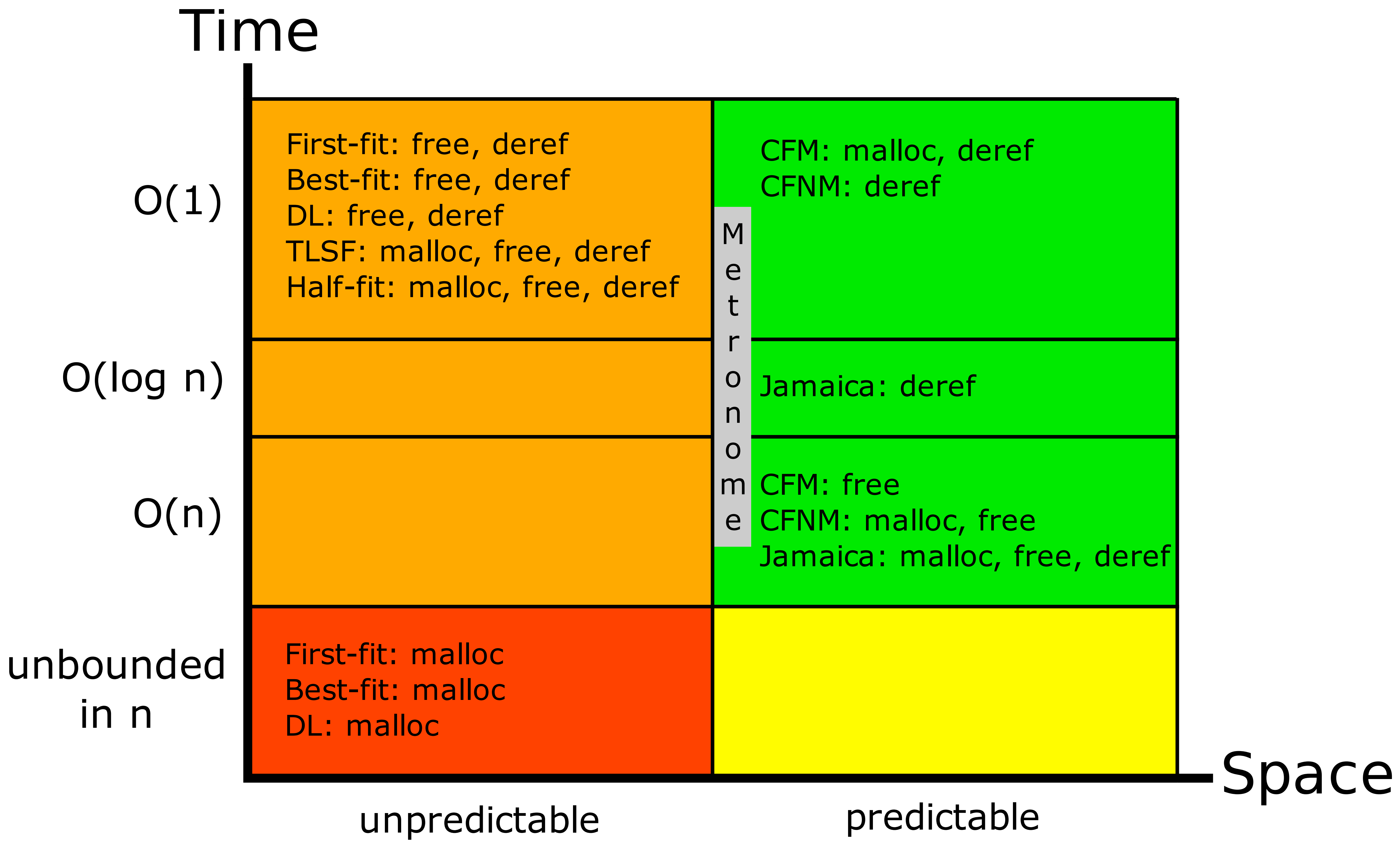
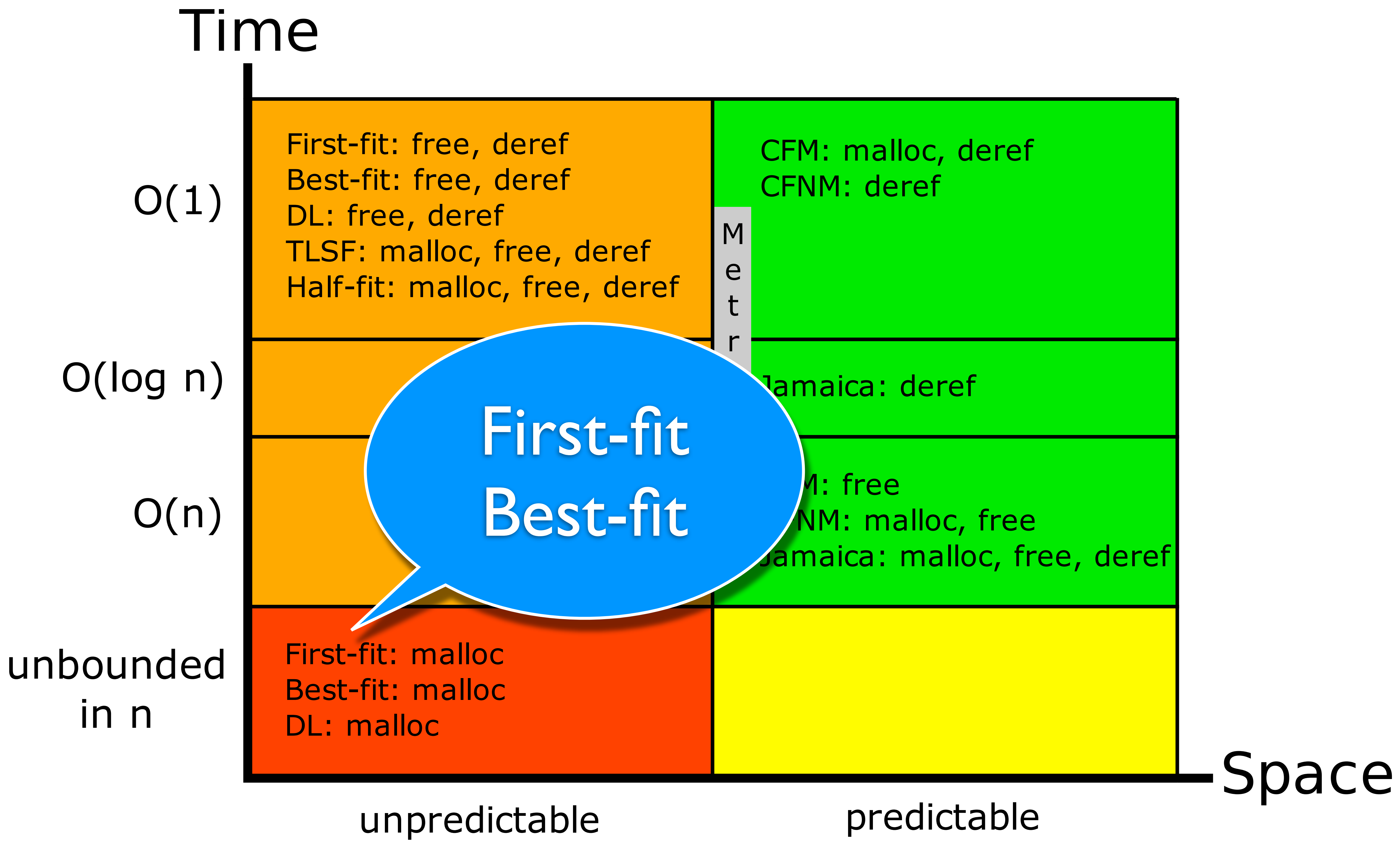
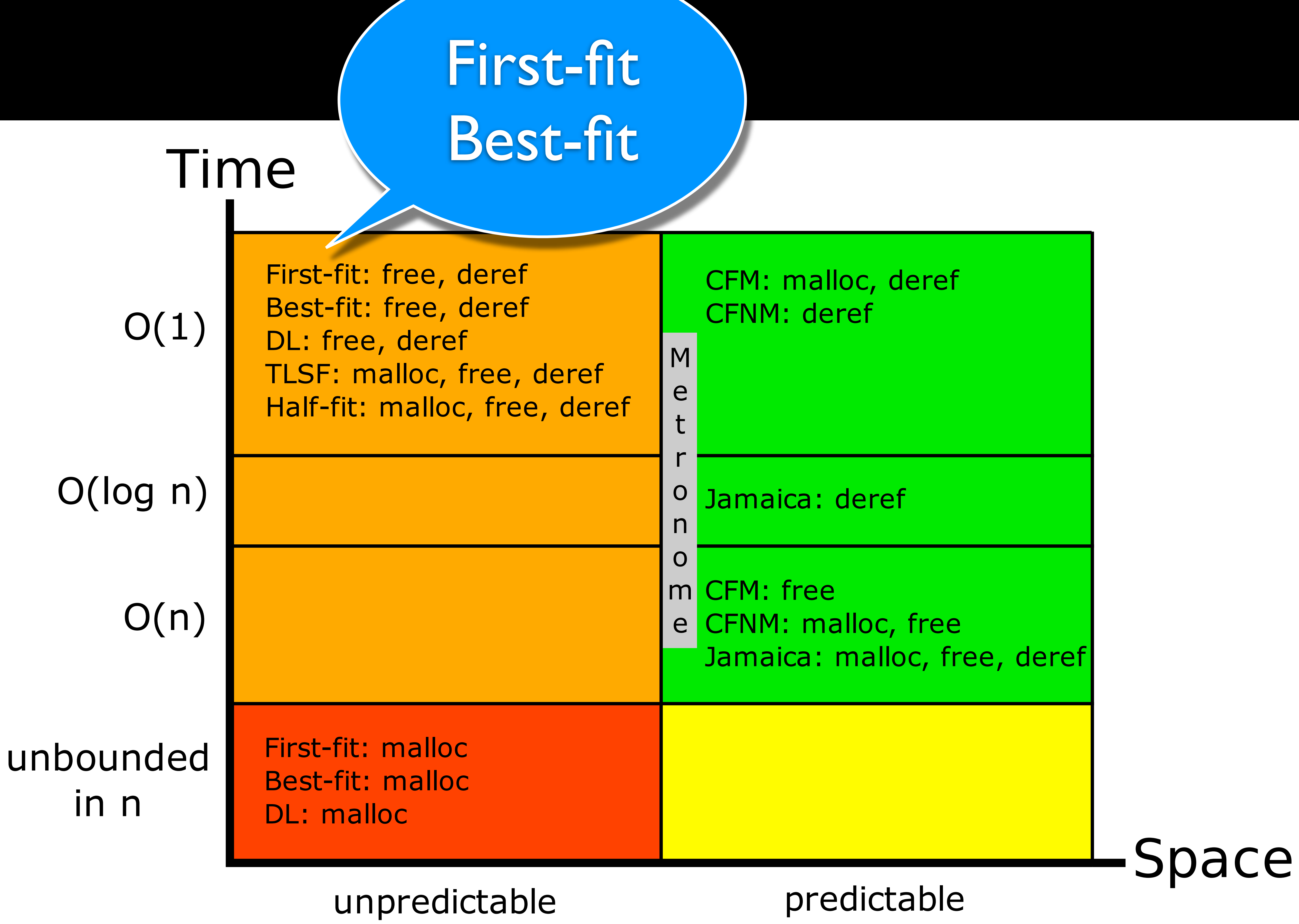
Memory Management Systems Overview



Time \ Space	unpredictable	predictable
O(1)	First-fit: free, deref Best-fit: free, deref DL: free, deref TLSF: malloc, free, deref Half-fit: malloc, free, deref	CFM: malloc, deref CFNM: deref
O(log n)		Jamaica: deref
O(n)		CFM: free CFNM: malloc, free Jamaica: malloc, free, deref
unbounded in n	First-fit: malloc Best-fit: malloc DL: malloc	


Time
O(1)
O(log n)
O(n)
unbounded in n
First-fit: free, deref
Best-fit: free, deref
DL: free, deref
TLSF: malloc, free, deref
Half-fit: malloc, free, deref
CFM: malloc, deref
CFNM: deref
Metr
Jamaica: deref
M: free
NM: malloc, free
Jamaica: malloc, free, deref
First-fit: malloc
Best-fit: malloc
DL: malloc
First-fit
Best-fit
Space
unpredictable
predictable



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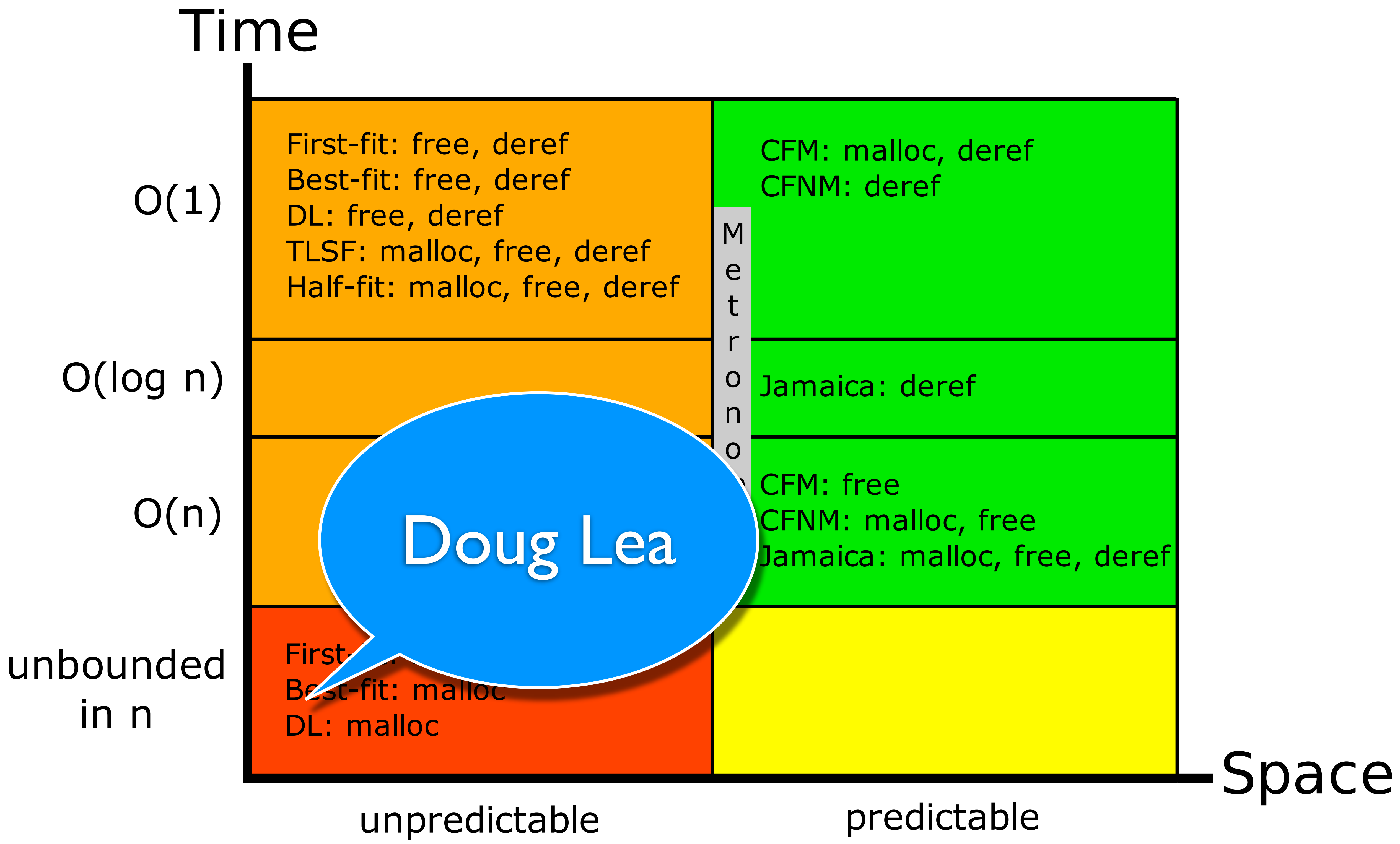
Time
O(1)
O(log n)
O(n)
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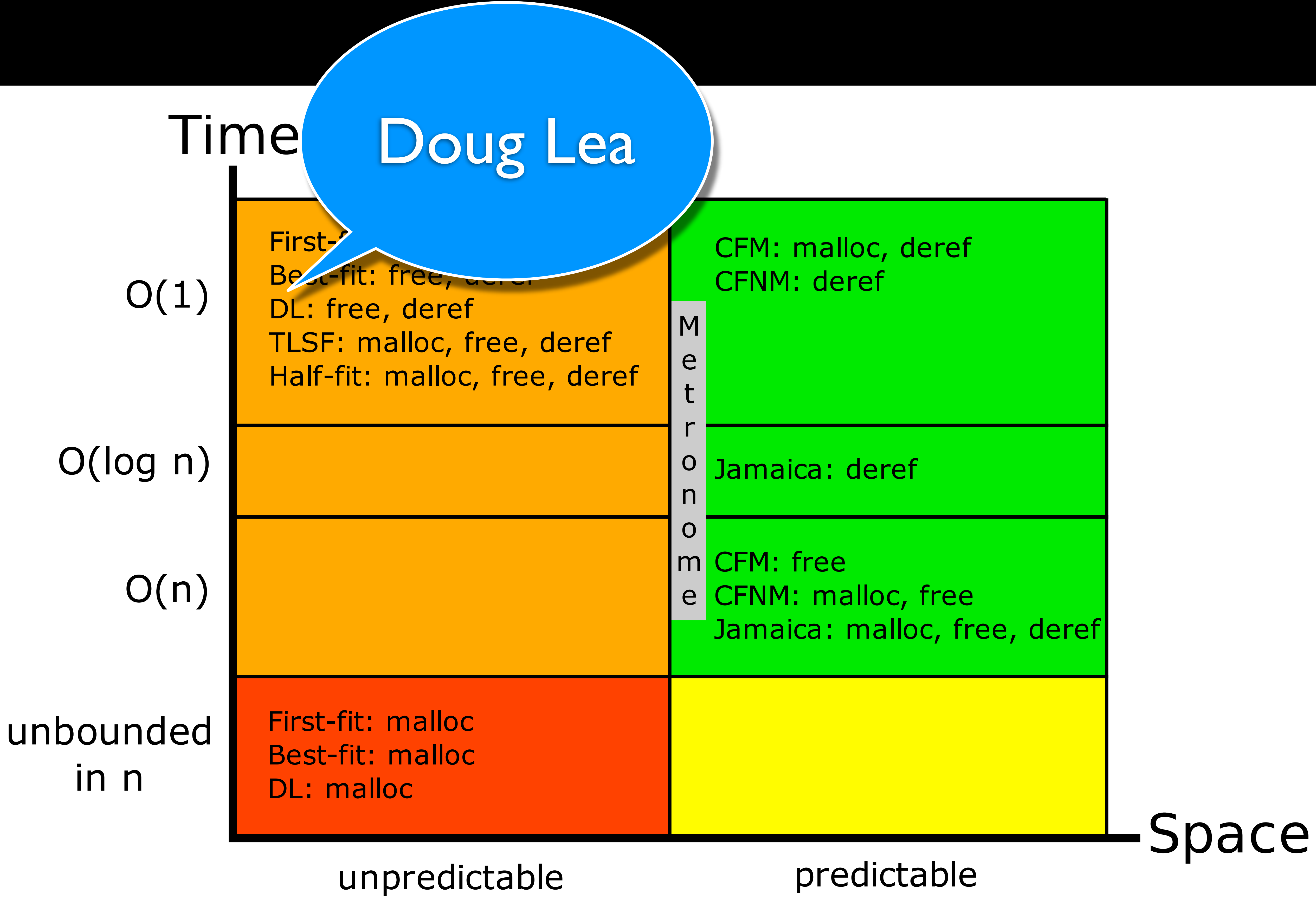
First-fit: free, deref
Best-fit: free, deref
DL: free, deref
TLSF: malloc, free, deref
Half-fit: malloc, free, deref
First-
Best-fit: malloc
DL: malloc
CFM: malloc, deref
CFNM: deref
Metrono
Jamaica: deref
CFM: free
CFNM: malloc, free
Jamaica: malloc, free, deref
Doug Lea
unpredictable
predictable
Space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O(1)
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O(n)
unbounded in n
First-
Be -fit: free,
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Metronome
Jamaica: deref
CFM: free
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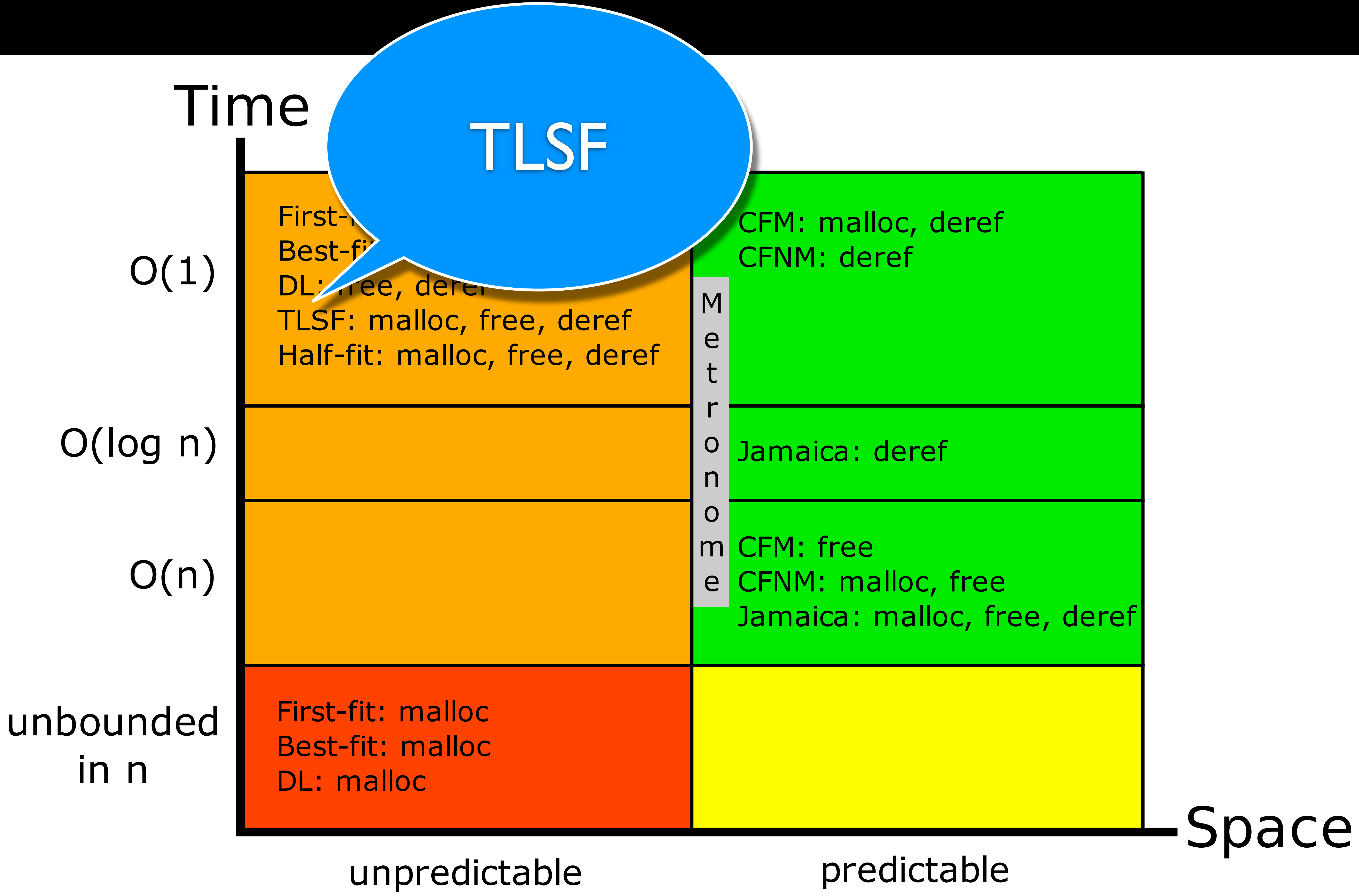
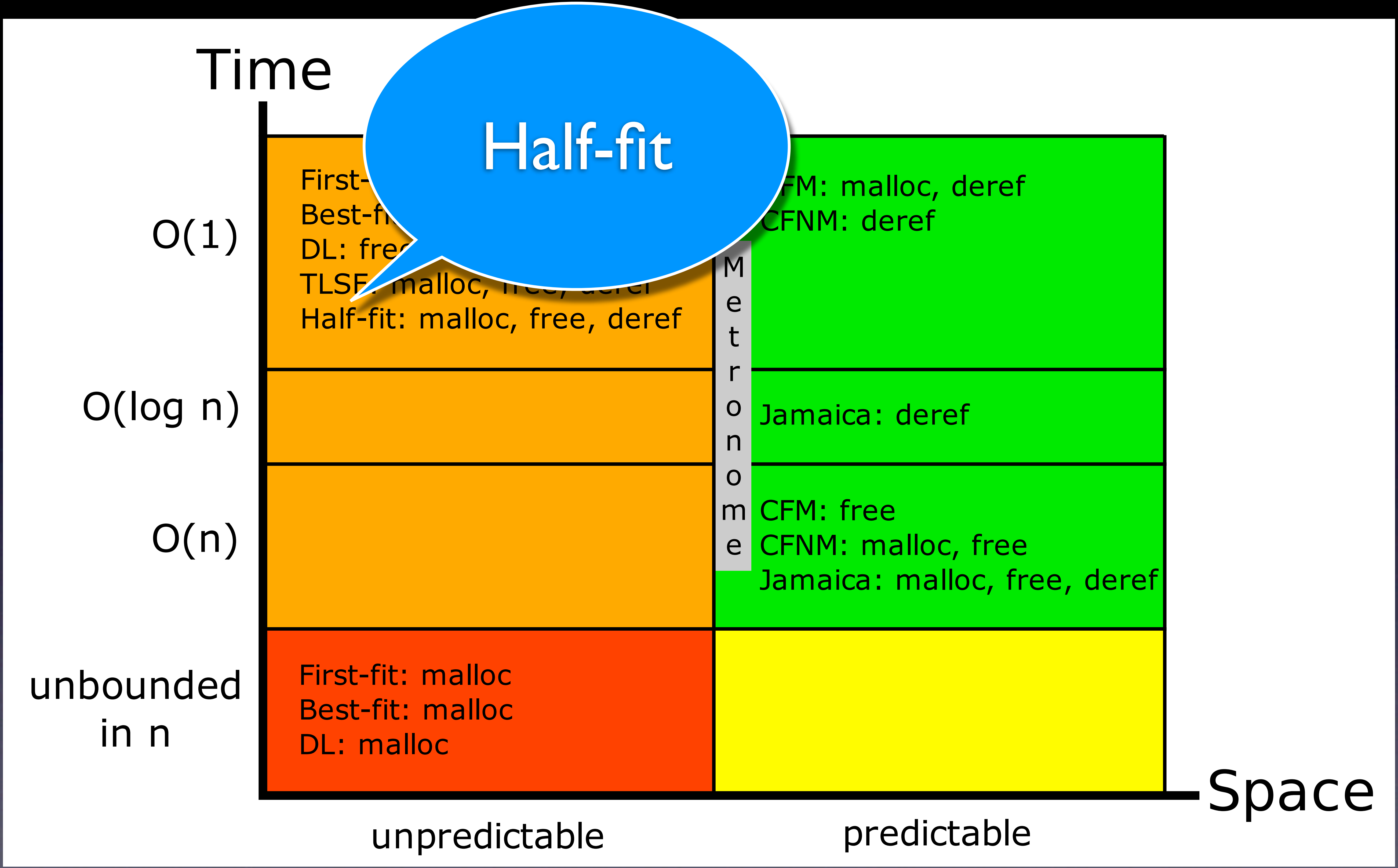
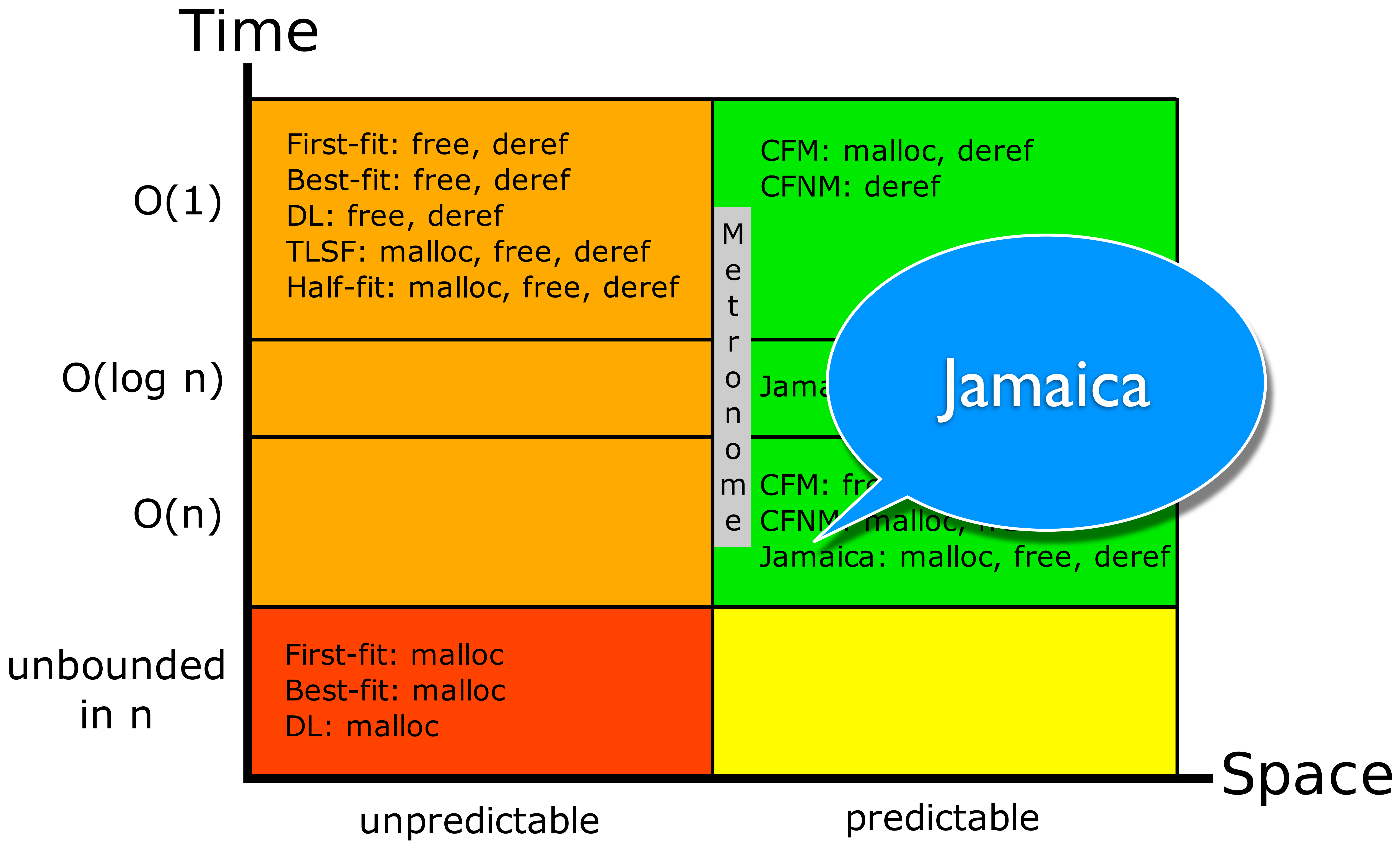
Jamaica: malloc, free, deref
First-fit: malloc
Best-fit: malloc
DL: malloc
Space
unpredictable
predictable


Time
TLSF
O(1)
First-
Best-fi
DL: free, deref
TLSF: malloc, free, deref
Half-fit: malloc, free, deref
CFM: malloc, deref
CFNM: deref
Metronome
O(log n)
Jamaica: deref
O(n)
CFM: free
CFNM: malloc, free
Jamaica: malloc, free, deref
unbounded in n
First-fit: malloc
Best-fit: malloc
DL: malloc
Space
unpredictable
predictable



Half-fit
Time
O(1)
O(log n)
O(n)
unbounded in n
First-
Best-fi
DL: free
TLSF: malloc, free, deref
Half-fit: malloc, free, deref
CFM: malloc, deref
CFNM: deref
Metronome
Jamaica: deref
CFM: free
CFNM: malloc, free
Jamaica: malloc, free, deref
First-fit: malloc
Best-fit: malloc
DL: malloc
Space
unpredictable
predictable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Metronome
Jama
CFM: fr
CFNM: malloc,
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Jamaica
First-fit: malloc
Best-fit: malloc
DL: malloc
unpredictable
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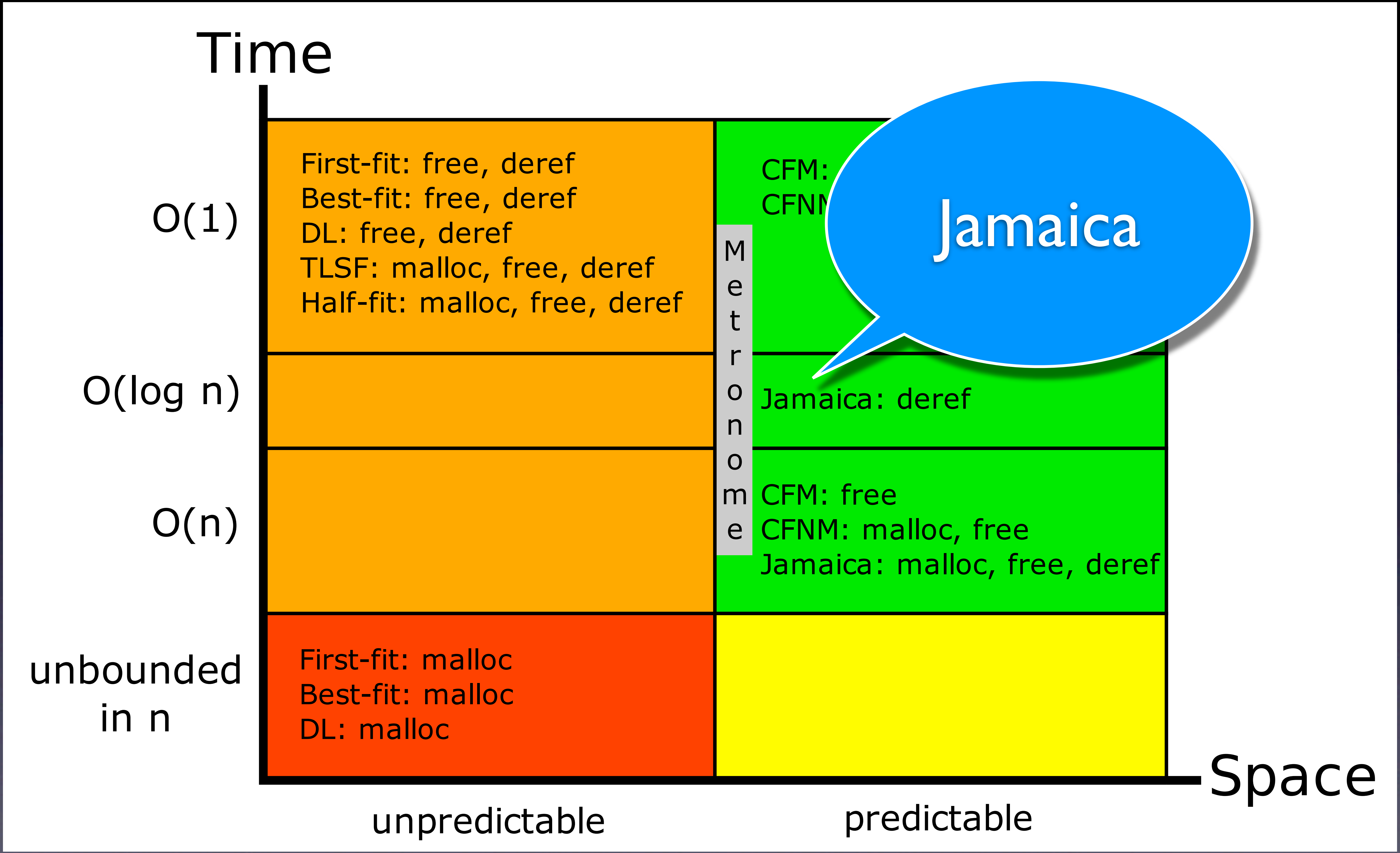
Space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CFN
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unpredictable
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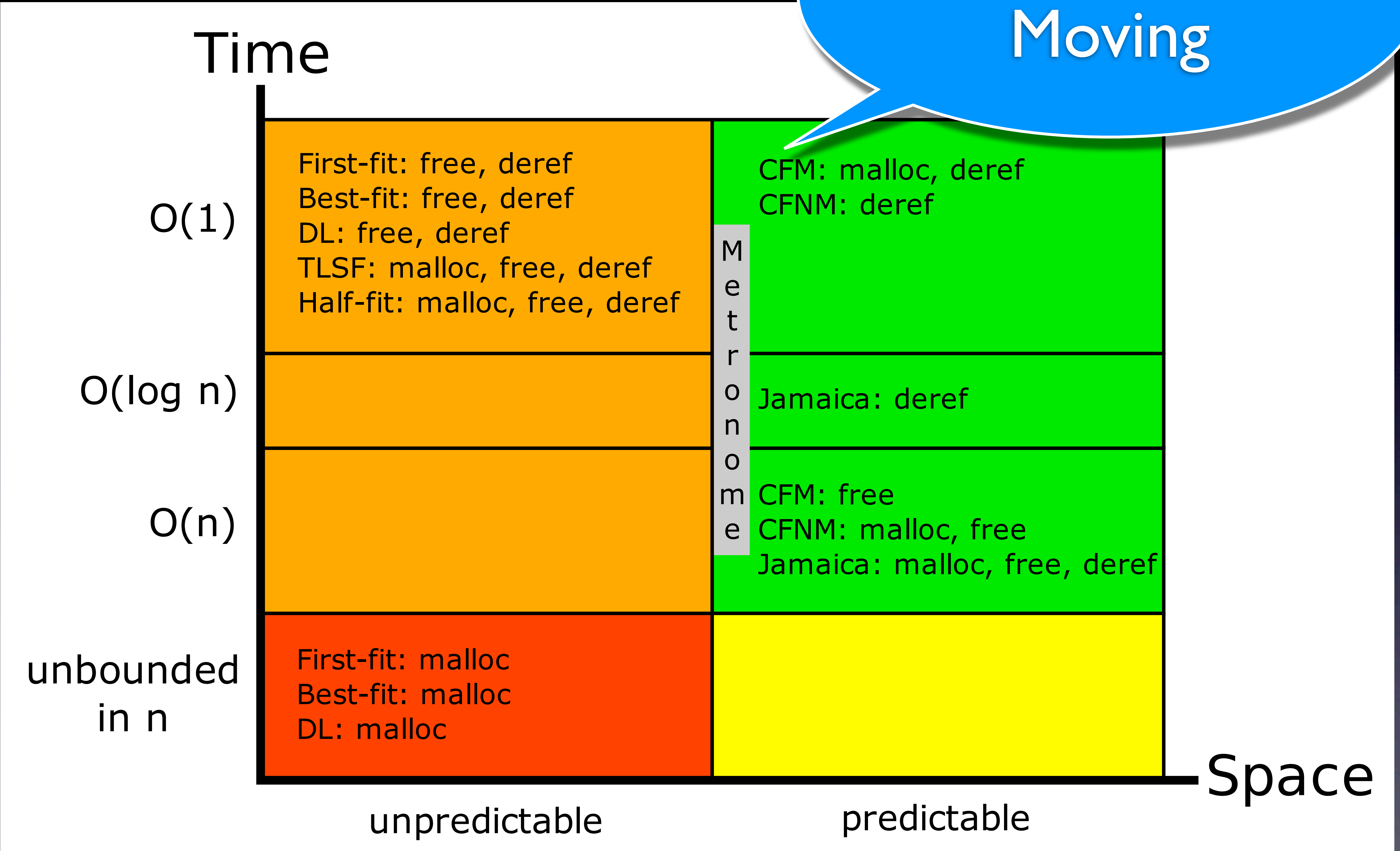

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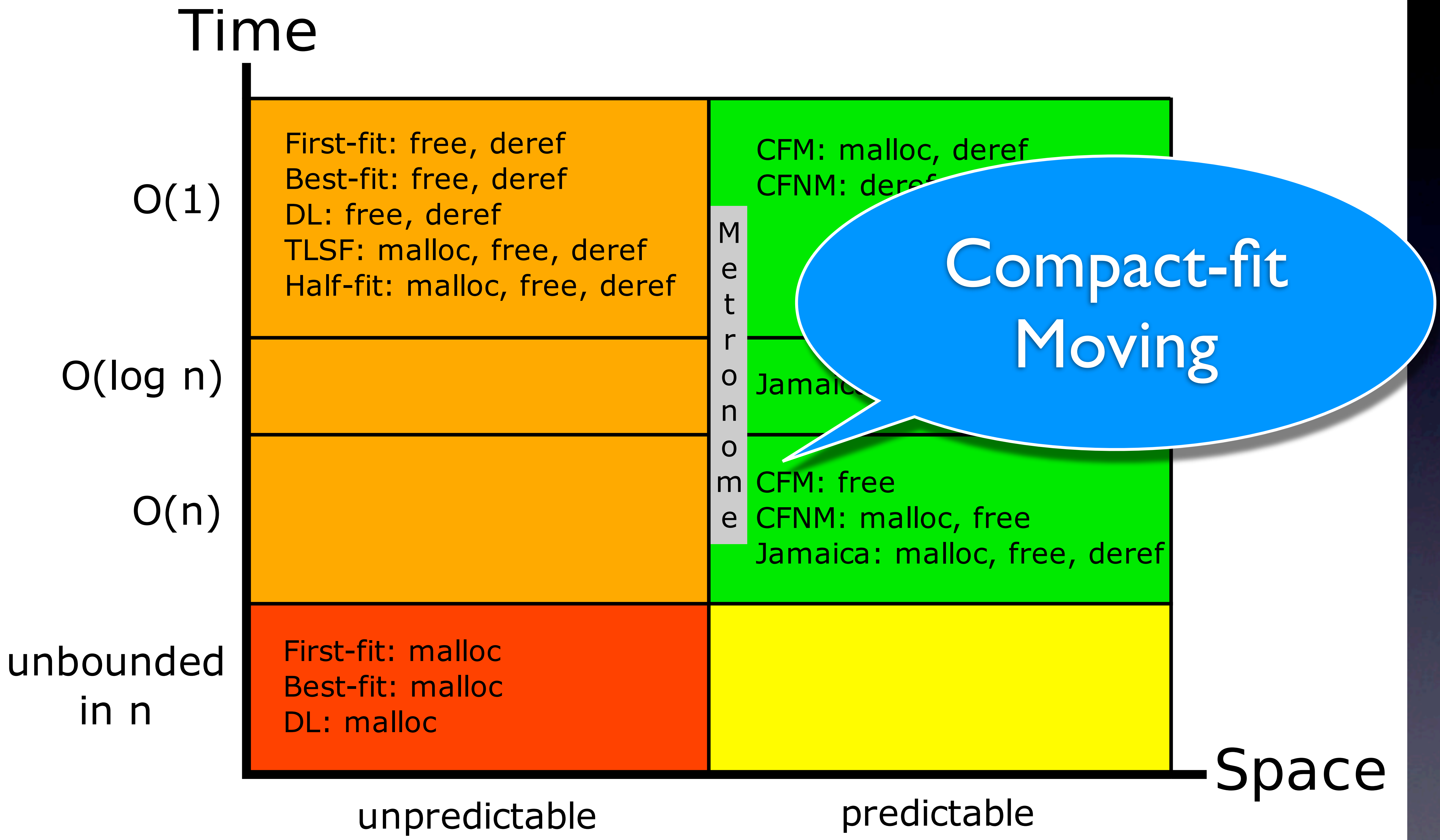
Compact-fit Moving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O(log n)
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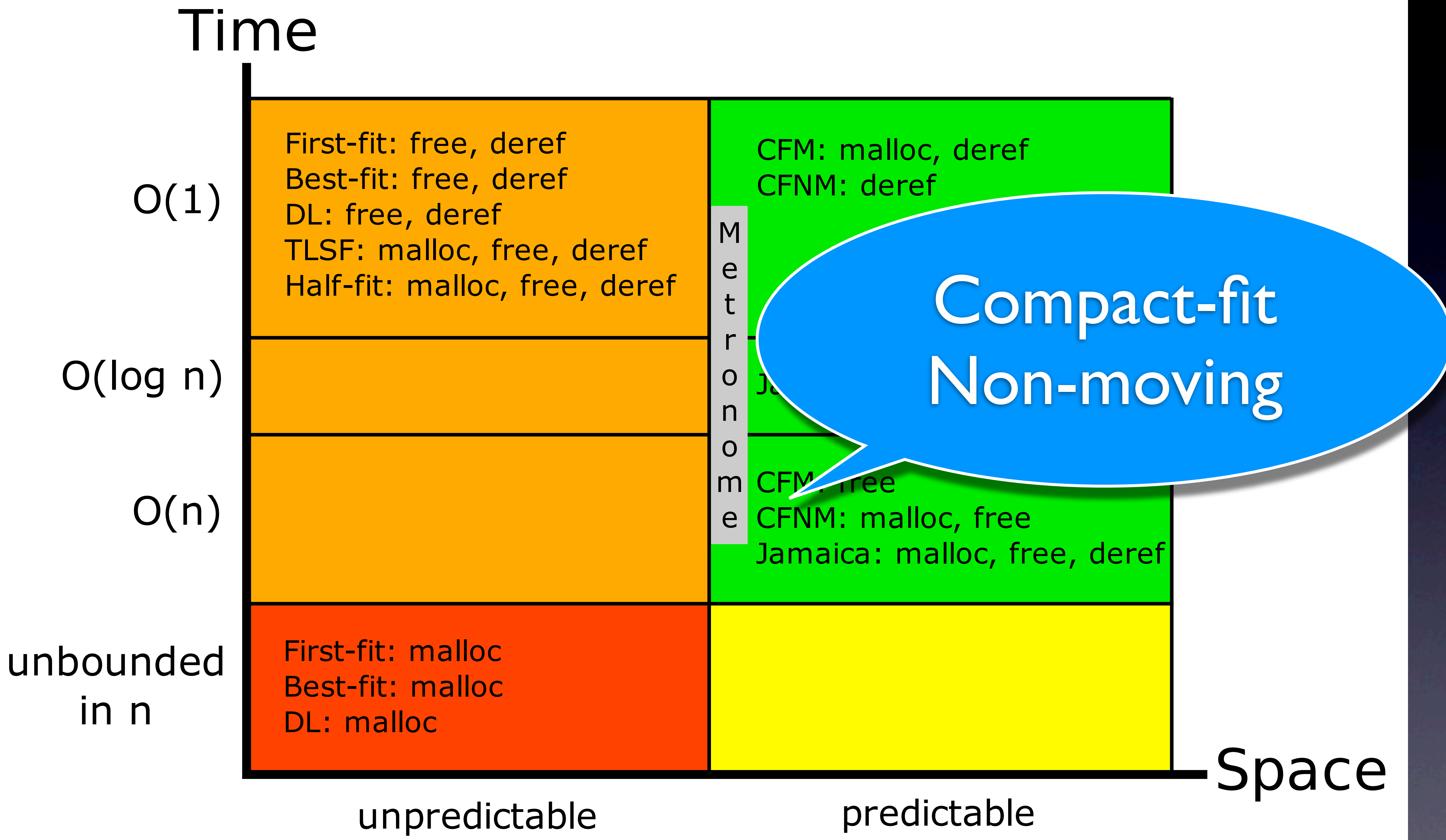
Compact-fit Moving
Space
unpredictable
predictable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Ja
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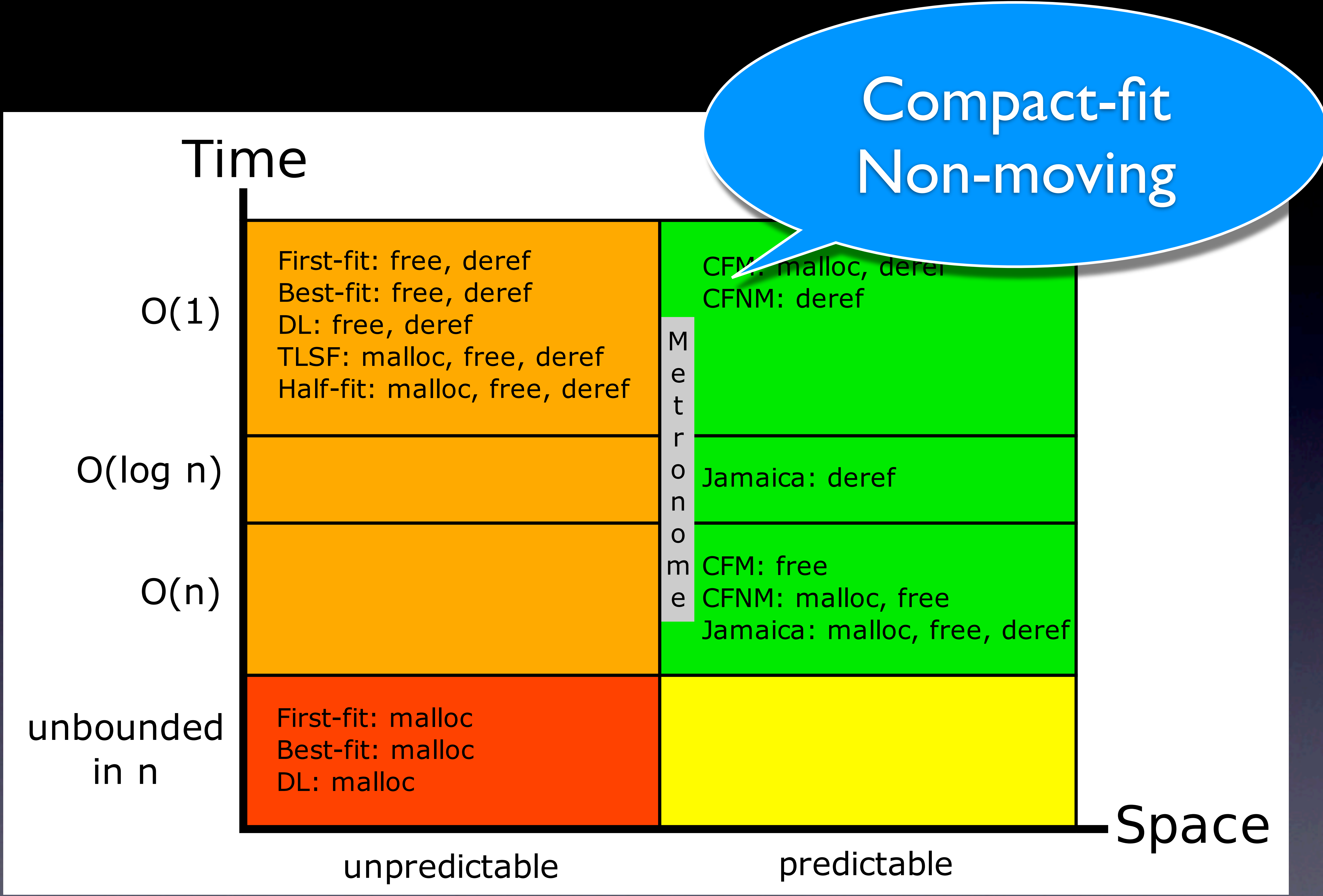
Compact-fit Non-moving
Space
unpredictable
predictable


Compact-fit
Non-moving
Time
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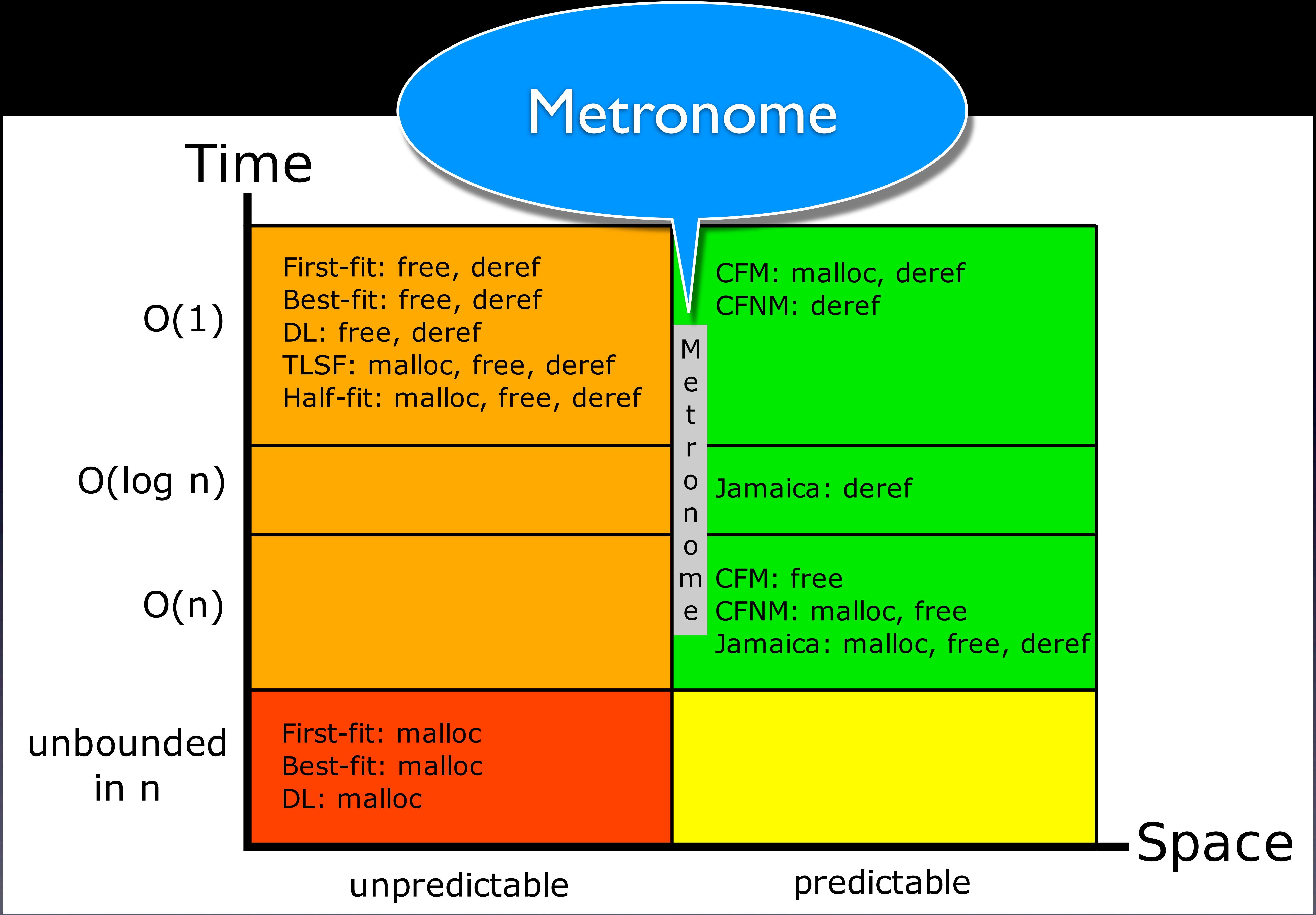

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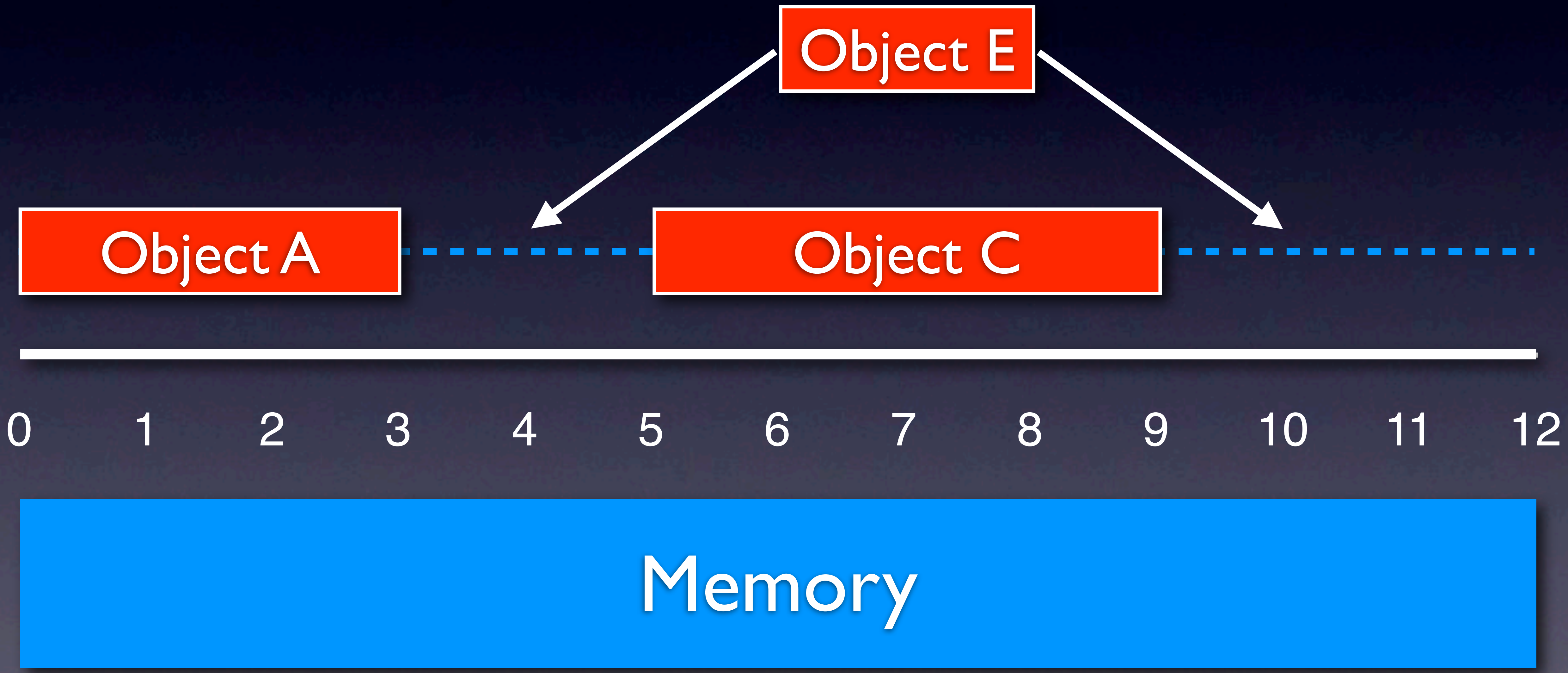
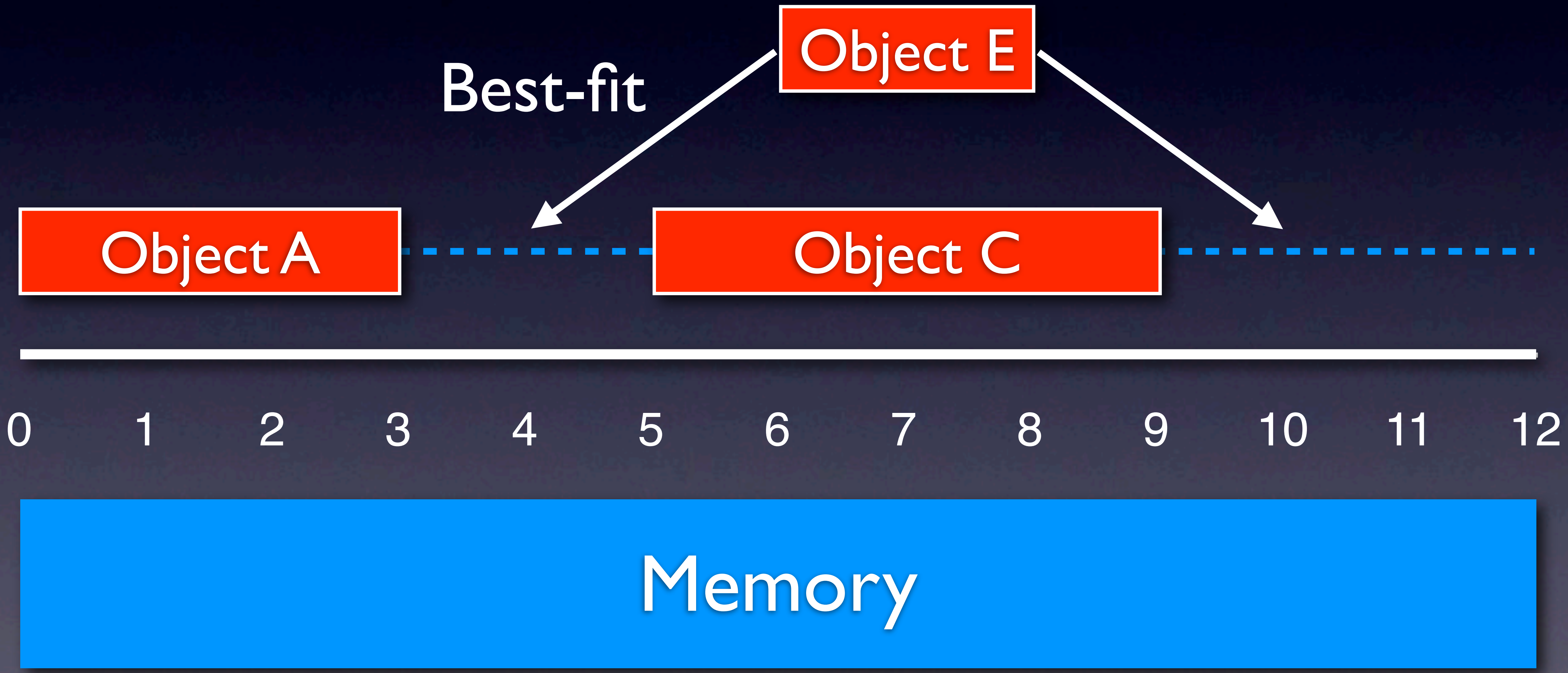
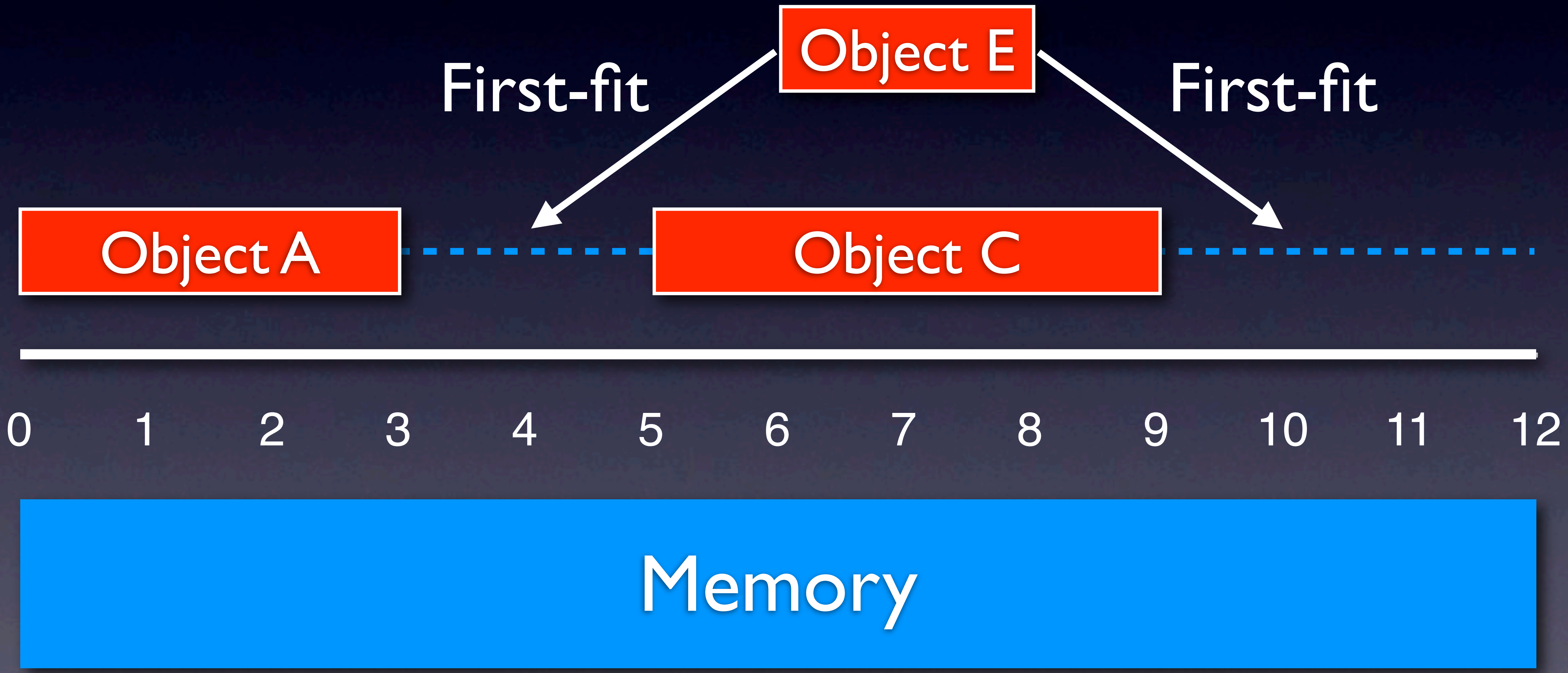
Best-fit versus First-fit



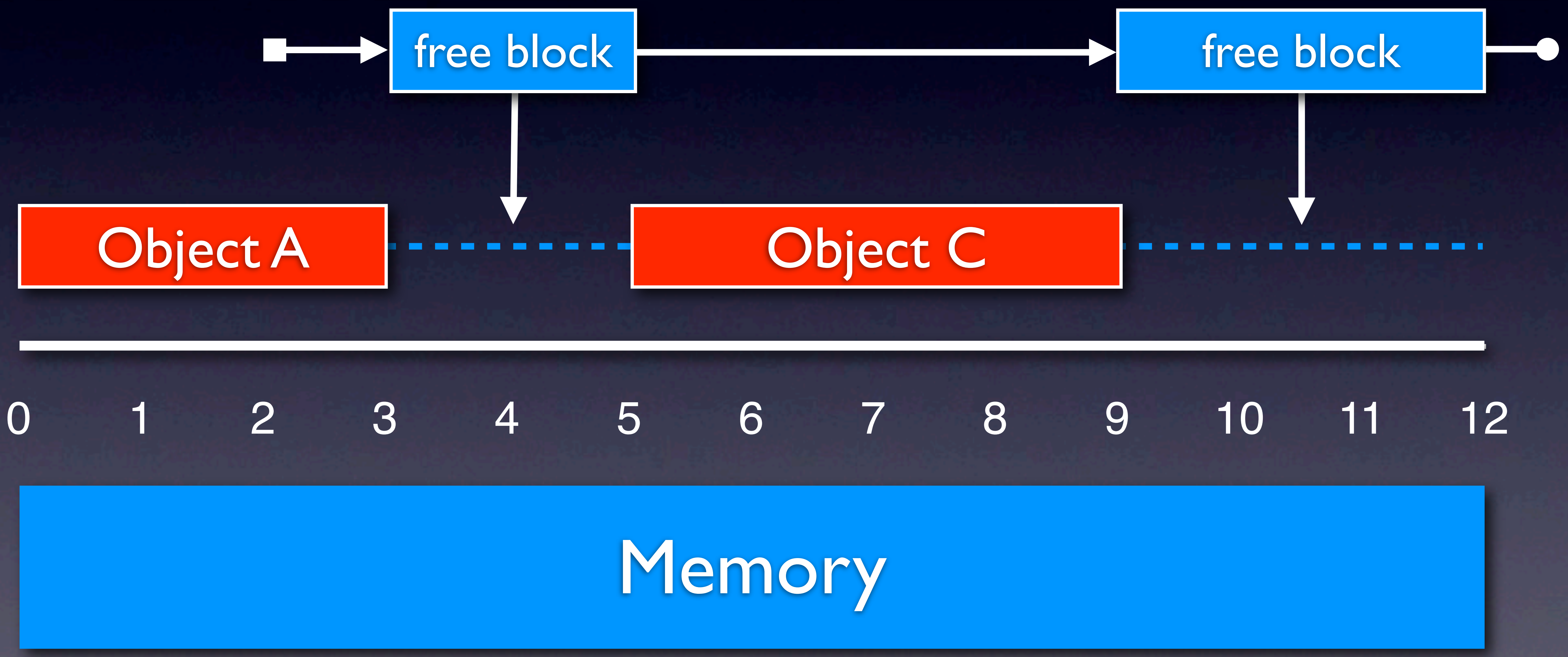
Best-fit versus First-fit



Best-fit versus First-fit



Free List


free block
free block
Object A
Object C
0
1
2
3
4
5
6
7
8
9
10
11
12
Memory

Best-fit, First-fit Complexity

- Allocation:
  - `malloc` may take time proportional to heap size

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- Allocation:
  - `malloc` may take time proportional to heap size
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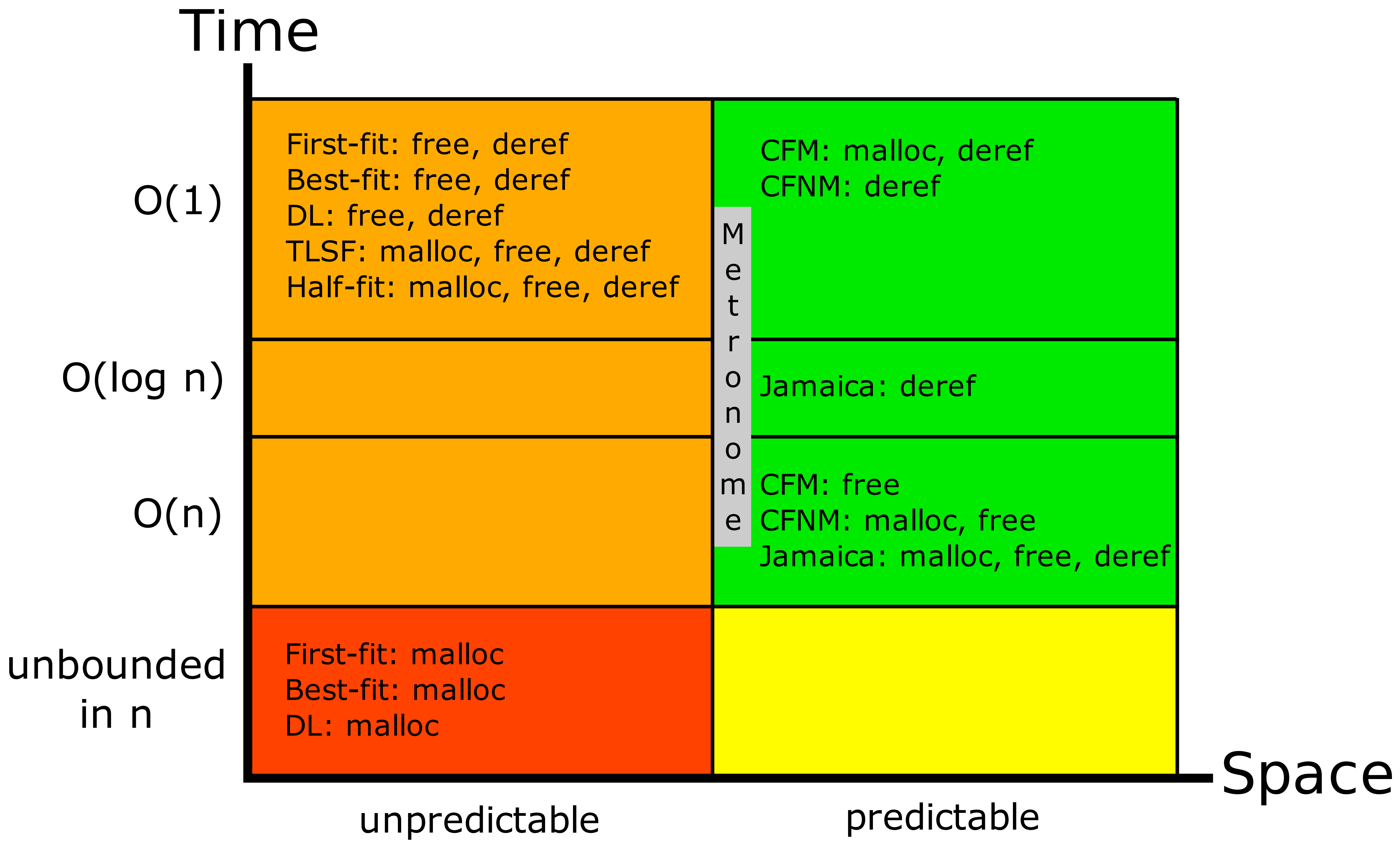
- <u>Unpredictable</u> fragmentation


Time
Space
Metronome

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Free List Operations

- Select:
  - `malloc`

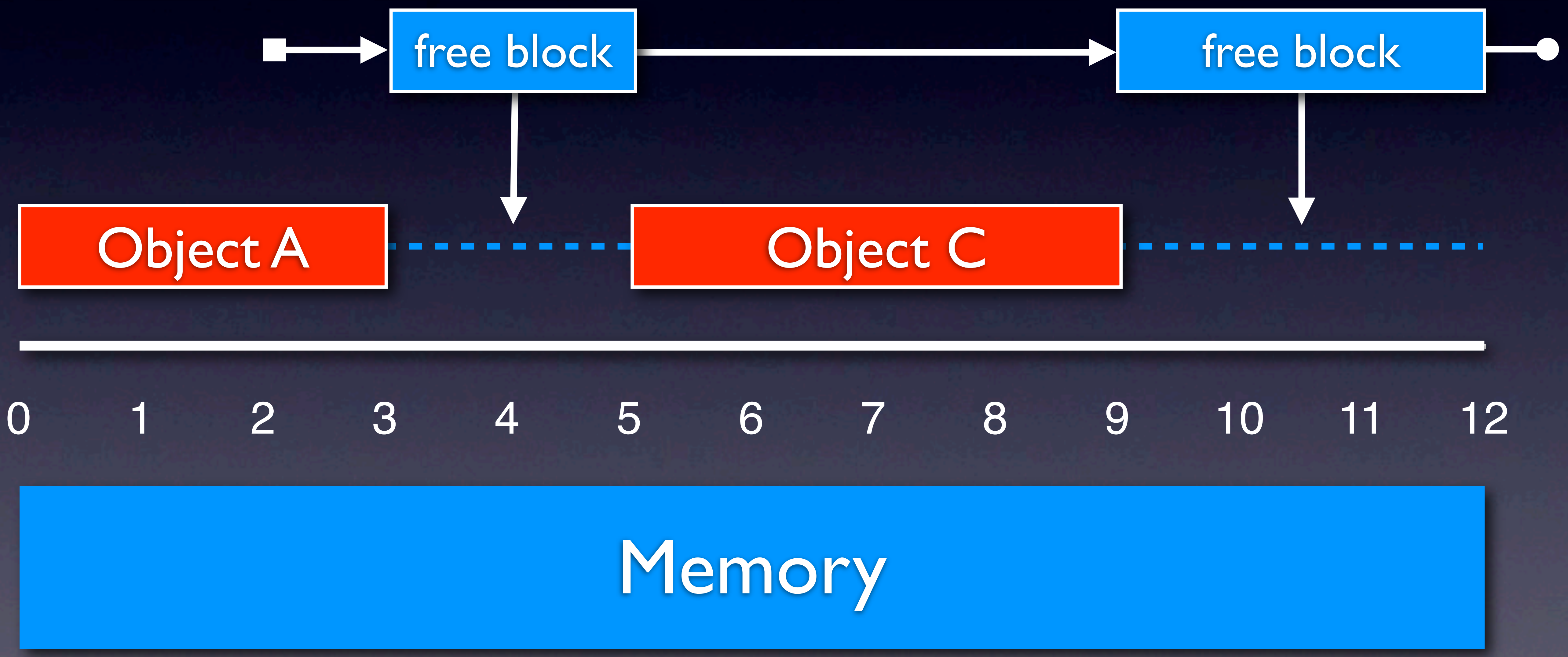
Free List Operations

- Select:
  - `malloc`
- Insert:
  - `free`

Free List Operations

- Select:
  - `malloc`
- Insert:
  - `free`
- Delete:
  - coalescing

Coalescing


free block
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Object A
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0
1
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3
4
5
6
7
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9
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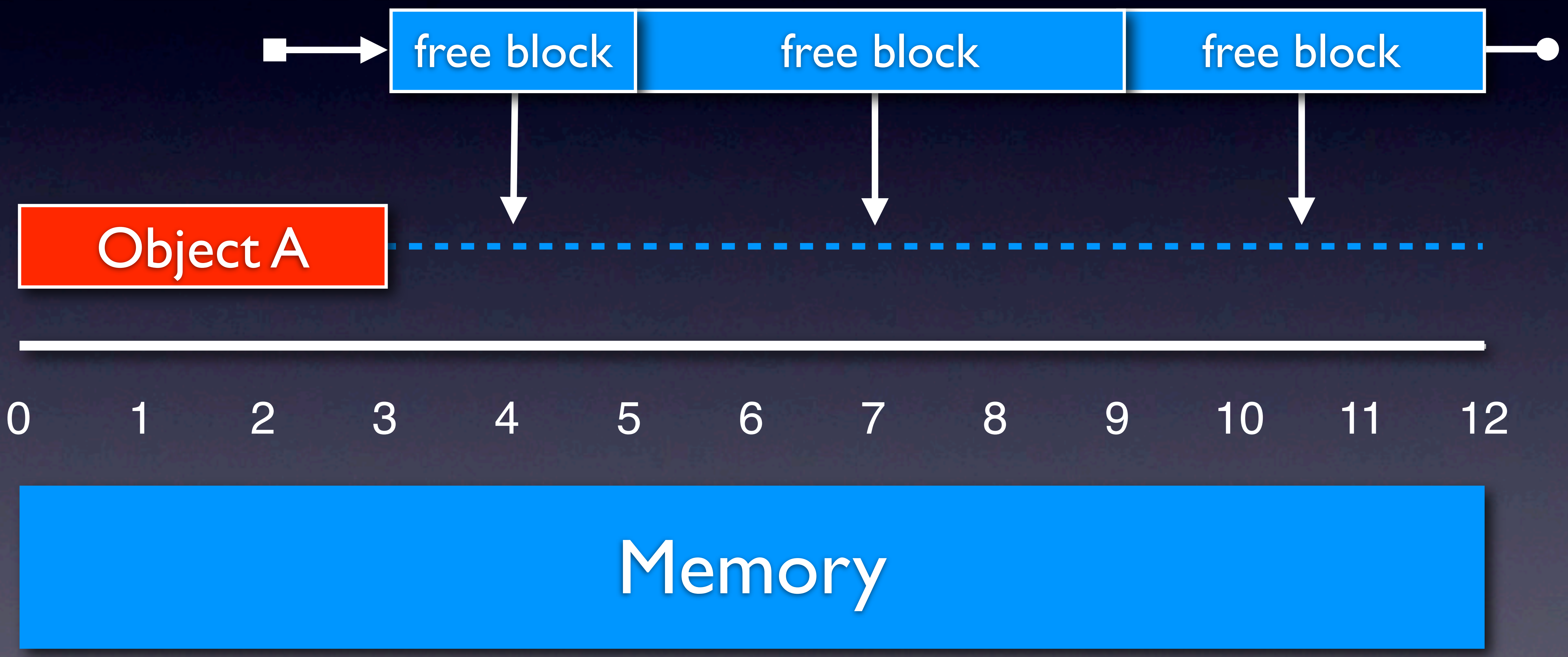
Memory

Coalescing


free block
free block
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Object A
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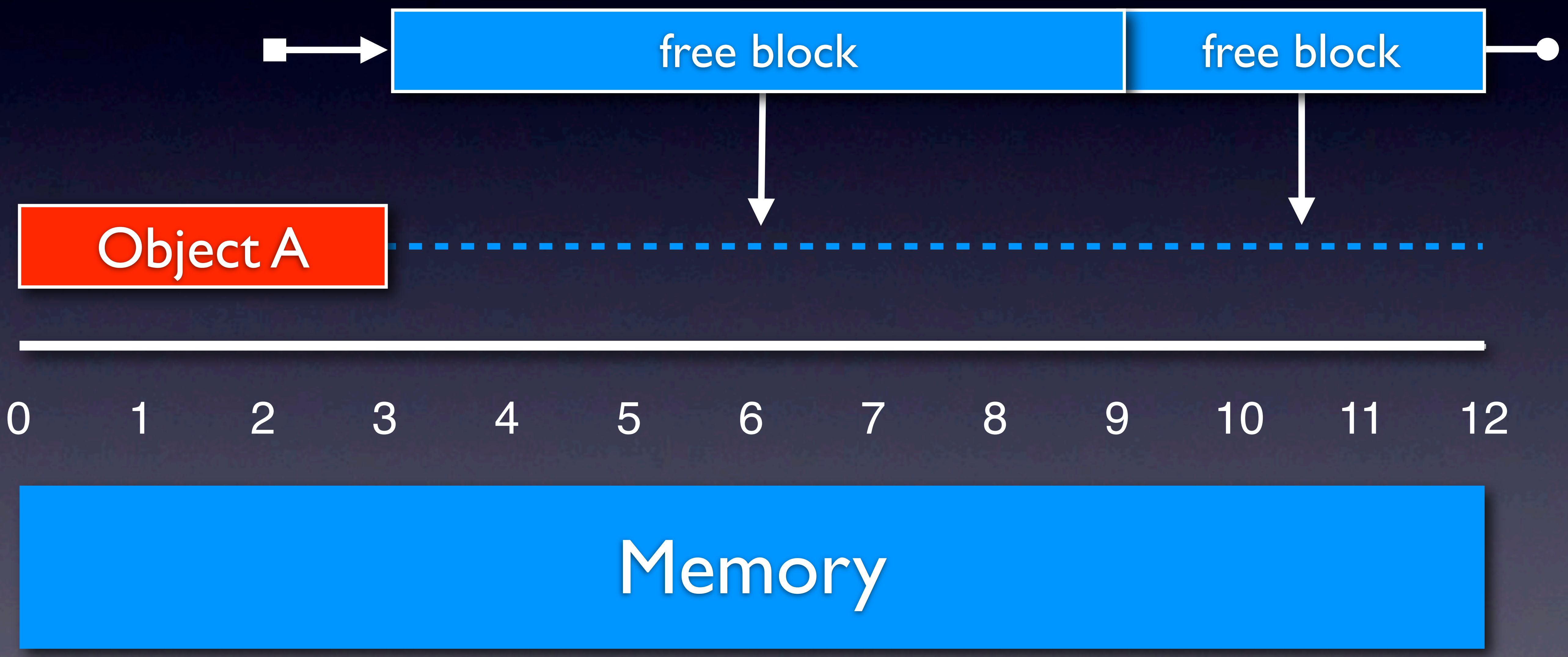
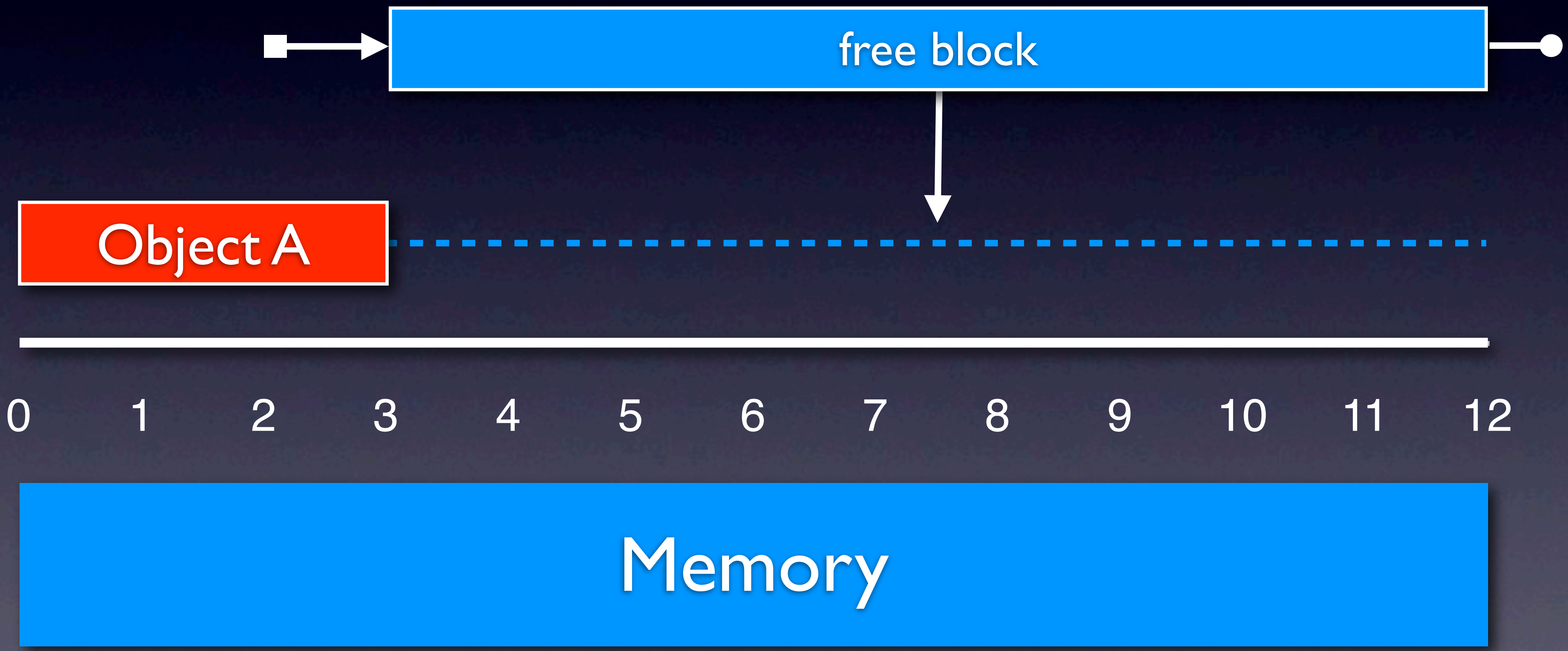
Memory

Coalescing



Coalescing



List Representations

- List: singly-linked or doubly-linked (using boundary tags)

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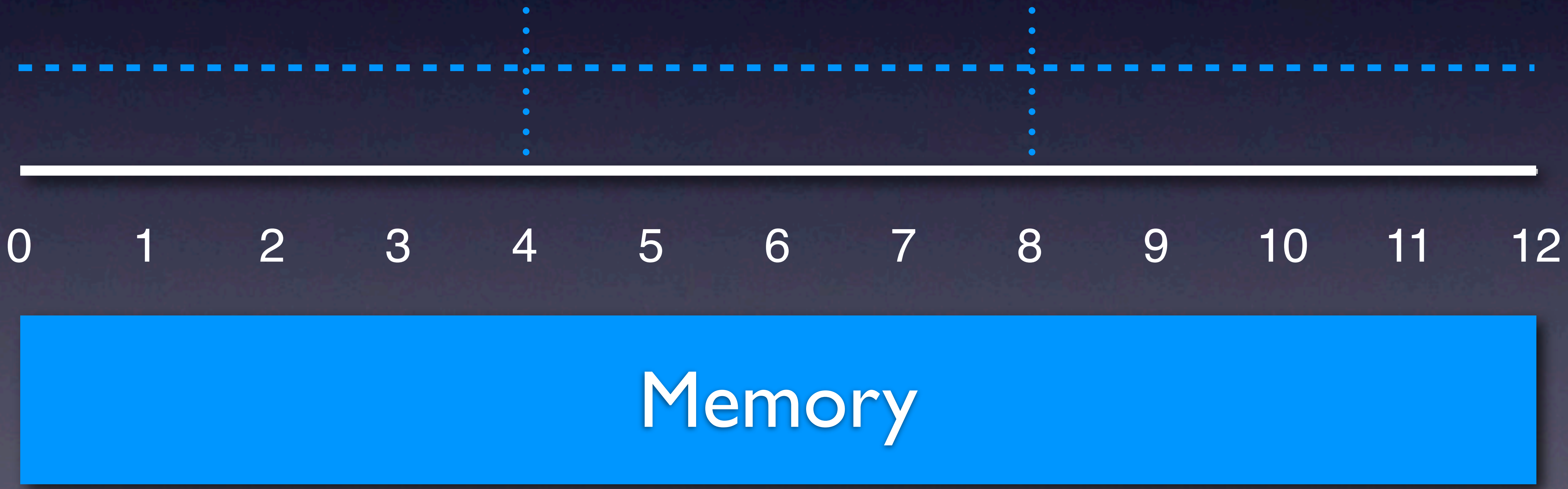
- Buddy systems: split blocks in powers of two (called buddies if same size)
- Indexed lists: trees, bitmaps
- Hybrid: Doug Lea's allocator

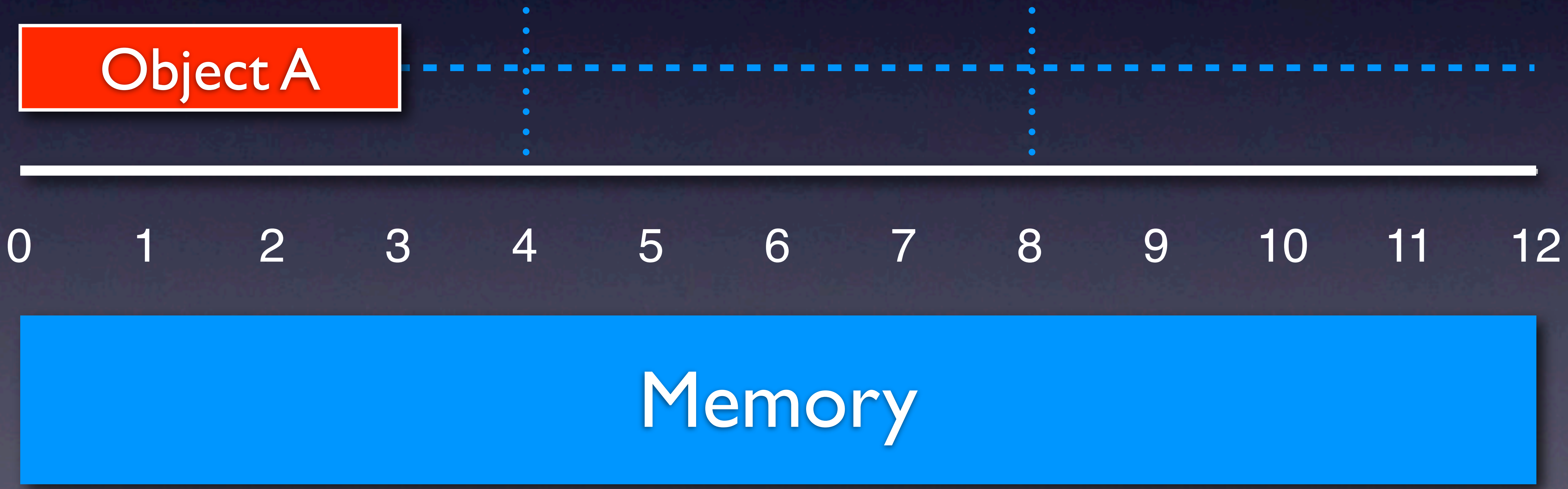
DL Complexity

- Allocation:
  - `malloc` may take time proportional to heap size
- Deallocation:
  - `free` takes constant time
- Access:
  - `read` and `write` take constant time
- Unpredictable fragmentation

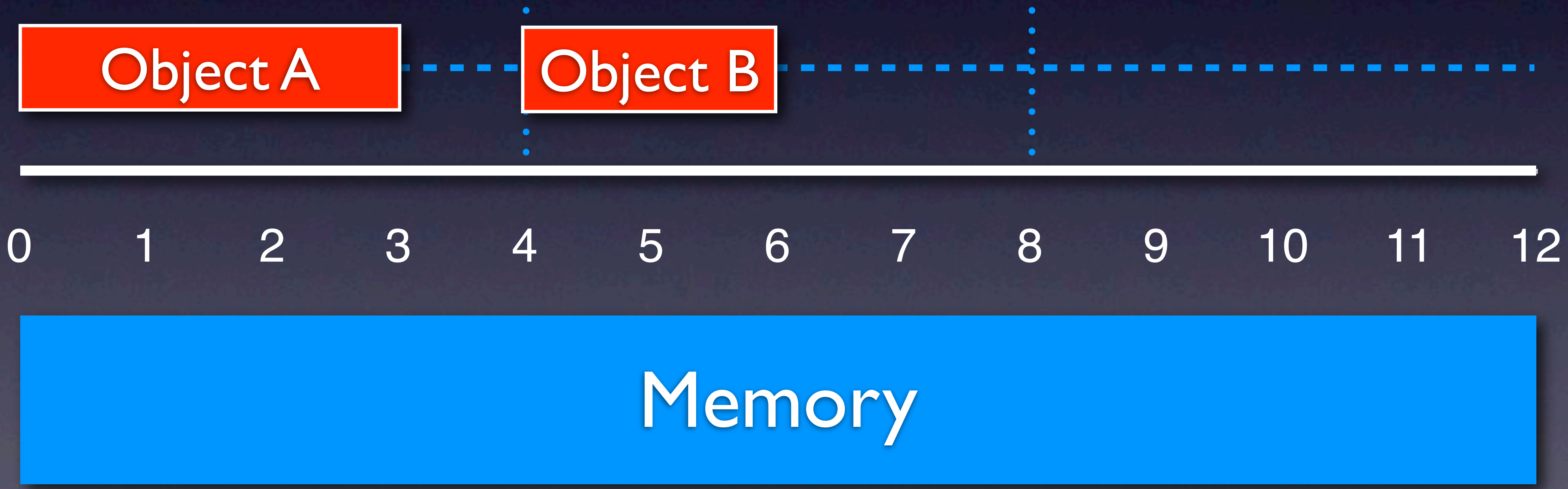
Partitioning



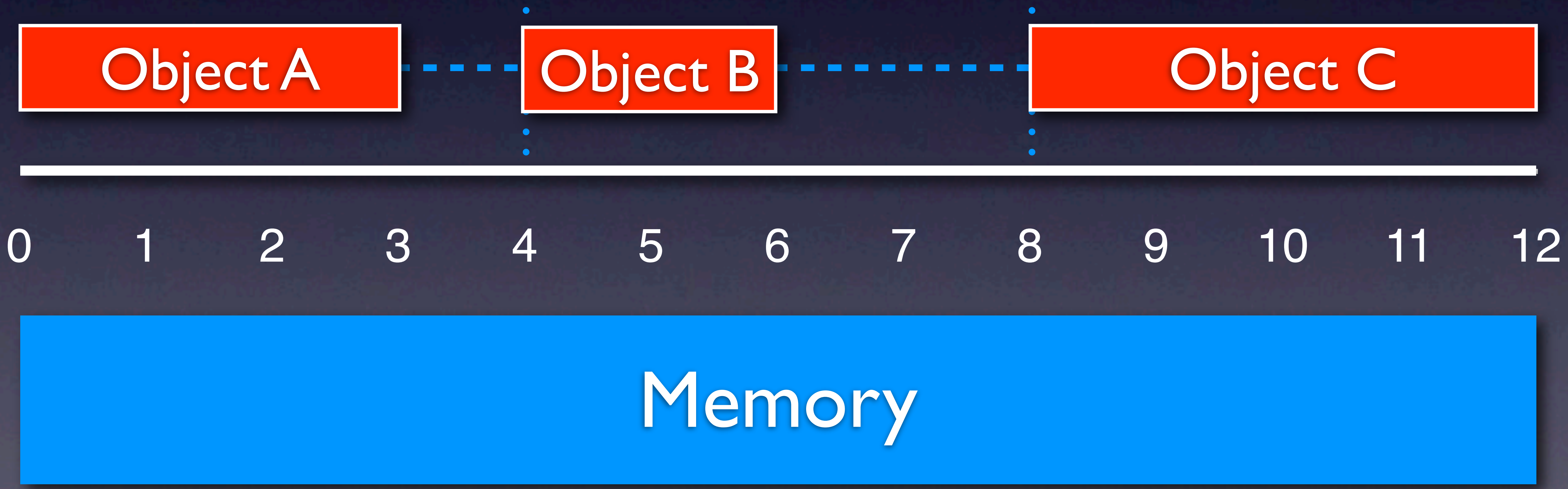
Partitioning



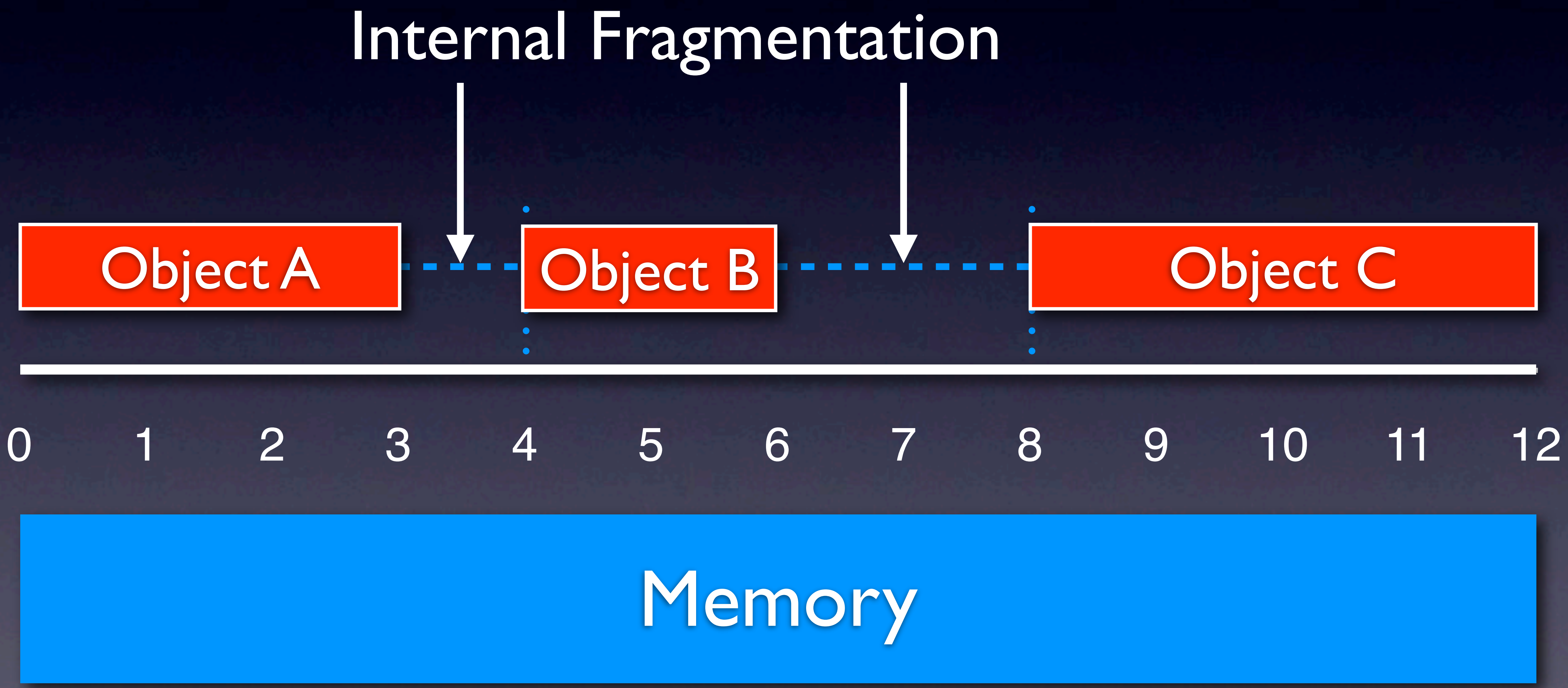
Partitioning



Partitioning

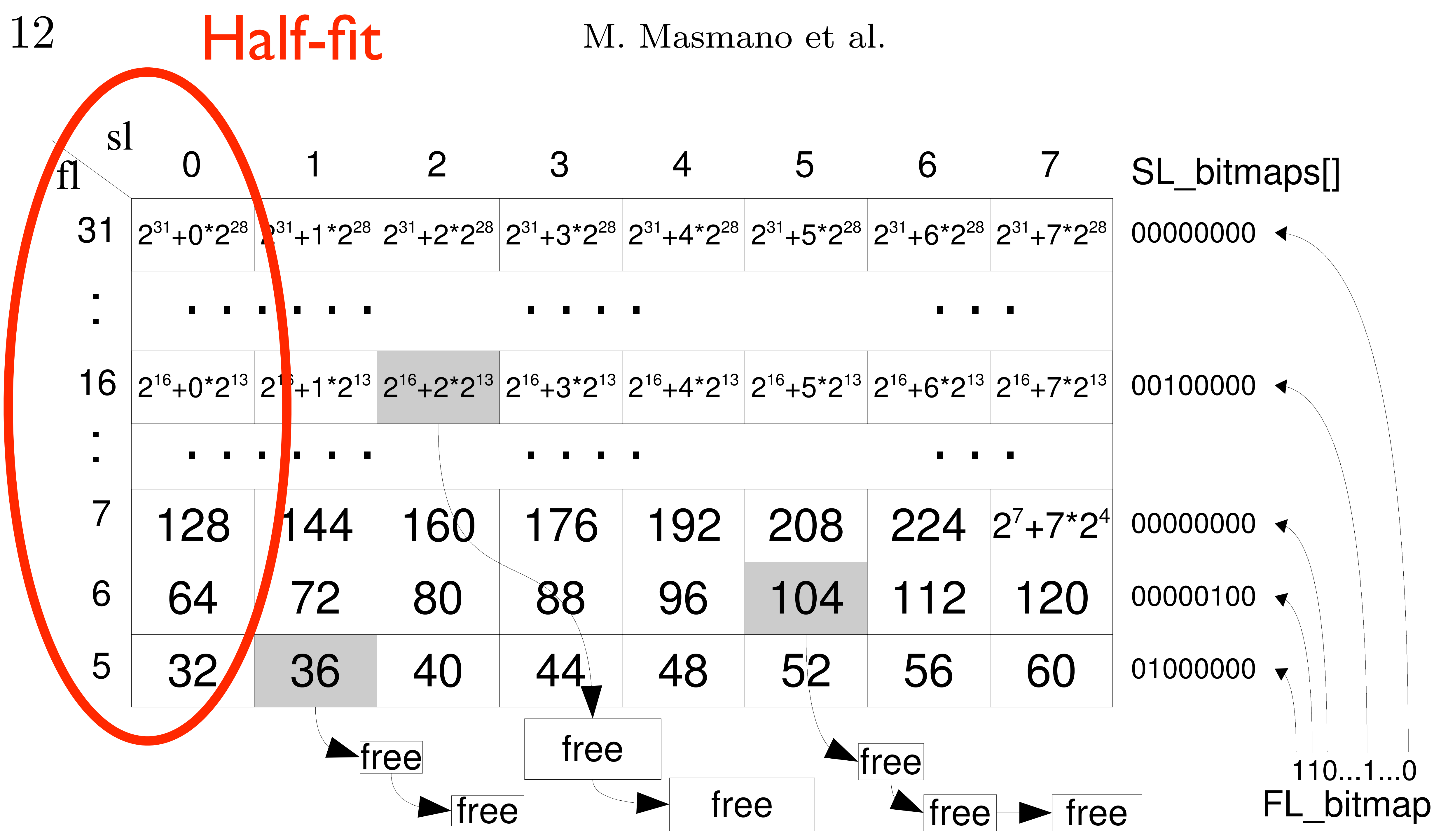


Partitioning



There is a trade-off between external and internal fragmentation

Half-fit


12 M. Masmano et al.

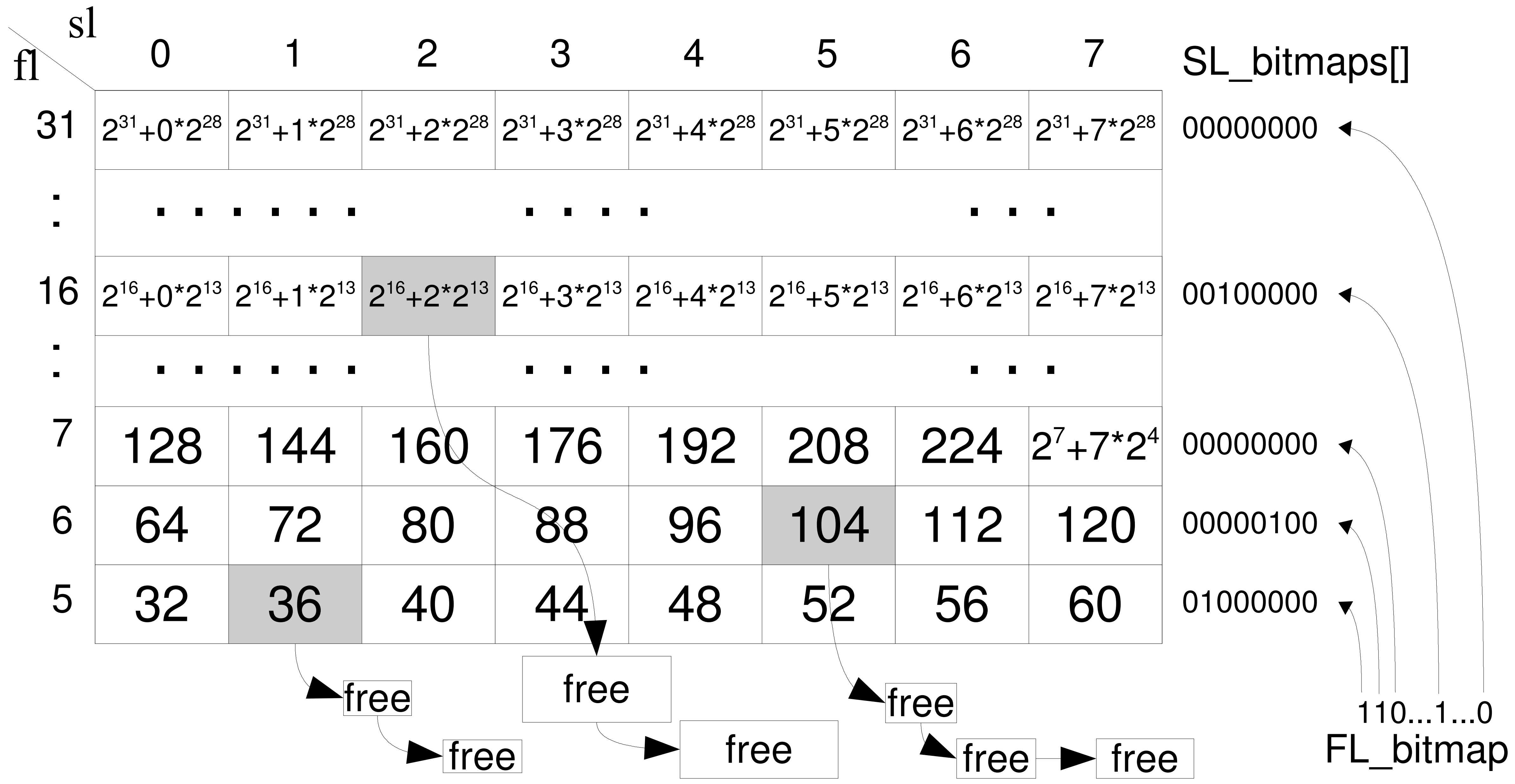
fl \ sl	0	1	2	3	4	5	6	7	SL_bitmaps[]
31	$2^{31}+0*2^{28}$	$2^{31}+1*2^{28}$	$2^{31}+2*2^{28}$	$2^{31}+3*2^{28}$	$2^{31}+4*2^{28}$	$2^{31}+5*2^{28}$	$2^{31}+6*2^{28}$	$2^{31}+7*2^{28}$	00000000
:	. . . .			. . . .			. . .		
16	$2^{16}+0*2^{13}$	$2^{16}+1*2^{13}$	$2^{16}+2*2^{13}$	$2^{16}+3*2^{13}$	$2^{16}+4*2^{13}$	$2^{16}+5*2^{13}$	$2^{16}+6*2^{13}$	$2^{16}+7*2^{13}$	00100000
:	. . . .			. . . .			. . .		
7	128	144	160	176	192	208	224	$2^{7}+7*2^{4}$	00000000
6	64	72	80	88	96	104	112	120	00000100
5	32	36	40	44	48	52	56	60	01000000

[Masmano et al., In J. of Real-Time Systems, 2008]

Half-fit Complexity

- Allocation:
  - `malloc` takes constant time
- Deallocation:
  - `free` takes constant time
- Access:
  - `read` and `write` take constant time
- Unpredictable fragmentation

Two-level Segregated Fit (TLSF)



fl \ sl	0	1	2	3	4	5	6	7	SL_bitmaps[]
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:	. . . .			. . . .			. . .		
16	$2^{16}+0*2^{13}$	$2^{16}+1*2^{13}$	$2^{16}+2*2^{13}$	$2^{16}+3*2^{13}$	$2^{16}+4*2^{13}$	$2^{16}+5*2^{13}$	$2^{16}+6*2^{13}$	$2^{16}+7*2^{13}$	00100000
:	. . . .			. . . .			. . .		
7	128	144	160	176	192	208	224	2^7+7*2^4	00000000
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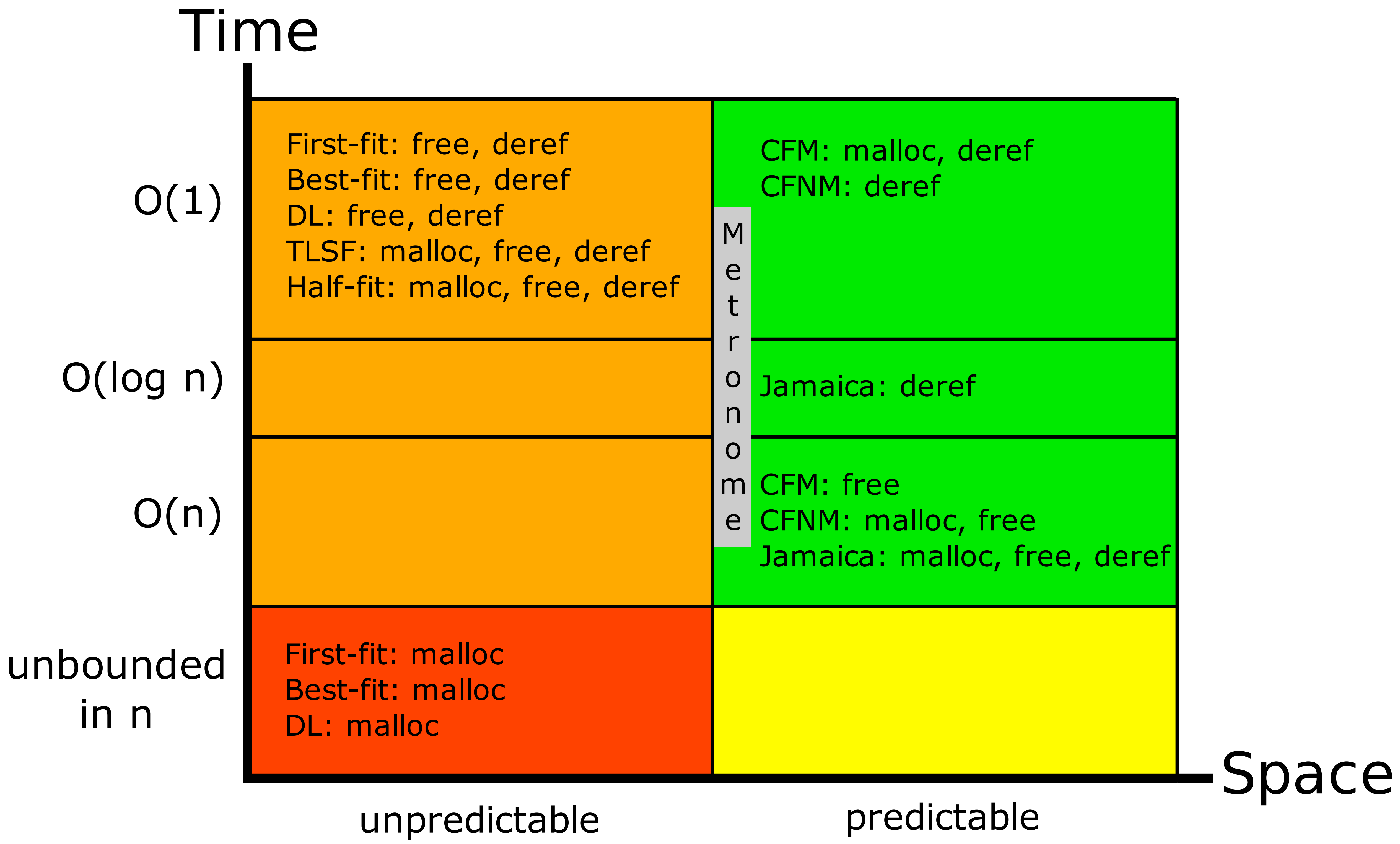
5	32	36	40	44	48	52	56	60	01000000

[Masmano et al., In J. of Real-Time Systems, 2008]

TLSF Complexity

- Allocation:
  - `malloc` takes constant time
- Deallocation:
  - `free` takes constant time
- Access:
  - `read` and `write` take constant time
- Unpredictable fragmentation (yet better than HF)



	unpredictable		predictable
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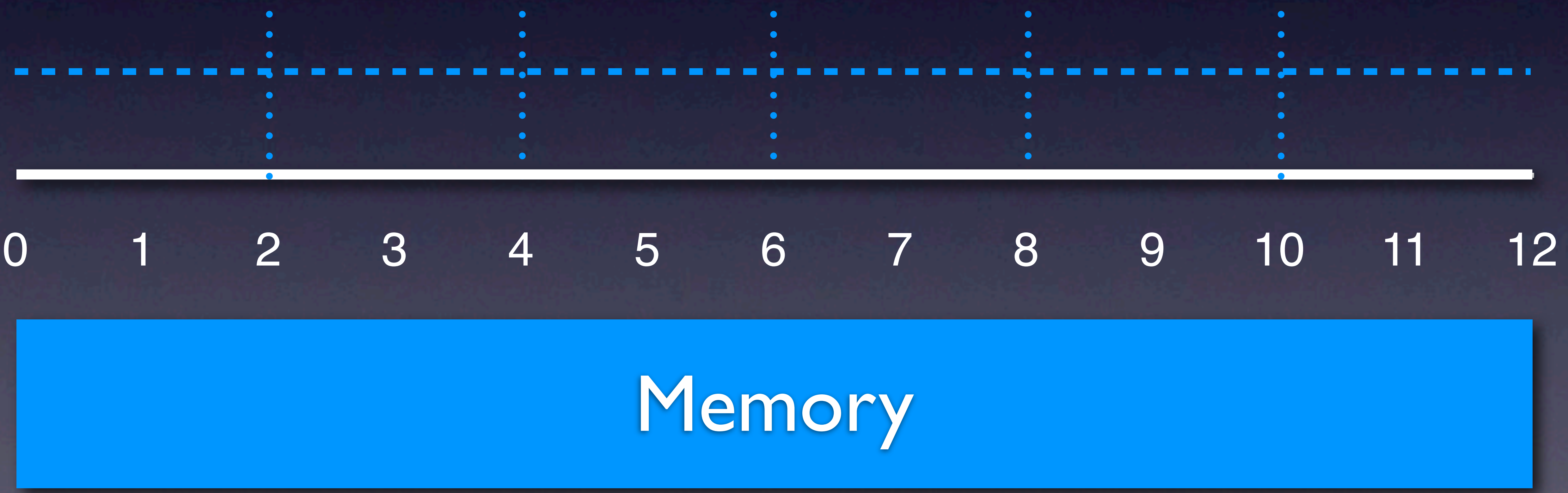
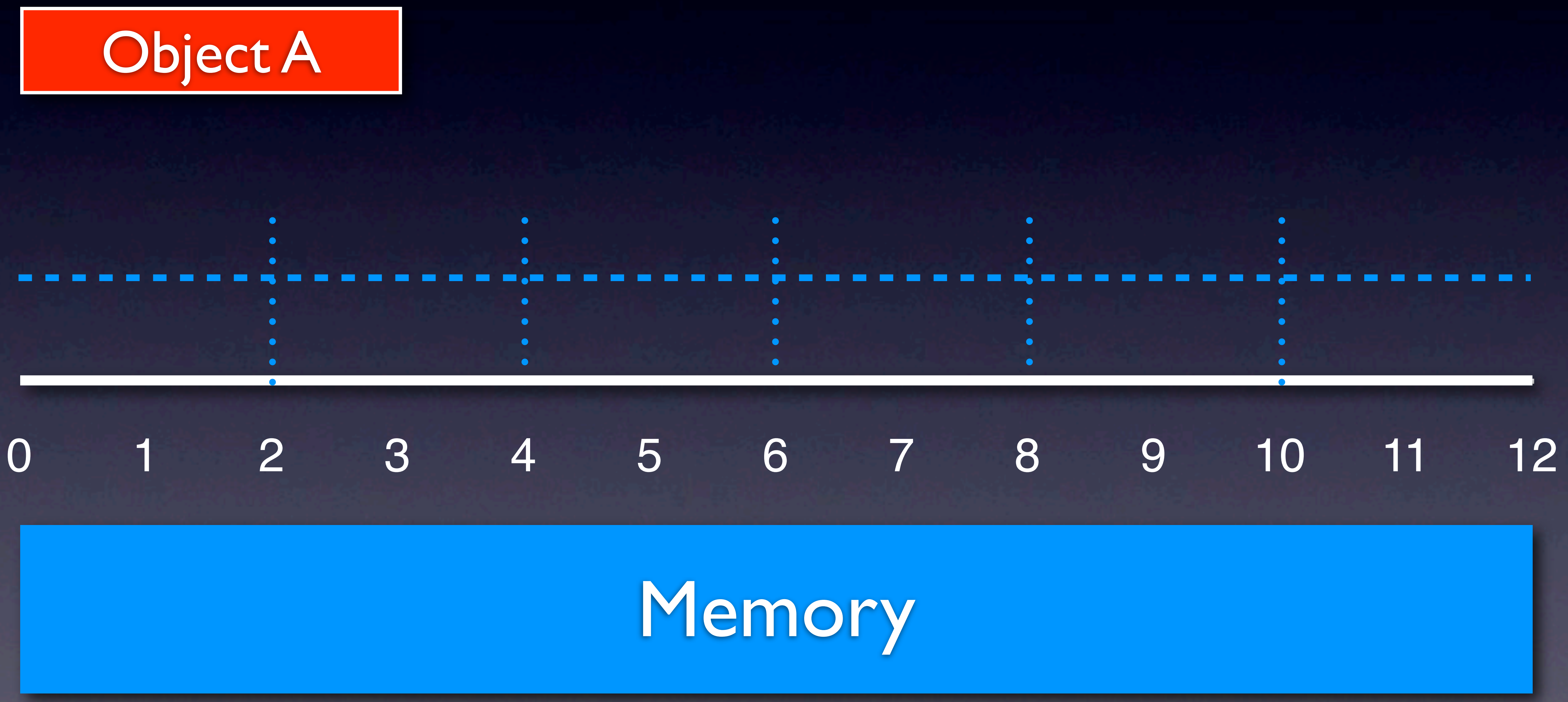
O(log n)		Metronome	Jamaica: deref
O(n)		Metronome	CFM: free CFNM: malloc, free Jamaica: malloc, free, deref
unbounded in n	First-fit: malloc Best-fit: malloc DL: malloc		

Jamaica



Jamaica



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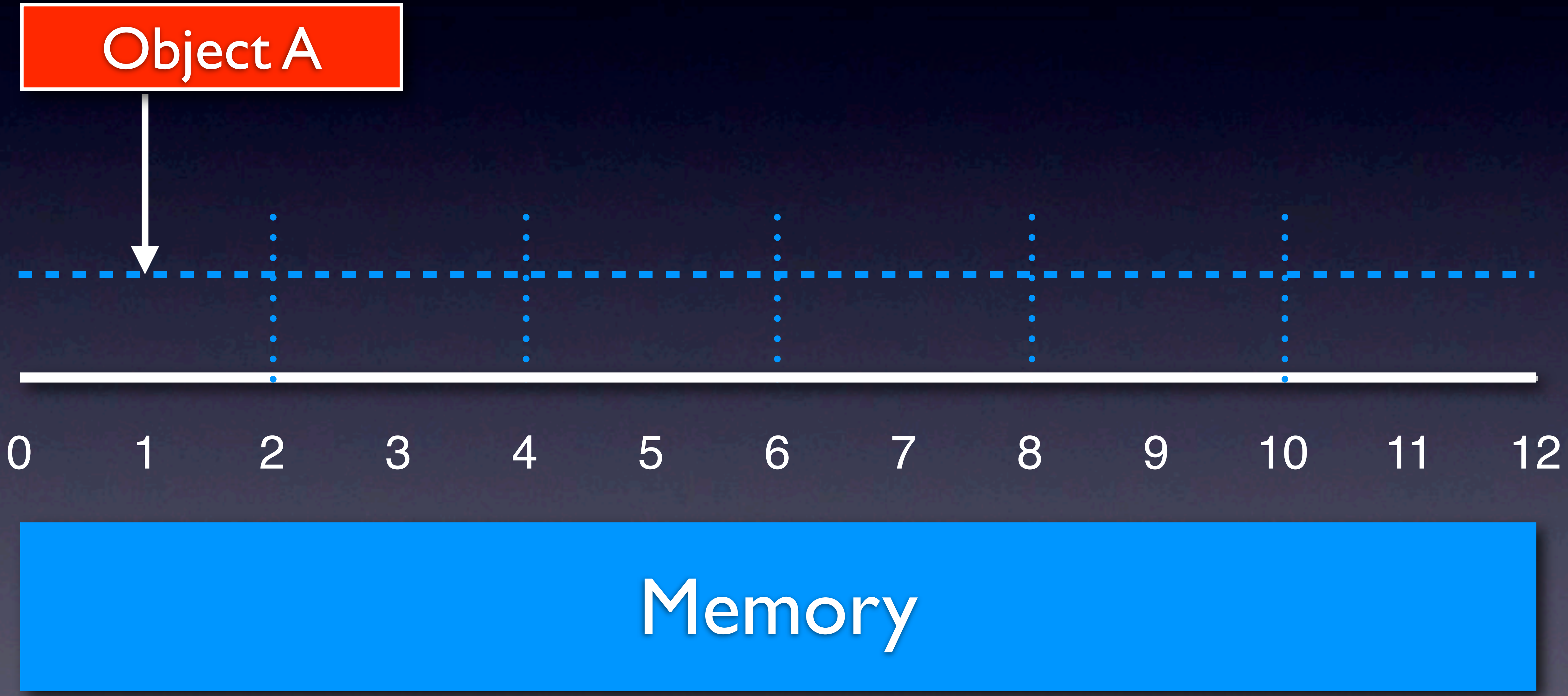
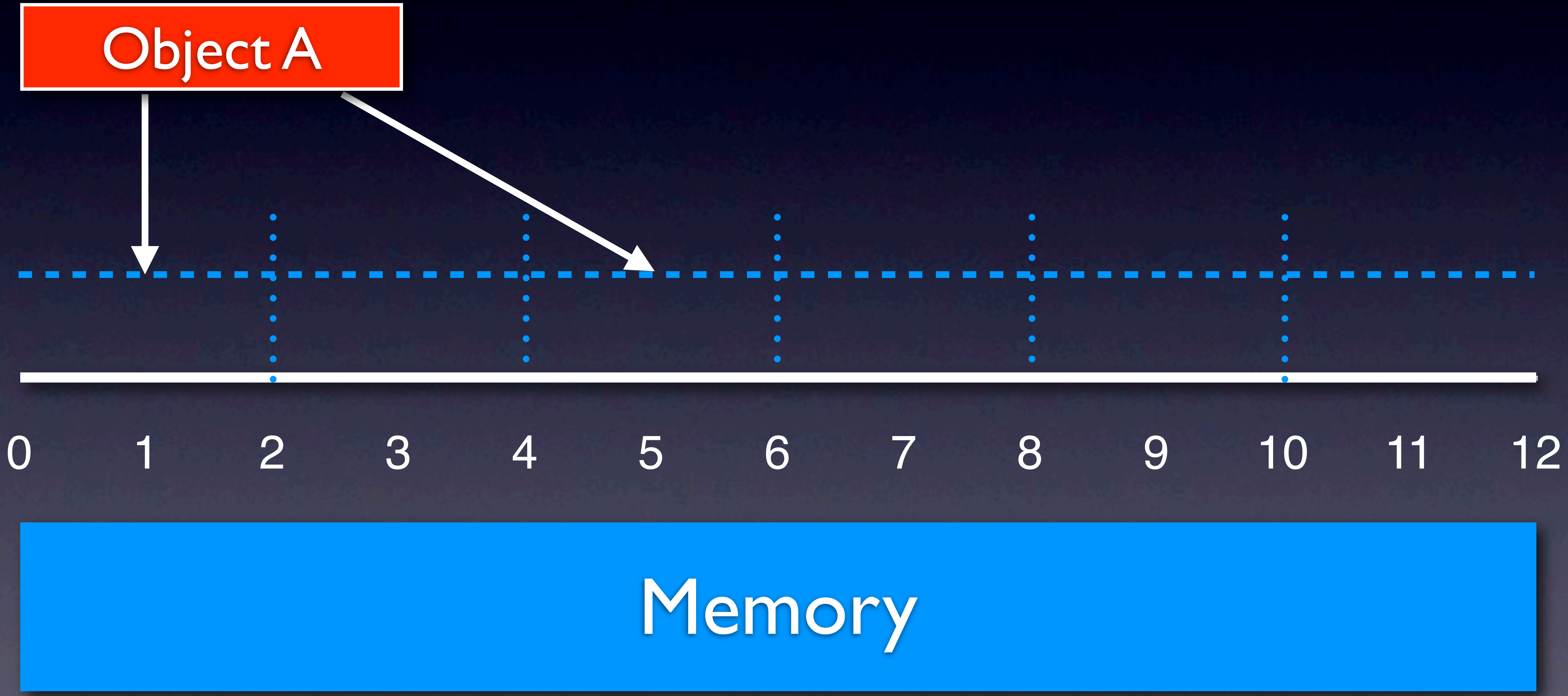
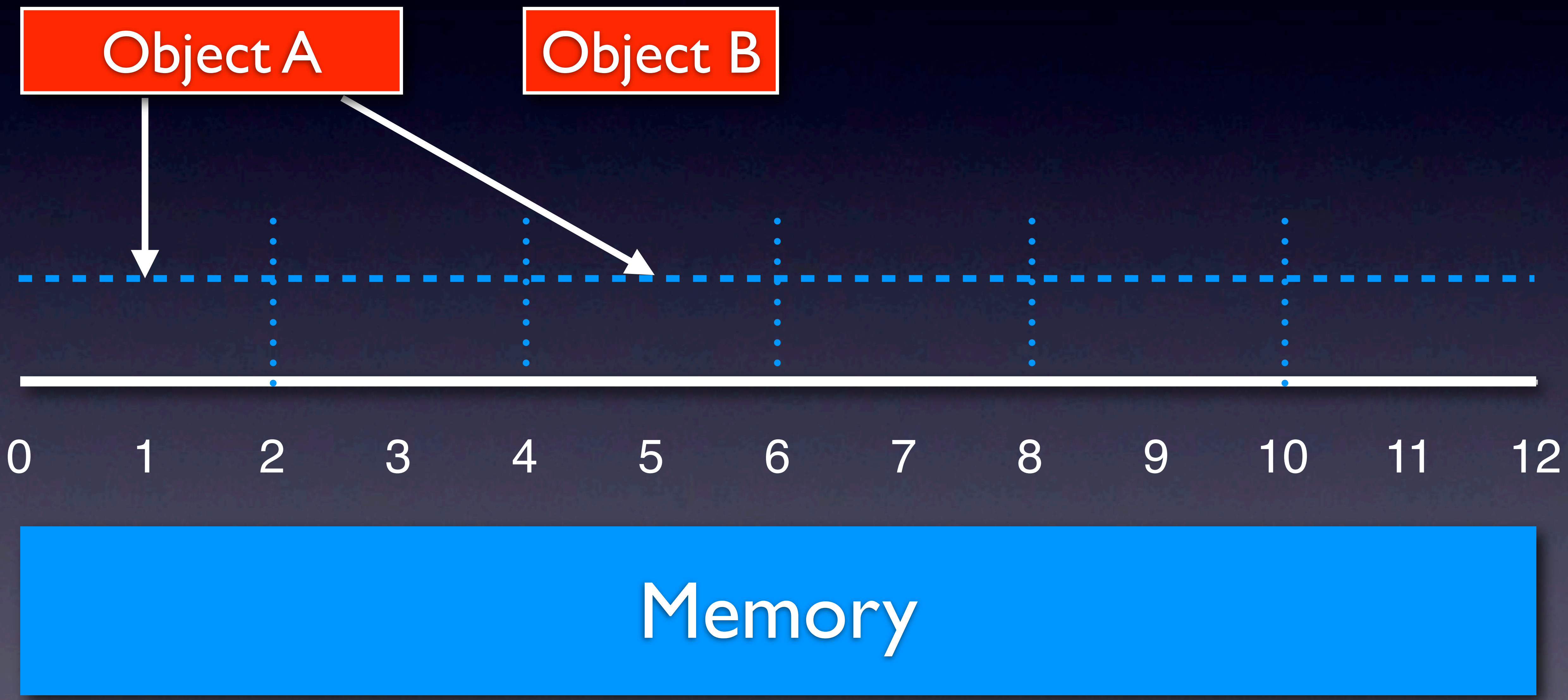


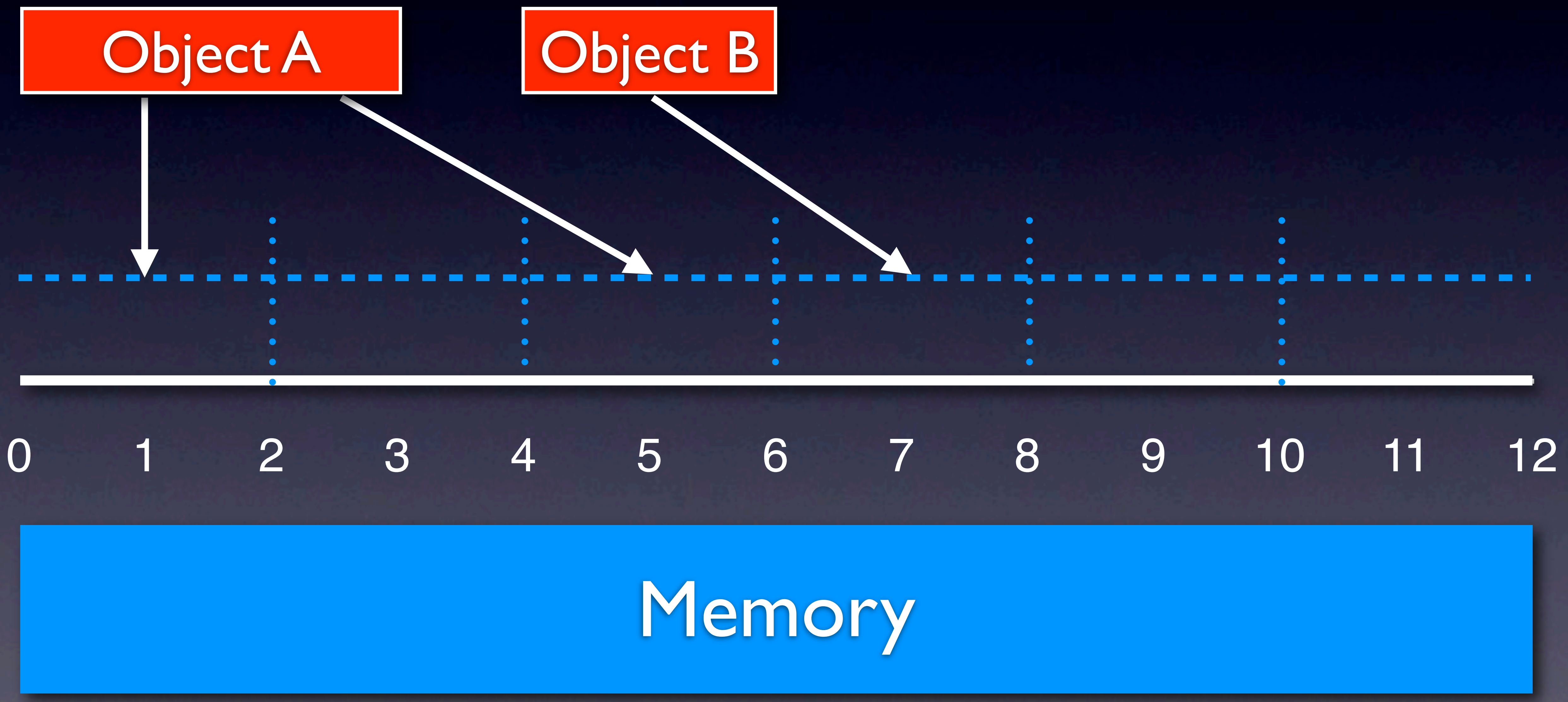
Jamaica



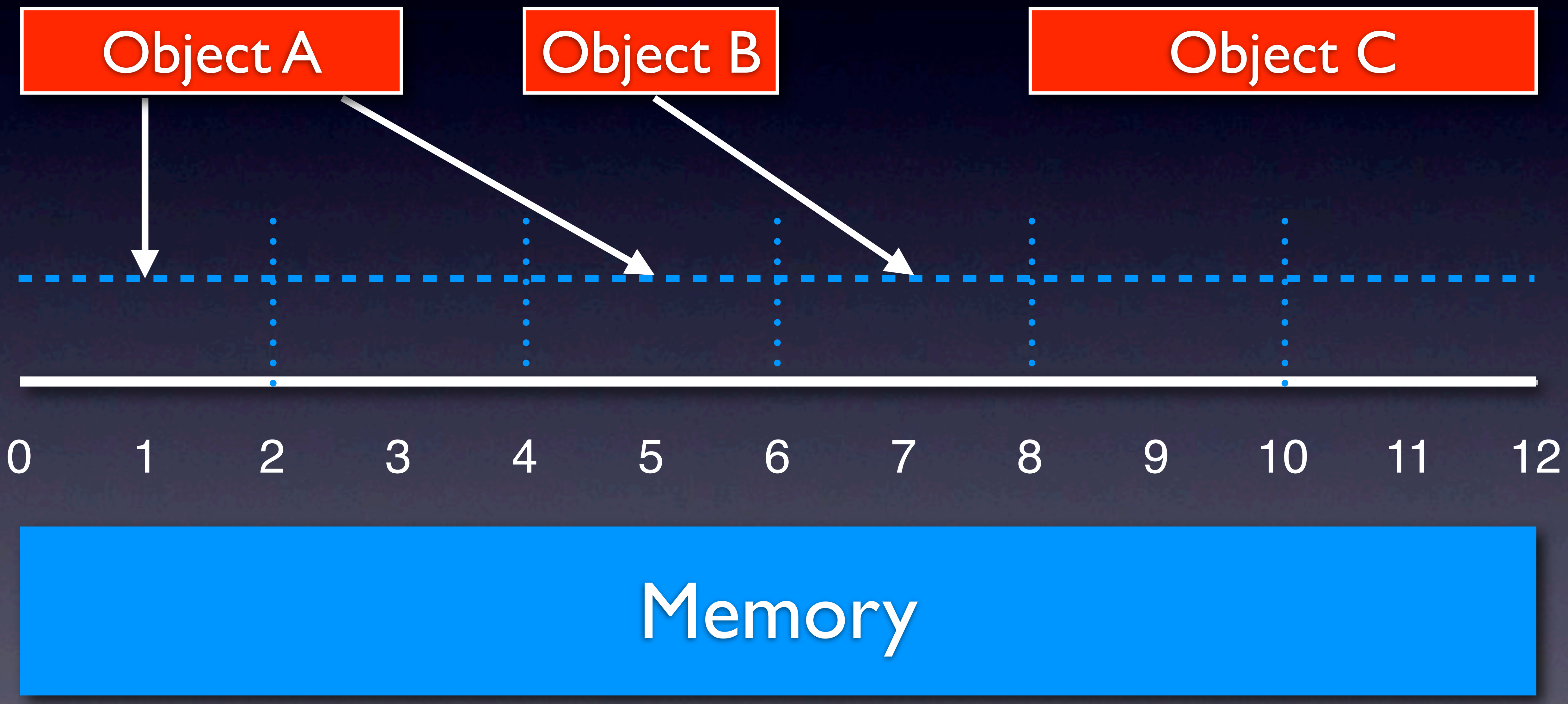
Jamaica



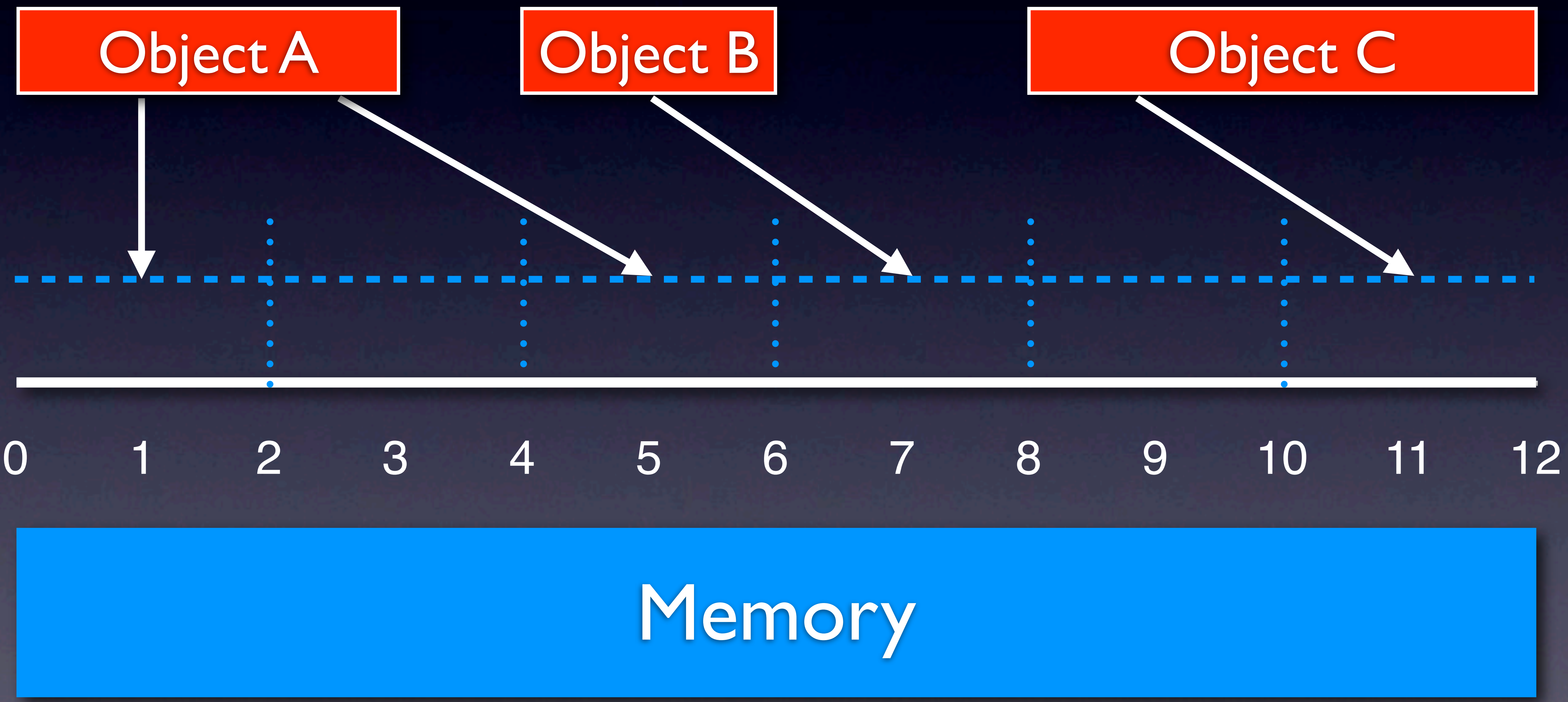
Jamaica



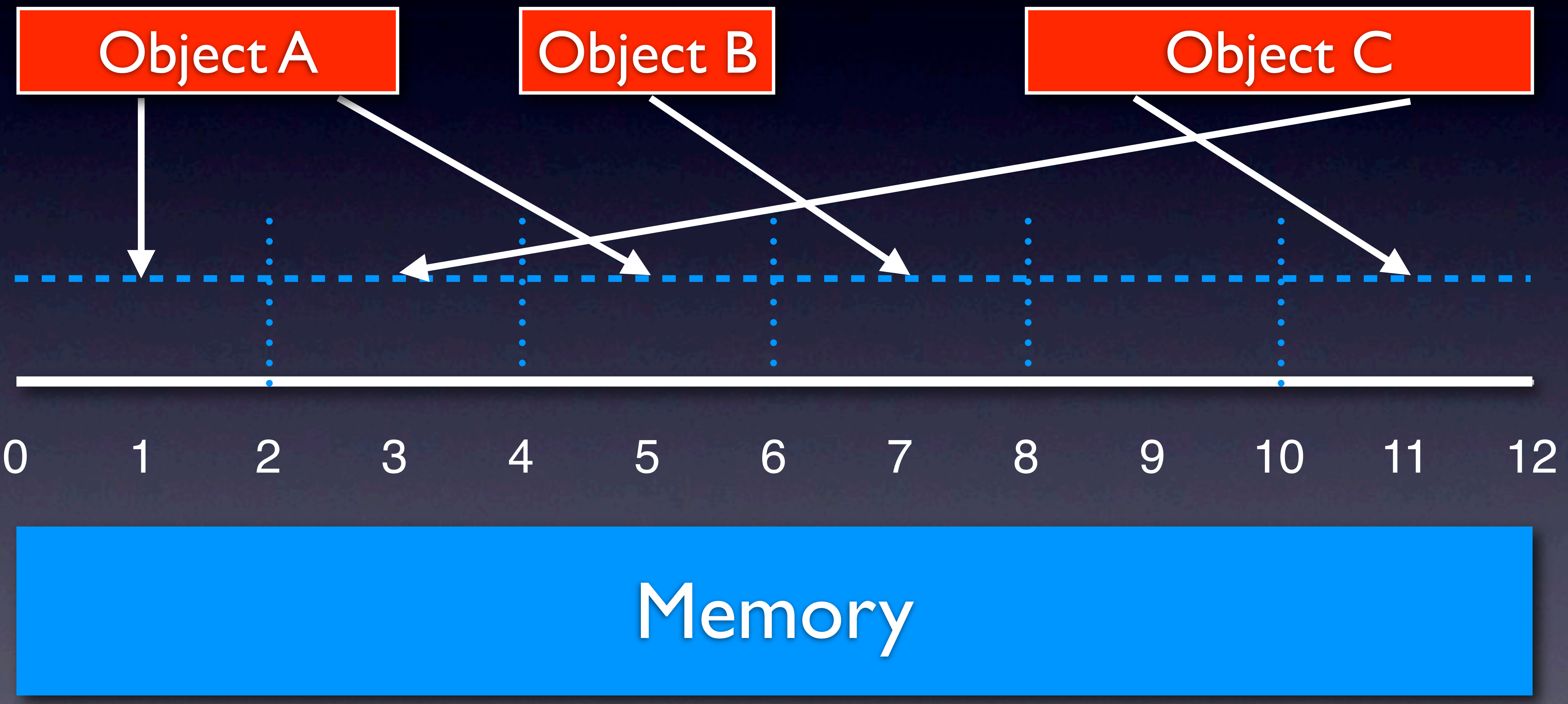
Jamaica



Jamaica

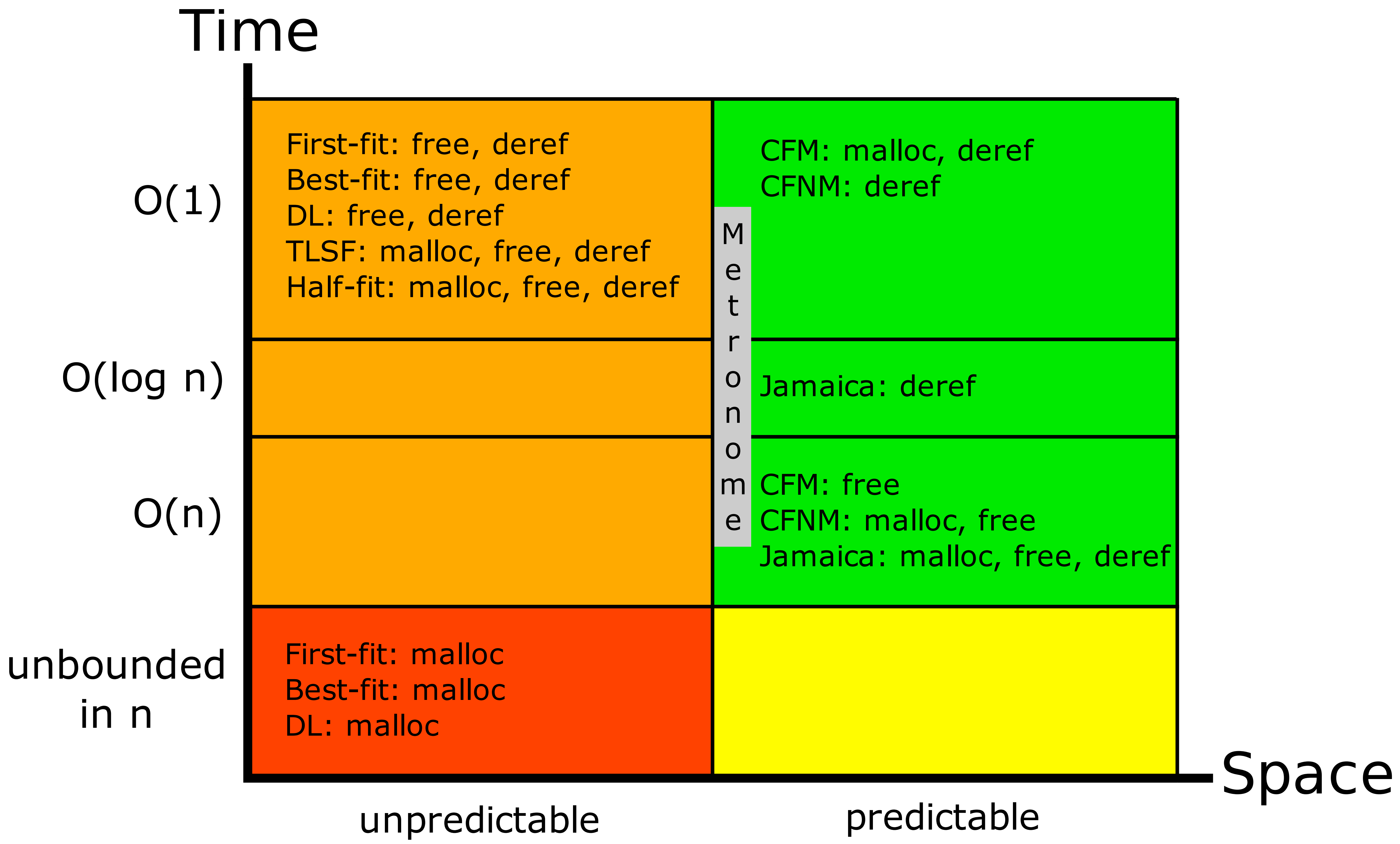


Jamaica



Jamaica Complexity

- Allocation:
  - `malloc(n)` takes time proportional to `n`
- Deallocation:
  - `free(n)` takes time proportional to `n`
- Access:
  - `read` and `write` take time <u>proportional</u> to `n`
- Predictable fragmentation



Time	unpredictable		predictable
O(1)	First-fit: free, deref Best-fit: free, deref DL: free, deref TLSF: malloc, free, deref Half-fit: malloc, free, deref	Metronome	CFM: malloc, deref CFNM: deref
O(log n)			Jamaica: deref
O(n)			CFM: free CFNM: malloc, free Jamaica: malloc, free, deref
unbounded in n	First-fit: malloc Best-fit: malloc DL: malloc		
			Space