txt
img8	1	11	12	**13**	Used
img7	2				
img6	3				
img5	4				
img4	5				
img3	6				
img2	7				
img1	8				
img0	9				

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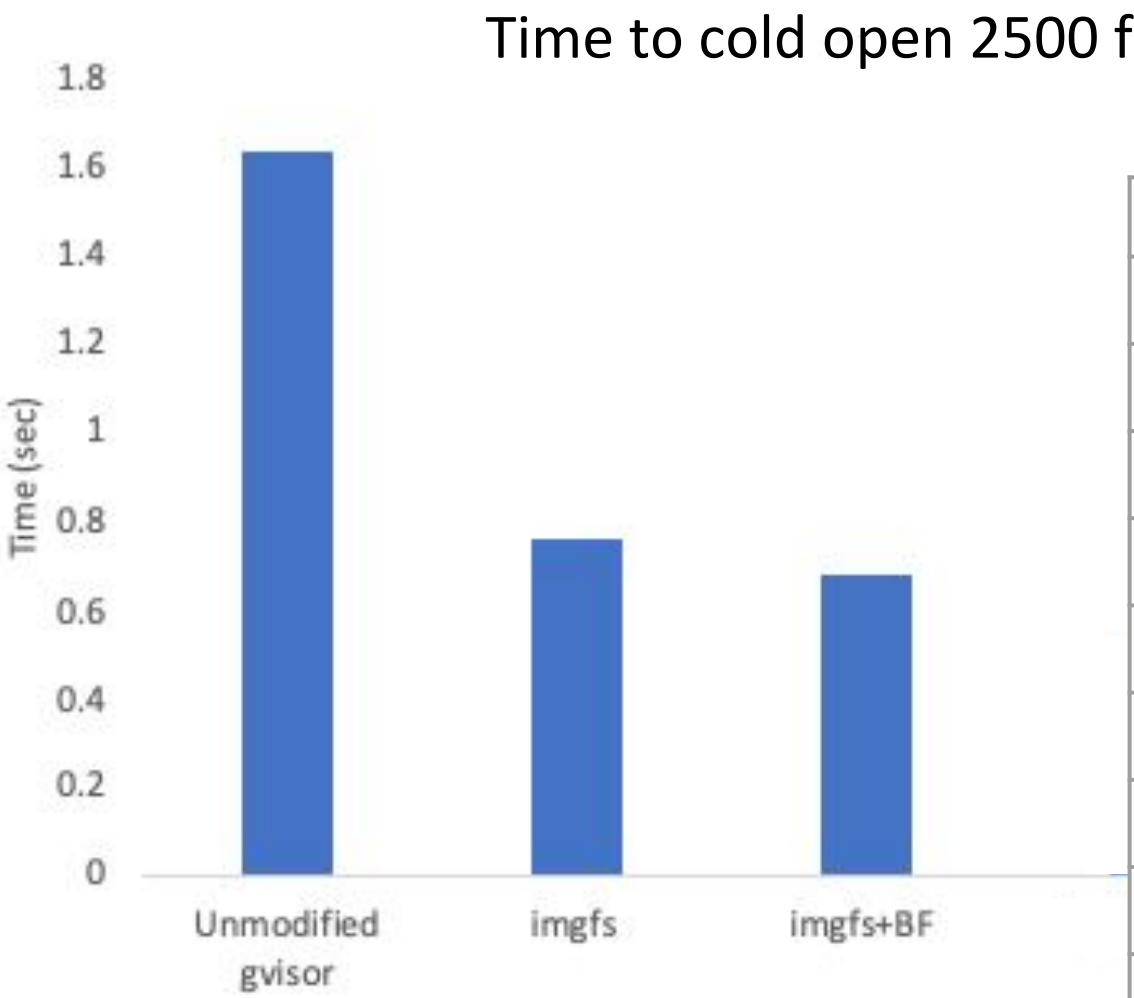

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img6	3				
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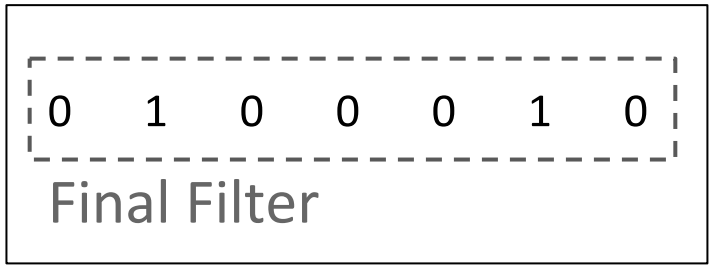
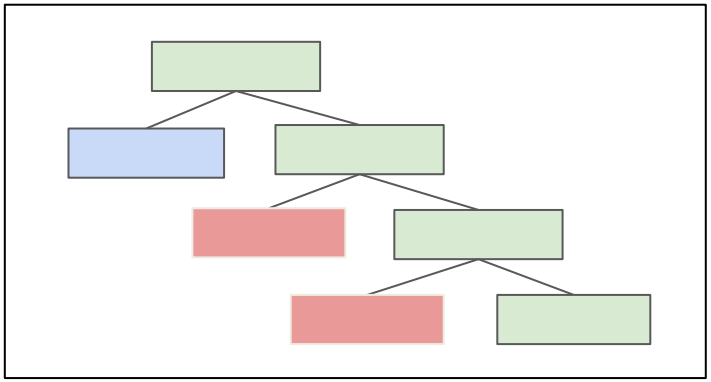
img4	5				
img3	6				
img2	7				
img1	8				
img0	9				

ContainerFS traverses the layers using two methods: Bloom Filter Traversal and Horizontal Traversal

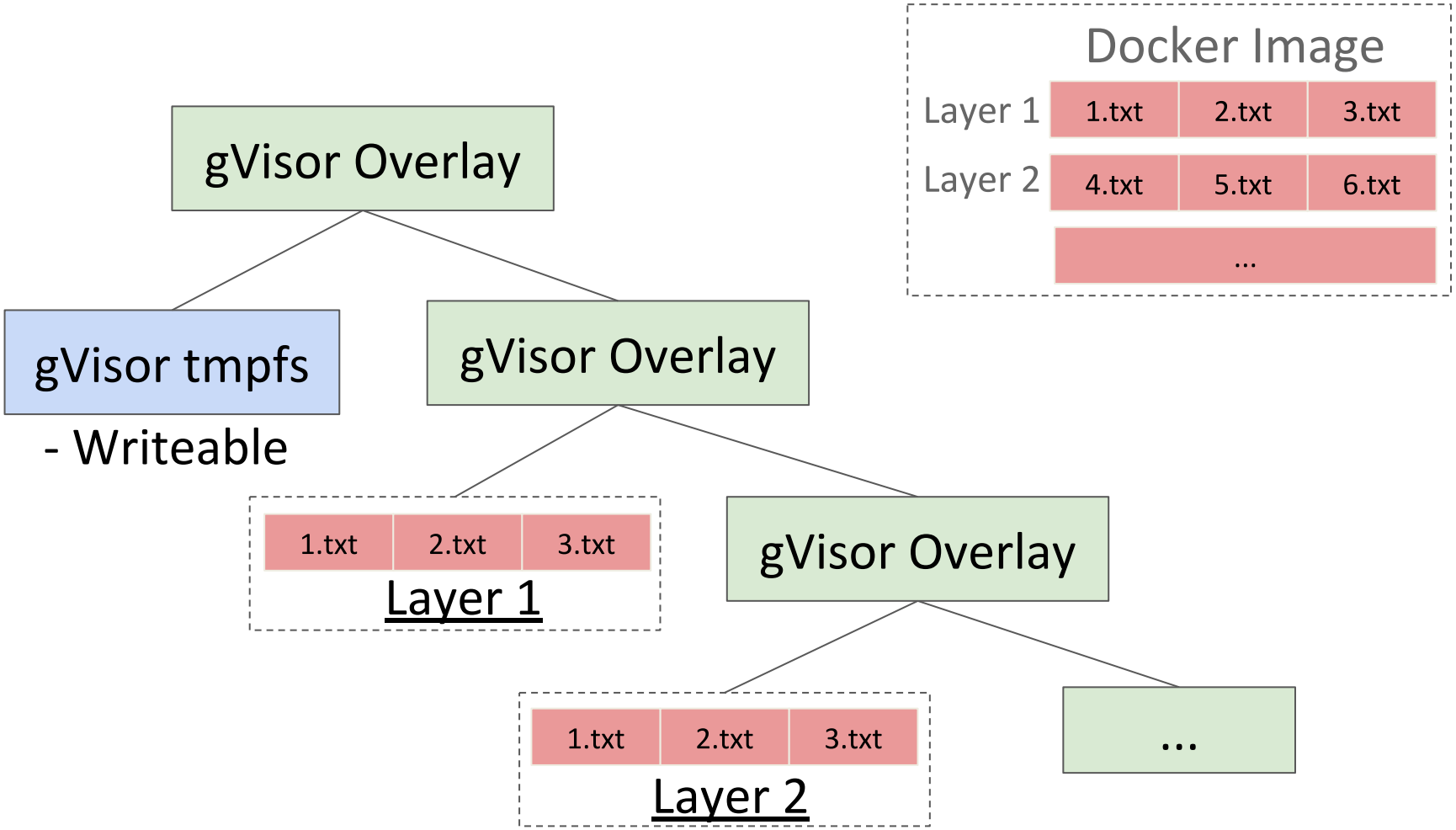


Bloom Filter Traversal



Horizontal Traversal

Horizontal Traversal: ContainerFS completely traverses a layer before moving to a lower layer



Horizontal Traversal eliminates unnecessary lookups in low layers

Without Horiz

Layer	/	dir1	dir2	file.txt
img8	1	10	**19**	Used
img7	2	11		
img6	3	12		
img5	4	13		
img4	5	14		
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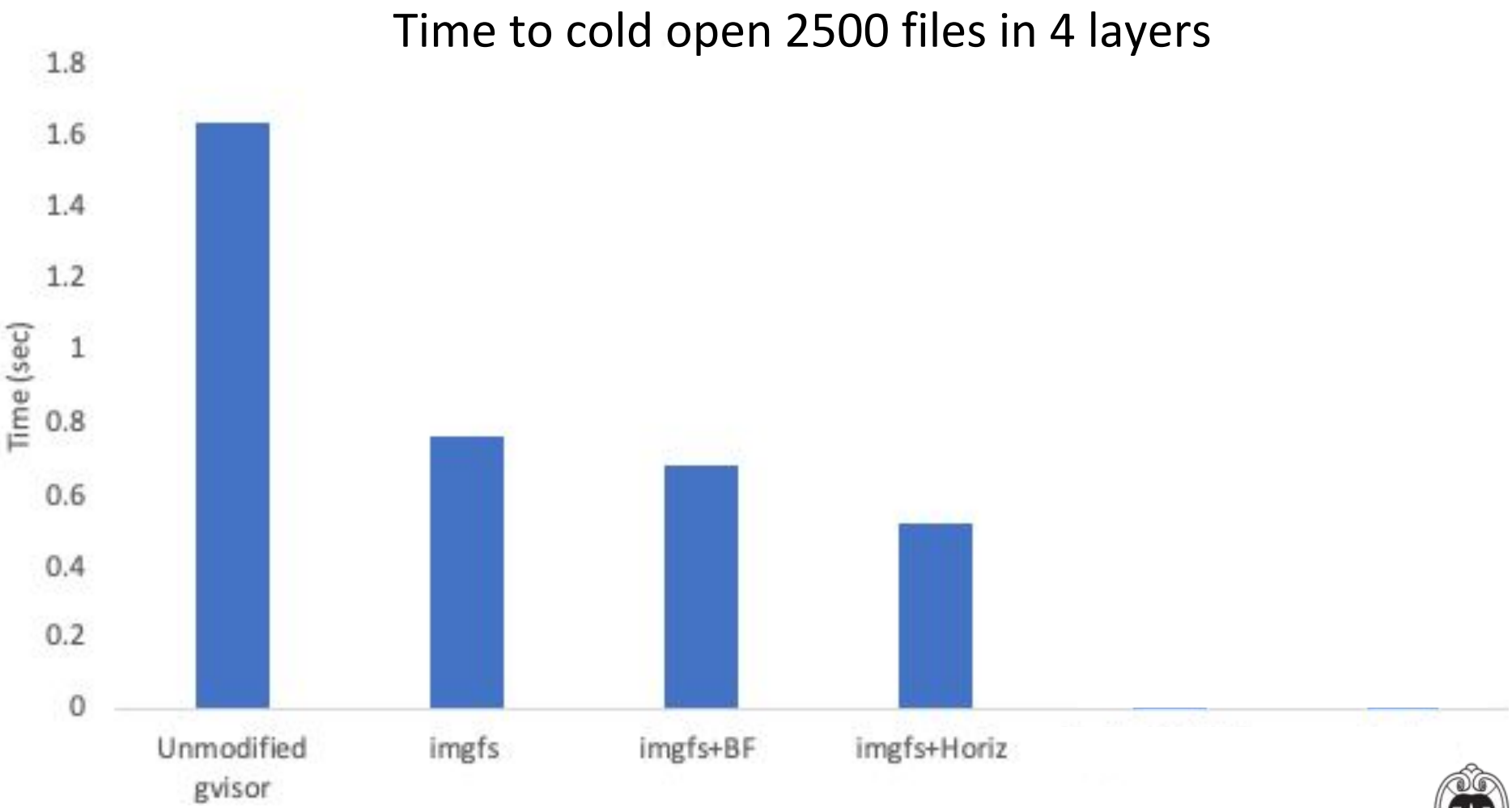
img4	5	14		
img3	6	15		
img2	7	16		
img1	8	17		
img0	9	18		

With Horiz

Layer	/	dir1	dir2	file.txt
img8	1	2	**3**	Used
img7				
img6				
img5				
img4				
img3				
img2				
img1				
img0				

Horizontal Traversal increases ContainerFS' cold open performance, but costly to check upper layers still



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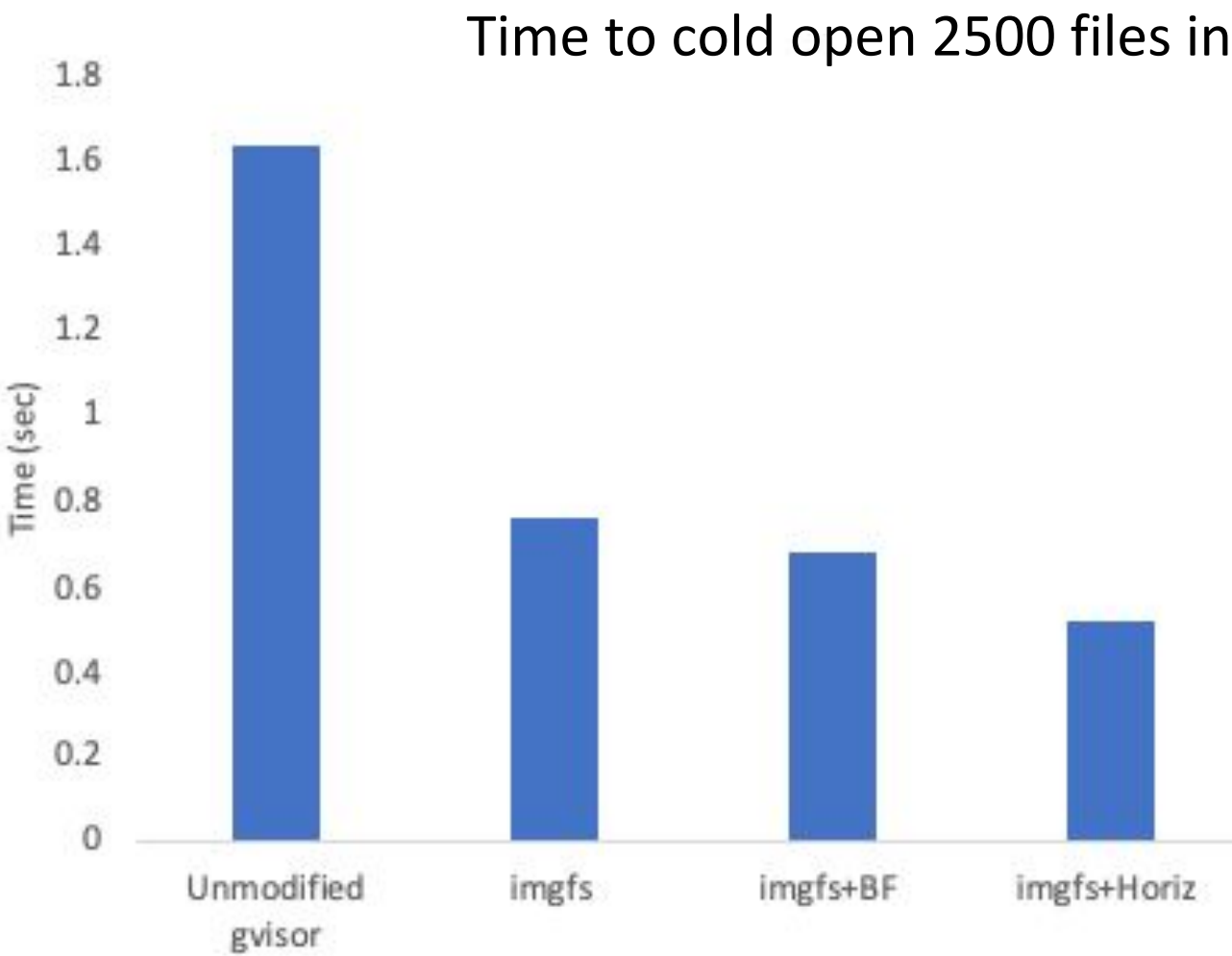
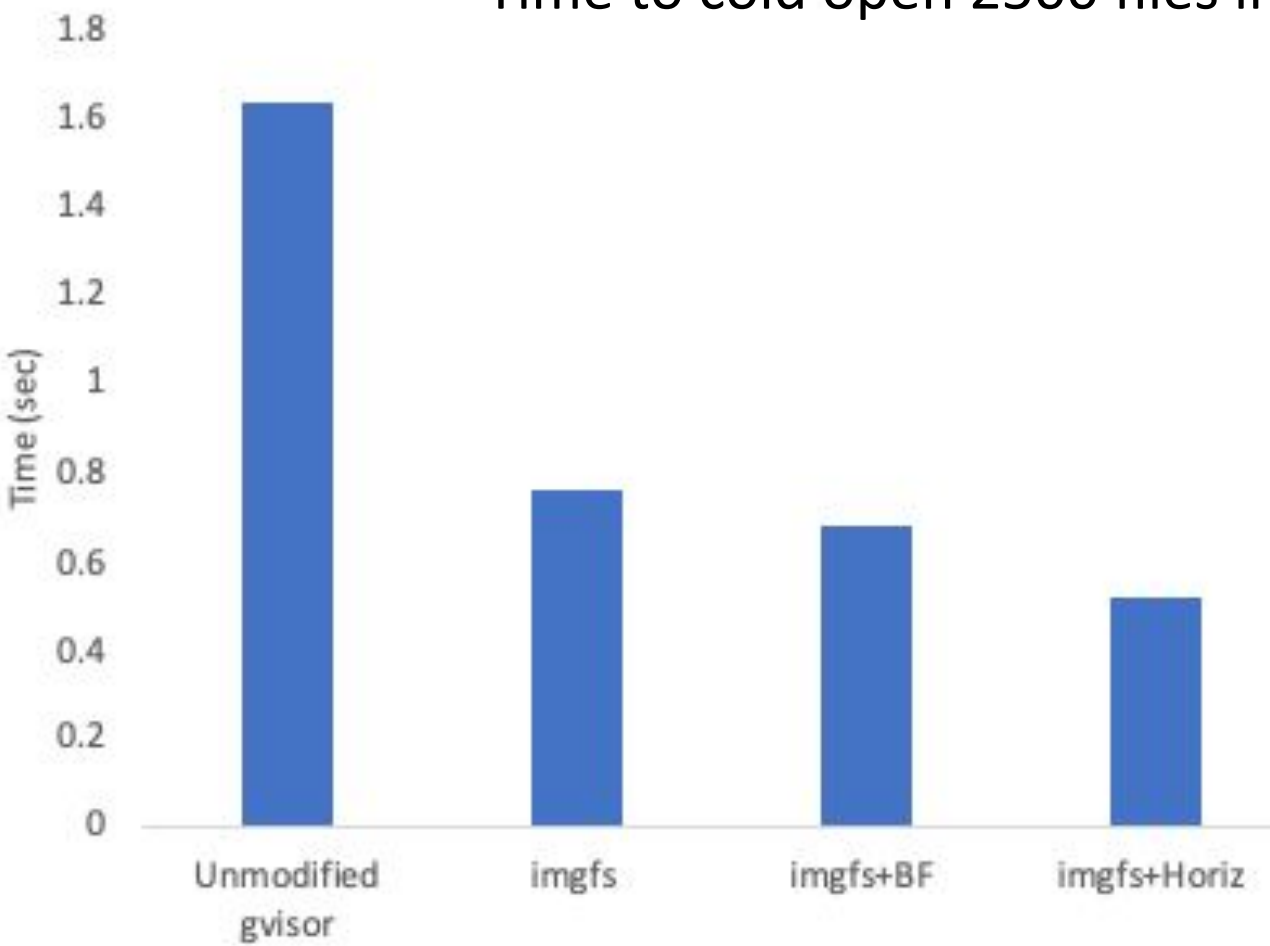


Layer	/	dir1	dir2	file.txt
img8	1	5	9	
img7	2	6	10	
img6	3	7	11	
img5	4	8	**12**	Used
img4				
img3				
img2				
img1				
img0				

Horizontal Traversal increases ContainerFS' cold open performance, but costly to check upper layers still

Time to cold open 2500 files in 4 layers



Layer	/	dir1	dir2	file.txt
img8	1	5	9	
img7	2	6	10	
img6	3	7	11	
img5	4	8	**12**	Used
img4				
img3				
img2				
img1				
img0				

Combining Horizontal Traversal and a Bloom Filter per layer eliminates lookups at high and low layers

Without Either

Layer	/	dir1	dir2	file.txt
img8	1	10	19	
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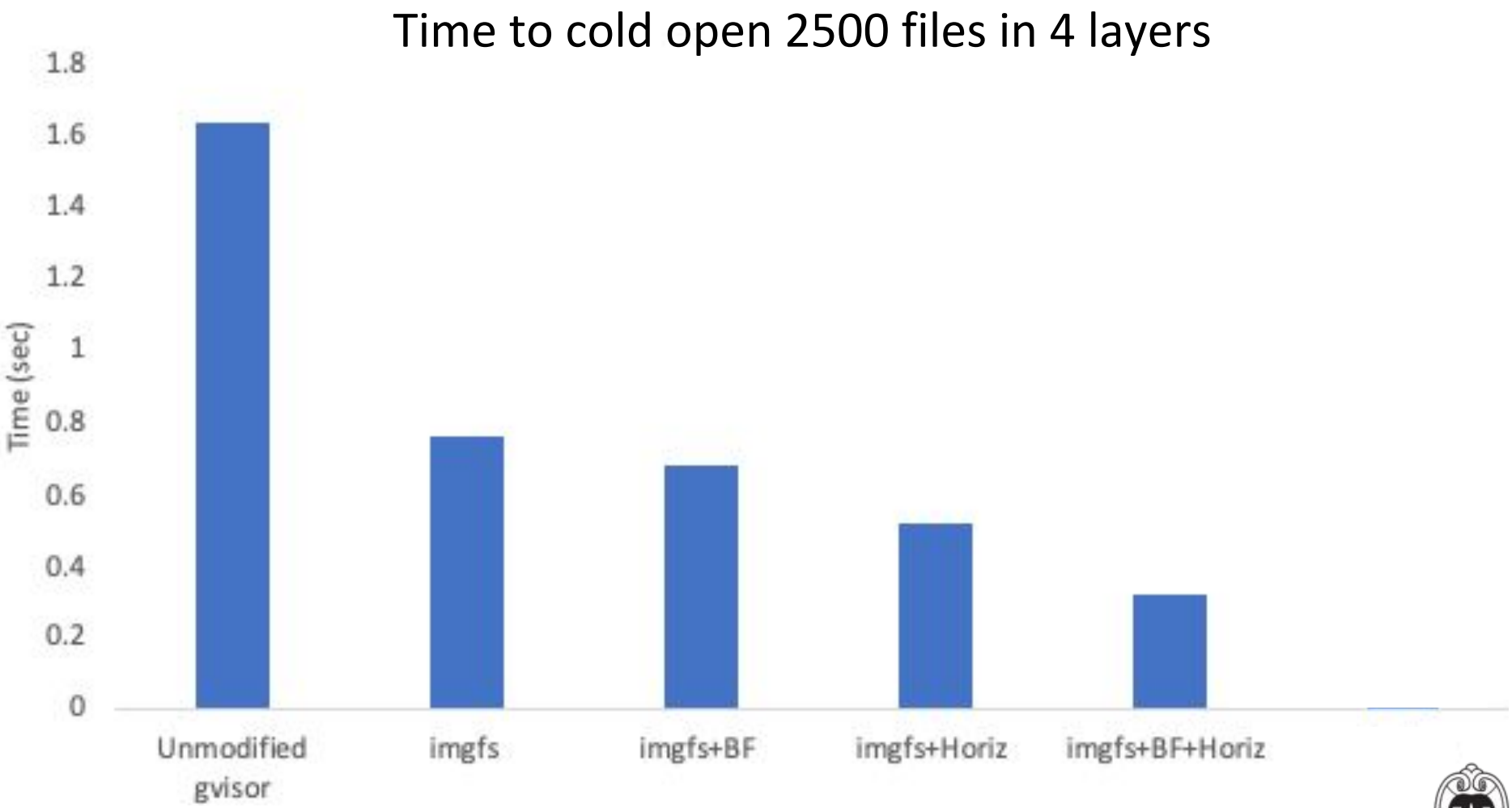
img1	8	17		
img0	9	18		

With Both

Layer	BF	/	dir1	dir2	file.txt
img8	1				
img7	2				
img6	3				
img5	4				
img4	5	6	7	**8**	Used
img3					
img2					
img1					
img0					

Combining Horizontal Traversal and a Bloom Filter per layer significantly increases performance



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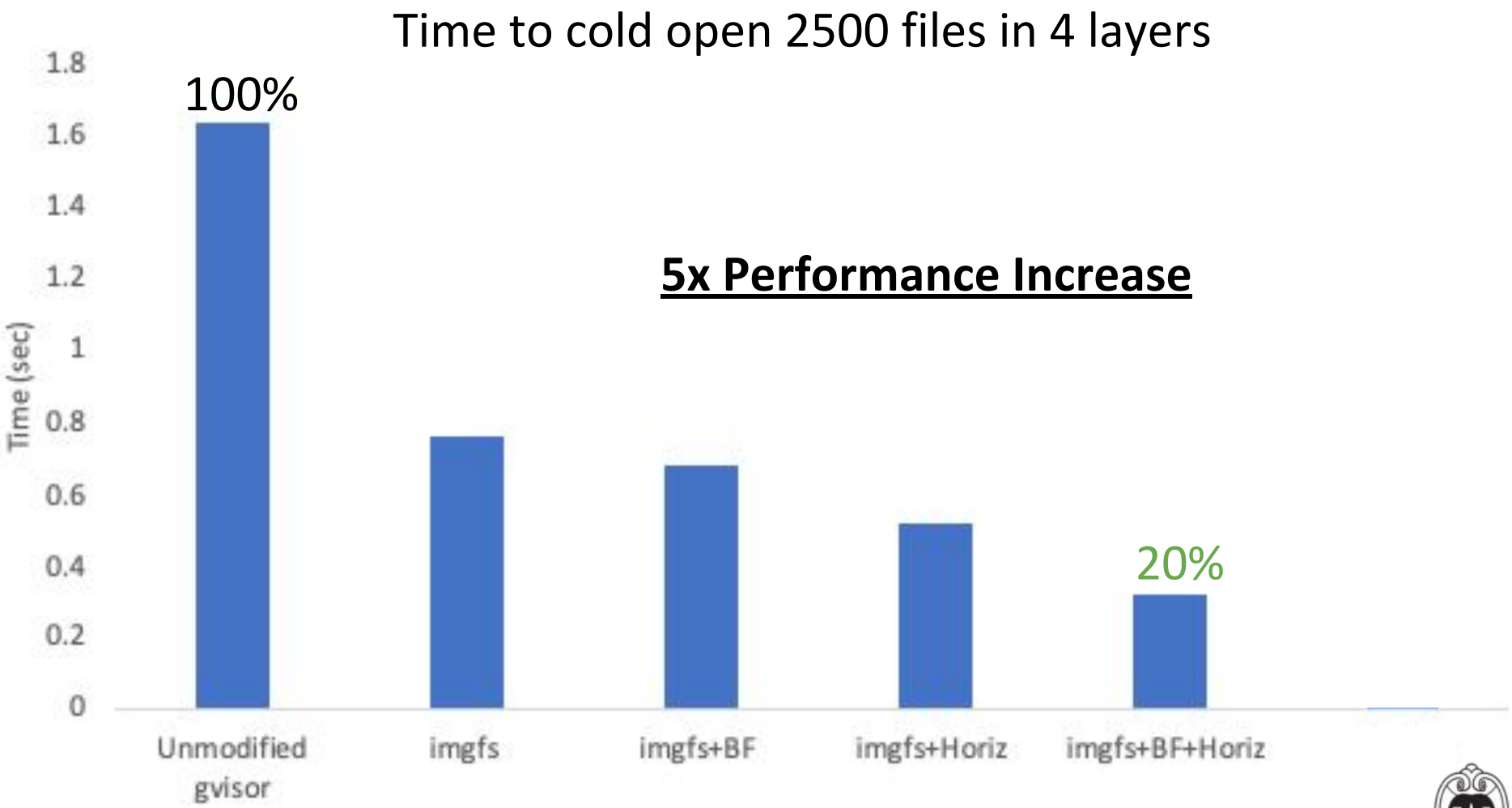

Related work includes Docker's build time merge algorithm and gVisor's future releases

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gVisor

gVisor will release a new VFS that delegates path resolution to the underlying FS

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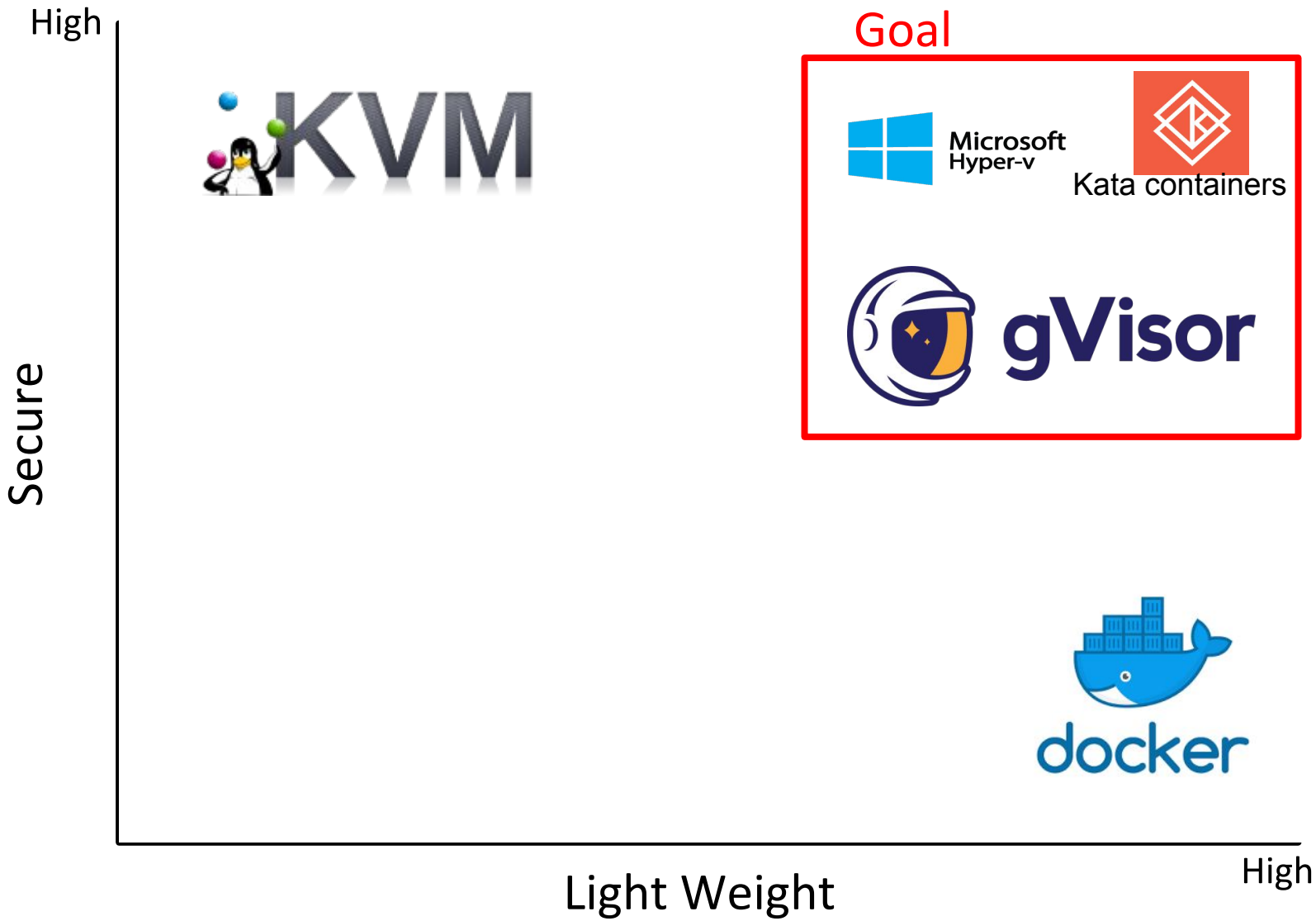
gVisor will release a new VFS that delegates path resolution to the underlying FS

gVisor is releasing a ext{2,3,4} image reader for the Sentry

Docker recursively merges image layers into one overlay at build time

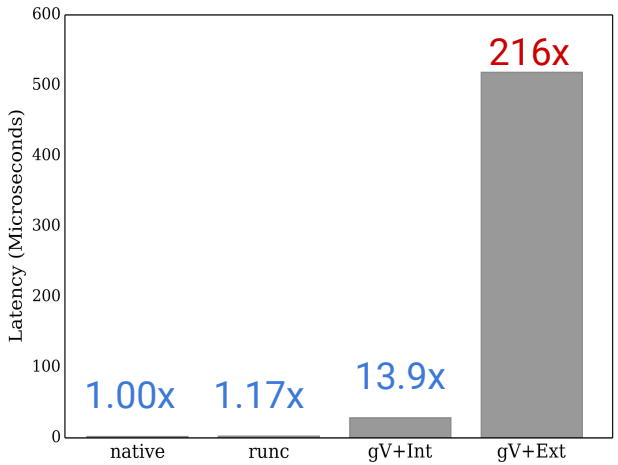
In summary, ContainerFS mitigates cold open file system latencies for gVisor



In summary, ContainerFS mitigates cold open file system latencies for gVisor

High

Secure



gVisor has high latency when operations utilize the gofer

Goal

Microsoft Hyper-v

Kata containers

gVisor

docker

High

Light Weight

In summary, ContainerFS mitigates cold open file system latencies for gVisor

High

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Microsoft Hyper-v

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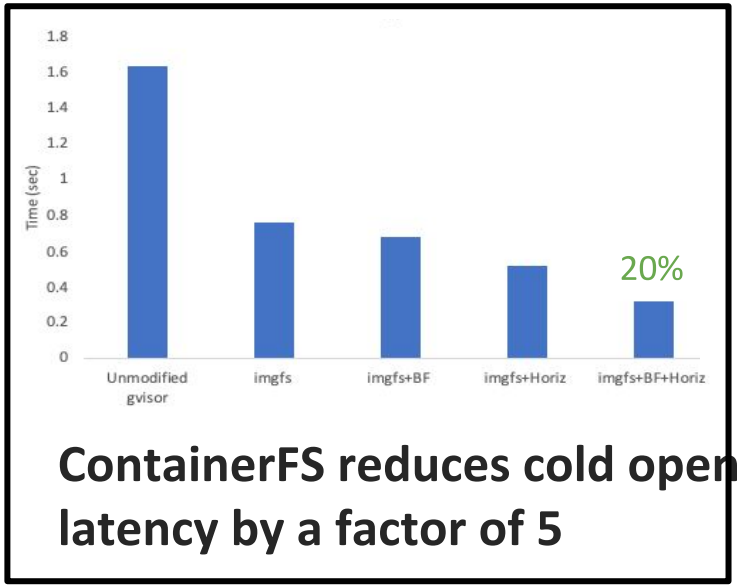

ContainerFS reduces cold open latency by a factor of 5

docker

Light Weight

High

In summary, ContainerFS mitigates cold open file system latencies for gVisor

High

Secure

Goal

Microsoft Hyper-v

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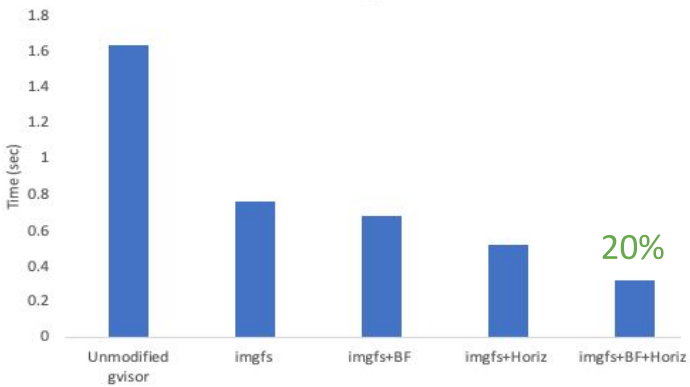
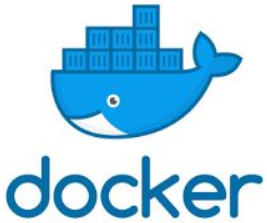


ContainerFS reduces cold open latency by a factor of 5

Questions?

Email:
eyoung8@wisc.edu



Light Weight

High