Compacting the Uncompactable!

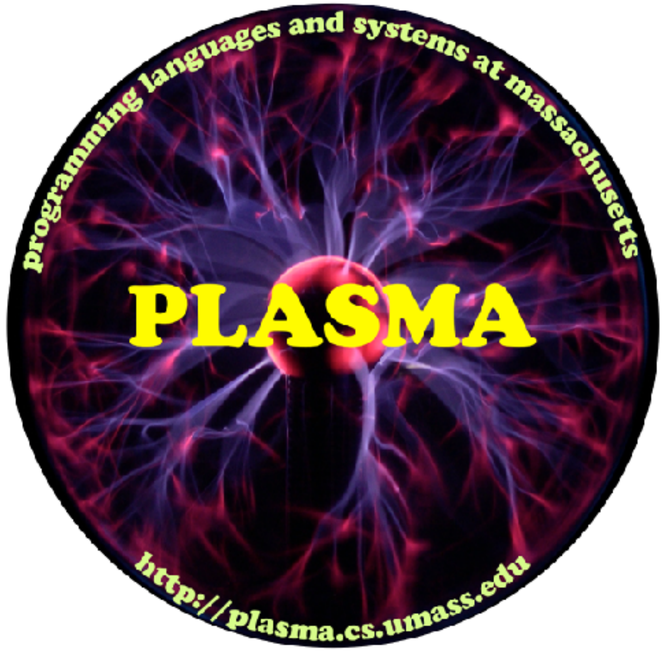
MESH

Automatically Compacting
Your C++ Application's Memory

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)

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Music by MITCH LEIGH

Reconquer
all of Spain!

PIANO · VOCAL · GUITAR

The Impossible Dream
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MALLOC

Reconquer
all of Spain!

MALLOC

~~Reconquer~~ Allocate all of Spain!

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The Impossible Dream
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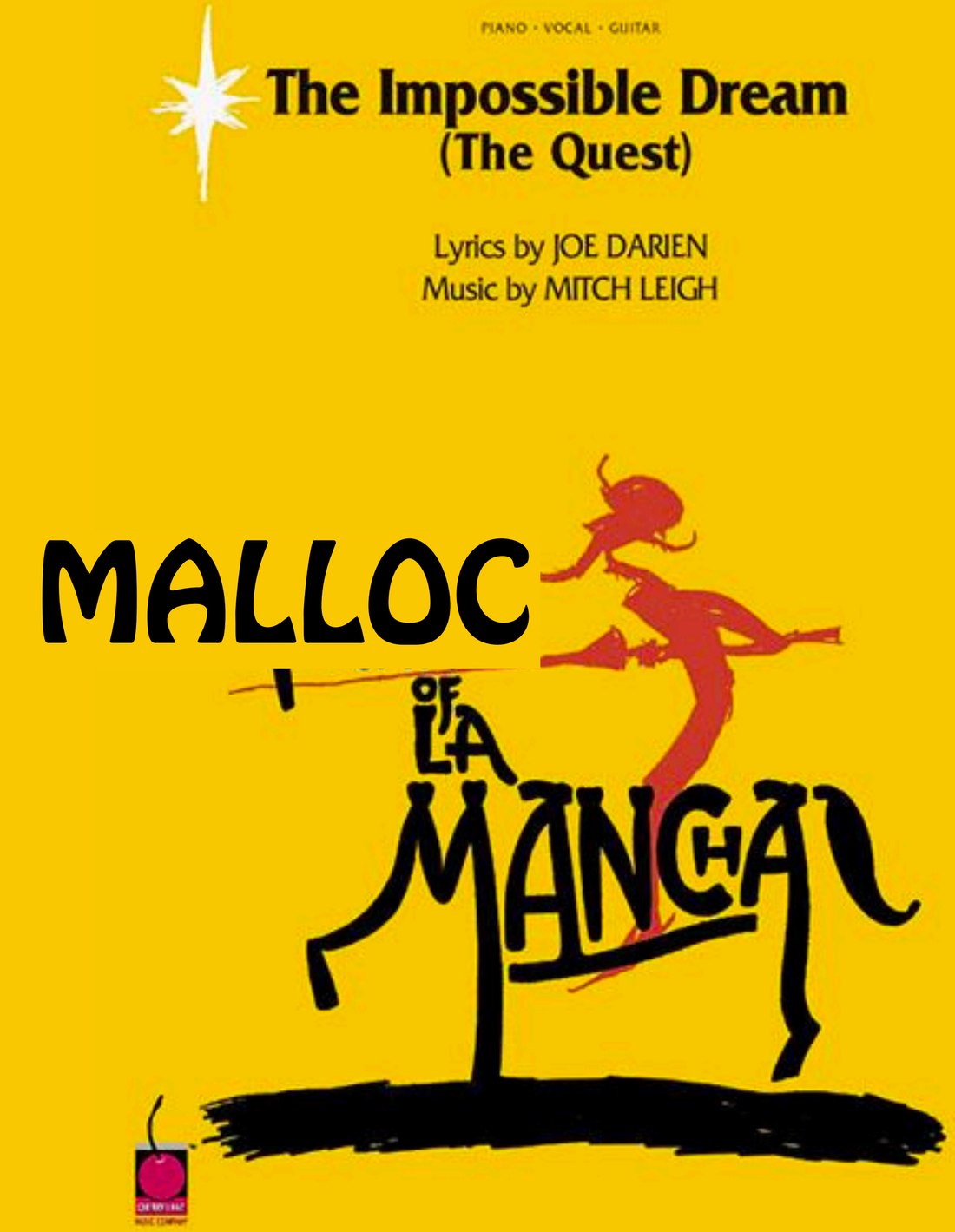
Music by MITCH LEIGH
MAN
OF
LA
MANCHA

(malloc)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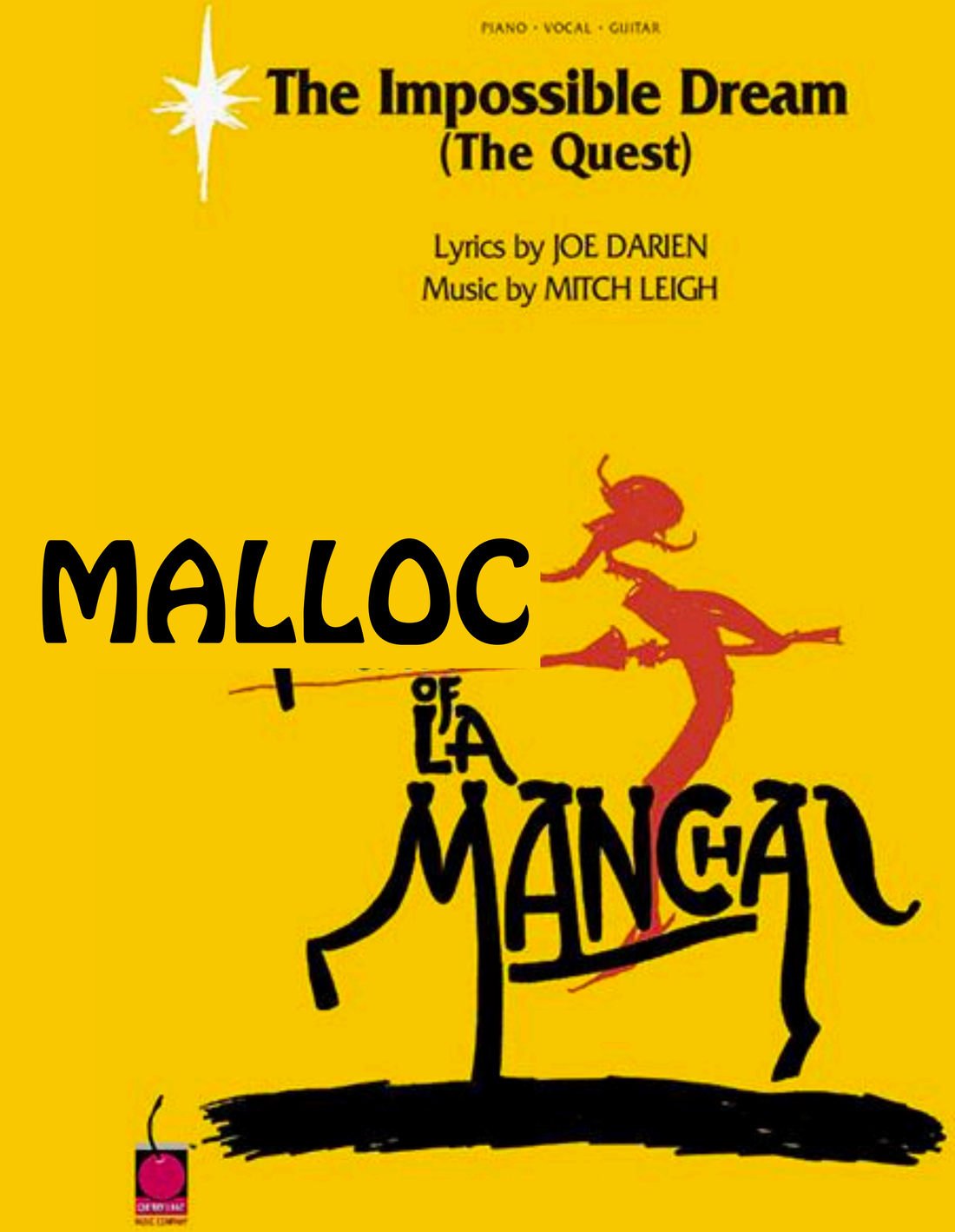
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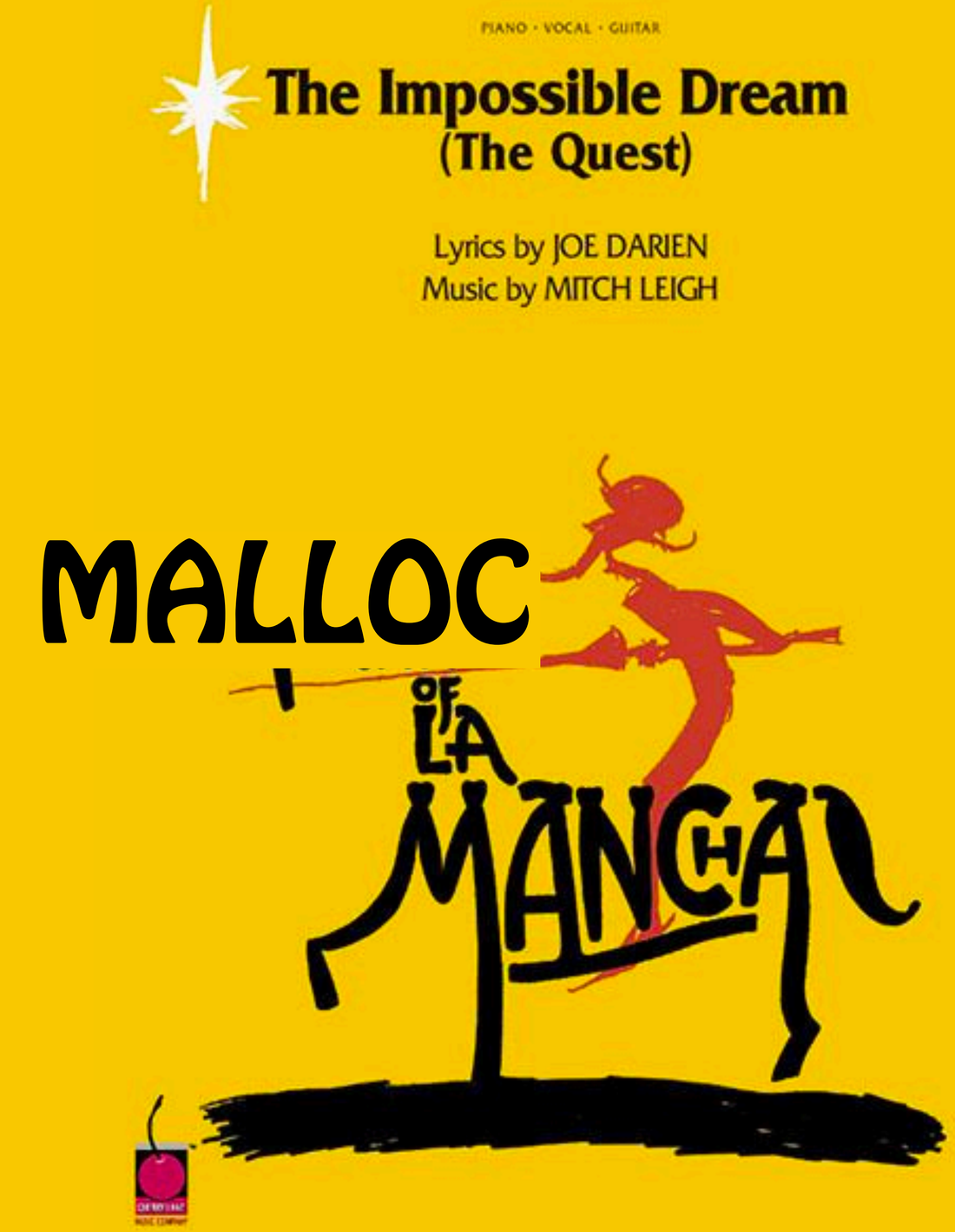
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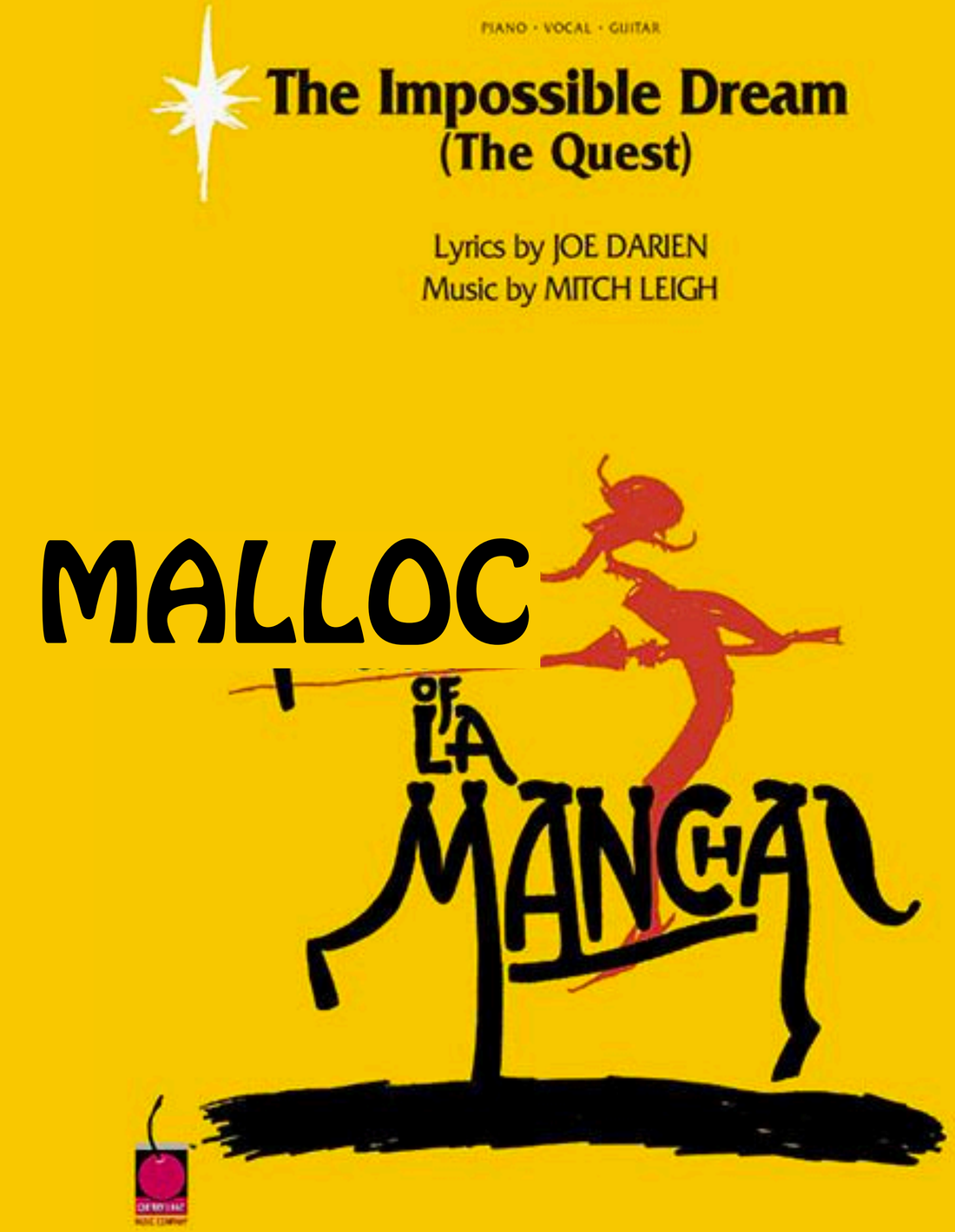
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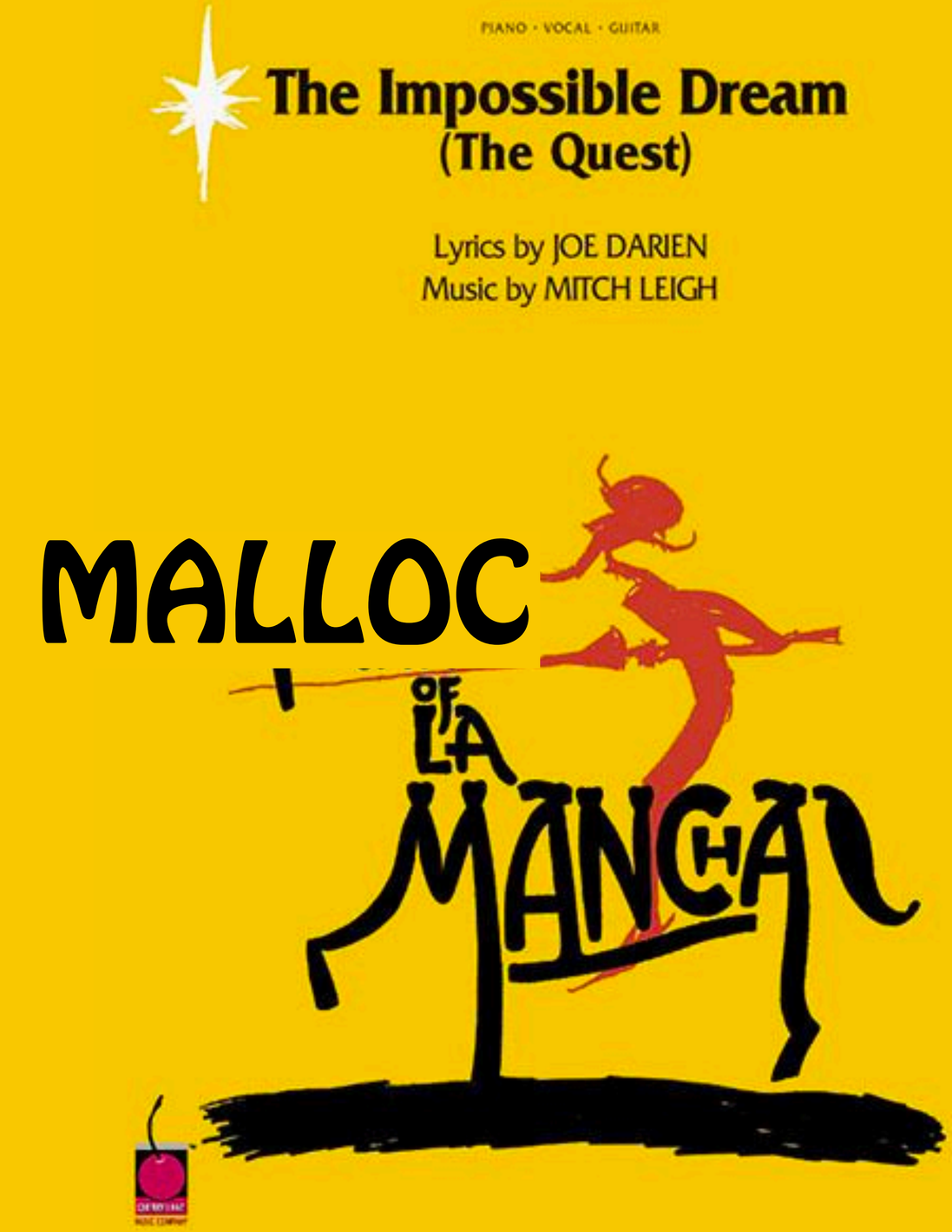
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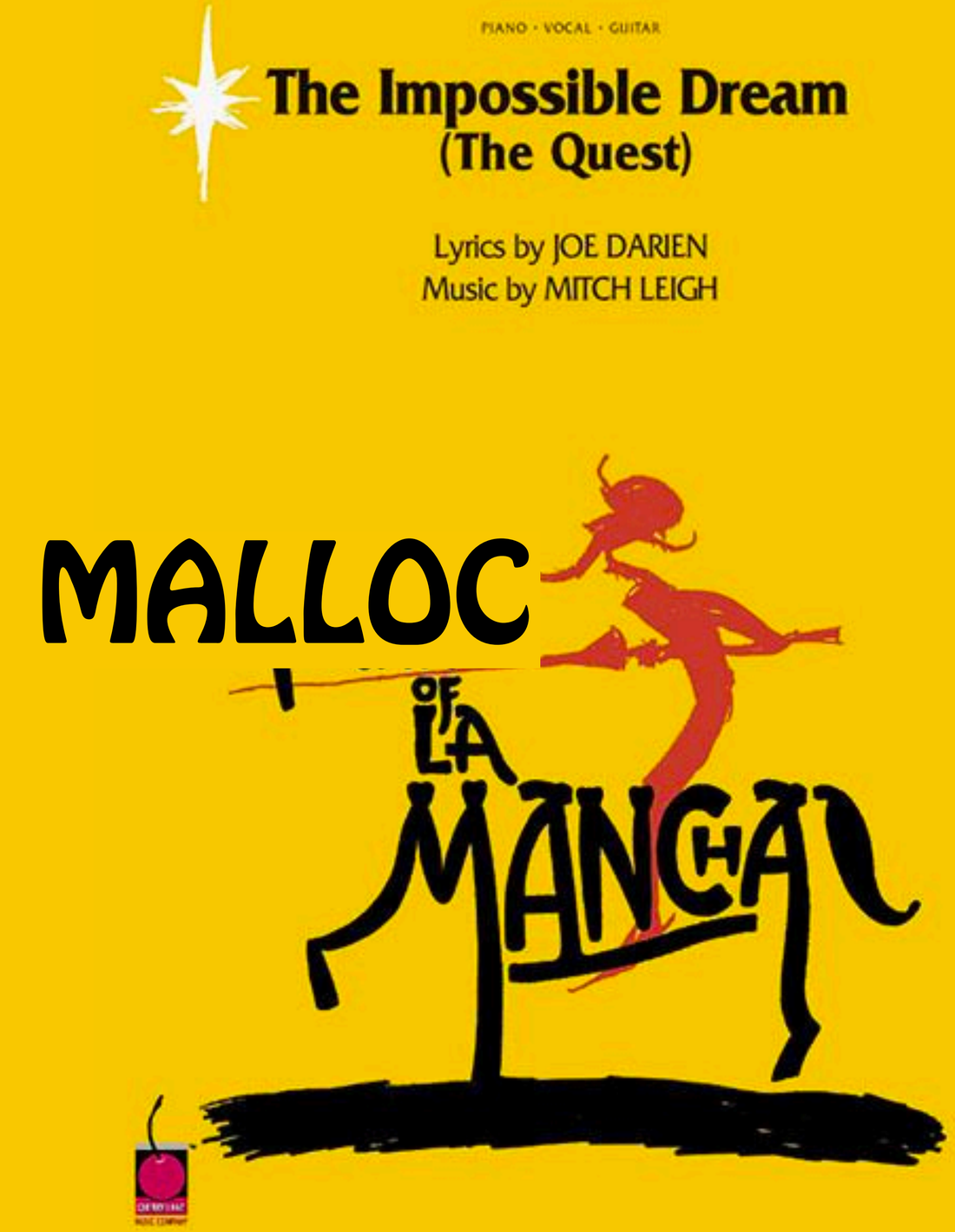
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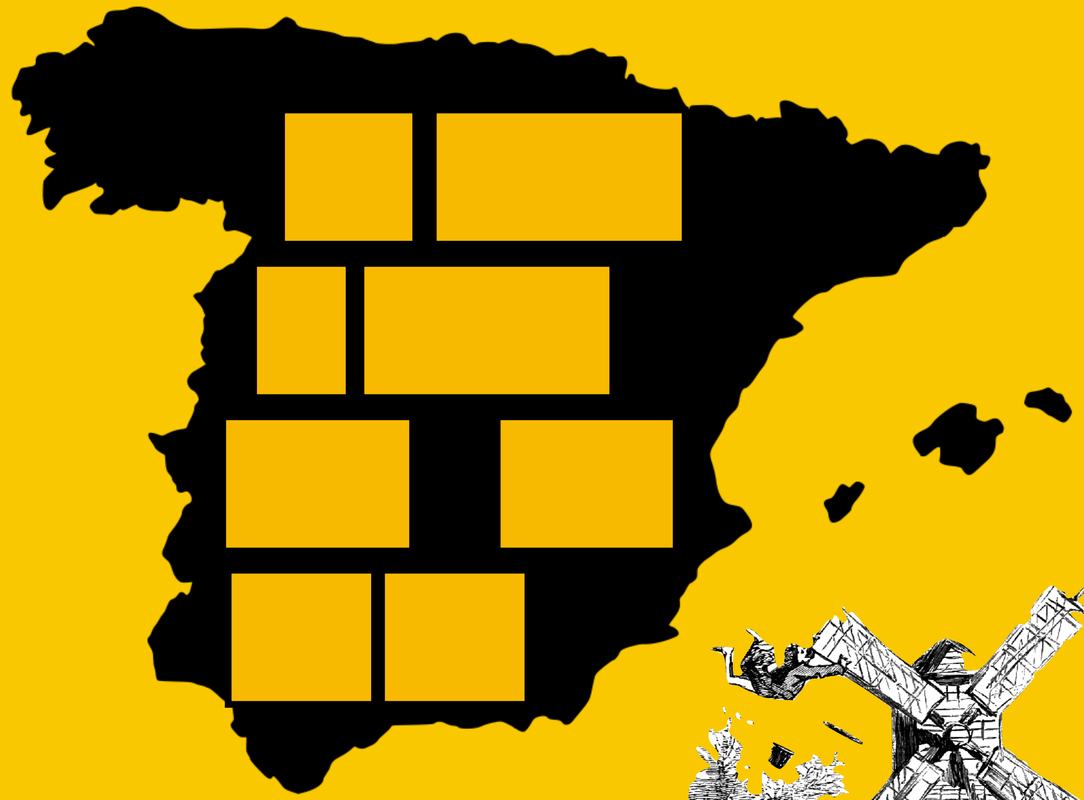

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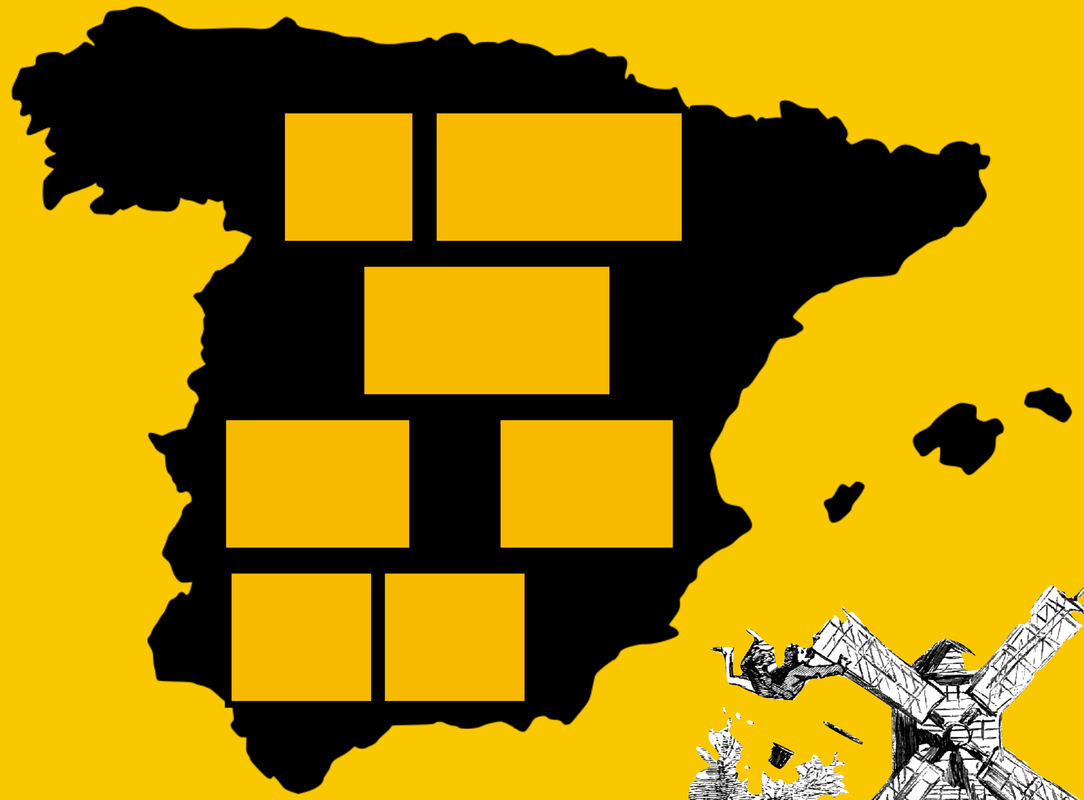

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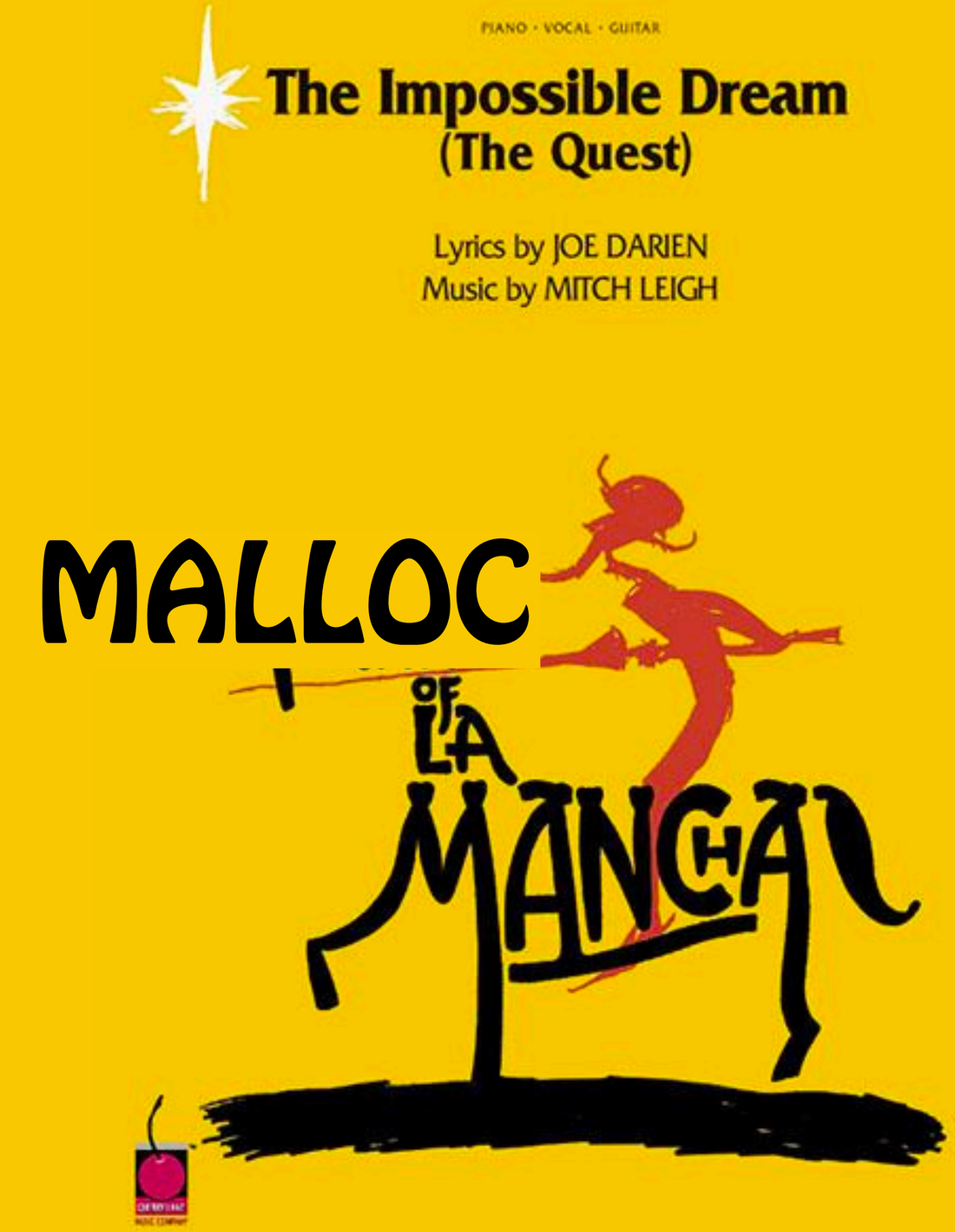
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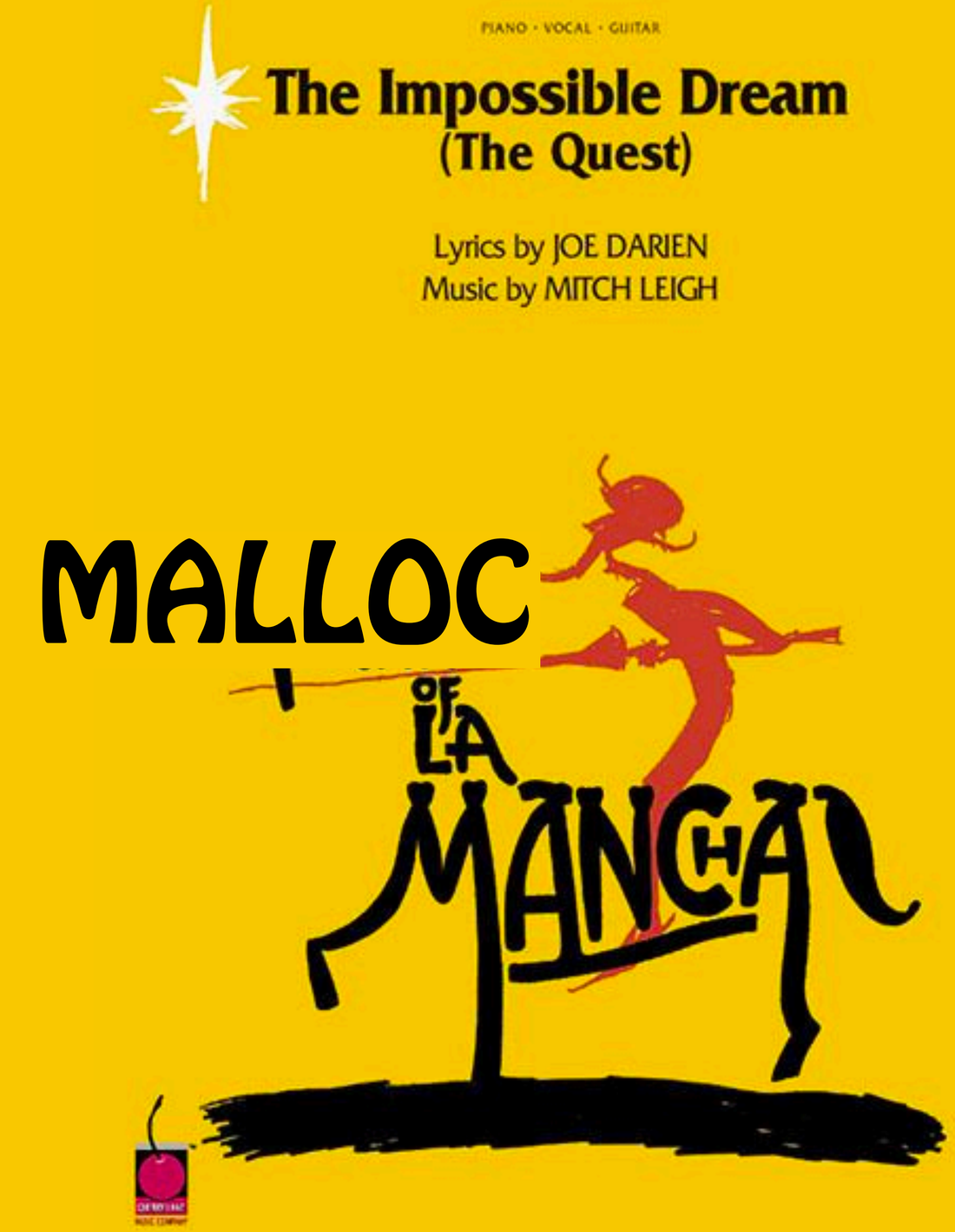
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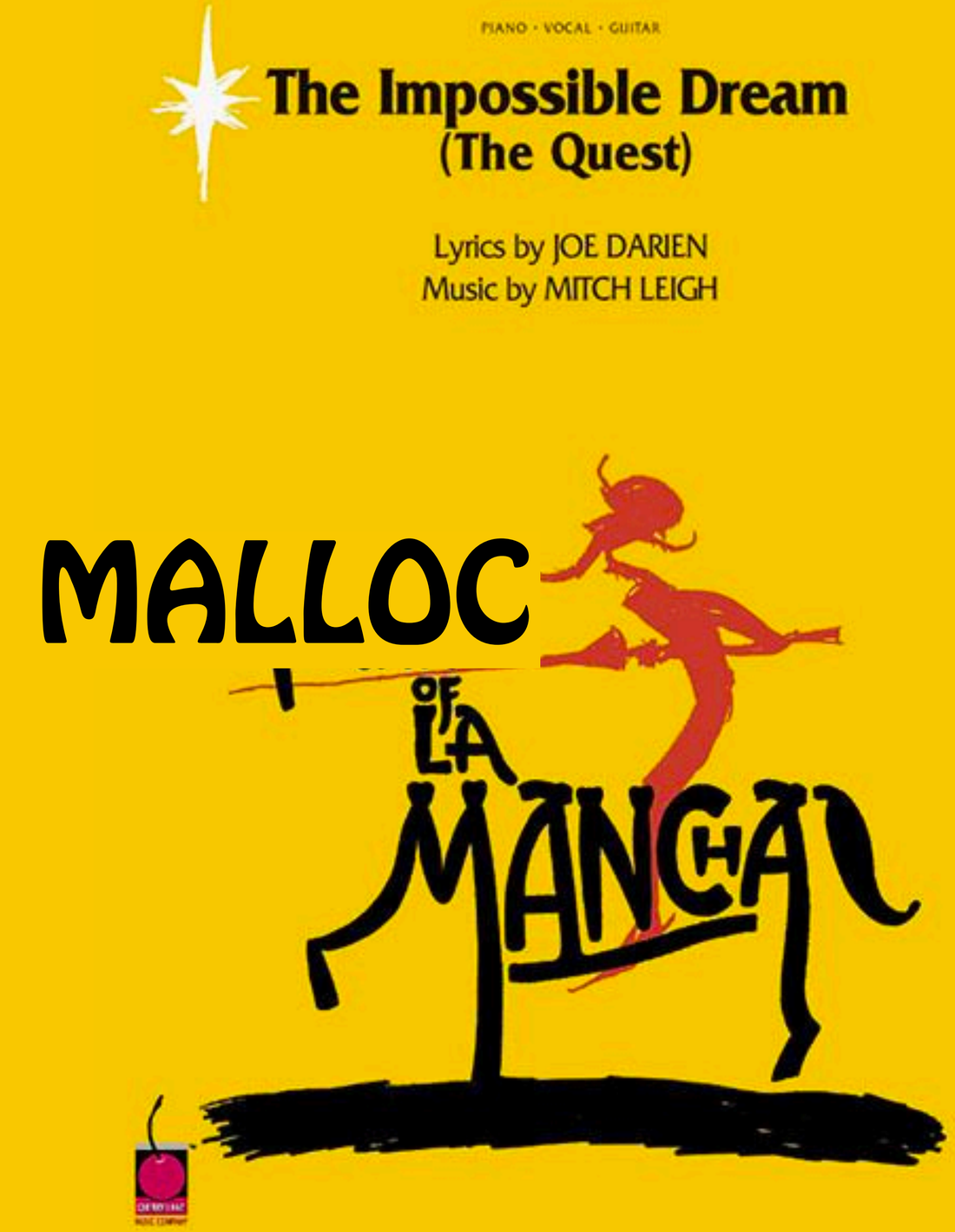
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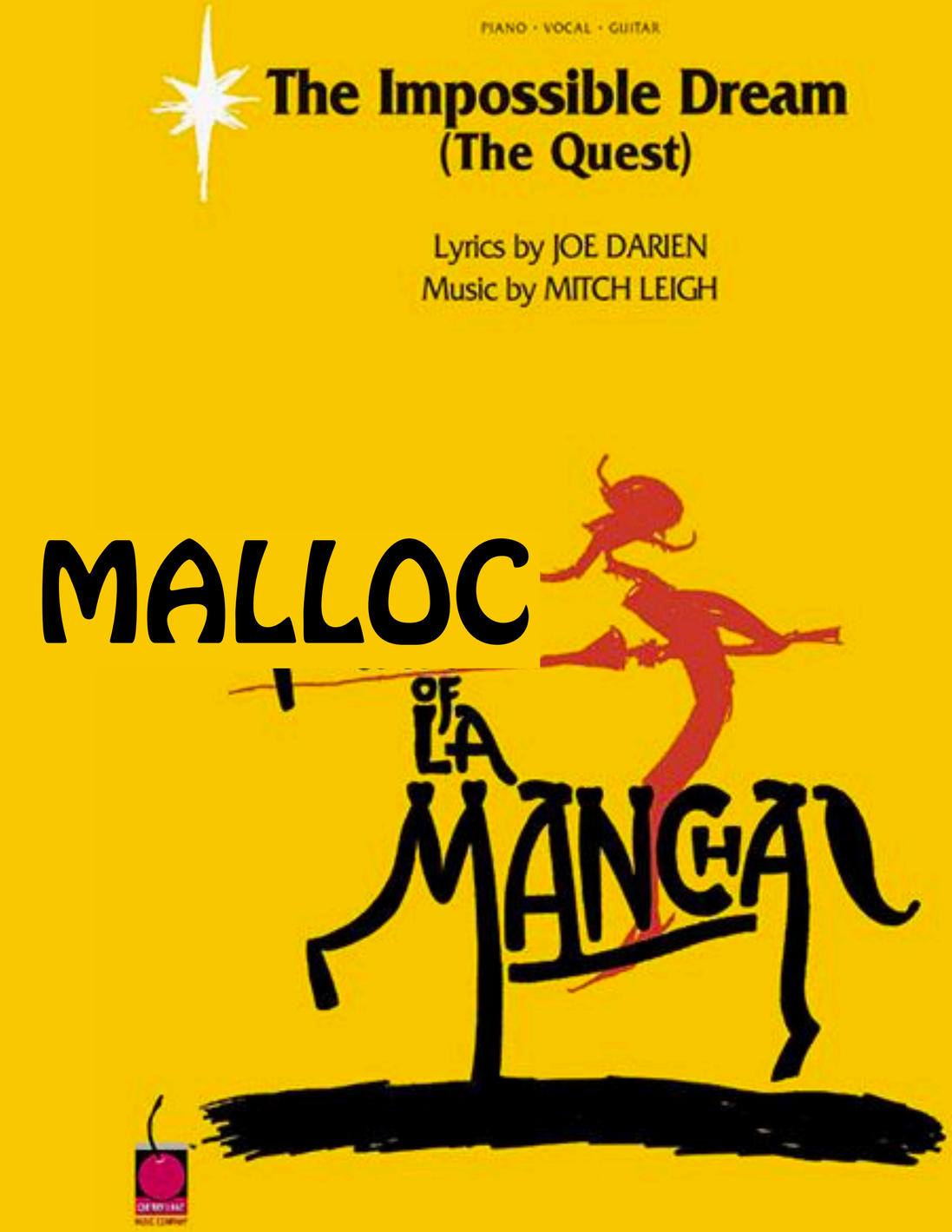
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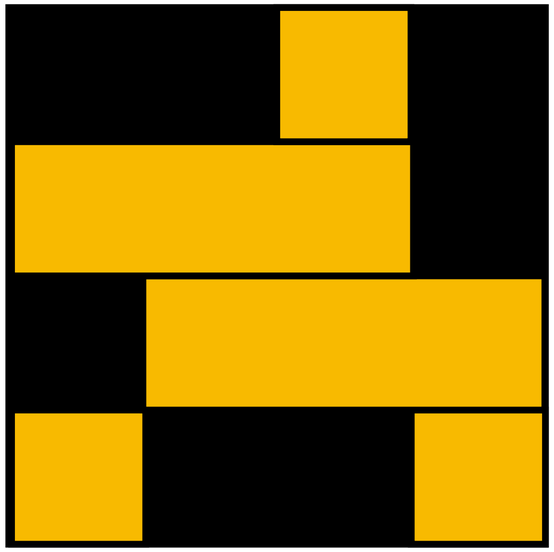
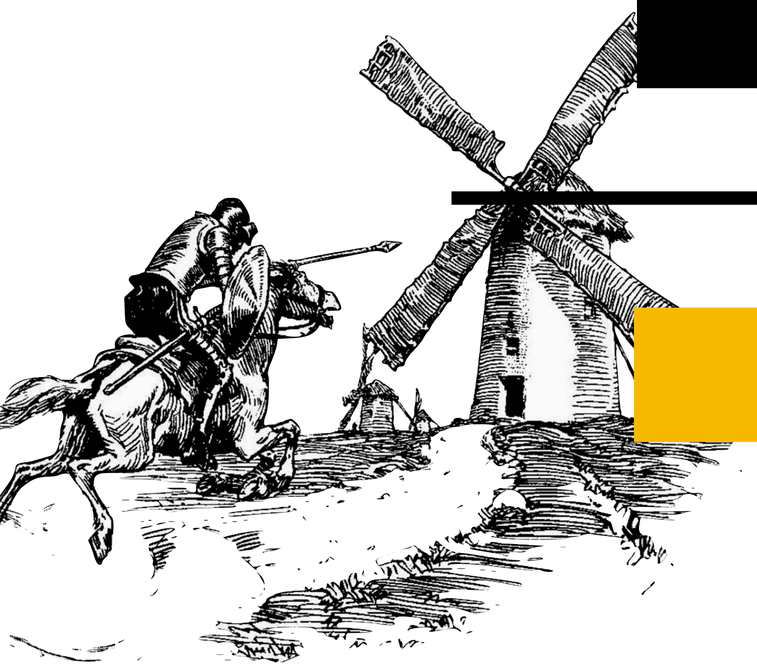
¡Fragmentación!

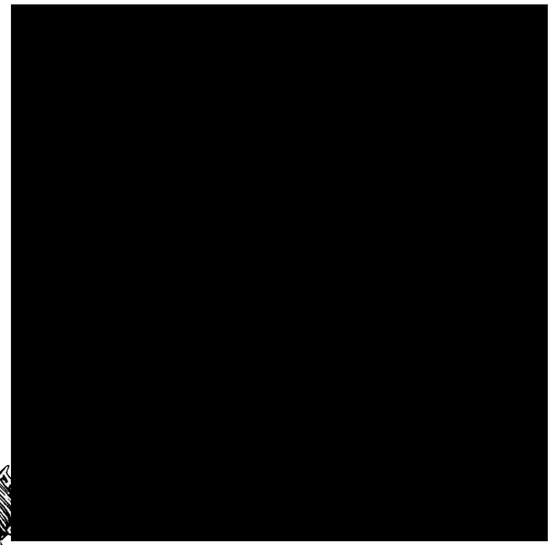


OS Page (“Spain”)

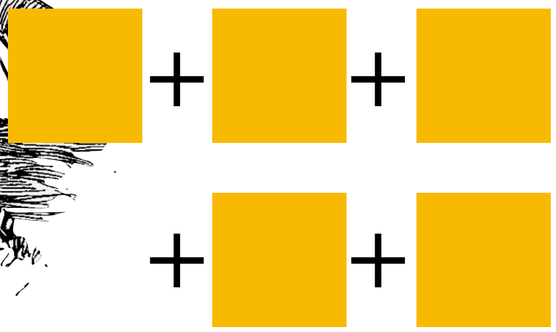
Live objects (malloc’d)

¡Fragmentación!



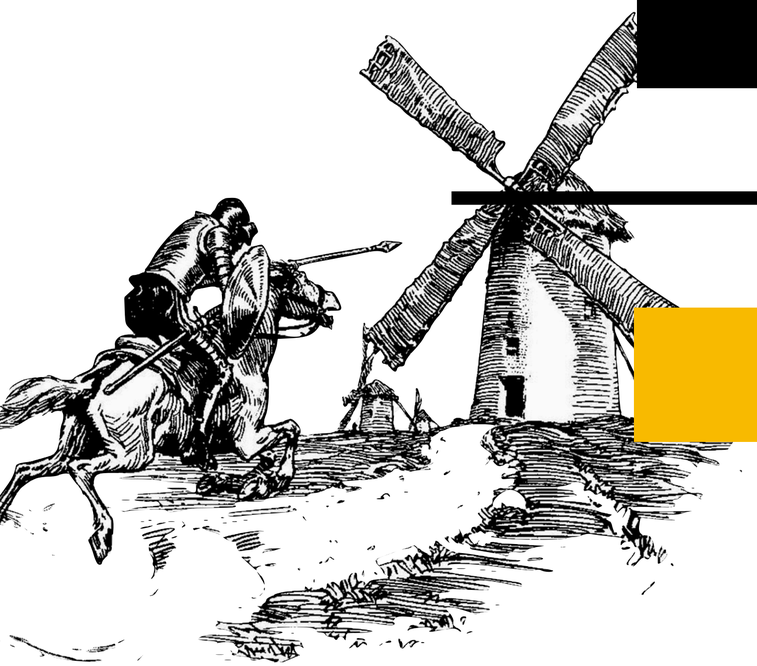


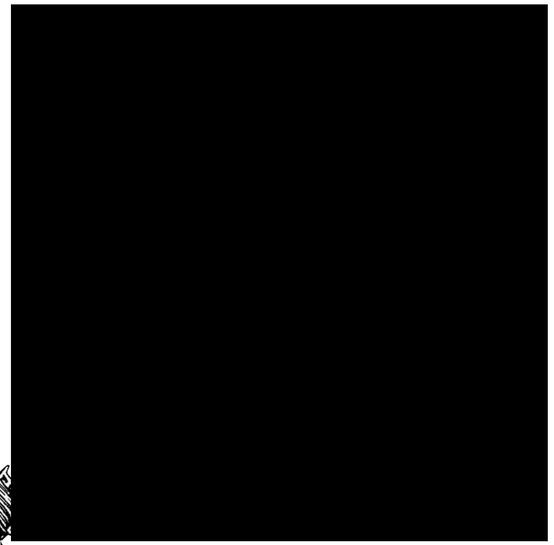
OS Pages



Live objects

¡Fragmentación!





OS Pages

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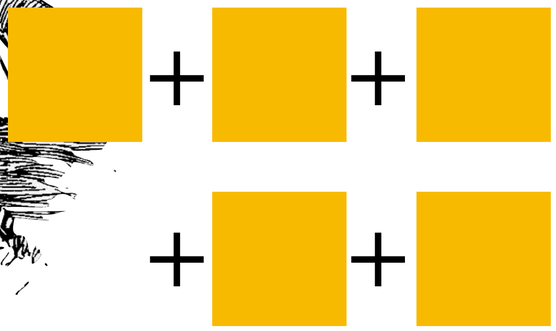
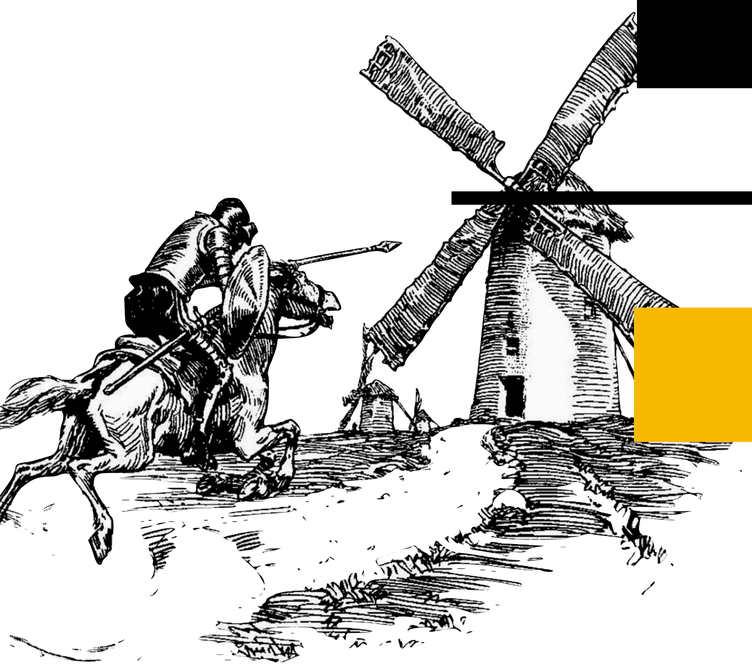
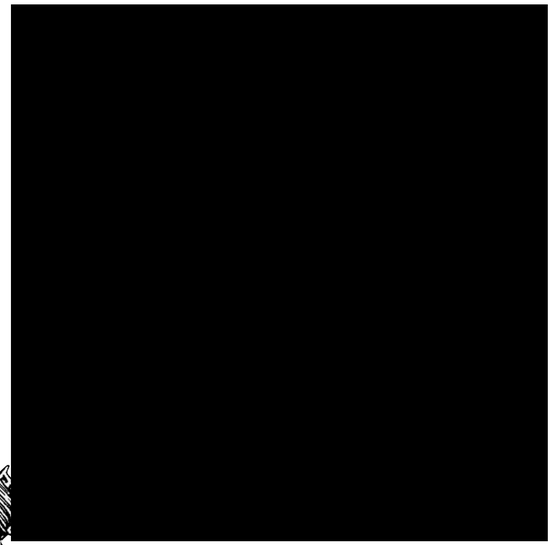


Live objects

¡Fragmentación!

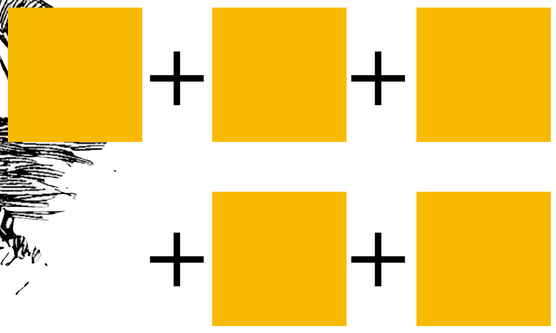




OS Pages

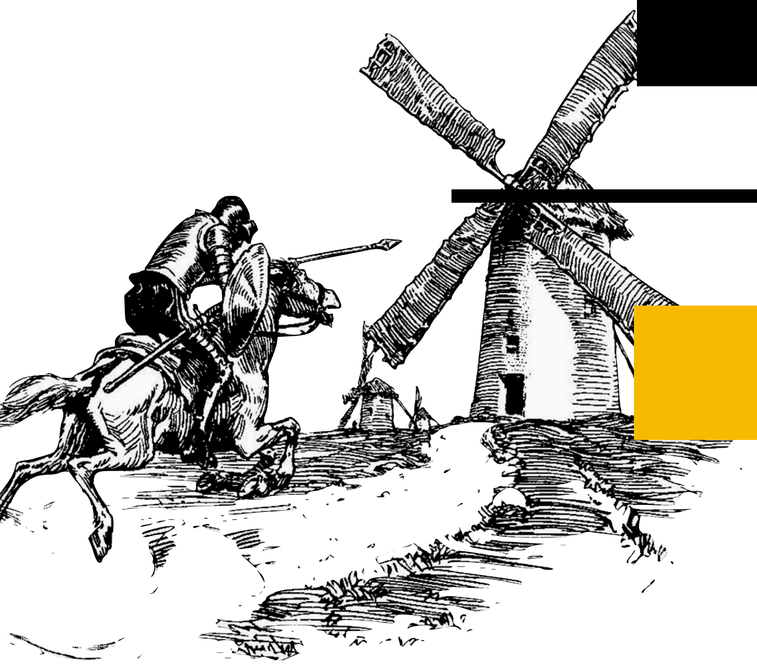
O(log ) 13x!

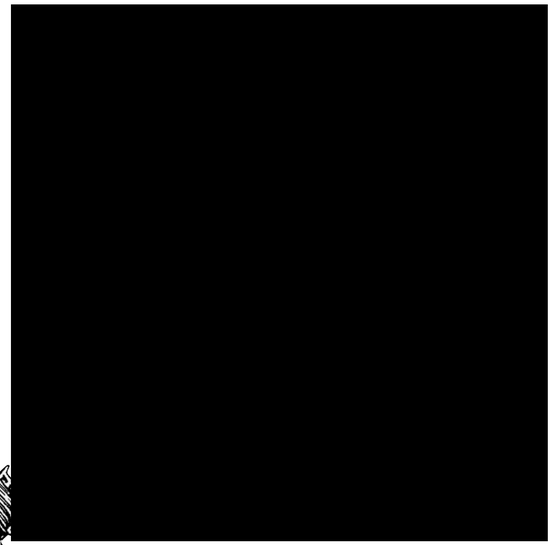
[Robson ’77]



Live objects

¿Compactación?





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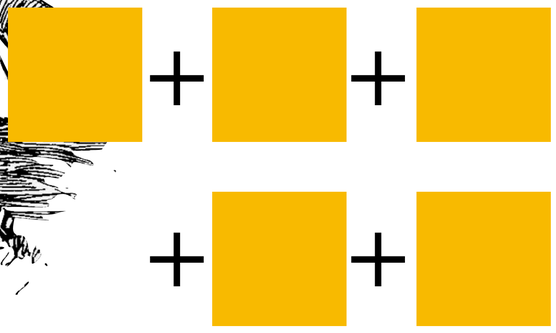

Live objects

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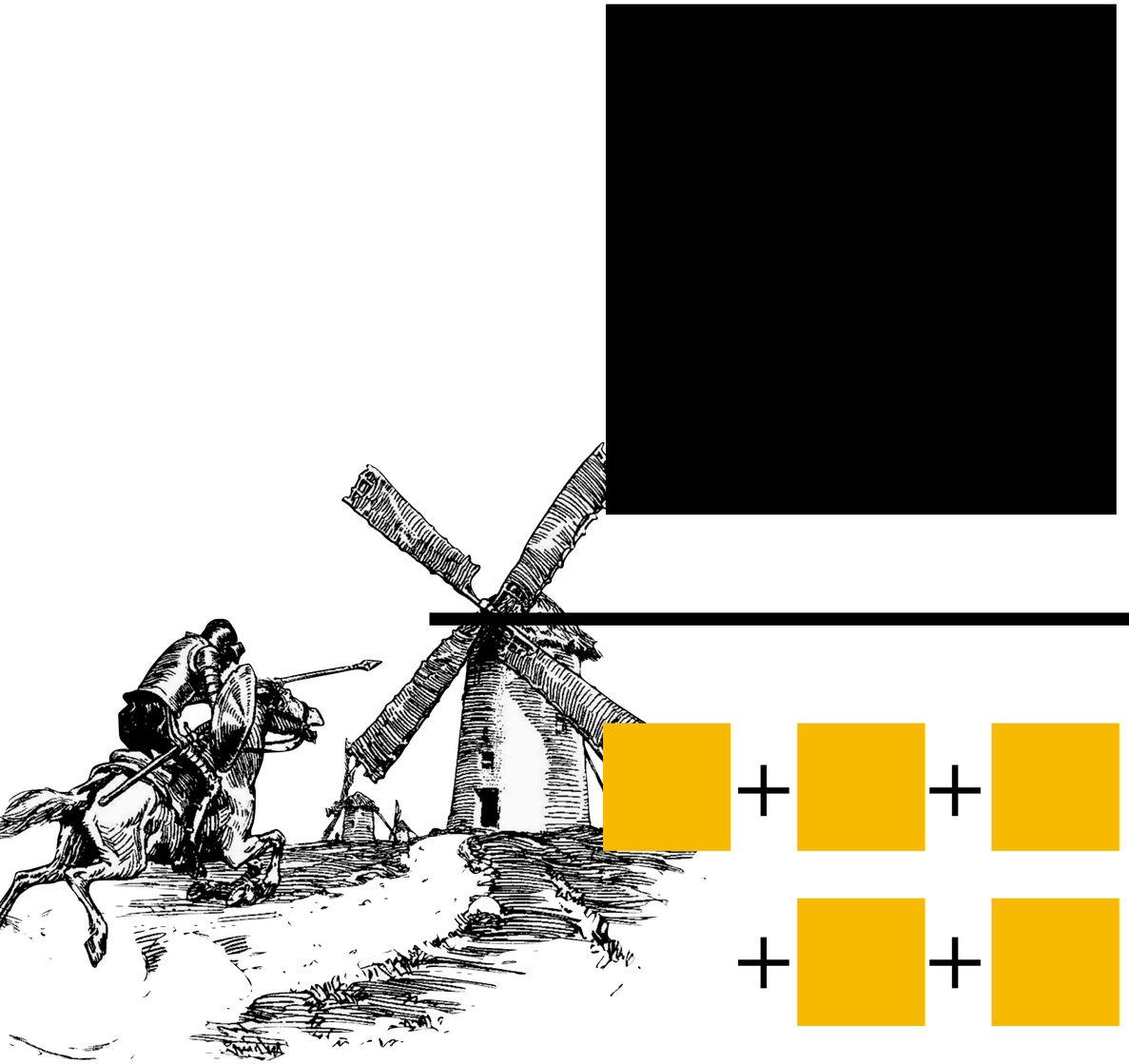

OS Pages

O(1)

Live objects

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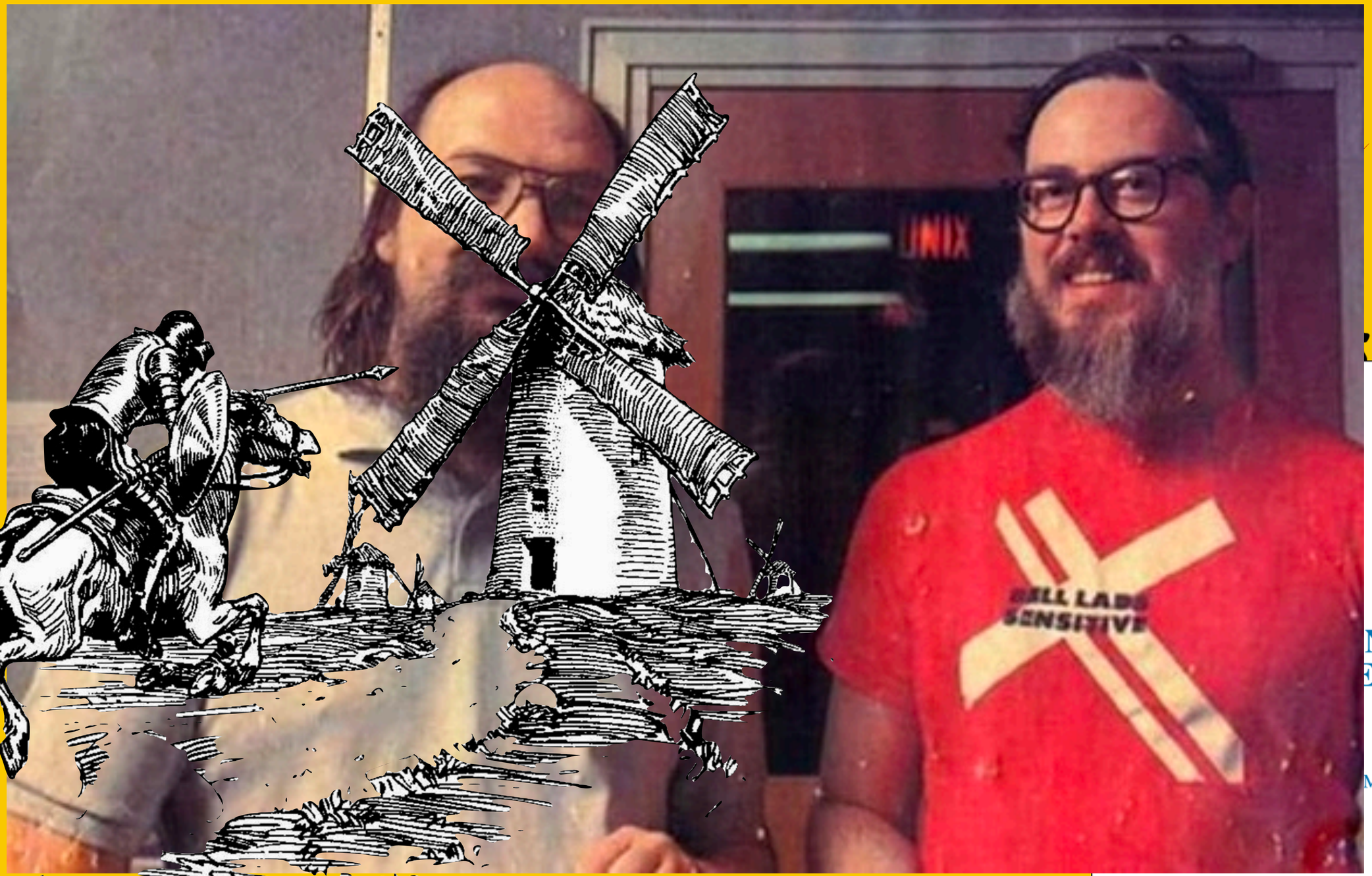

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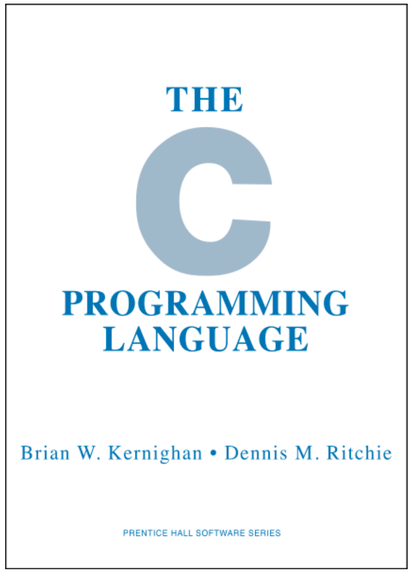
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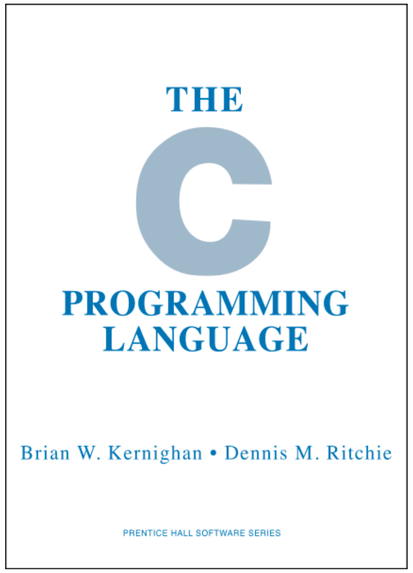
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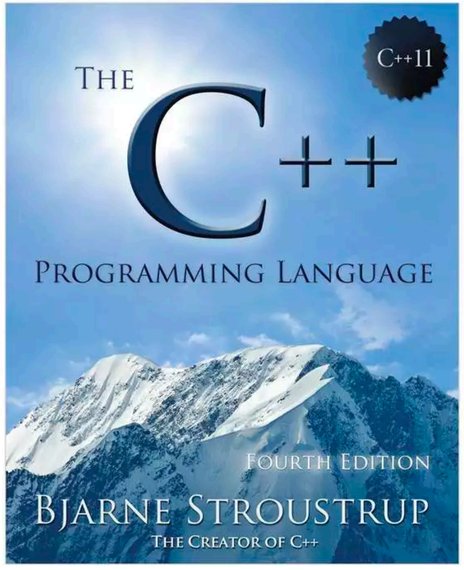
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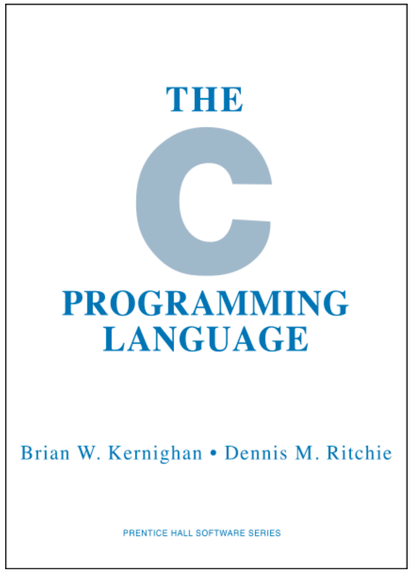
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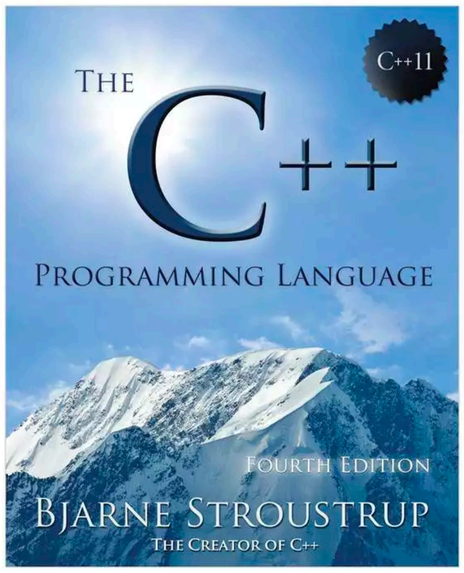
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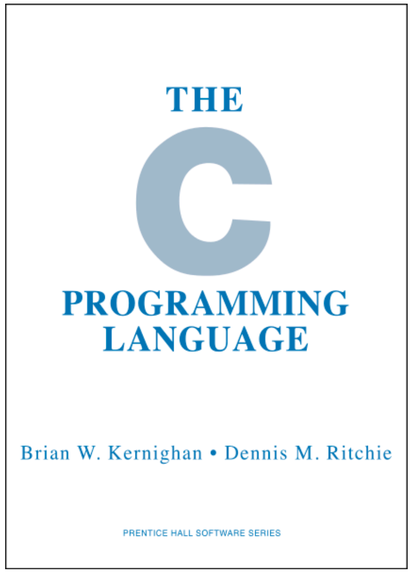

[Lattner, 2016]

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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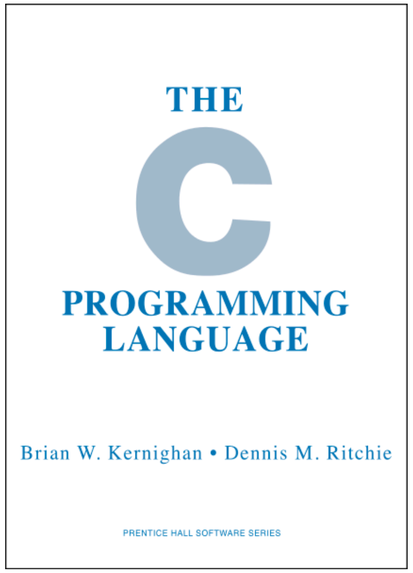
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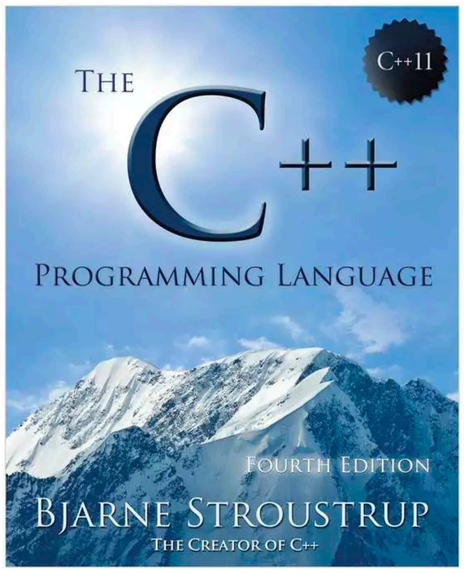
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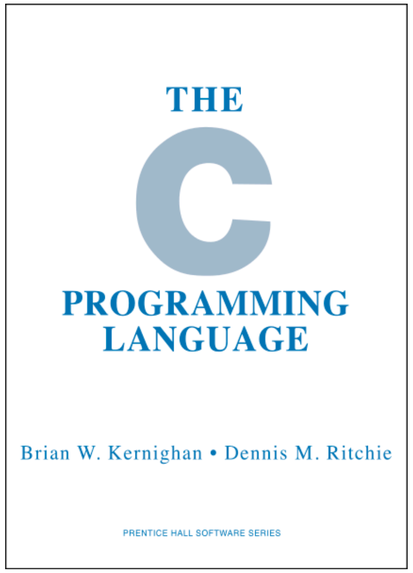
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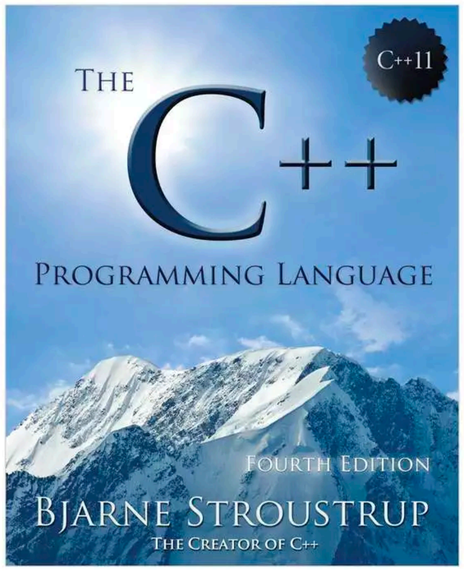
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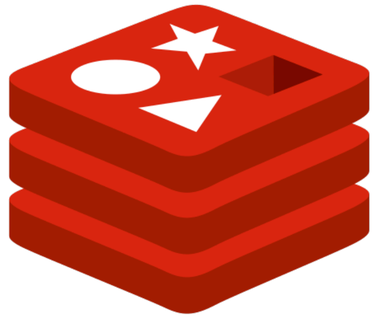

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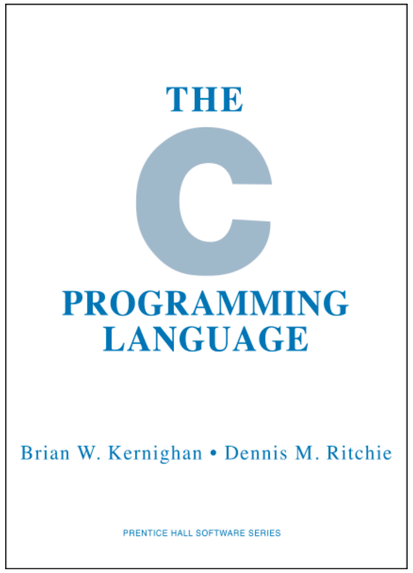
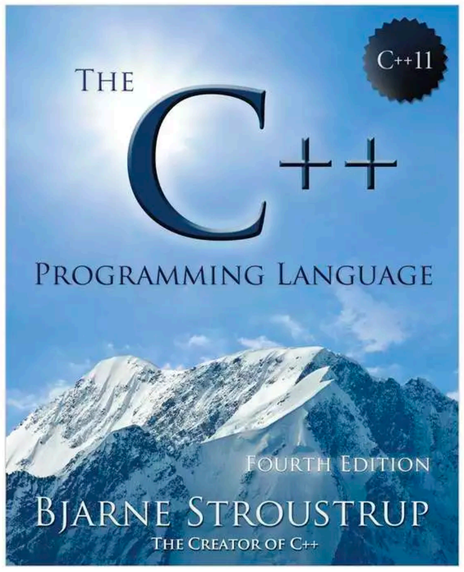
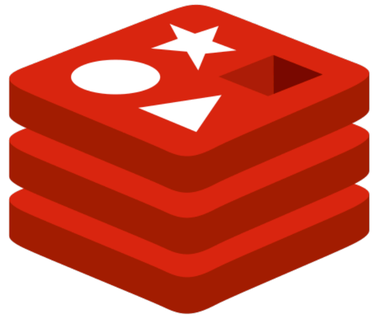
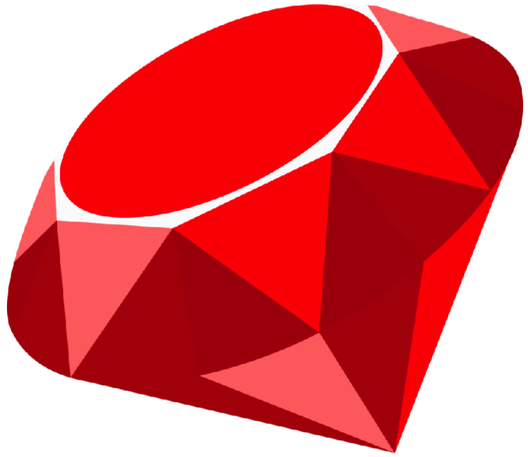

THE
C
PROGRAMMING
LANGUAGE
Brian W. Kernighan • Dennis M. Ritchie
PRENTICE HALL SOFTWARE SERIES


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


The Swift
Programming
Language
Swift 5 Edition



redis




MySQL™


Office


W
P
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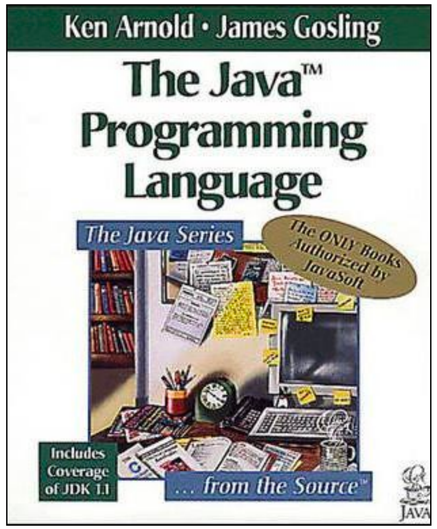
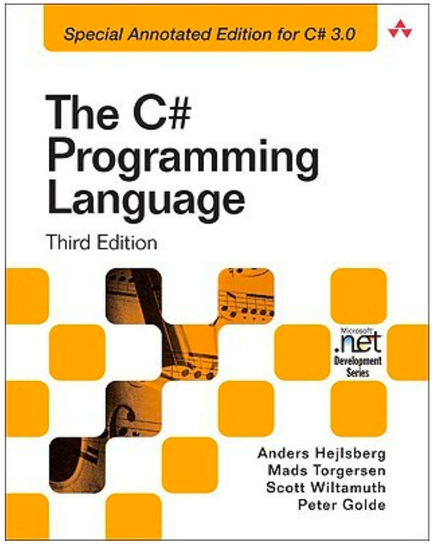
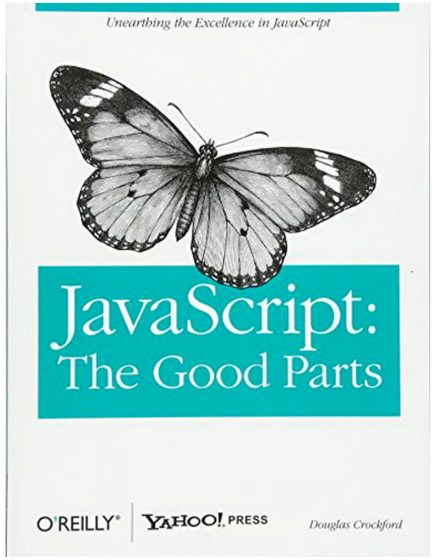
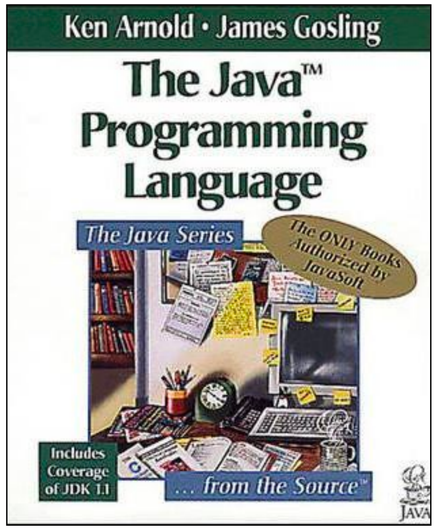
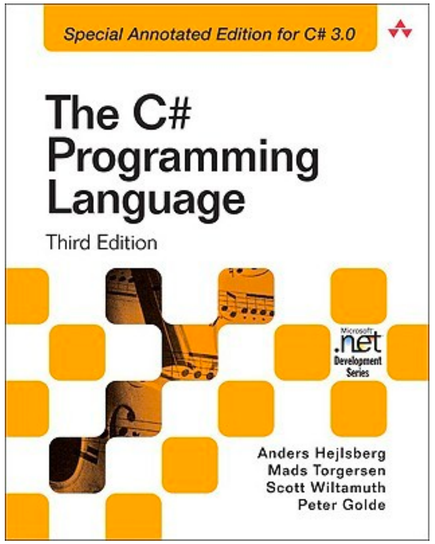
A

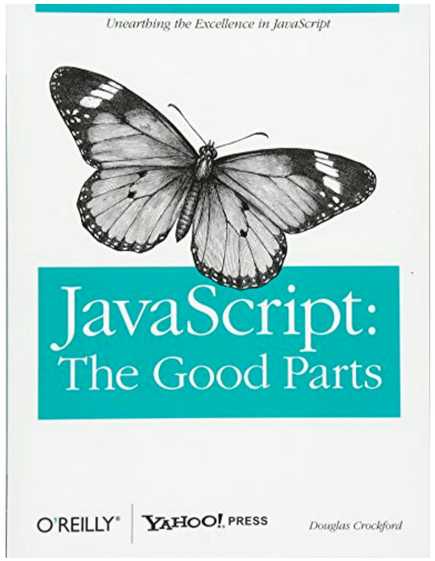

Ken Arnold • James Gosling
The Java™ Programming Language
The Java Series
The ONLY Books Authorized by JavaSoft
Includes Coverage of JDK 1.1
... from the Source™
JAVA


Special Annotated Edition for C# 3.0
The C# Programming Language
Third Edition
Microsoft .net Development Series
Anders Hejlsberg
Mads Torgersen
Scott Wiltamuth
Peter Golde


Unearthing the Excellence in JavaScript
JavaScript: The Good Parts
O'REILLY
YAHOO! PRESS
Douglas Crockford

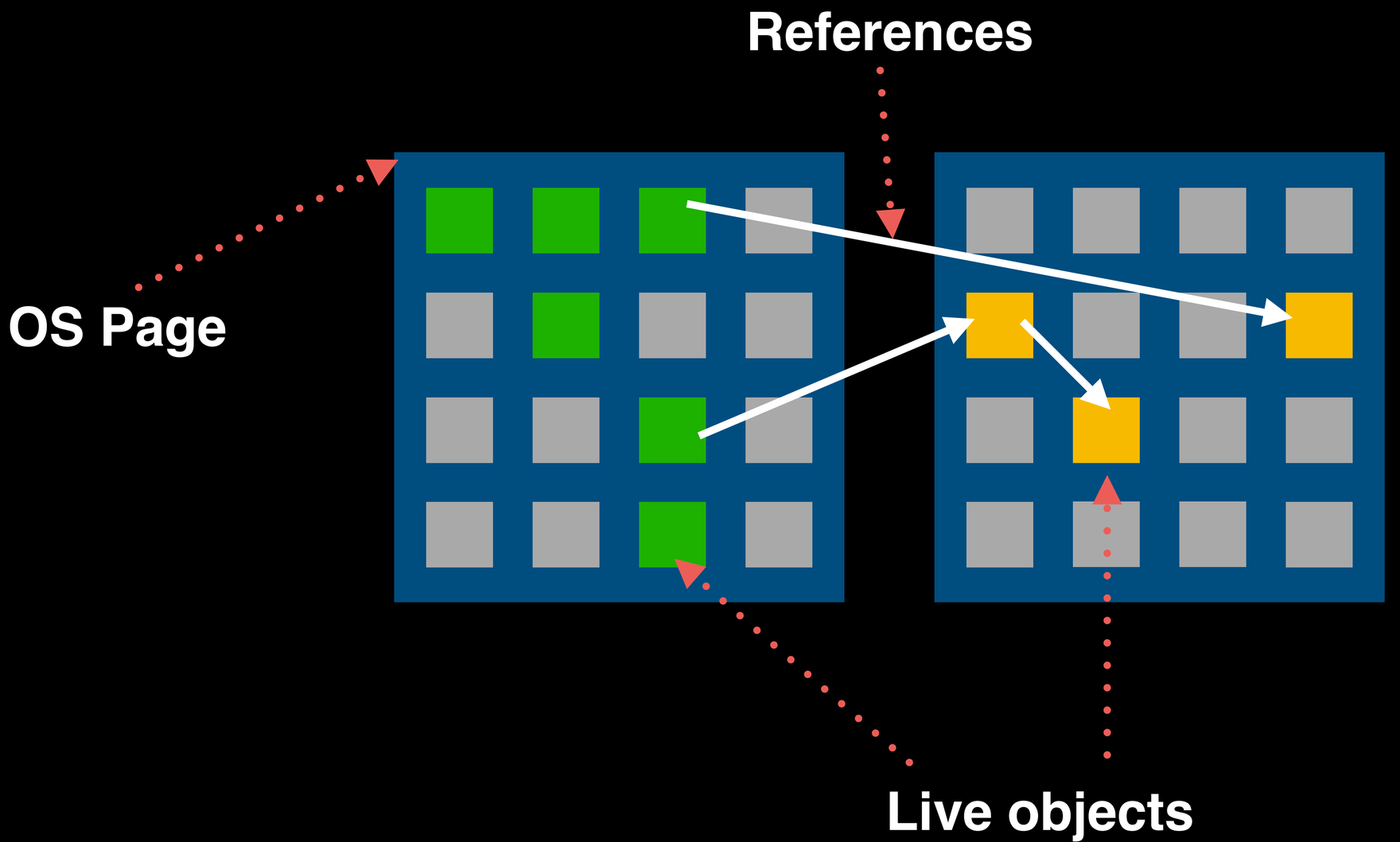


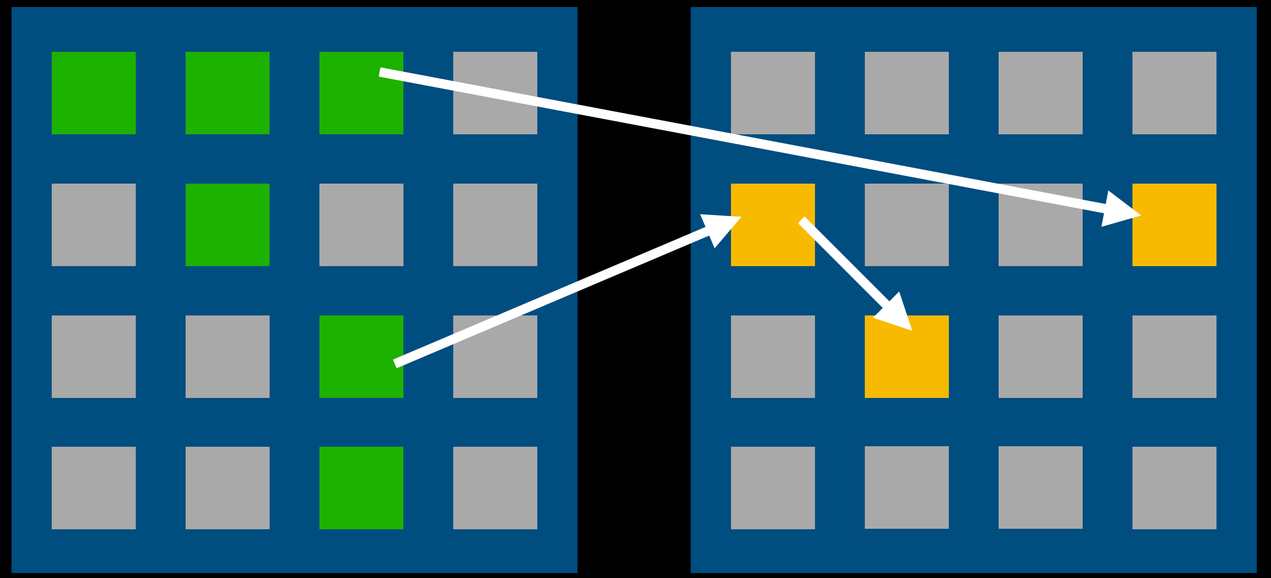


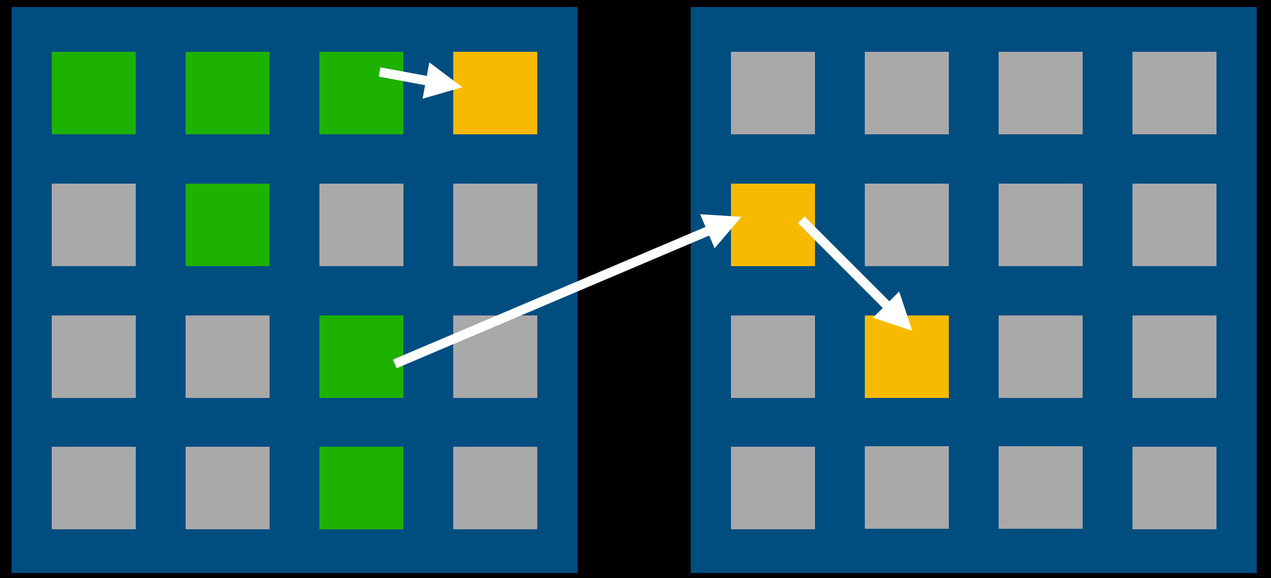


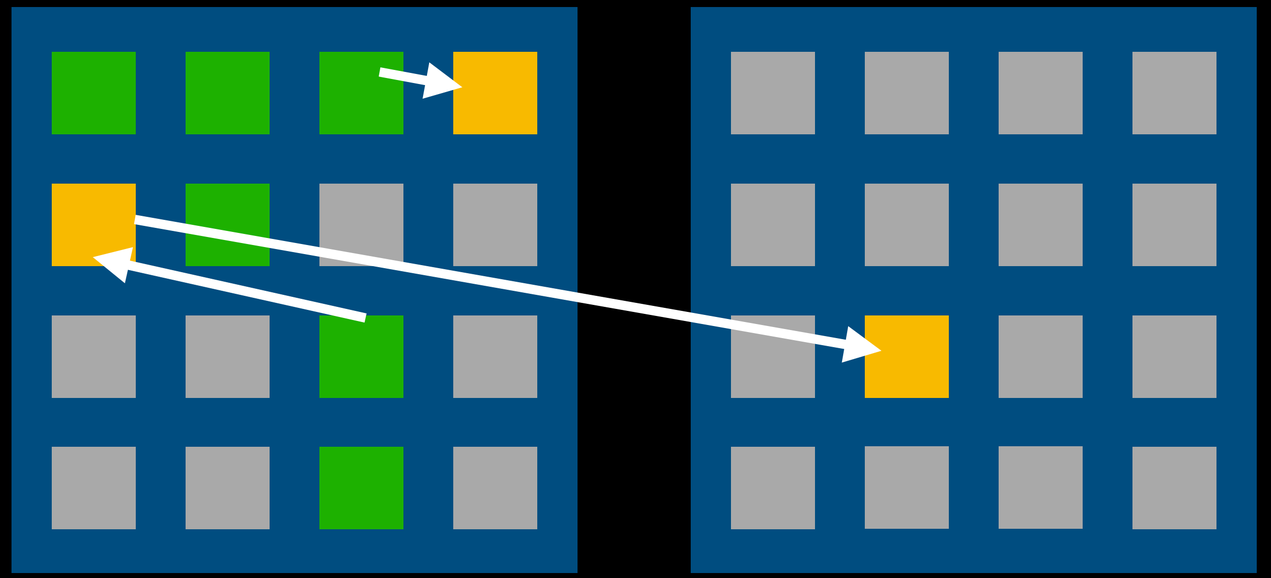
¡Compactación!

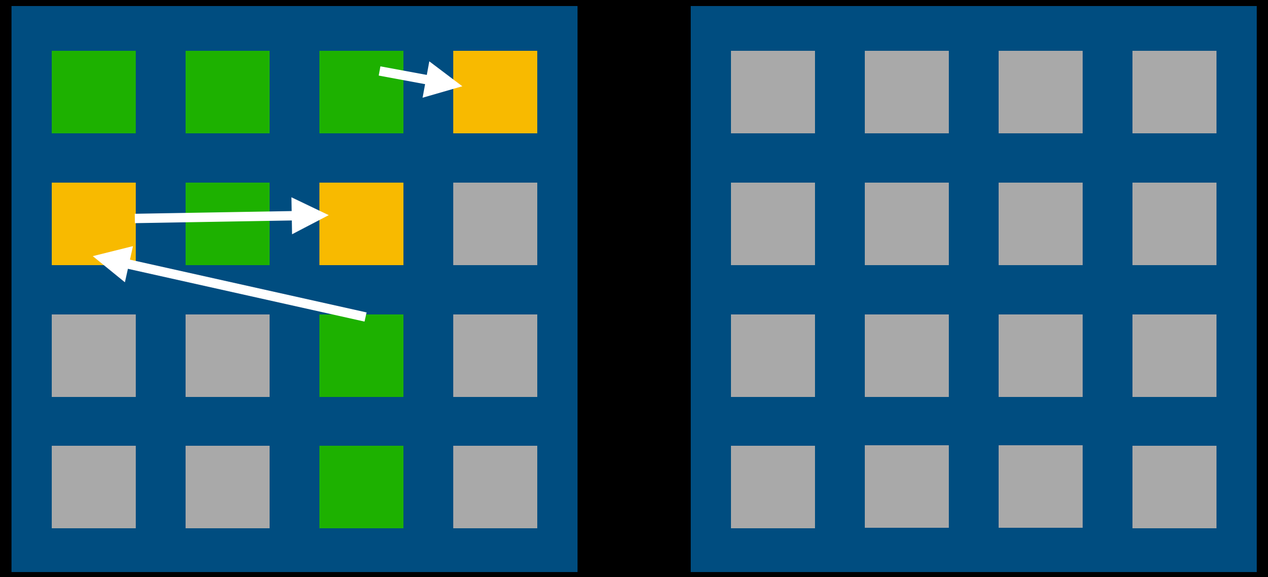
Compaction In Action

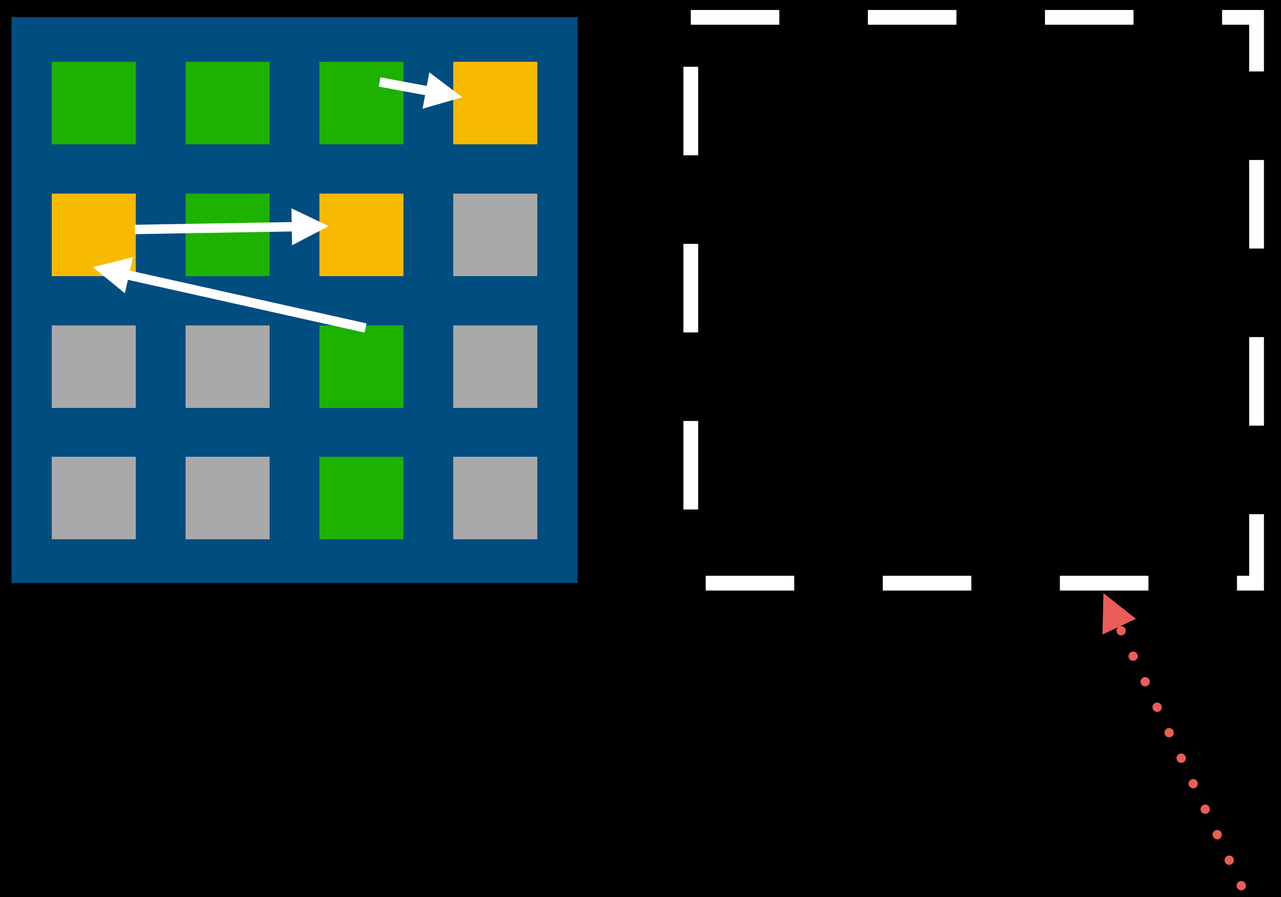












Page returned
to the OS

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

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

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

No way to precisely distinguish pointers from integers

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

0xDEADC000

No way to precisely distinguish pointers from integers

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

0xDEADC000

No way to precisely distinguish pointers from integers

0xBEEFC000

```
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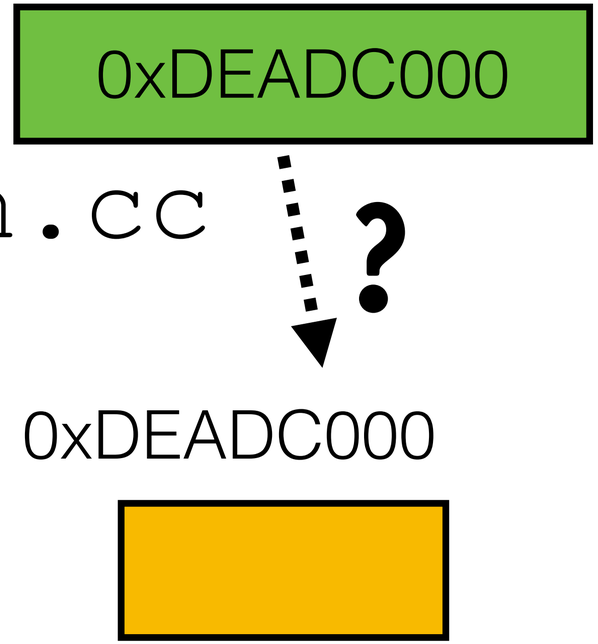
$ strip yolo
$ ./yolo
```

No way to precisely distinguish pointers from integers

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



No way to precisely distinguish pointers from integers

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

// initialize
x.ptr = new int;

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

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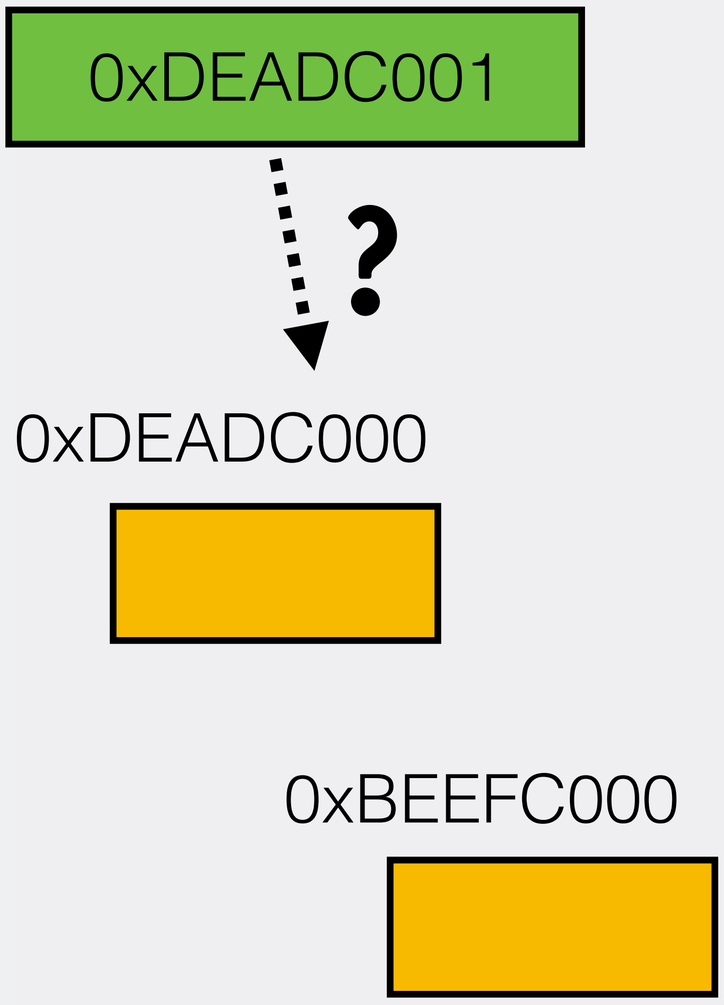

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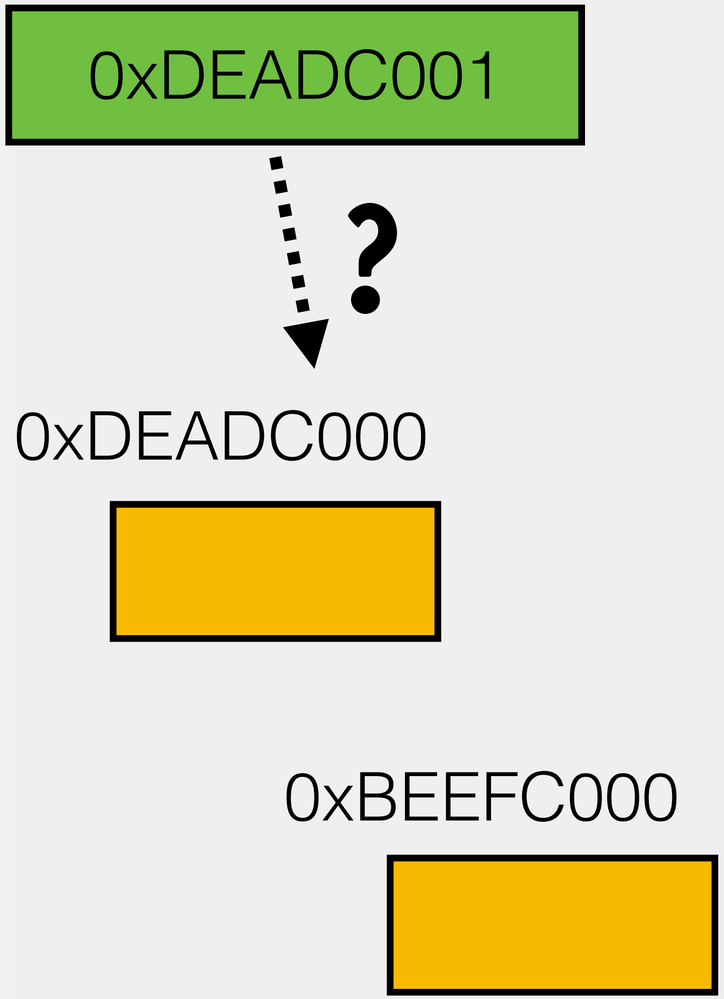


MESH

Compaction without Relocation for C/C++

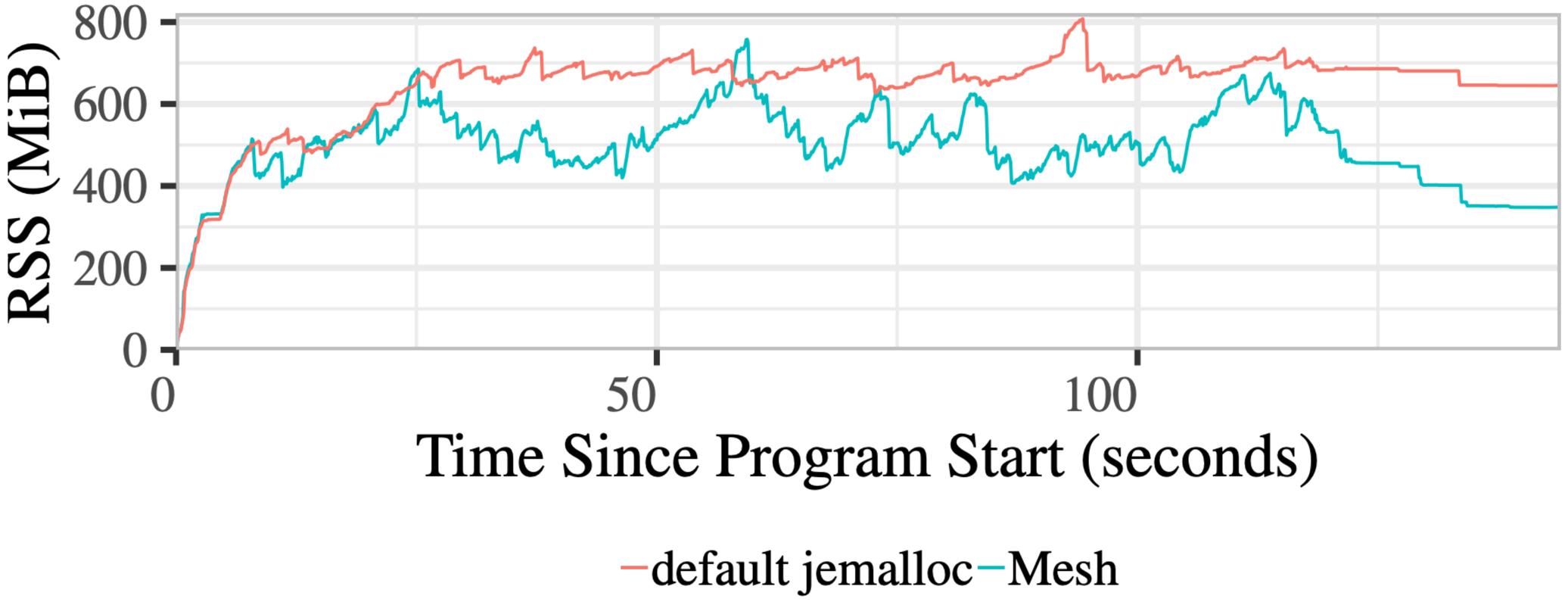
No code changes

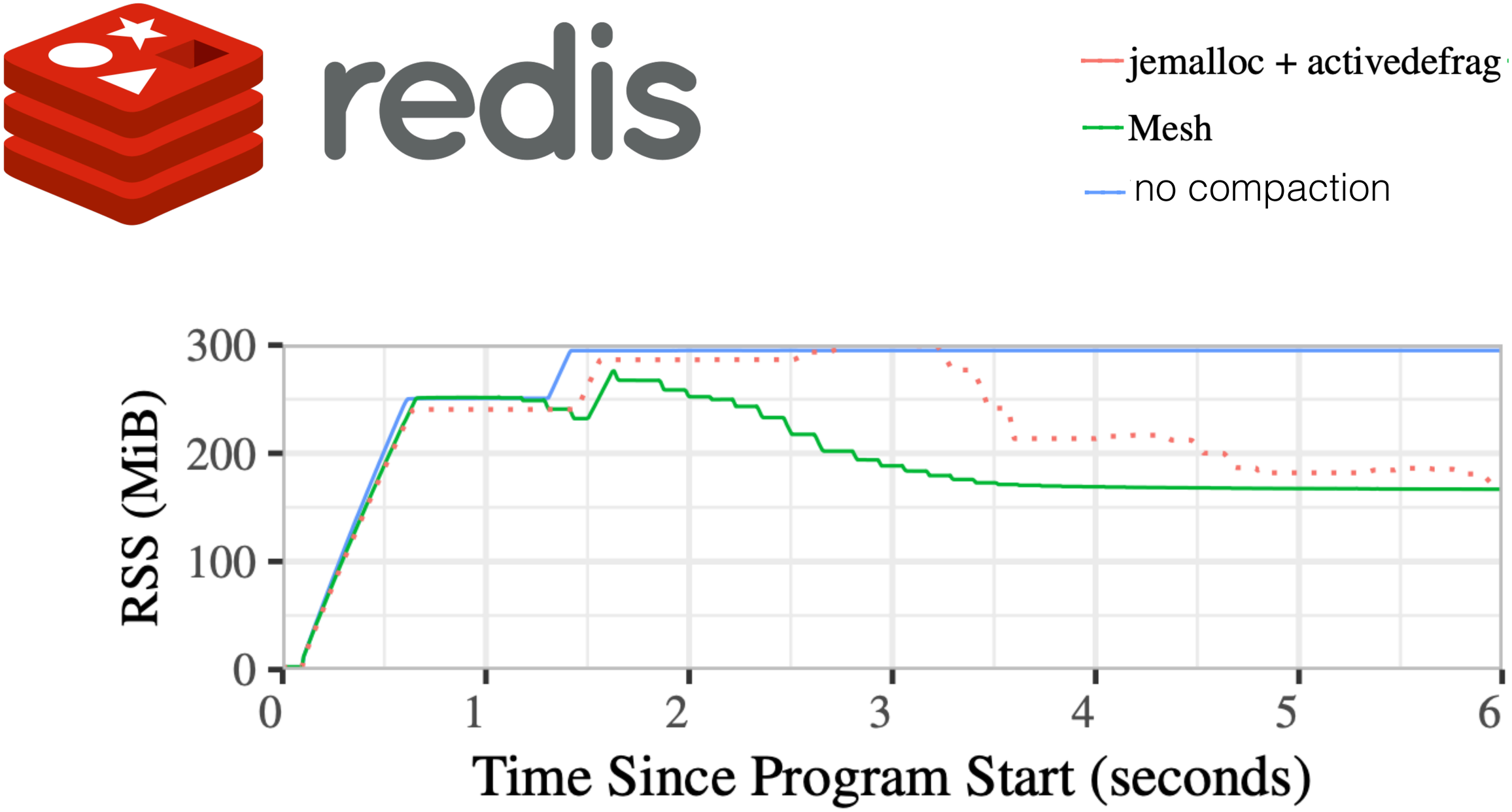
No recompilation

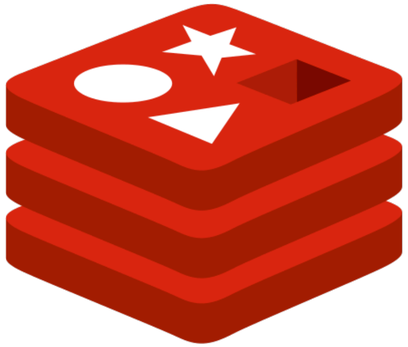
`LD_PRELOAD` and go

17% heap size reduction

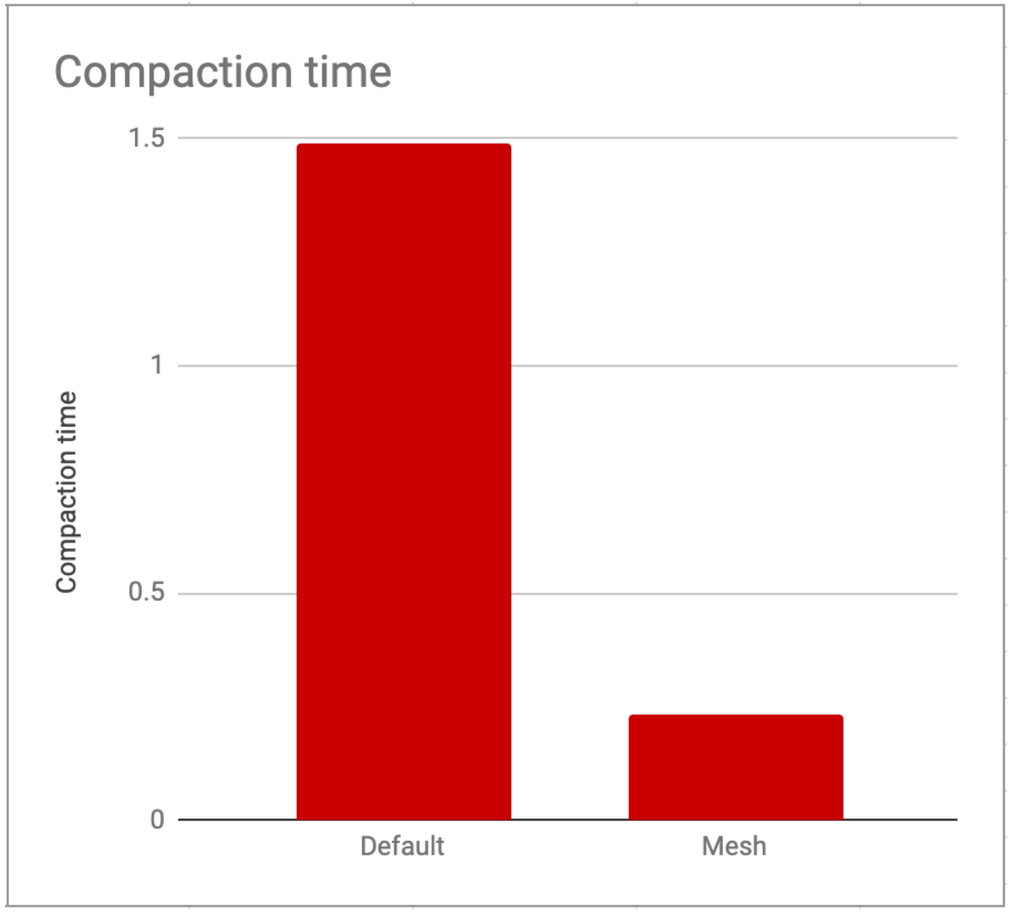
< 1% performance overhead




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

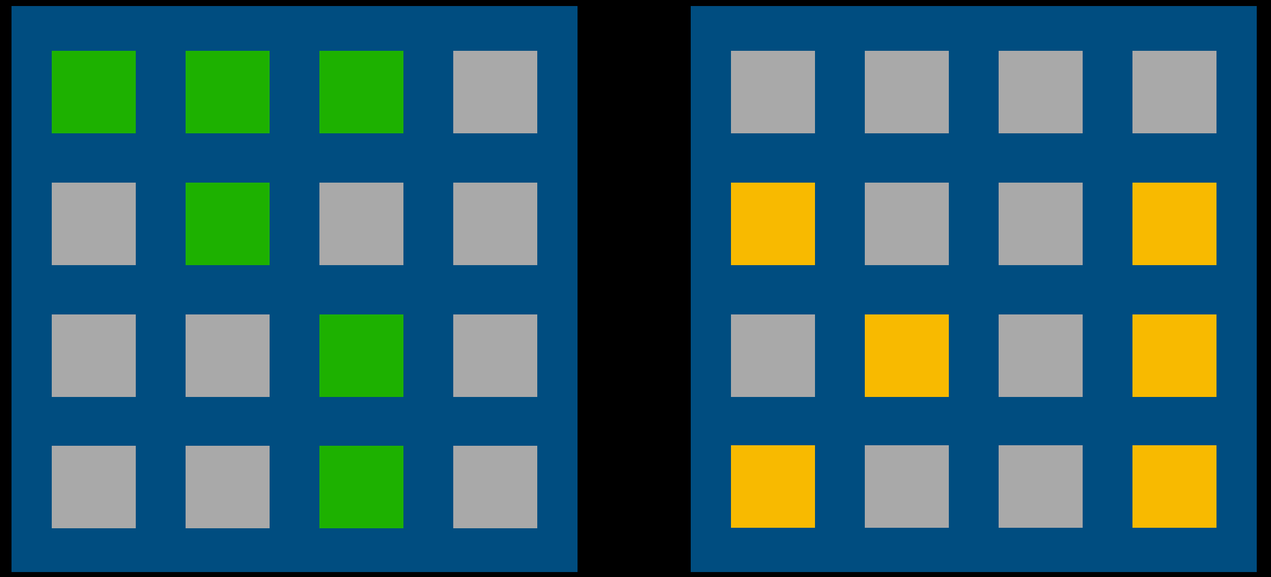


redis



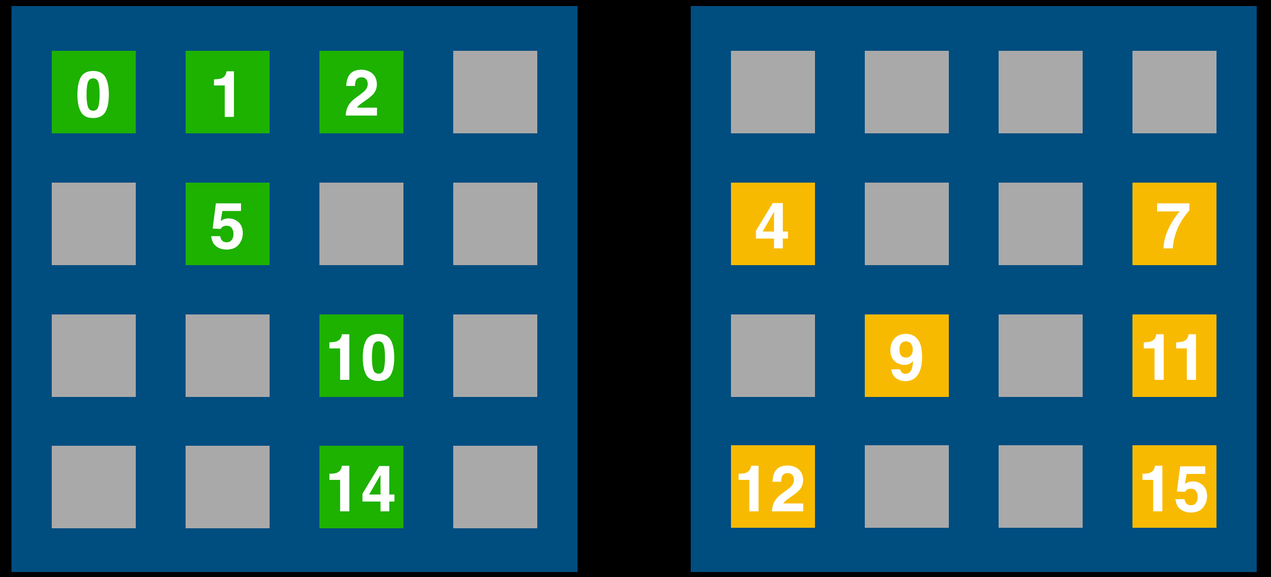
5x reduction in time spent compacting

Meshing: *compaction without (virtual!) relocation*



Pages are **Meshable** when they:

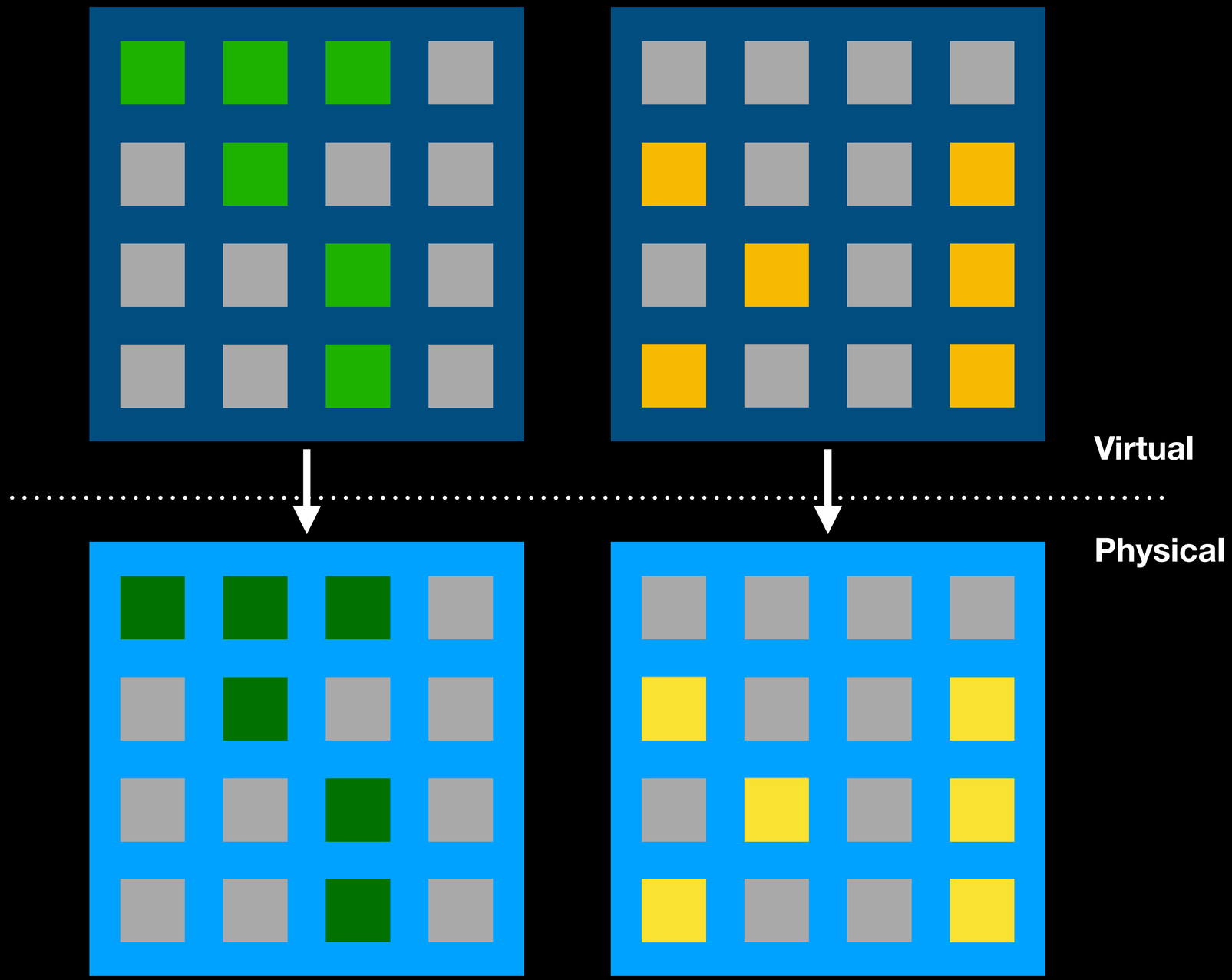
- Hold objects of the same size class



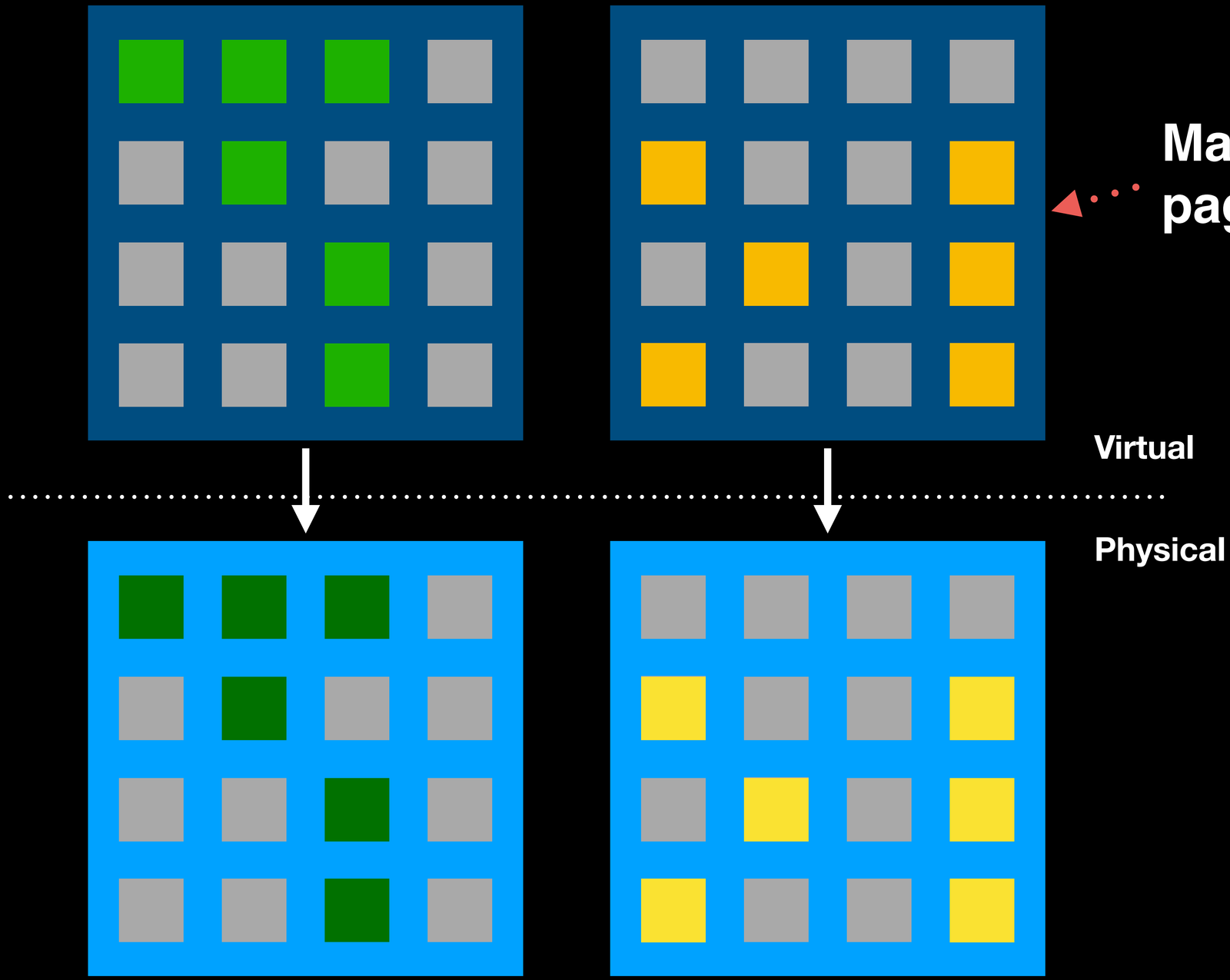
Pages are **Meshable** when they:

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

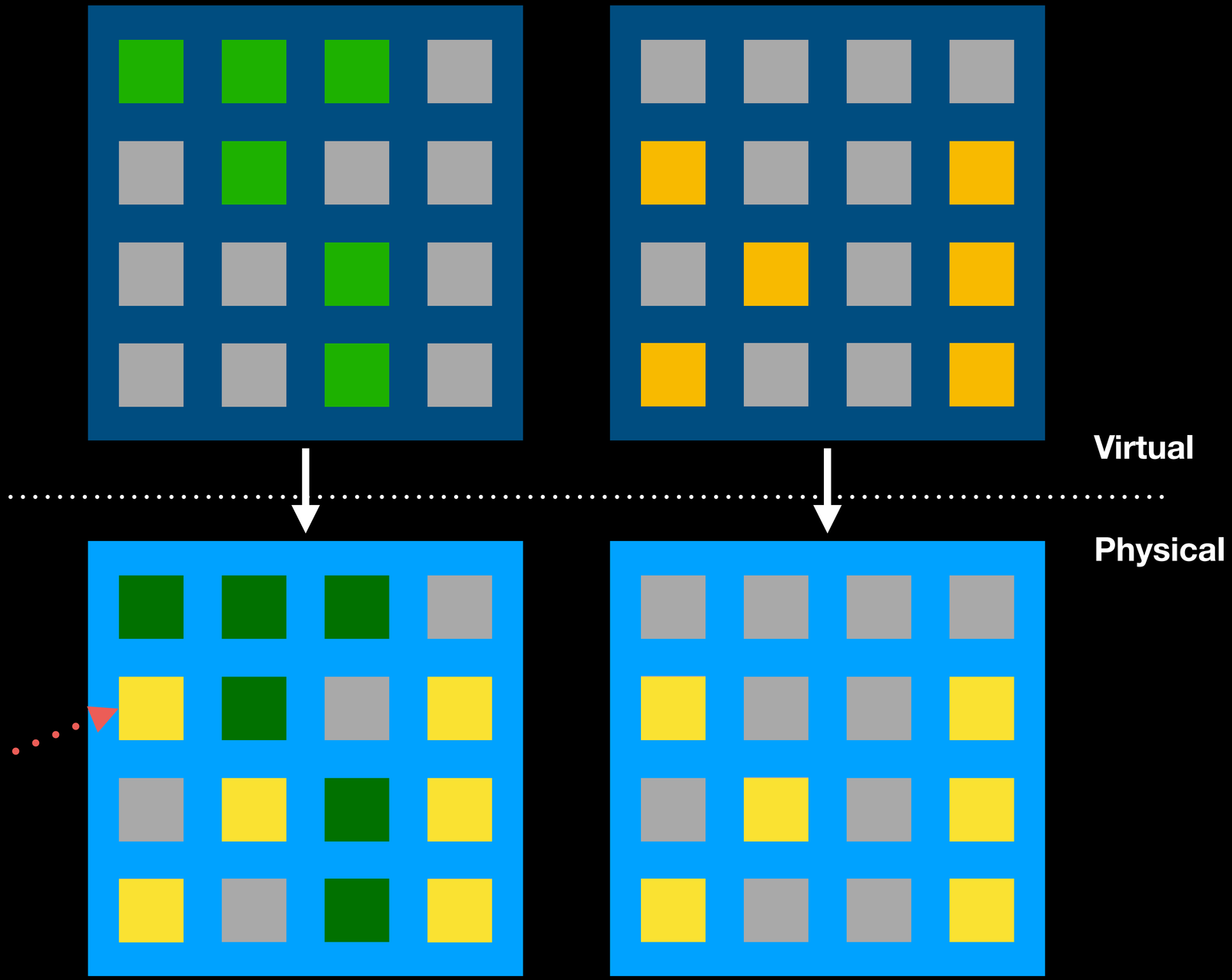
Meshing



Meshing

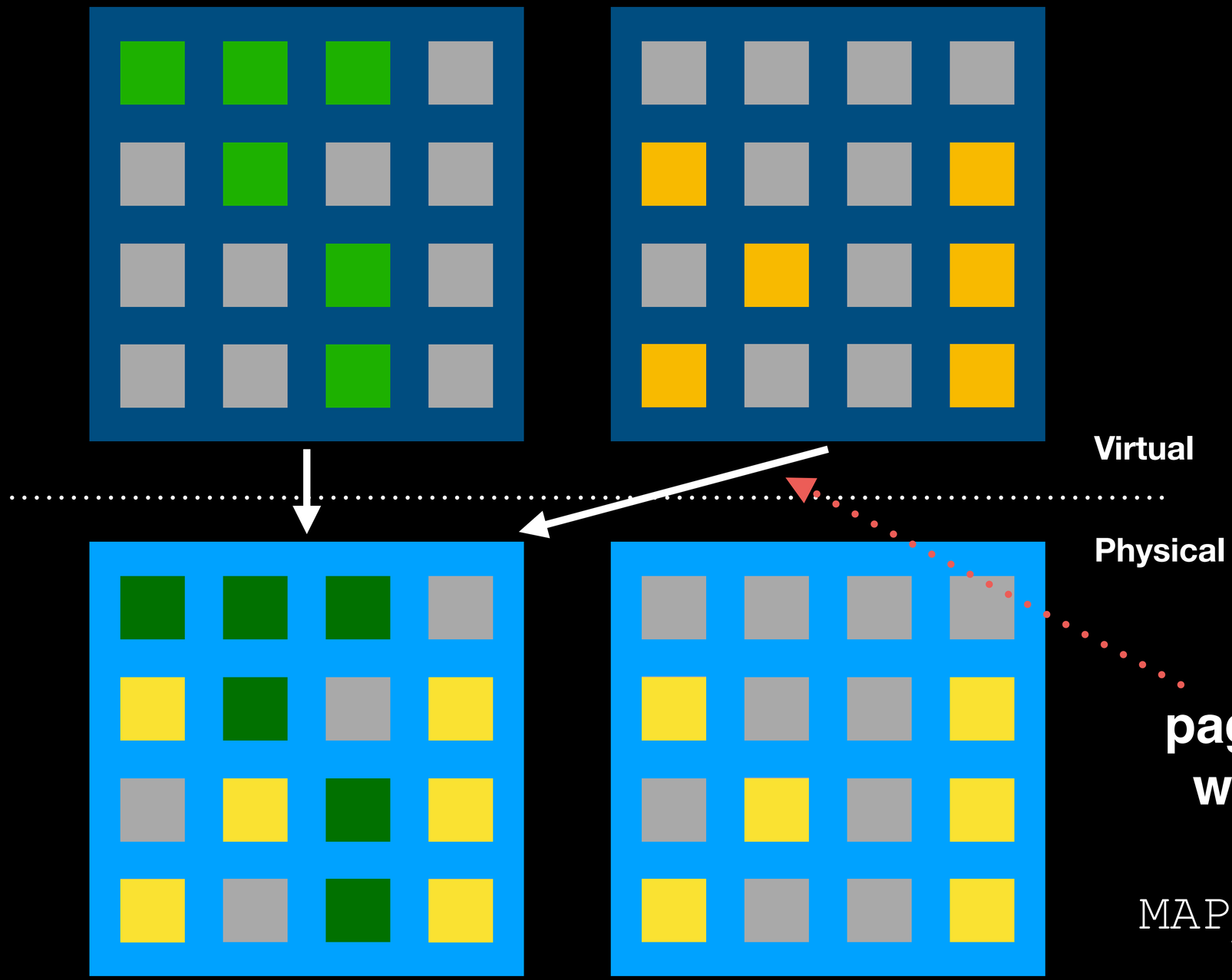


Meshing



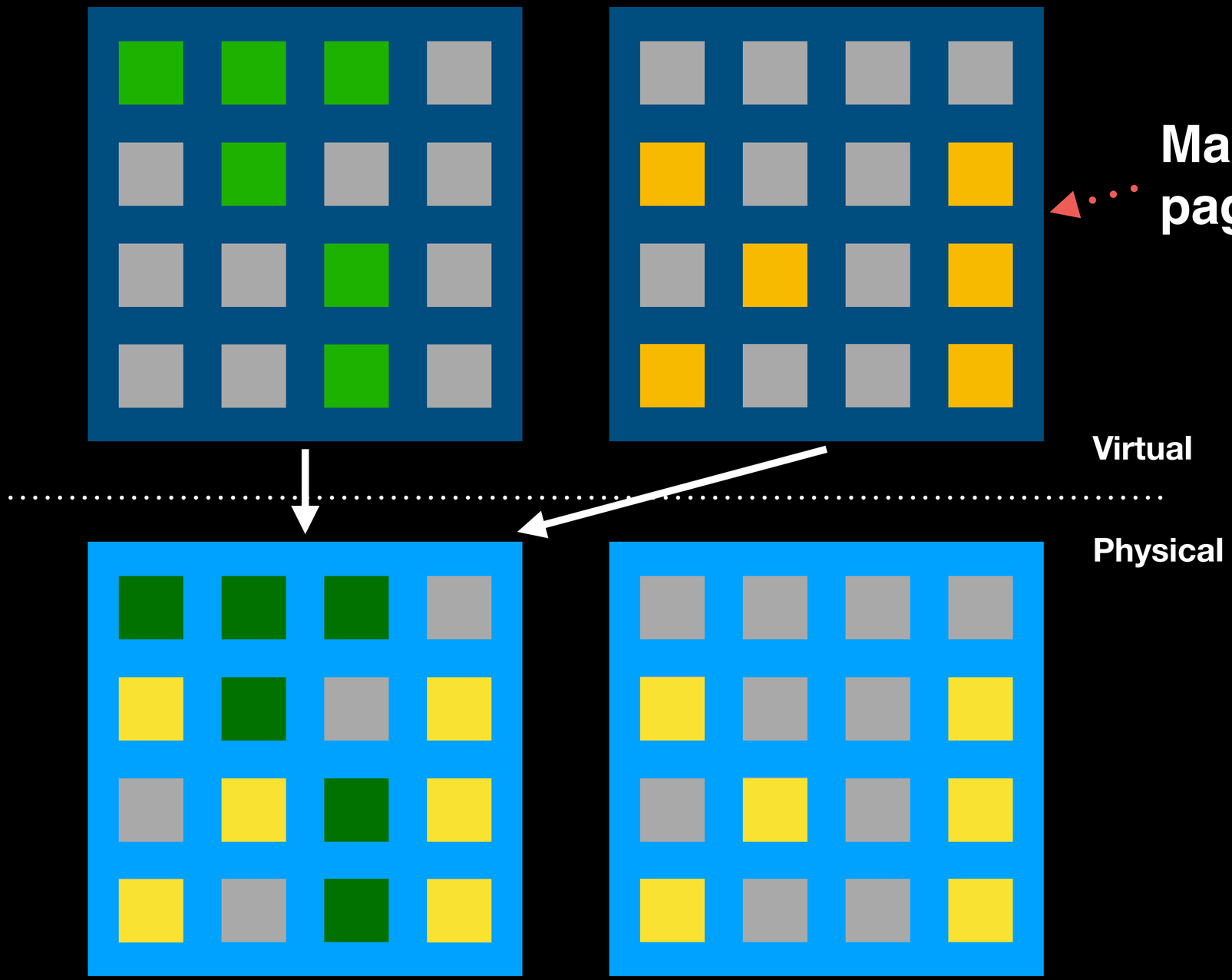
Copy (maintaining offsets)

Meshing

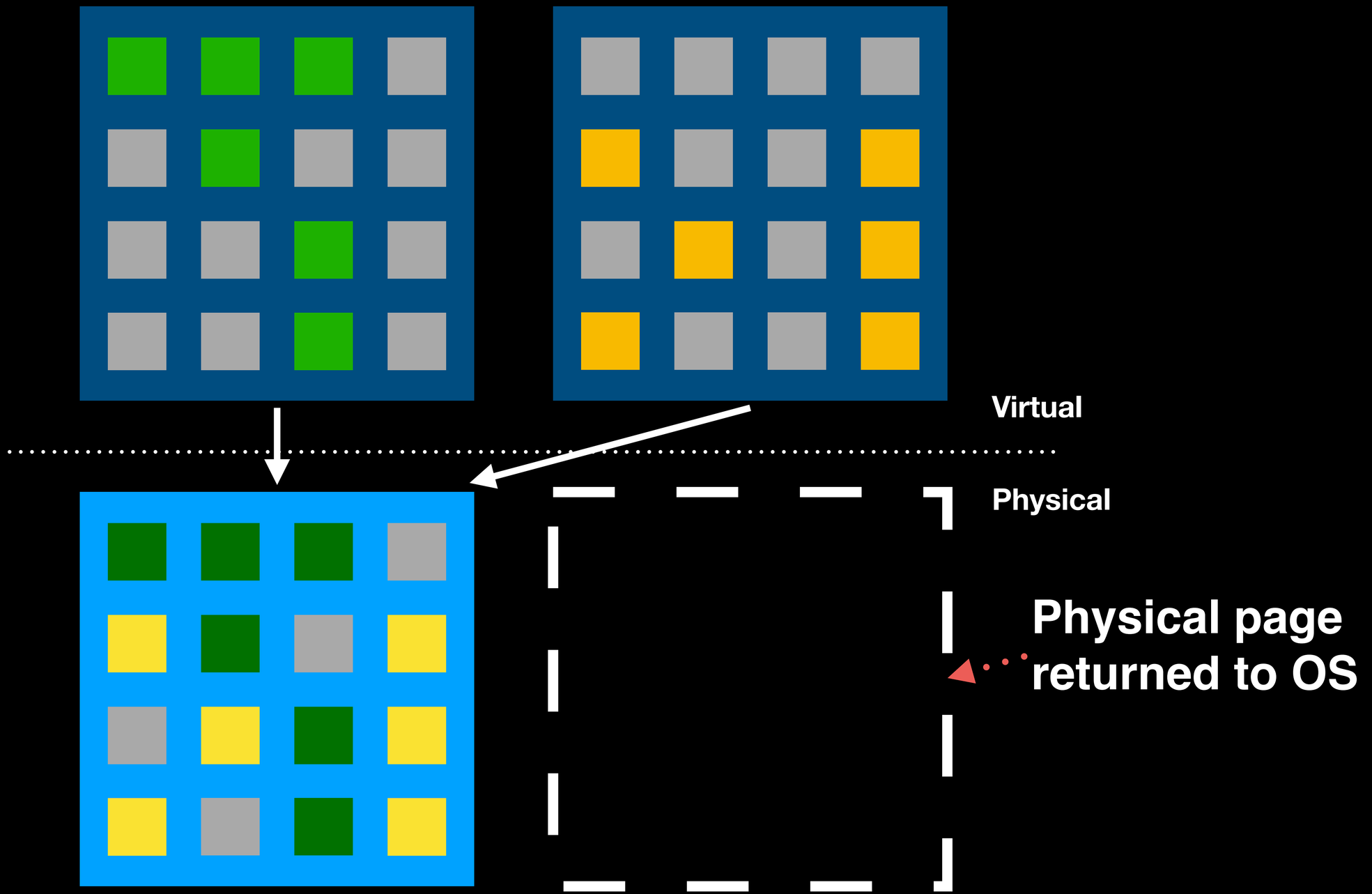


Update page tables with `mmap`, `memfd`, `MAP_SHARED`

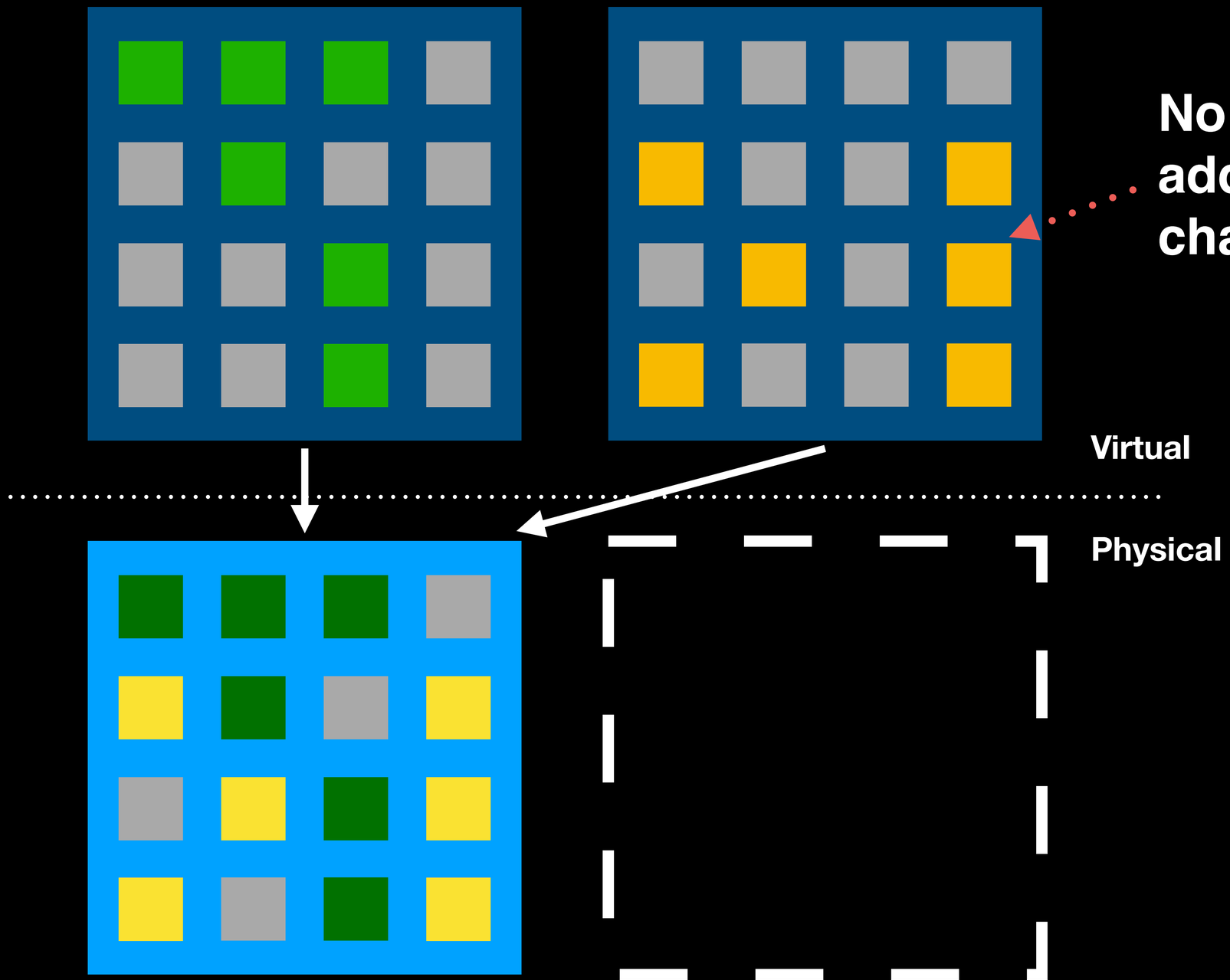
Meshing



Meshing



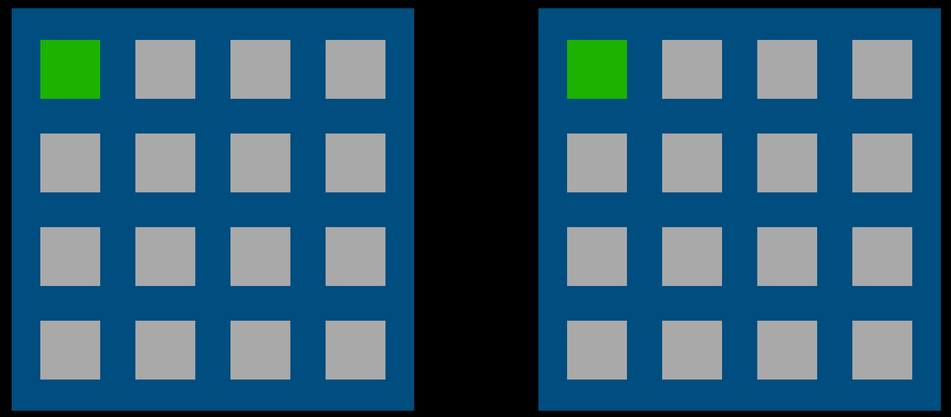
Meshing



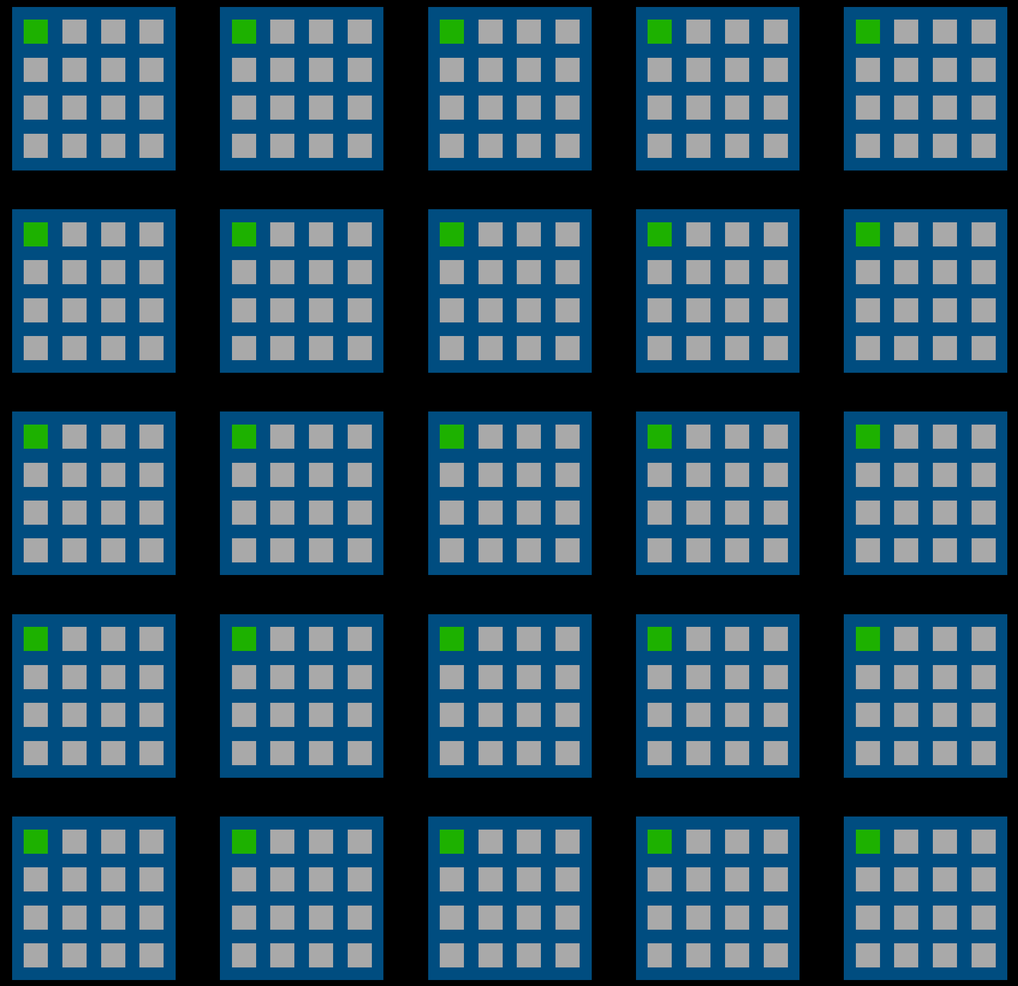
Worst Case:

Worst Case:

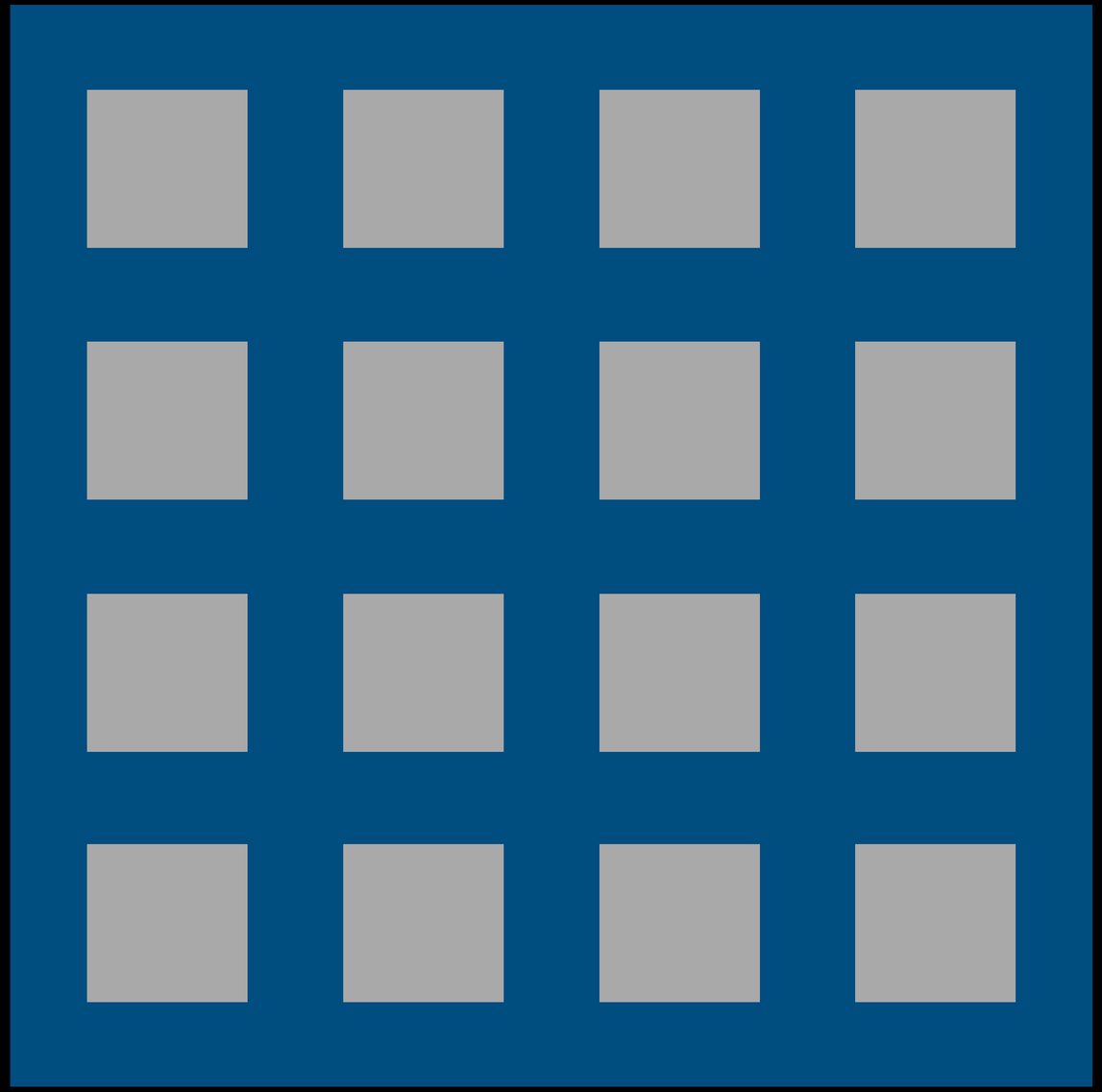
low occupancy, non-meshable pages



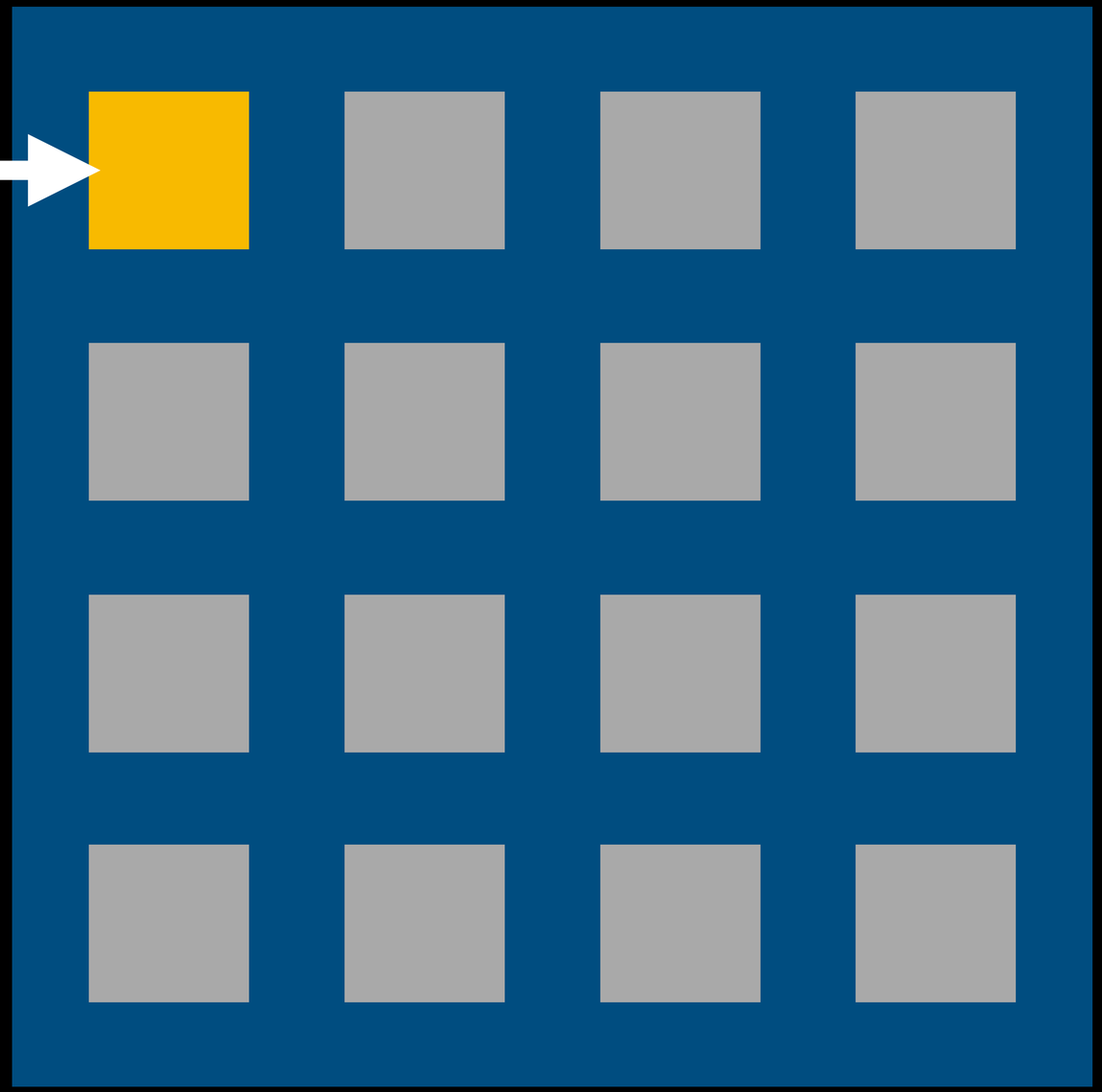
Worst Case:
many
low occupancy,
non-meshable
pages



Standard allocators



```
malloc(256)
```



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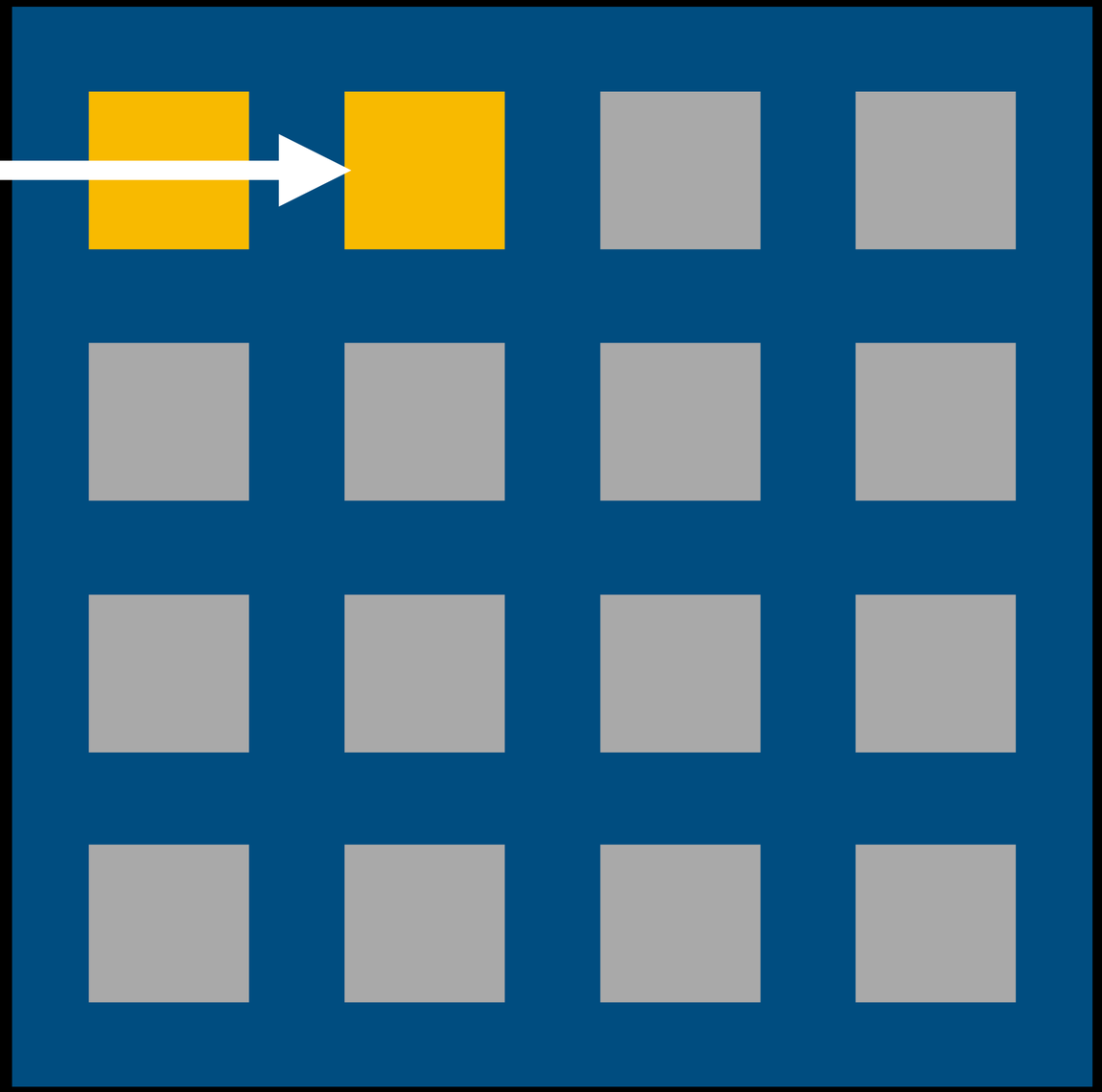

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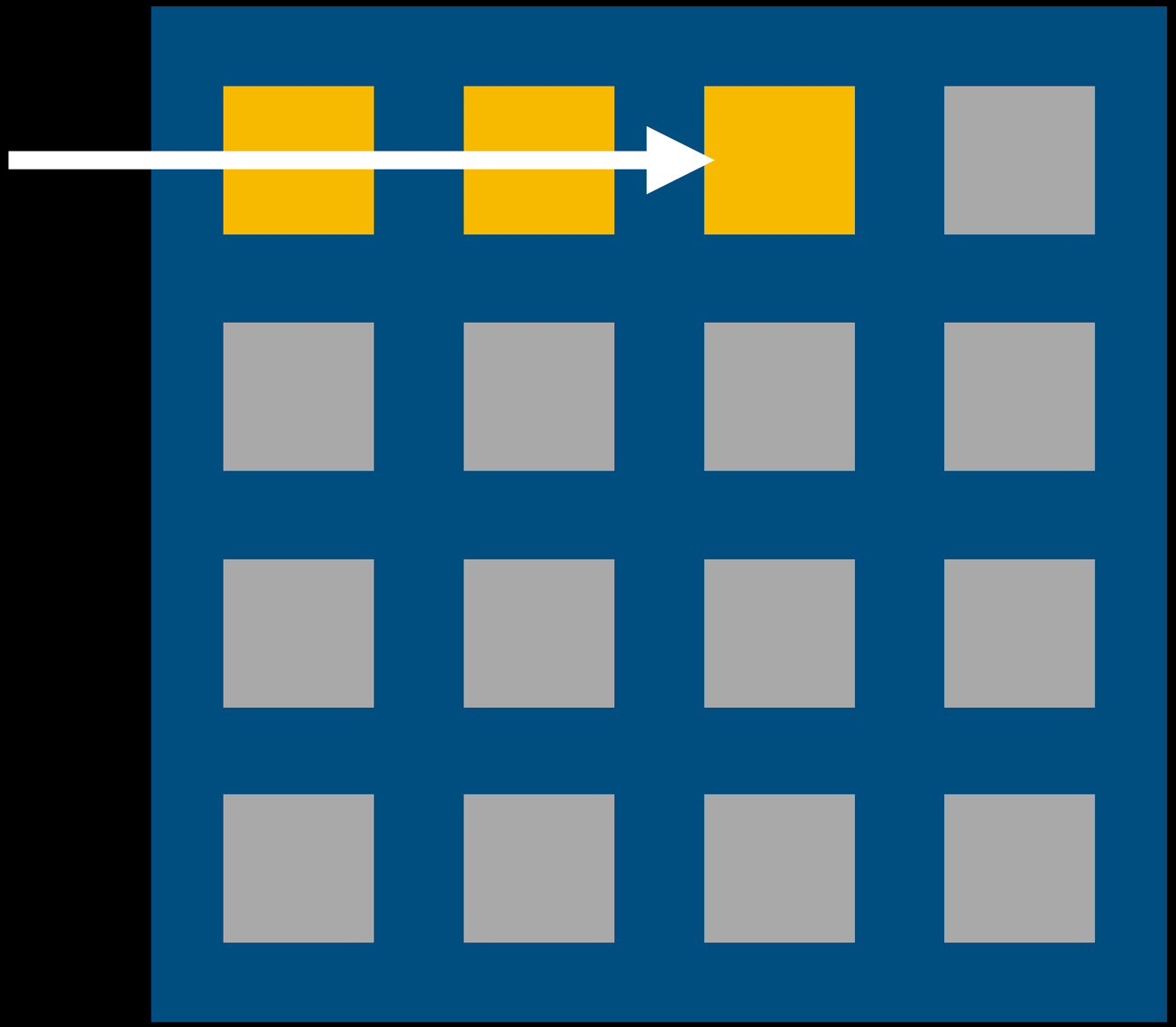
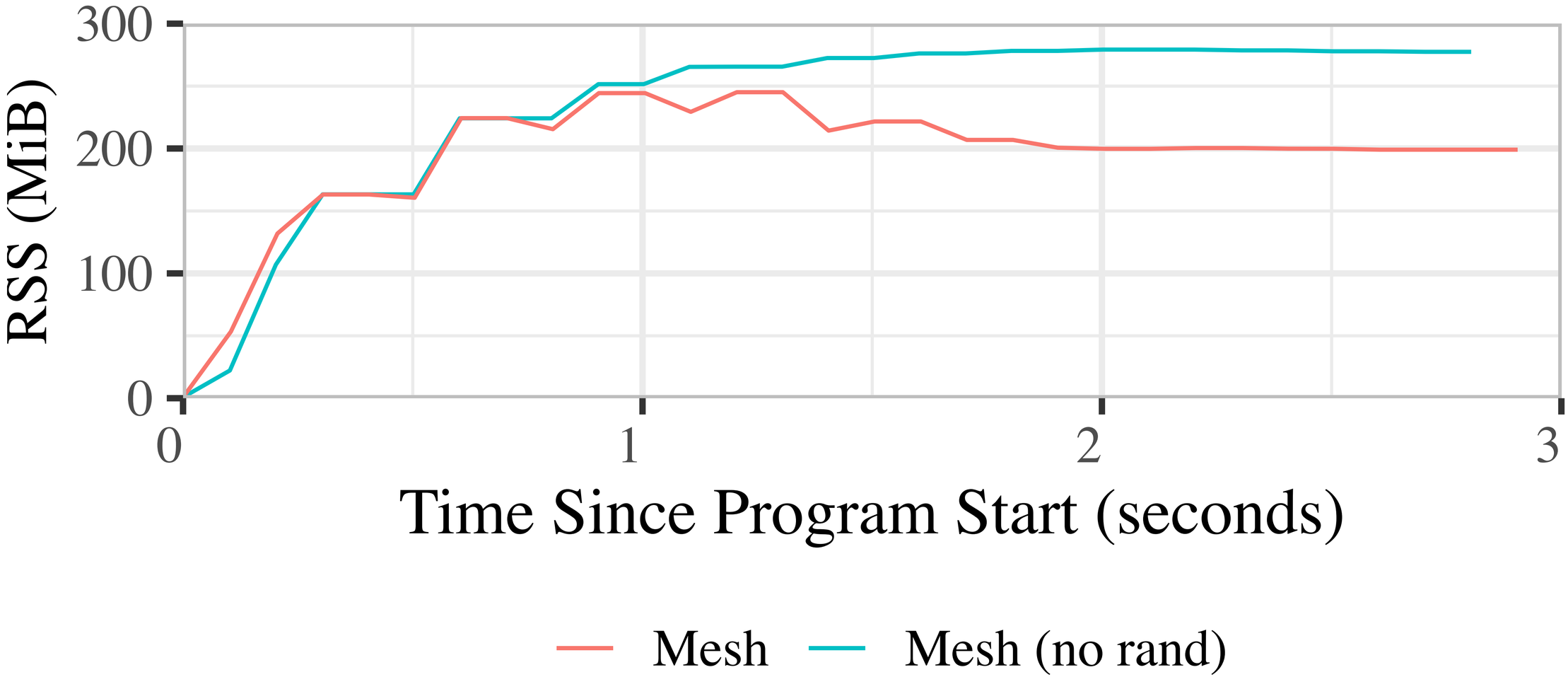


Standard allocators

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

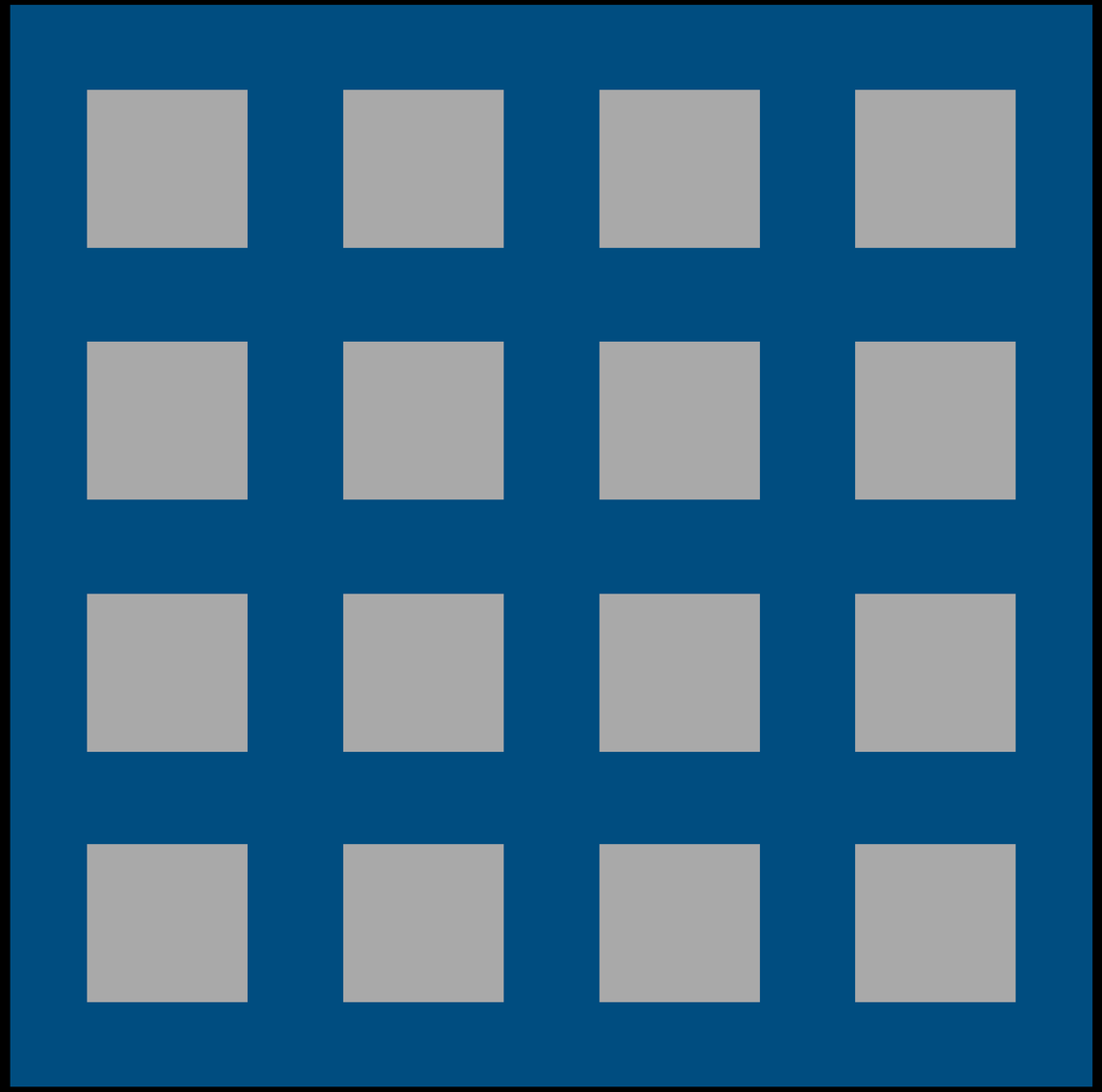
Regular allocation patterns are real



How to **randomize** allocation?

Random probing:

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



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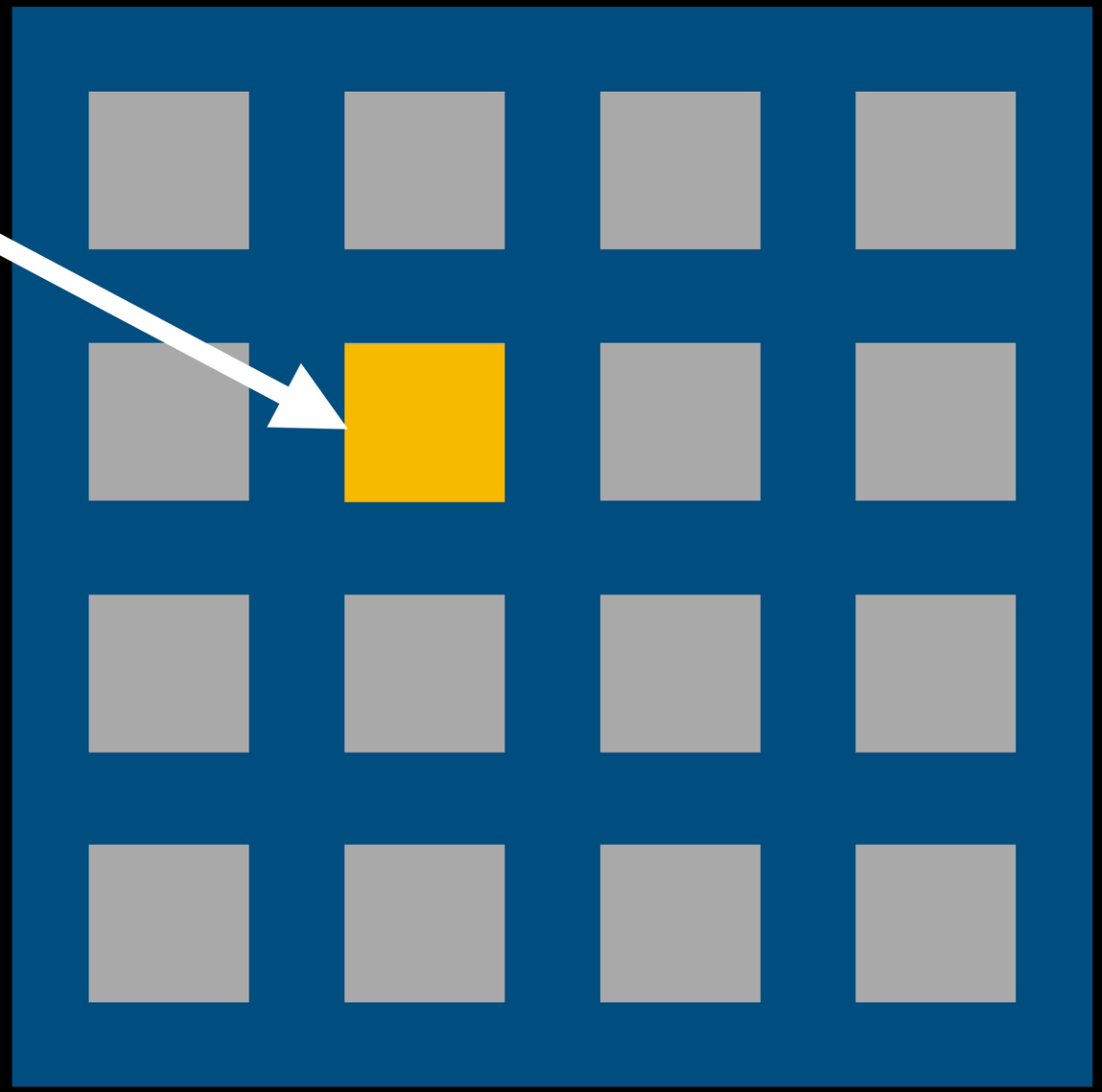

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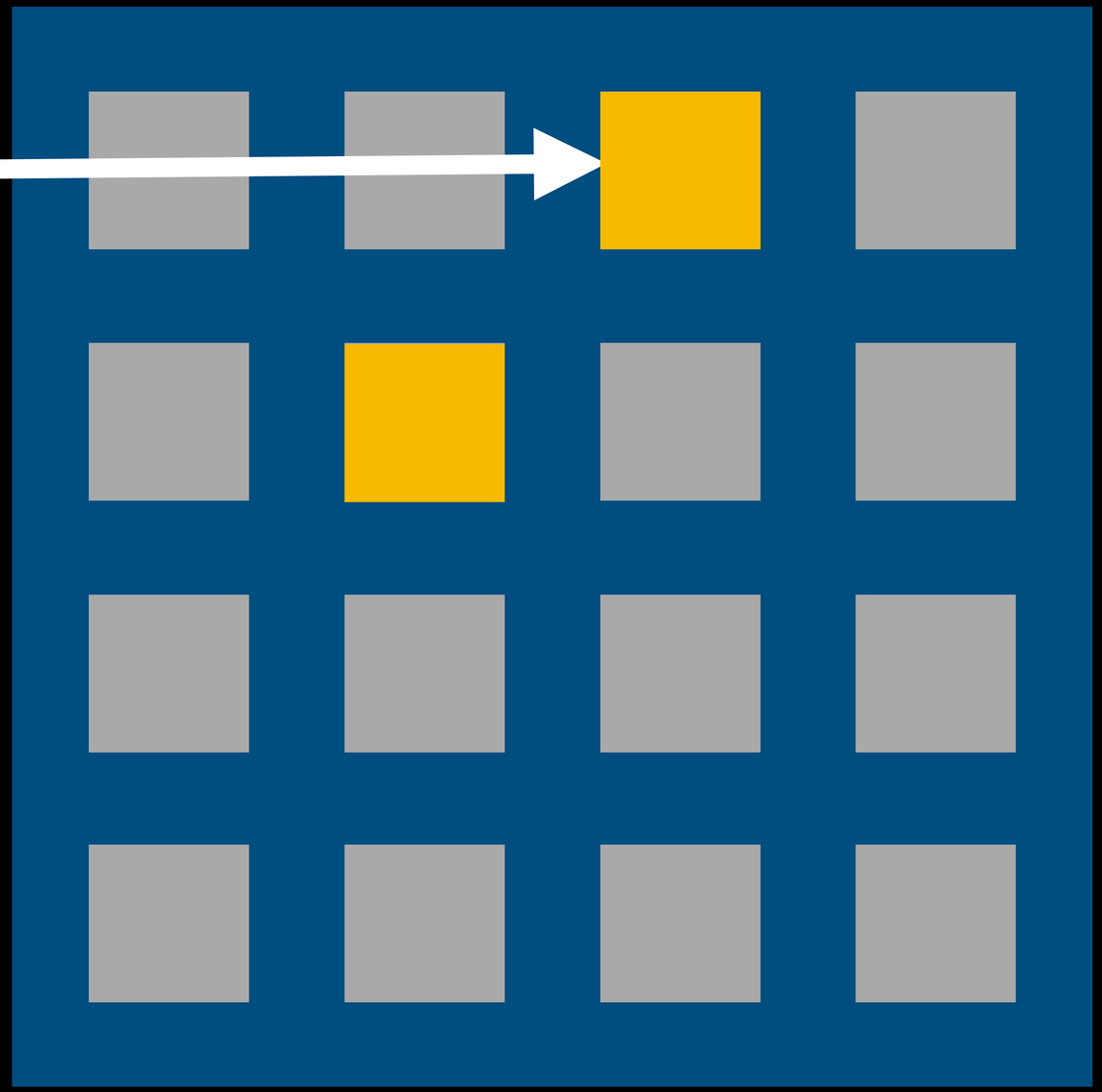

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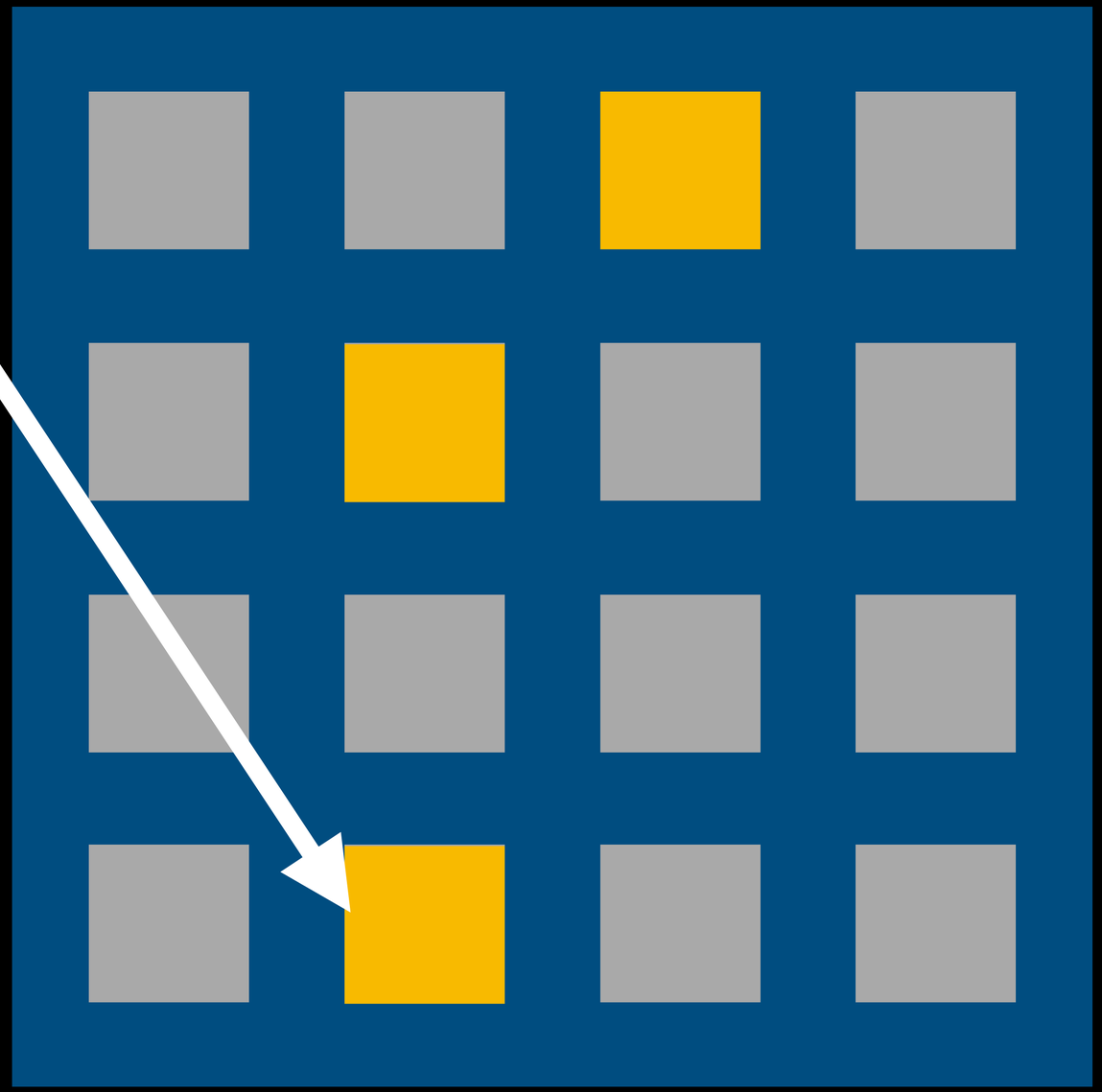

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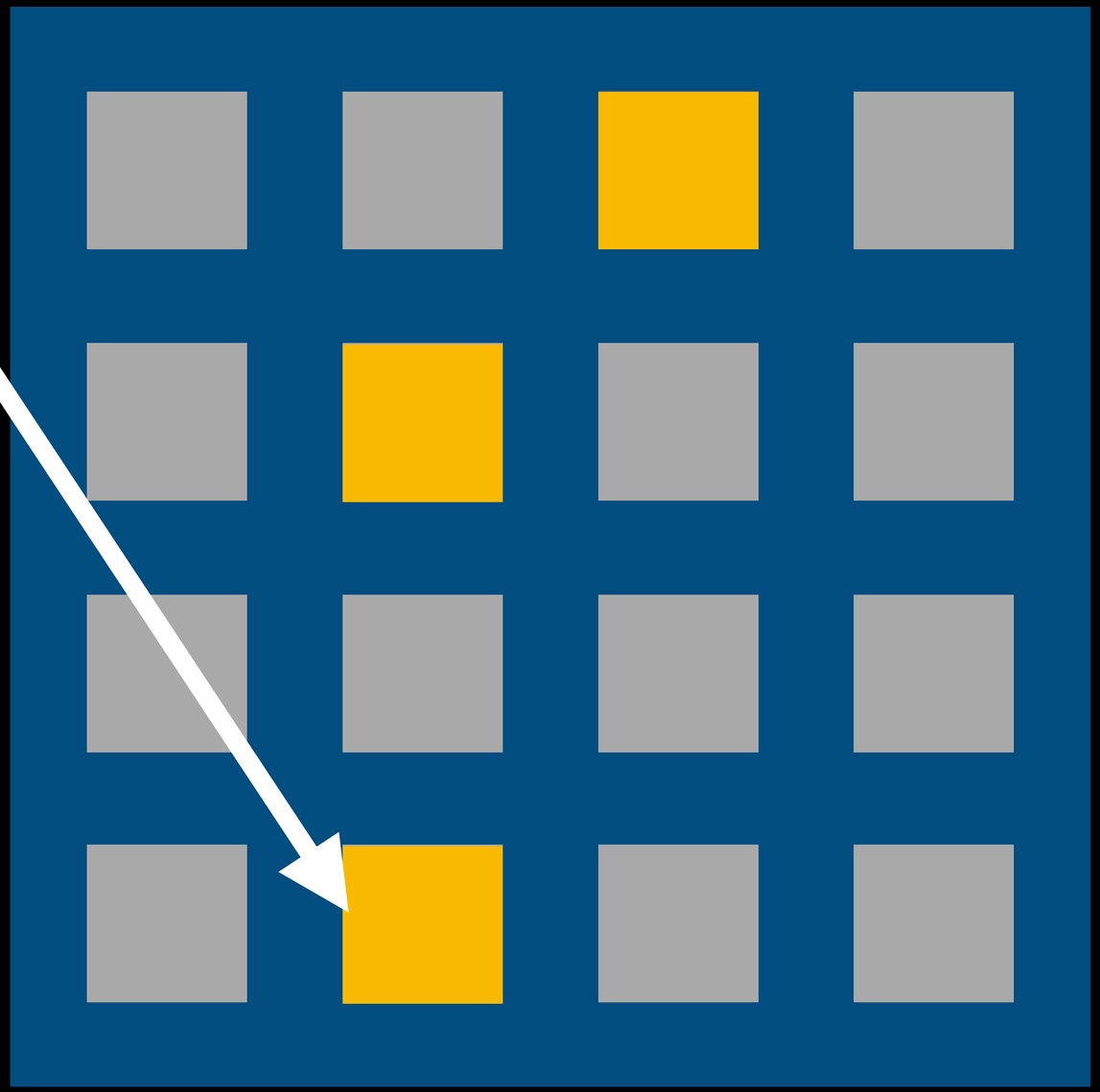

Random probing:

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```

(DieHard [Berger & Zorn 2006])

Random probing fast in expectation *iff page occupancy is low*

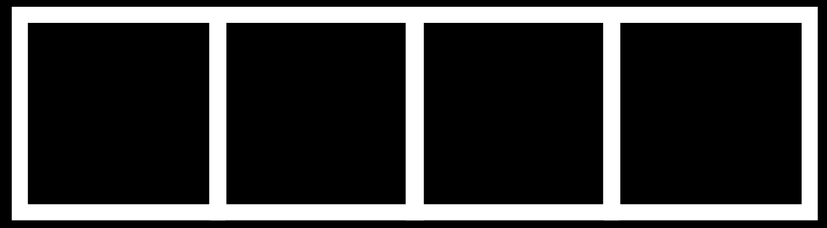
Random probing fast in expectation *iff page occupancy is low*

but this is at odds with minimizing heap size!

Shuffle Vector:
Fast randomized allocation + full page utilization

Shuffle Vector: Fast randomized allocation

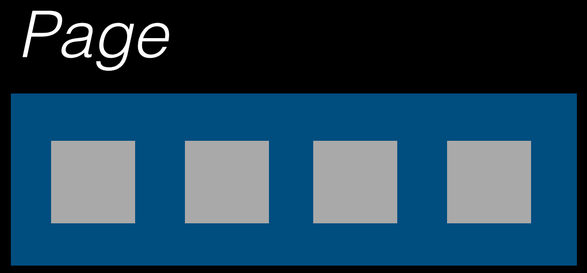
```
load
```

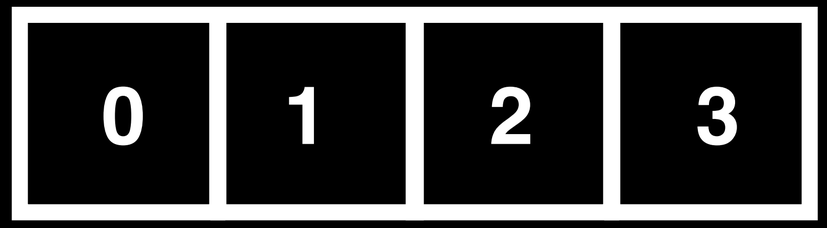


Thread-local shuffle vector

Shuffle Vector: Fast randomized allocation

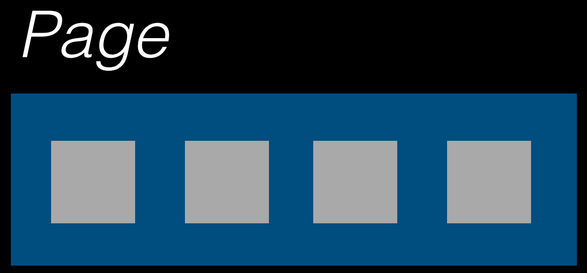
```
load
```

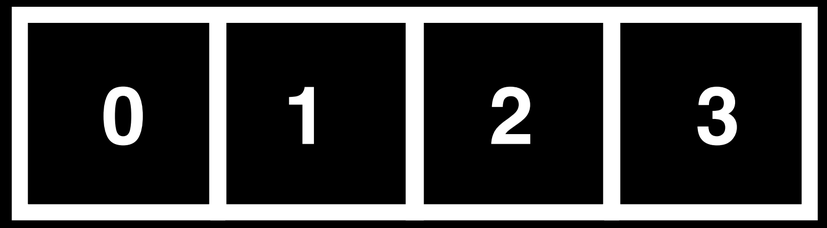




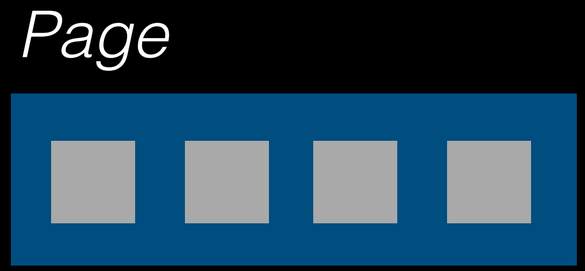
Thread-local shuffle vector

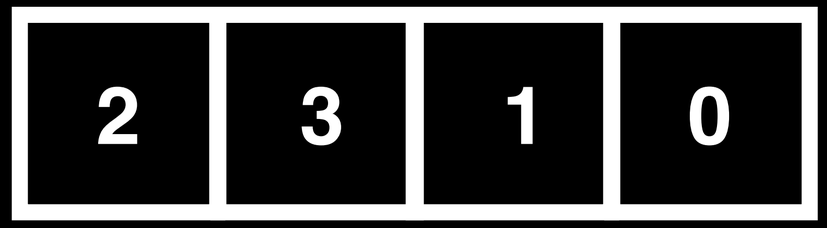
Shuffle Vector: Fast randomized allocation





Shuffle Vector: Fast randomized allocation

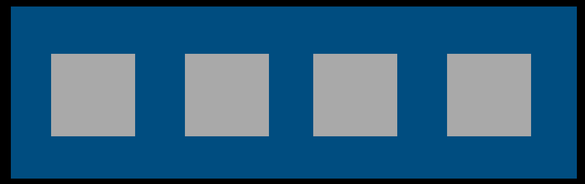


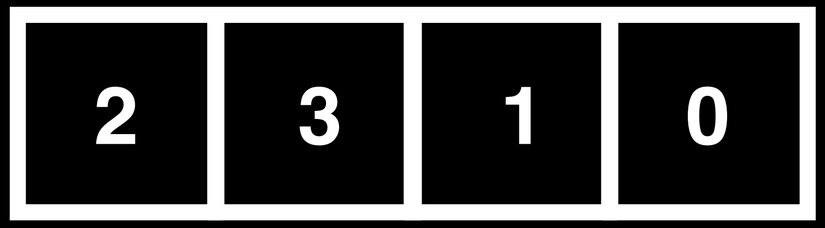


Shuffle Vector: Fast randomized allocation

`malloc()`

Page

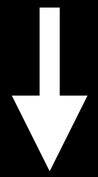




Thread-local shuffle vector

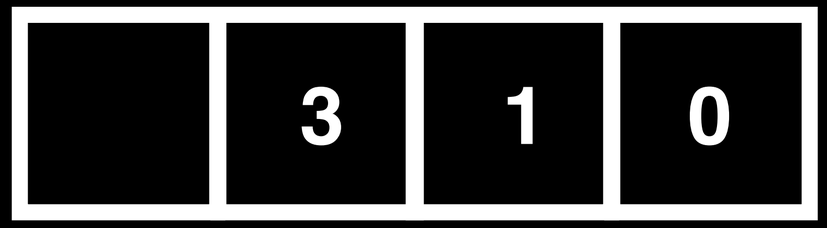
Shuffle Vector: Fast randomized allocation

```
malloc()
```



```
page_start +
2 * object_size
```

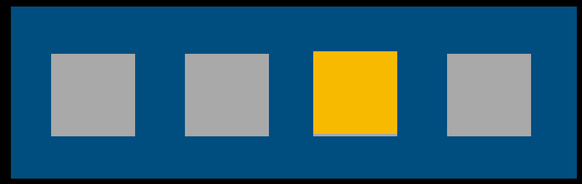
Page

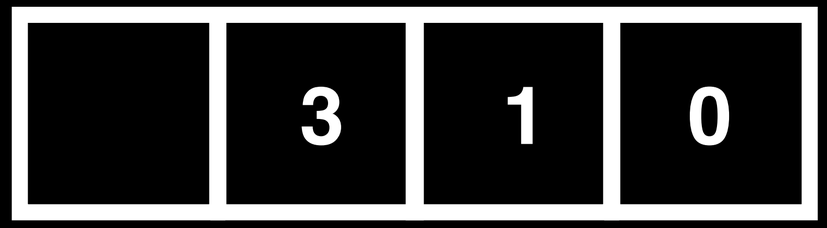


Thread-local shuffle vector

Shuffle Vector: Fast randomized allocation

```
free(2)
```

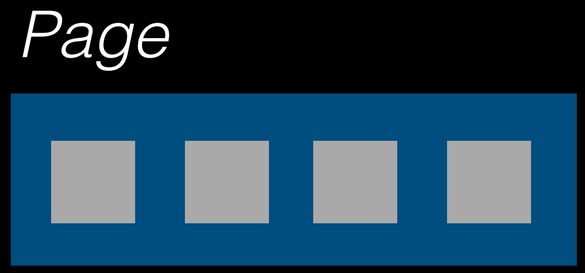


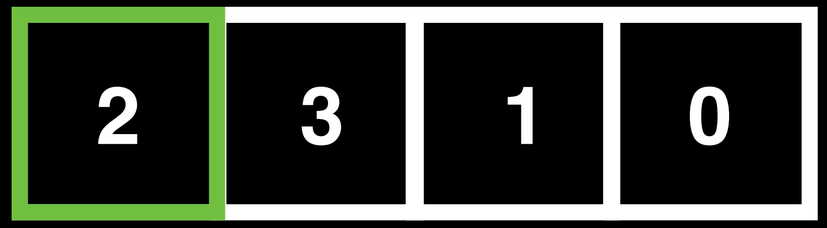


Thread-local shuffle vector

Shuffle Vector: Fast randomized allocation

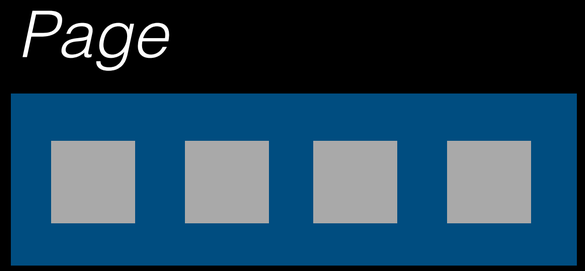
```
free( )
```





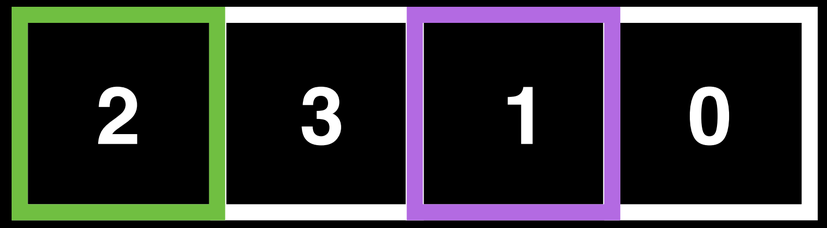
Thread-local shuffle vector

Shuffle Vector: Fast randomized allocation




```
free( )

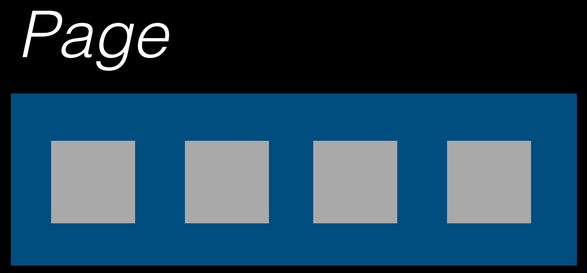
shuffle_one(
```




```
)
```

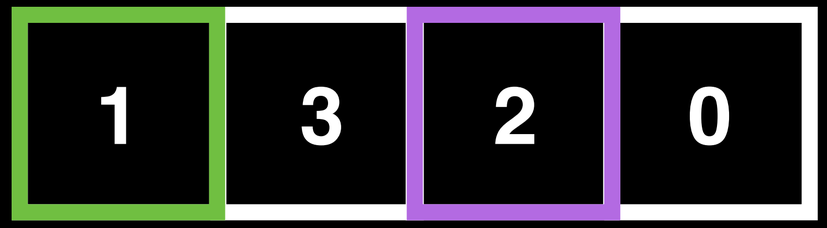
Thread-local shuffle vector

Shuffle Vector: Fast randomized allocation




```
free( )

shuffle_one(
```

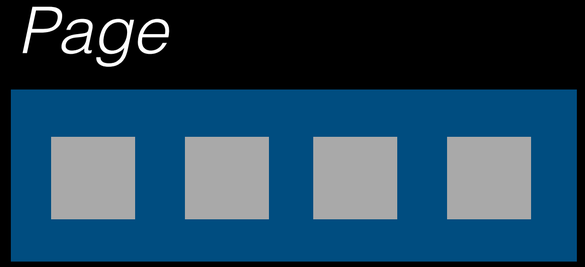


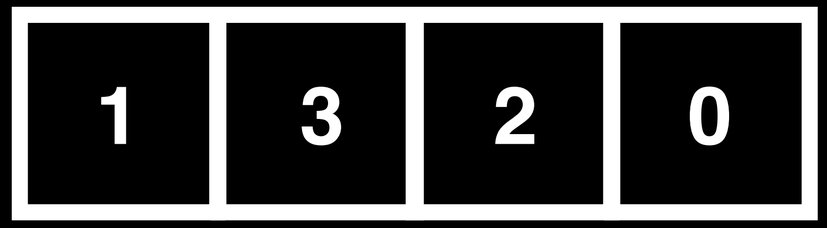

```
)
```

Thread-local shuffle vector

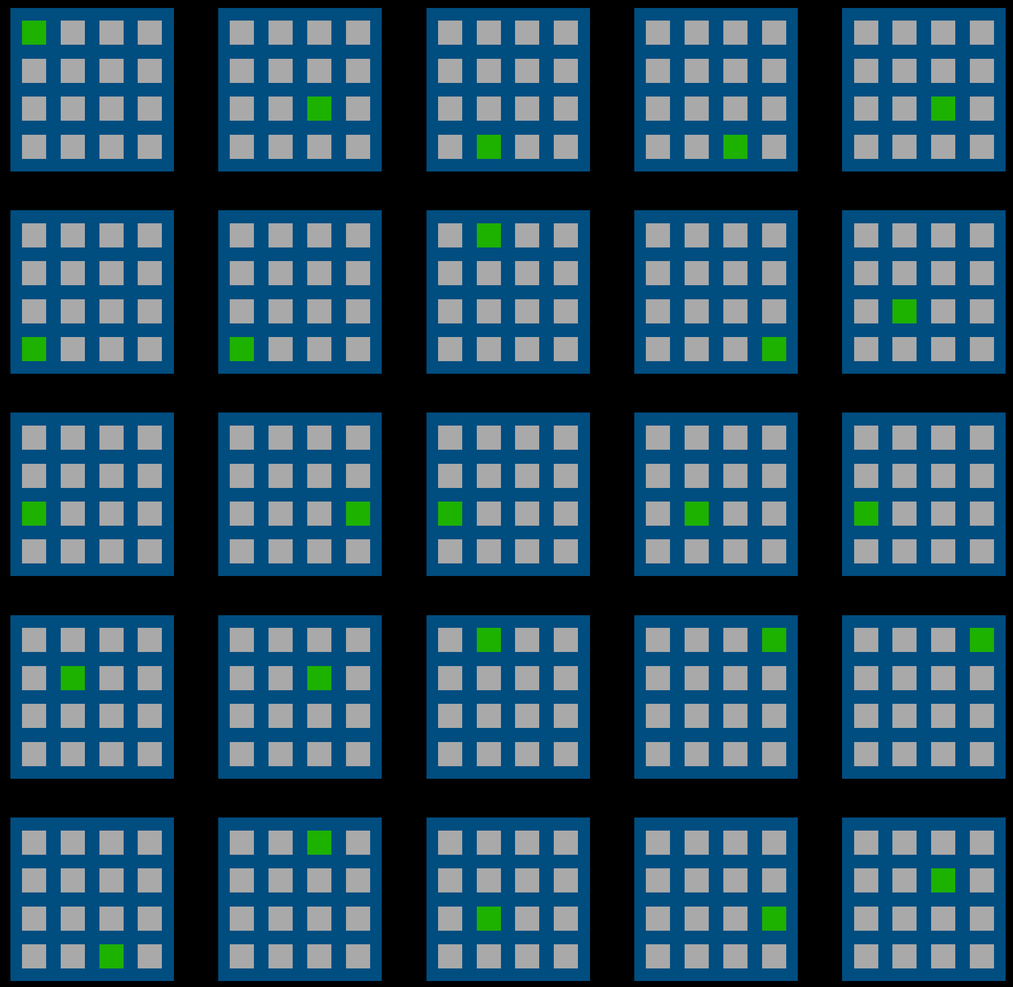
Shuffle Vector: Fast randomized allocation

```
free( )
```





Thread-local shuffle vector



All
Pages
Meshable

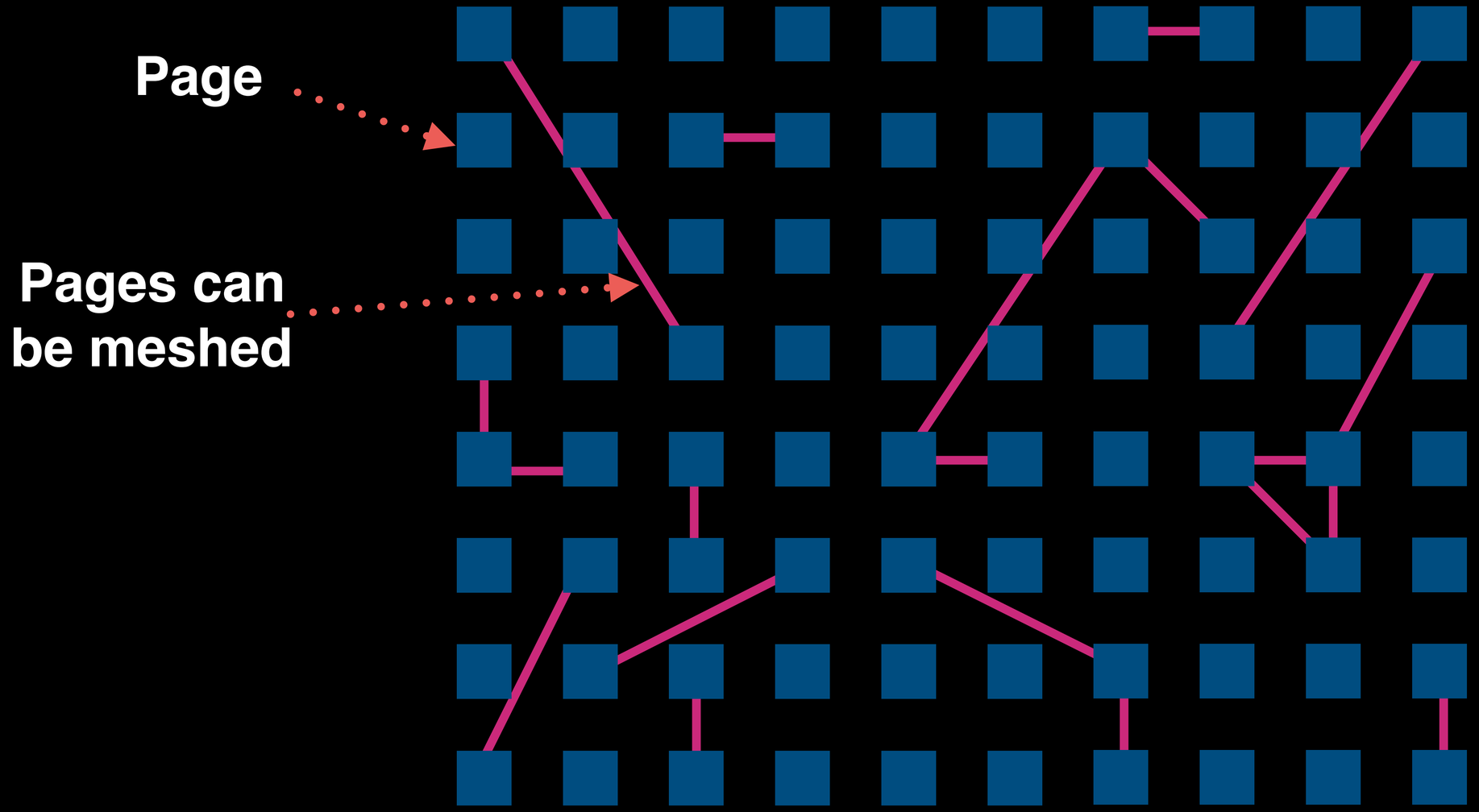
Finding pages to Mesh

Problem: Find meshing that releases maximum number of pages

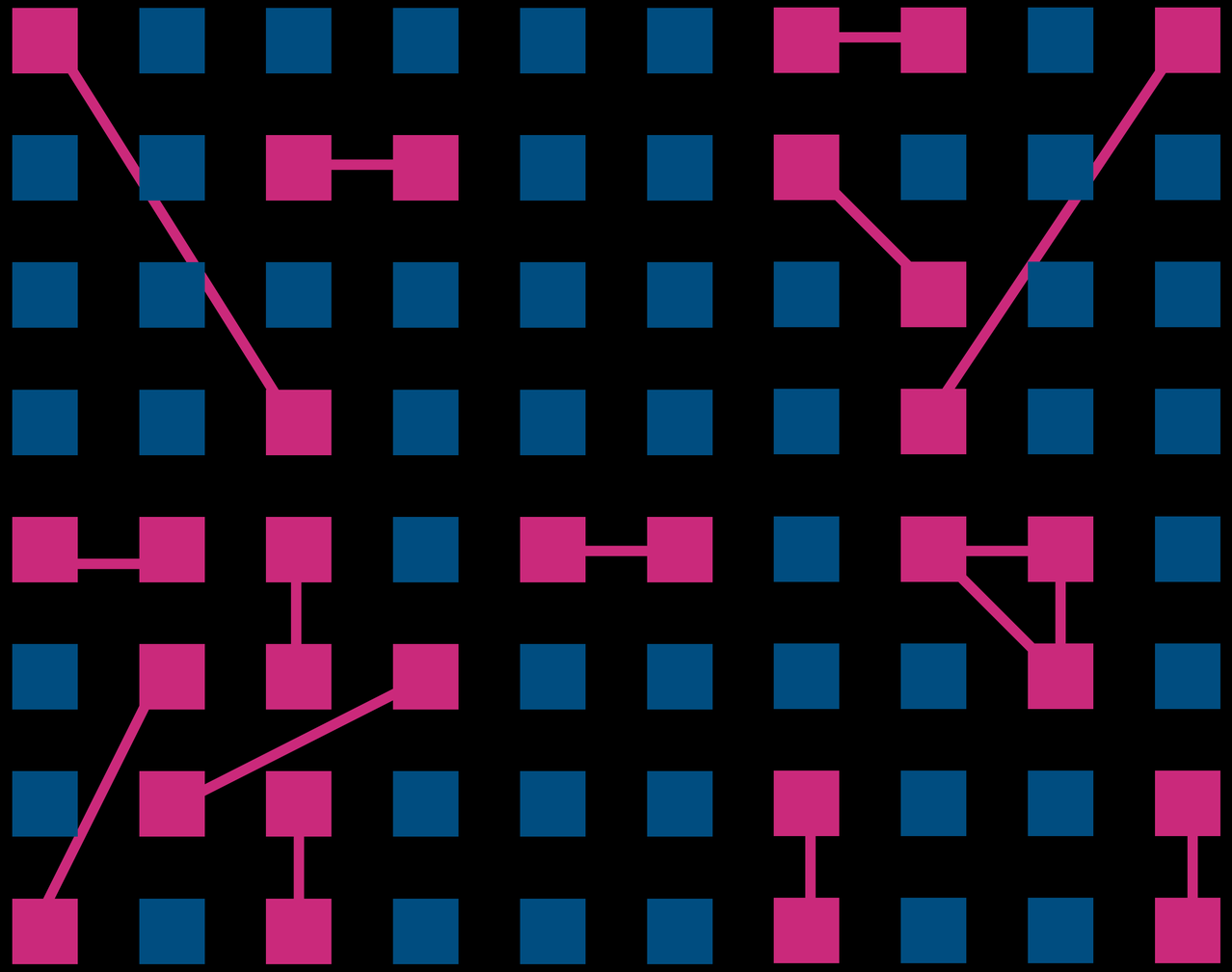
Problem: Find meshing that releases maximum number of pages

Run in the `free()` slowpath
At most once every 100 ms
Treat each size class independently

Problem: Find meshing that releases the maximum number of pages



MinCliqueCover



MinCliqueCover

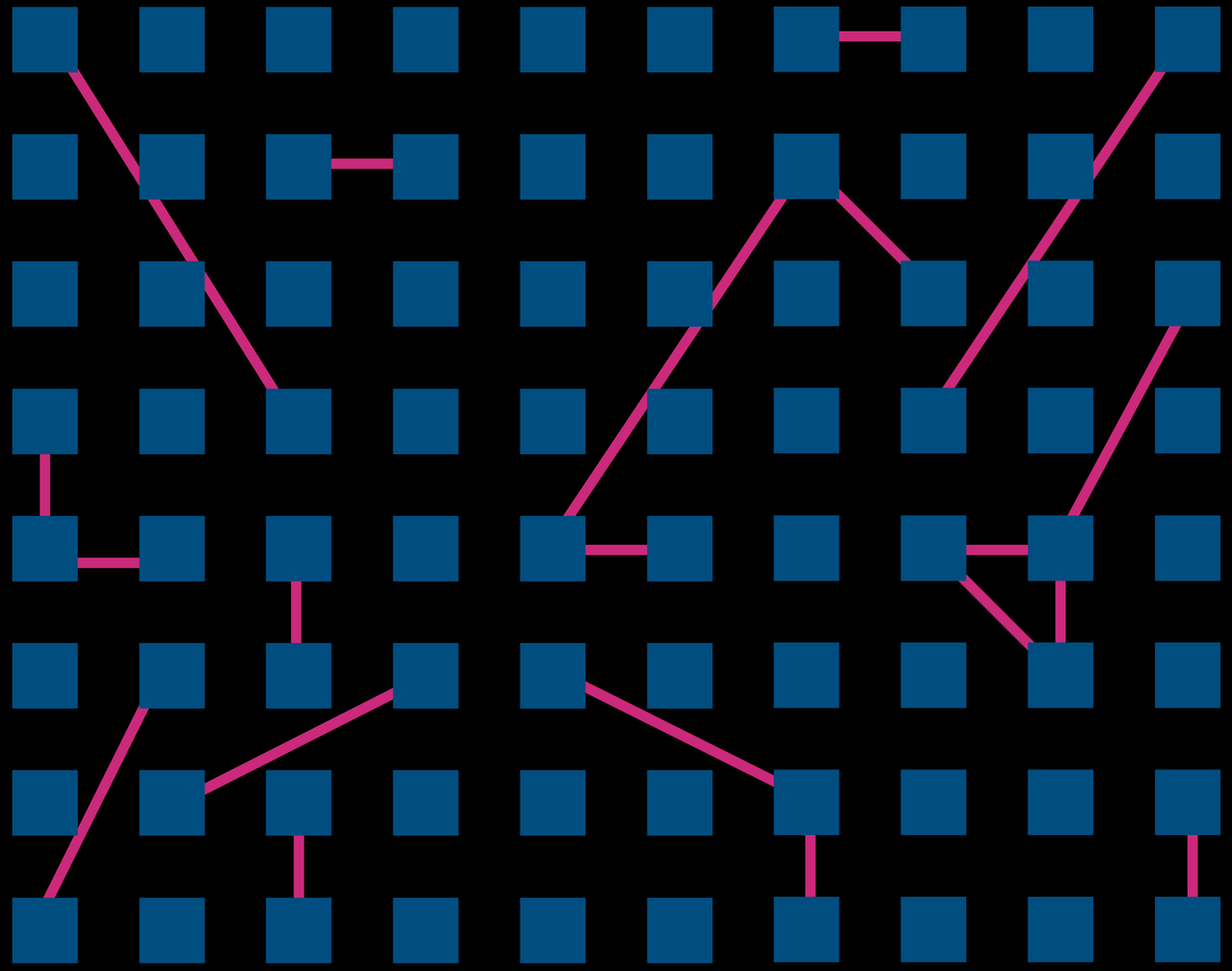
(NP-Complete)

MinCliqueCover

(NP-Complete)

BUT! Randomness ensures we can get away with solving simpler graph problem (Matching)

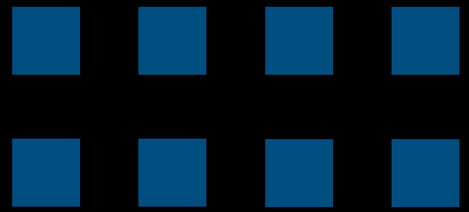
Wrinkle: building this graph would require RAM + time



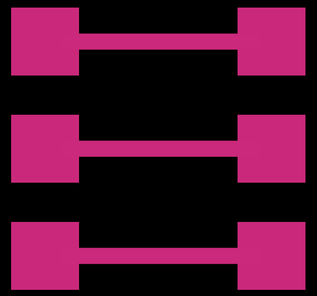
SplitMesher: approximates **Matching** without materializing meshing graph

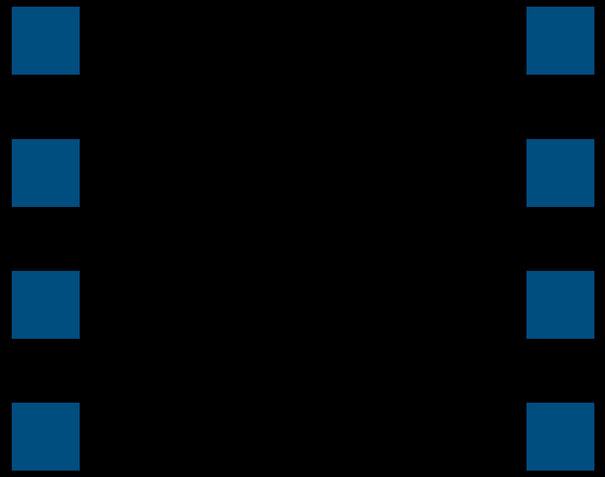
SplitMesher: approximates **Matching** without materializing meshing graph

Set of partially full pages

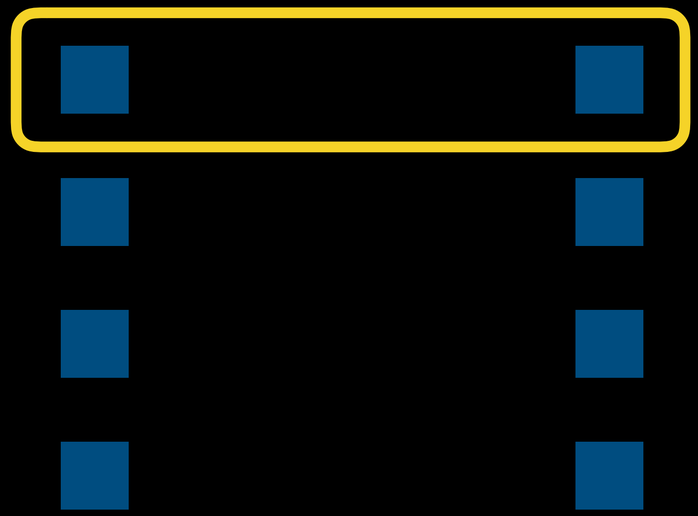


Pairs of meshable pages

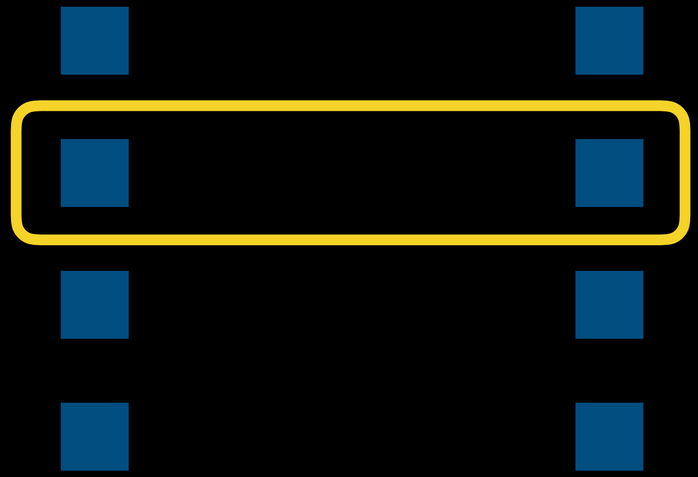




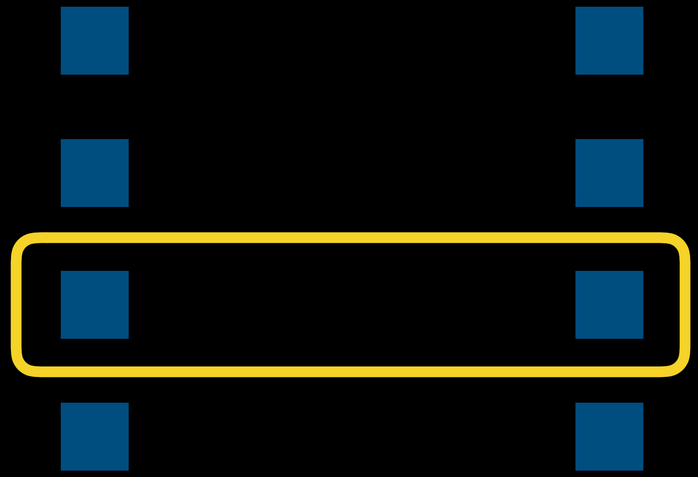
Iterate, comparing a[i] to b[i]



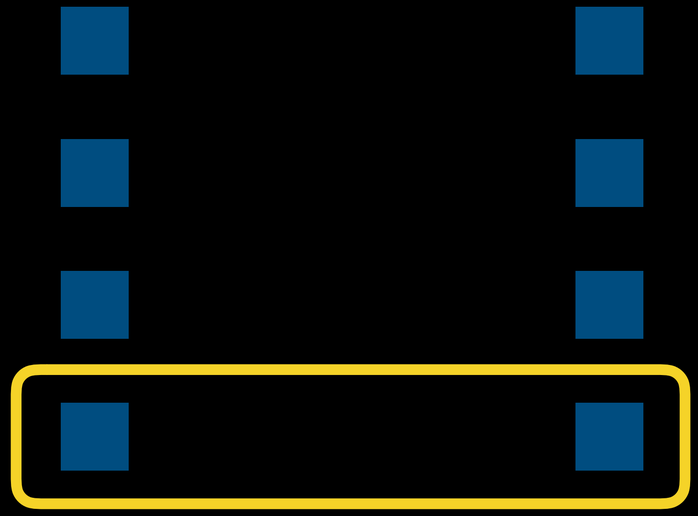
Iterate, comparing a[i] to b[i]



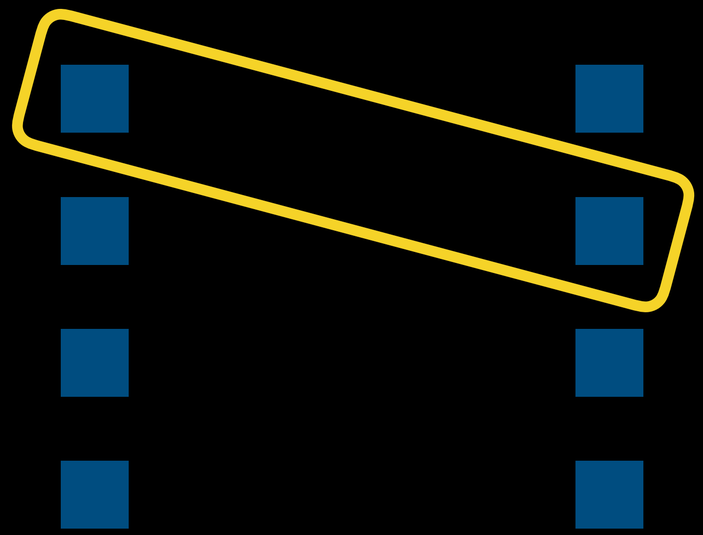
Iterate, comparing a[i] to b[i]



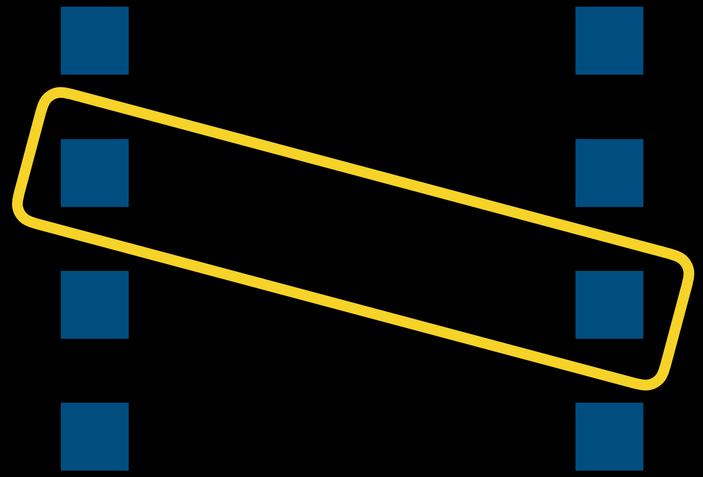
Iterate, comparing a[i] to b[i]

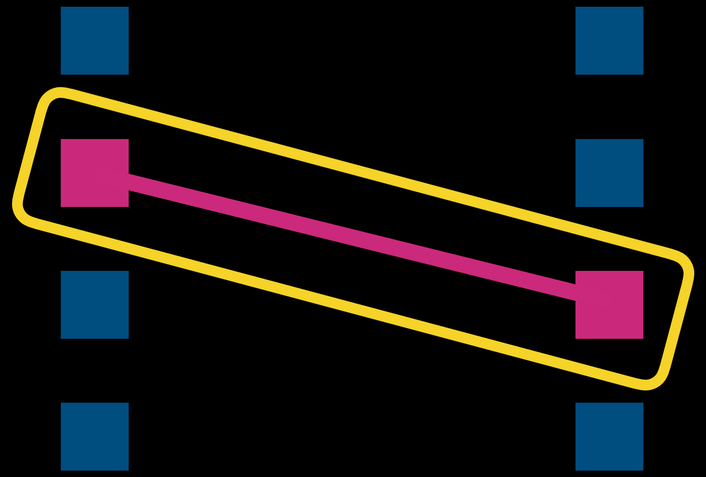


loop, comparing a[i] to b[(i+1)%len]

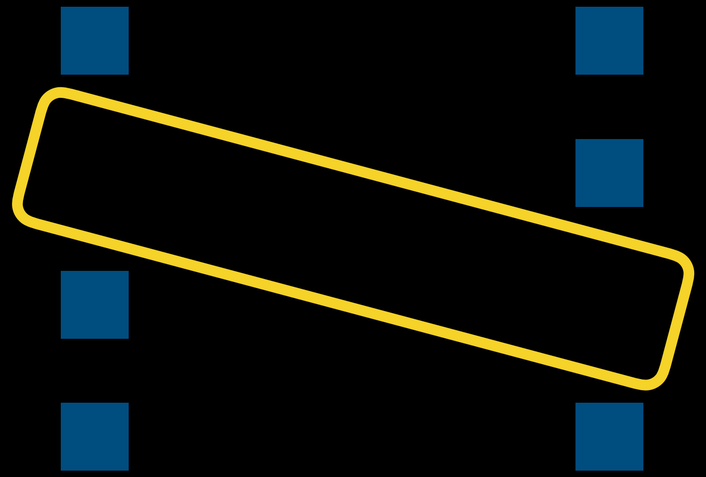


loop **fixed** number of times,
comparing a[i] to b[(i+1)%len]

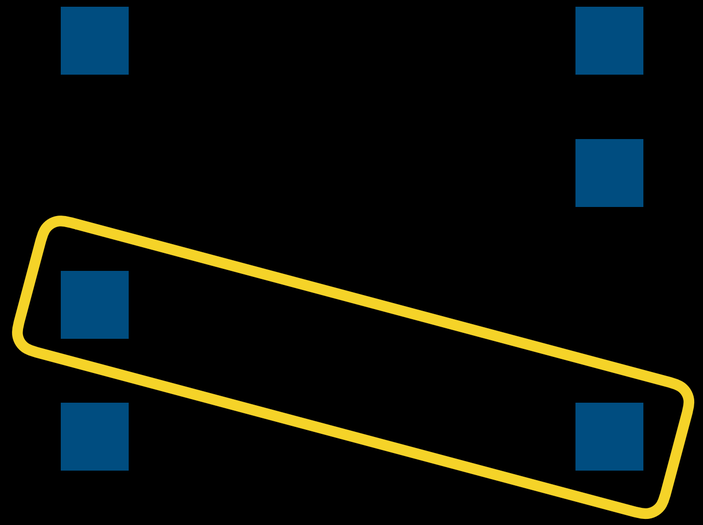




Remove found match



Continue



SplitMesher: approximates **Matching** without materializing meshing graph

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$O(n/q)$ time

(*q* is the global probability of spans meshing)

SplitMesher: approximates **Matching**
without materializing meshing graph

$O(n/q)$ time

(q is the global probability of spans meshing)

1/2* approximation w.h.p.

MESH *implementation details*

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built using **Heap Layers**

github.com/emeryberger/Heap-Layers

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(used to build Hoard, DieHard, DieHarder…)

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fast framework for building custom allocators!

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< 5K SLOC, C++

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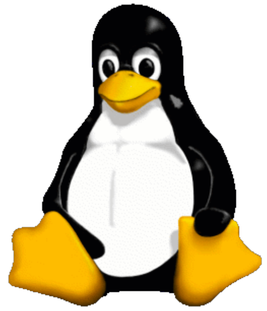

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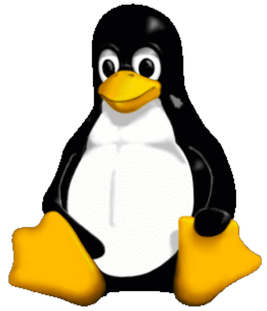

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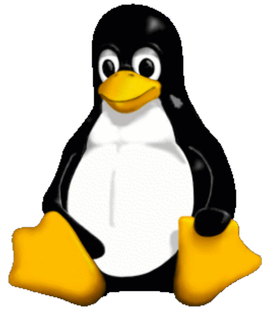

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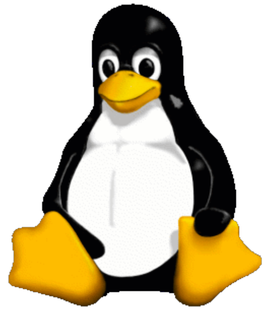

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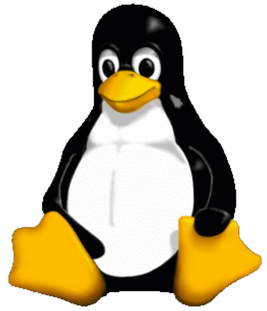
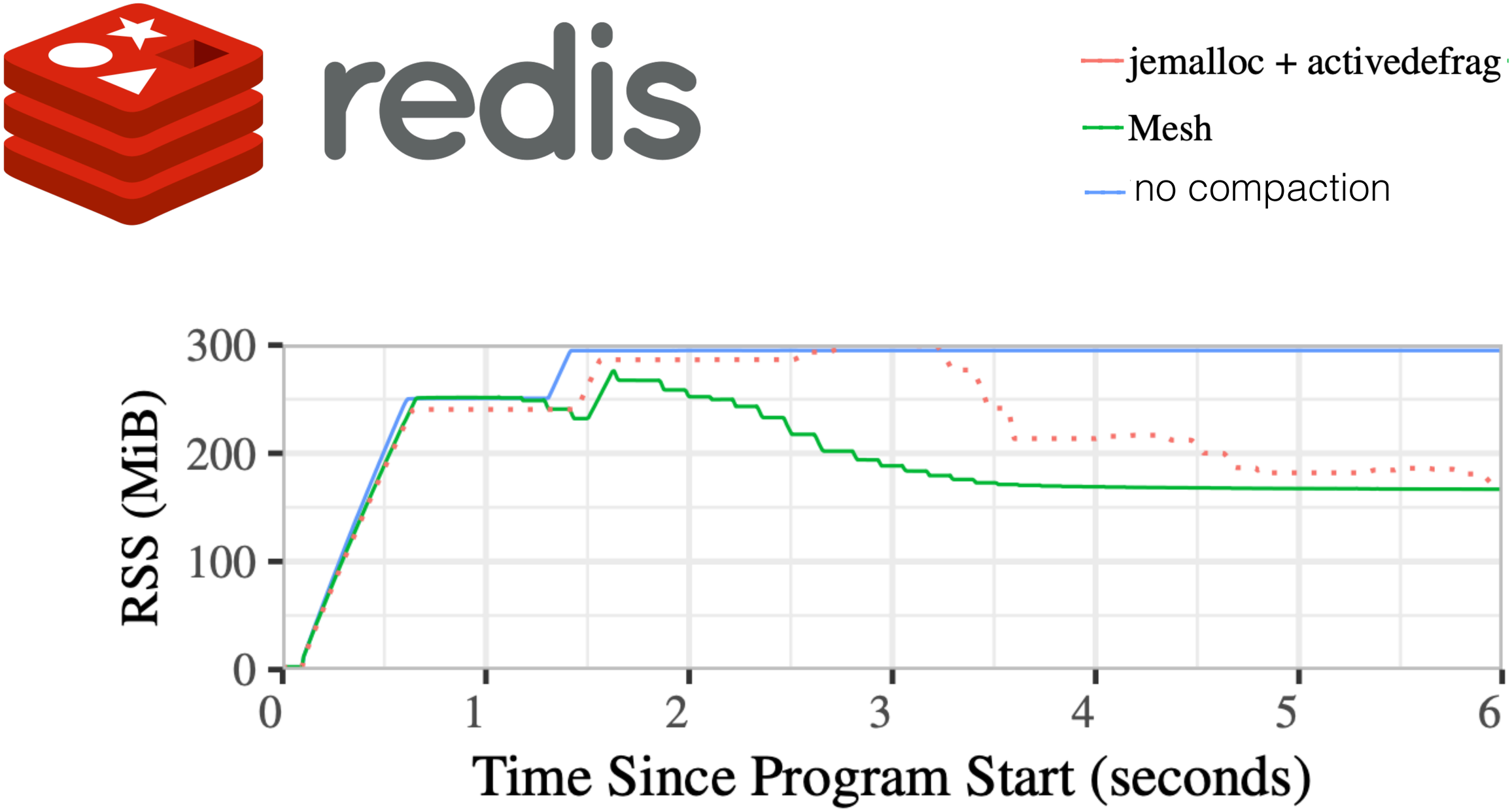
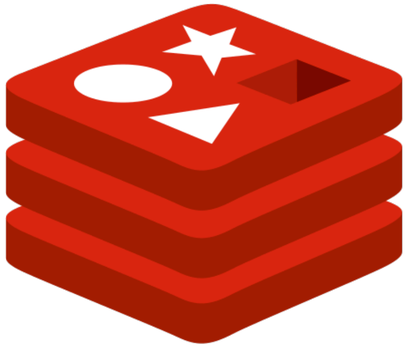
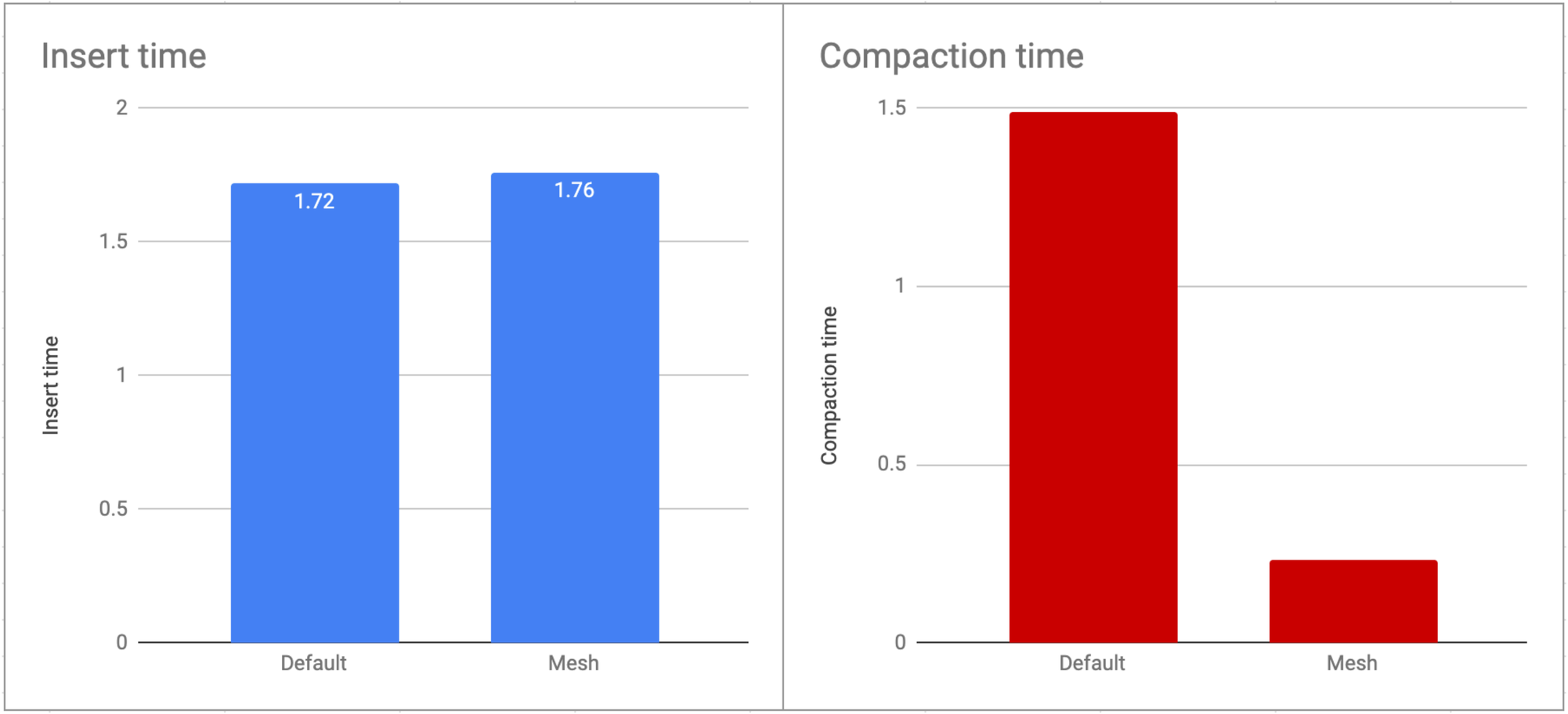




redis
jemalloc + activedefrag
Mesh
no compaction
RSS (MiB)
300
200
100
0
0
1
2
3
4
5
6
Time Since Program Start (seconds)

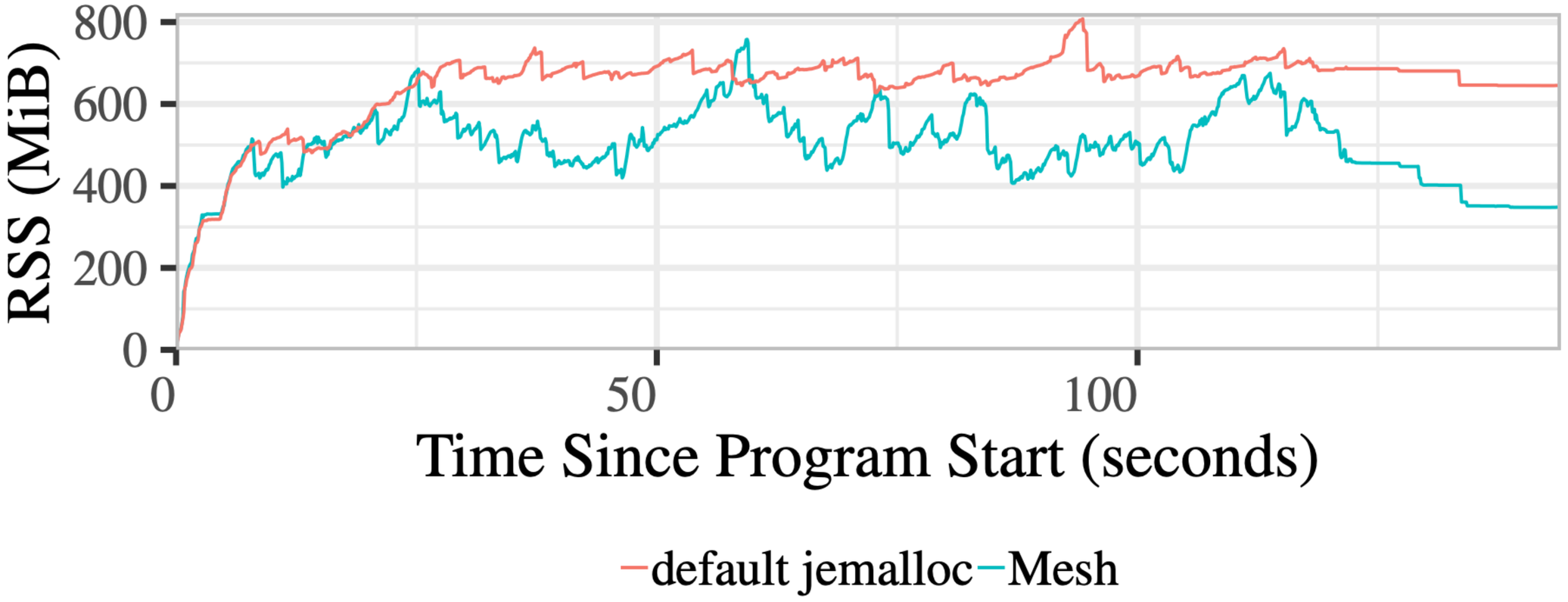


redis + MESH

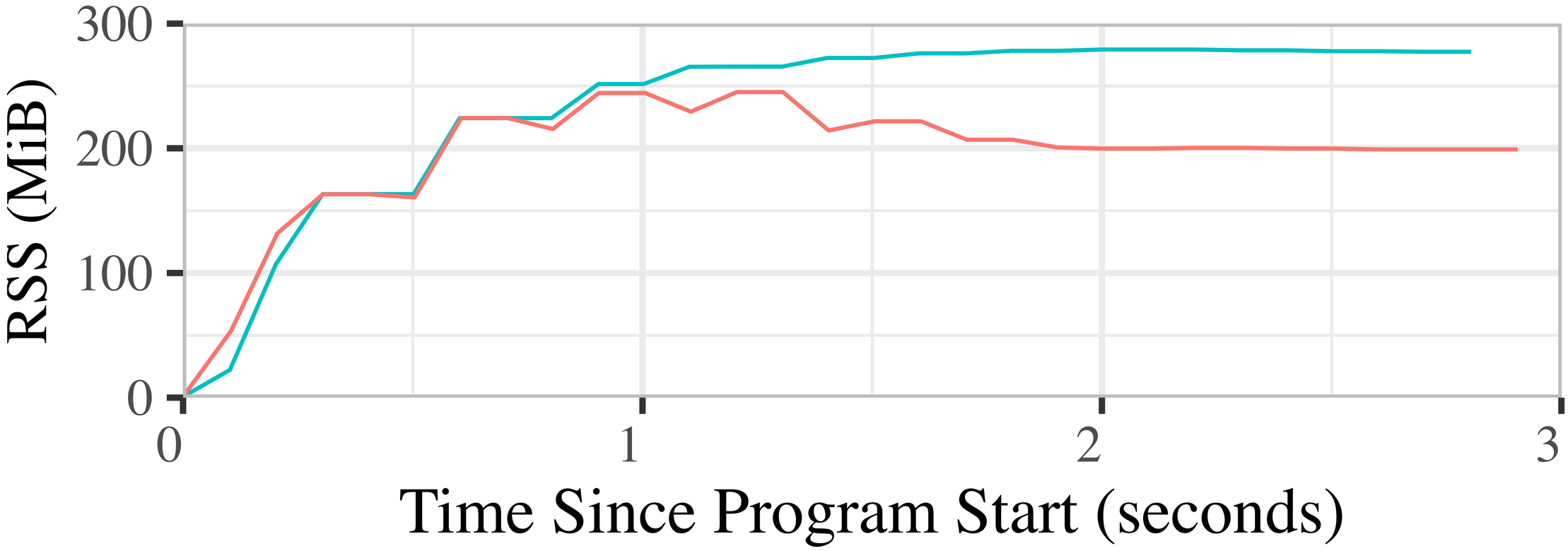

Insert time
2
1.5
1
0.5
0
Insert time
1.72
1.76
Default
Mesh
Compaction time
1.5
1
0.5
0
Compaction time
Default
Mesh

17% heap size reduction

< 1% performance overhead



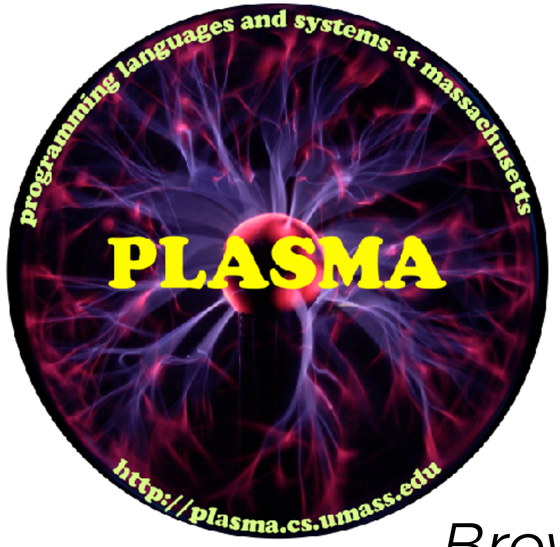
Ruby Compaction for Free



http:// **LIBMESH** .org

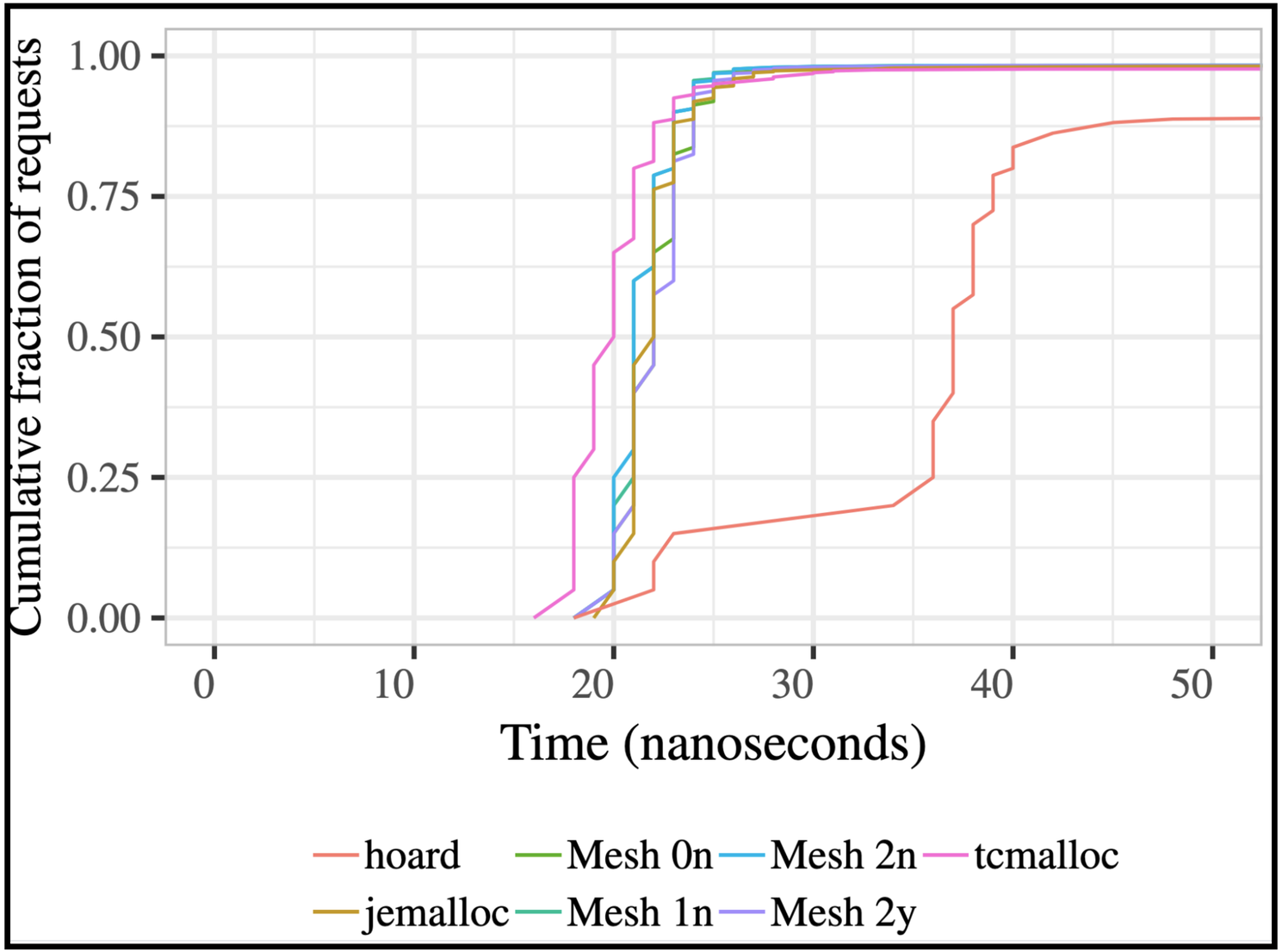
¡Compactación sin Relocación!

(compaction without relocation)



Browsix, Coz, DieHard, Hoard...

Latency: `malloc`



Latency: free