Compacting the Uncompactable!

MESH

Automatically Compacting
Your C/C++ Application's Memory (& more!)

Emery Berger
UMass Amherst

with Bobby Powers, David Tench, & Andrew McGregor
University of Massachusetts Amherst
http://libmesh.org

[PLDI 2019]

PIANO • VOCAL • GUITAR

The Impossible Dream
(The Quest)

Lyrics by JOE DARIEN
Music by MITCH LEIGH

PIANO · VOCAL · GUITAR

The Impossible Dream
(The Quest)

Lyrics by JOE DARIEN
Music by MITCH LEIGH

Reconquer
all of Spain!

MALLOC

Reconquer
all of Spain!

MALLOC

~~Reconquer~~ Allocate all of Spain!


PIANO · VOCAL · GUITAR
The Impossible Dream
(The Quest)
Lyrics by JOE DARION
Music by MITCH LEIGH
MALLOC
OF LA MANCHA


PIANO · VOCAL · GUITAR
The Impossible Dream
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MALLOC
MAN OF LA MANCHA


PIANO · VOCAL · GUITAR
The Impossible Dream
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MAN OF LA MANCHA

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(malloc)


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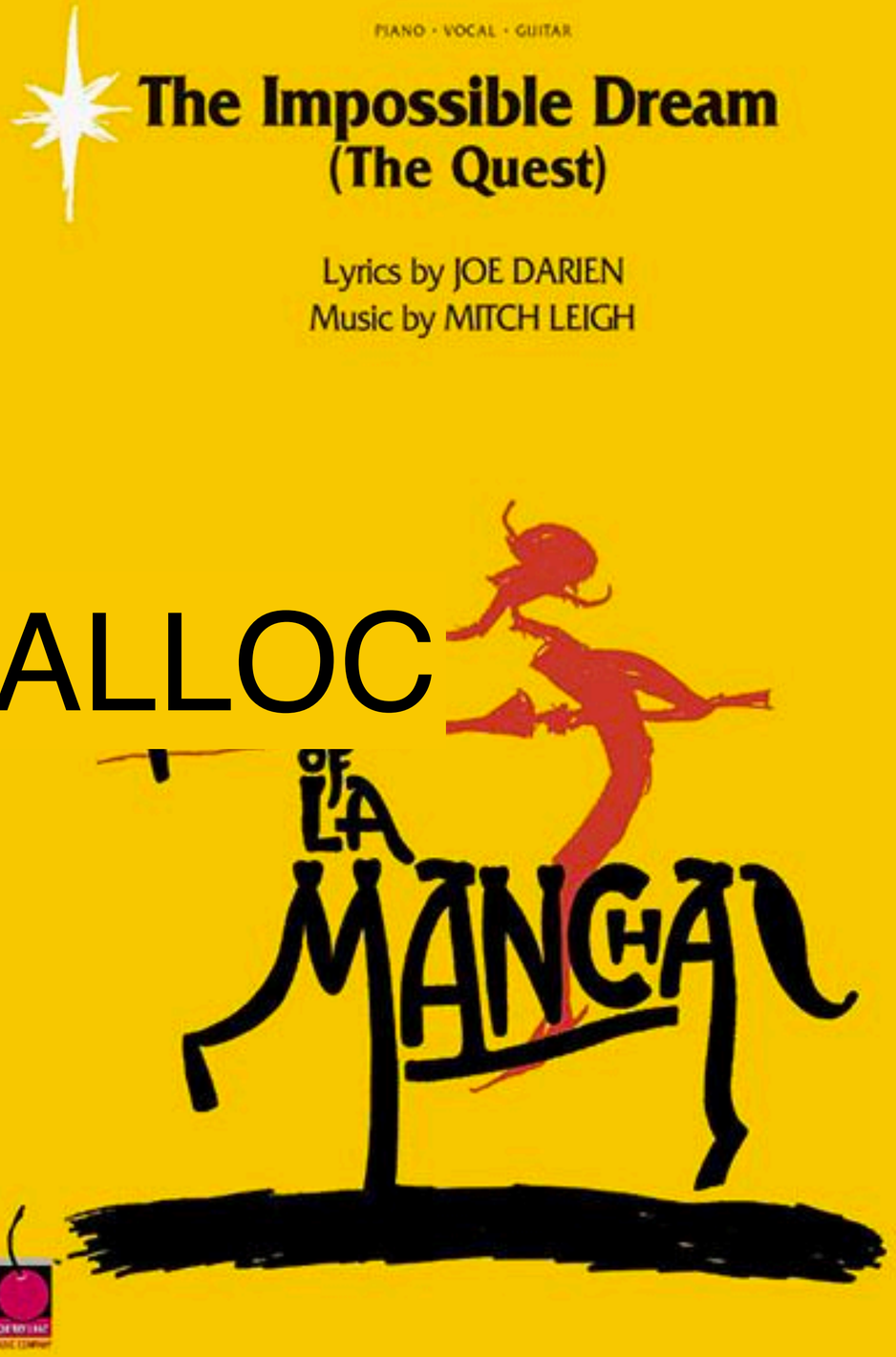
PIANO · VOCAL · GUITAR
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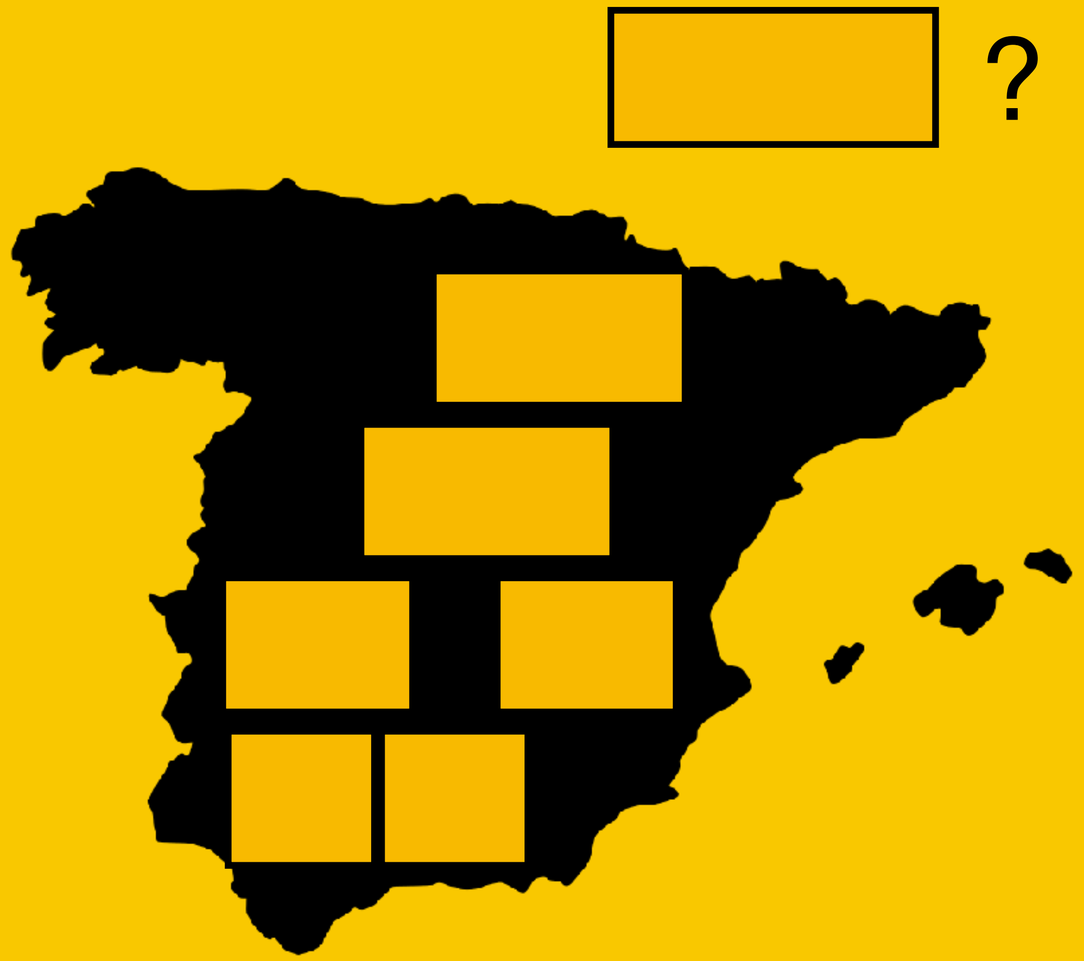
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?


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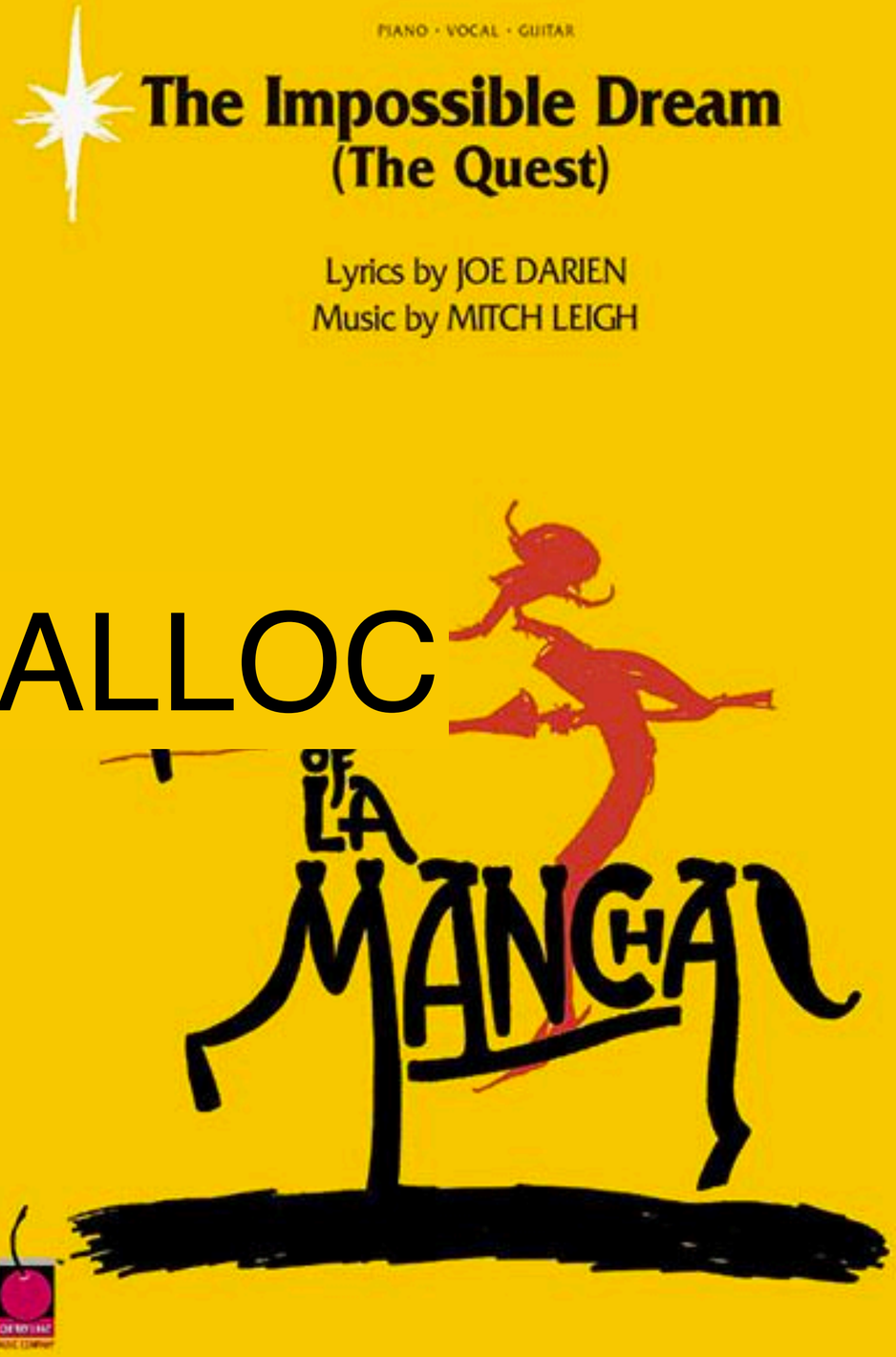
MAN OF LA MANCHA


PIANO · VOCAL · GUITAR
The Impossible Dream
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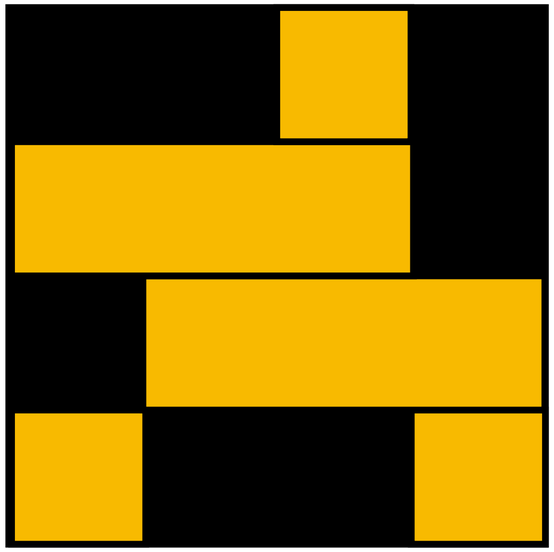
MAN OF LA MANCHA

MALLOC

¡ !

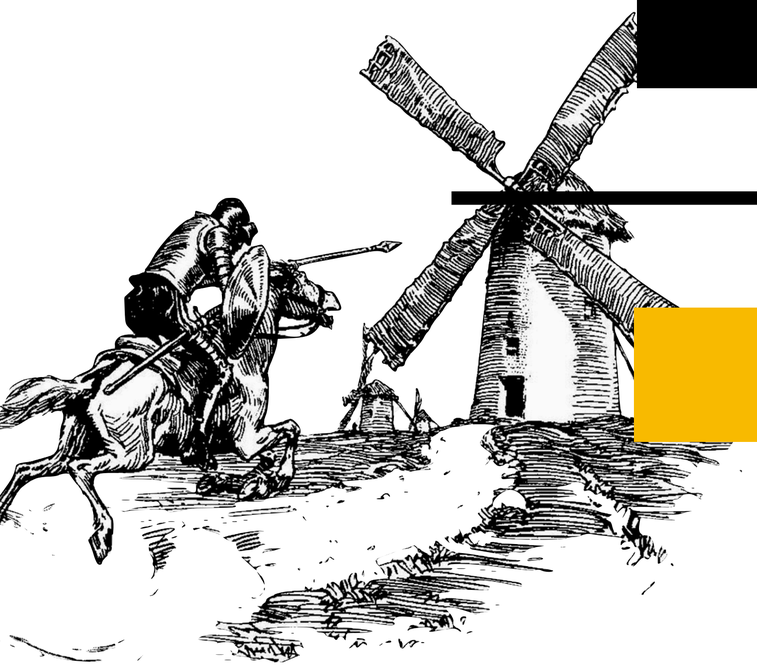
¡Fragmentación!

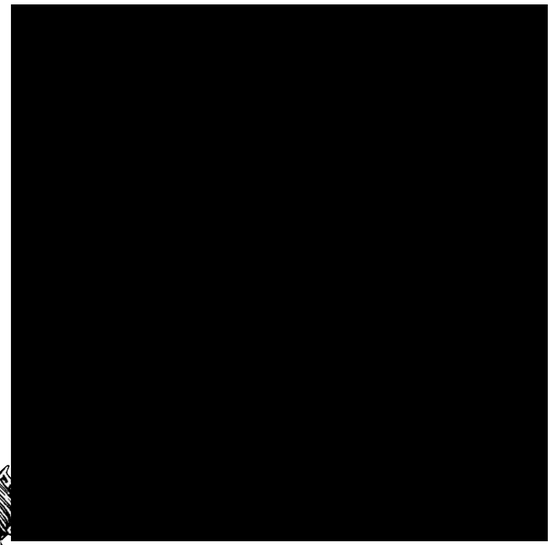


OS Page (“Spain”)

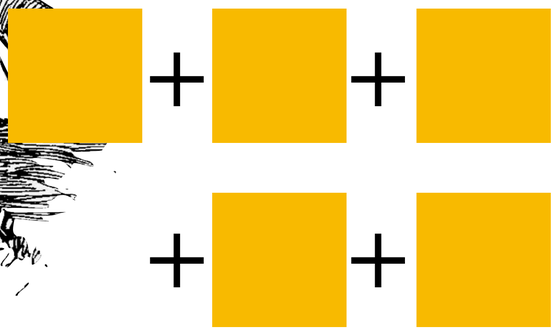
Live objects (malloc’d)

¡Fragmentación!



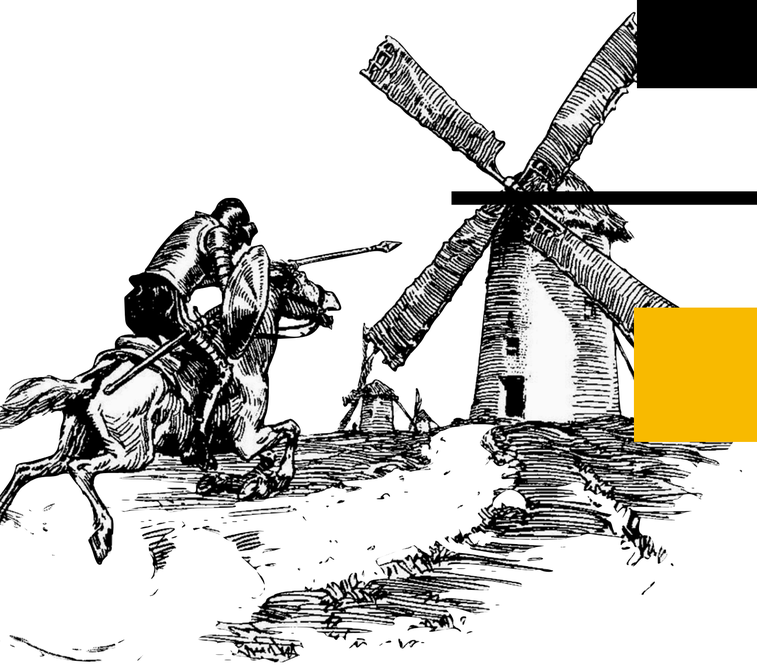


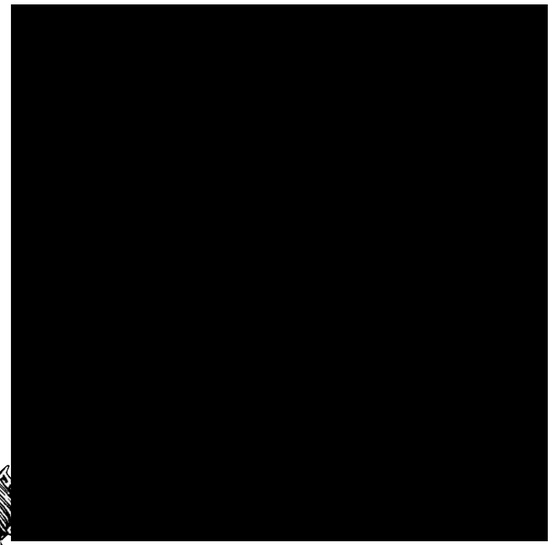
OS Pages



Live objects

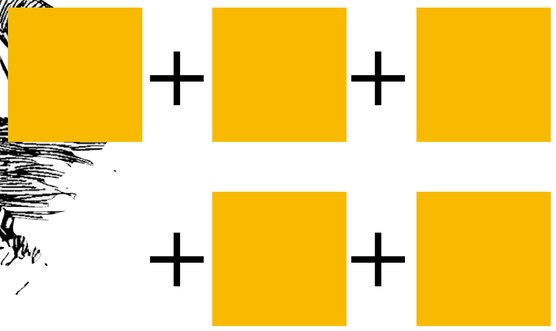
¡Fragmentación!





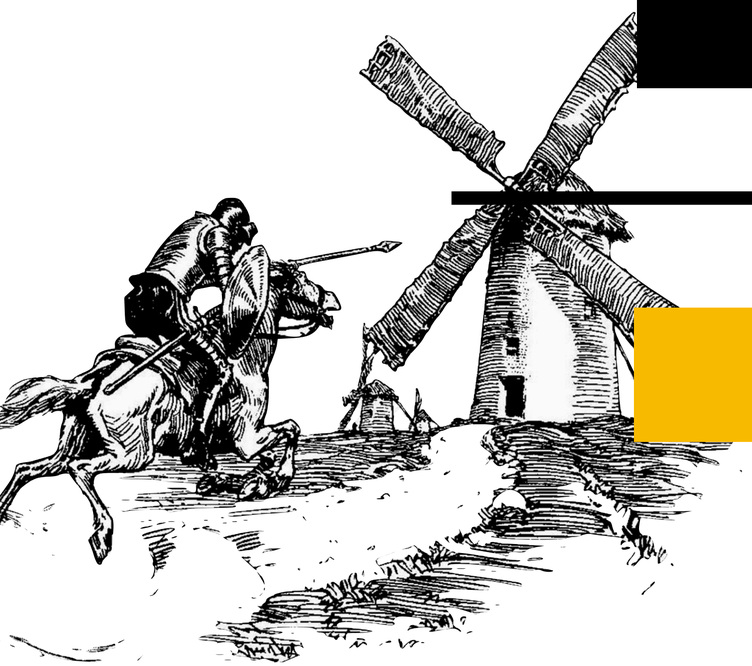
OS Pages

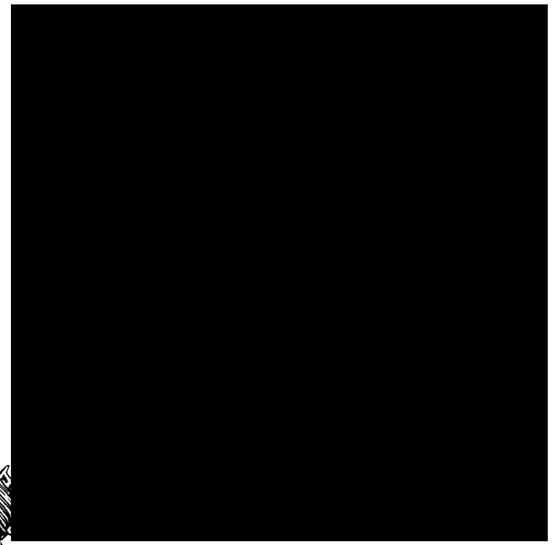
≫ 1



Live objects

¡Fragmentación!

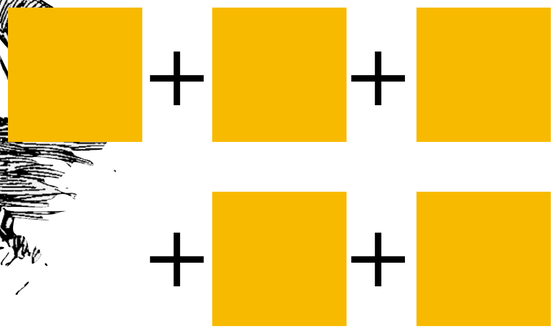




OS Pages

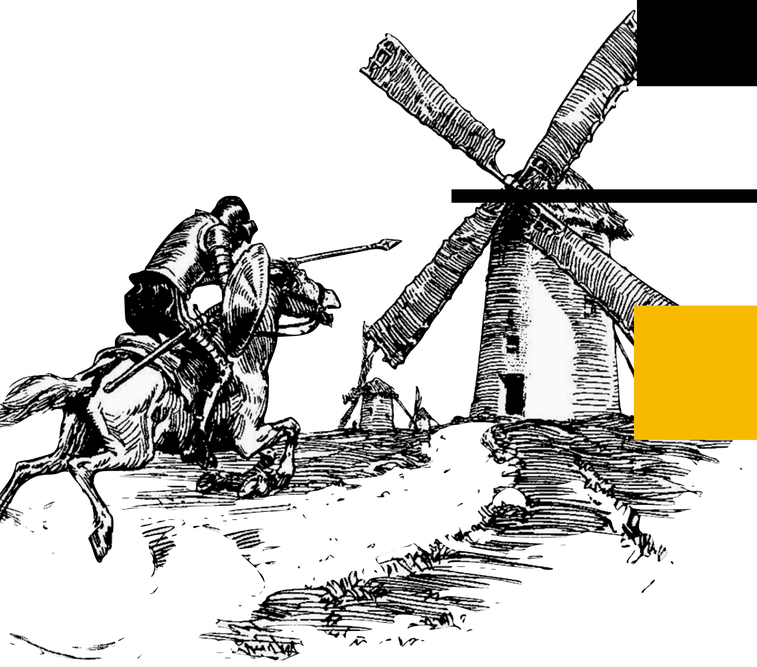
O(log ) 13x!

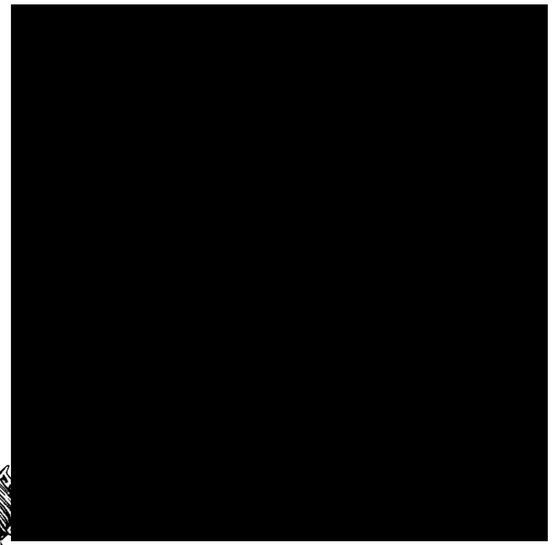
[Robson ’77]



Live objects

¿Compactación?





OS Pages

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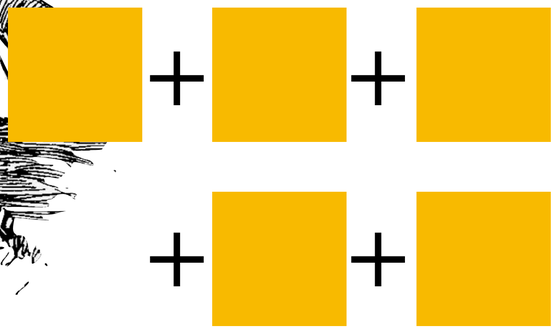
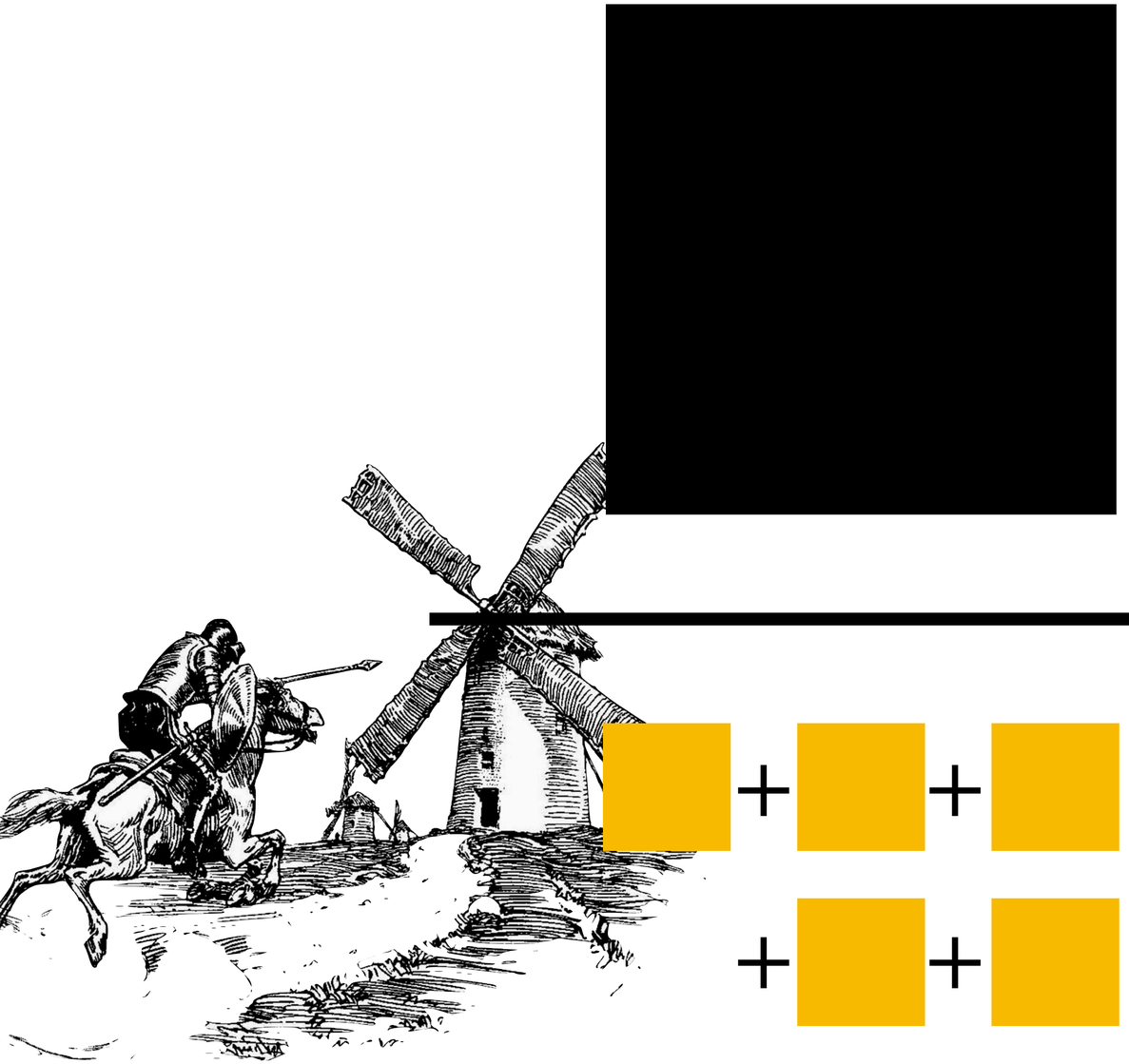


Live objects

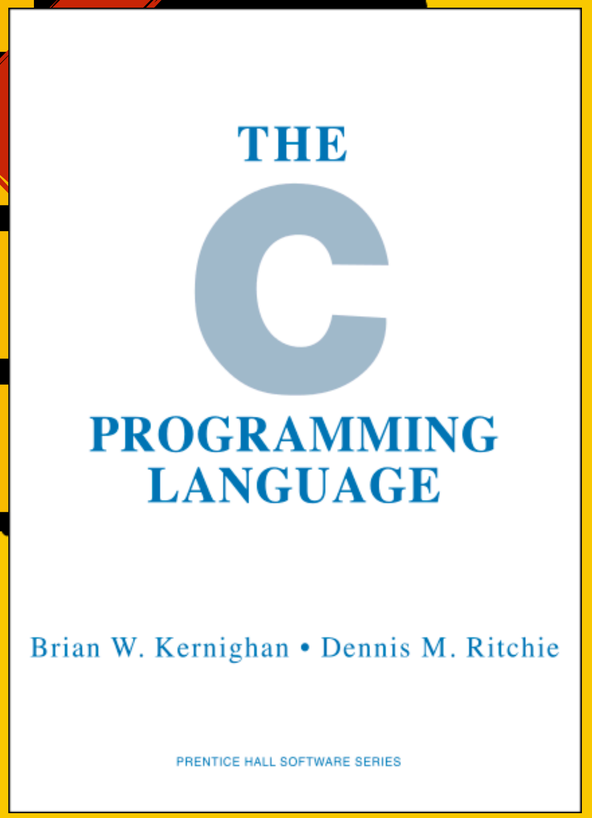
¿Compactación?

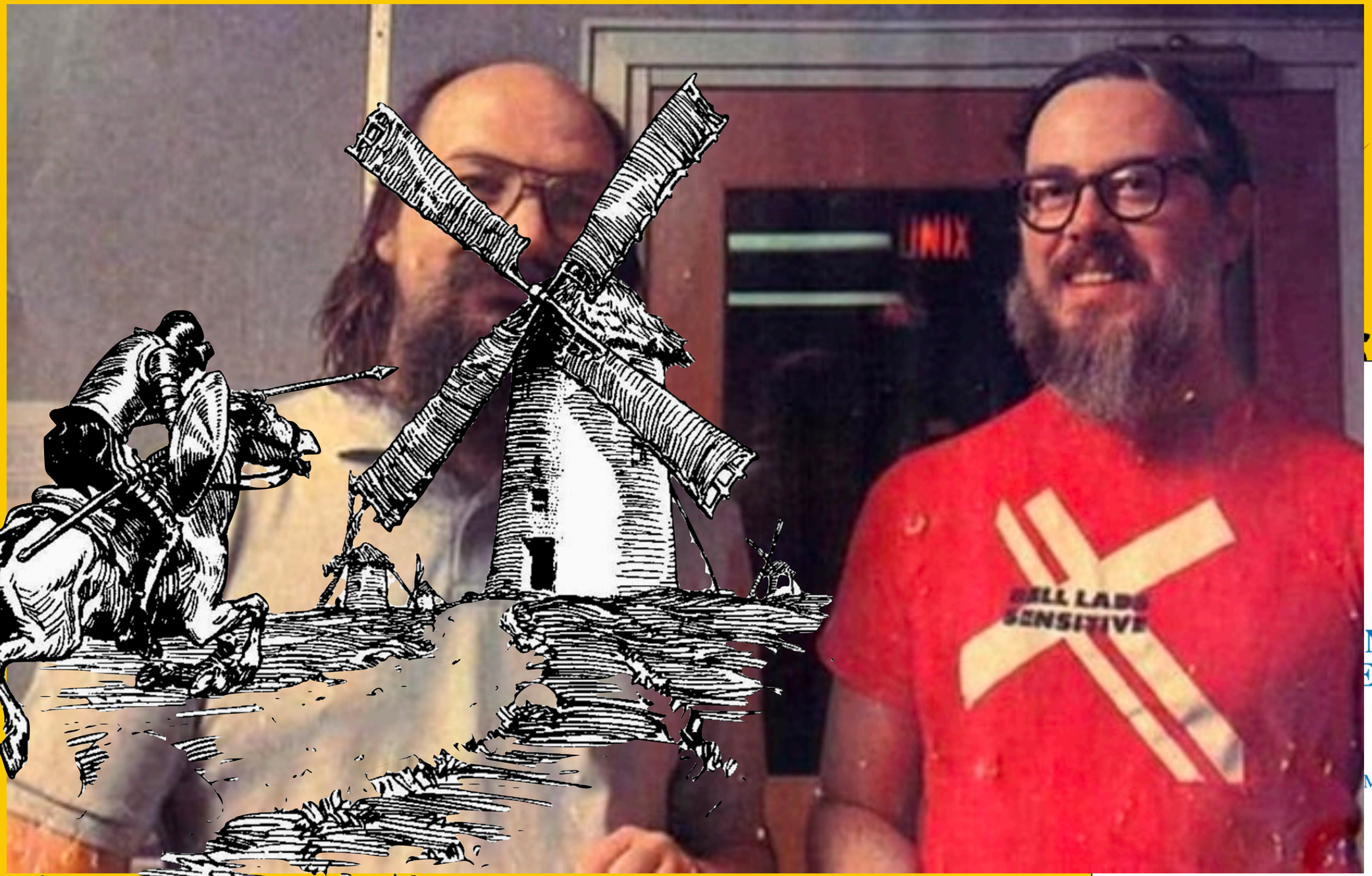


OS Pages

O(1)

Live objects


THE
C
PROGRAMMING
LANGUAGE
Brian W. Kernighan • Dennis M. Ritchie
PRENTICE HALL SOFTWARE SERIES



NG
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M. Ritchie

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M. Ritchie

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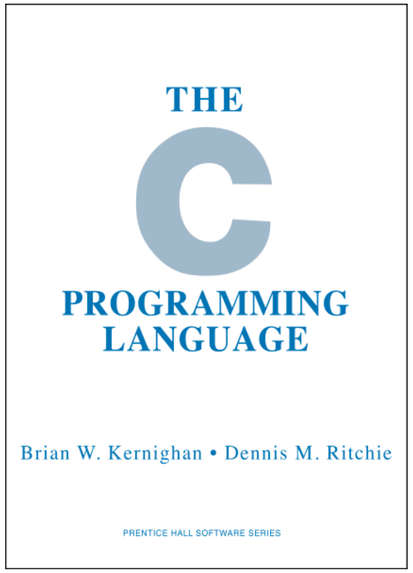
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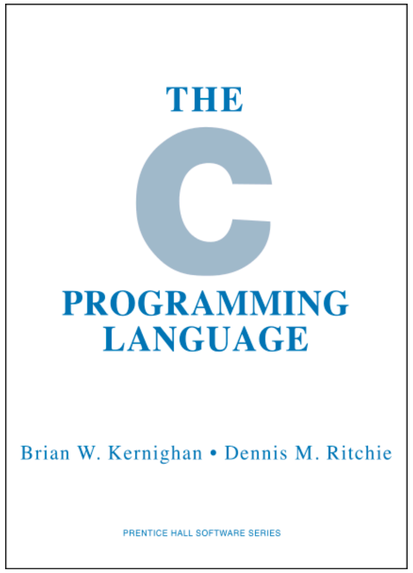
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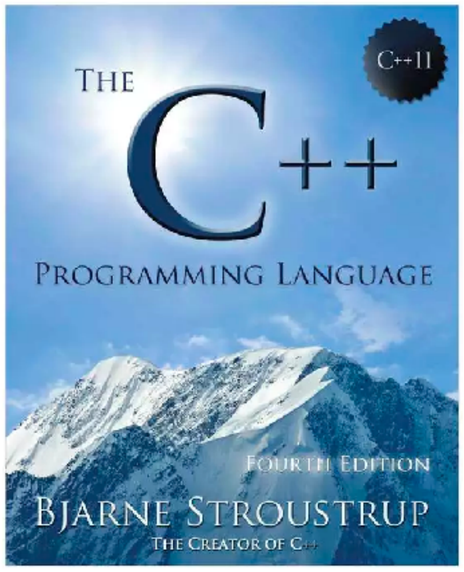
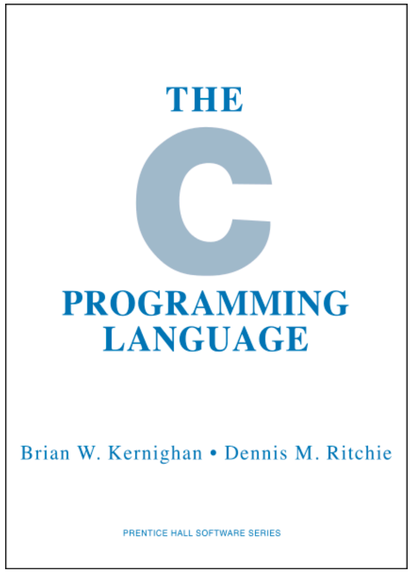

THE
C++
C++11
PROGRAMMING LANGUAGE
FOURTH EDITION
BJARNE STROUSTRUP
THE CREATOR OF C++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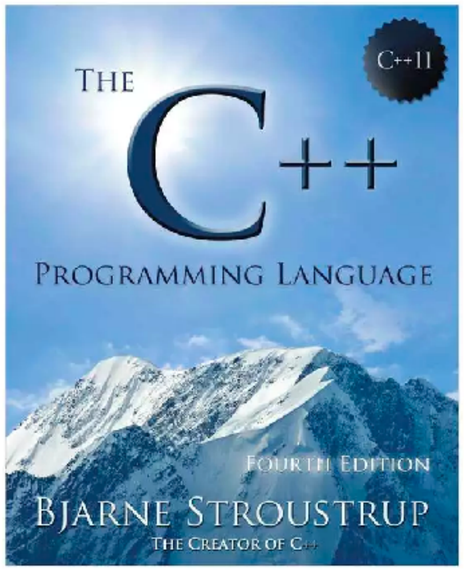
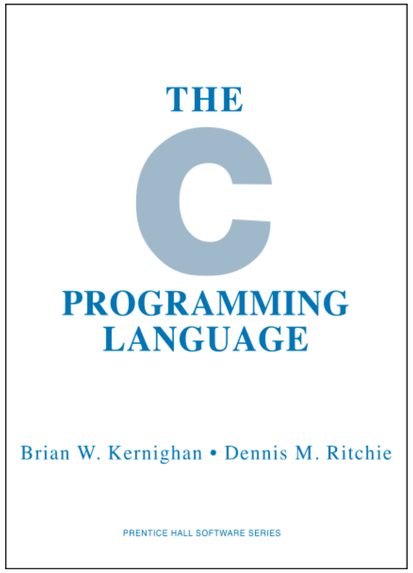

THE
C++
C++11
PROGRAMMING LANGUAGE
FOURTH EDITION
BJARNE STROUSTRUP
THE CREATOR OF C++


The Swift
Programming
Language
Swift 5 Edition



[Lattner, 2016]

Why not a tracing GC?

- Native interoperability with unmanaged code
- Deterministic destruction provides:
  - No "finalizer problems" like resurrection, threading, etc.
  - Deterministic performance: can test/debug performance stutters
- Performance:
  - GC use ~3-4x more memory than ARC to achieve good performance
  - Memory usage is very important for mobile and cloud apps
  - Incremental/concurrent GCs slow the mutator like ARC does

Quantifying the Performance of Garbage Collection vs. Explicit Memory Management
Matthew Hertz, Emery D. Berger. OOPSLA'05

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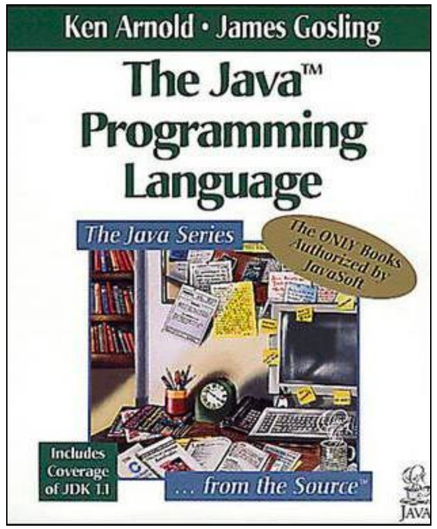
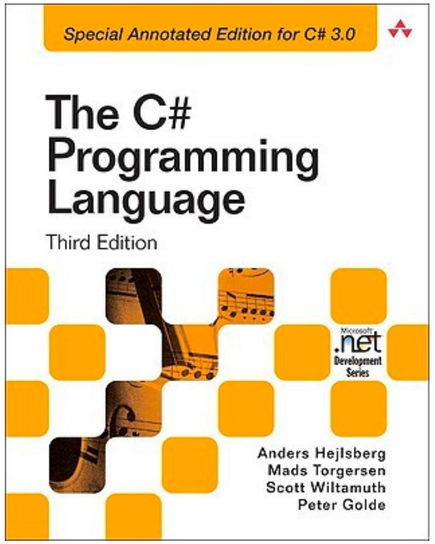
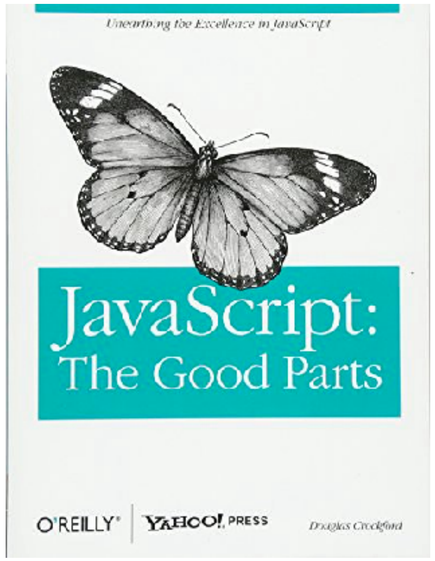
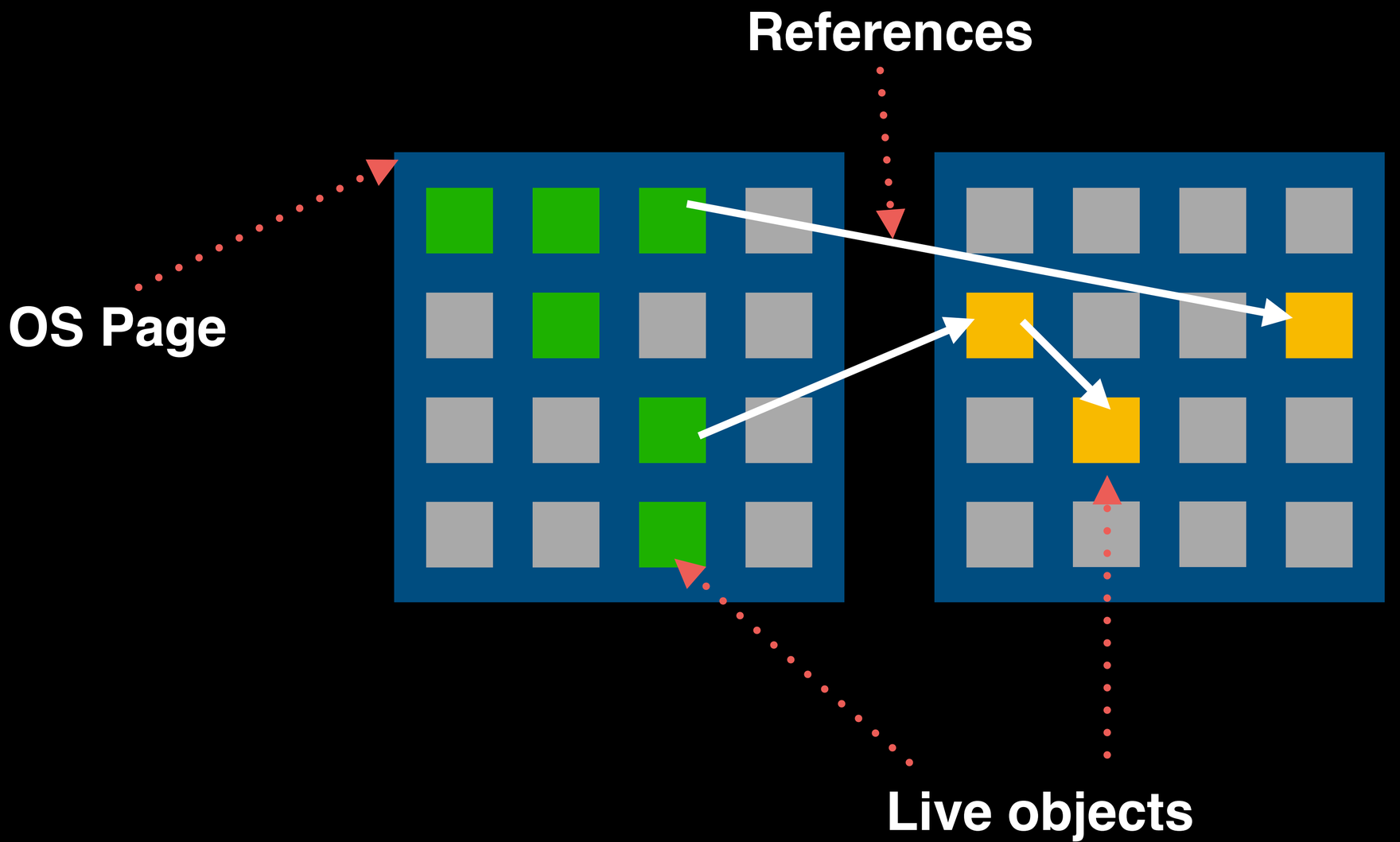


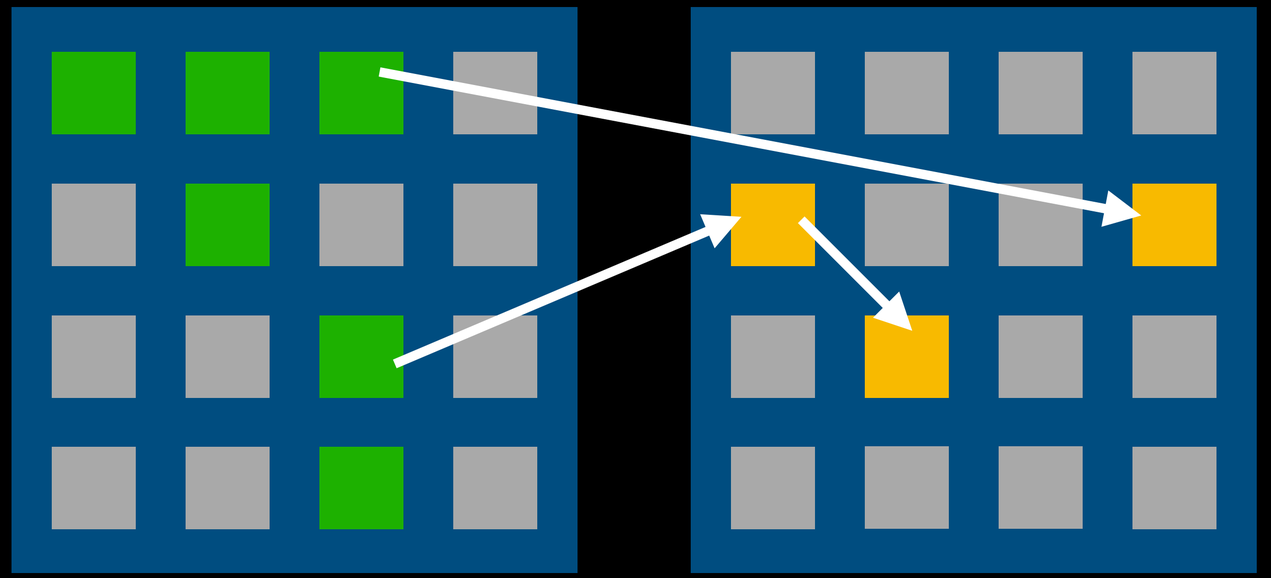


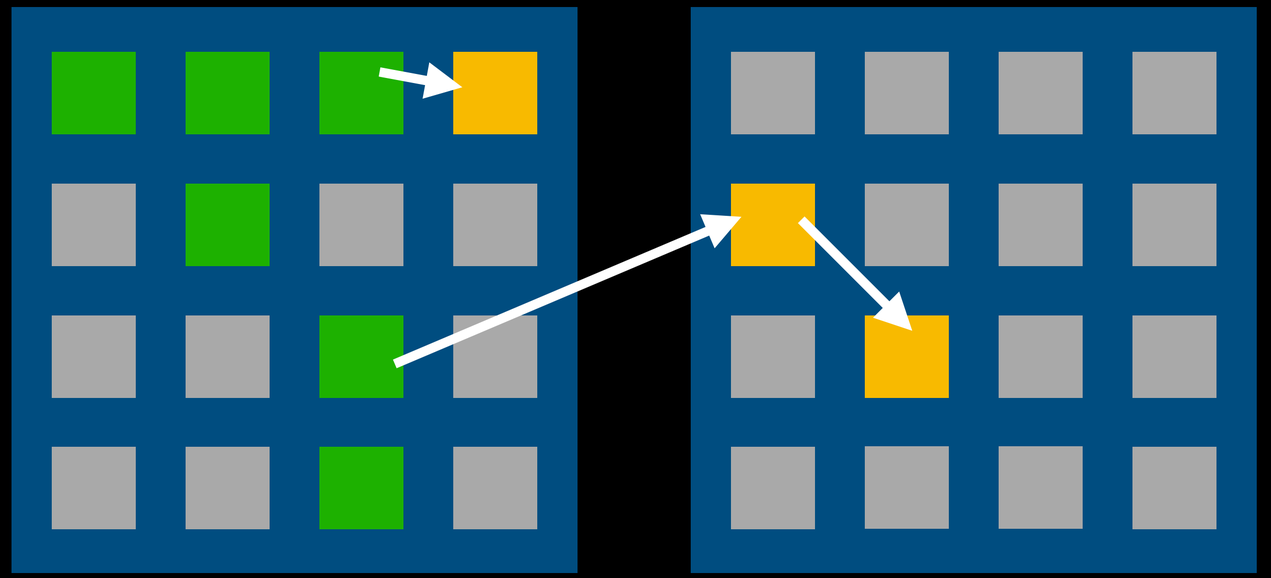


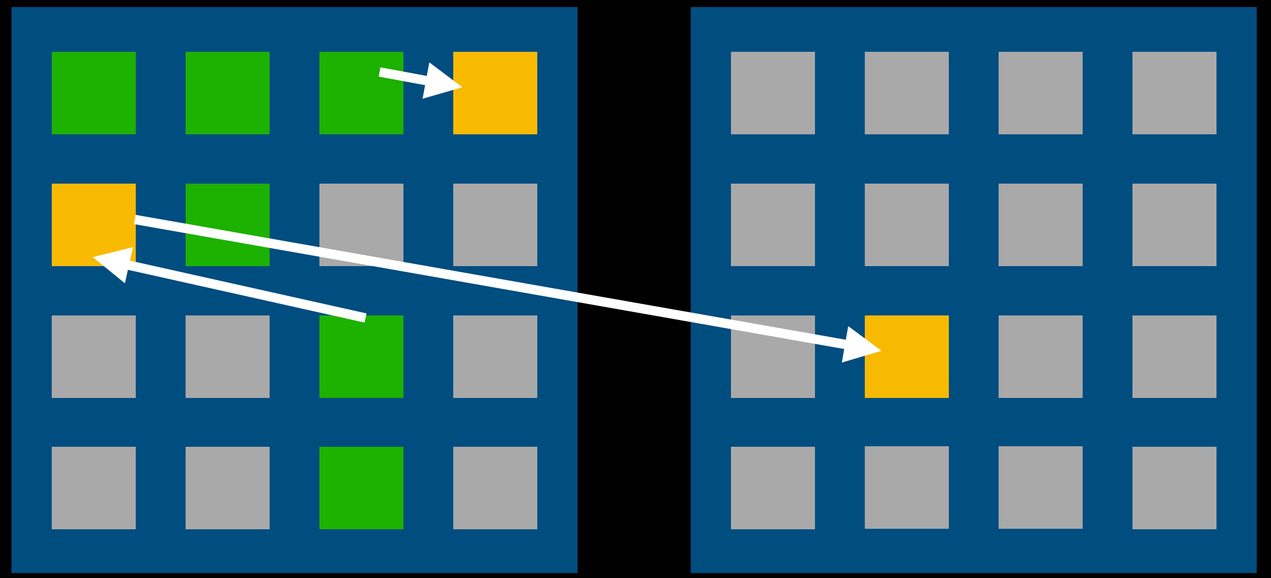
¡Compactación!

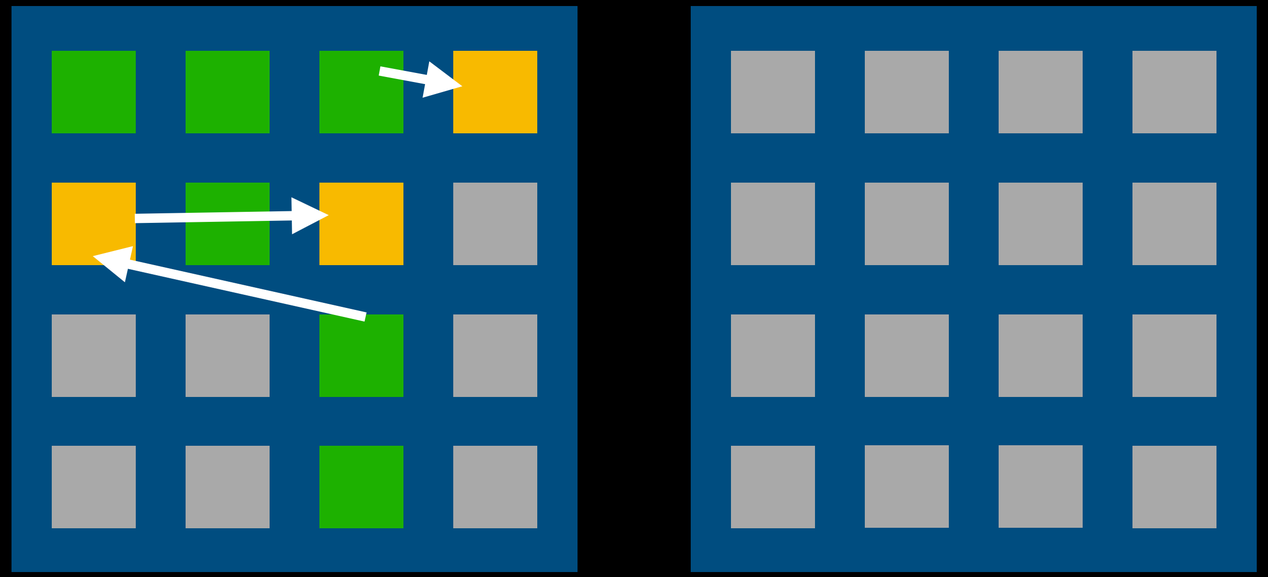
Compaction In Action

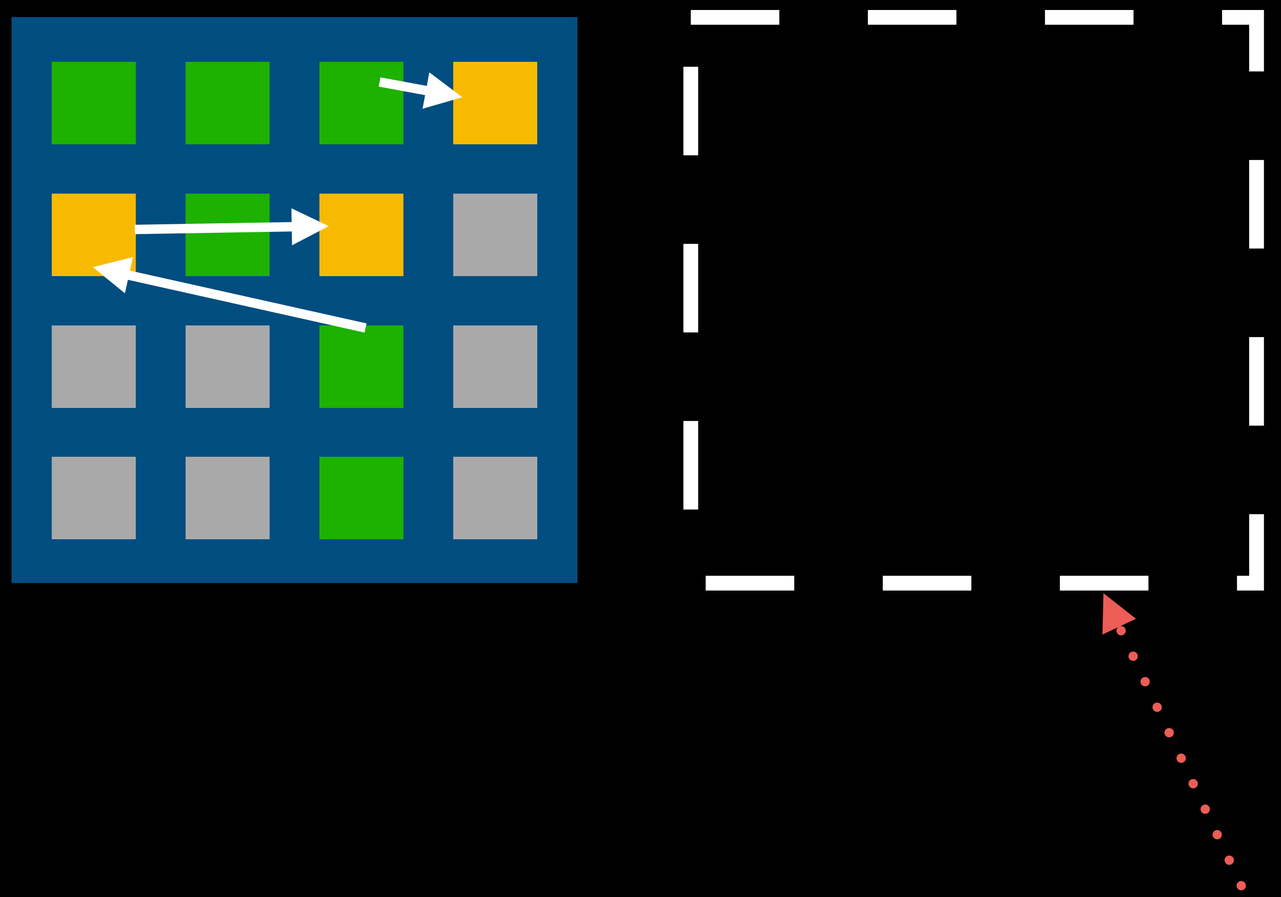












Page returned
to the OS

```
$ clang++ -o yolo main.cc
$ strip yolo
$ ./yolo
```

No way to precisely distinguish pointers from integers

```
$ clang++ -o yolo main.cc
$ strip yolo
$ ./yolo
```

No way to precisely distinguish pointers from integers

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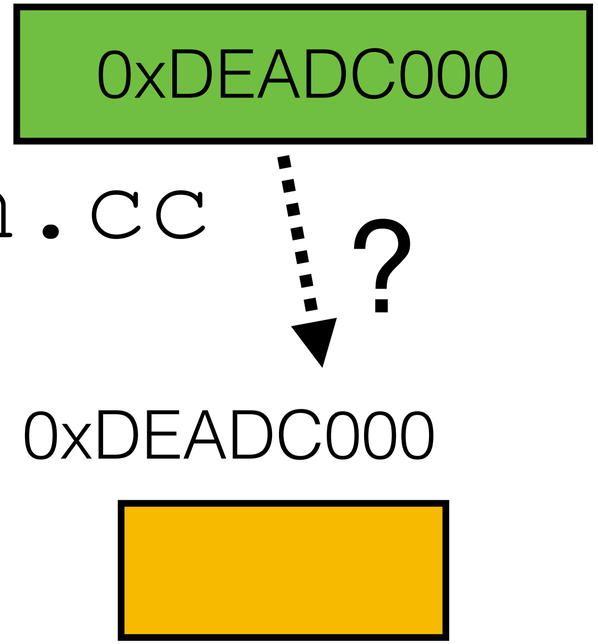
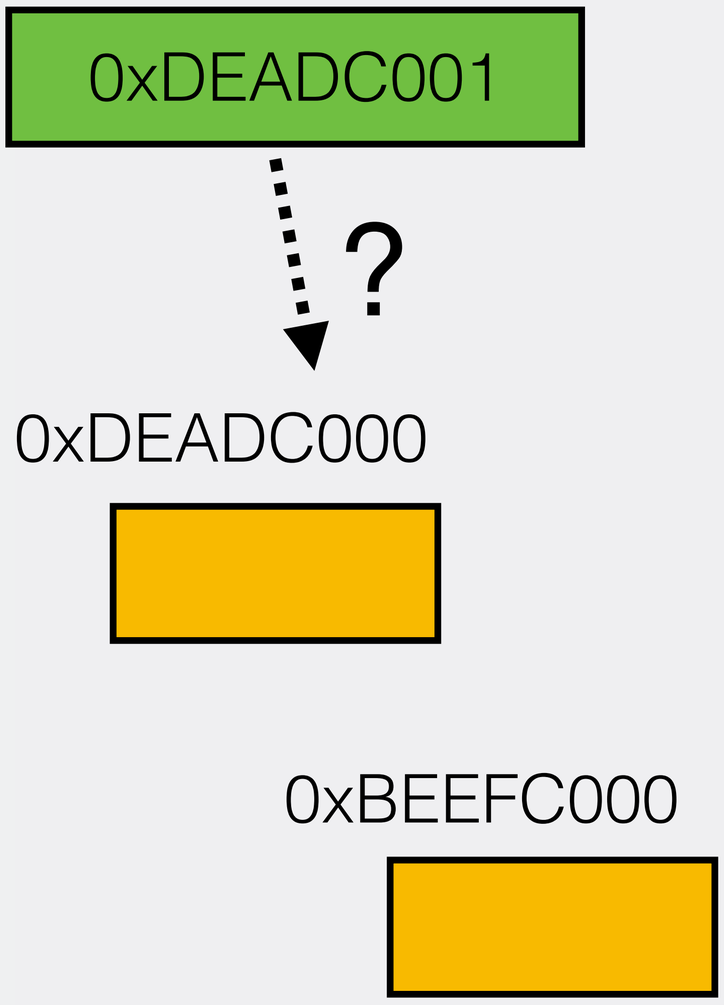


No way to precisely distinguish pointers from integers

```
union tiny
{
 int * ptr;
 uintptr_t flag;
};
tiny x;

// initialize
x.ptr = new int;

// set flag true
x.flag |= 1;
```



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Compaction without Relocation!

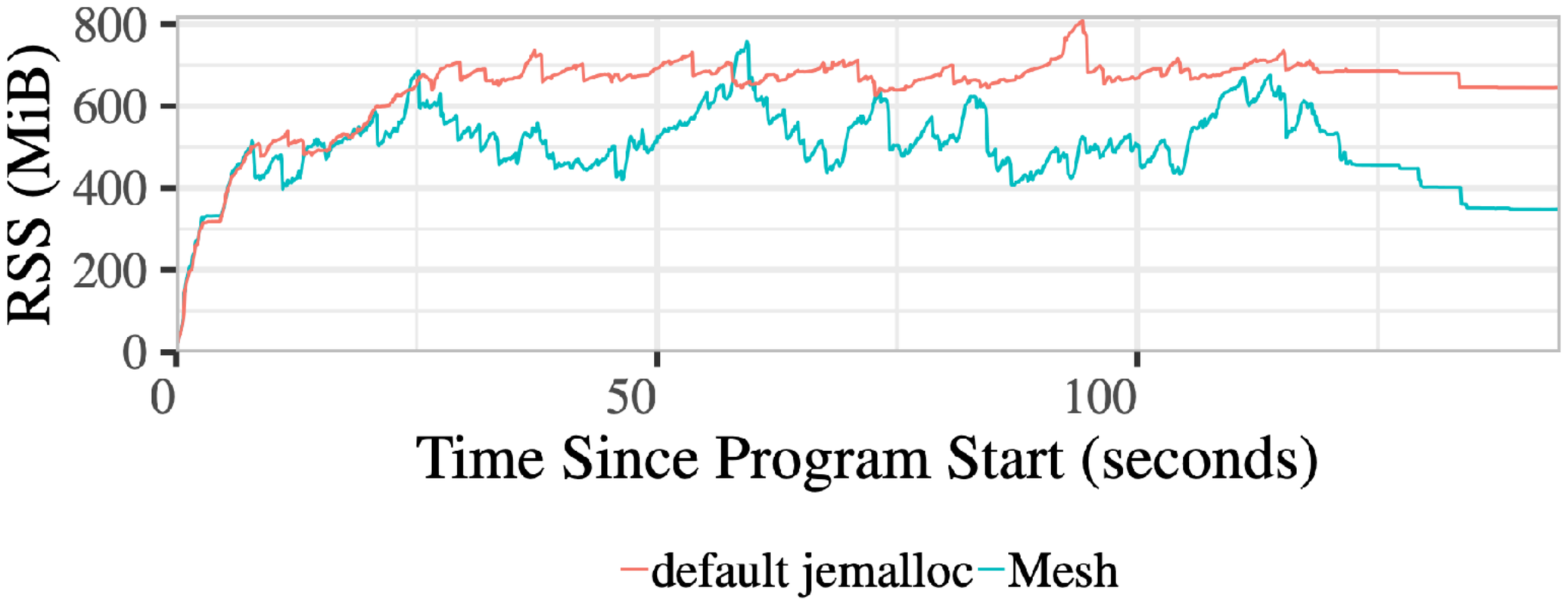
No code changes

No recompilation

(`LD_PRELOAD`)

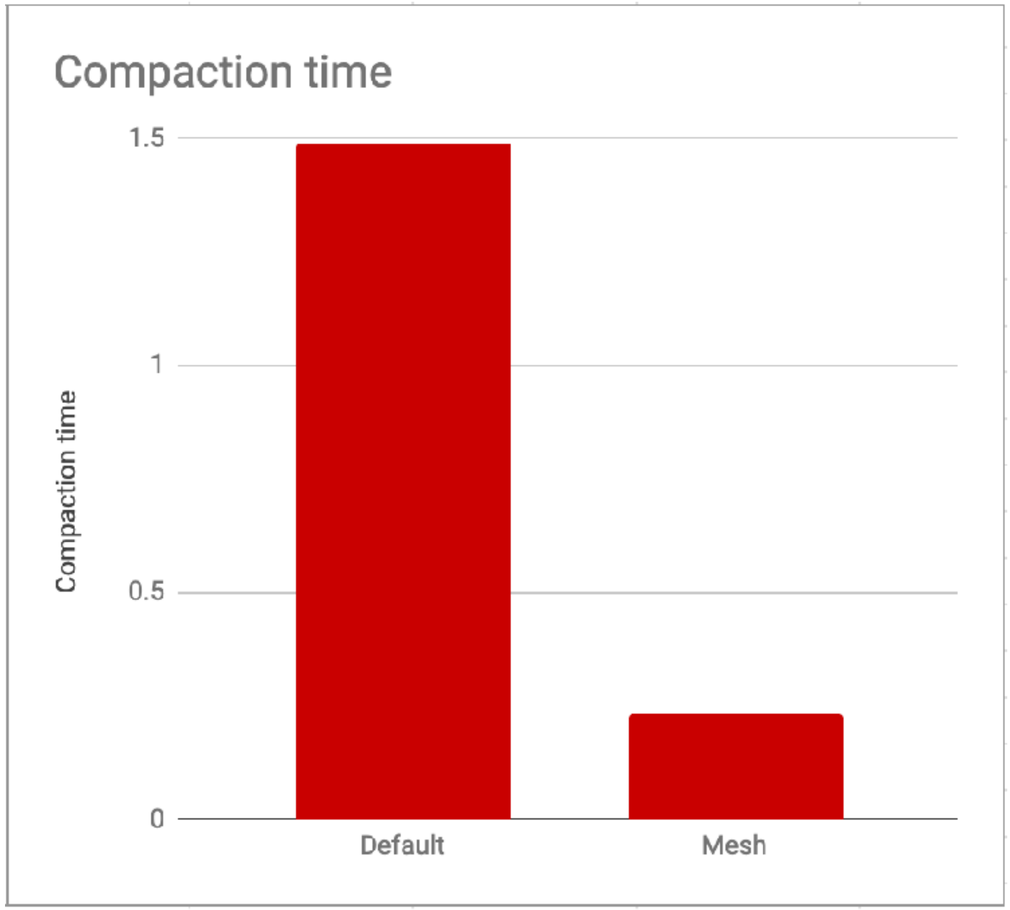
17% heap size reduction

< 1% performance overhead

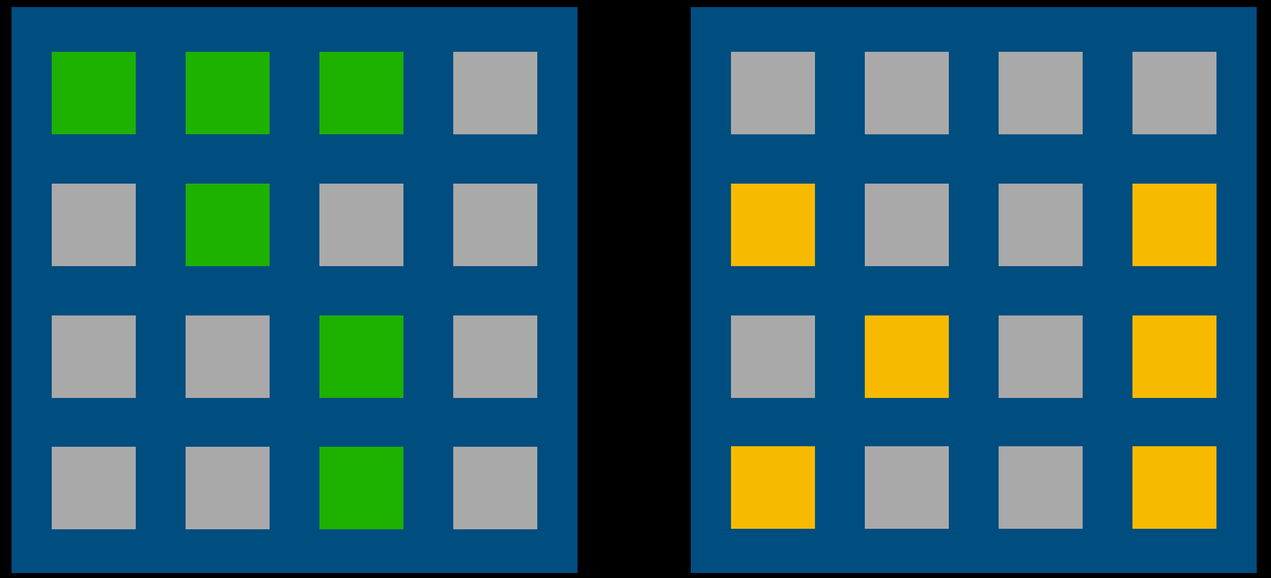


redis


jemalloc + activedefrag
Mesh
no compaction
RSS (MiB)
300
200
100
0
0
1
2
3
4
5
6
Time Since Program Start (seconds)

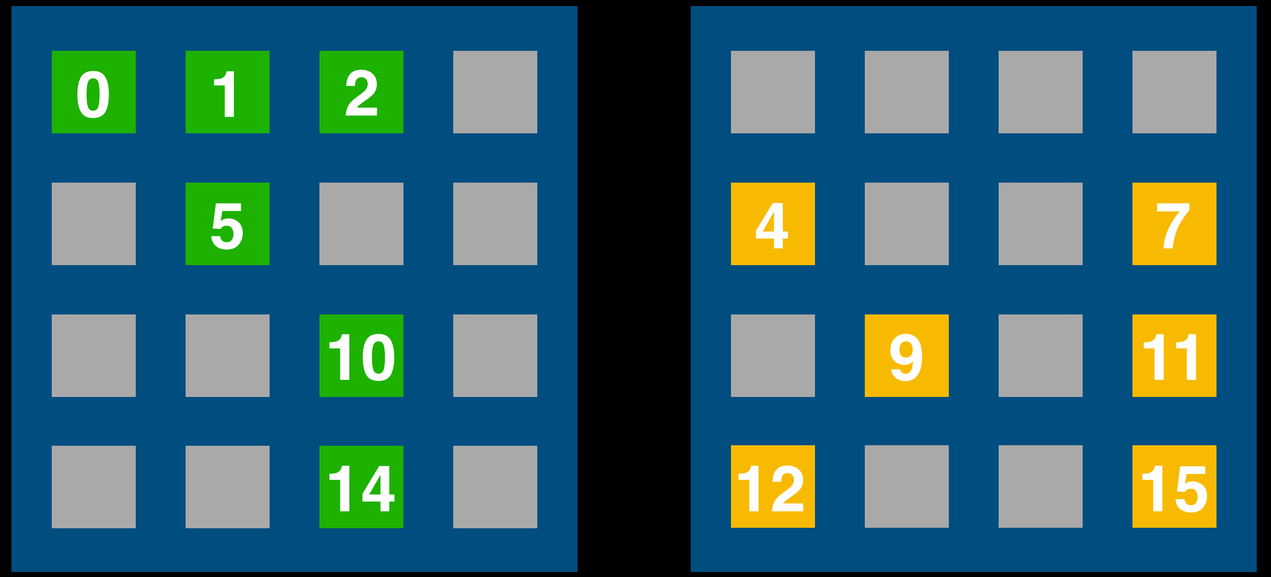


5x reduction in time spent compacting



Pages are ***meshable*** when they:

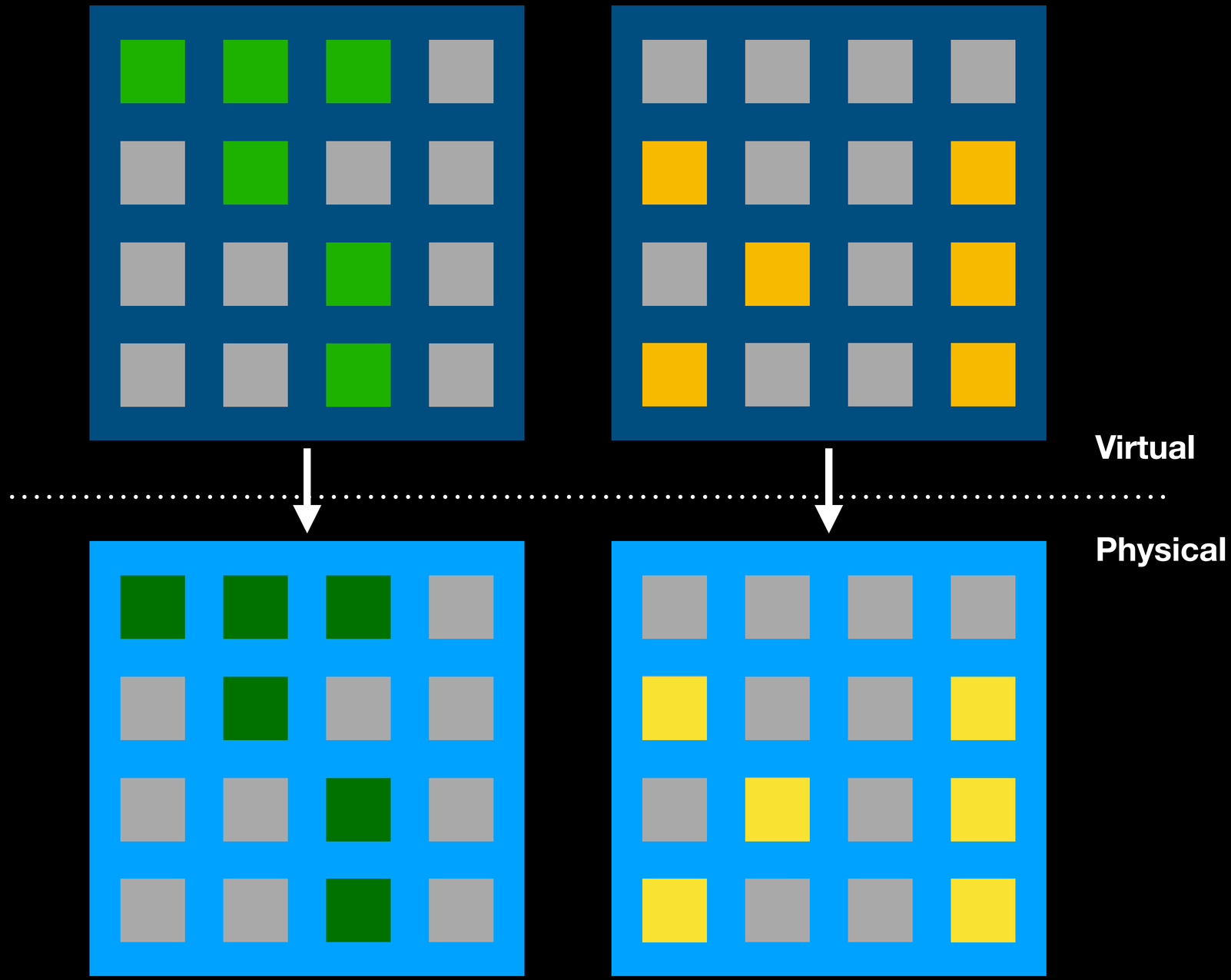
- Hold objects of the same size class



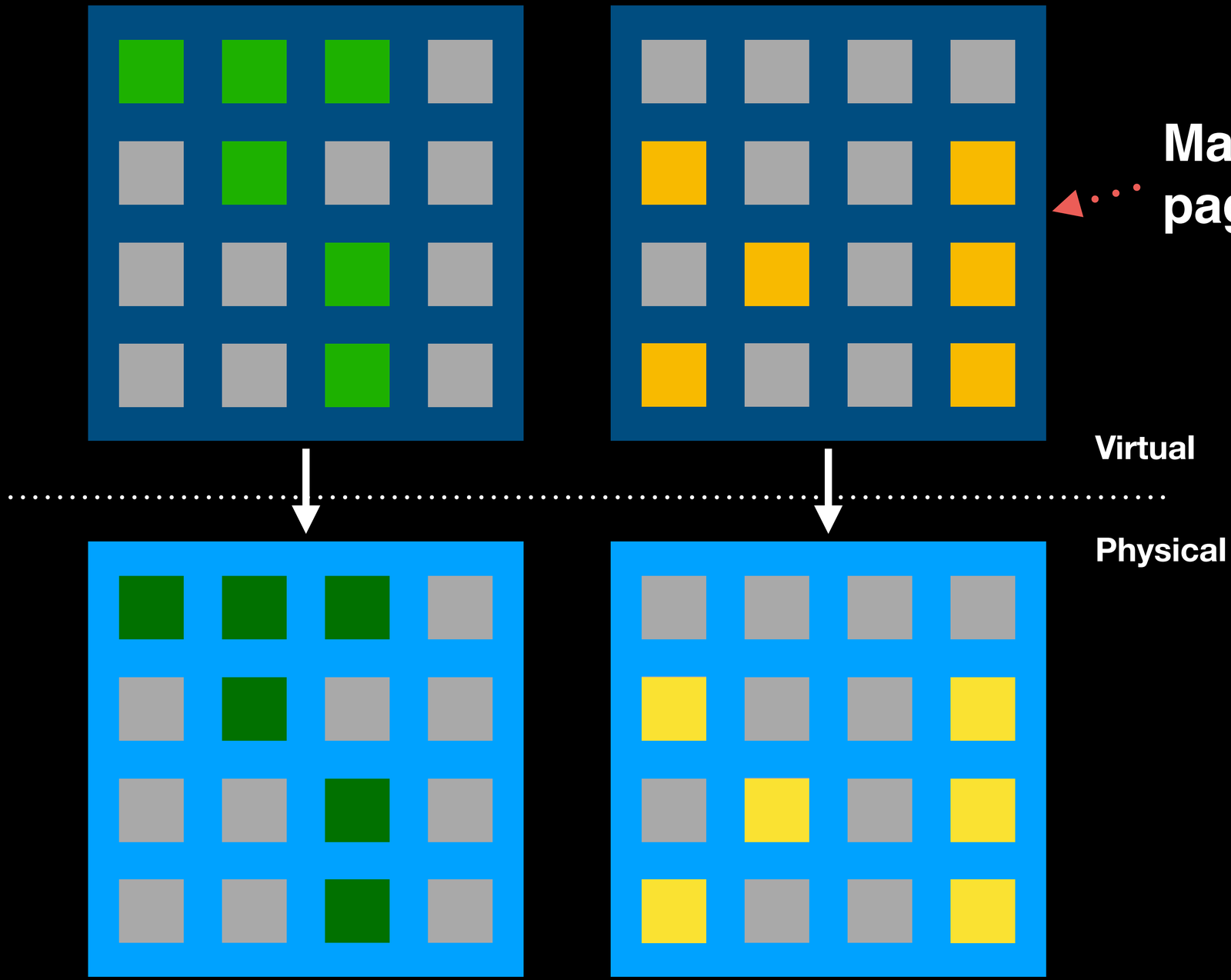
Pages are ***meshable*** when they:

- Hold objects of the same size class
- Have non-overlapping object offsets

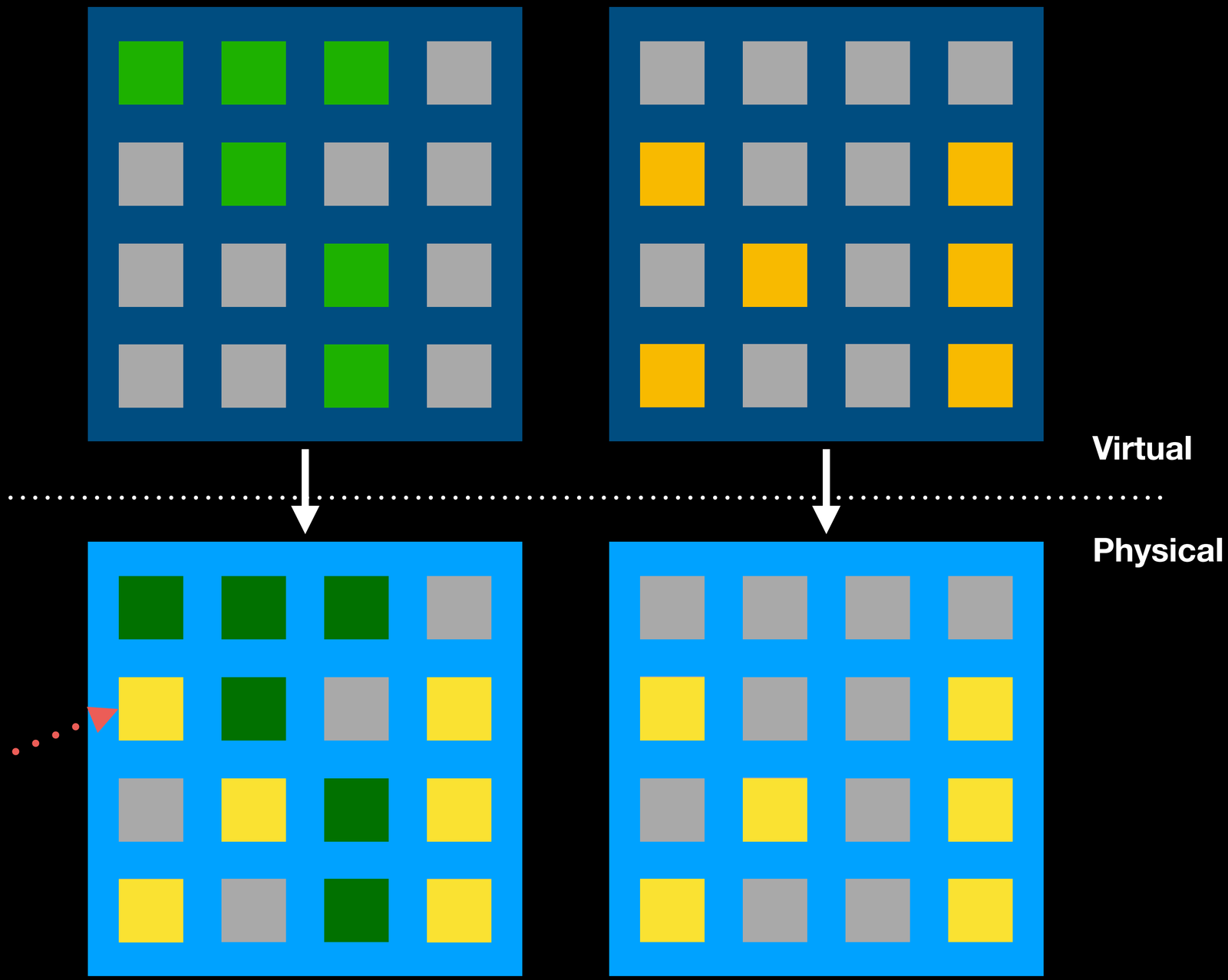
Meshing



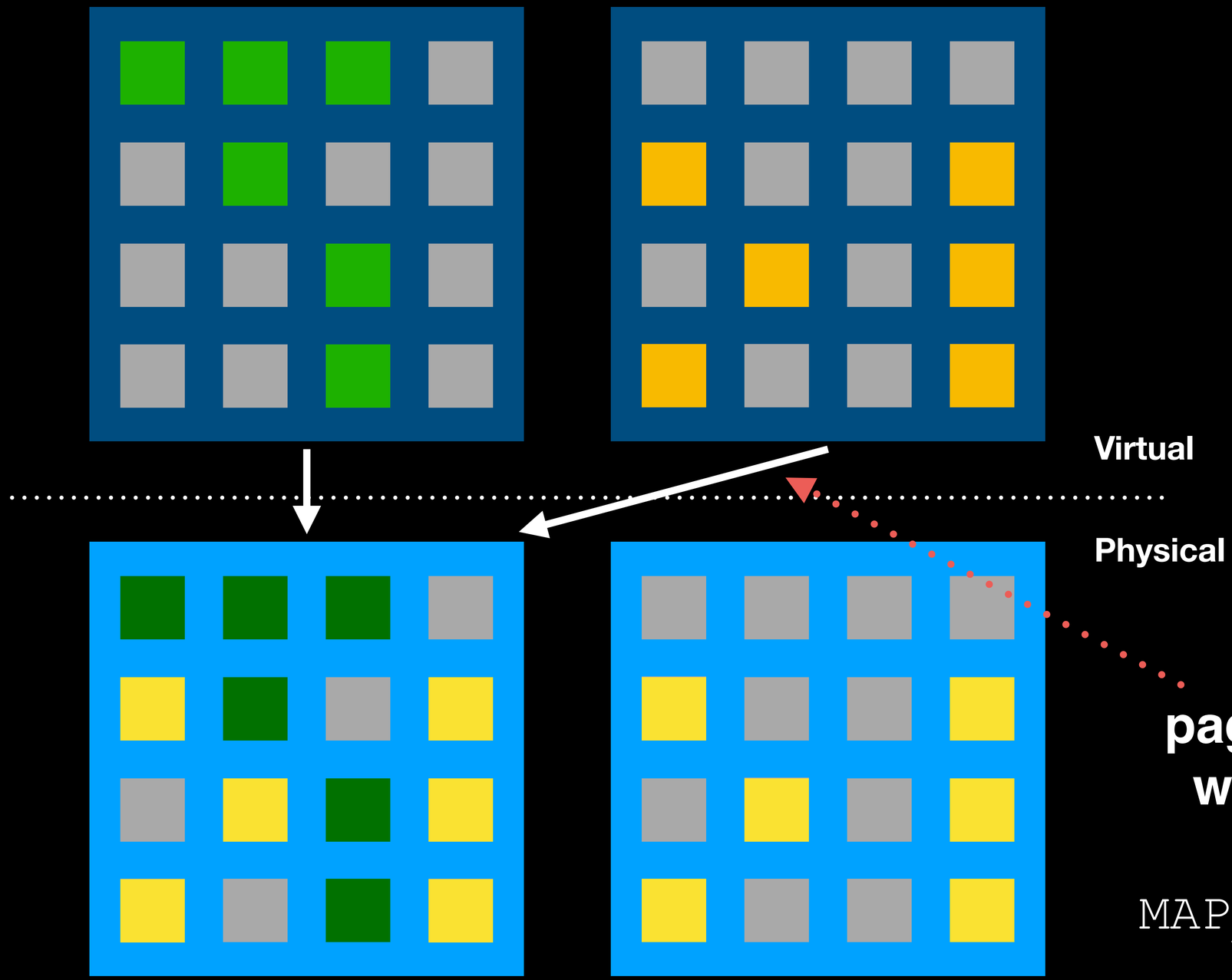
Meshing



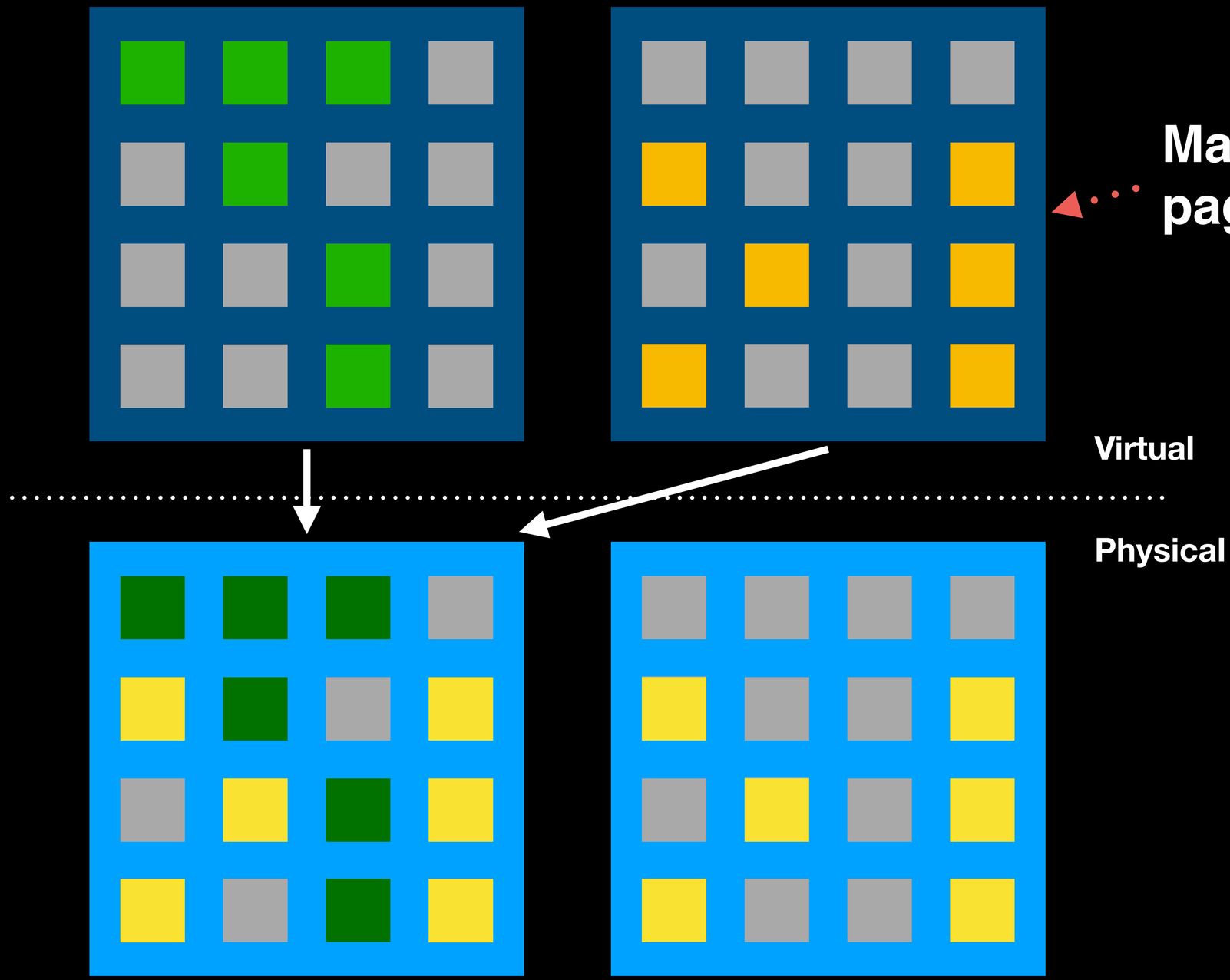
Meshing



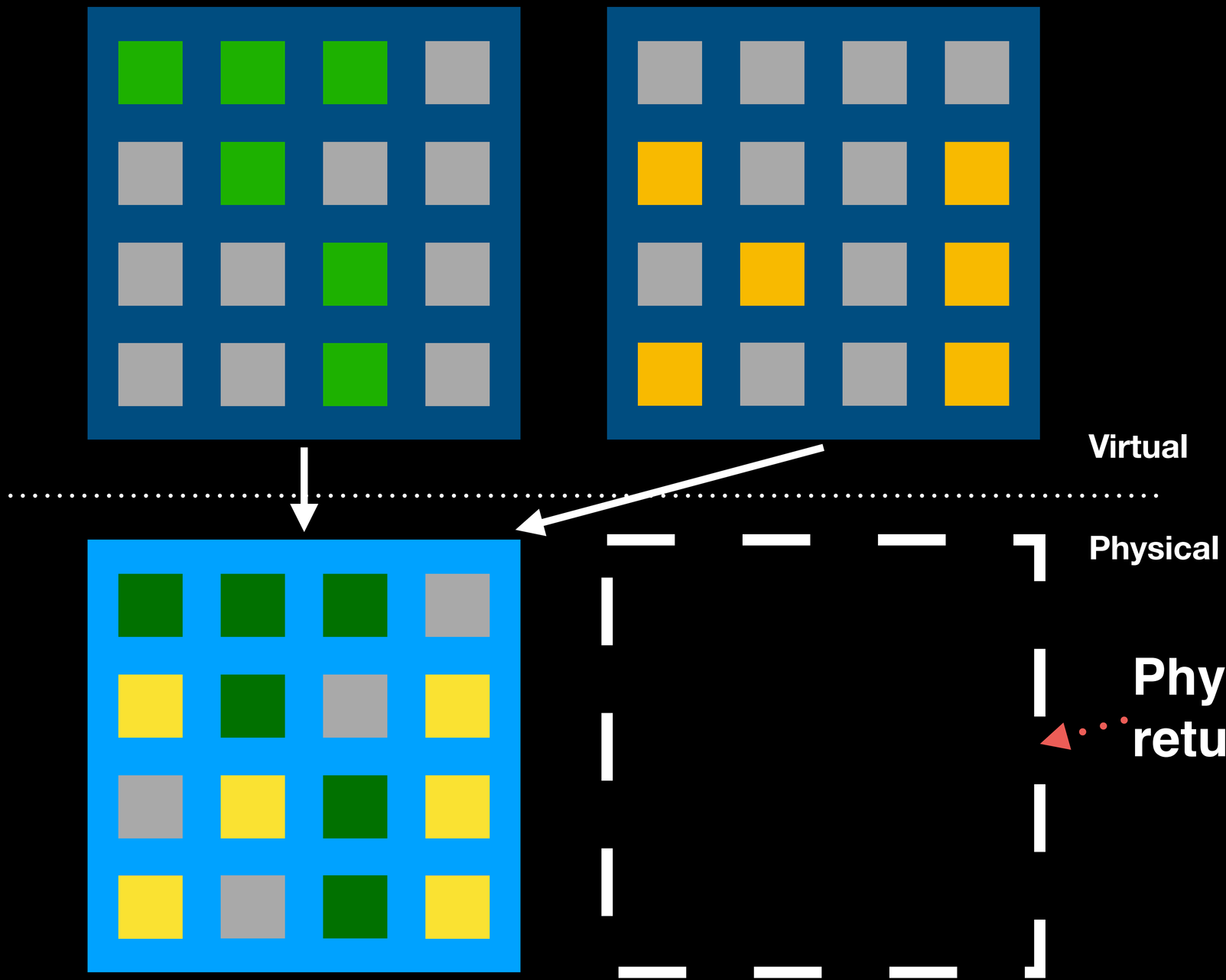
Meshing


Virtual
Physical
Update page tables with mmap, memfd, MAP_SHARED

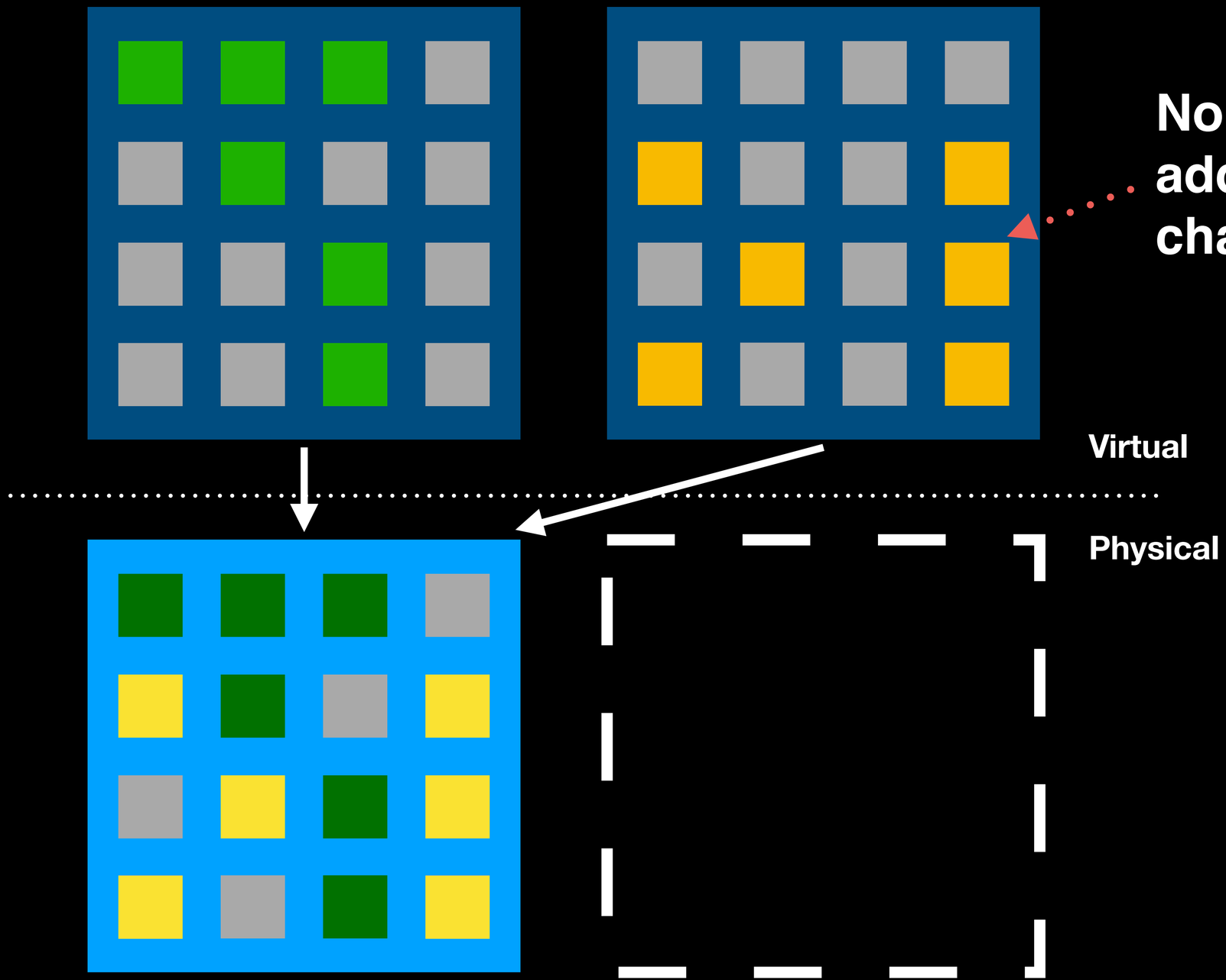
Meshing



Meshing



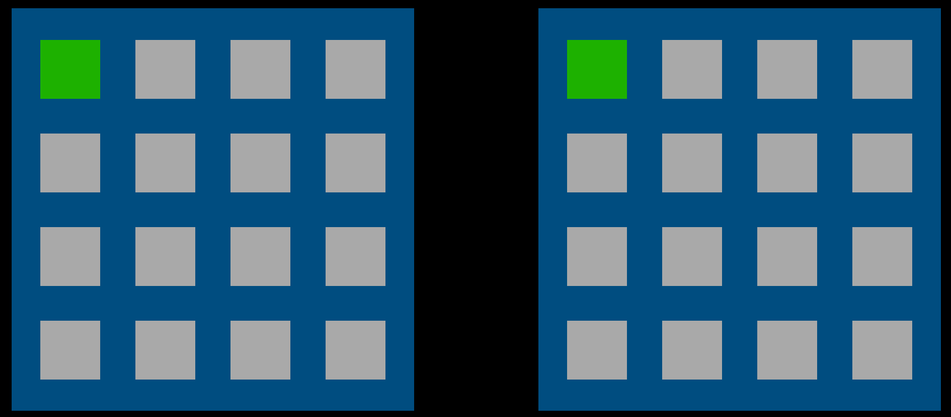
Meshing



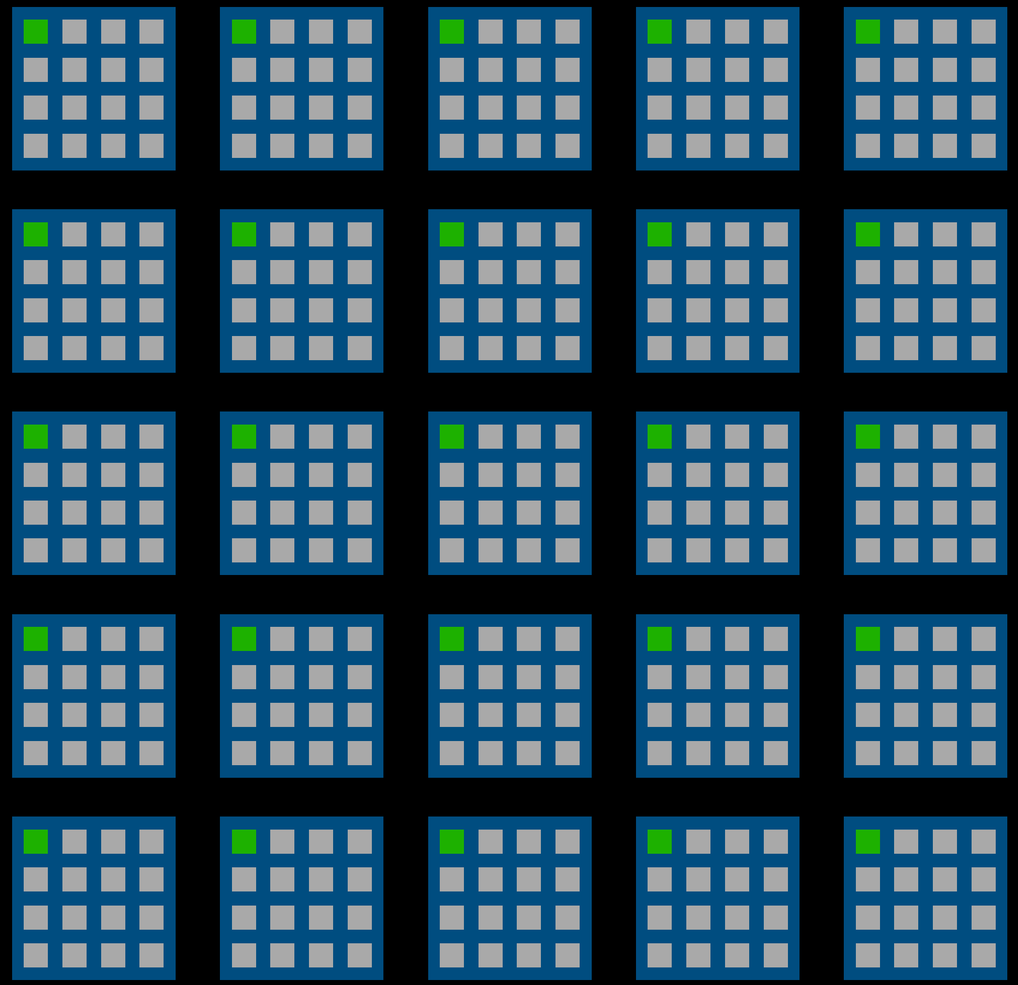
Worst Case:

Worst Case:

low occupancy, non-meshable pages

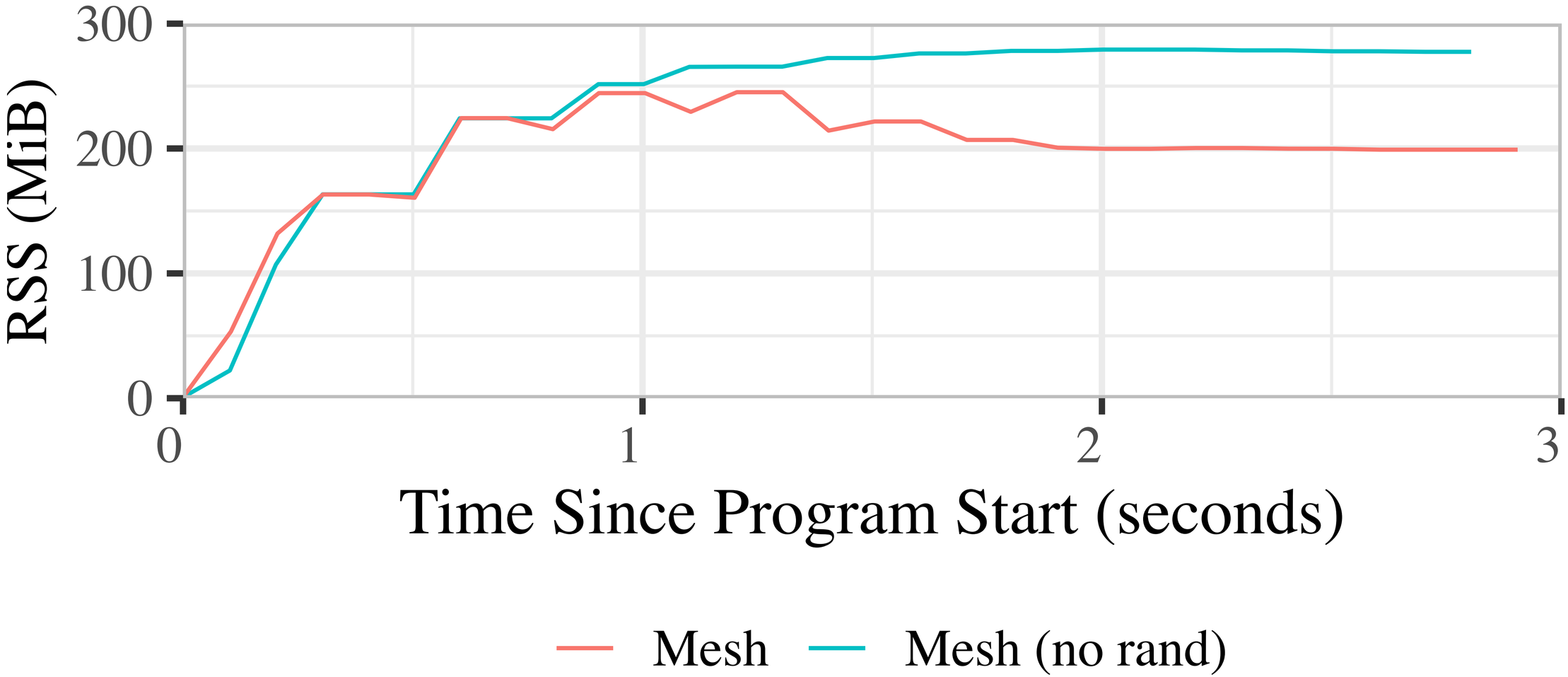


Worst Case:
many
low occupancy,
non-meshable
pages



Mesh uses **randomization** to ensure live objects are uniformly distributed

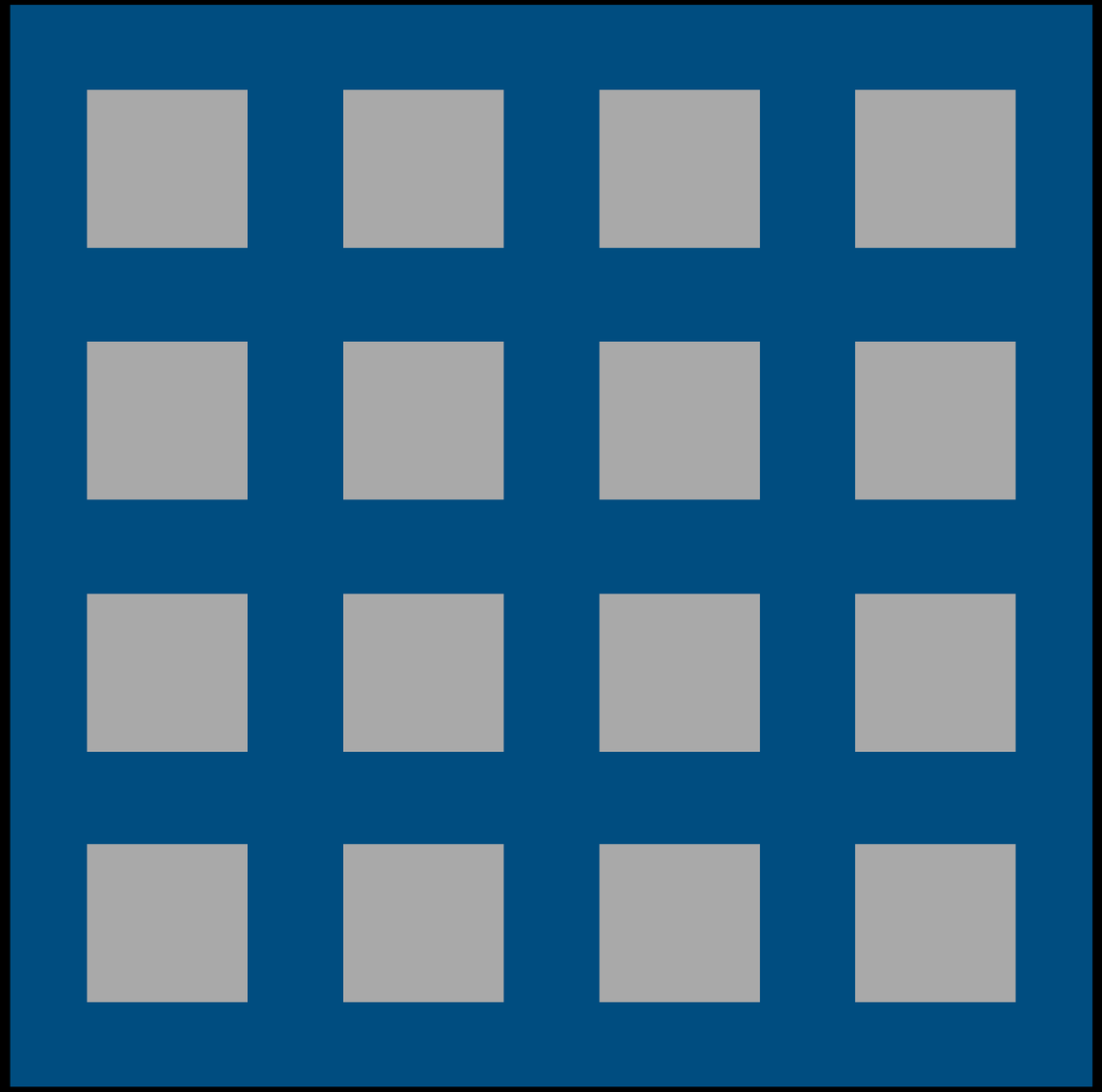
Impact of randomized allocation



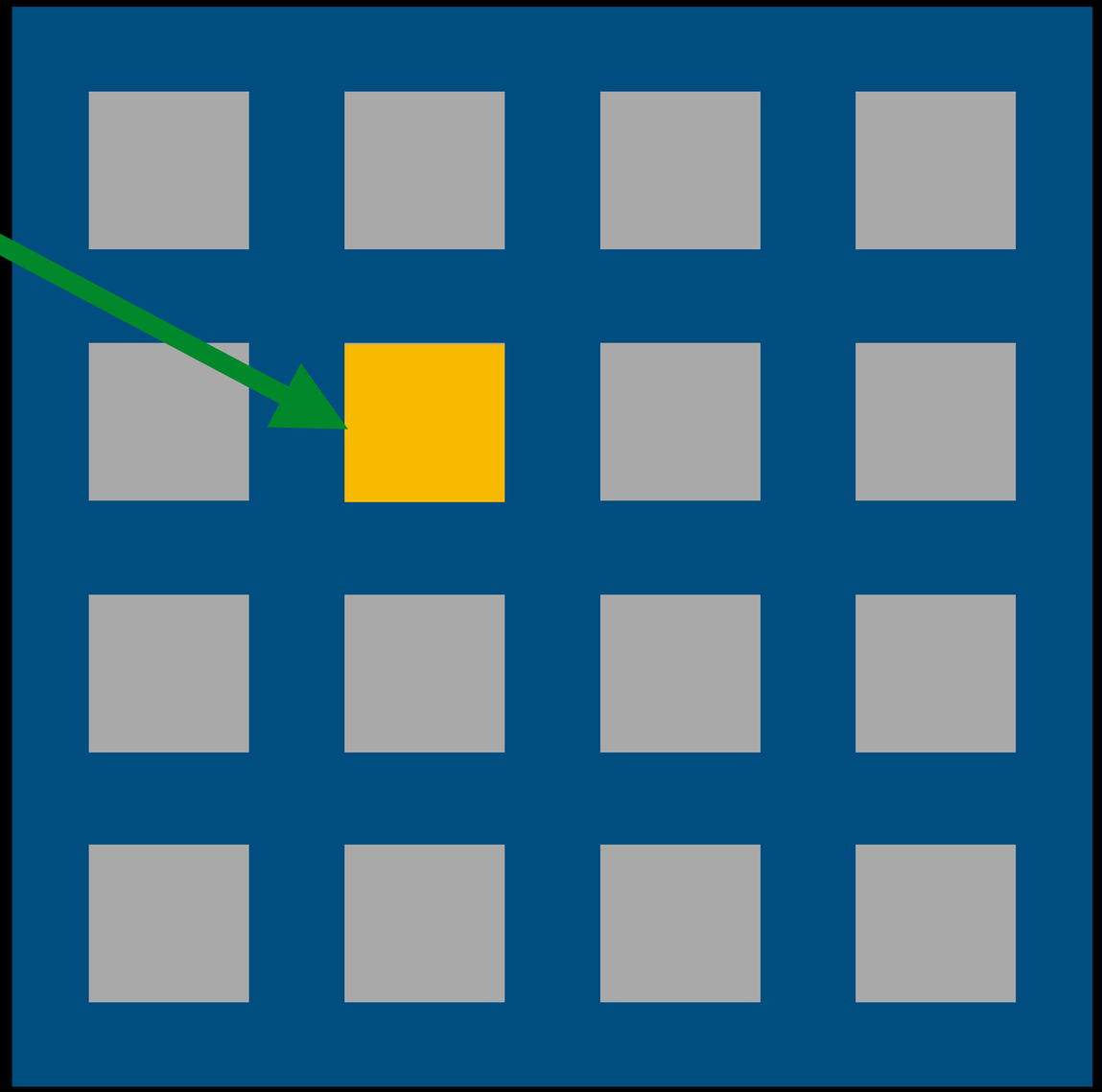
How does Mesh *efficiently* **randomize** allocation?

Random probing:

```
while true:
   if rand_off().is_free:
      return rand_off
```



```
malloc(256)
```



Random probing:

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while true:
   if rand_off().is_free:
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malloc(256)
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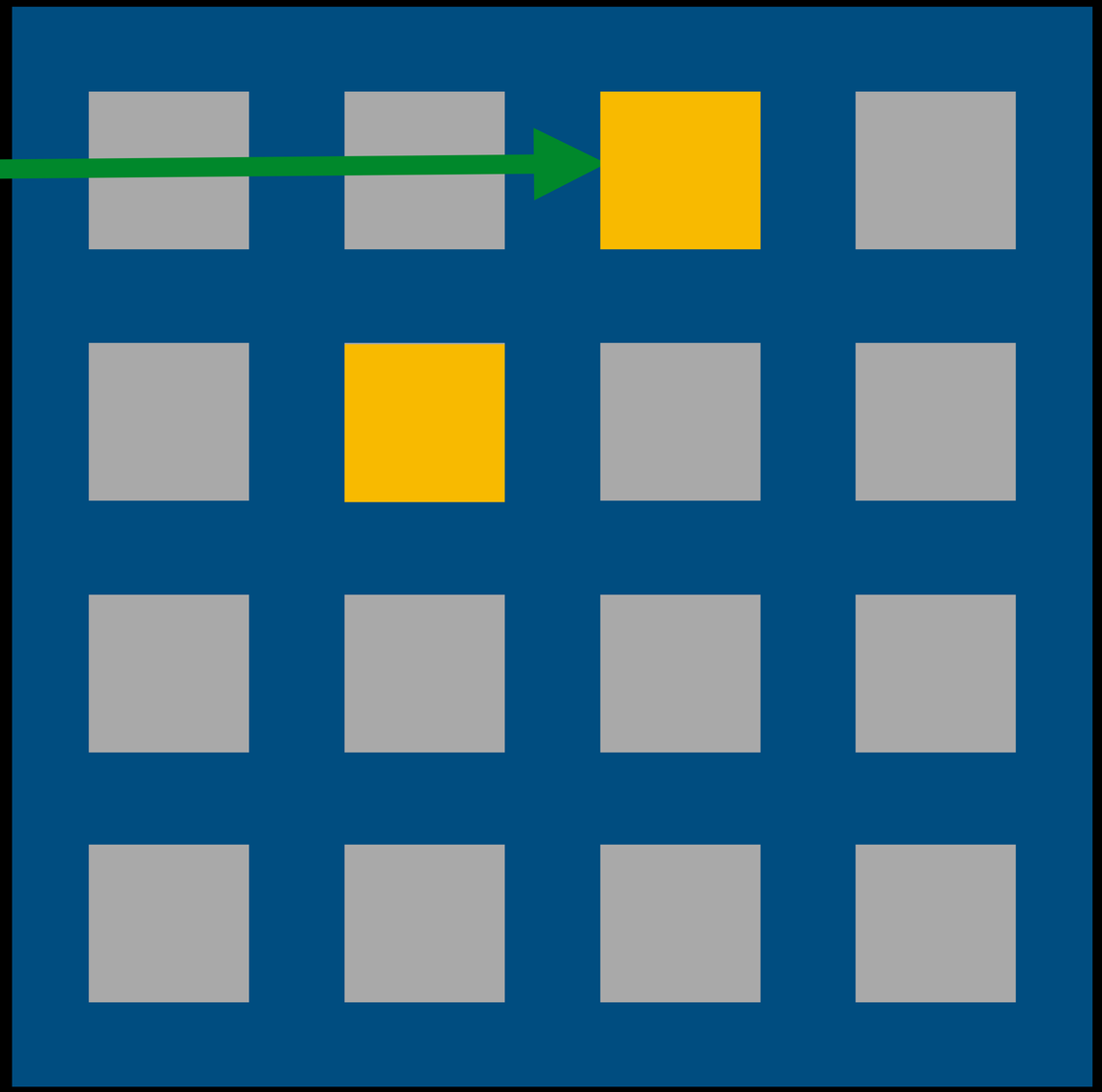

Random probing:

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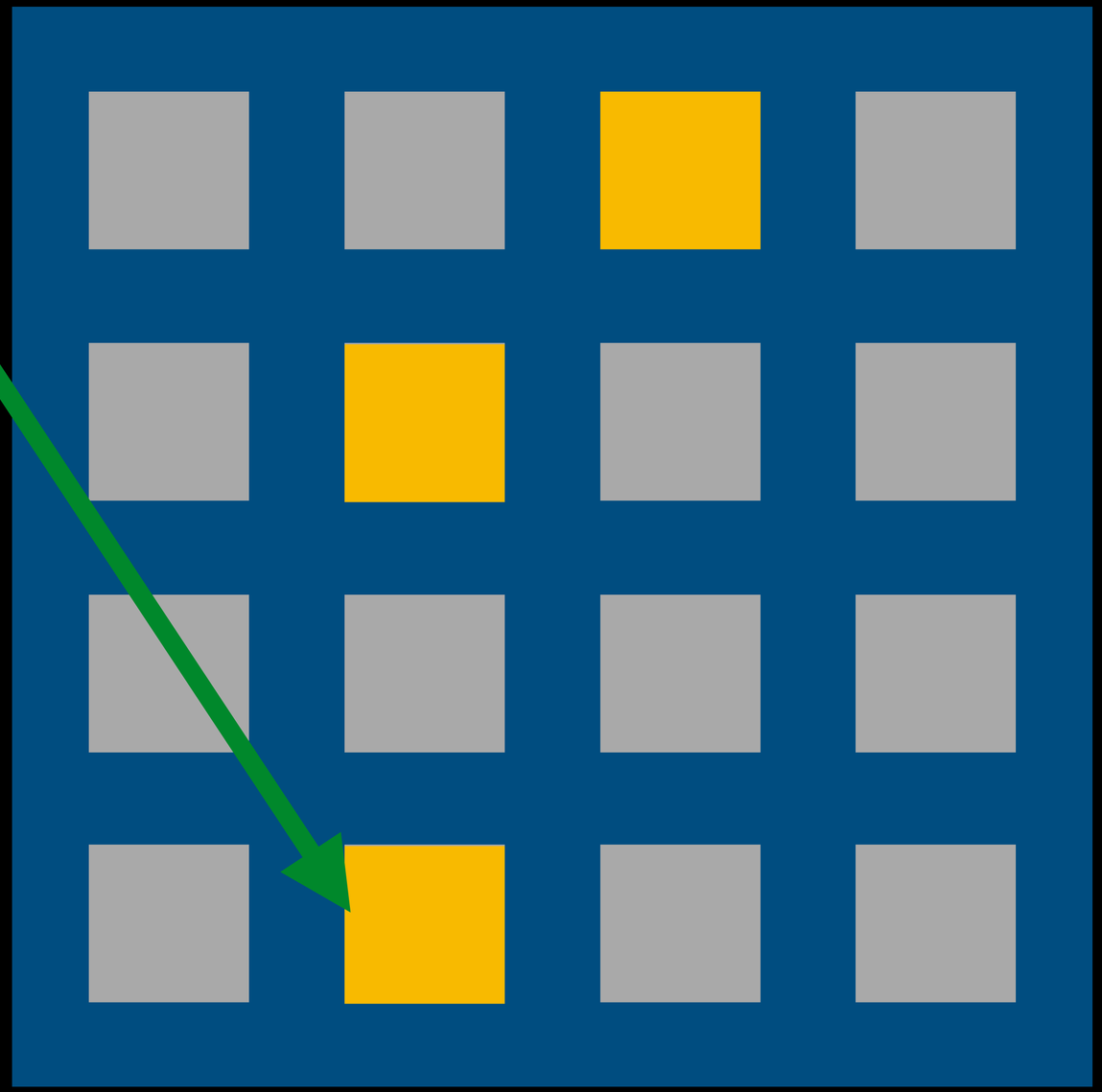
while true:
   if rand_off().is_free:
      return rand_off
```

```
malloc(256)
```



Random probing:

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malloc(256)
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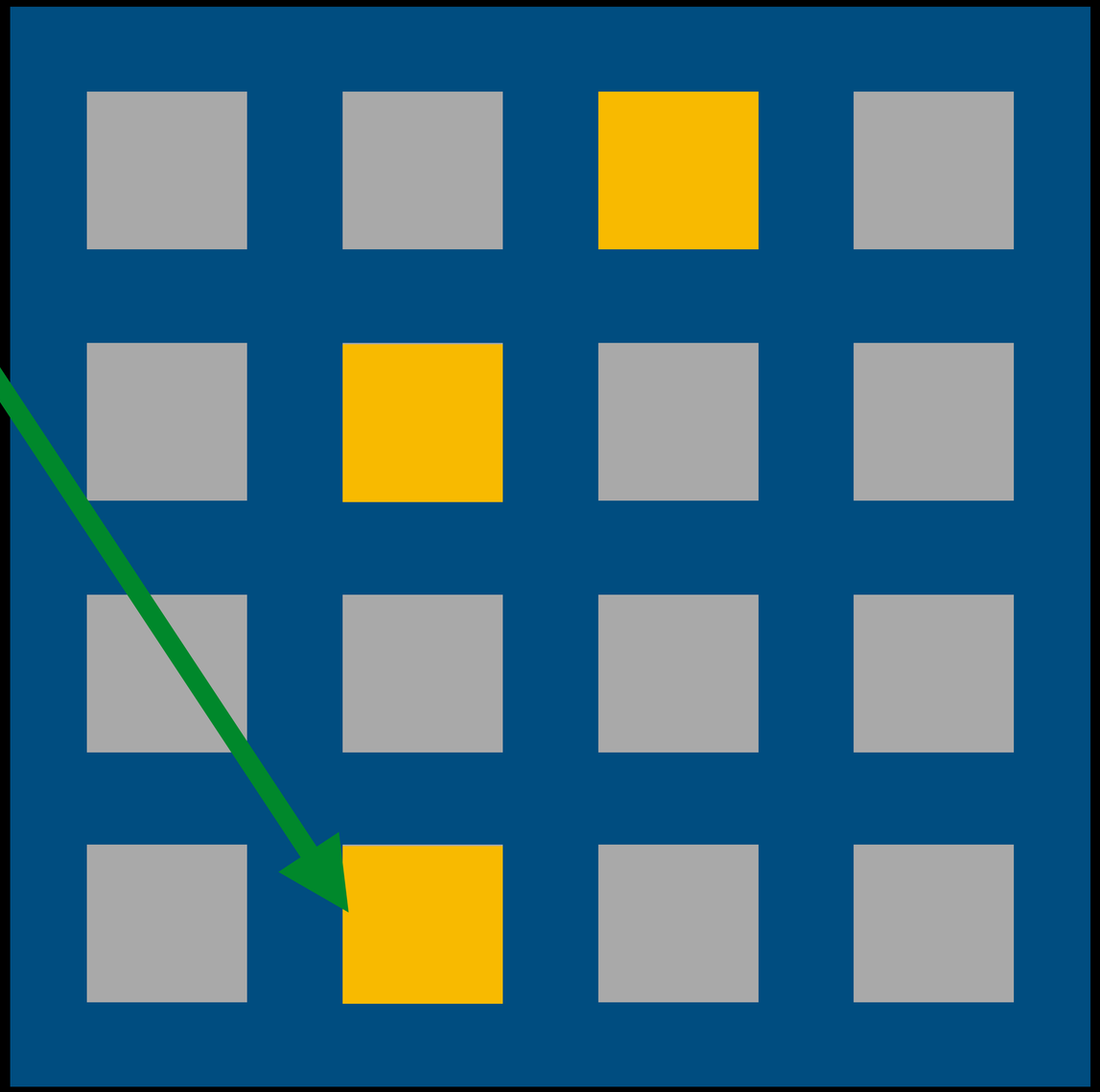
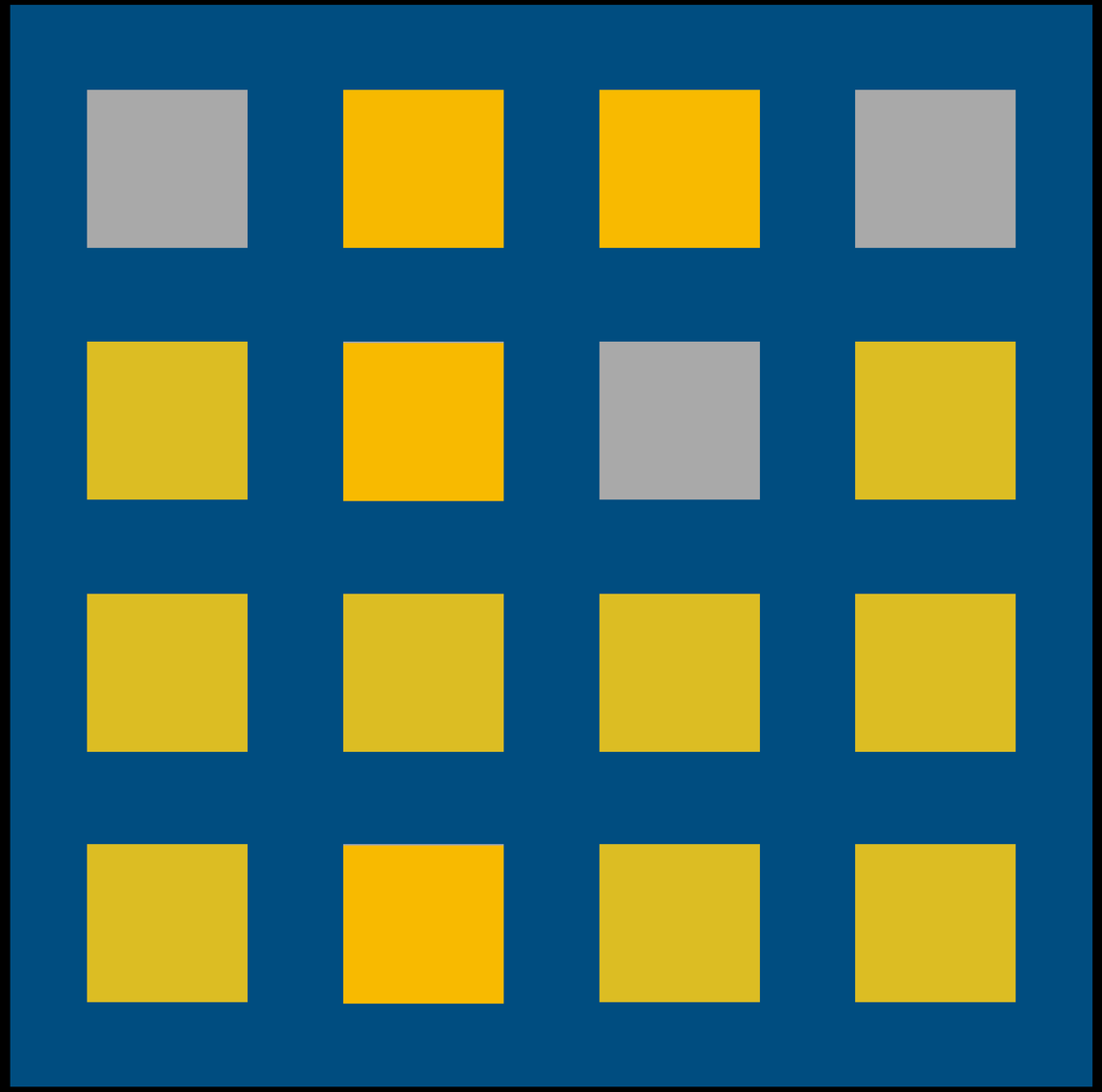


Random probing:

```
while true:
   if rand_off().is_free:
      return rand_off
```

(DieHard [Berger & Zorn 2006])

`malloc(256)`



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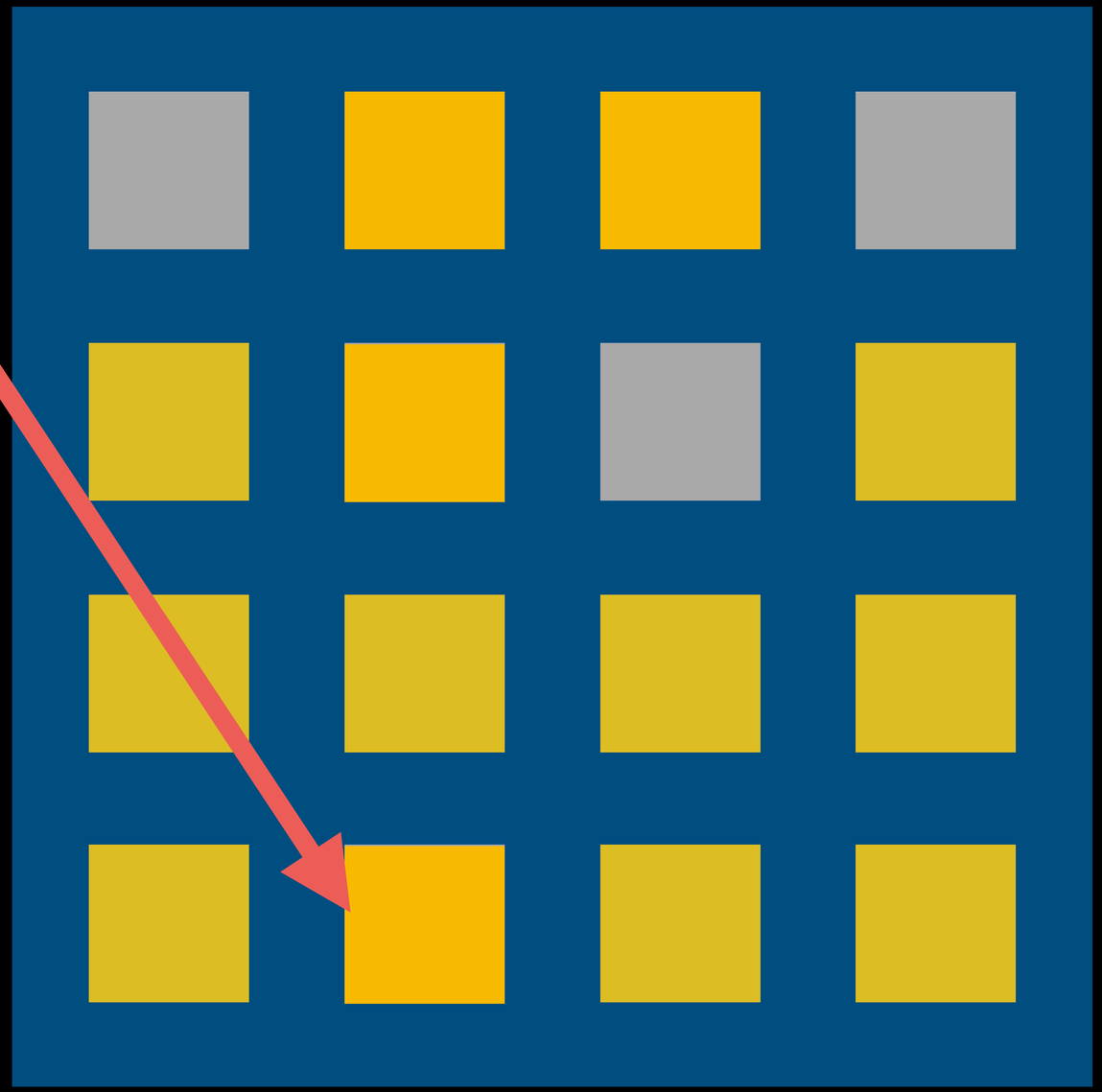
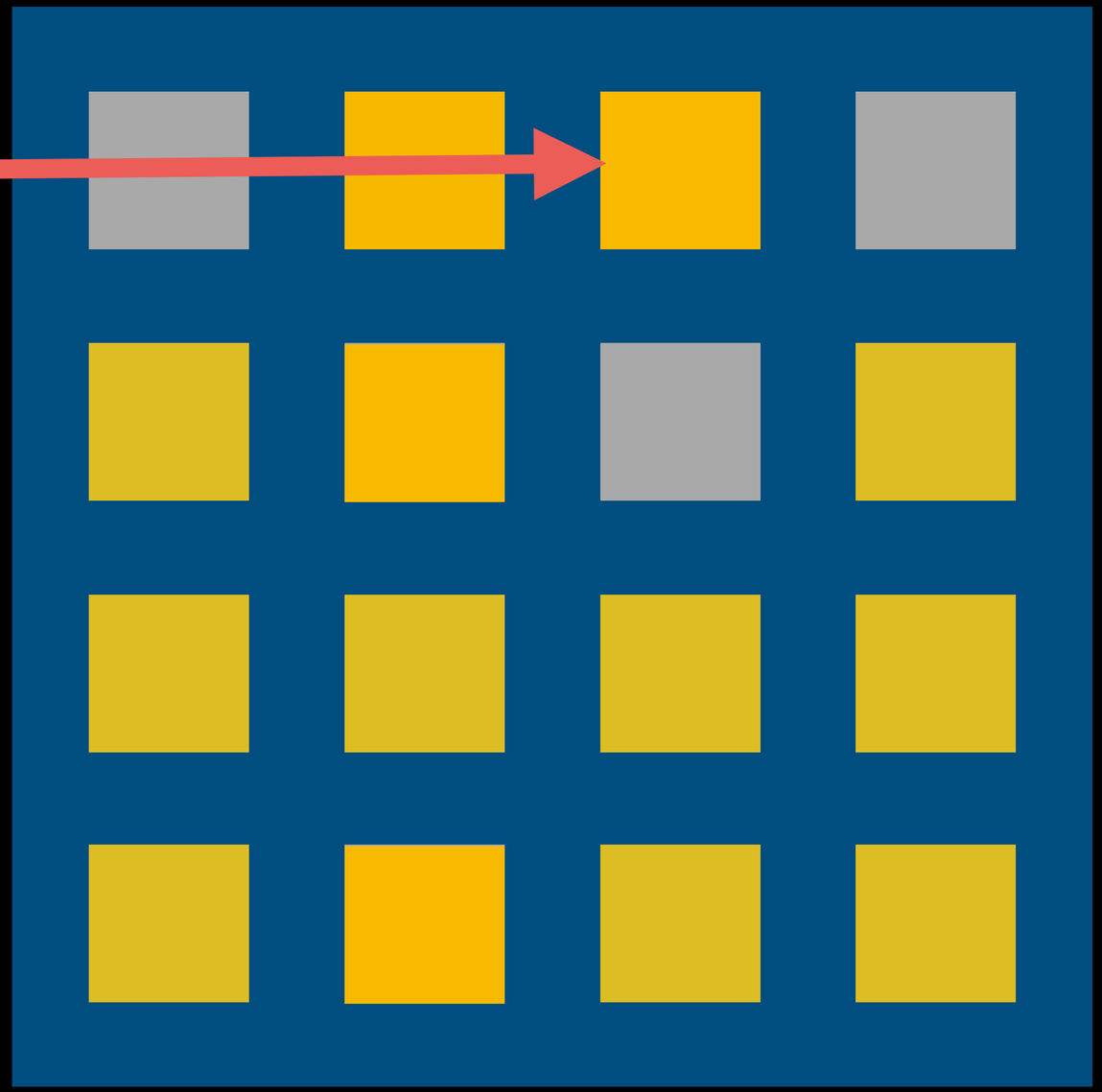
```
malloc(256)
```



Random probing:

```
while true:
   if rand_off().is_free:
      return rand_off
```

```
malloc(256)
```



Random probing:

```
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   if rand_off().is_free:
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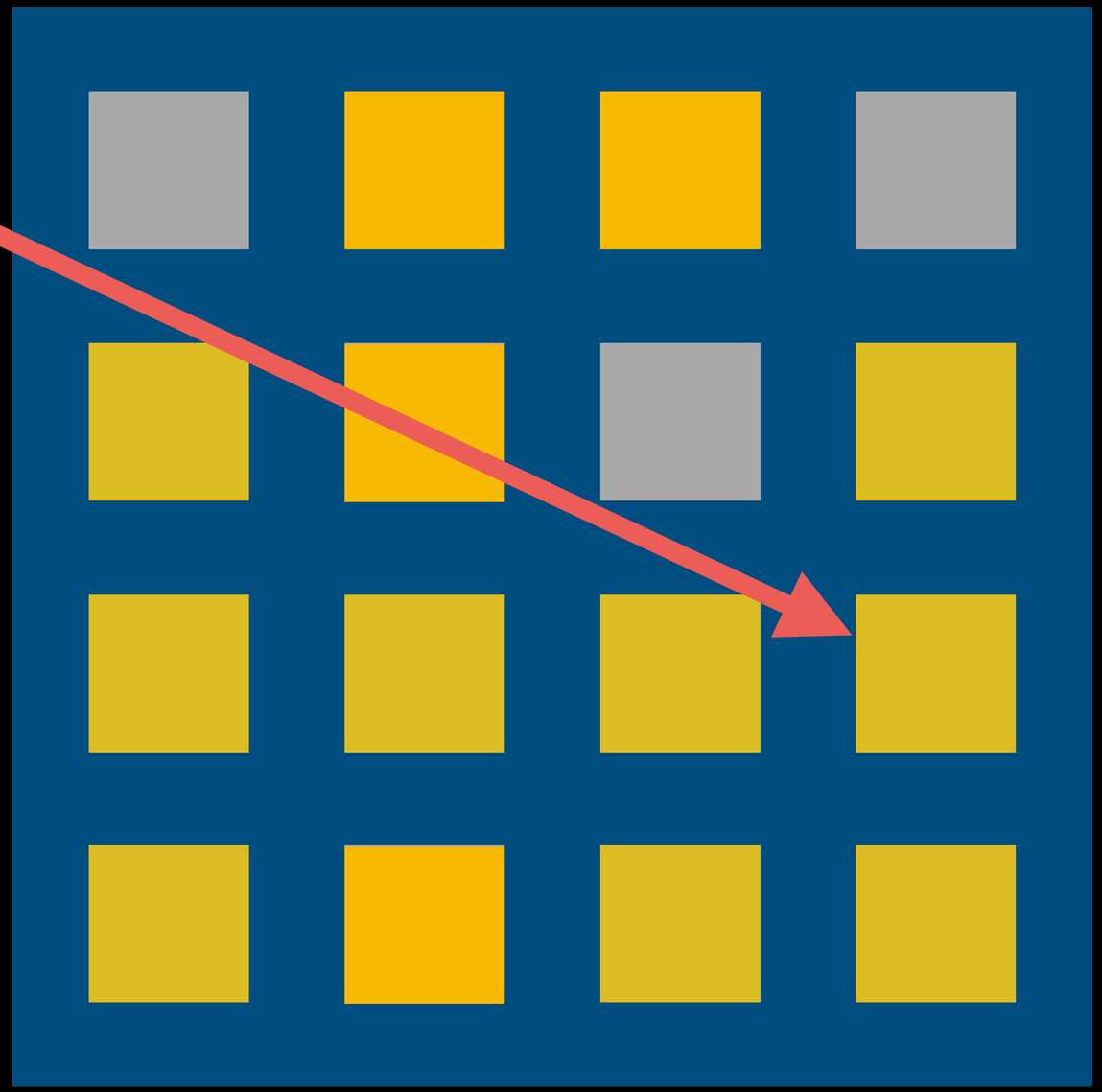
```

```
malloc(256)
```



Random probing:

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while true:
   if rand_off().is_free:
      return rand_off
```
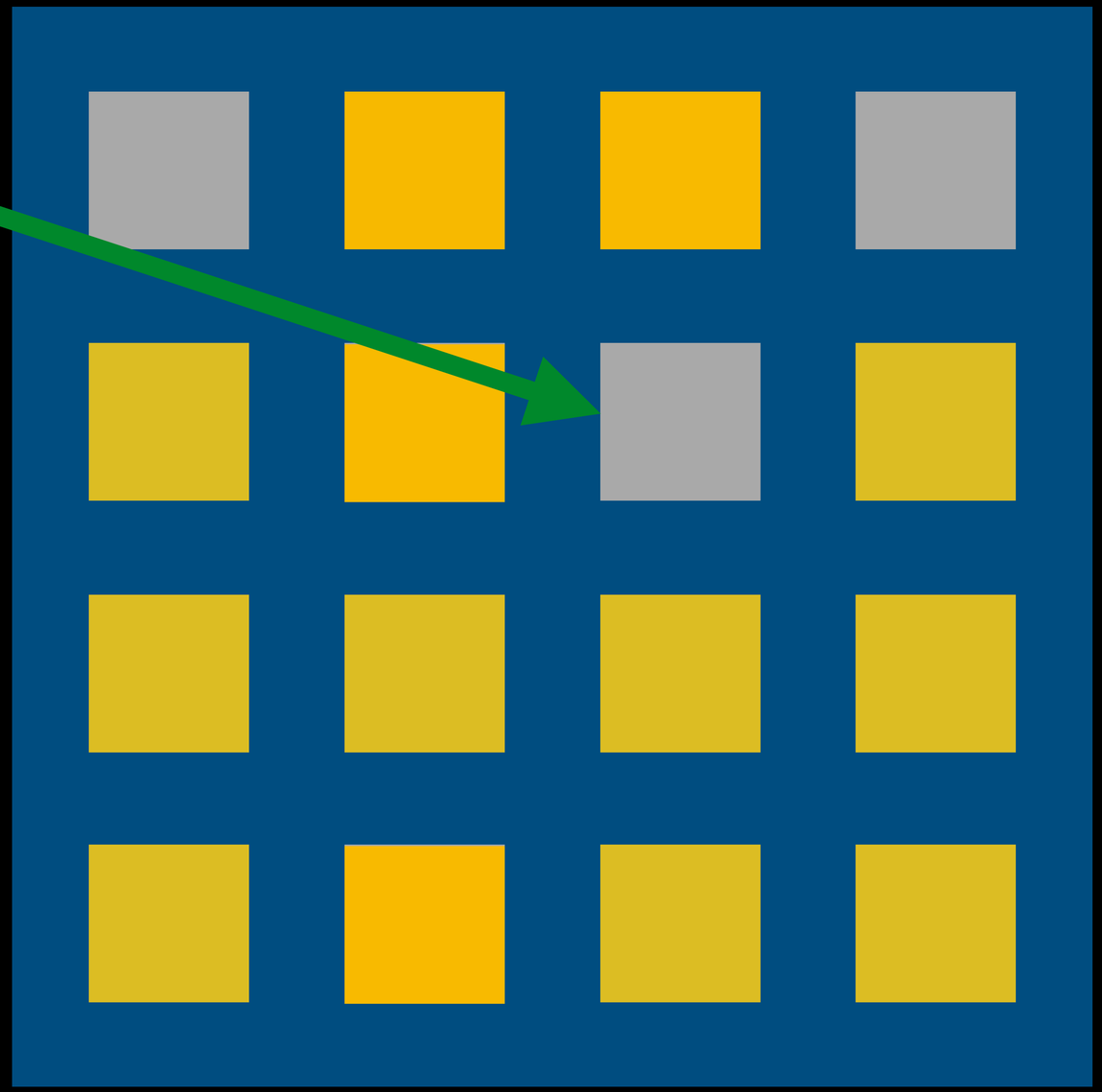
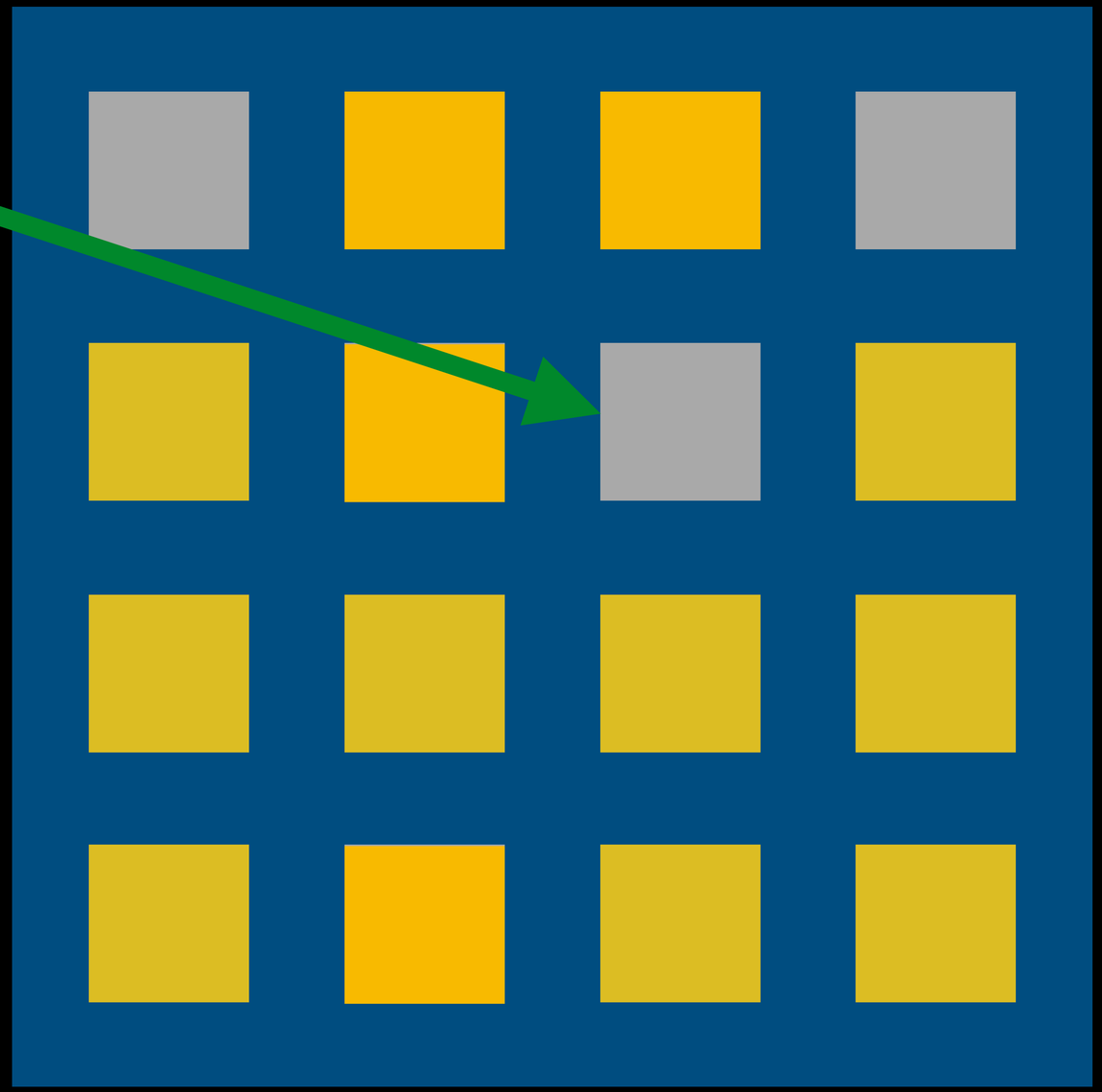

```
malloc(256)
```



Random probing:

```
while true:
   if rand_off().is_free:
      return rand_off
```

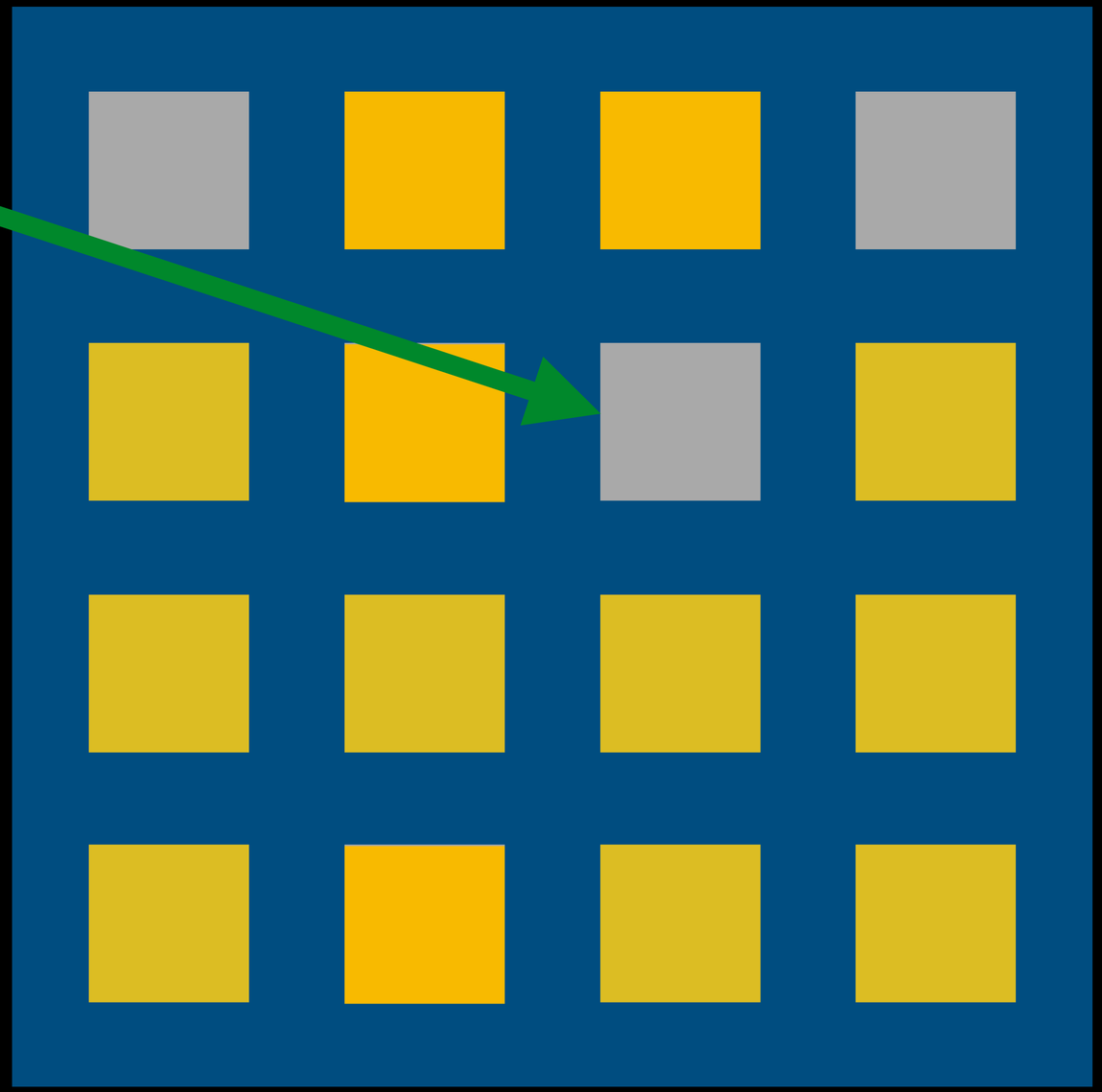
`malloc(256)`



Random probing:

Slow + space-efficient

`malloc(256)`



Random probing:

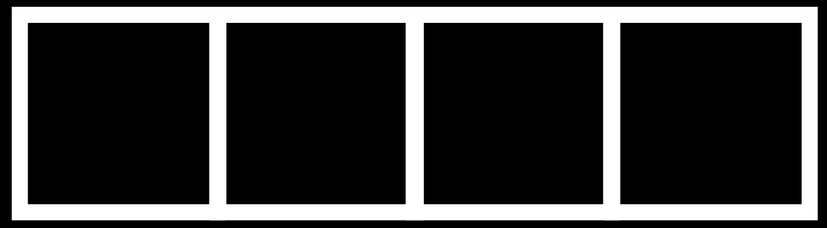
Slow + space-efficient
Fast + space-inefficient

Shuffle Vector:
Fast + space-efficient
random malloc

Shuffle Vector:
Fast + space-efficient
random malloc

Page

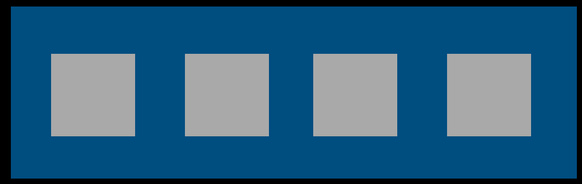

```
load
```



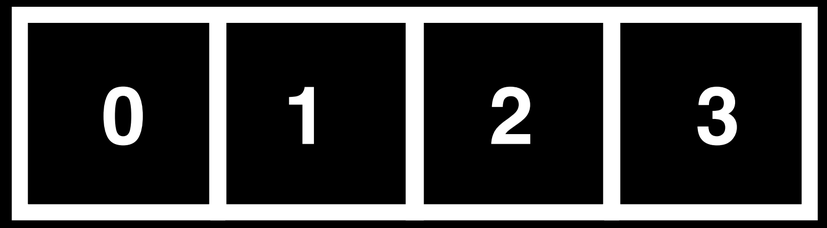
Thread-local shuffle vector

Shuffle Vector:
Fast + space-efficient random malloc

Page

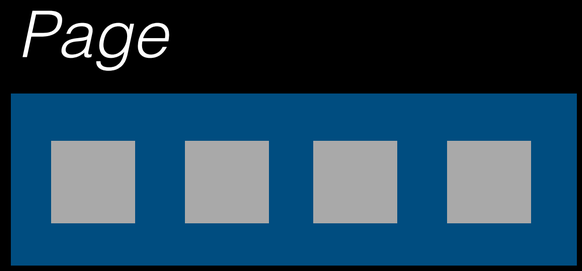


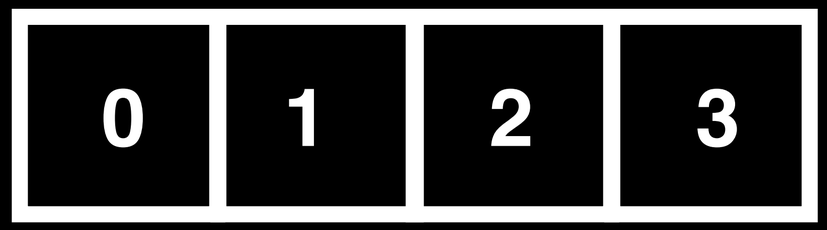
```
load
```



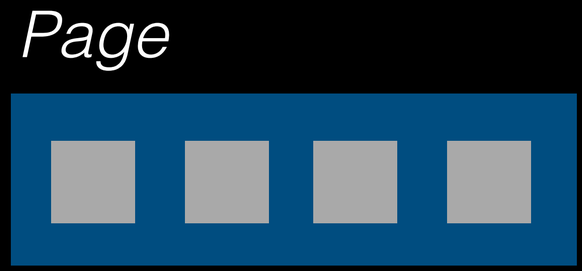
Thread-local shuffle vector

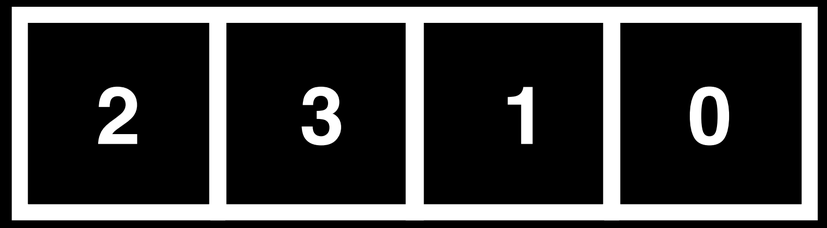
Shuffle Vector:
Fast + space-efficient random malloc





Shuffle Vector:
Fast + space-efficient random malloc

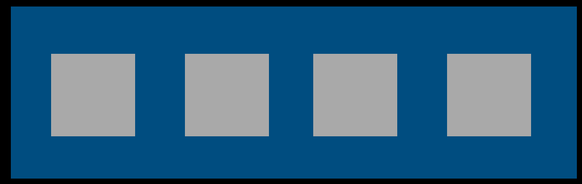




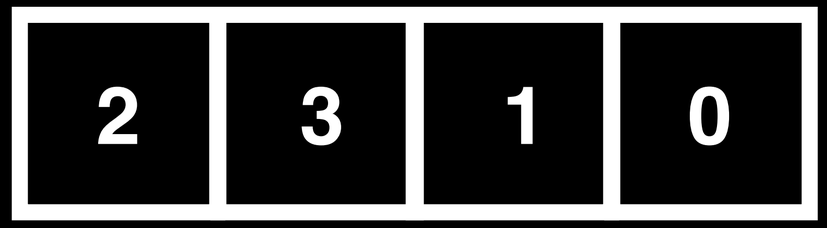
Thread-local shuffle vector

Shuffle Vector:
Fast + space-efficient random malloc

Page



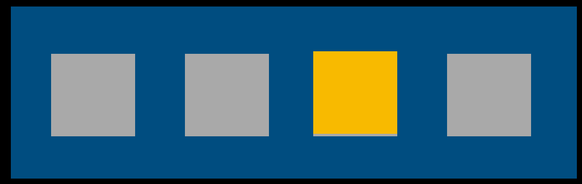
`malloc()`



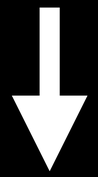
Thread-local shuffle vector

Shuffle Vector:
Fast + space-efficient random malloc

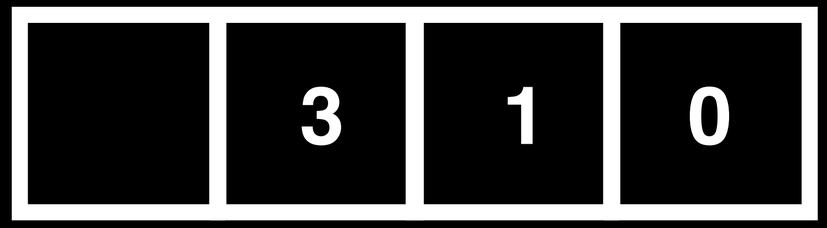
Page



```
malloc()
```



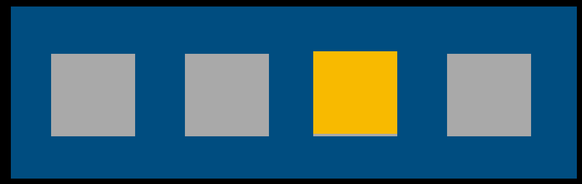
```
page_start +
2 * object_size
```



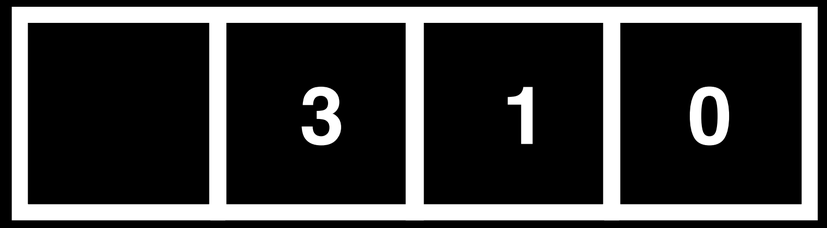
Thread-local shuffle vector

Shuffle Vector:
Fast + space-efficient random malloc

Page



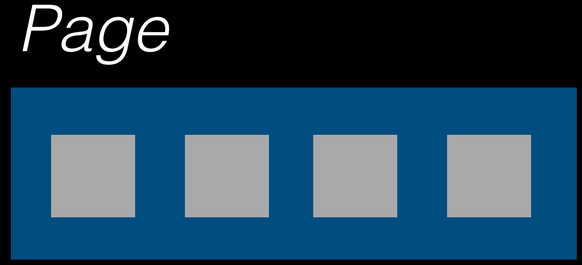
```
free(2)
```

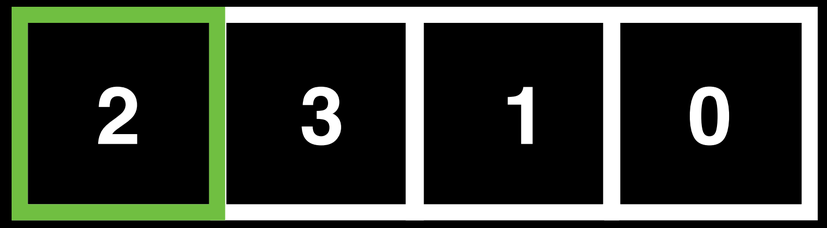


Thread-local shuffle vector

Shuffle Vector:
Fast + space-efficient random malloc

```
free( )
```

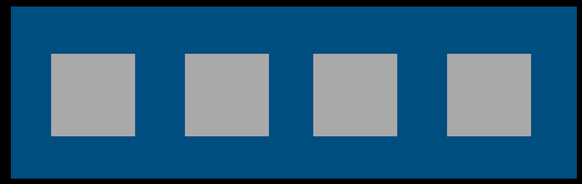




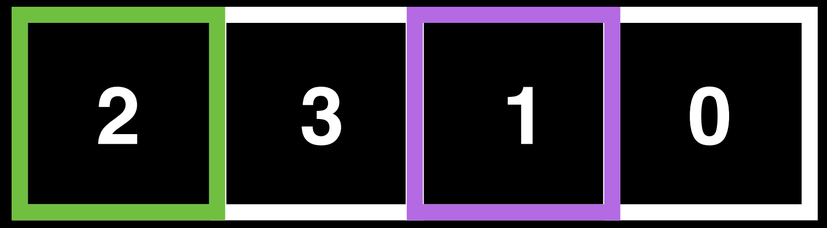
Thread-local shuffle vector

Shuffle Vector:
Fast + space-efficient random malloc

Page



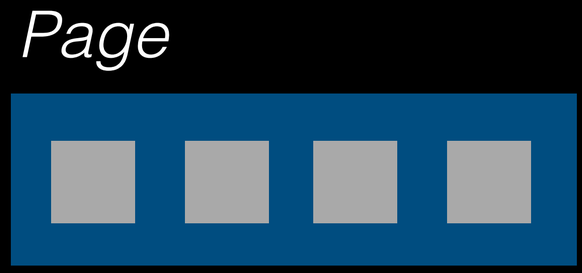
```
free( )

shuffle_one(
```




```
)
```

Thread-local shuffle vector

Shuffle Vector:
Fast + space-efficient random malloc

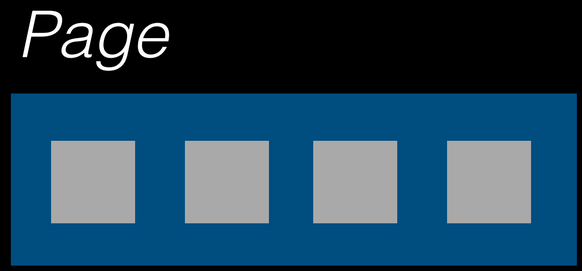


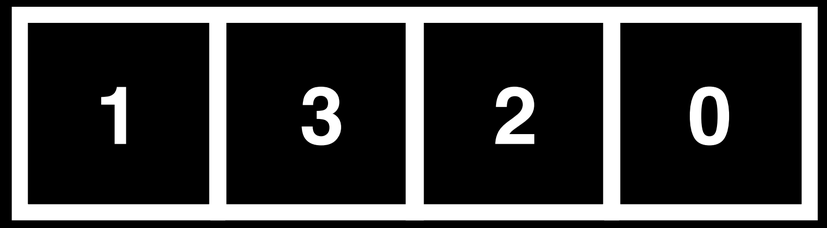

```
free( )

shuffle_one( 1 3 2 0 )
```

Thread-local shuffle vector

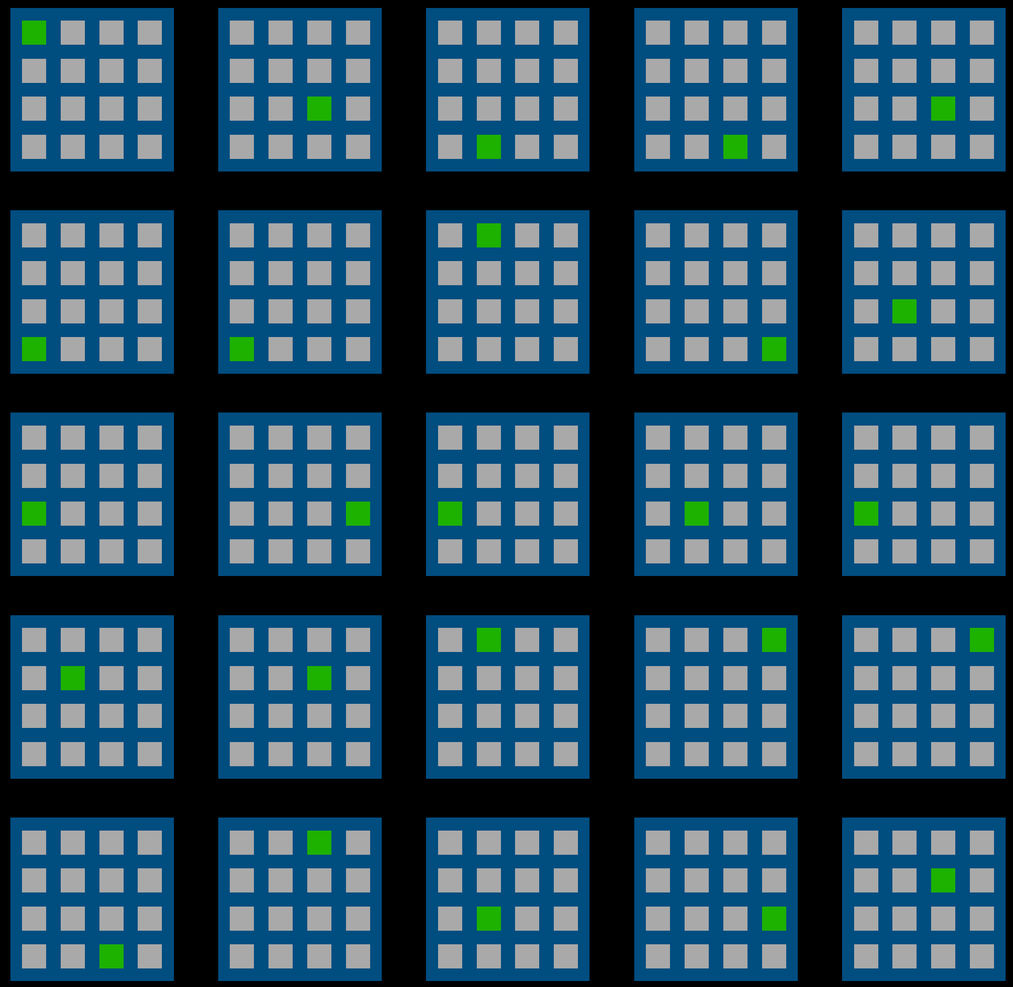
Shuffle Vector:
Fast + space-efficient random malloc

```
free( )
```

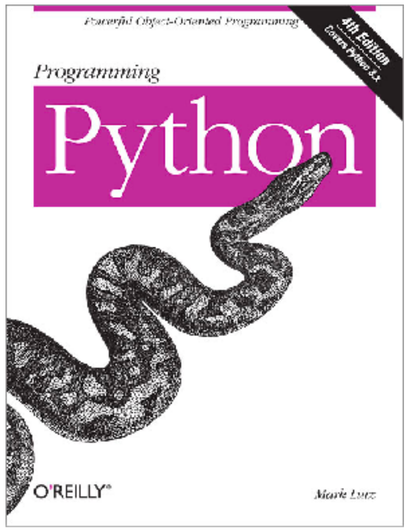


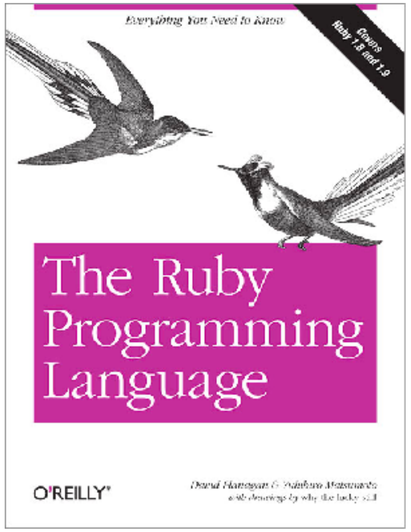


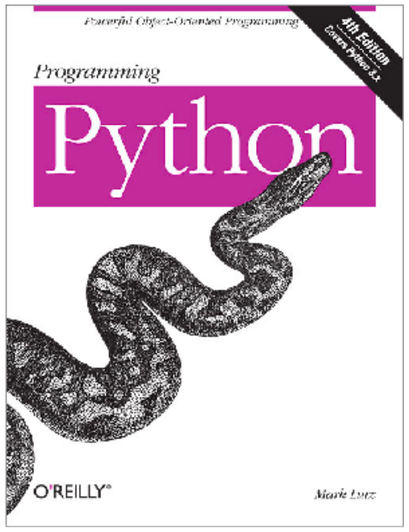
Thread-local shuffle vector



Many
Pages
Meshable


Programming
Python
O'REILLY
Mark Lutz


The Ruby
Programming
Language
O'REILLY


Programming
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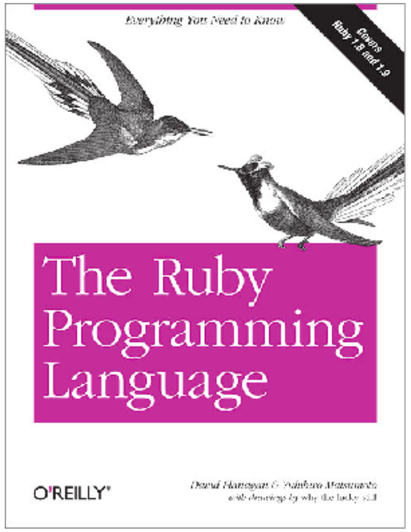
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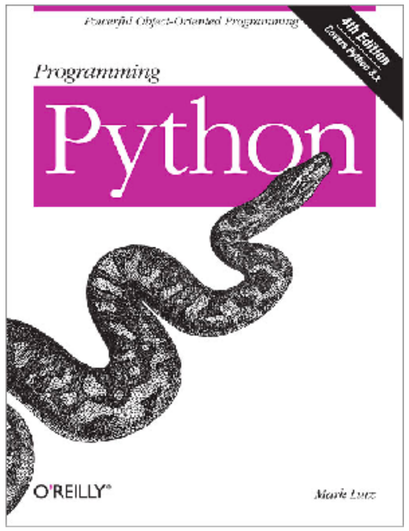
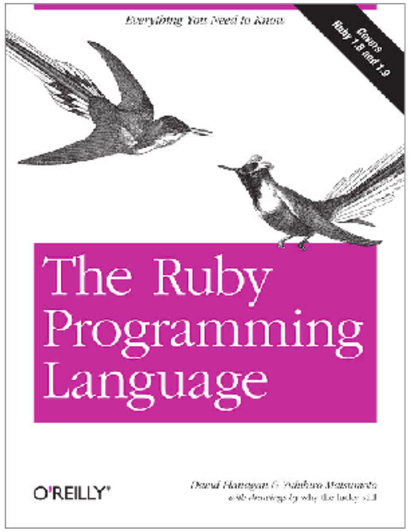
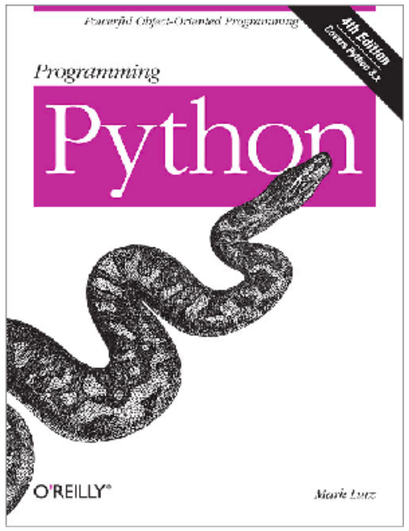
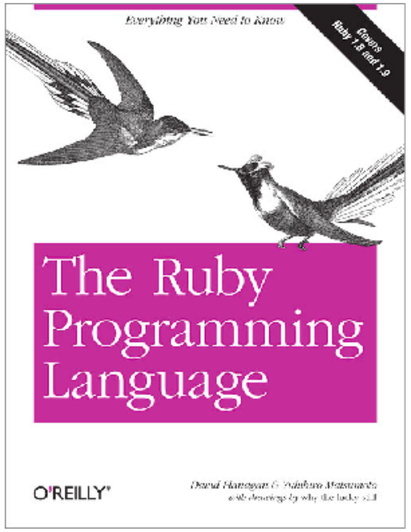




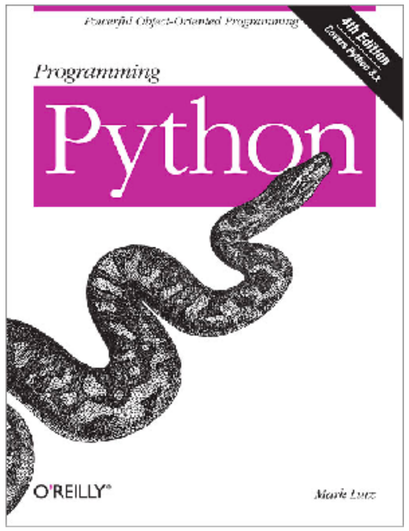
Q: Python: bytes for an int?

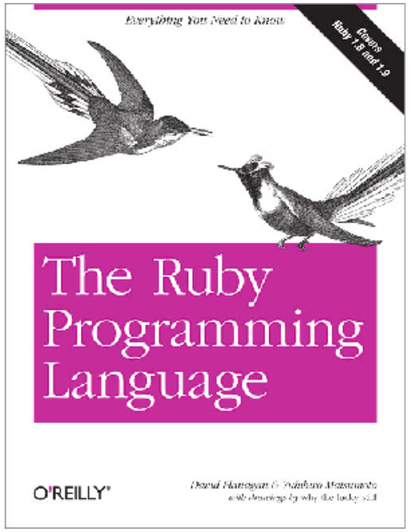




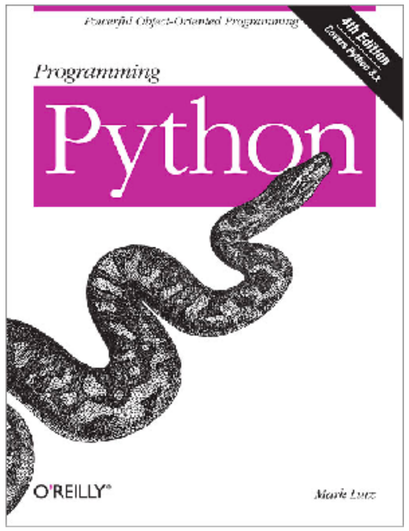
Q: Python: bytes for an int?

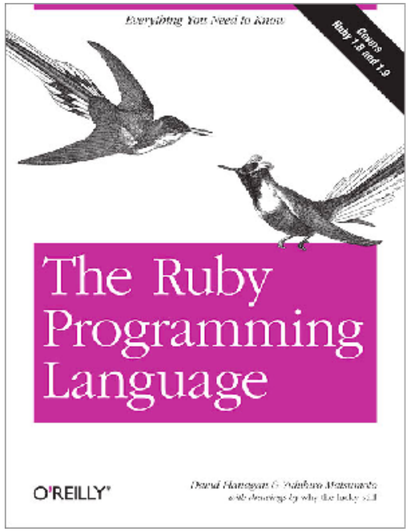
A: 28





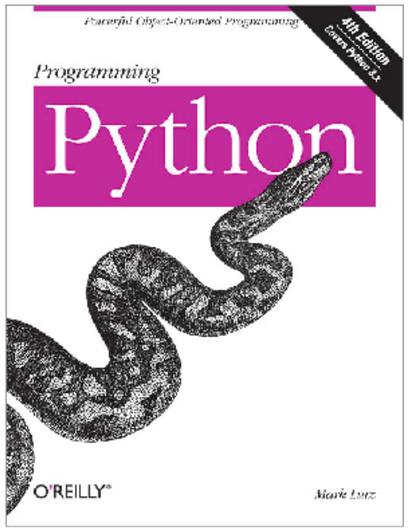
Q: Python: bytes in *empty* dict?

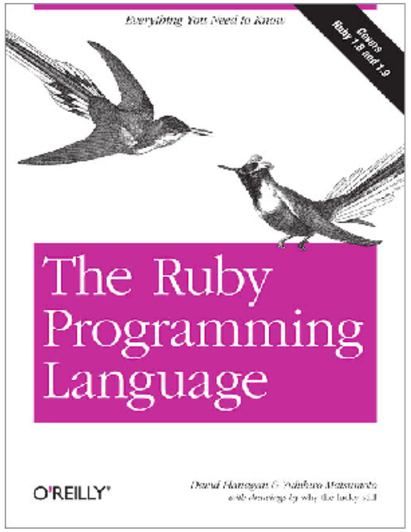




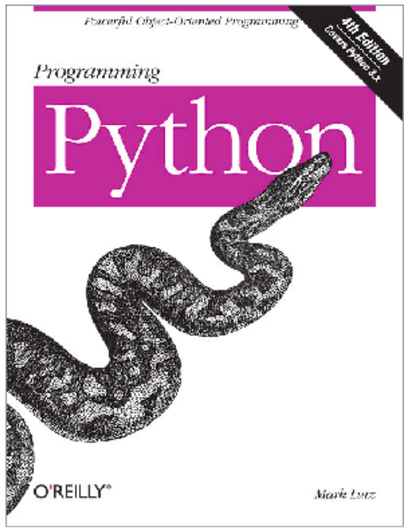
Q: Python: bytes in *empty* dict?

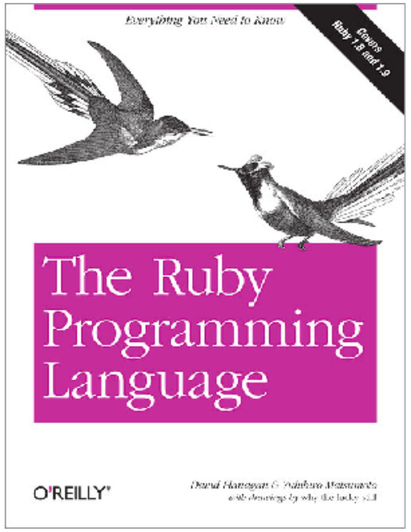
A: 240





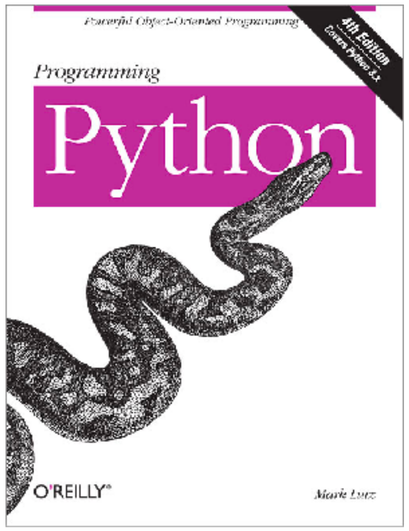
GC, but no / partial compaction

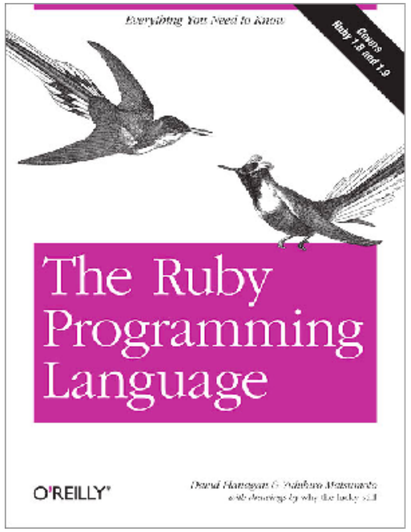




GC, but no / partial compaction

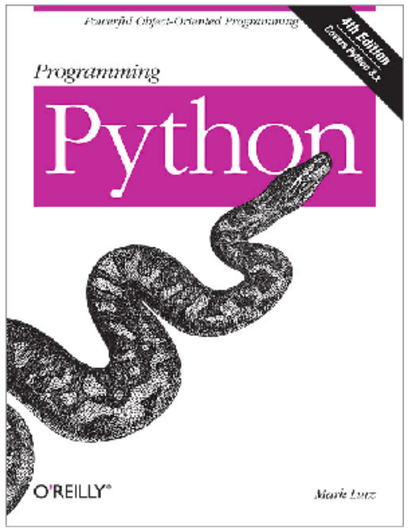
- Mesh = compaction for free!

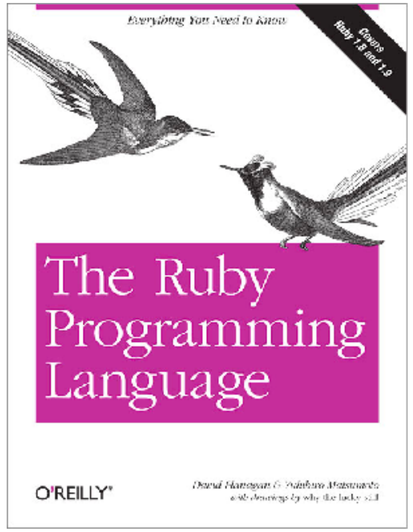




GC, but no / partial compaction

- **Mesh = compaction for free!**
- ***integrated* GC + Mesh**



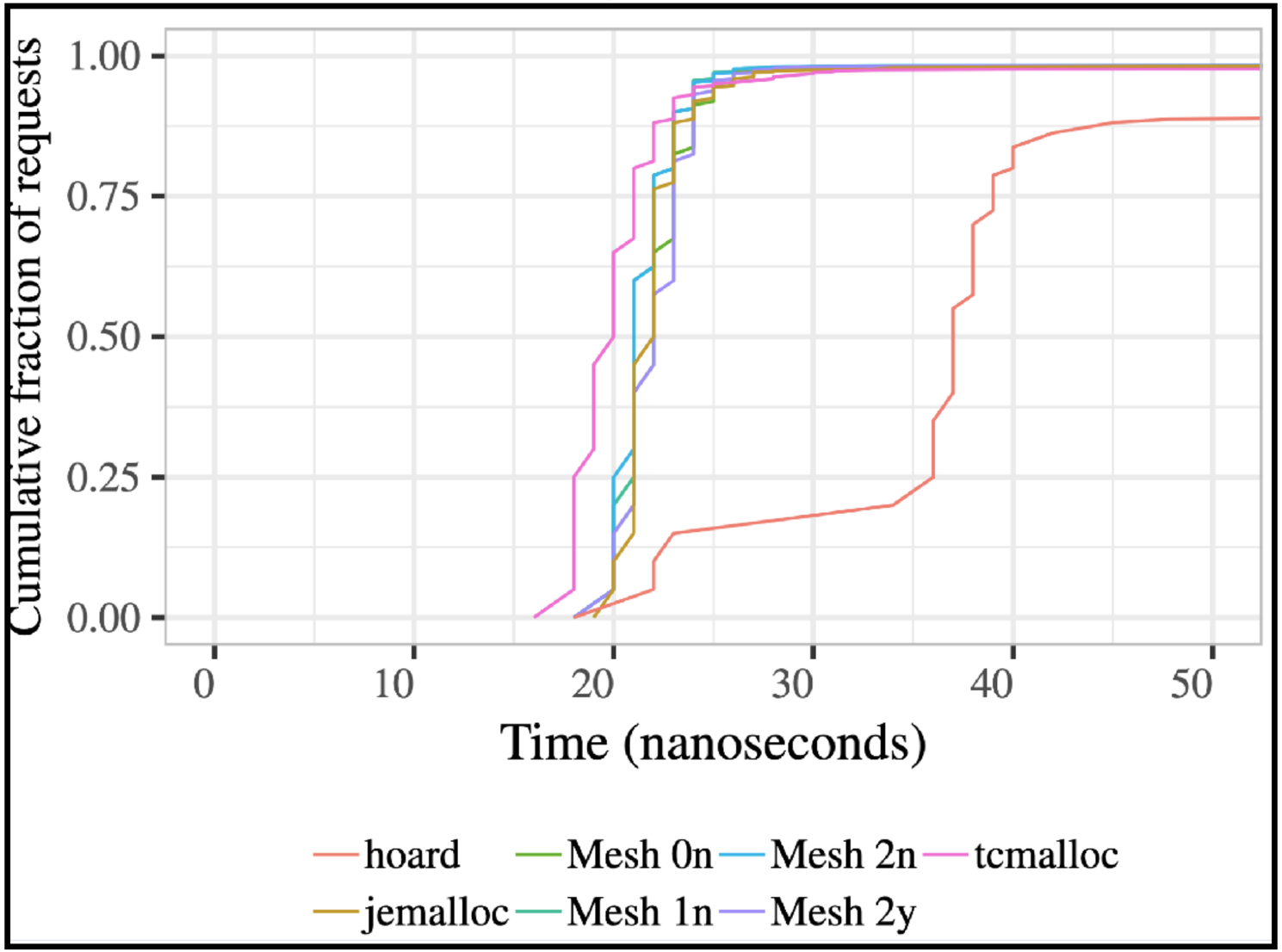


GC, but no / partial compaction

- Mesh = compaction for free!
- *integrated* GC + Mesh
- *vectorized* Mesh operations

http:// LIBMESH .org

Latency: malloc



Latency: free