SIMD-enhanced libc string functions

how it's done

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Common Tasks

- copying strings (*strcpy*, *memcpy*, ...)
- finding string length (*strlen*, *strnlen*, ...)
- finding characters (*strchr*, *memchr*, ...)
- comparing strings (*strcmp*, *memcmp*, ...)
- finding substrings (*strstr*, *memmem*, ...)
- splitting at delimiters (*strspn*, *strcspn*, ...)

Common Tasks

- copying strings (*read* then *write*)
- finding string length (*read* then *compare*)
- finding characters (*read* then *compare*)
- comparing strings (*read* then *compare*)
- ~~finding substrings~~ (complicated)
- splitting at delimiters (*read* then *set match*)

What does that mean?

read

- char by char until end of string
- one load/compare/conditional branch per character

write

- char by char until end of string
- one write per character

compare

- char by char until match or end of string
- one compare/conditional branch per character

What does that mean?

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- char by char until end of string
- one load/compare/conditional branch per character (**slow**)

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- char by char until end of string
- one write per character (**slow**)

compare

- char by char until match or end of string
- one compare/conditional branch per character (**slow**)

Conclusion

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Strings suck

What can we do about that?

- Get rid of strings (oof...)
- special-purpose instructions (arch dependent)
  - speed varies depending on CPU model
  - often only *memcpy*(), *memset*() supported
- strange hacks (hmm...)

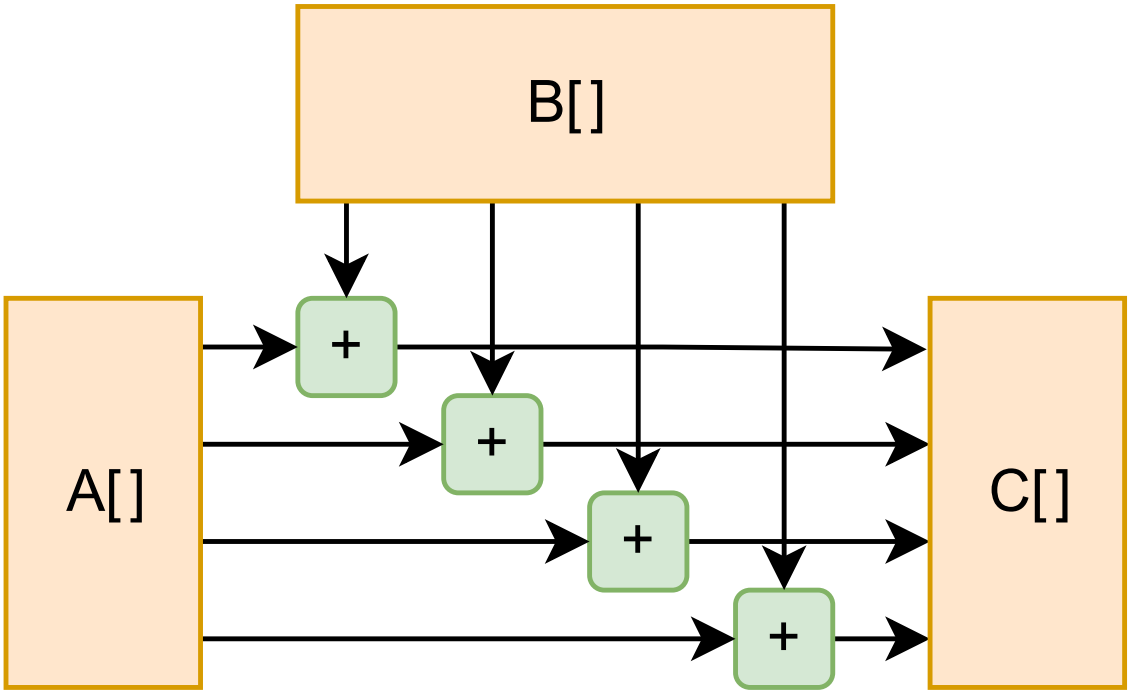
SIMD

Your new best friend

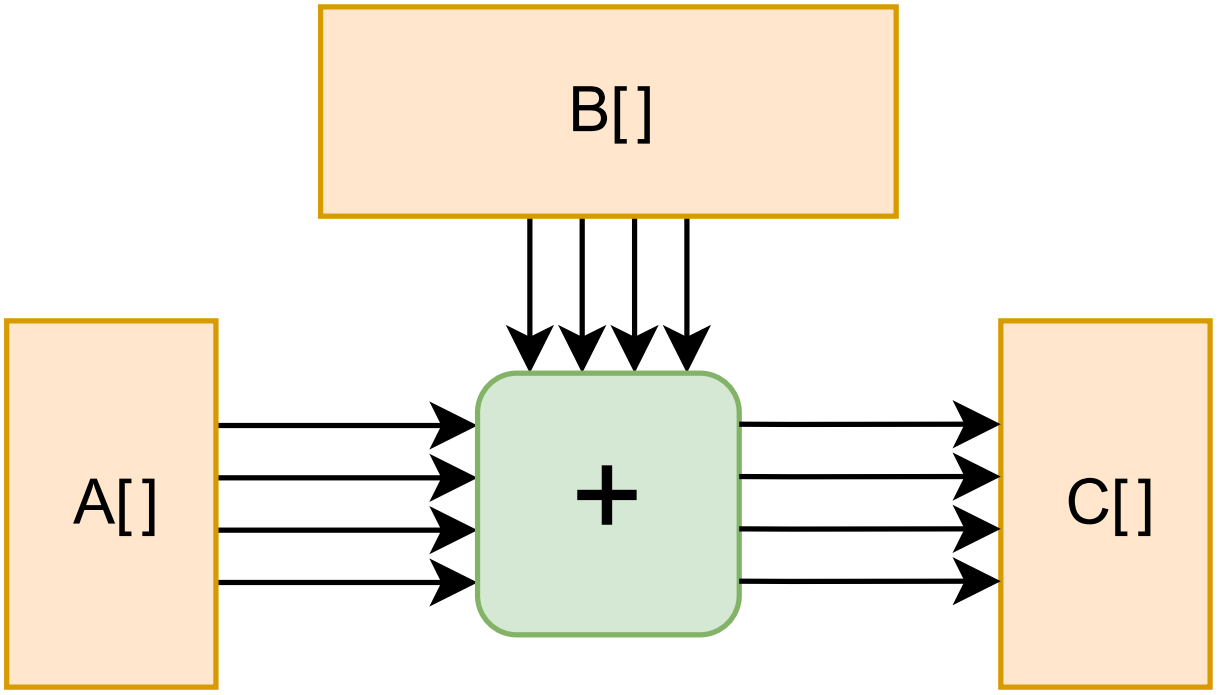
SIMD

- **S**ingle **I**nstruction **M**ultiple **D**ata
- *SIMD register*: short arrays of numbers
- common lengths: 16, 32, 64 bytes
- *same operation* on all elements
- but as fast as scalar operations
- SIMD with 16 bytes: 16x scalar performance

Scalar vs. SIMD



Scalar vs. SIMD



typical SIMD operations

Arithmetic (integer/FP)

- addition, subtraction, multiplication, ...

Logic

- element-wise comparison, and, or, xor, ...

Data transfer

- read, write, extract masks, ...

... many more

Strings and SIMD

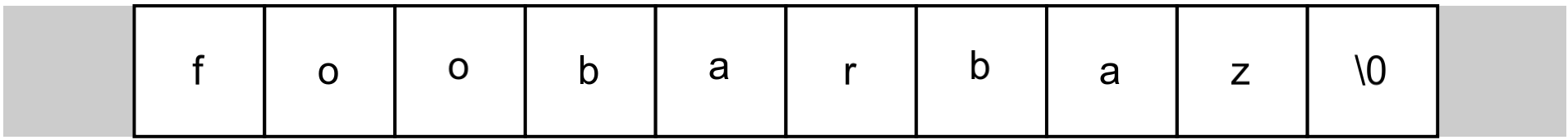
How can this help us with string processing?

Strings and SIMD

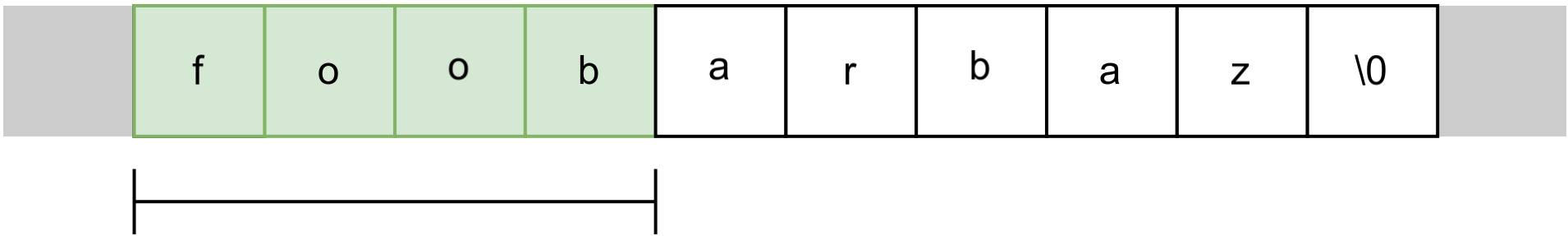
How can this help us with string processing?

- load multiple characters at once
- process them simultaneously
- ...
- profit?

Difficulties



Difficulties



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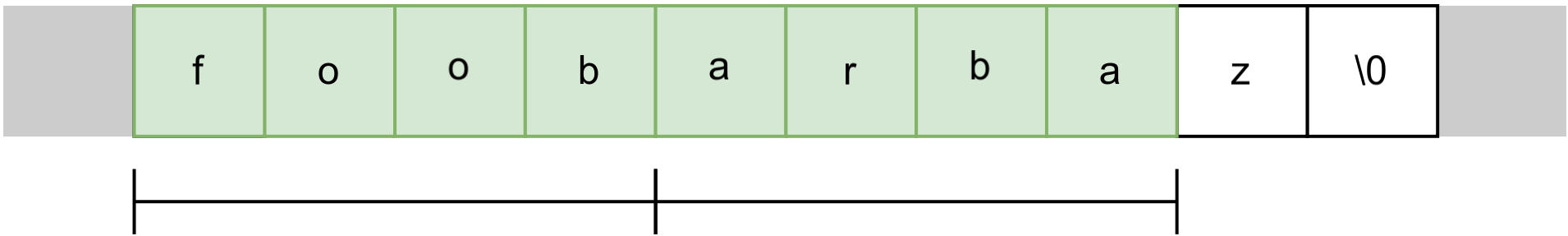

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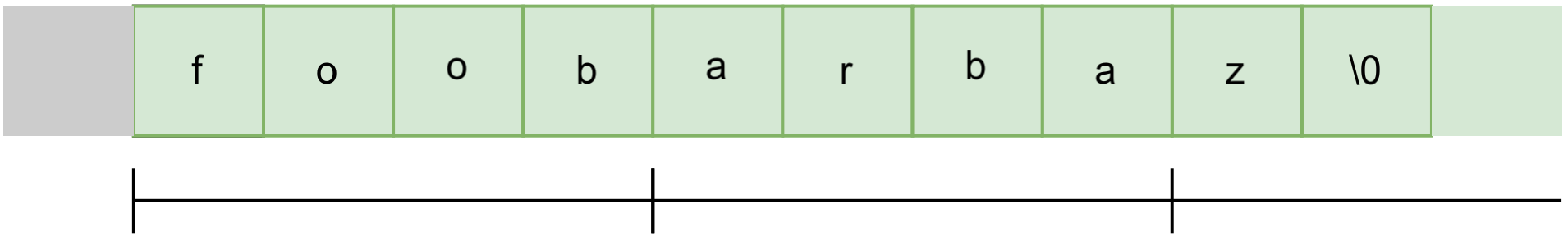

Difficulties

- We can easily overshoot the string's end
- For nul-terminated strings, we won't know where that is until we see the nul byte
- Do we have to iterate char-by-char after all?

What can we do?

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String bounds are fictious

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String bounds are fictious
Let's overcome them!

Overcoming array bounds

- the computer does not know what an array is
- it only knows that there's memory at some addresses but not at others

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thus:

- if we don't go too far out of bounds, it'll be fine!
- C doesn't let us, so let's use assembly

How far is too far?

- Memory is organised in *pages*
- size: arch dependent, usually 4096 bytes
- pages are either accessible entirely or not at all
- there is no more fine-grained memory protection
  - (check out CHERI, it's cool)

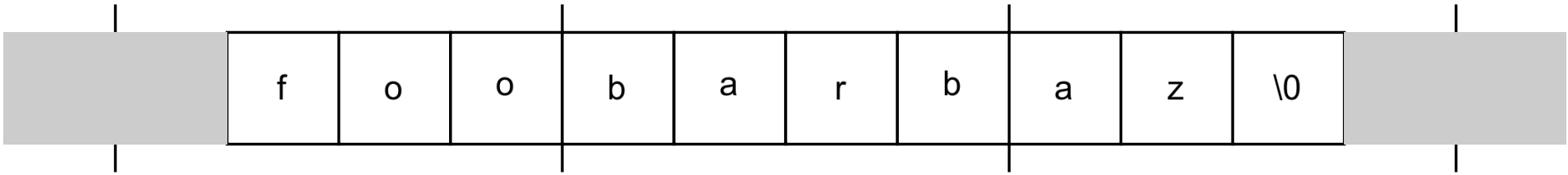
How far is too far?

- if at least one byte of a string is on a page, the whole page is accessible
- aligned accesses never cross page boundaries

thus:

- if we're careful, it might just work!

What does that look like?



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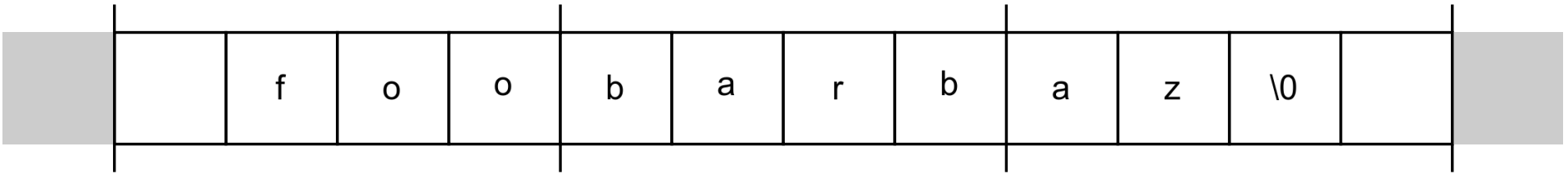

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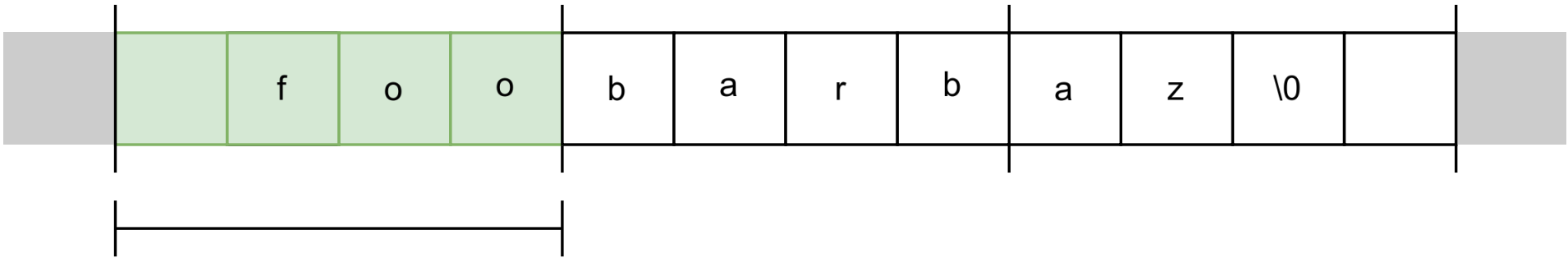

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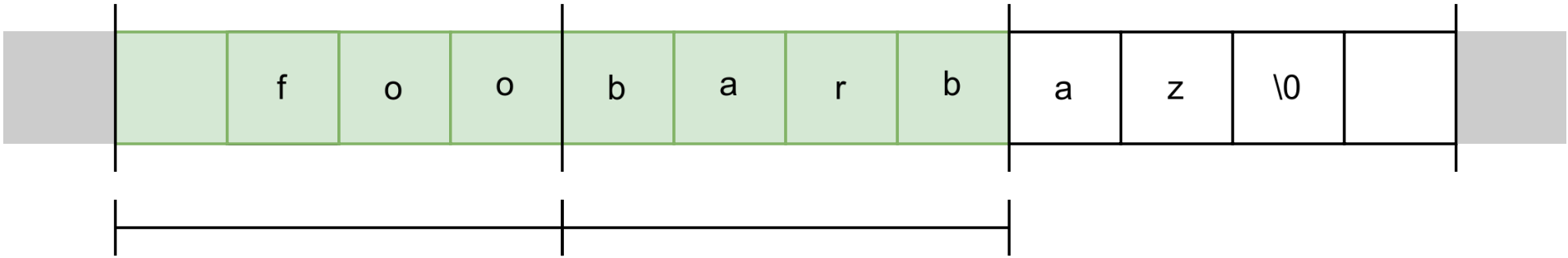

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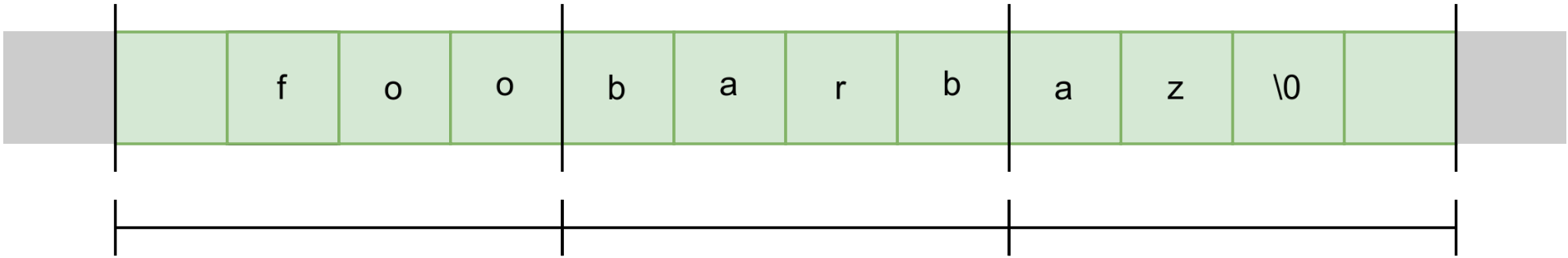

Writing Strings

Can't use the same approach:

- overreads are fine, overwrites are no good

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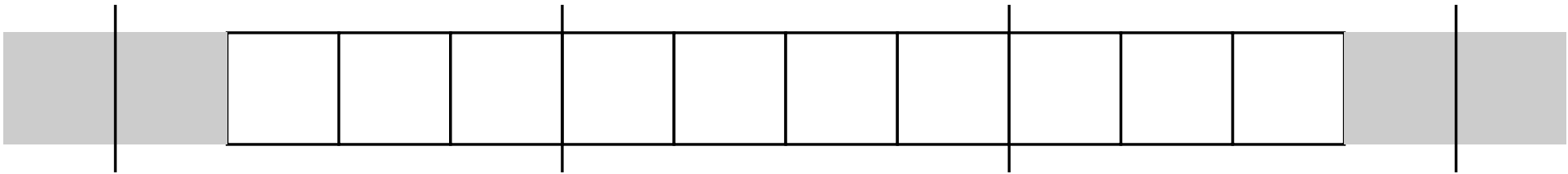
Instead

- write (possibly unaligned) chunks
- last write may overlap previous writes

Writing Strings



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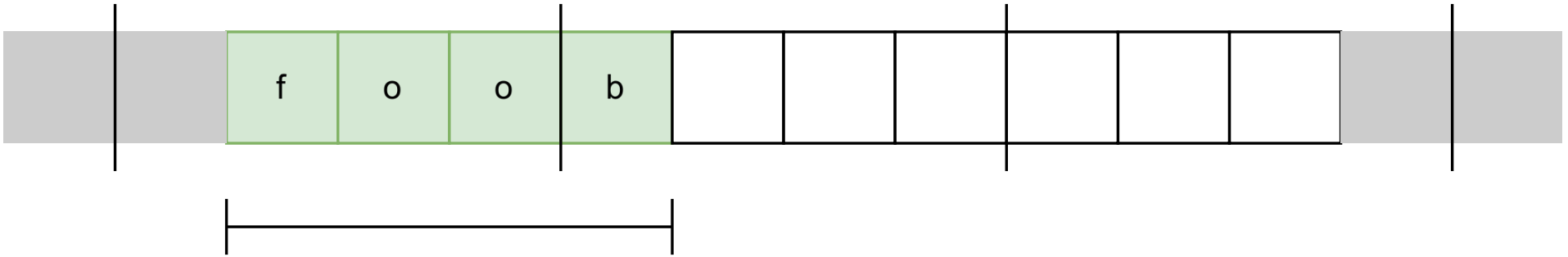

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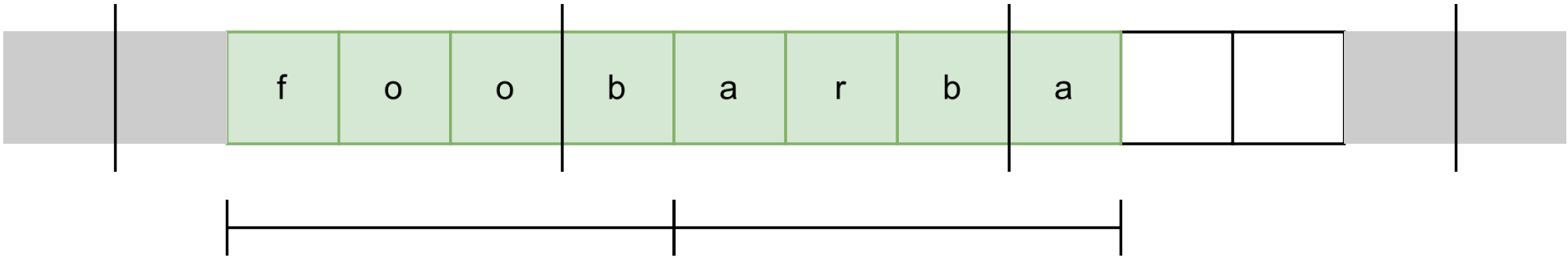

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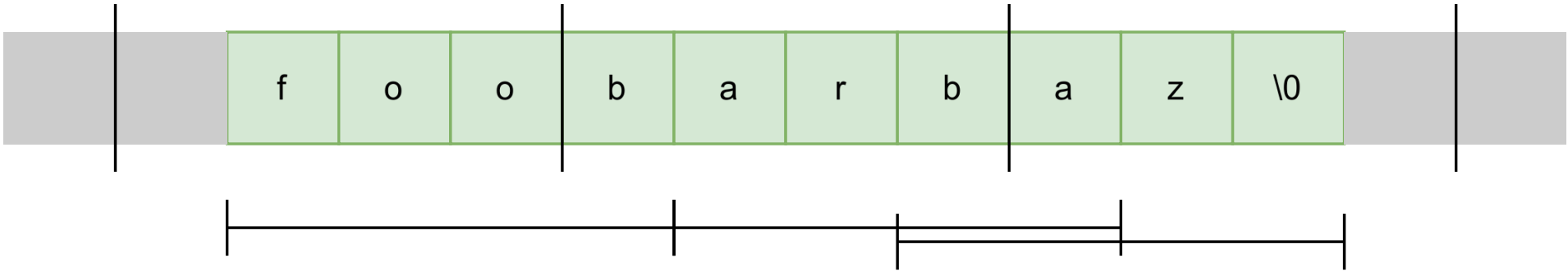

Comparing Strings

Can't use the same approach

- strings may have different misalignment
- can't fix this after loading with SSE2

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Instead

- do aligned reads to check for nul bytes
- then unaligned reads to compare characters

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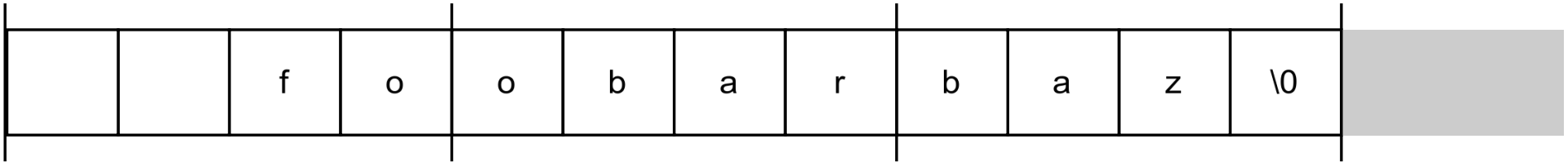

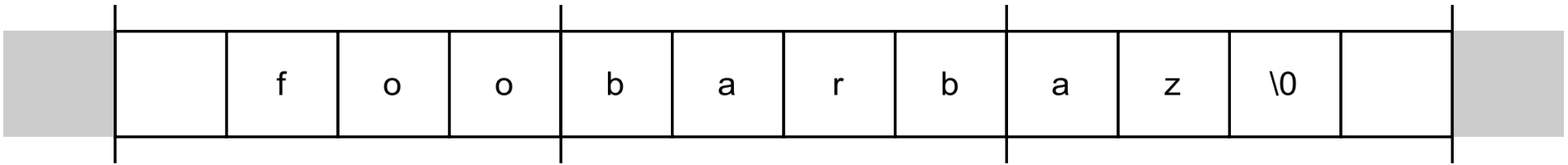

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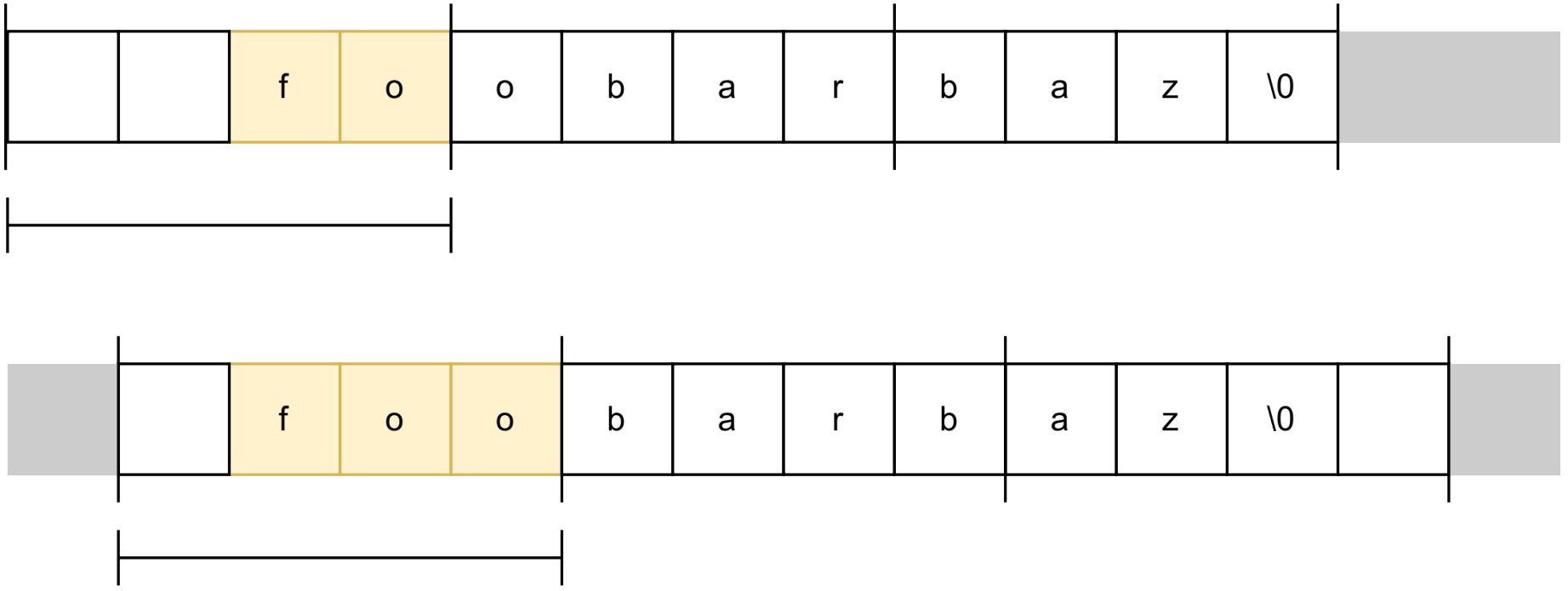

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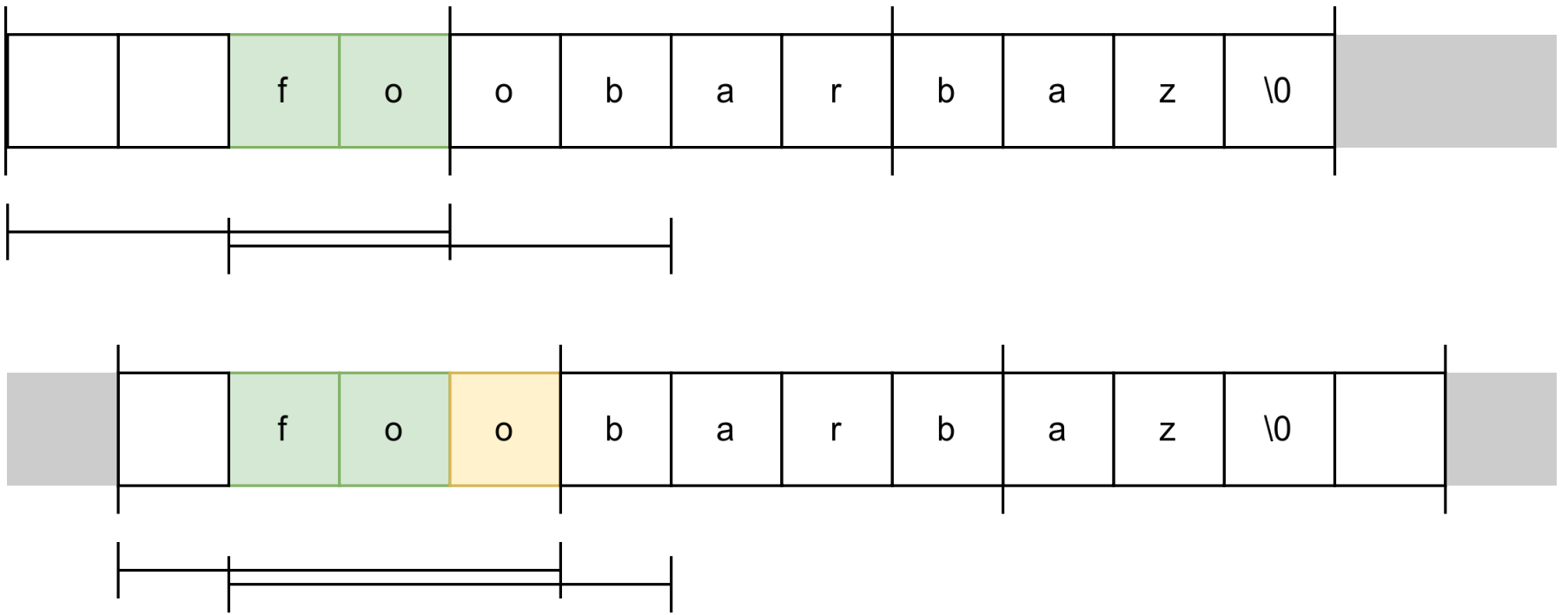

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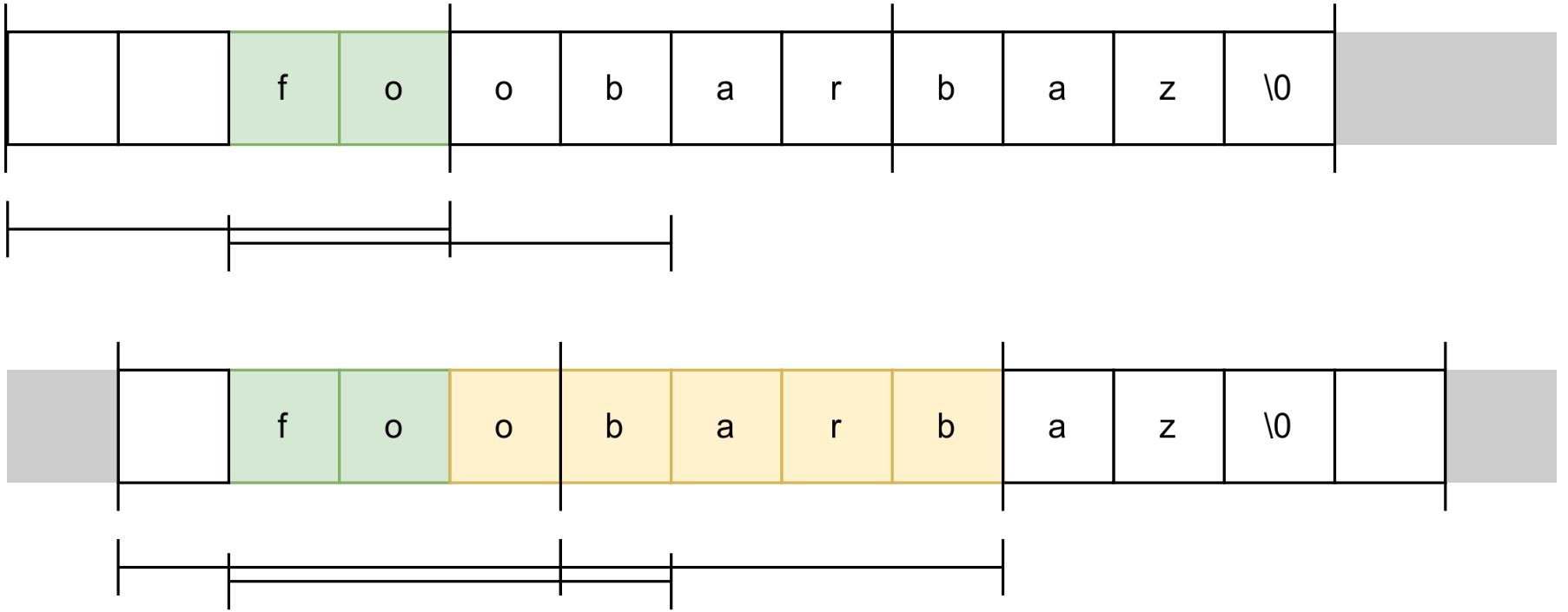

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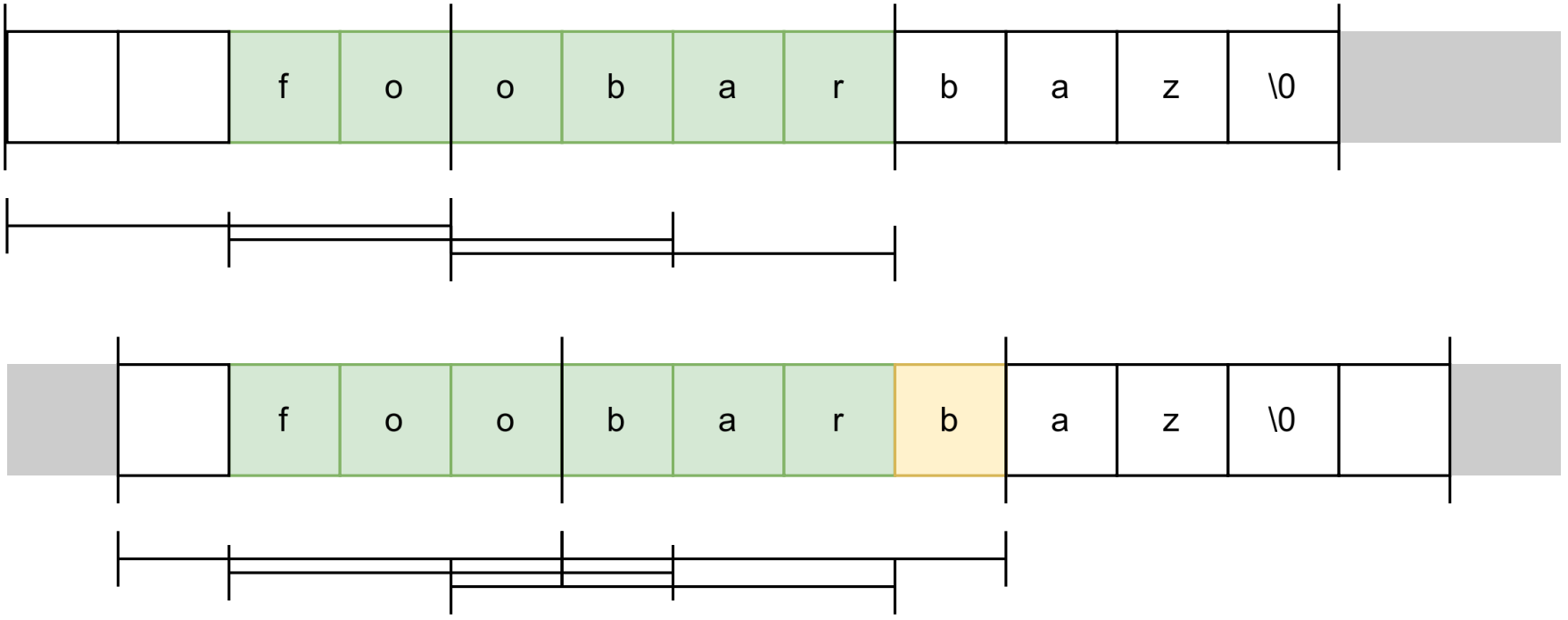

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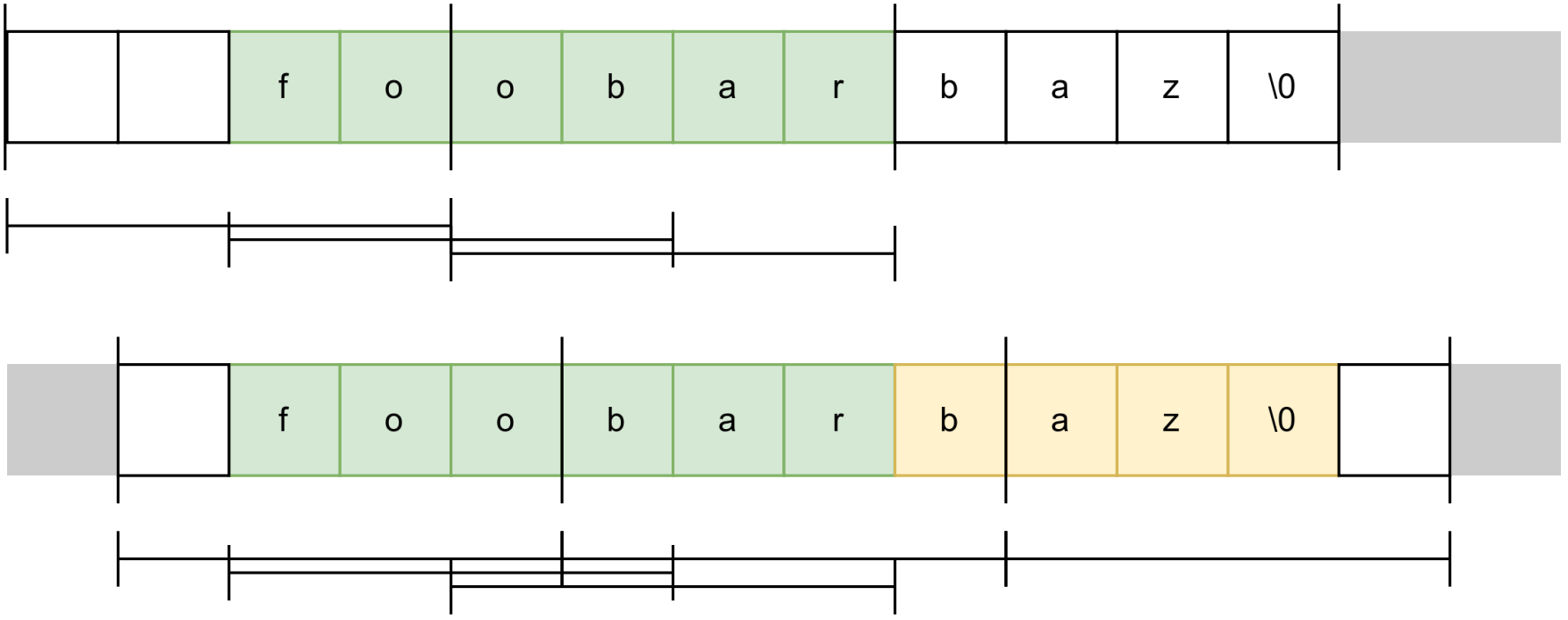

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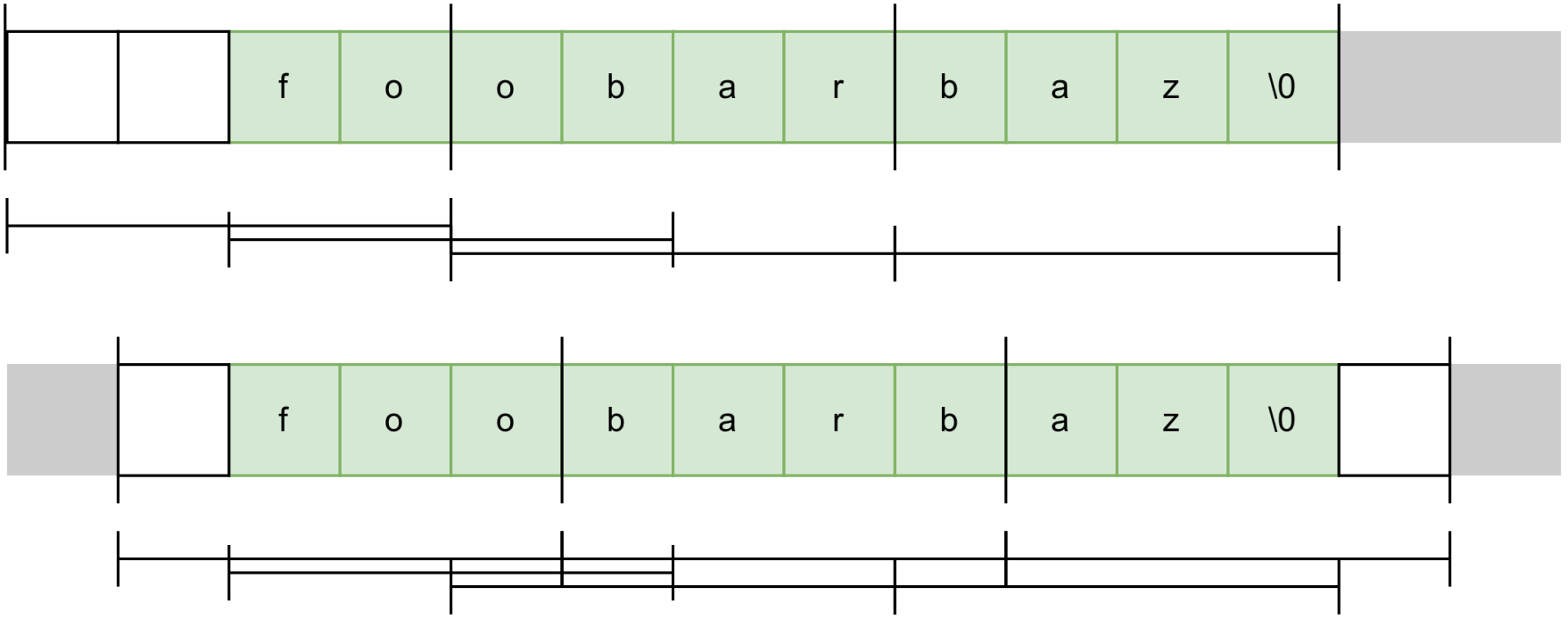

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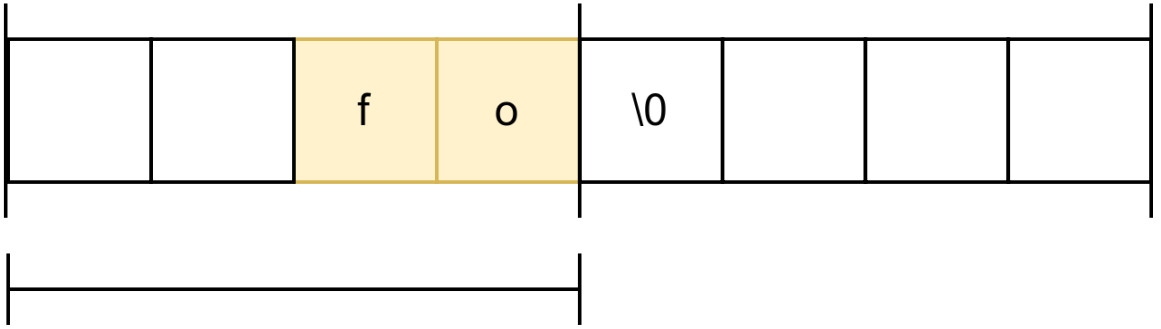

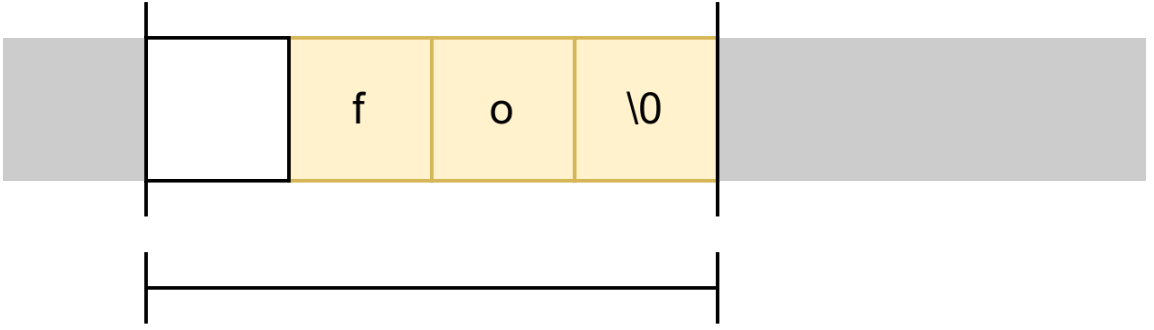

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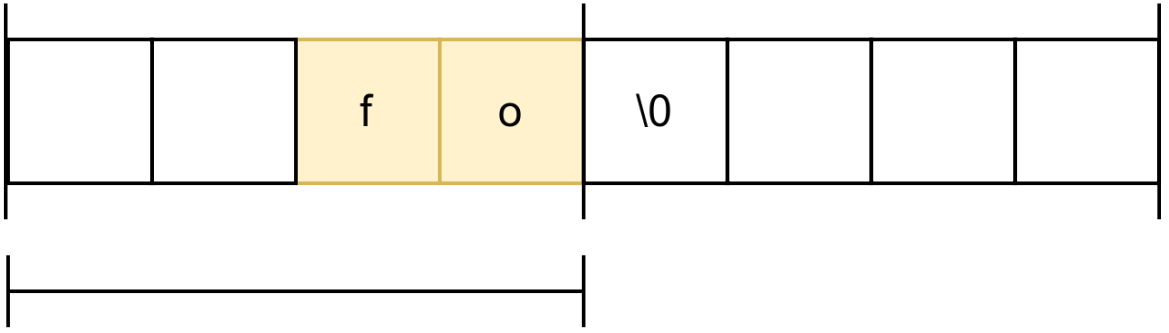
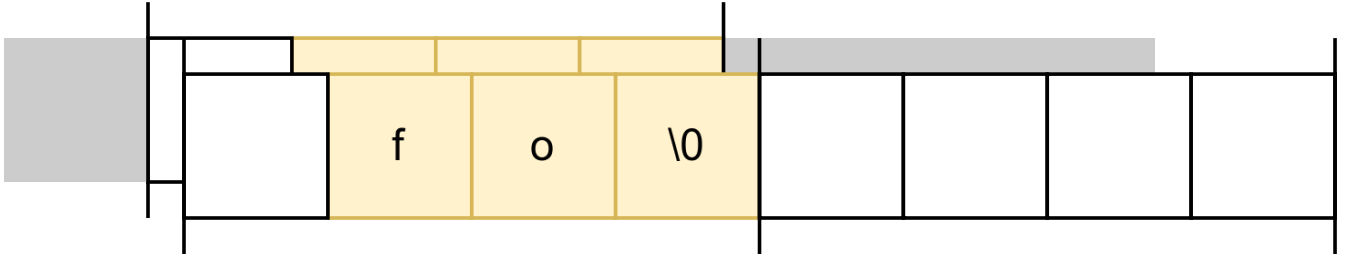


copy to bounce buffer on stack



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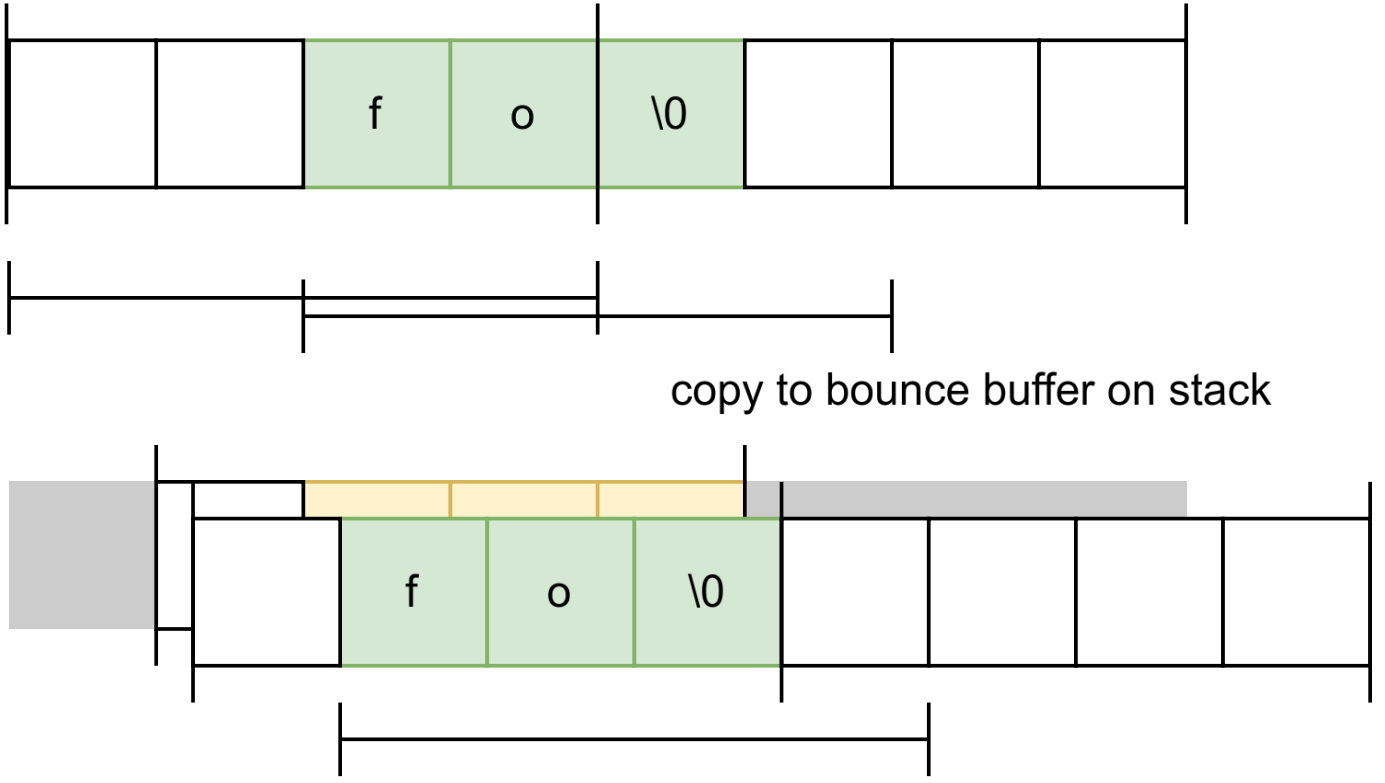


Set Matching

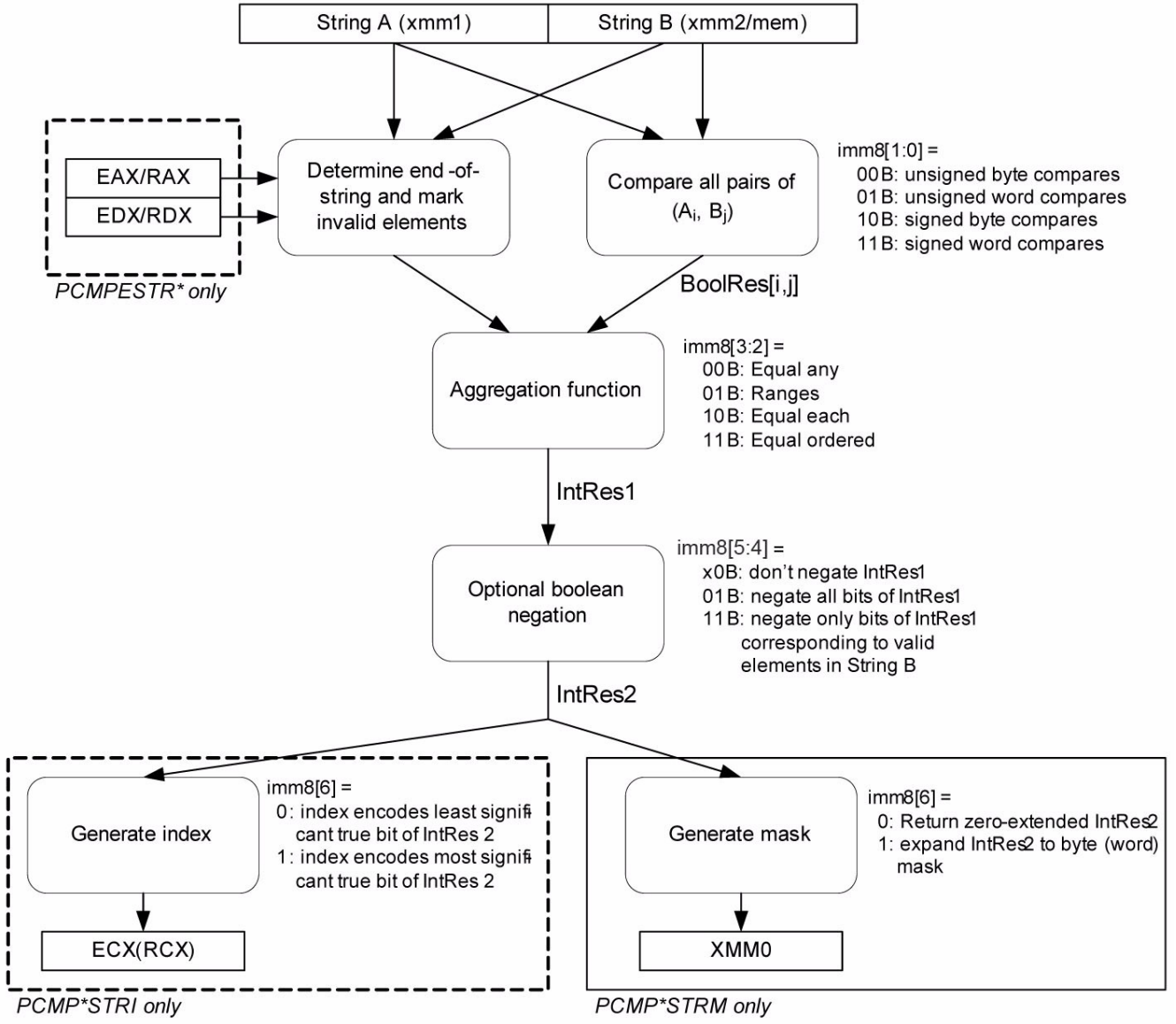
strcspn("foo bar", " \t\n");

- matches each char in string against set
- portable approach: Muła / Langdale algorithm
  http://0x80.pl/articles/simd-byte-lookup.html
- can we do better?

Set Matching

The Intel way: **pcmpistrm**

- **p**acked **c**o**mp**are **i**mplicity-terminated **str**ing, return **m**ask
- set matching and lots of other features
- conveniently also checks for nul terminators
- probably also brews coffee if you ask nicely

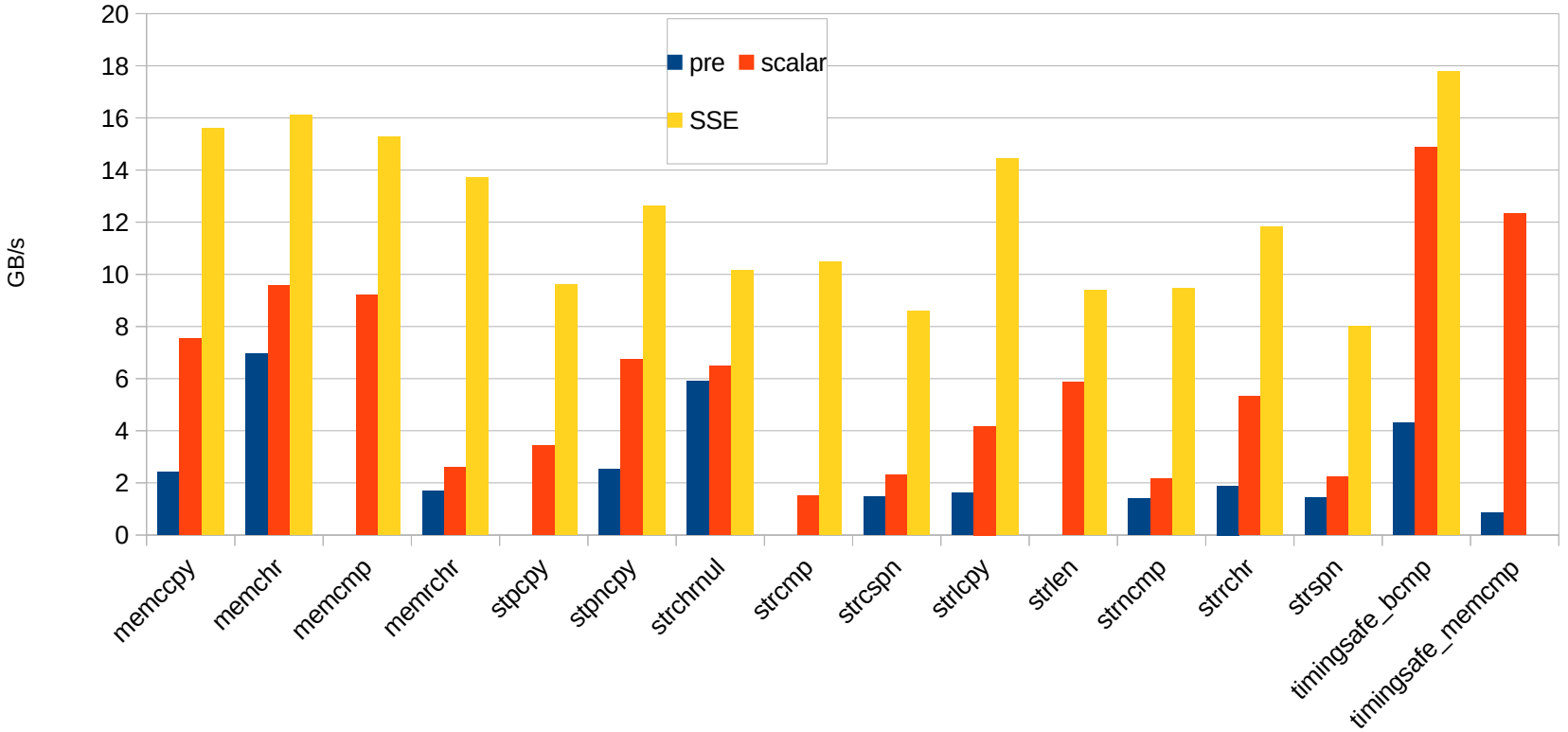

String A (xmm1)
String B (xmm2/mem)
EAX/RAX
EDX/RDX
PCMPESTR* only
Determine end -of-string and mark invalid elements
Compare all pairs of (A_i, B_j)
imm8[1:0] =
00B: unsigned byte compares
01B: unsigned word compares
10B: signed byte compares
11B: signed word compares
BoolRes[i,j]
Aggregation function
imm8[3:2] =
00B: Equal any
01B: Ranges
10B: Equal each
11B: Equal ordered
IntRes1
Optional boolean negation
imm8[5:4] =
x0B: don't negate IntRes1
01B: negate all bits of IntRes1
11B: negate only bits of IntRes1 corresponding to valid elements in String B
IntRes2
Generate index
imm8[6] =
0: index encodes least significant true bit of IntRes 2
1: index encodes most significant true bit of IntRes 2
ECX(RCX)
PCMP*STRI only
Generate mask
imm8[6] =
0: Return zero-extended IntRes2
1: expand IntRes2 to byte (word) mask
XMM0
PCMP*STRM only

Substring Matching

That means *strstr()*, *memmem()*

- really tricky
- most fancy algorithms are optimised for long strings, but our strings are usually short
- wip

Results (amd64)



AArch64 port

- work by Getz Mikalsen
- complements the ARM Optimized Routines
- some functions redone due to poor perf
- others not present in ARM's codebase
- assembly functions: *strcmp*(), *strspn*(), *strcspn*(), *strlcpy*(), *strncmp*(), *memccpy*(), *strlen*(), *timingsafe_bcmp*(), *timingsafe_memcp*()
- new wrappers: *strpbrk*(), *strsep*(), *strcat*(), *strncat*(), *strlcat*(), *bcopy*(), *bzero*()

AArch64 difficulties

- no easy way to get syndrome bitmask from syndrome vector
  - amd64: *pmovmskb*
  - aarch64: *shrn* + *fmov* to get nibble mask
  - other tricks when only zero / nonzero is needed
- no *pcmpistrm*, Muła/Langdale algorithm instead
- can't count trailing zeroes, only leading zeroes

Current Progress

- 2023 rework of the libc string functions for amd64
  - paid by The FreeBSD Foundation
  - almost all of <string.h>
  - for amd64 baseline (SSE2), some for x86-64-v2
  - landed for 14.1-RELEASE
- later ports as part of GSoC 2024
  - AArch64 by getz@ (landed for upcoming 15-RELEASE)
  - riscv64 by strajabot@ (under acceptance testing)
- Future work: *strstr*(), CHERI / Morello support, PPC64?