[544] Cache-Friendly Code

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Learning Objectives

- write cache-friendly code with Numpy and PyArrow
- use memory mappings via PyArrow to access data that is larger than physical memory
- enable swapping to alleviate memory pressure
- configure Docker memory limits on physical memory used

Outline

CPU: L1-L3

Demos: Numpy+PyArrow...

Background: Virtual Address Spaces

OS (Operating System): Page Cache

Demos: PyArrow+Docker

Granularity

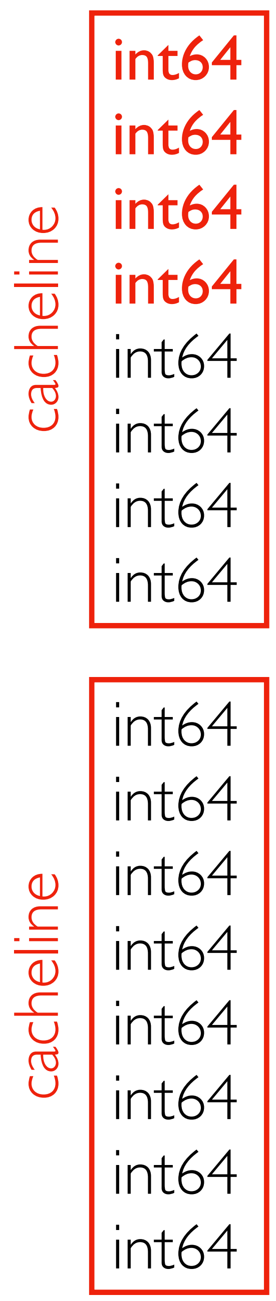
If a process reads 1 byte and misses, *how much data should the CPU bring into the cache?*

- **too little:** we'll have many more misses if we read nearby bytes soon
- **too much:** wasteful to load data to cache that might never be accessed

L1-L3 cache data in units called **cache lines**

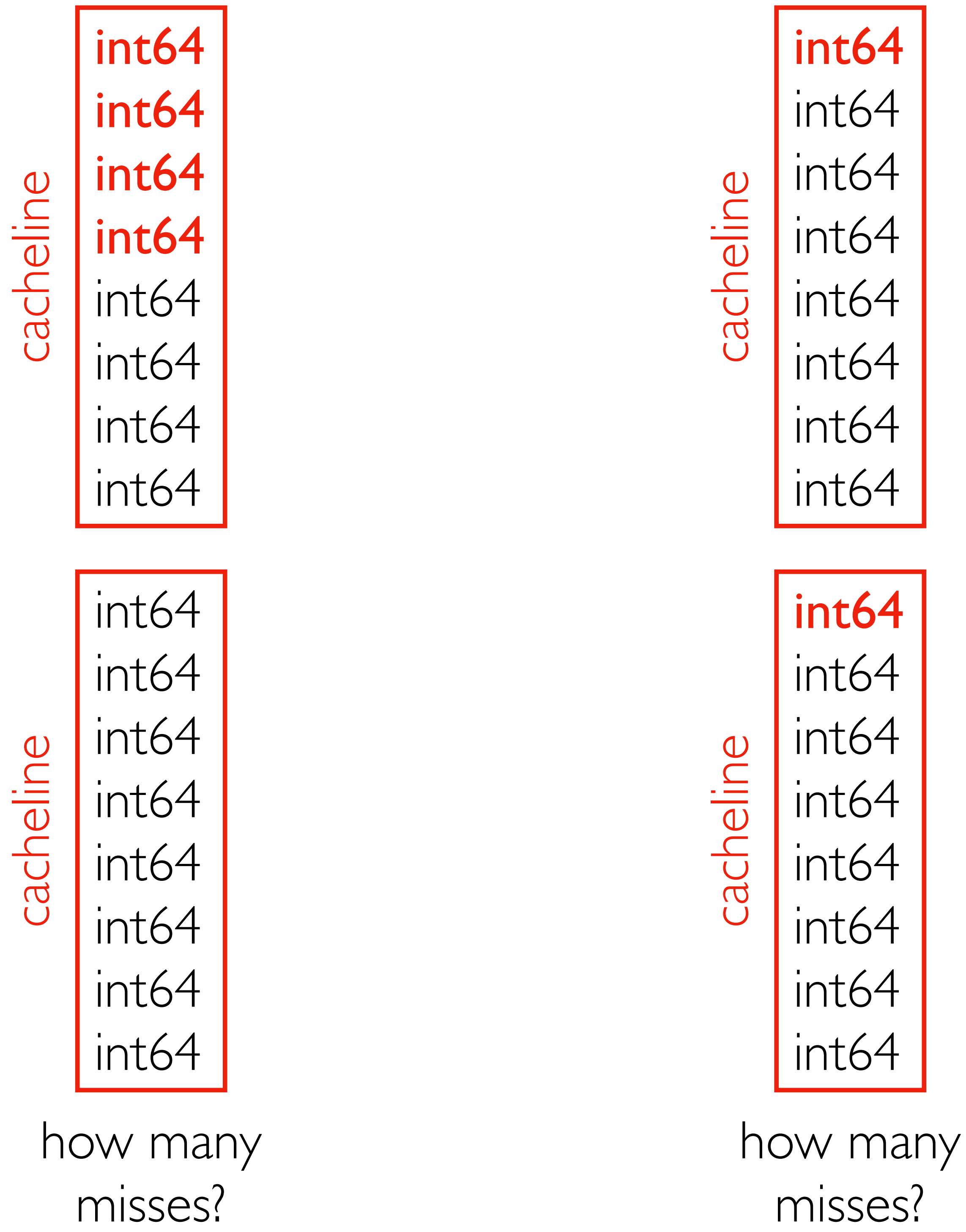
- modern CPUs typically 64 bytes (for example, 8 int64 numbers)
- M1/M2 uses 128

Cache Lines and Misses



how many misses?

Cache Lines and Misses



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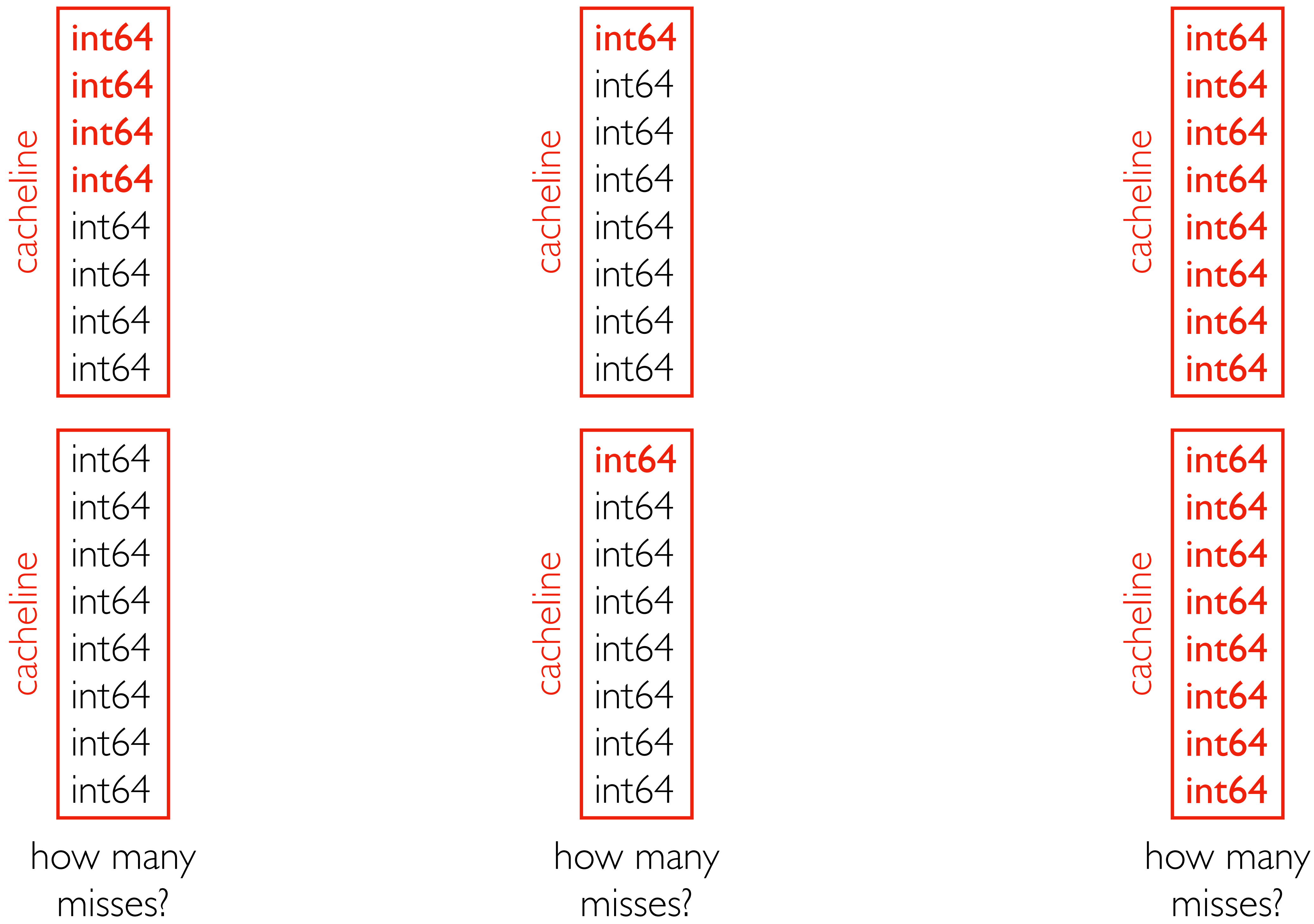
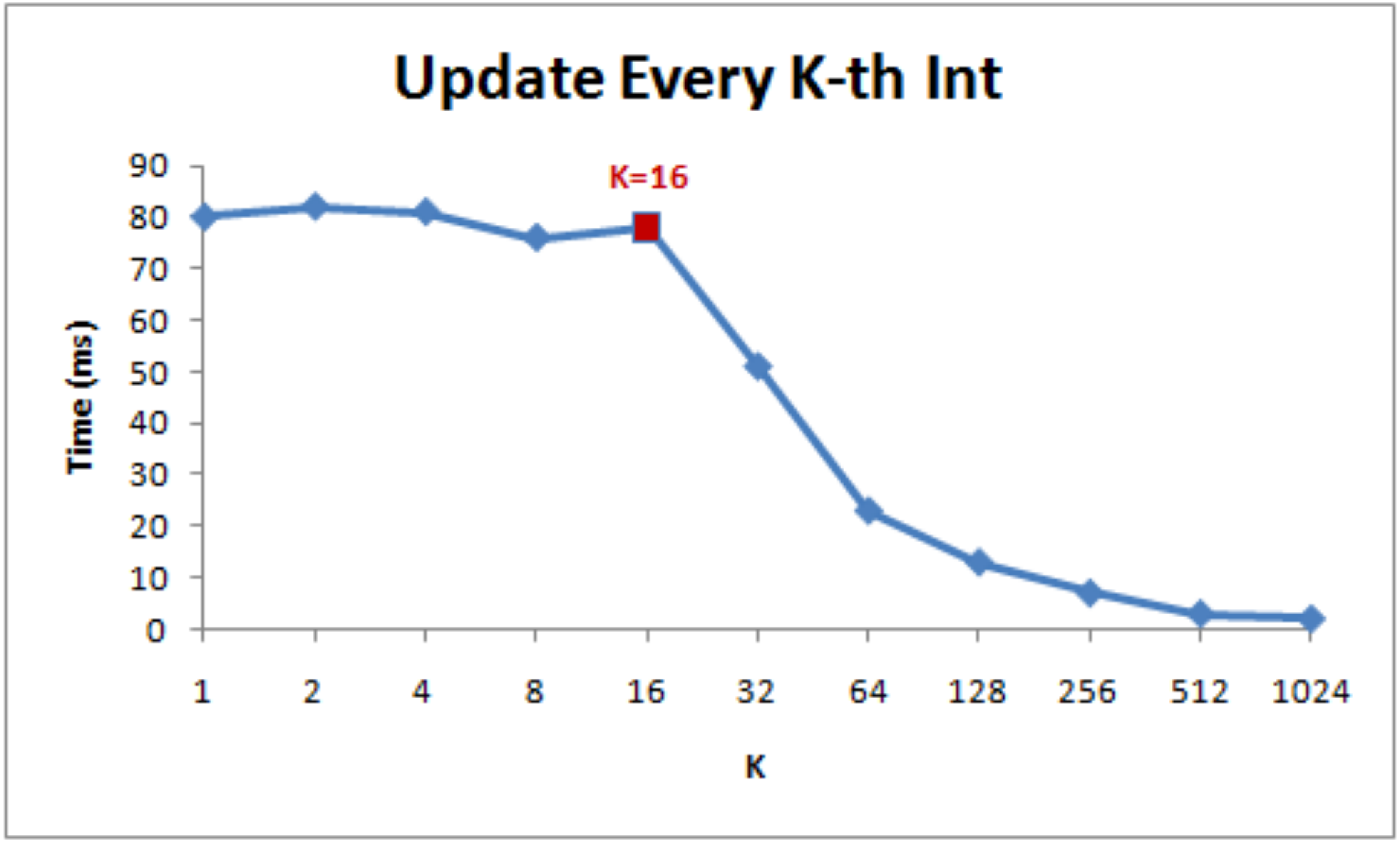


Example 1: Step and Multiply

as K gets bigger, we do fewer multiplications. But does it matter?

```
for (int i = 0; i < arr.Length; i += K) arr[i] *= 3;
```



[Gallery of Processor Cache Effects](http://igoro.com/archive/gallery-of-processor-cache-effects/)
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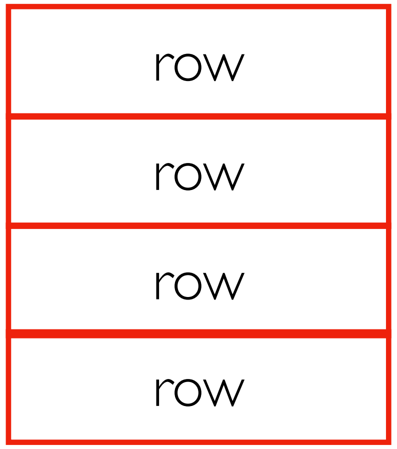
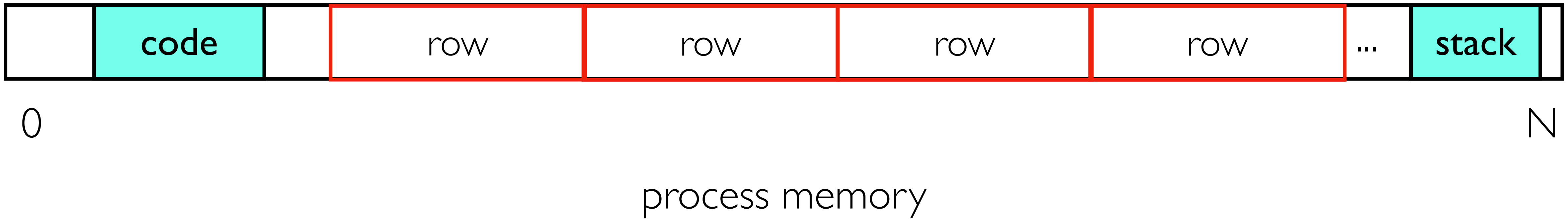
Example 2: Matrices

matrix of numbers
logically, 2-dimensional



physically, those rows are arranged along 1-dimension in the virtual address space



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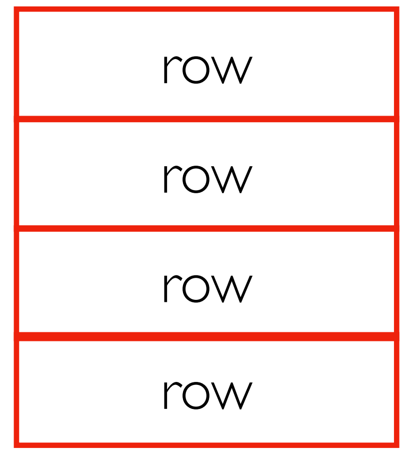
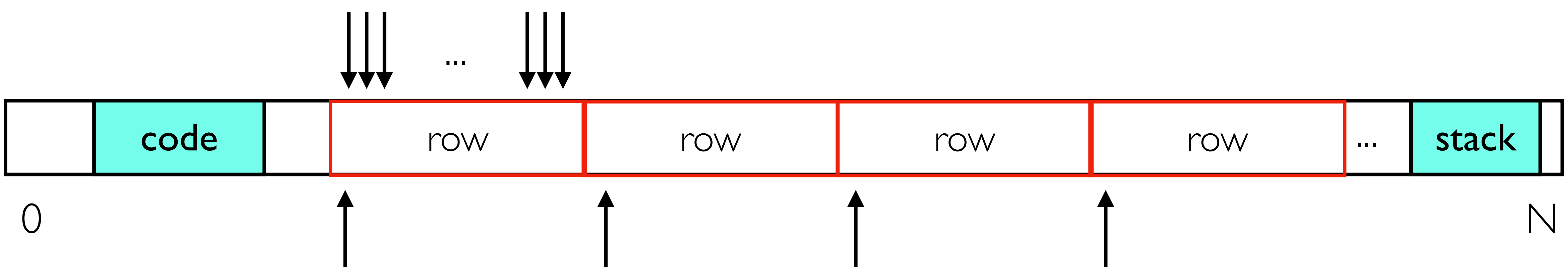


summing over row:
data consolidated over few cache lines



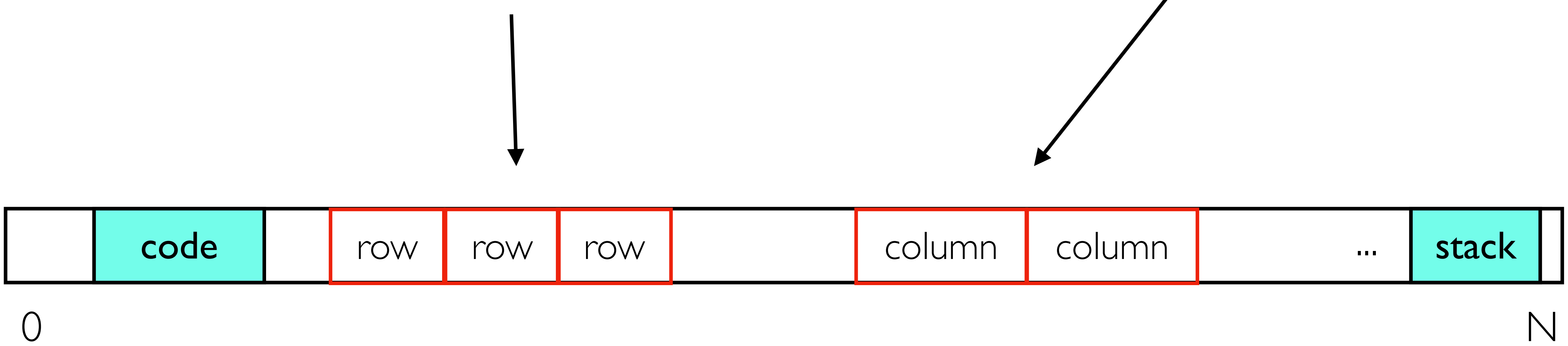
summing over column: each number is in its own cache line and triggers a cache miss

Numpy: Controlling Layout with Transpose

for efficiency, transpose doesn't actually move/copy data, meaning we can get fast column sum by (a) putting column data in rows and (b) transposing

```
np.array([[1,2],
          [3,4],
          [5,6]])
```

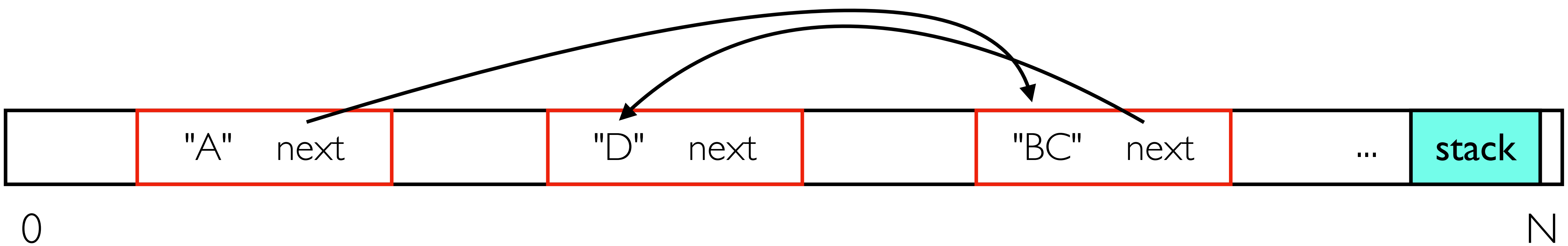
```
np.array([[1,3,5],
          [2,4,6]]).T
```



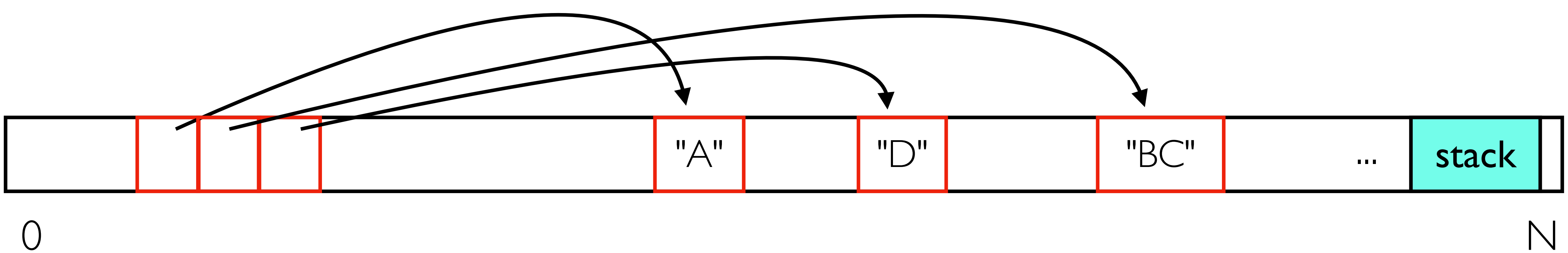
any calculations on the two tensors will produce the same results, but they'll each be faster for different access patterns!

Example 3: Ordered Collections of Strings

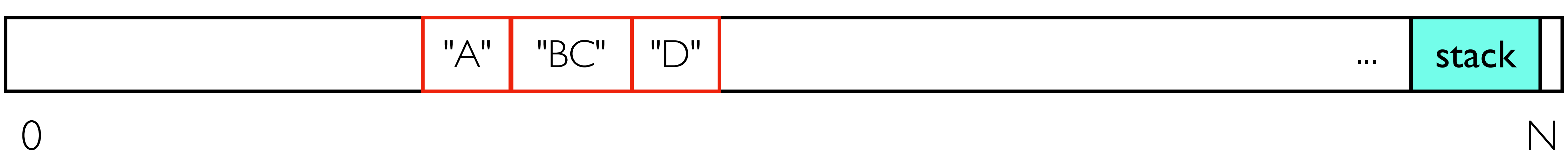
which layout is most cache friendly?



linked list



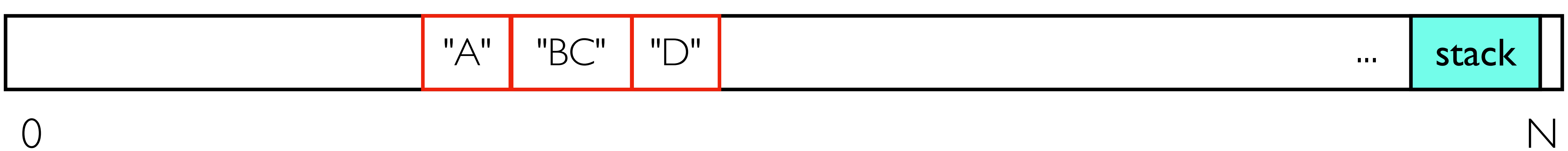
array of references to strings



array of inline strings

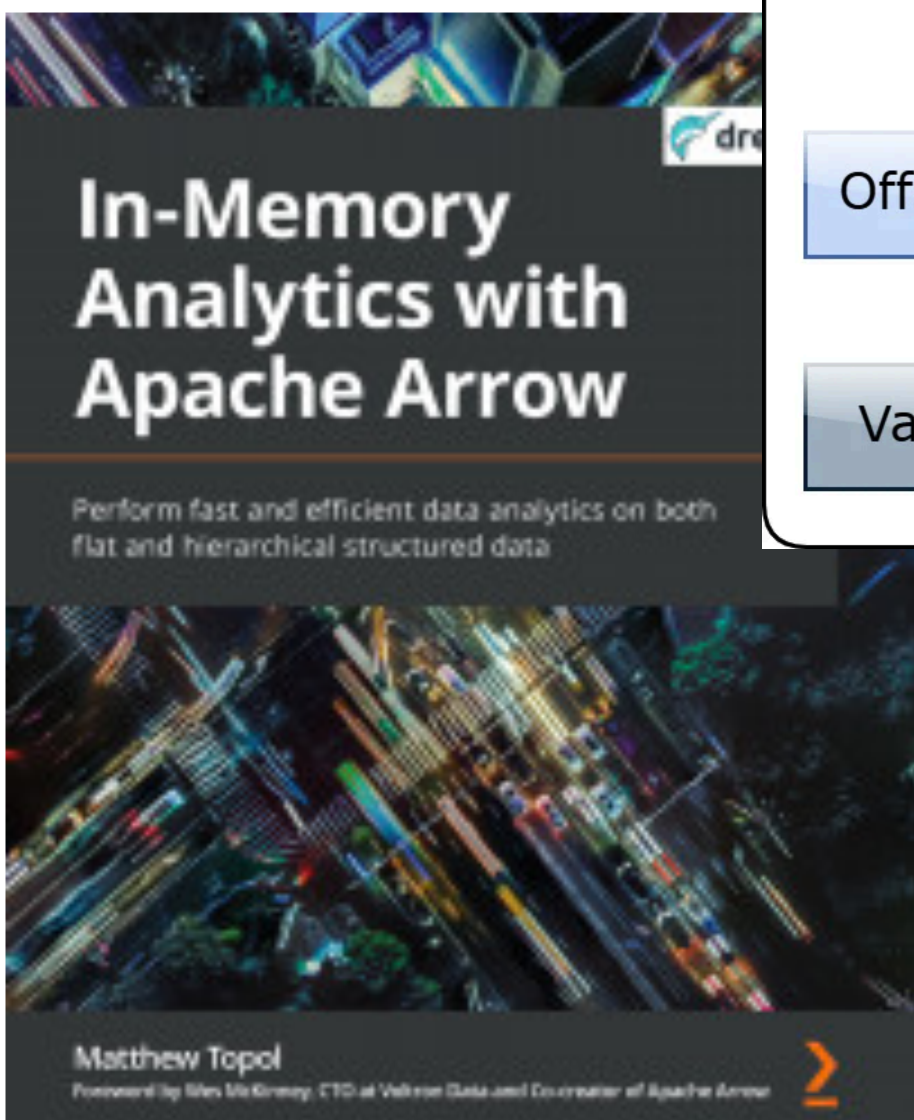
Example 3: Ordered Collections of Strings

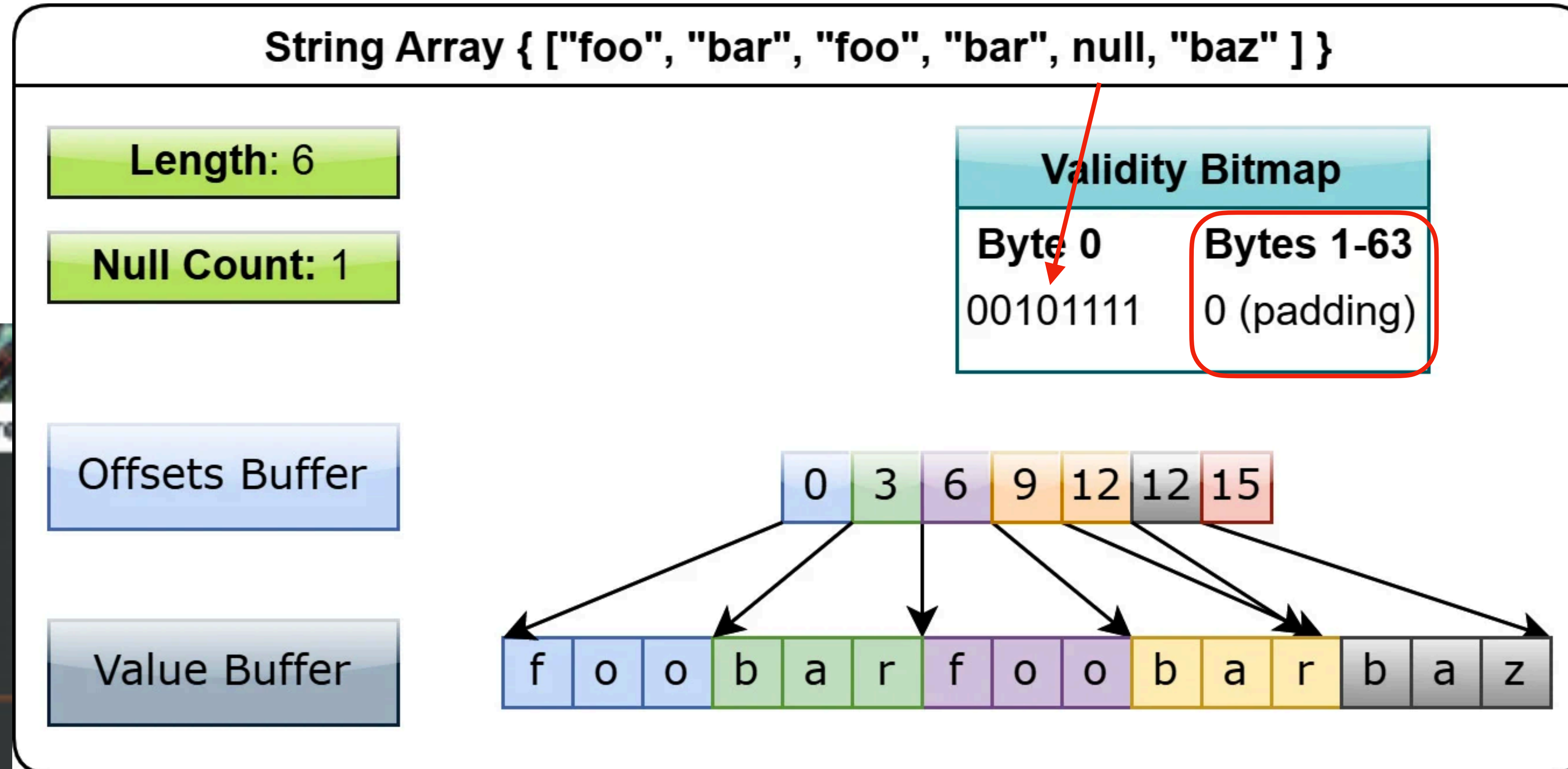
how to tell the end of one string from the start of the next?
how to jump immediately to string at index i?
how support null/None?



array of inline strings

PyArrow String Array Data Structure





data is packed into fewest possible cache lines

- collection of named arrays is a Table
- arrays for different types, each cache friendly
- null support for types like int (not forced into floats)

https://www.packtpub.com/product/in-memory-analytics-with-apache-arrow/9781801071031

Outline

CPU: L1-L3

Demos: Numpy+PyArrow...

Background: Virtual Address Spaces

OS (Operating System): Page Cache

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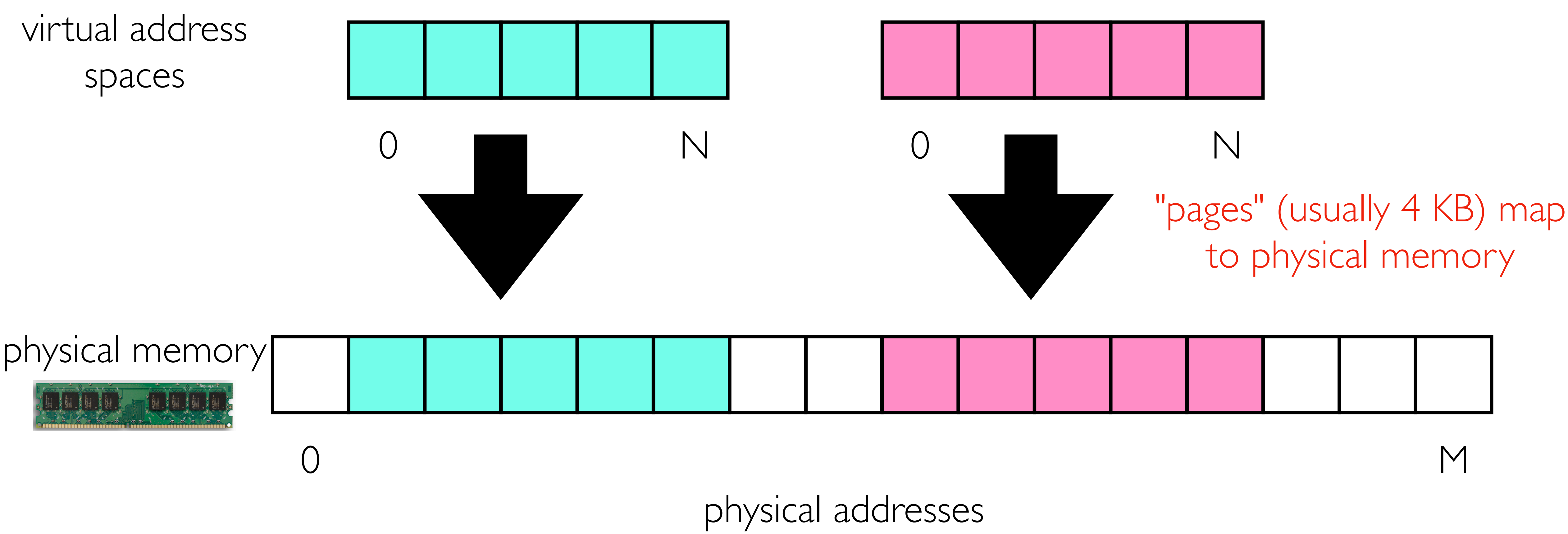
Processes and Address Spaces

Address spaces

- A process is a running program
- Each process has it's own virtual address space
- The same virtual address generally refers to different memory in different processes
- Regular processes cannot directly access physical memory or other addr spaces



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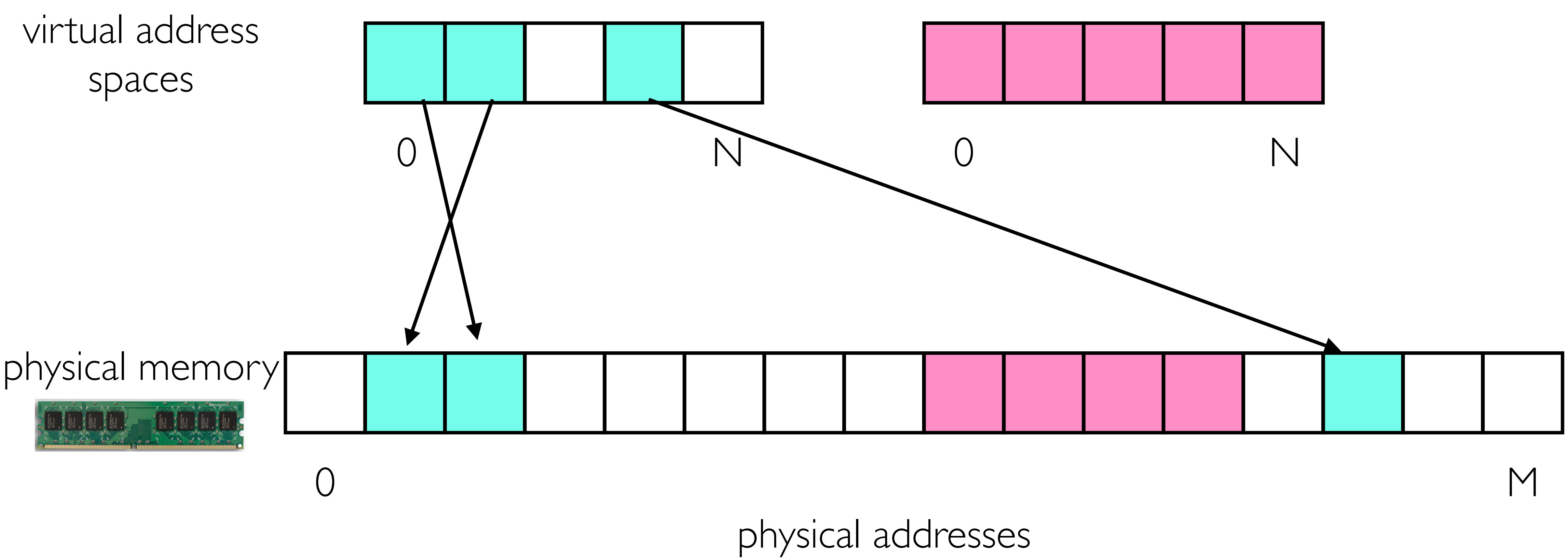
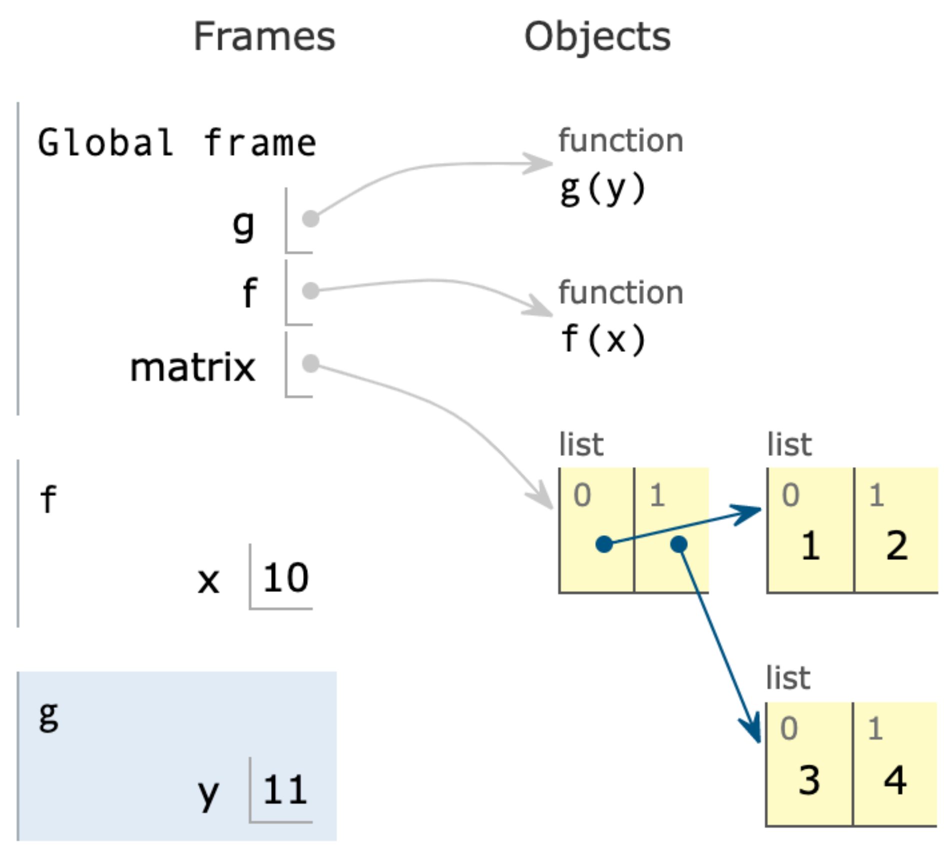
- Regular processes cannot directly access physical memory or other addr spaces
- Address spaces can have holes (N is usually MUCH bigger than M)
- Physical memory for a process need not be contiguous



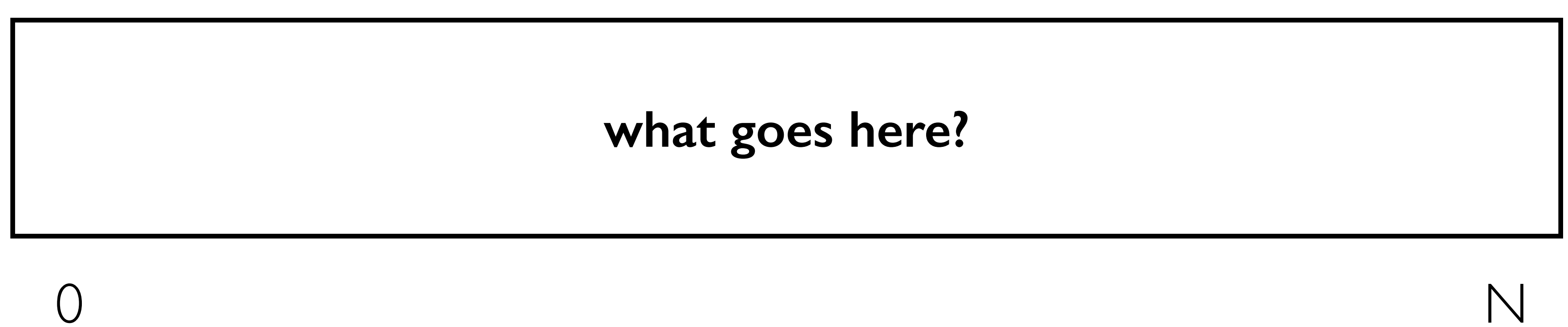
What goes in an address space?

```
def g(y):
    return y * 2

def f(x):
    return g(x+1)

matrix = [[1,2], [3,4]]
f(10)
```



https://pythontutor.com/

virtual address spaces



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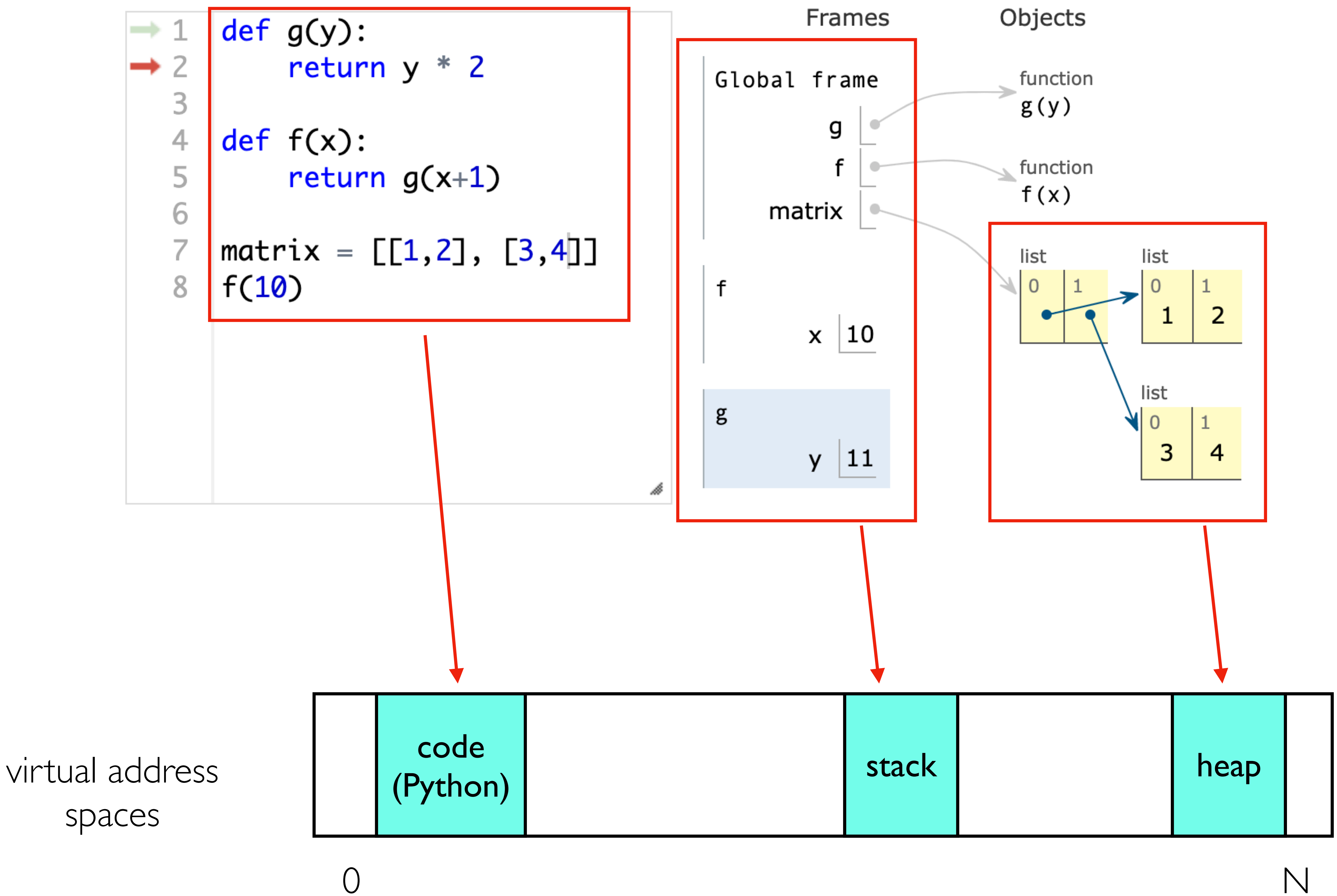

Note: code and heap generally not contiguous

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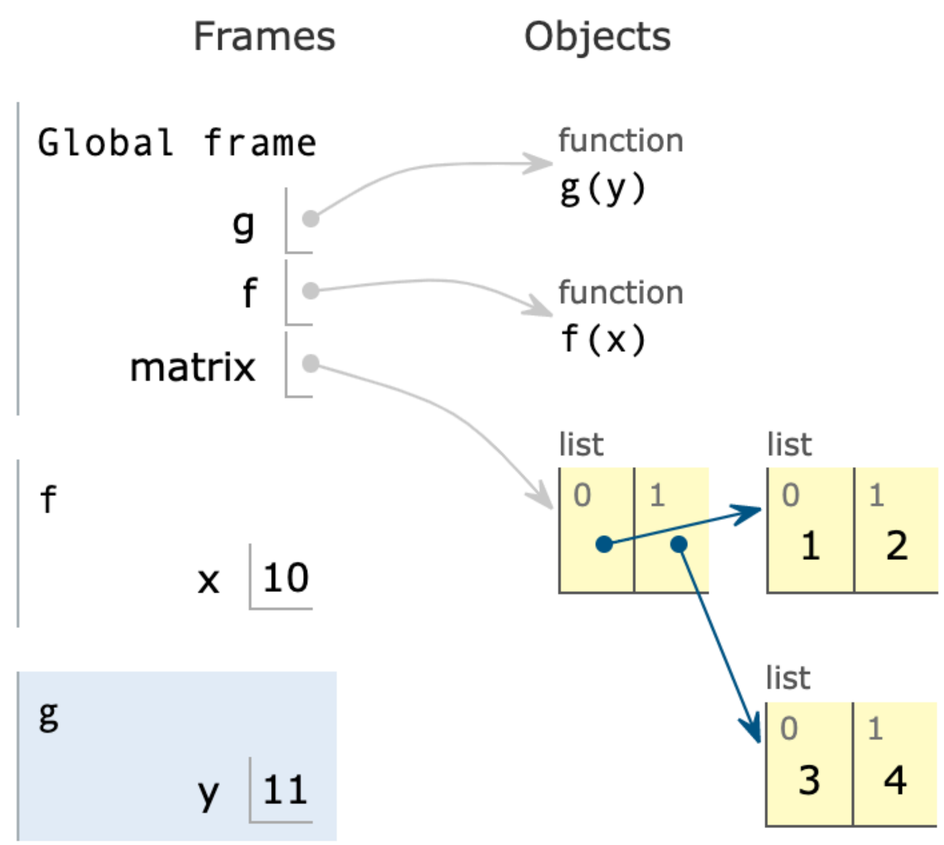
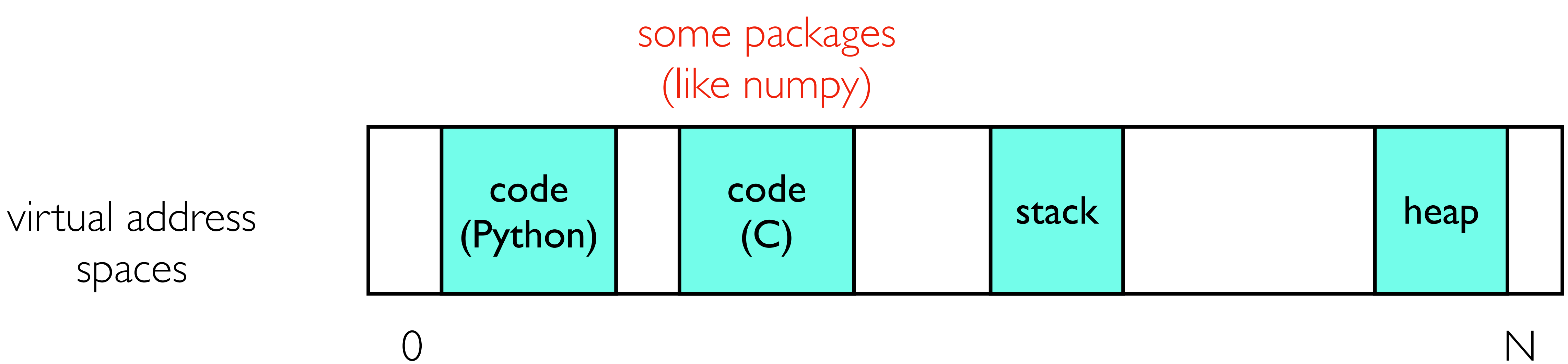
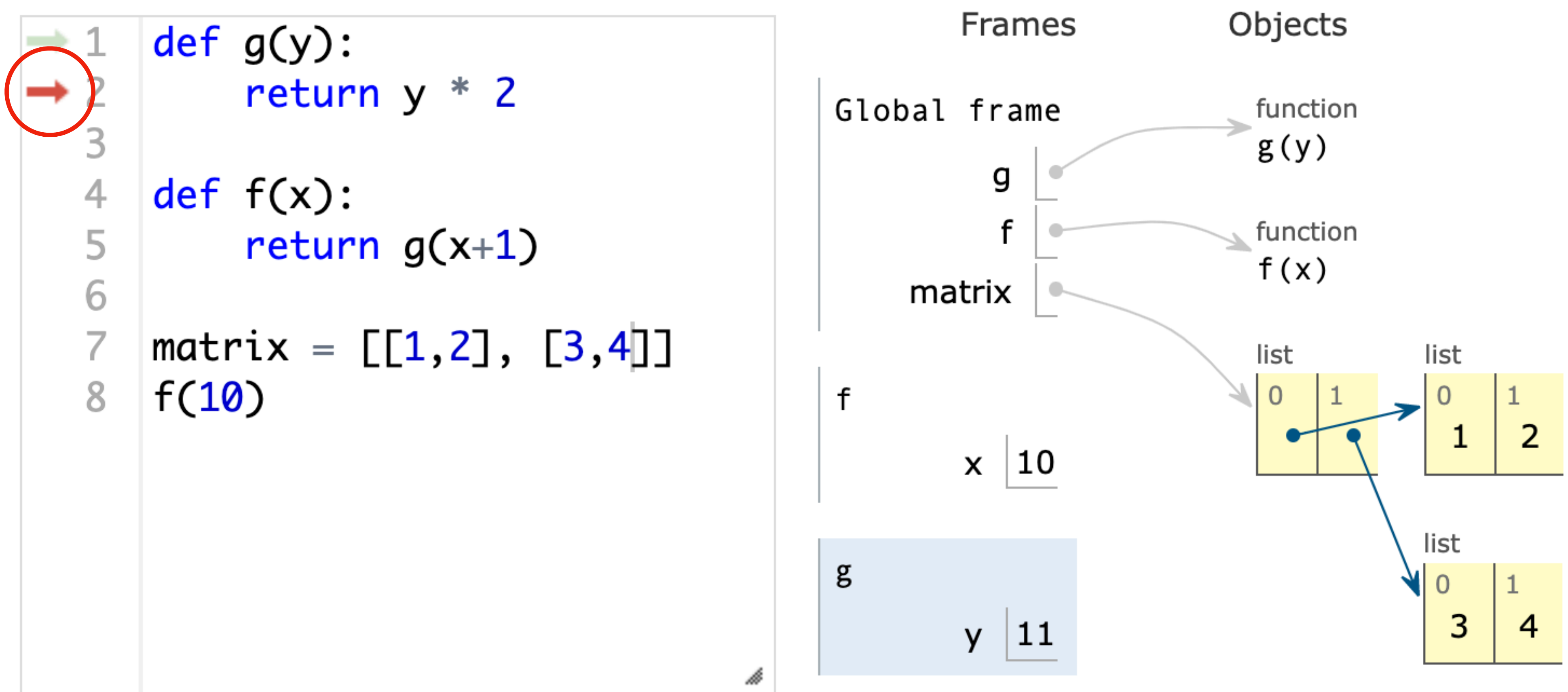
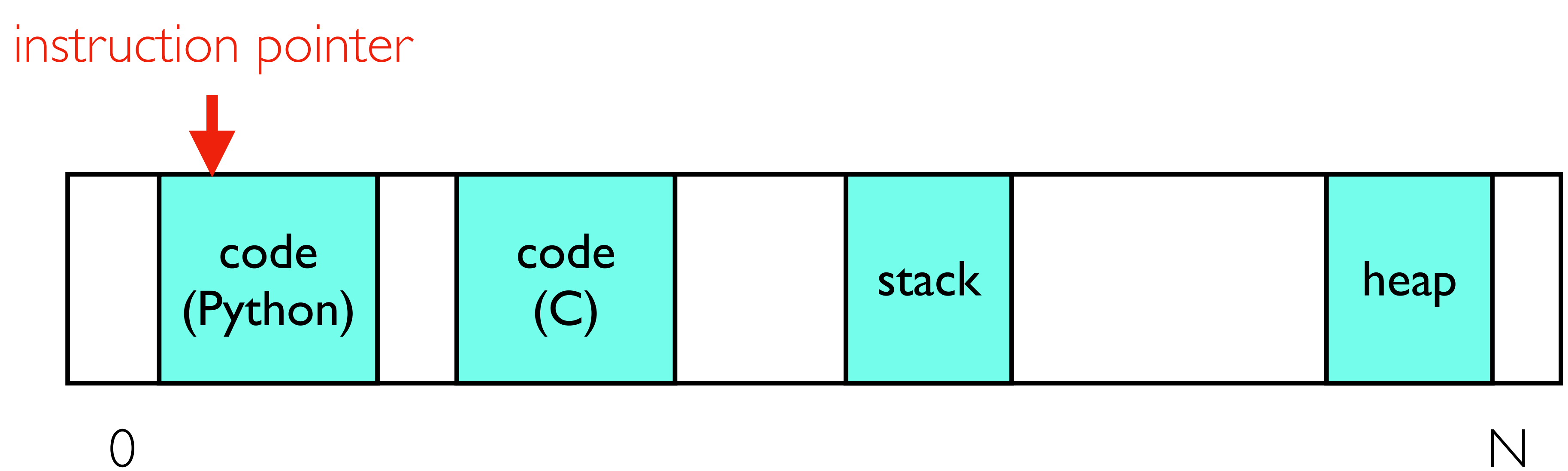




How does code execute?



virtual address spaces



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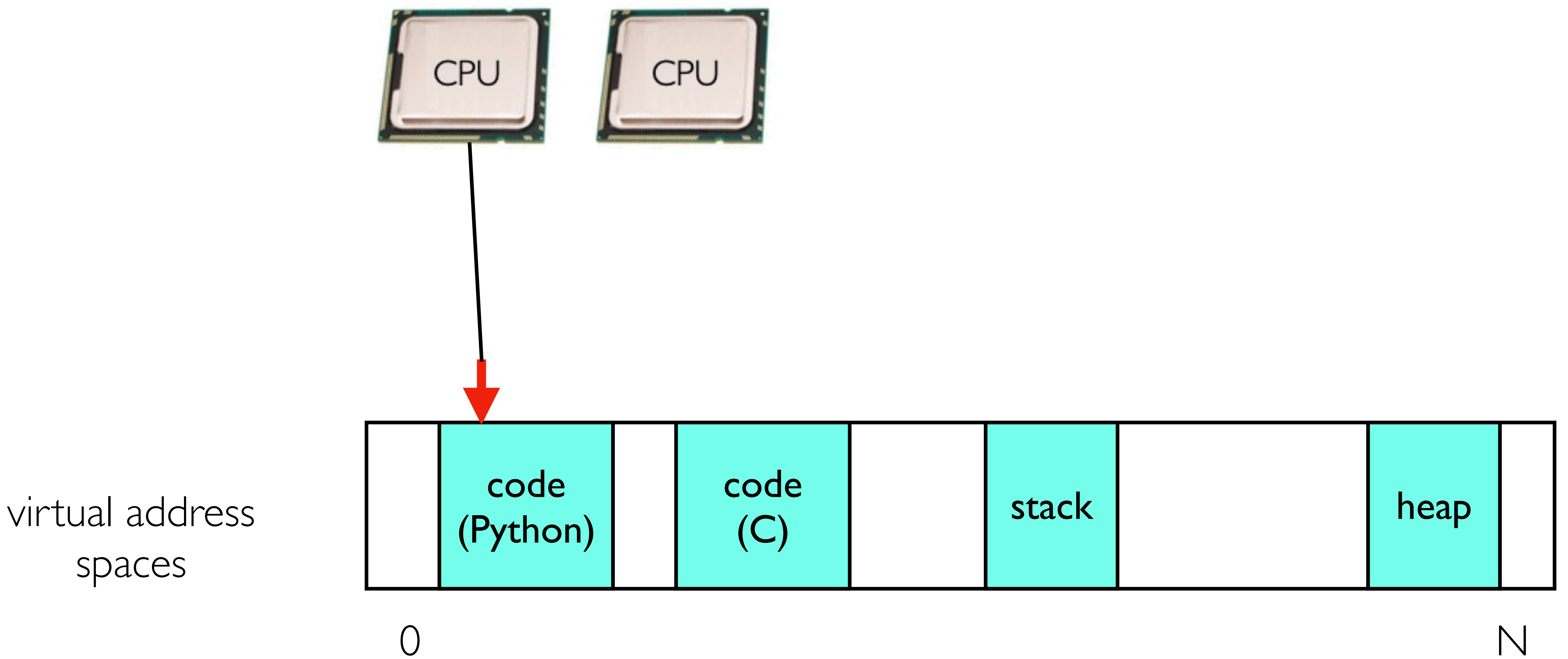
CPUs

- CPUs are attached to at most one instruction pointer at any given time
- they run code by executing instructions and advancing the instruction pointer
- **Note**: interpreter left out for simplicity (CPU points to interpreter code, which points to Python bytecode)



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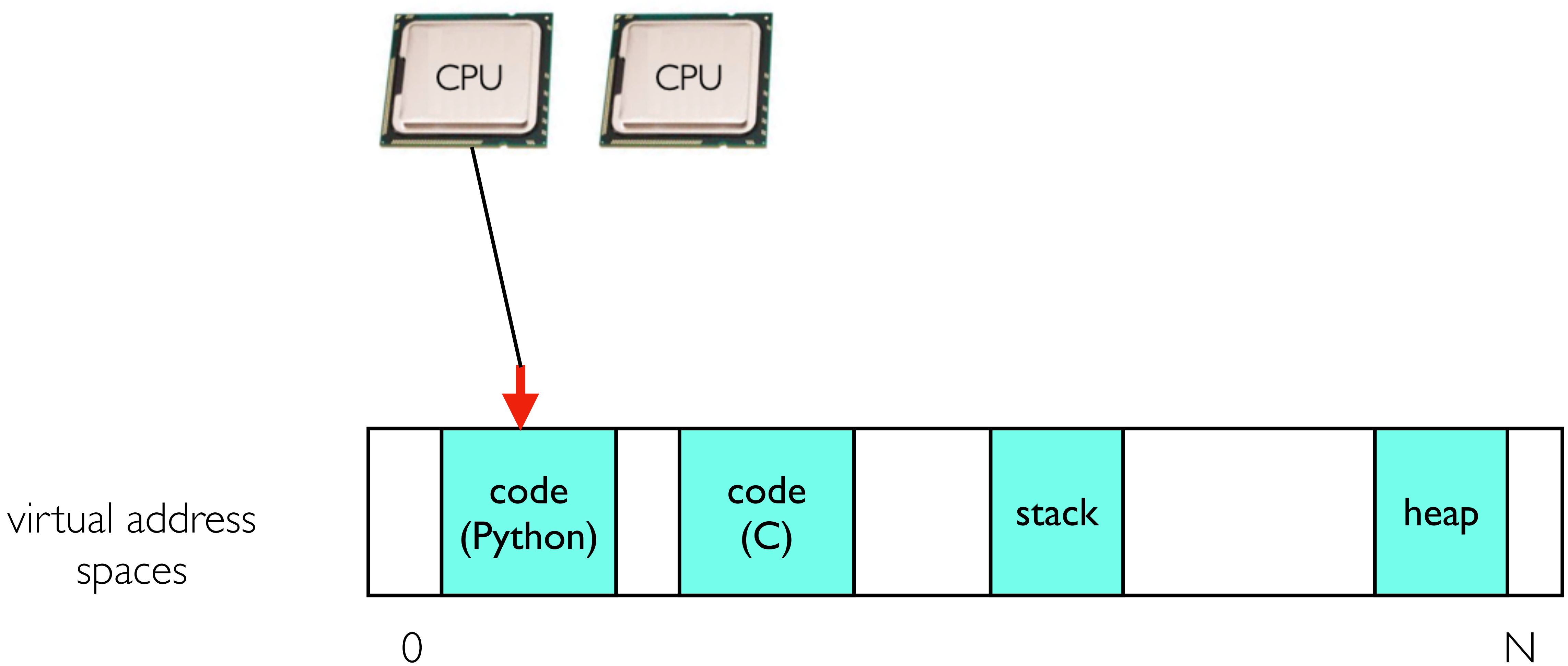

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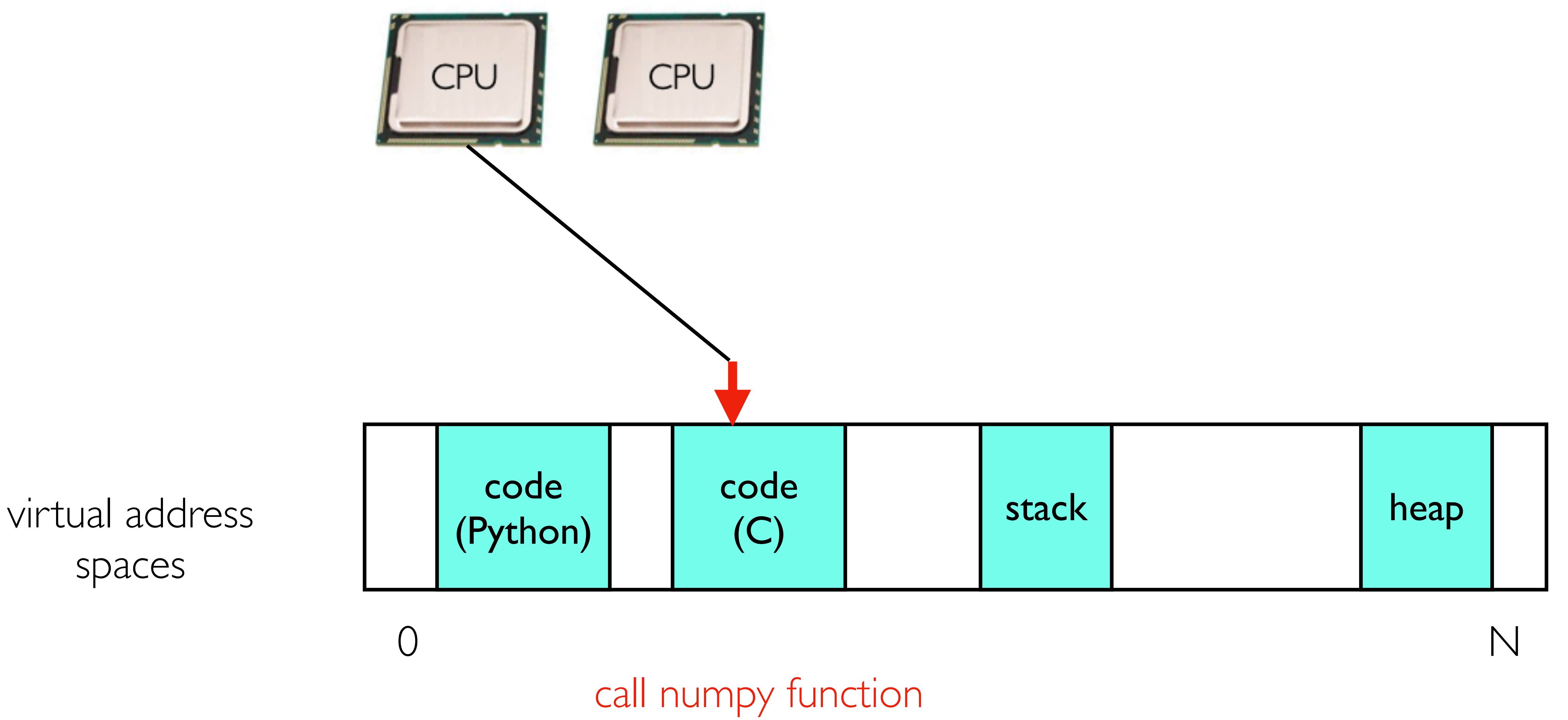

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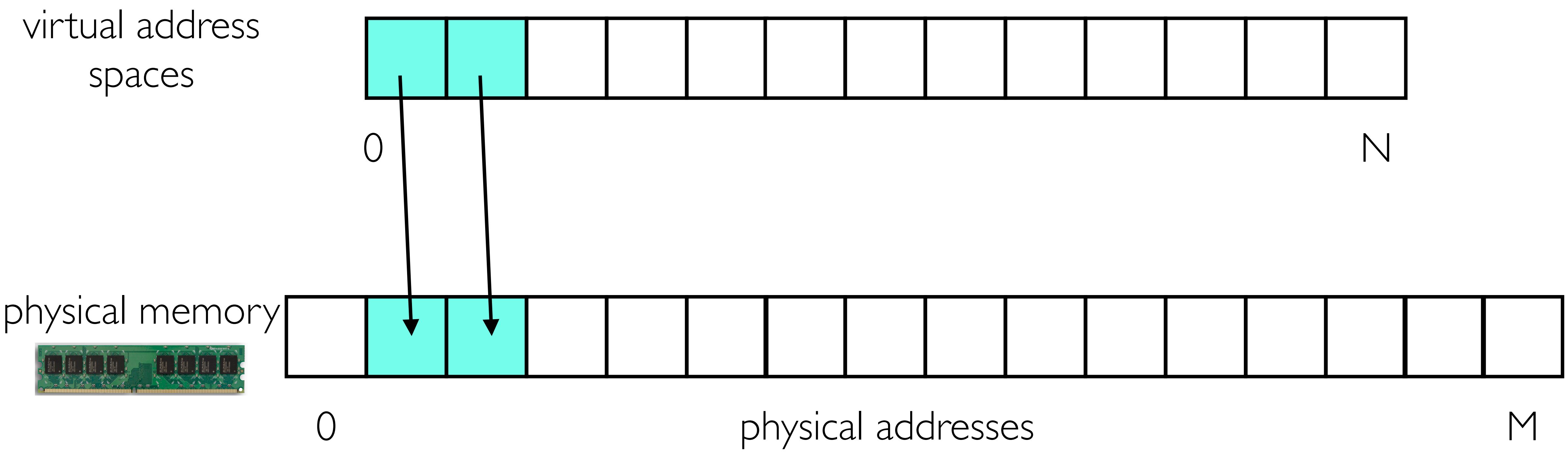
mmap (Memory Map)

An mmap call can add new regions to a virtual address space. Two varieties:

- anonymous
- backed by a file



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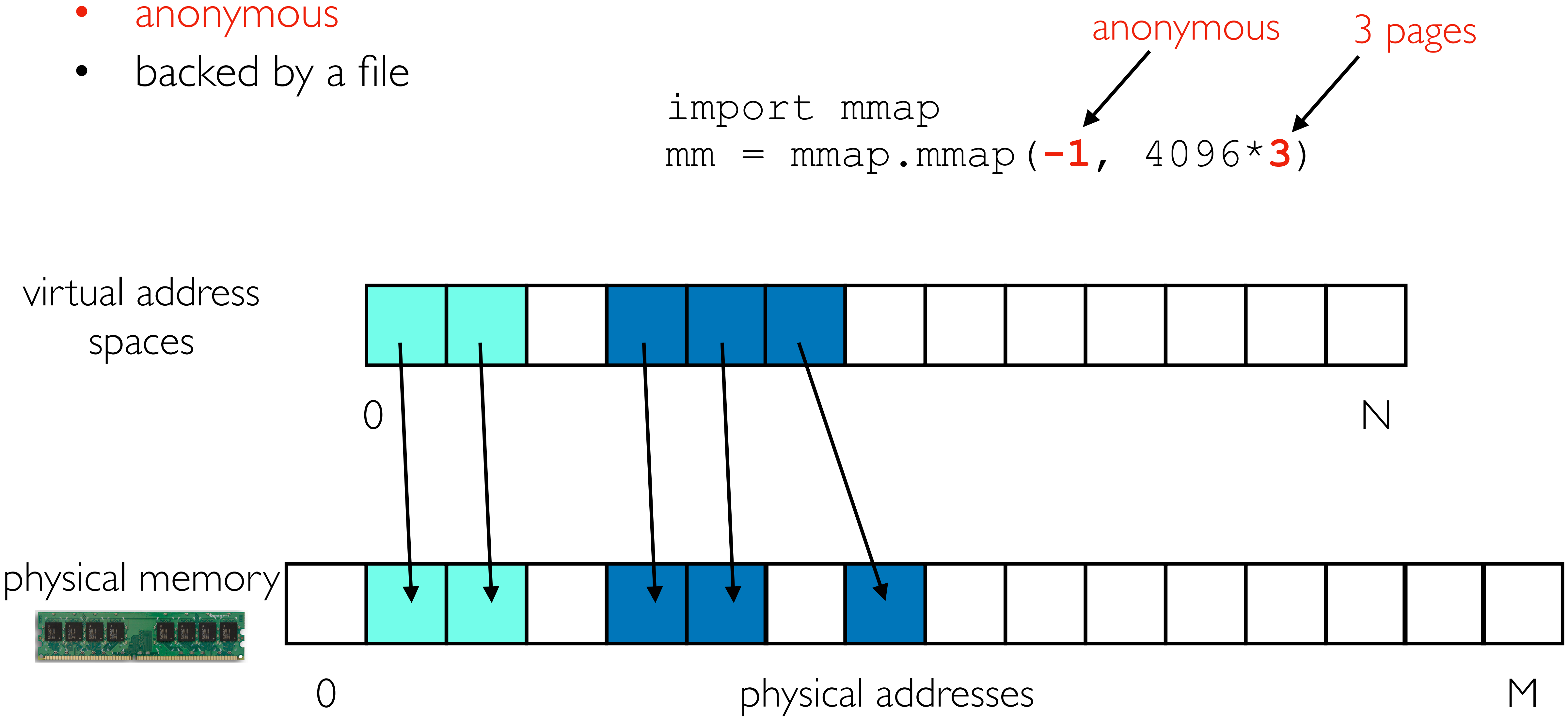

- Python (and other language runtimes) will mmap some anonymous memory when they need more heap space
- this will be used for Python objects (ints, lists, dicts, DataFrames, etc.)

File-Backed mmap

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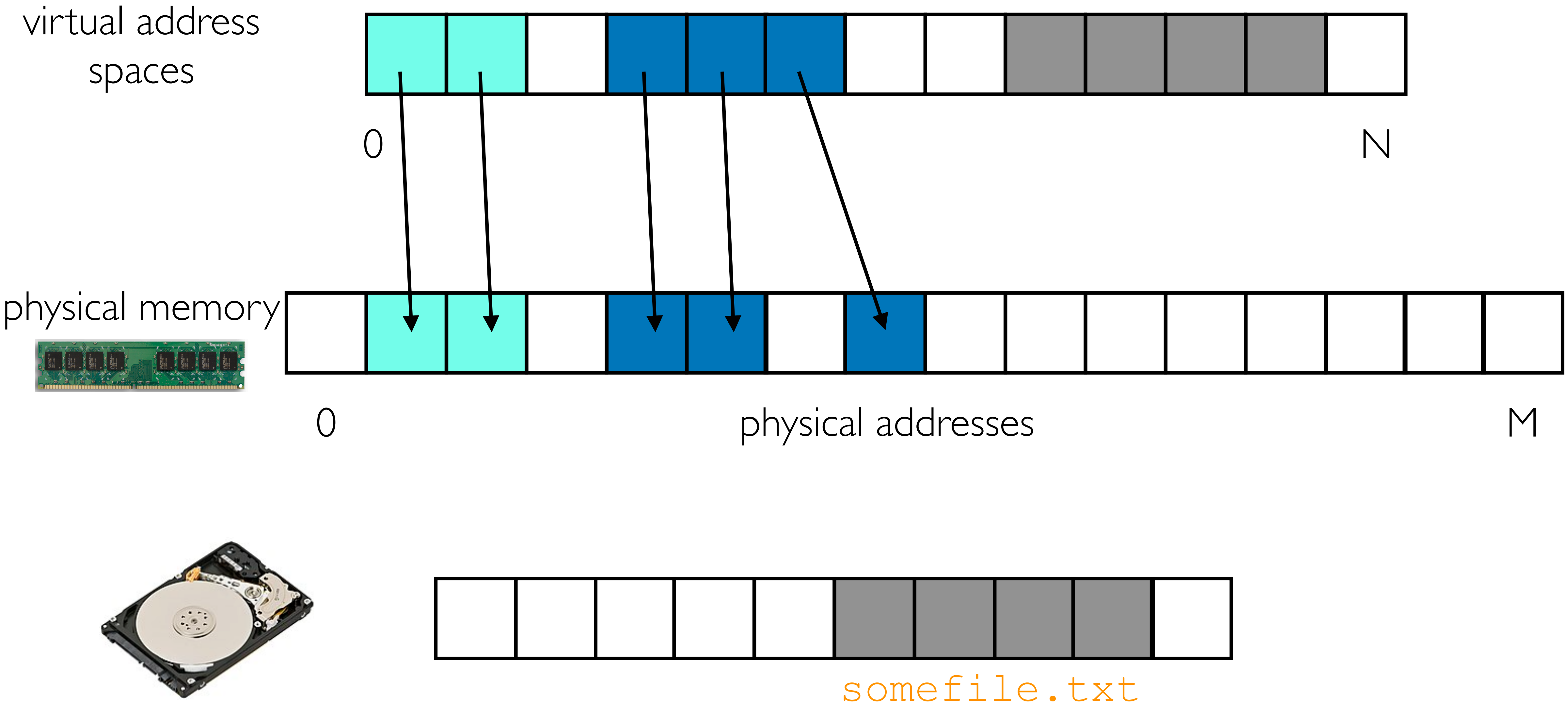
```
import mmap
f = open("somefile.txt", mode="rb")
mm = mmap.mmap(f.fileno(), 0, # 0 means all
               access=mmap.ACCESS_READ)
```



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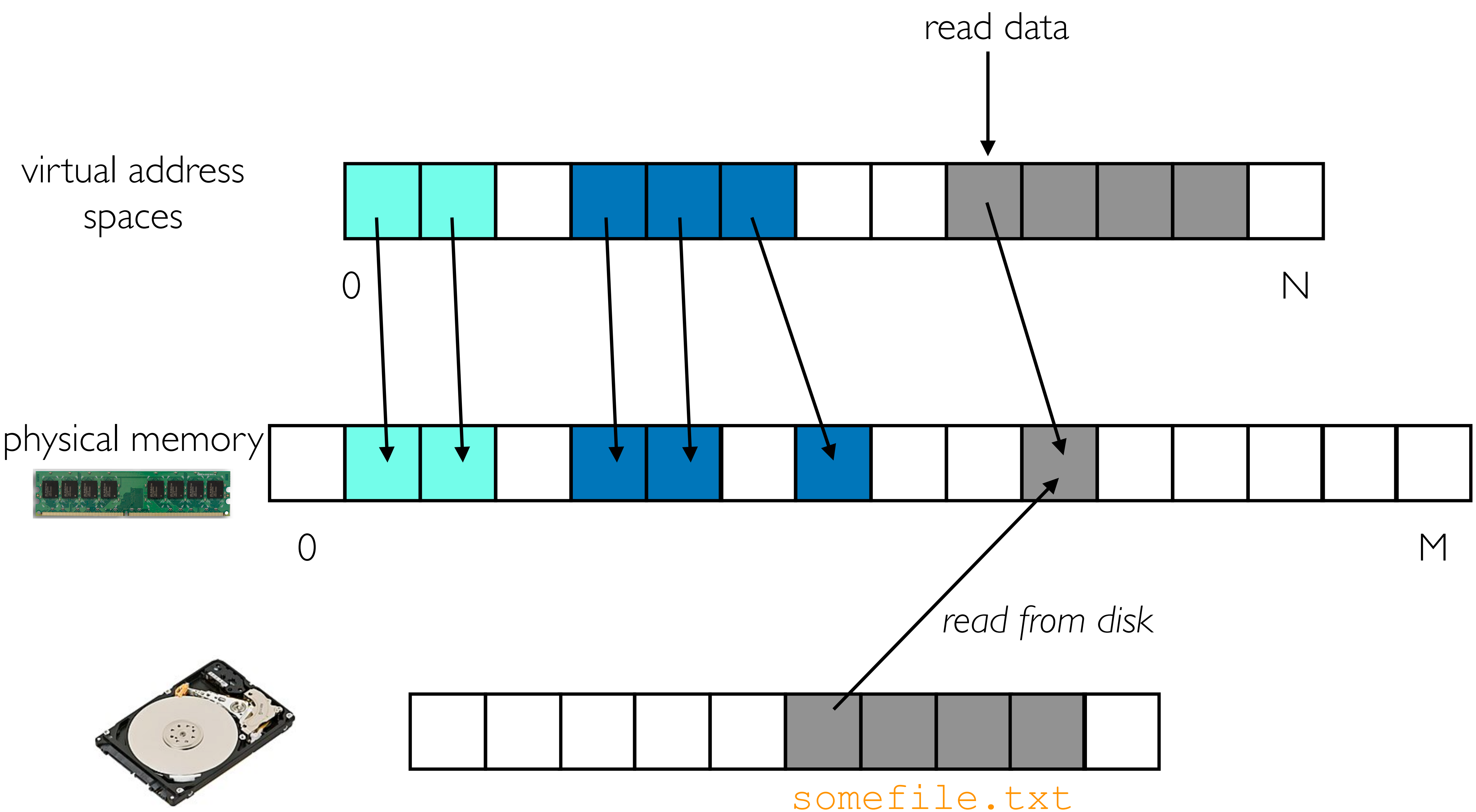

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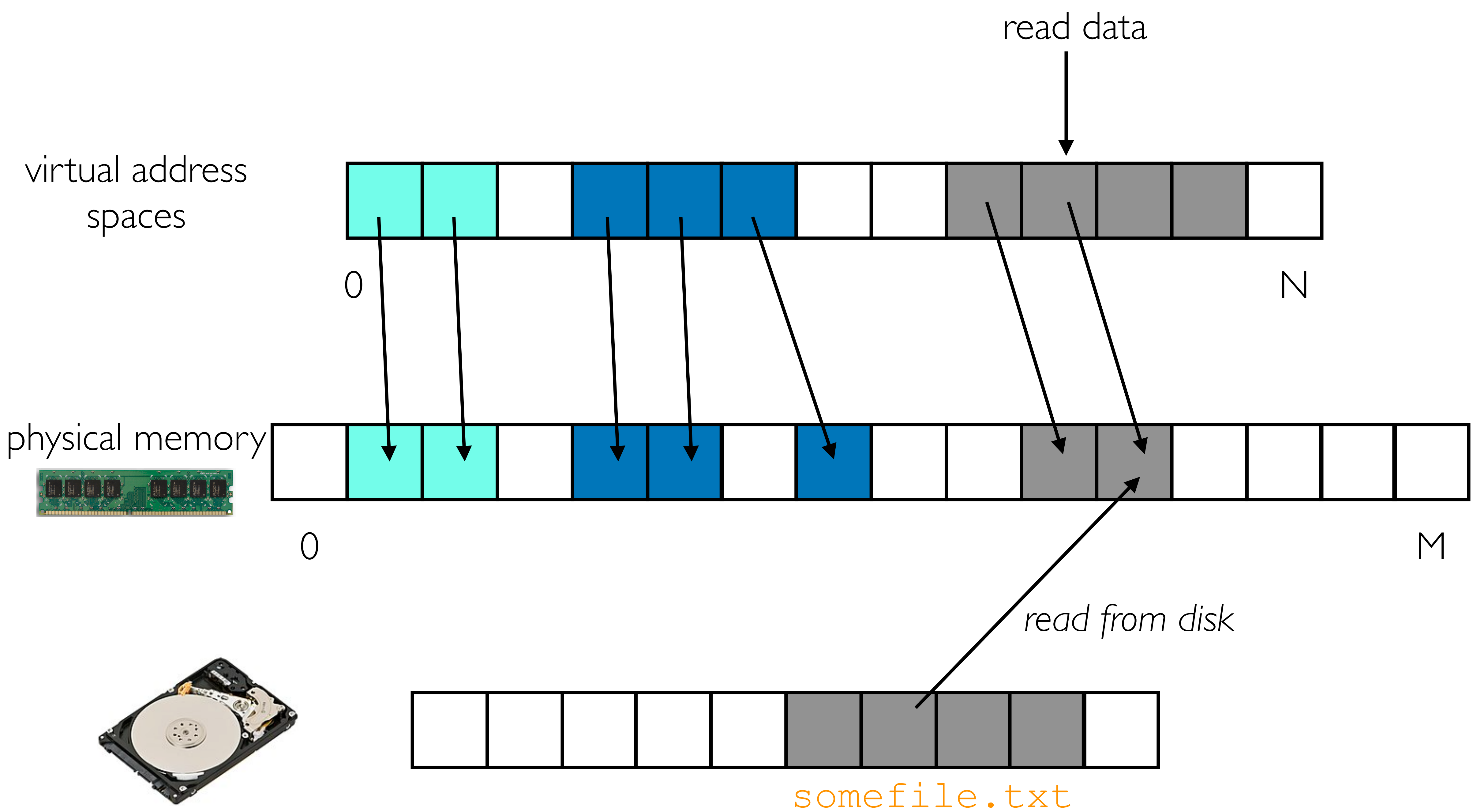

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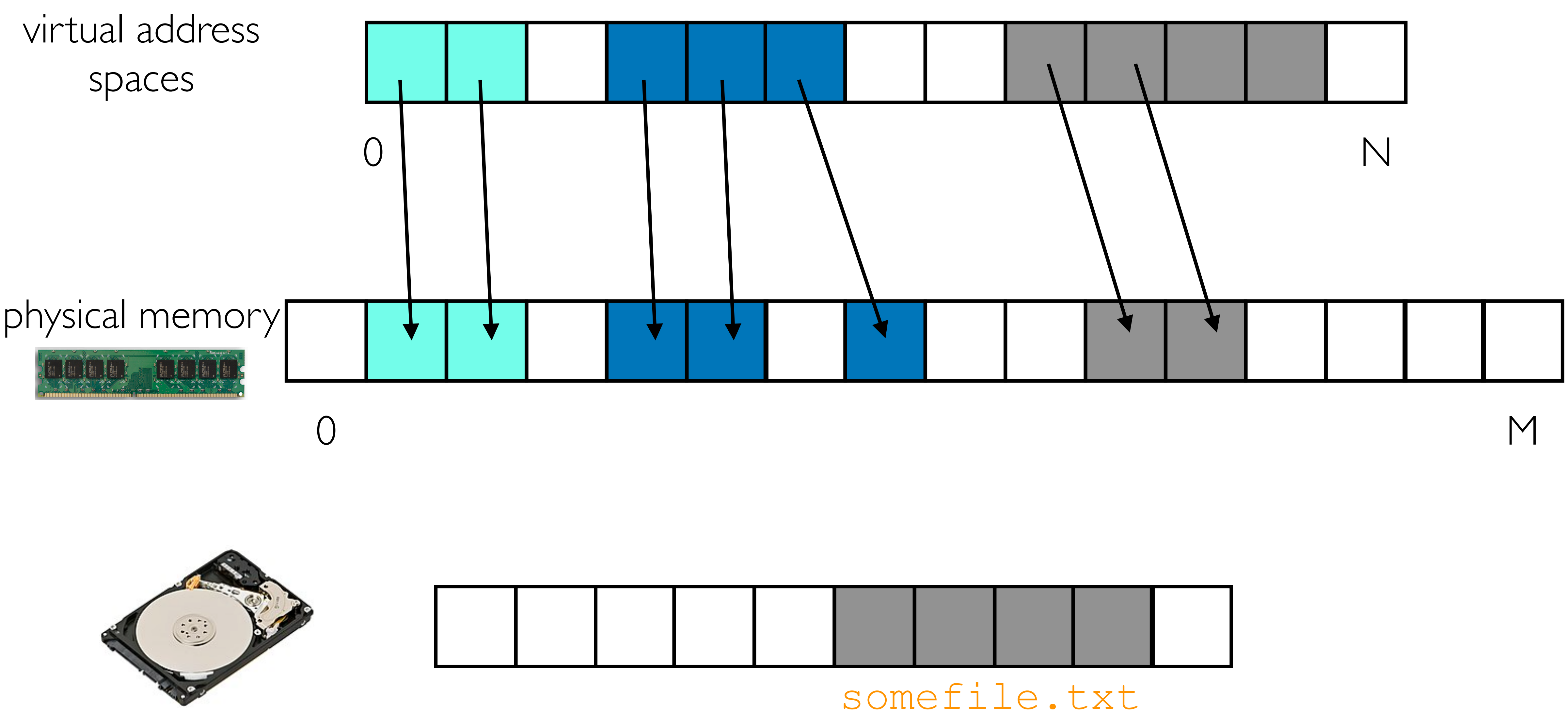
- **virtual** memory used: 9*pagesize = 36 KB
- **physical** memory used: 7*pagesize = 28 KB



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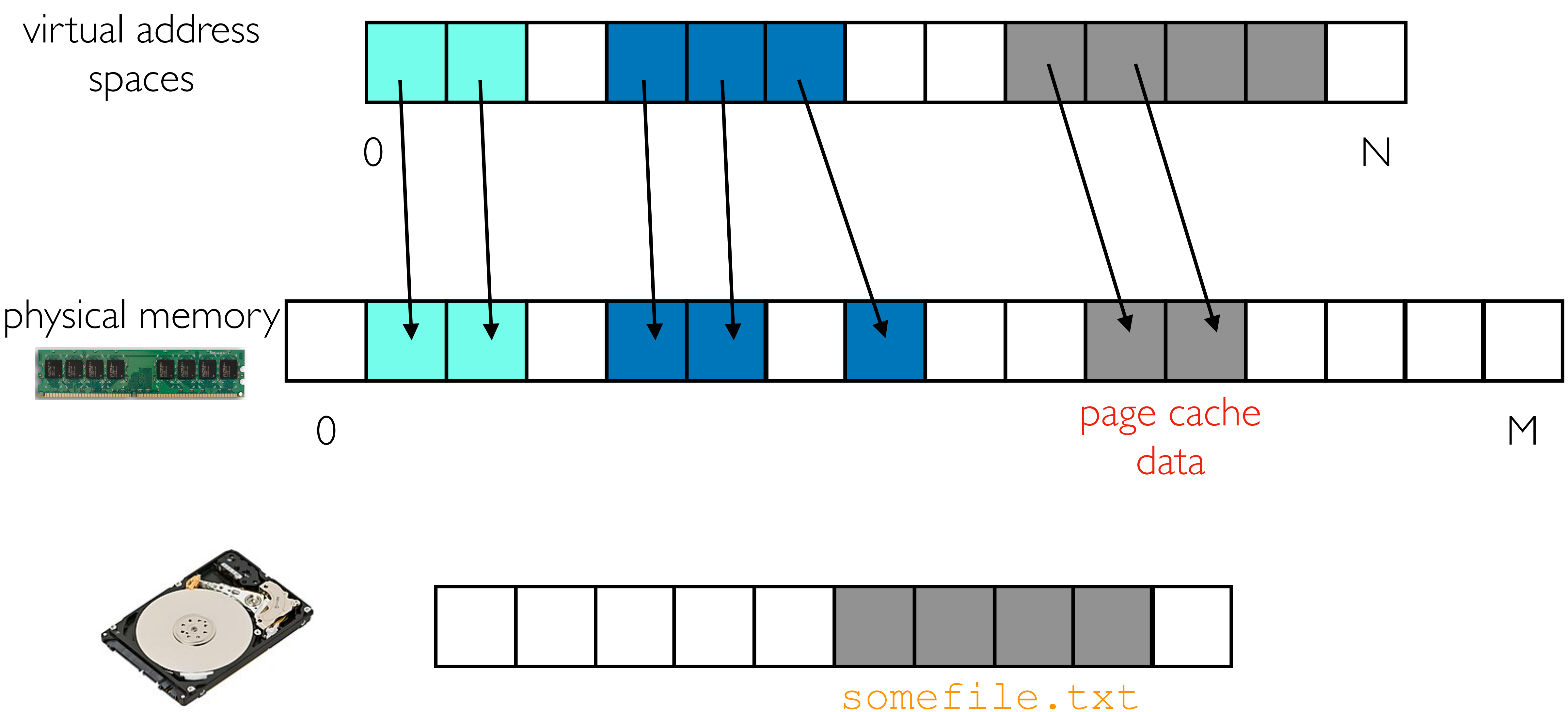

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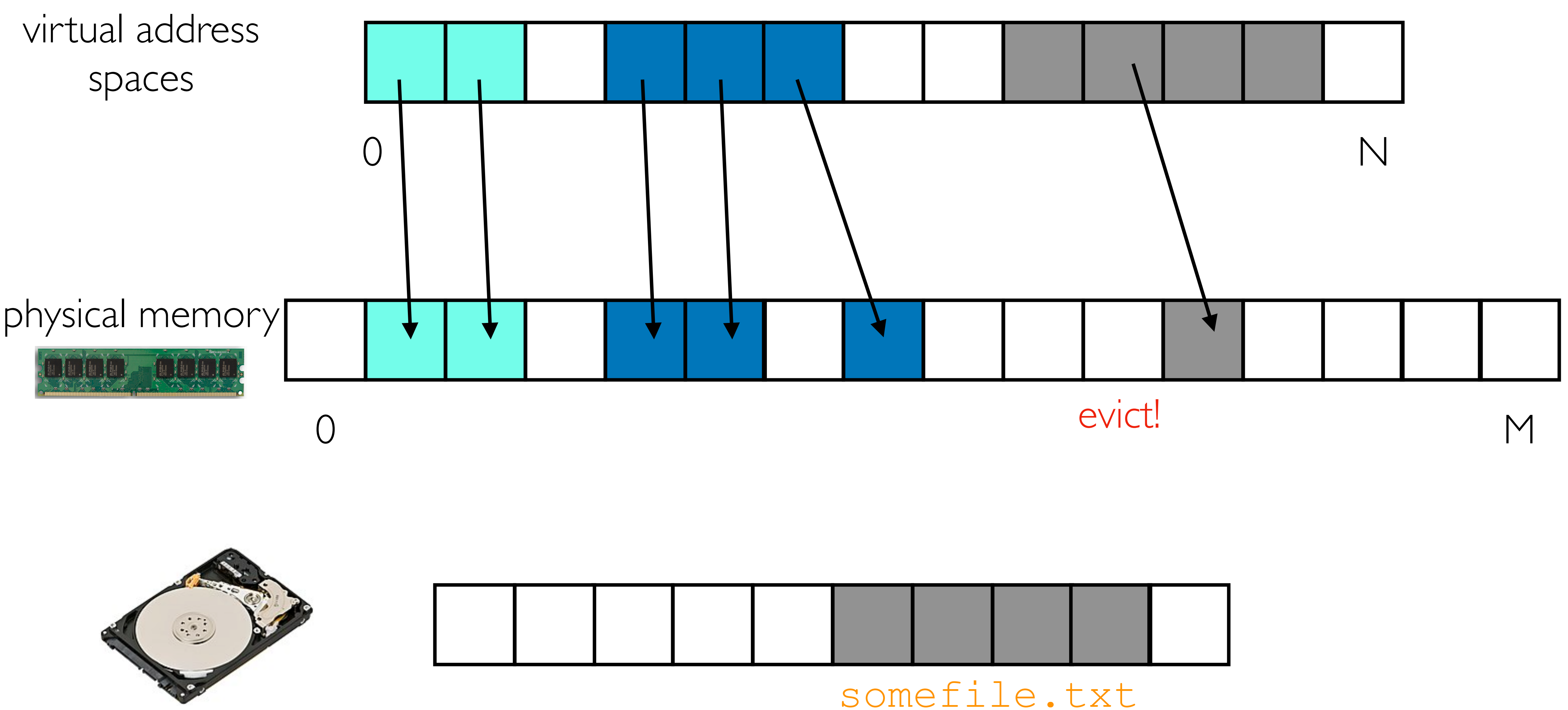
- data loaded for accesses to file-backed mmap regions are part of the "page cache"
- it works like a cache because there is another copy on disk, so we can evict under memory pressure



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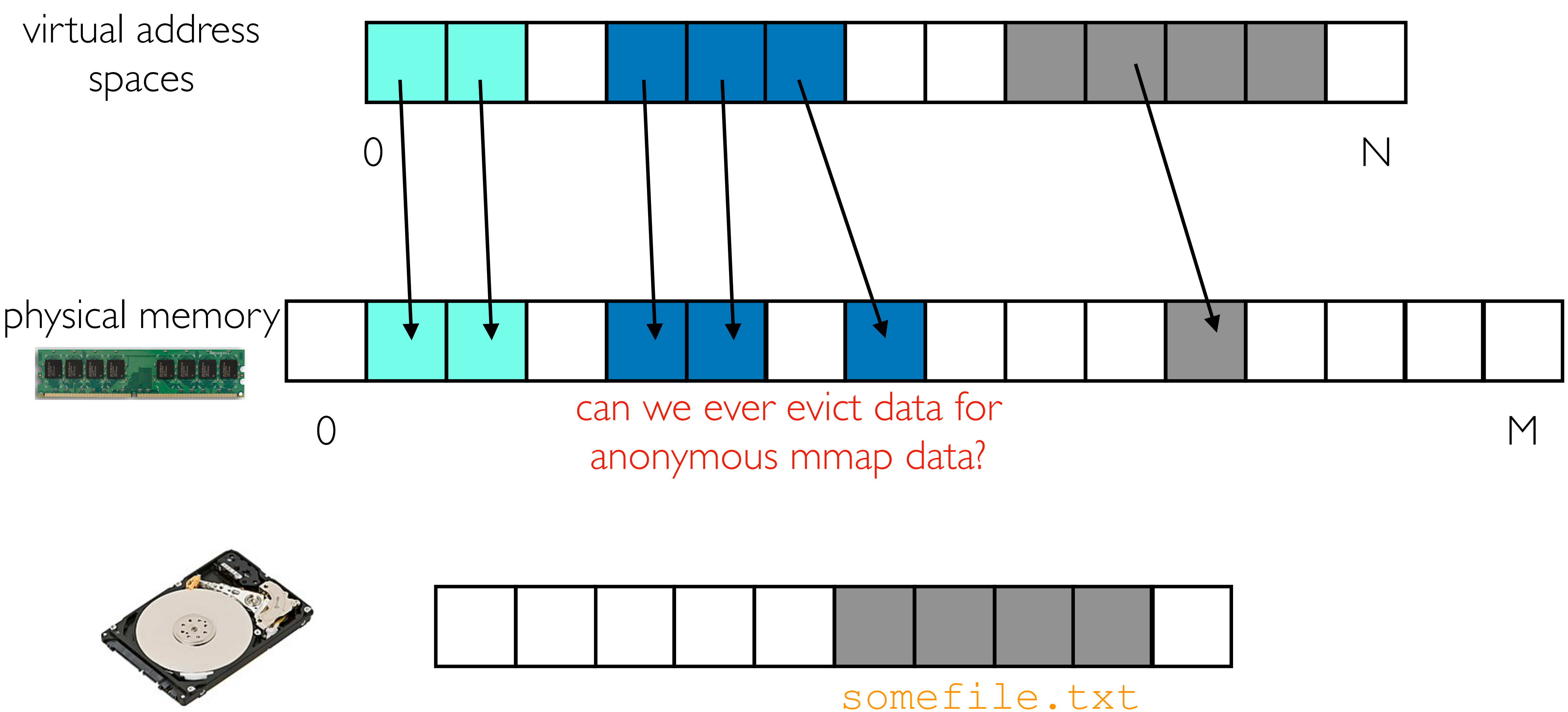

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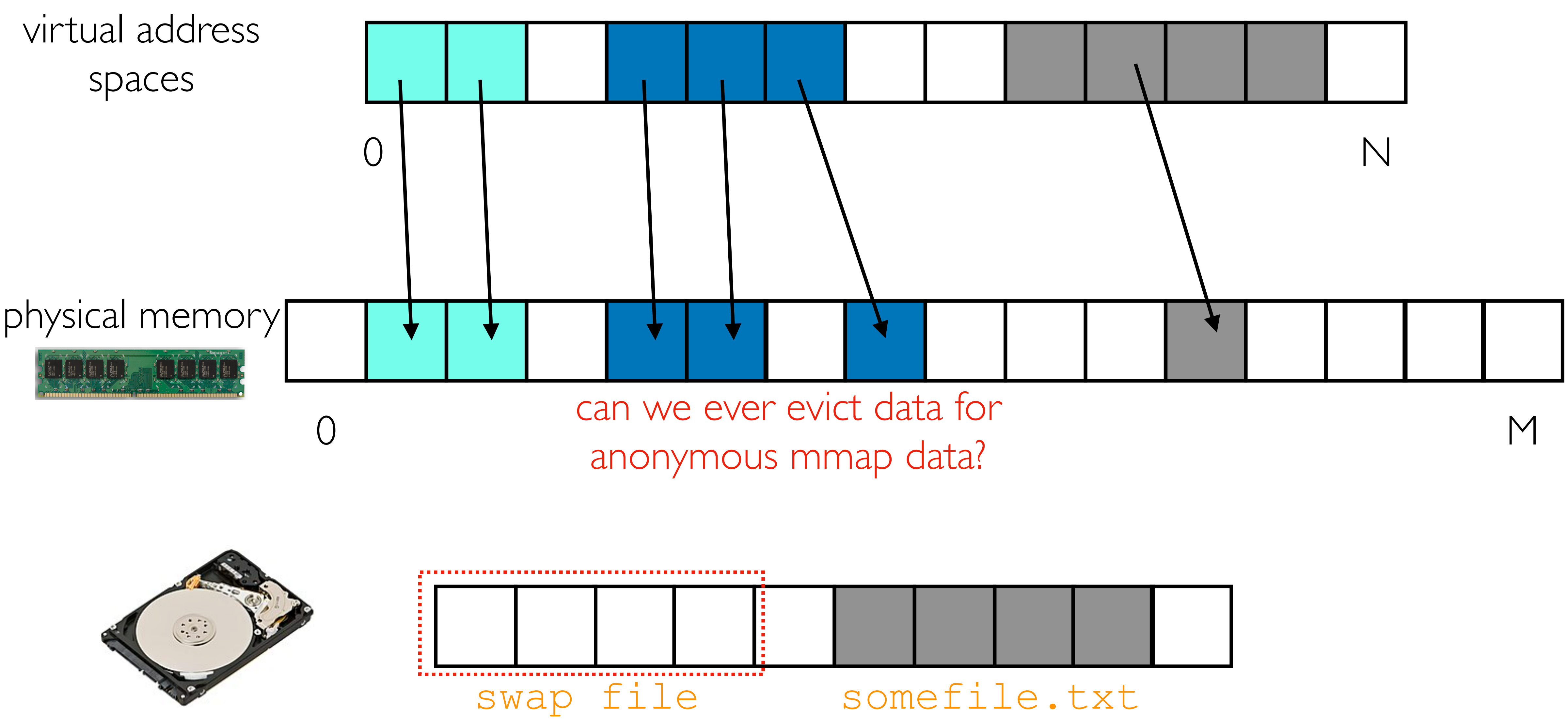
- we can create same space (a swap file) to which the OS can evict data from anonymous mappings



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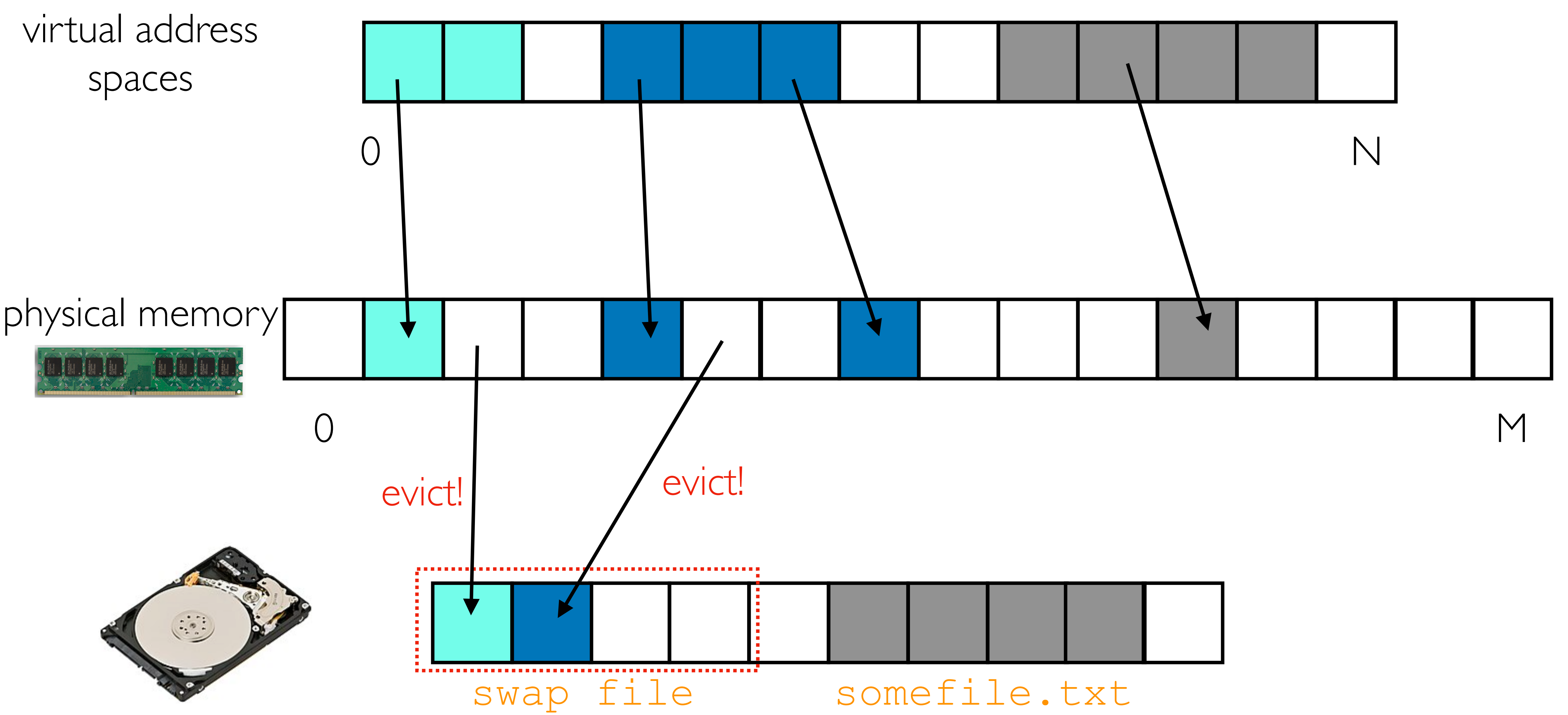
- we can create same space (a swap file) to which the OS can evict data from anonymous mappings
- of course, if we access these virtual addresses again, it will be slow to bring the data back



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