High-Performance Processing of Large Data Sets via Memory Mapping A Case Study in R and C++

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Motivation

Working with large data sets in R is restricted by virtual memory and the virtual address space.

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```

R on Windows XP, 2 GB RAM (Parallels VM)

```
> numeric(1024^3*2/8)
Error: cannot allocate vector of size 2.0 Gb
Reached total allocation of 1535Mb..
> memory.limit()
[1] 1535.36
```

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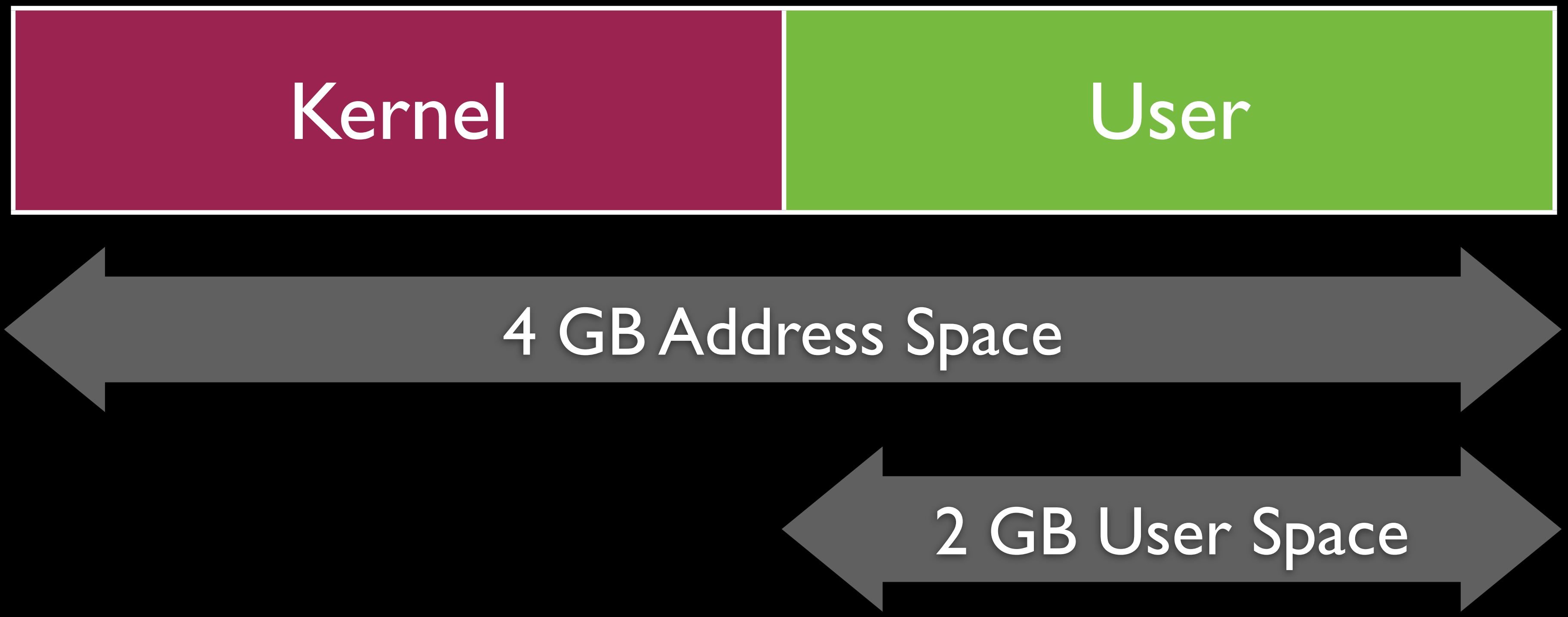
R on 32-Bit Windows



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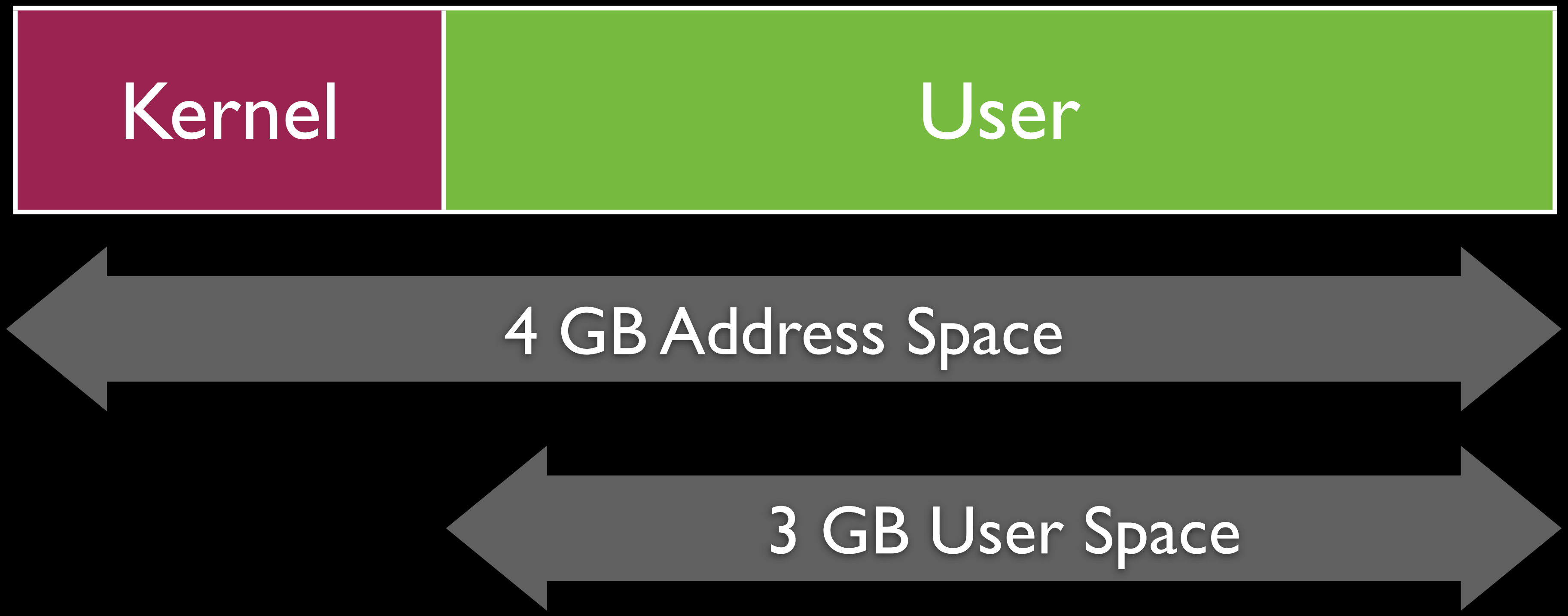
(tweaked with "/3GB")



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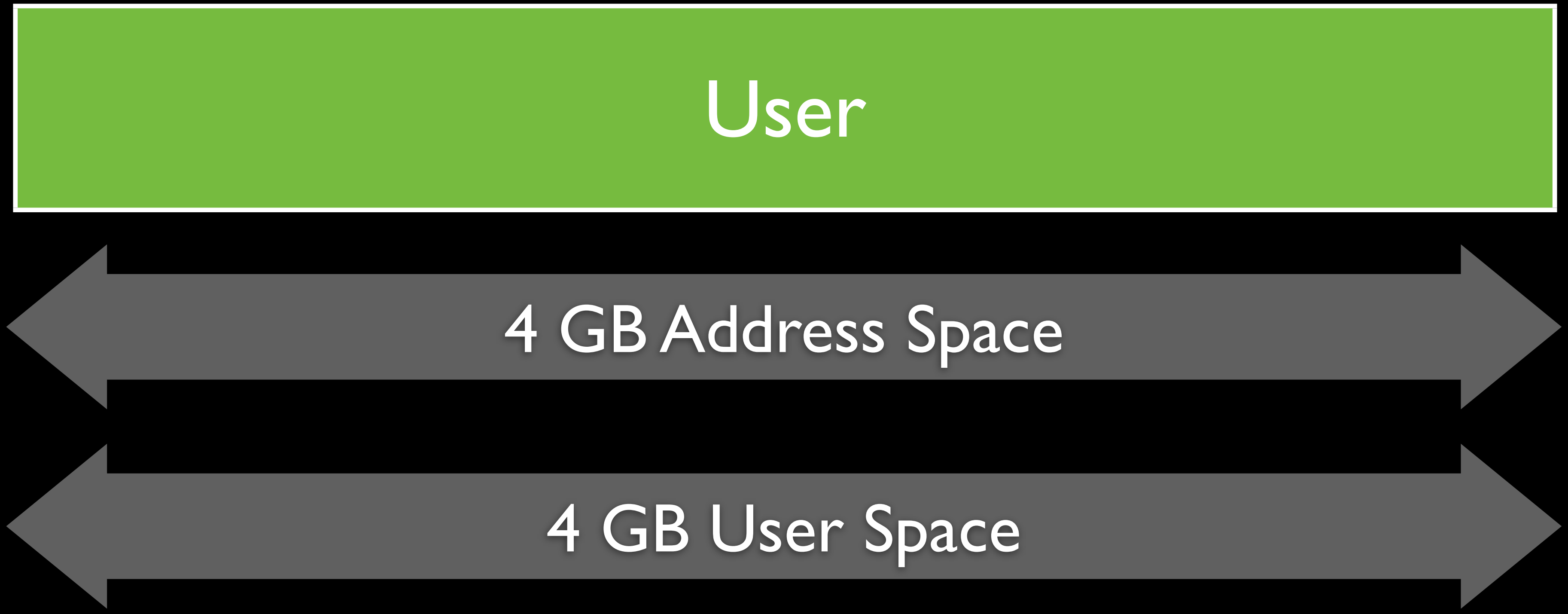
R on 64-Bit Windows



User

4 GB Address Space

4 GB User Space

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Goal

Enabling work with large data sets on desktop PCs.

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Idea

Data resides on disk storage. Parsimonious use of virtual address space via “paging”.

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Data resides on disk storage. Parsimonious use of virtual address space via “paging”.

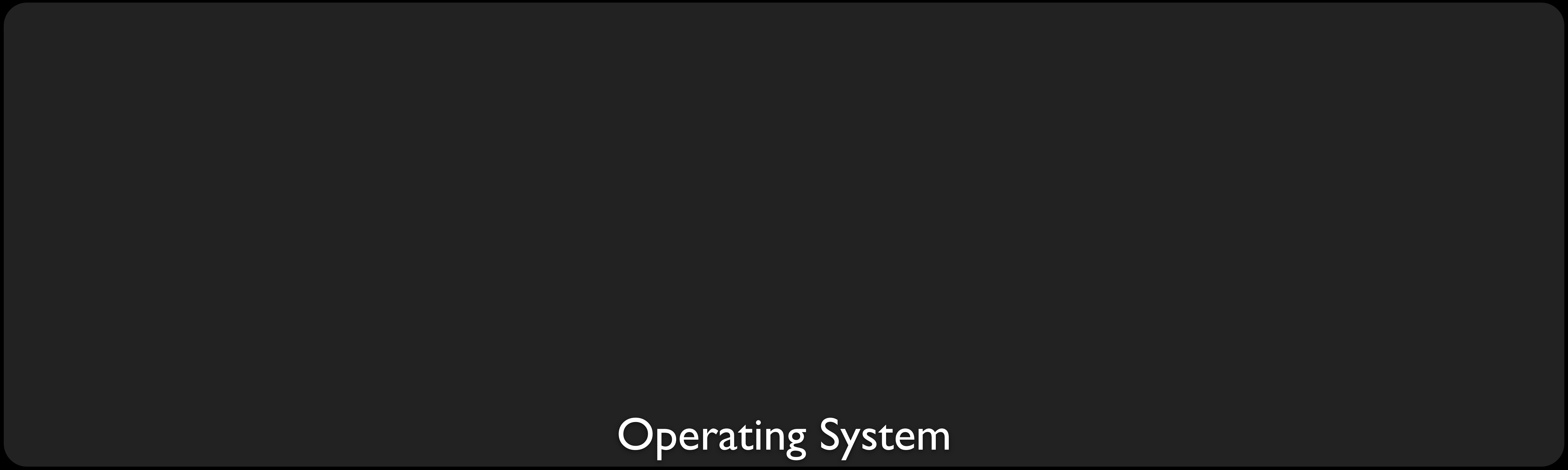
Efficiency problem

Disk I/O is slow (1 million times slower than RAM).

Overview

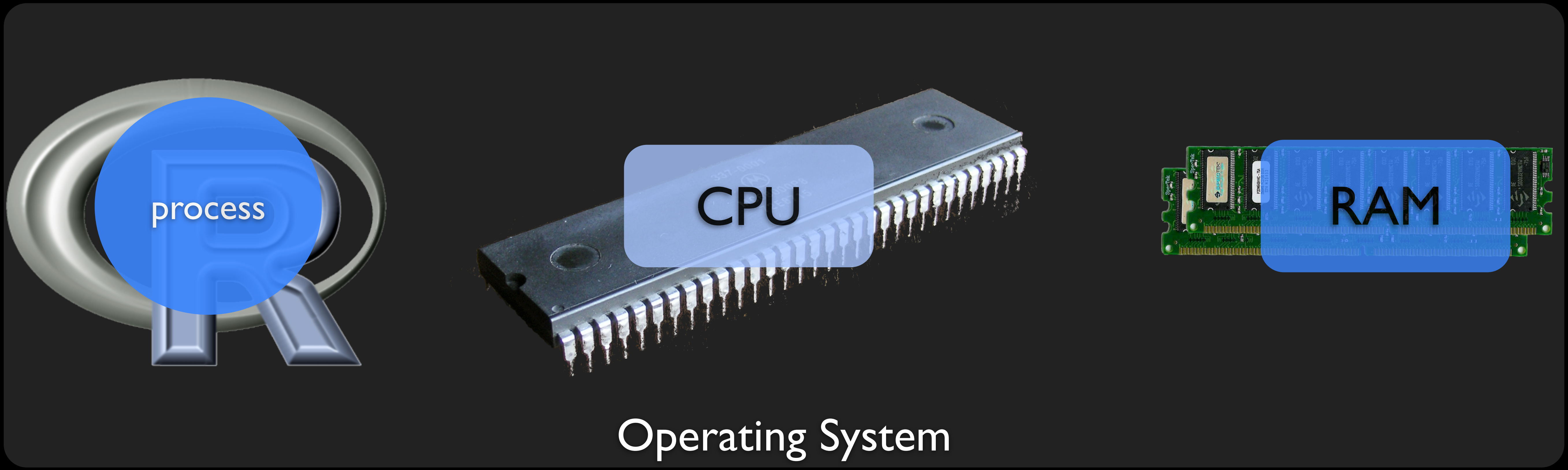
- 'ff' low-level C++ Library (Daniel)
  Virtual Memory & Memory-Mapping,
  Flat Files & Paging
- 'ff' high-level R Package (Jens)
  Virtual Atomic Objects, Batch processing,
  Data types, Hybrid Indexing
- Performance
  Page size & System cache, Enhancements
- Epilog
  Possible Improvements & Conclusion

Virtual Memory and Memory-Mapping



Operating System

Virtual Memory and Memory-Mapping



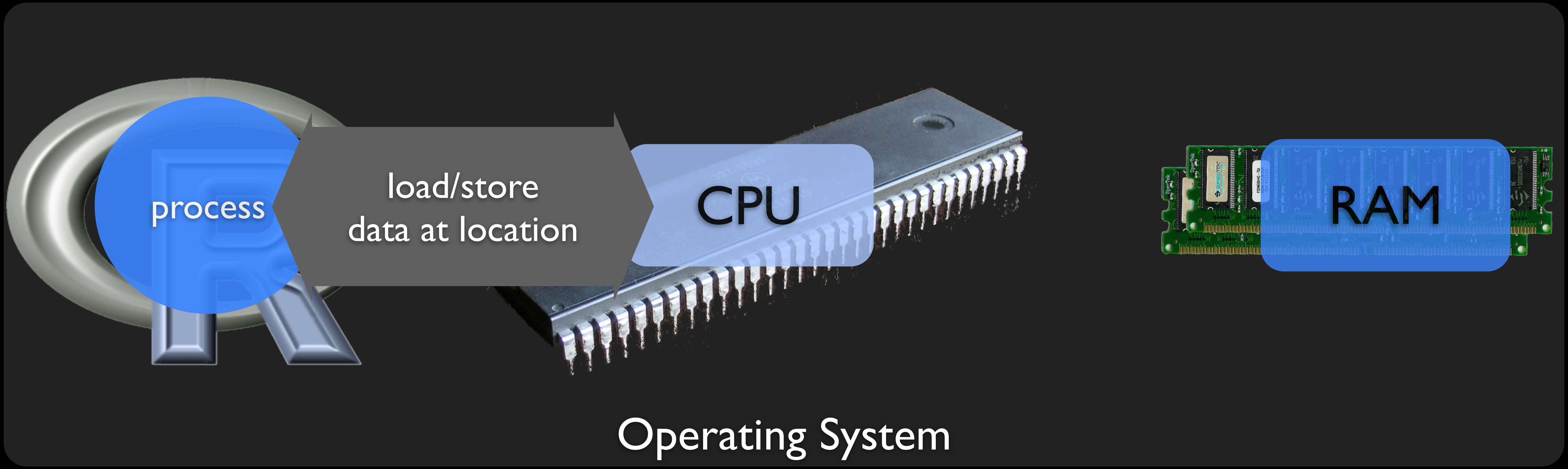
process

CPU

RAM

Operating System

Virtual Memory and Memory-Mapping



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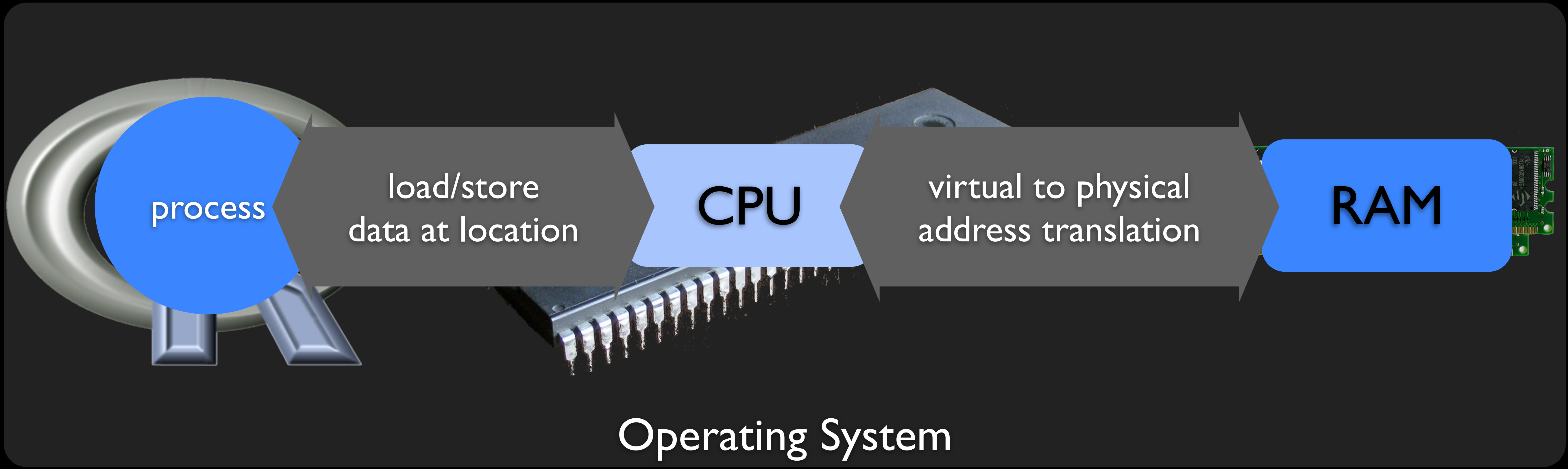

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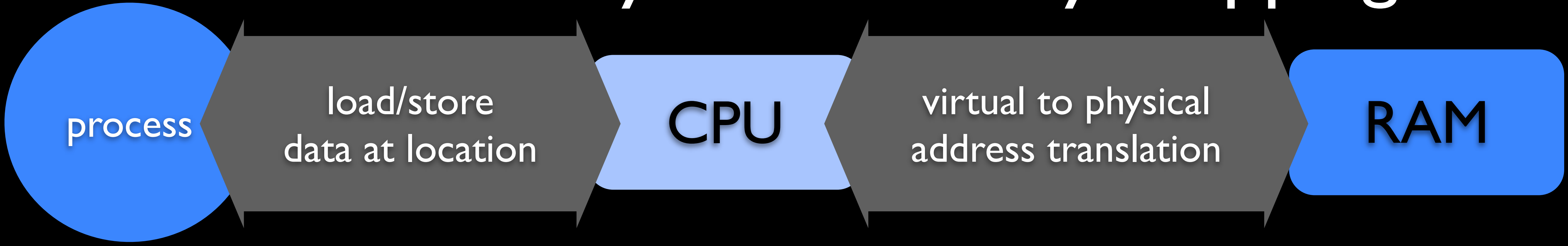

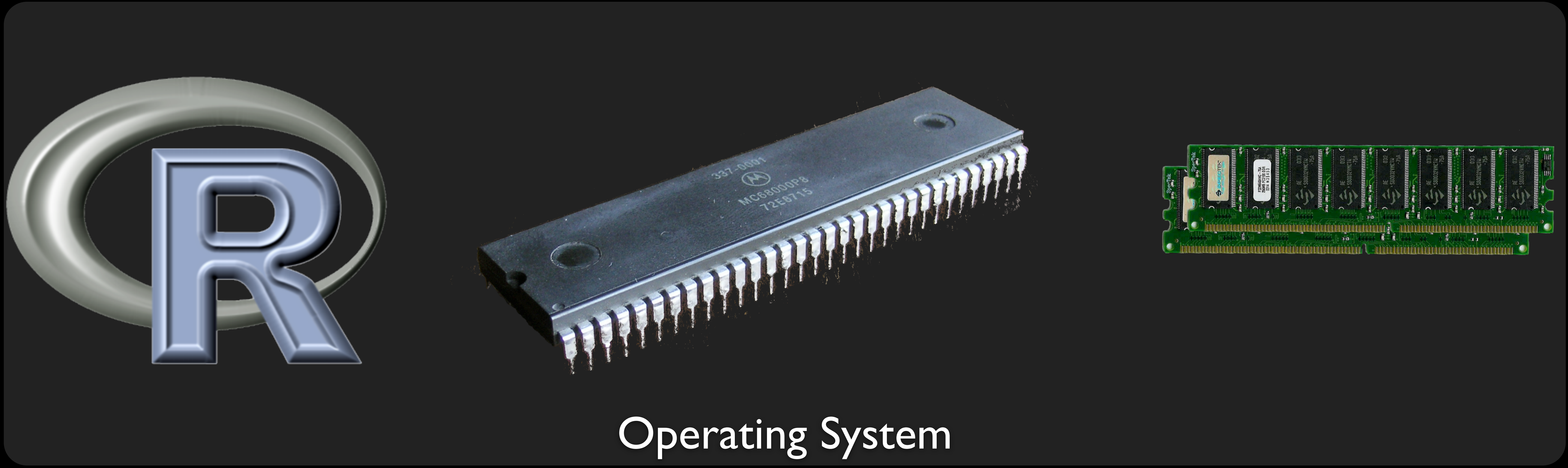

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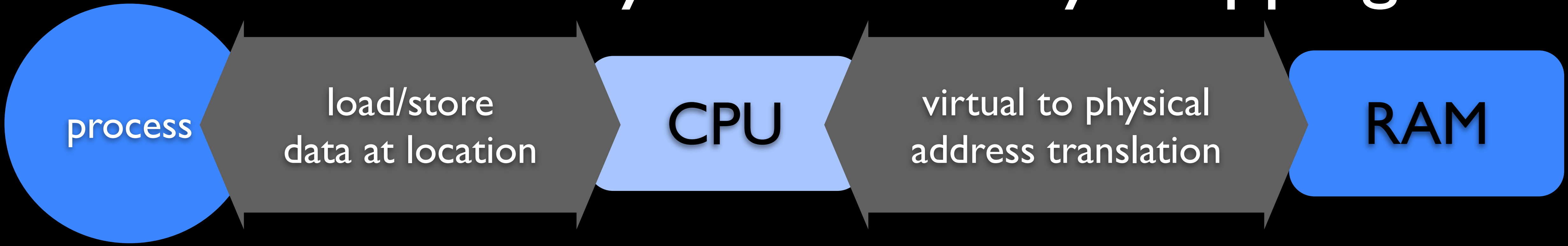


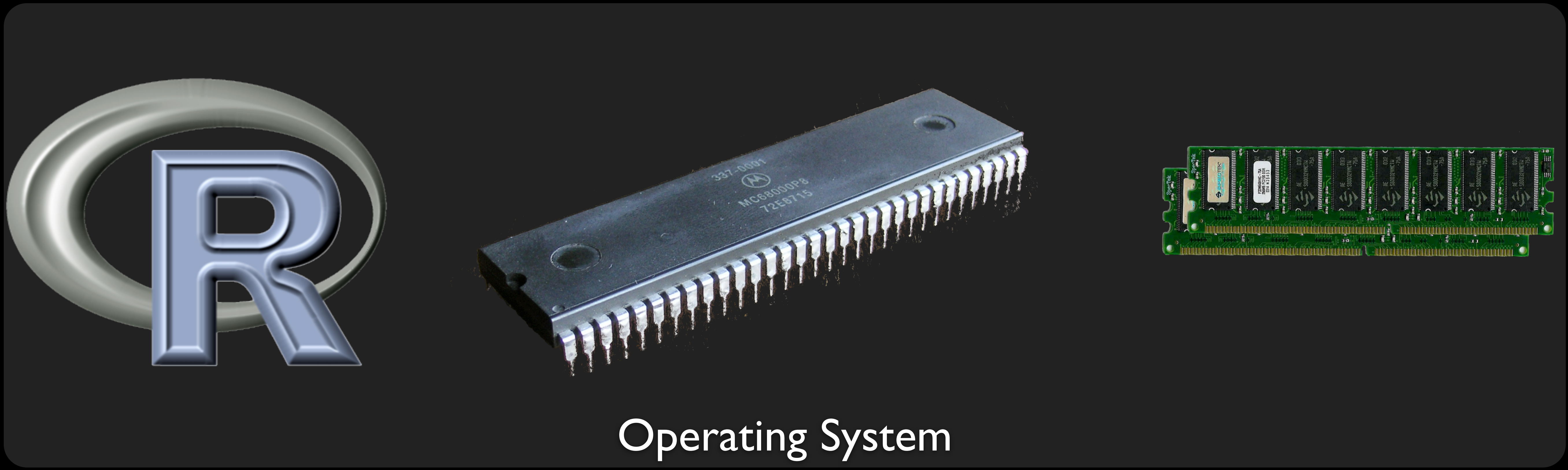
process

load/store data at location

CPU

virtual to physical address translation

RAM



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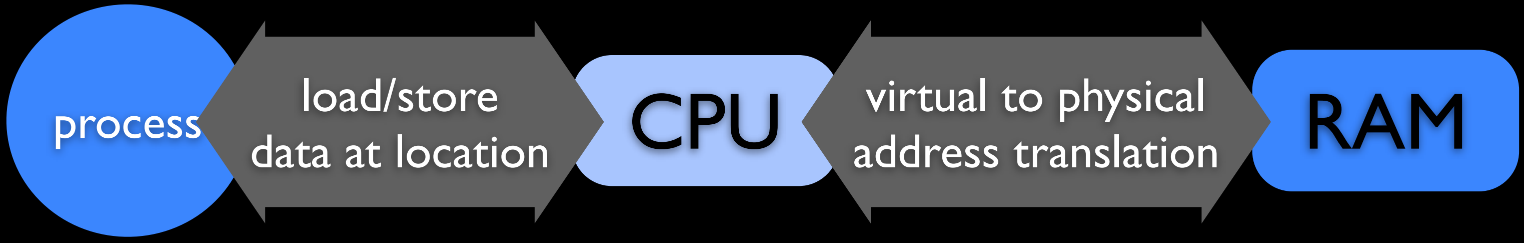

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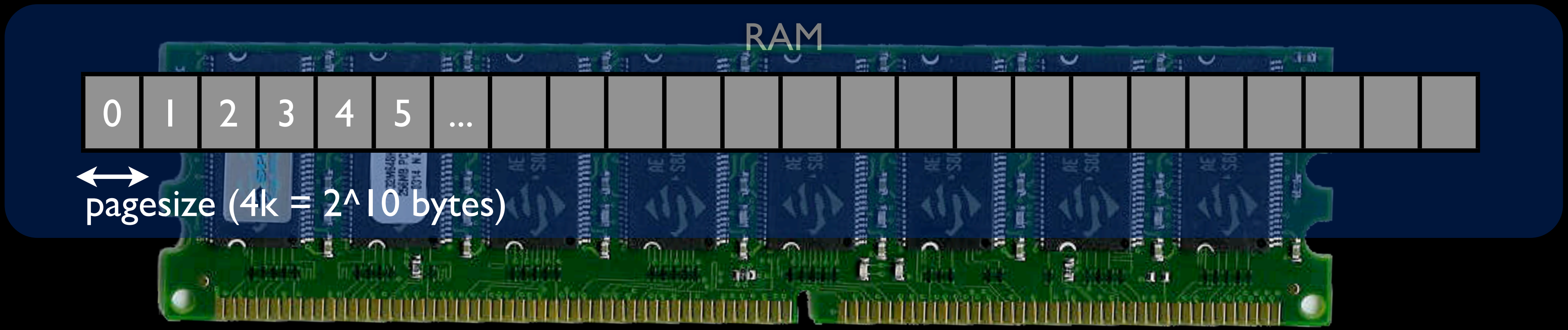
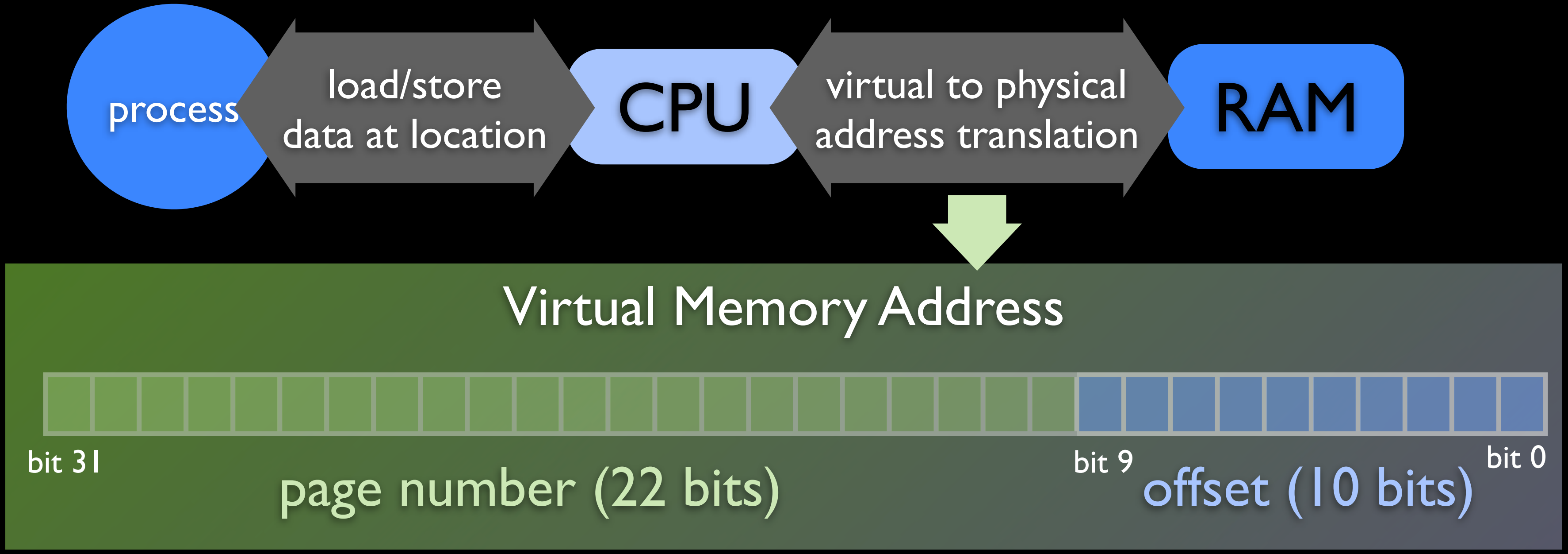


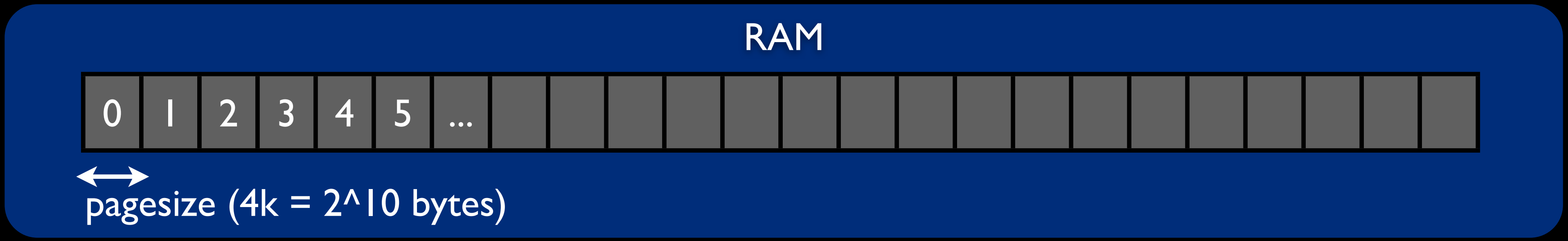
RAM

0 | 1 | 2 | 3 | 4 | 5 | ...

pagesize (4k = 2^10 bytes)

Virtual Memory and Memory-Mapping





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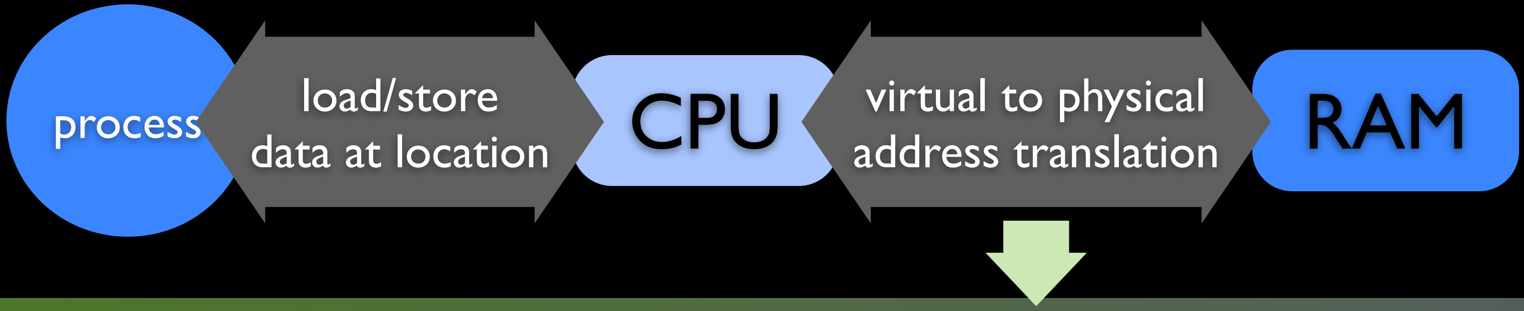

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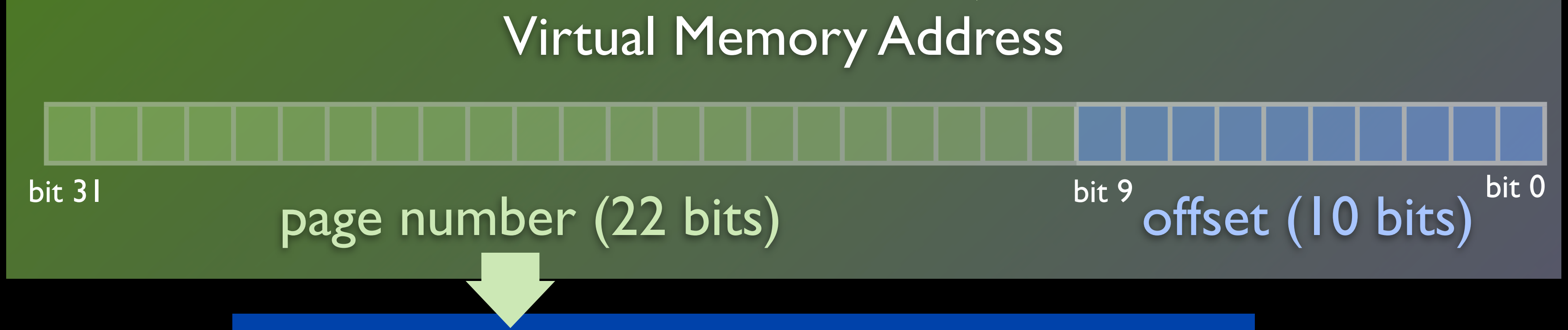


Virtual Memory Address

bit 31

bit 9

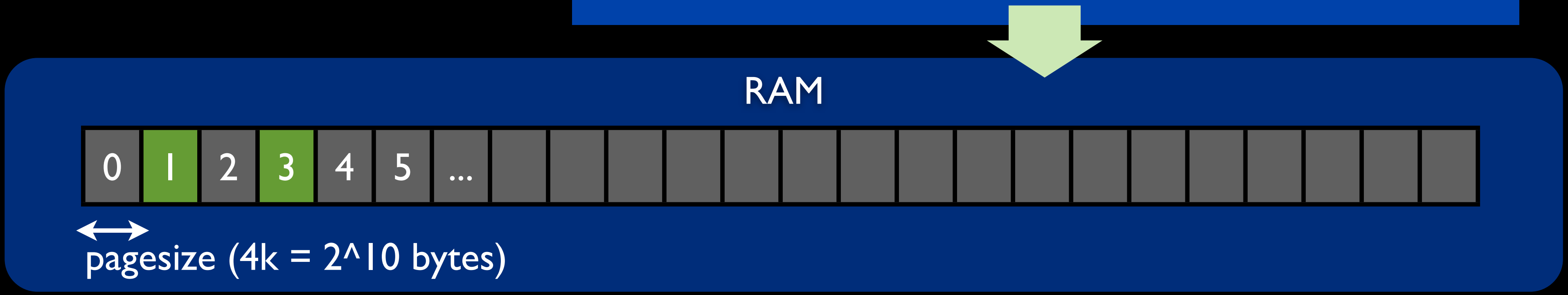
bit 0

page number (22 bits)

offset (10 bits)

Process Page Table, e.g

Page	Physical location
200	RAM page 3
201	RAM page 1
202	N/A



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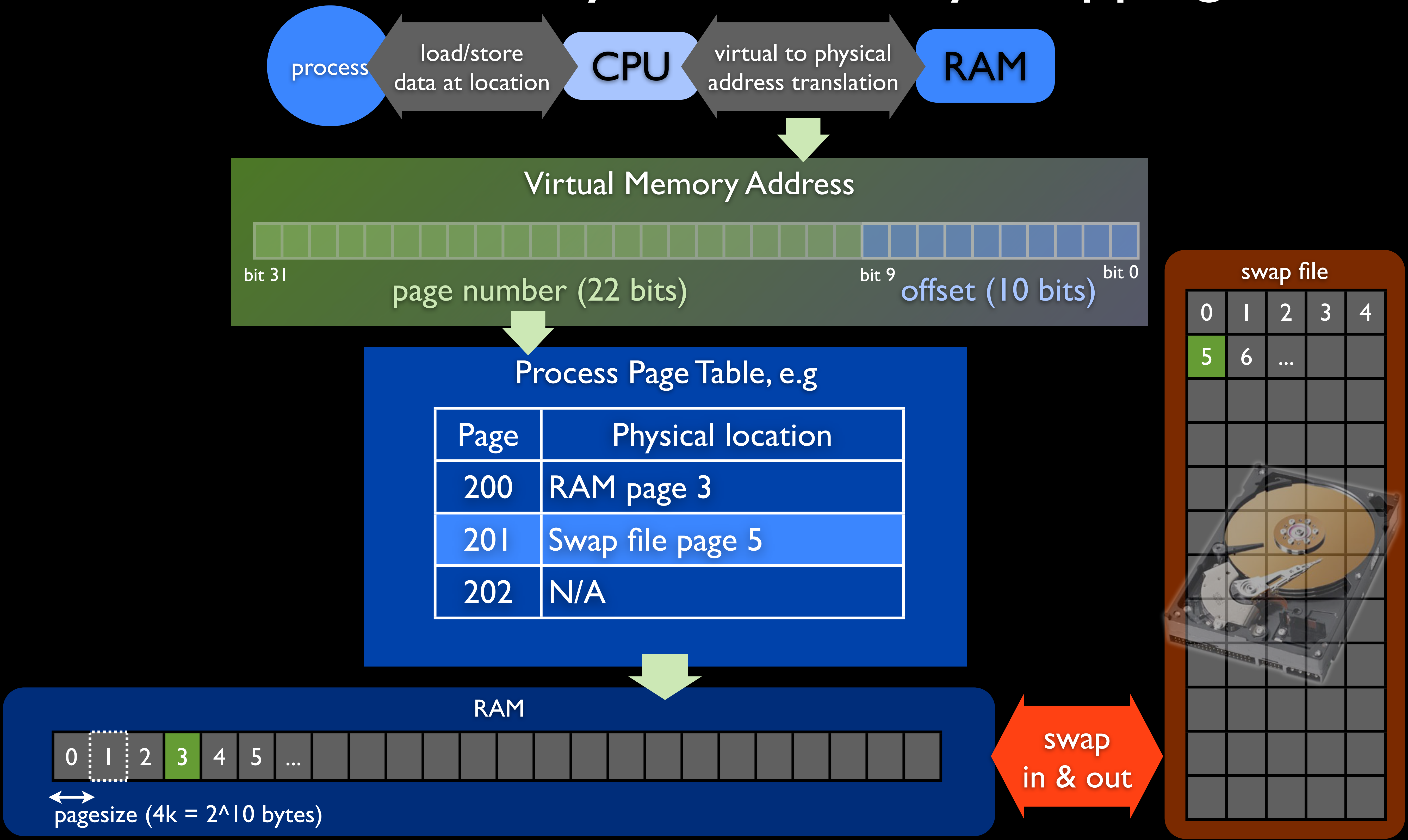

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bit 31

page number (22 bits)

bit 9

offset (10 bits)

bit 0

Process Page Table, e.g

Page	Physical location
200	RAM page 3
201	Swap file page 5
202	N/A

RAM

0 1 2 3 4 5 ...

pagesize (4k = 2^10 bytes)

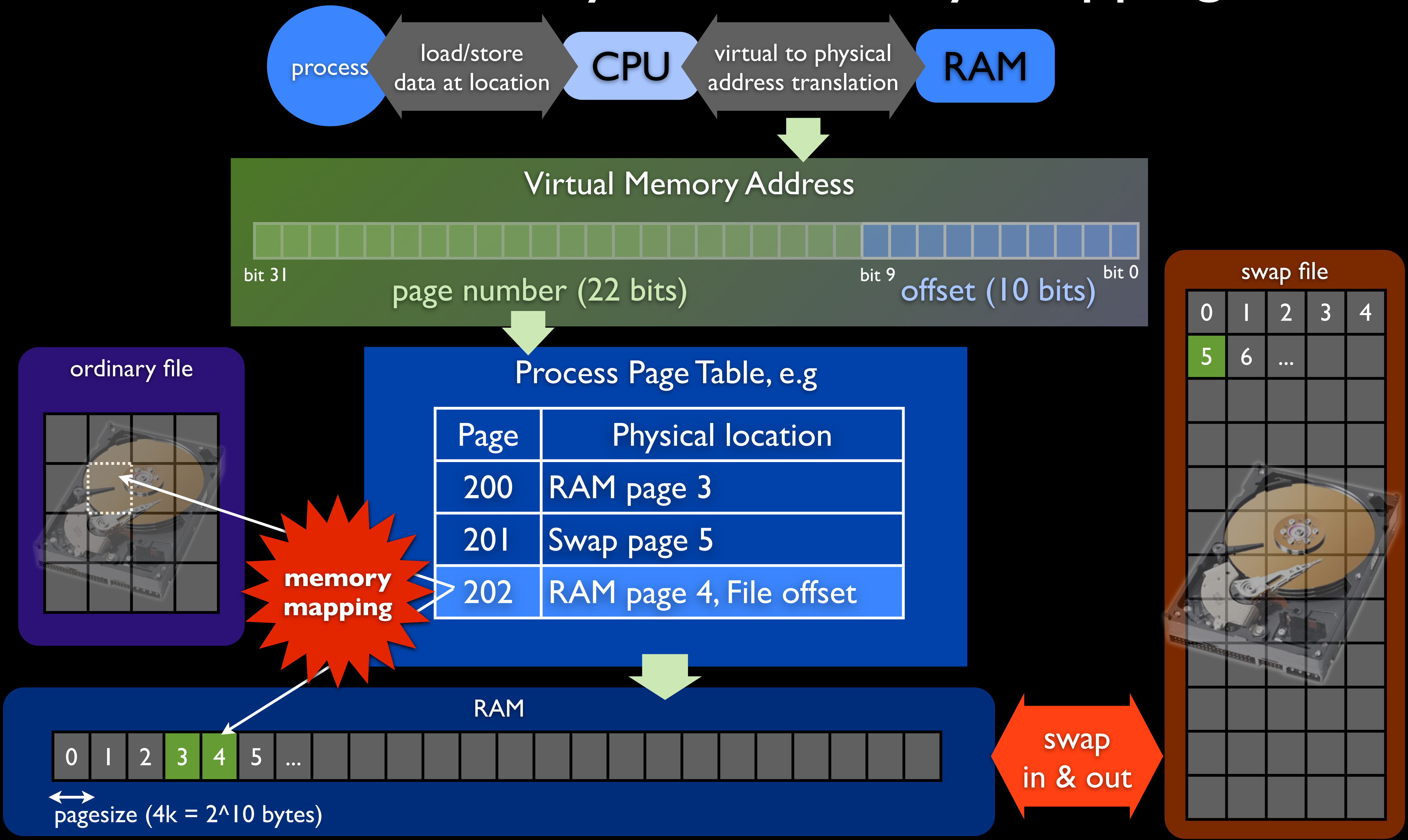
swap in & out

swap file

0 1 2 3 4

5 6 ...

Virtual Memory and Memory-Mapping



Page	Physical location
200	RAM page 3
201	Swap page 5
202	RAM page 4, File offset

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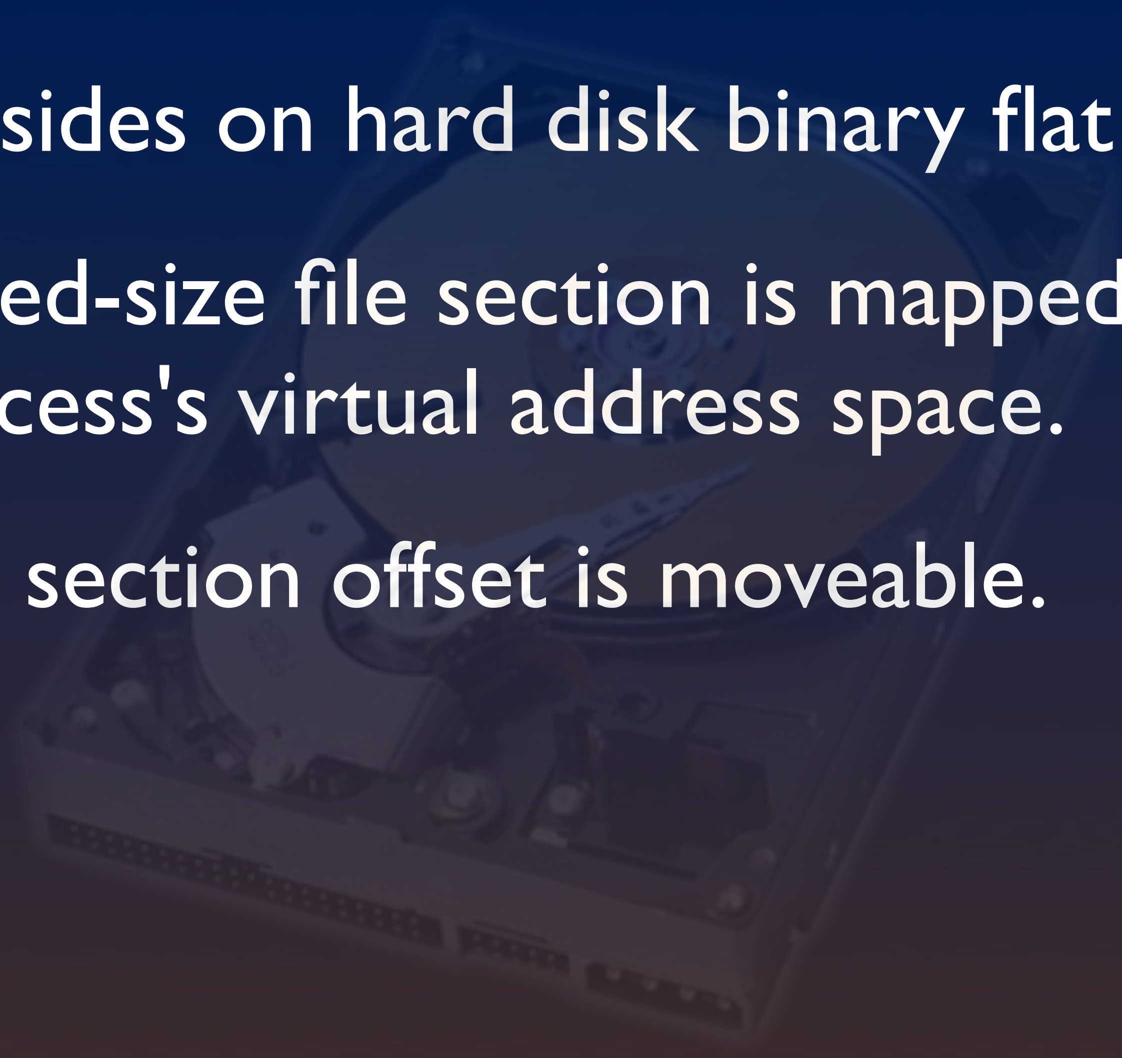

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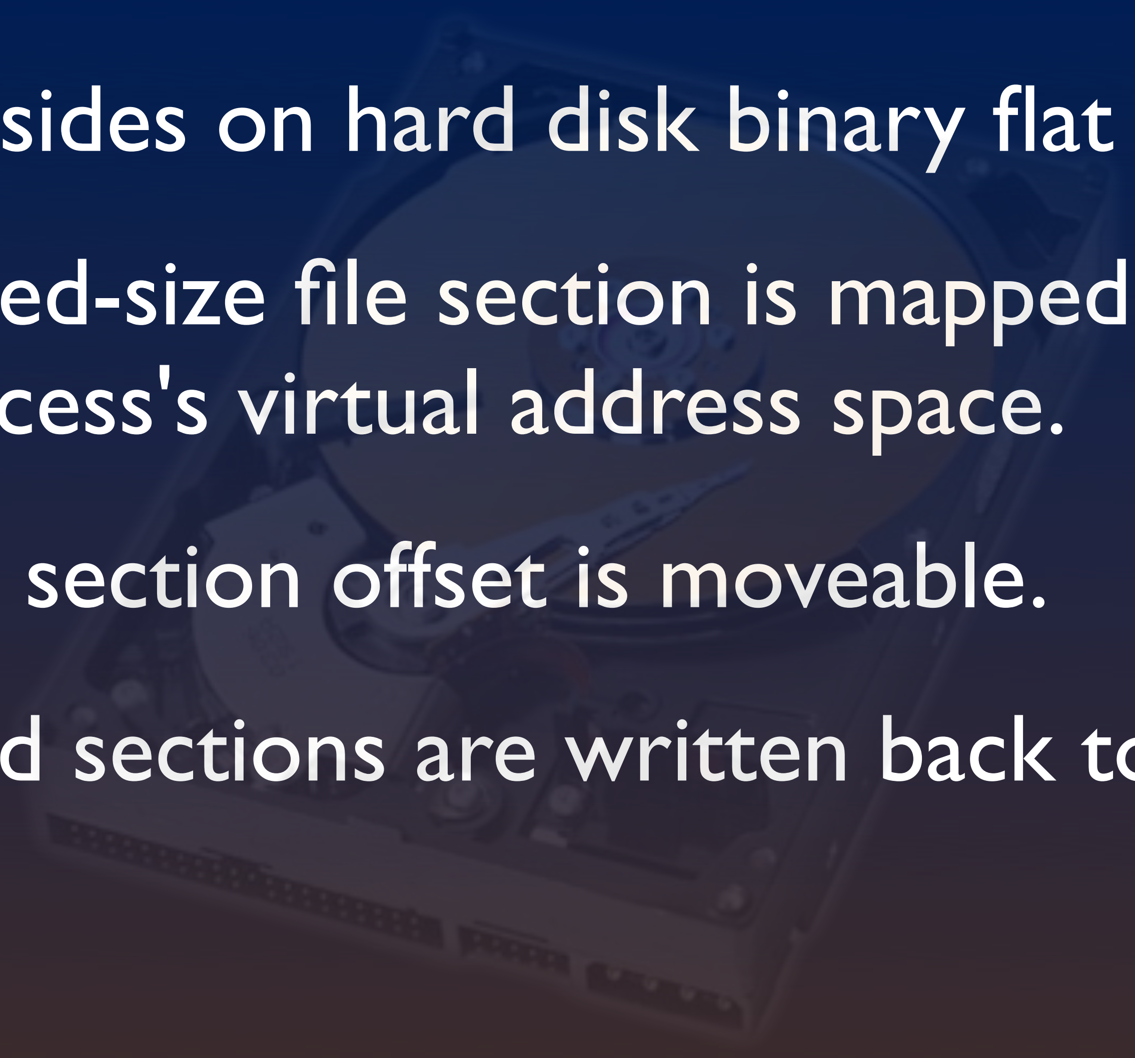

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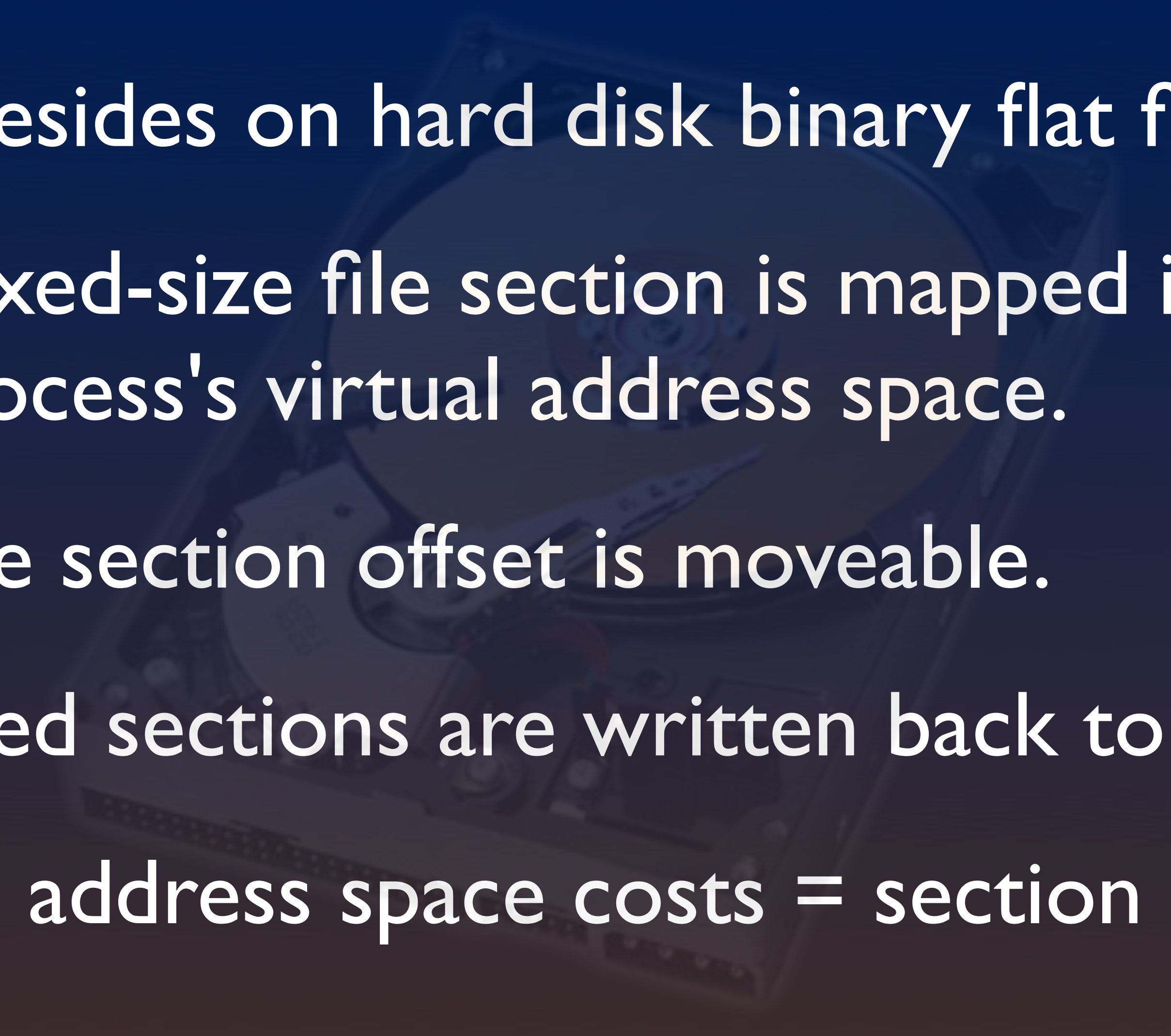

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- One fixed-size file section is mapped into the process's virtual address space.
- The file section offset is moveable.
- Modified sections are written back to disk.
- Virtual address space costs = section size.

Virtual atomic R objects

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Creating vectors, matrices, arrays and factors.

```
> vec <- ff(vmode=”double”,length=100000000)
> mat <- ff(vmode=”double”,dim=c(5000,6000))
> arr <- ff(vmode=”integer”,dim=c(10,200,300))
> fac <- ff(vmode="integer",levels=c('A','B'),length=10e6))
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Standard subsetting in R

```
> vec[1:1000] <- rnorm(1000)
> sum(mat[c(1,3,4),])
> arr[5:1,100,150]
> fac[] <- 'B'
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> arr[5:1,100,150]
> fac[] <- 'B'
```

Batch processing

```
> s <- 0
> ffvecapply( s <<- s + sum(vec[i1:i2]), X=vec )
> mymean <- s/length(vec)
```

data types and packing

data types and packing

vmode	size	R mode	NA handling	range
boolean	1 bit	logical		TRUE,FALSE
logical	2 bit	logical	NA	TRUE,FALSE
quad	2 bit	integer		0:3
nibble	4 bit	integer		0:15
byte	8 bit	integer	NA	-127:+127
ubyte	8 bit	integer		0:255
short	16 bit	integer	NA	-32767:+32767
ushort	16 bit	integer		0:65535
integer	32 bit	integer	NA	-(2^31-1):+(2^31-1)
single	32 bit	double	NA	C float
double	64 bit	double	NA	C double
raw	8 bit	raw		0:255

Hybrid Indexing

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index expressions are packed (if possible) before evaluated. Saves space!

```
> vec[1:(length(vec)/2)] <- 1
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otherwise...

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> 1:(length(vec)/2)
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```
> vec[1:(length(vec)/2)] <- 1
```

from	to	by
1	length(vec)/2	1

otherwise...

```
> 1:(length(vec)/2)
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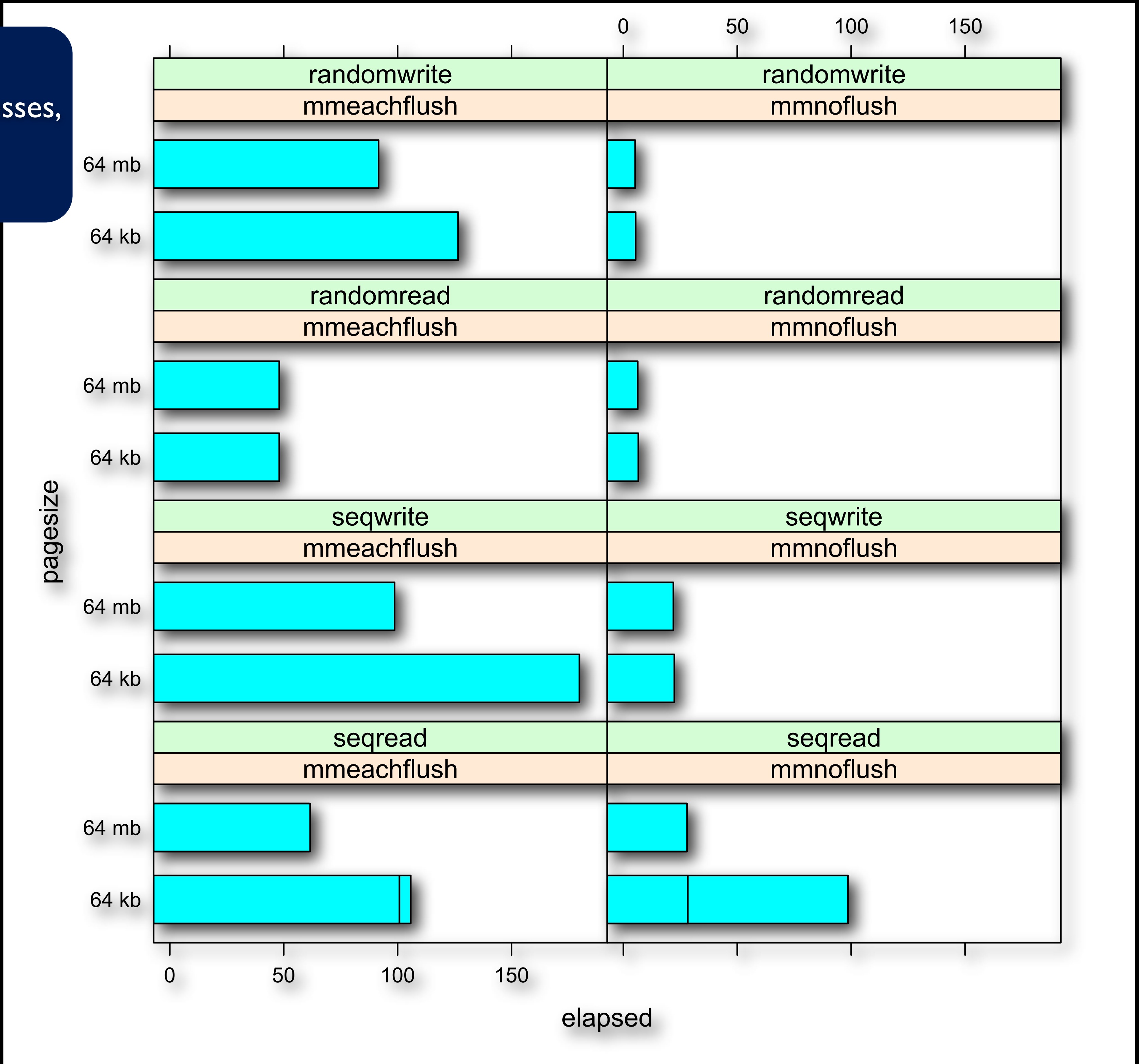
```

Page size and system cache

2 GB double ff vector,
10,000,000 random accesses,
Intel Mac OS X 10.5,
4 GB, 2.5 GhZ



Performance Enhancements

- Presorting indices in ascending order to minimize disk head movements.
- Fast creation of flat files.
- Using system cache to prevent Disk I/O.
- Increase page size to reduce pagings.
- Exploit parallelism; Flat files are shareable among multiple R processes.

Possible improvements

- Increase index resolution to 52 bits in R.
- Support for mixed-type data frames.
- On-demand presorting indices.
- Automatic adjustments of system cache usage and page size.
- Paging Garbage Collector?

Conclusion

- Memory-mapping in contrast to stream-based Disk I/O has advantage of exploiting system cache and - at the same time - allow to share pages among multiple processes.
- While system cache enabled will also consume physical memory it still does not consume more virtual address space.

Availability of the 'ff' package

- Version 2.0.0 on CRAN (since Monday)
  GPL-2, C++ Library ISCL (BSD style)
- Web resources:
  http://134.76.173.220/ff *
  http://www.truecluster.com/ff.htm

* contains version 1(64 bit internal indexing), slides, datasets