SIMD-enhanced libc string functions

how it's done

Robert Clausecker <fuz@FreeBSD.org>
Getz Mikalsen <getz@FreeBSD.org>

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**)

write

- 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...)

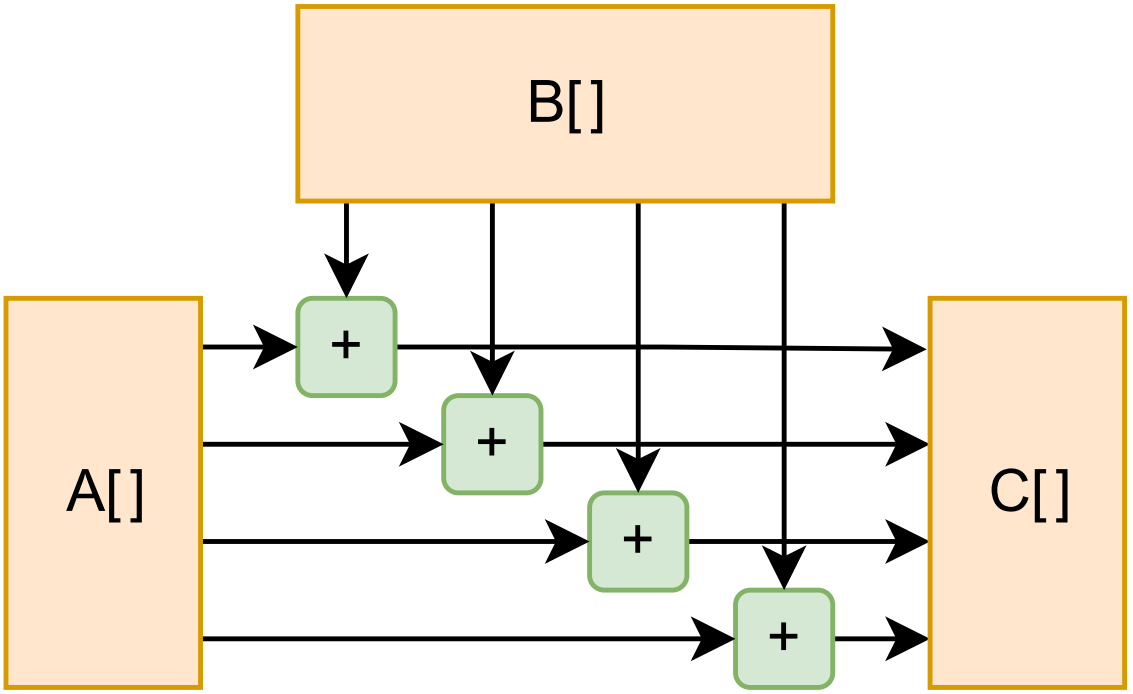
SIMD

Your new best friend

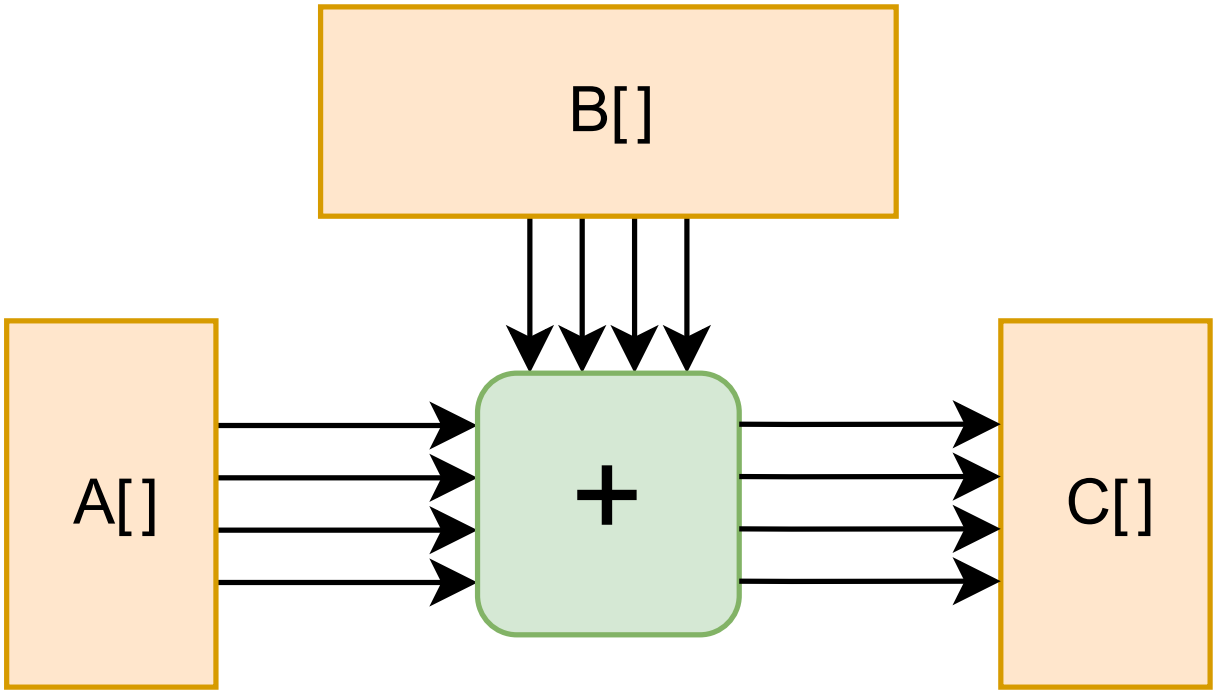
SIMD

- **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

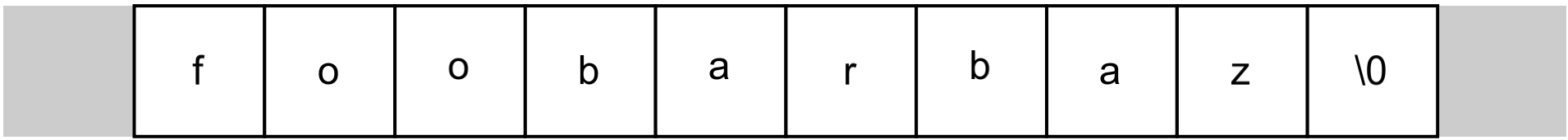
How can this help us with string processing?

Strings and SIMD

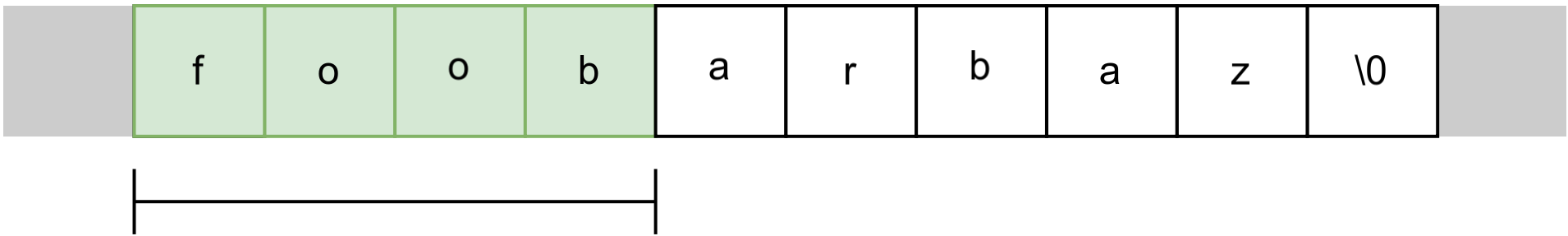
How can this help us with string processing?

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

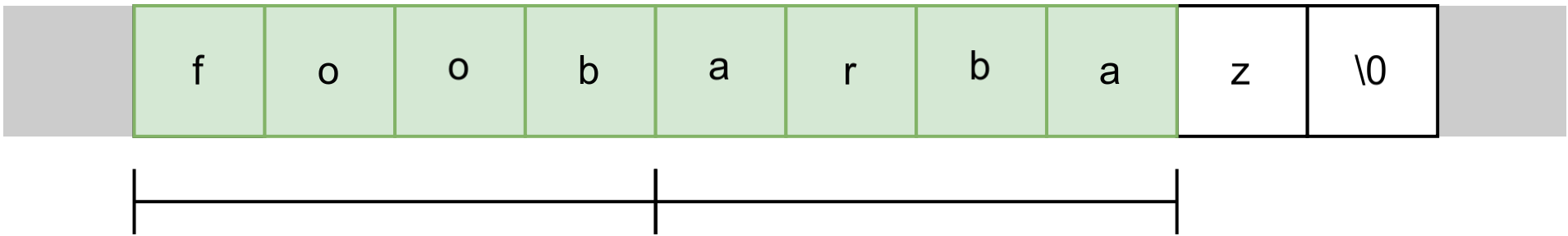
Difficulties



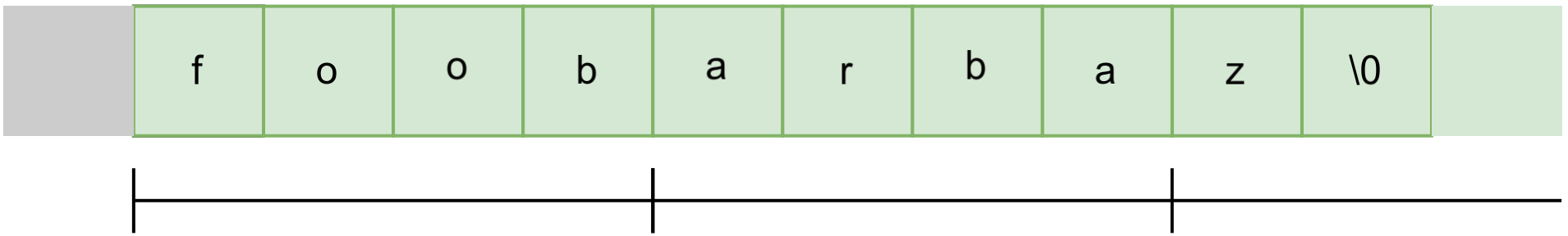
Difficulties



Difficulties



Difficulties



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)

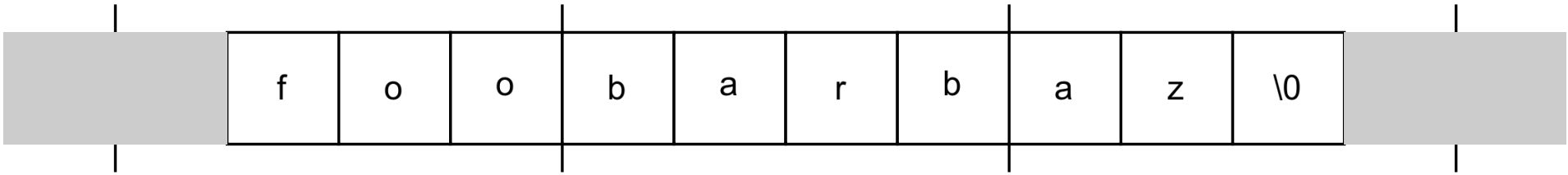
How far is too far?

- 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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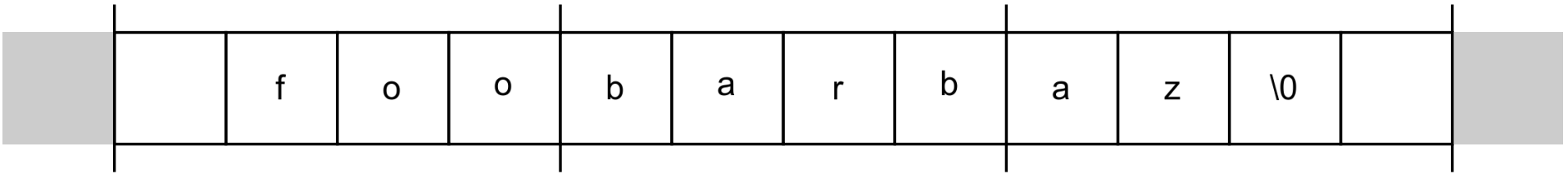

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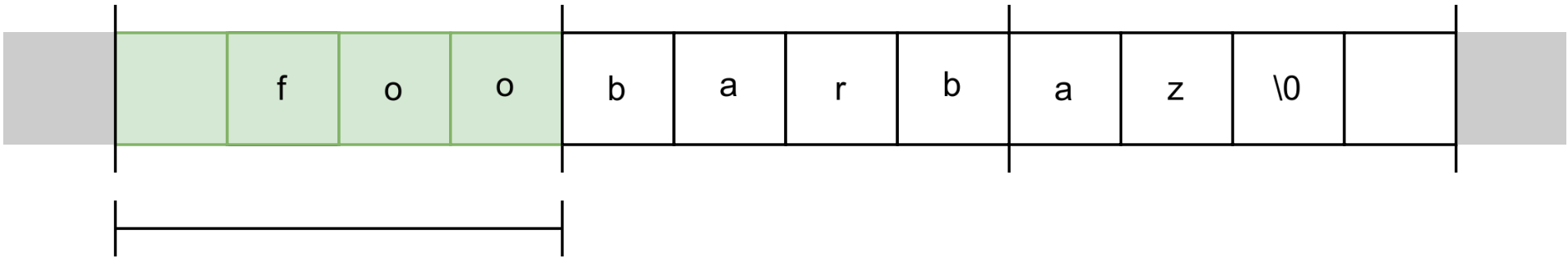

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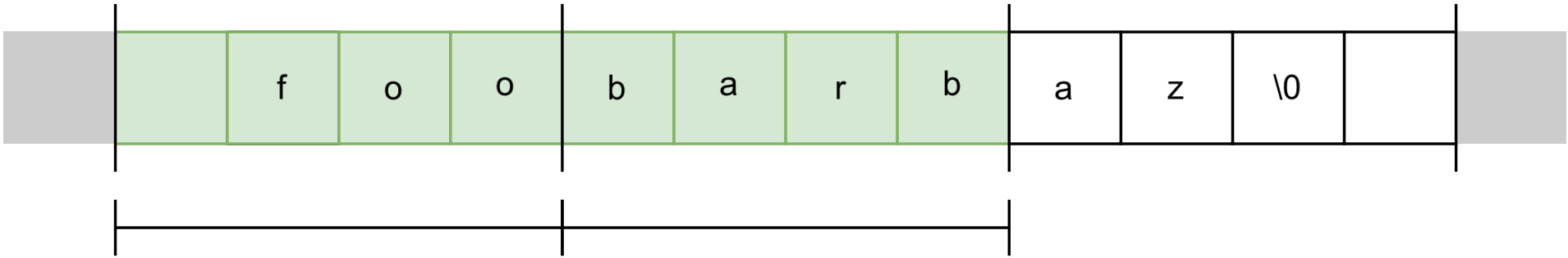

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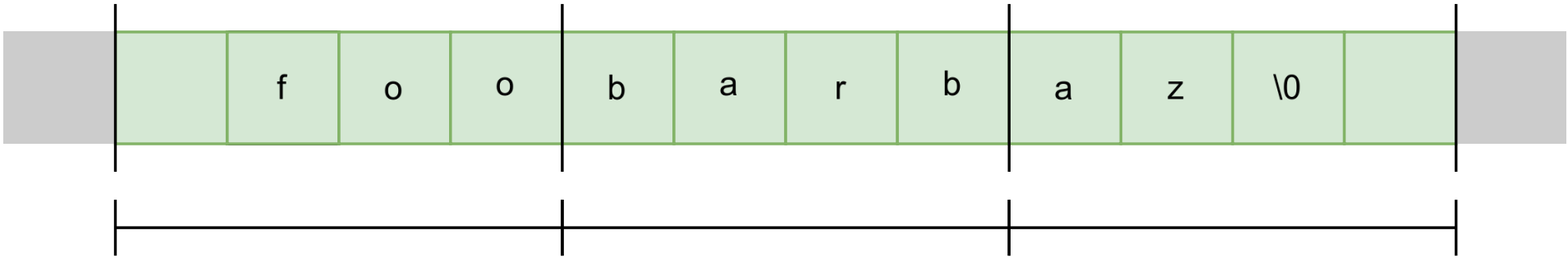

Writing Strings

Can't use the same approach:

- overreads are fine, overwrites are no good

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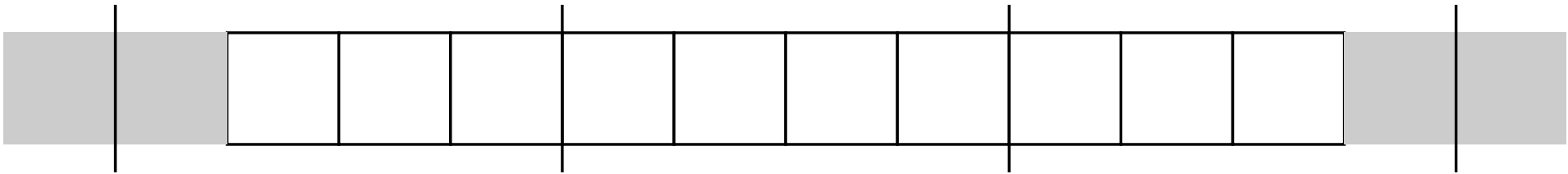
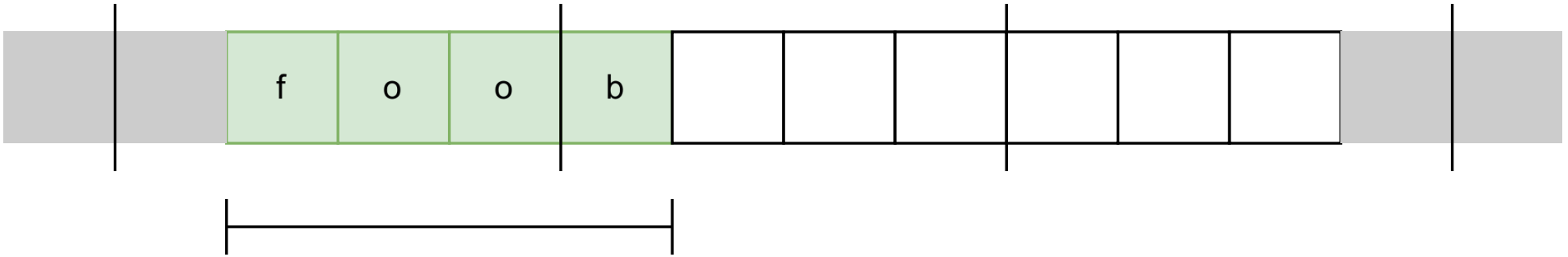
Instead

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

Writing Strings



Writing Strings



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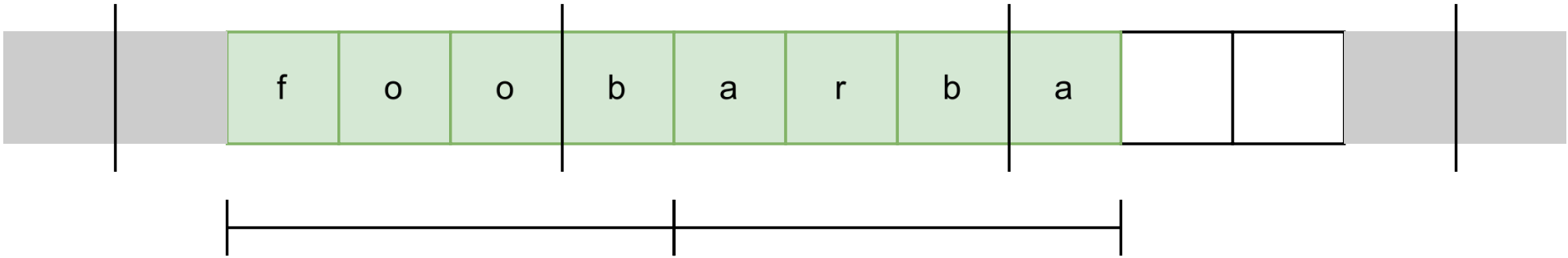

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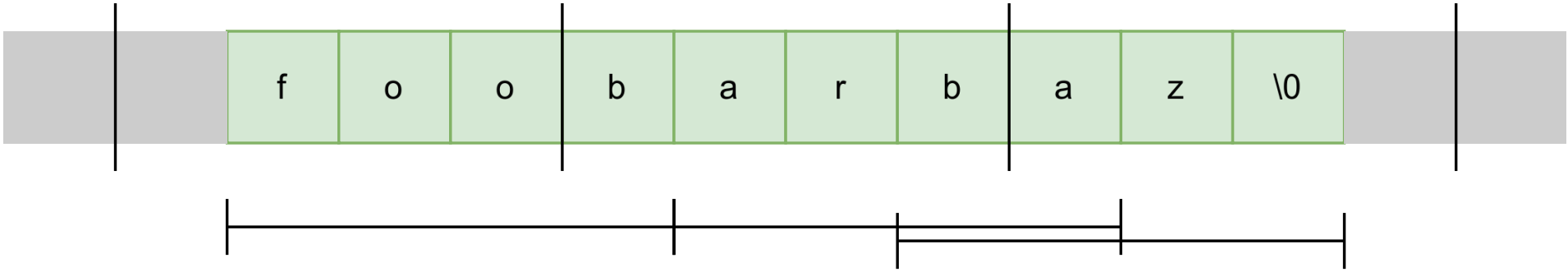

Comparing Strings

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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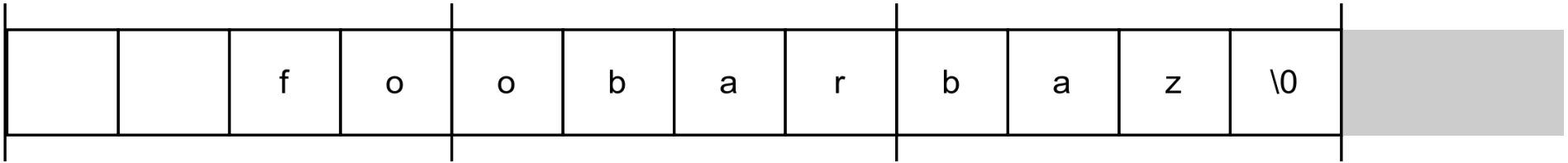

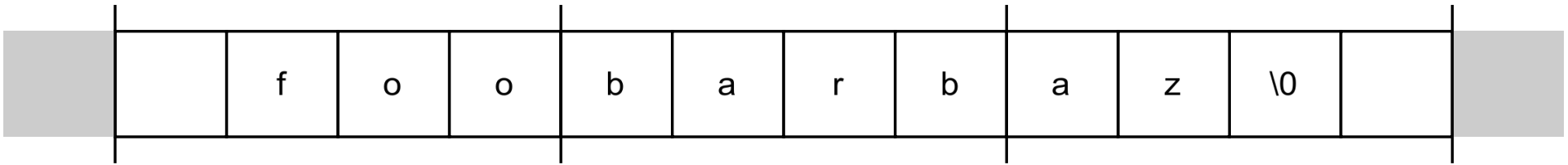

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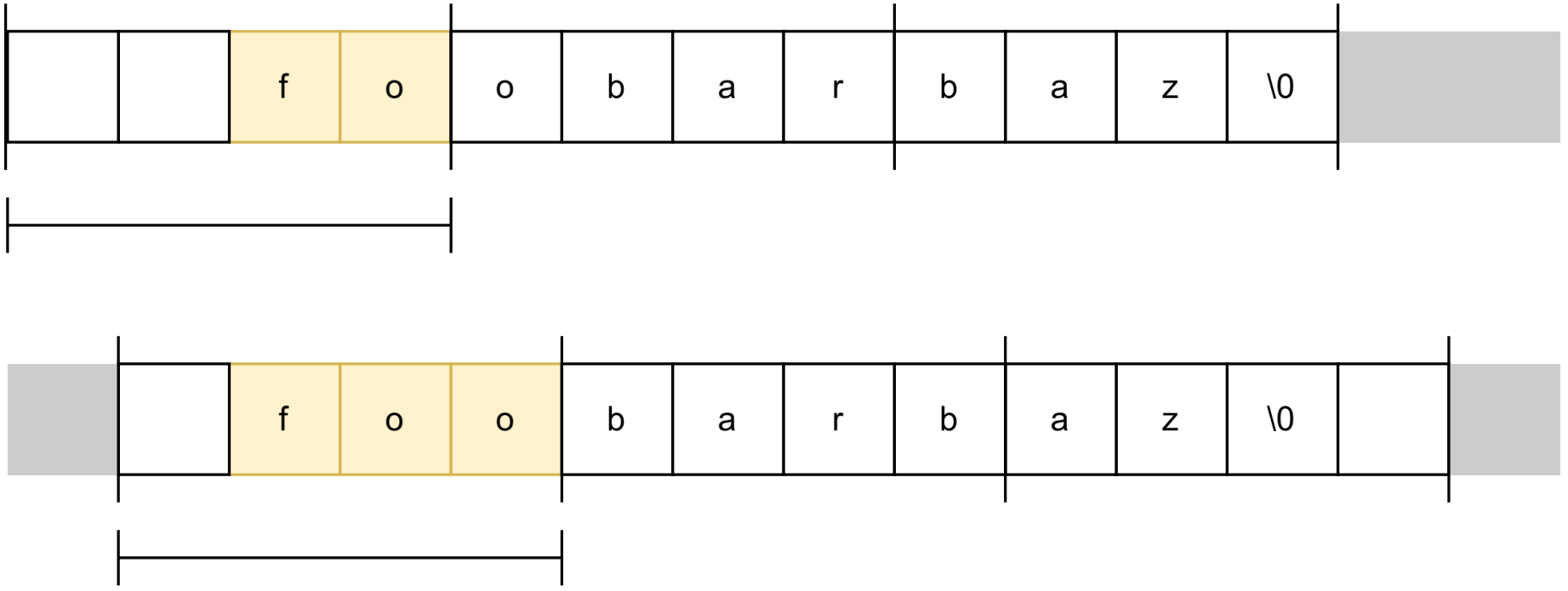

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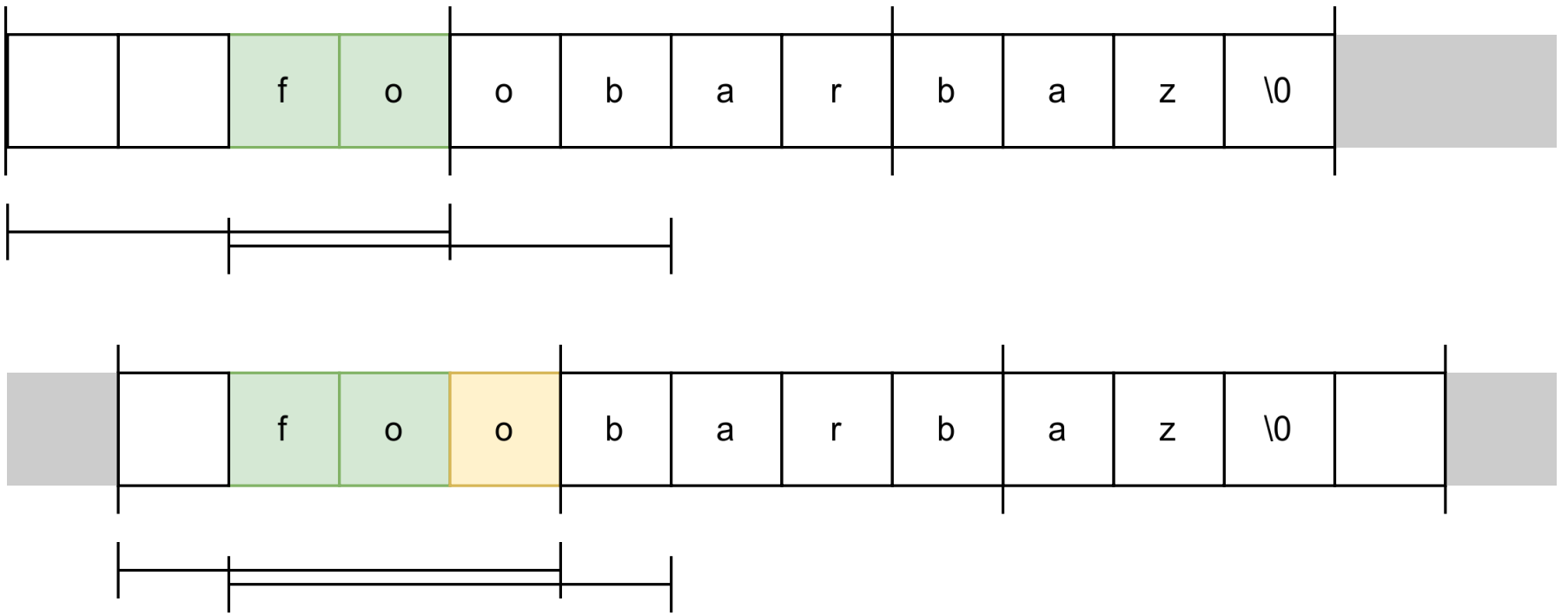

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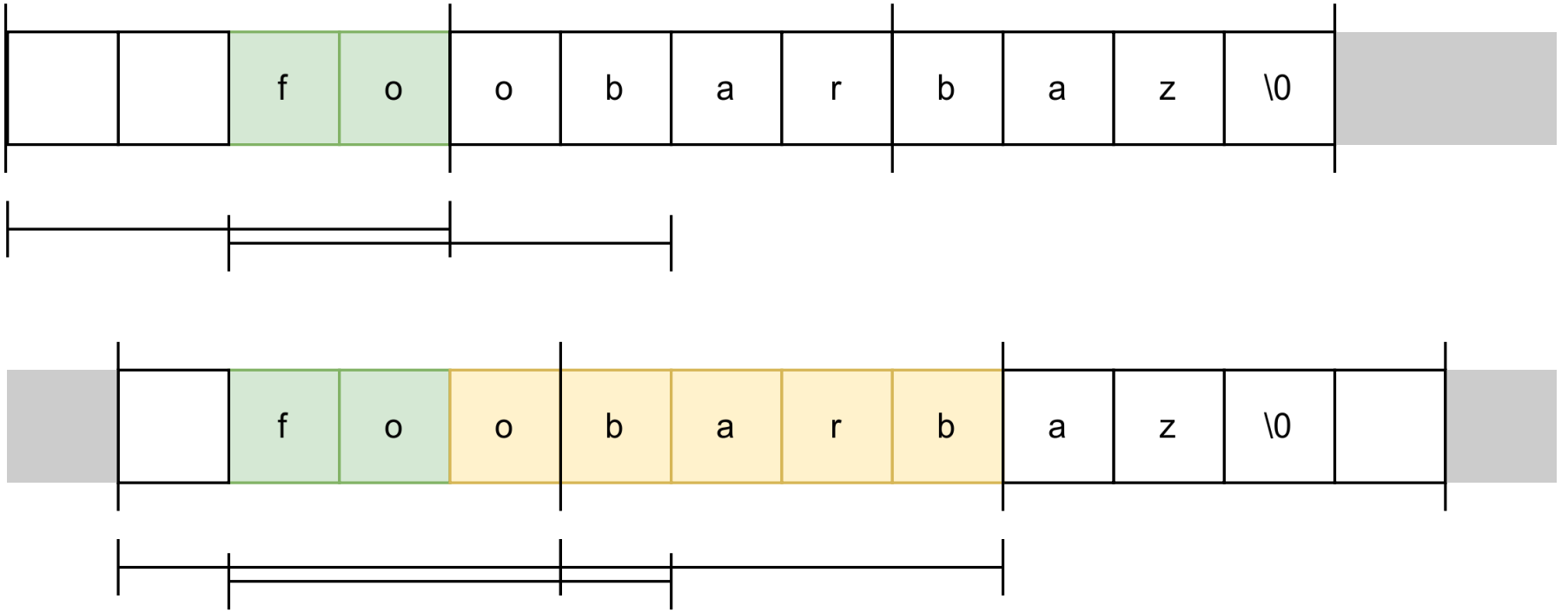

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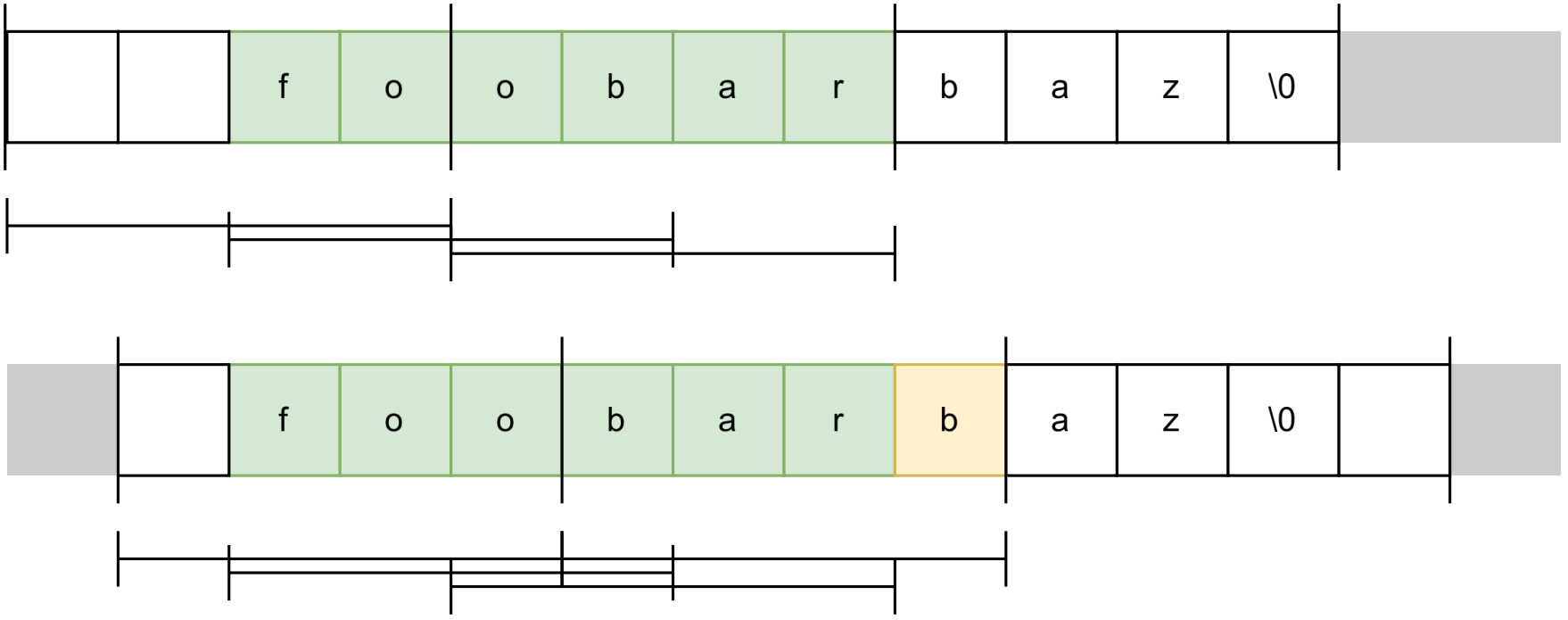

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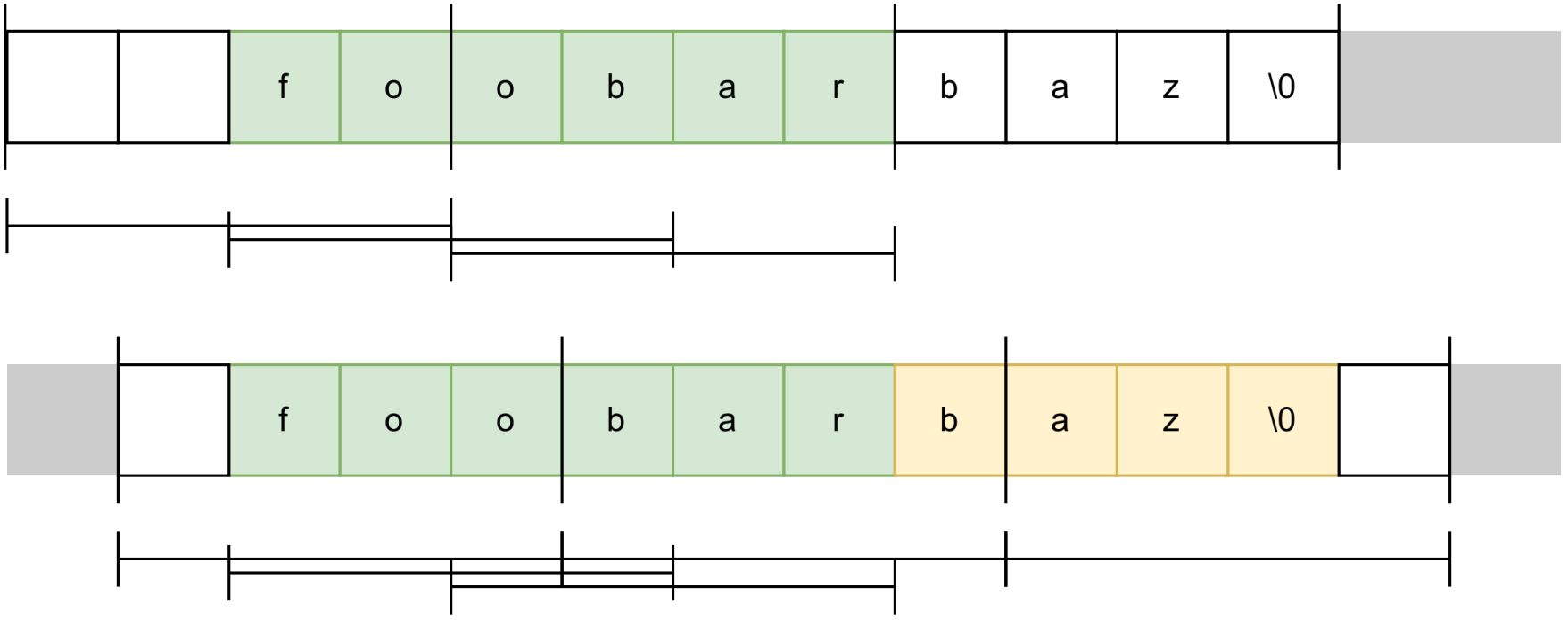

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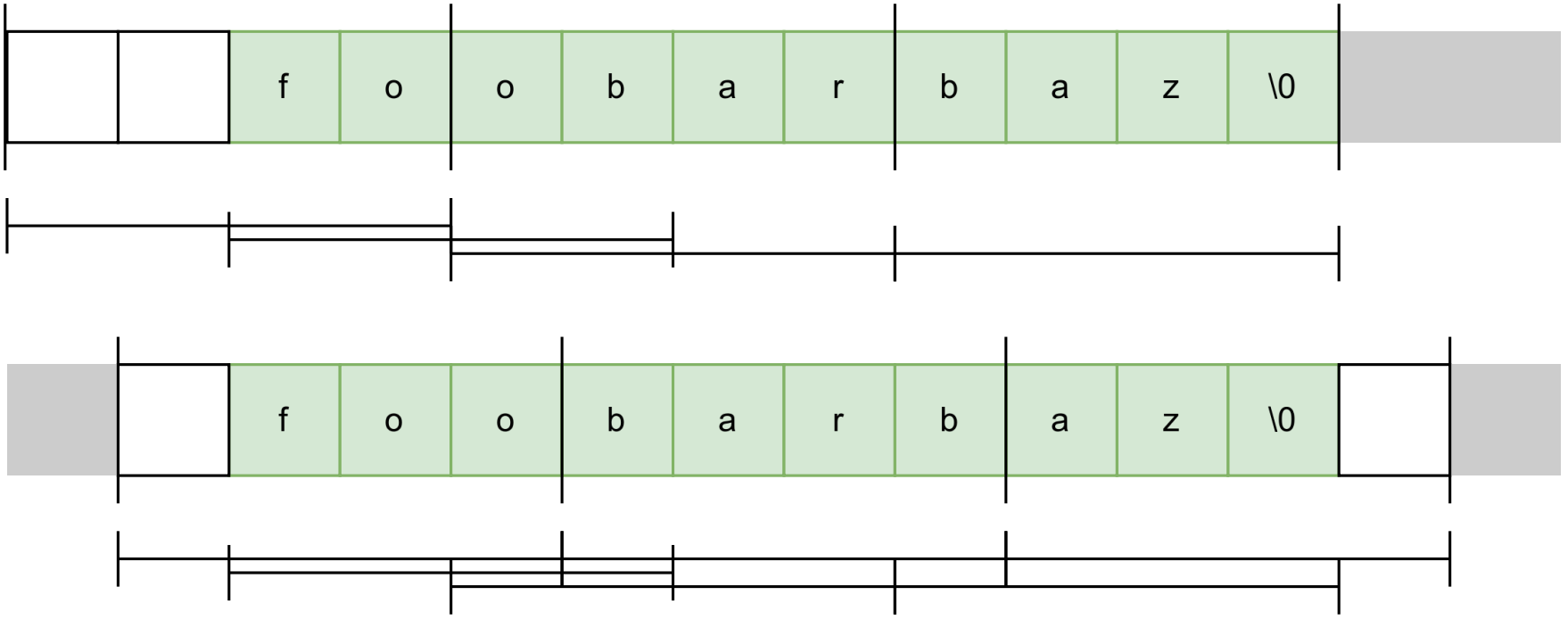

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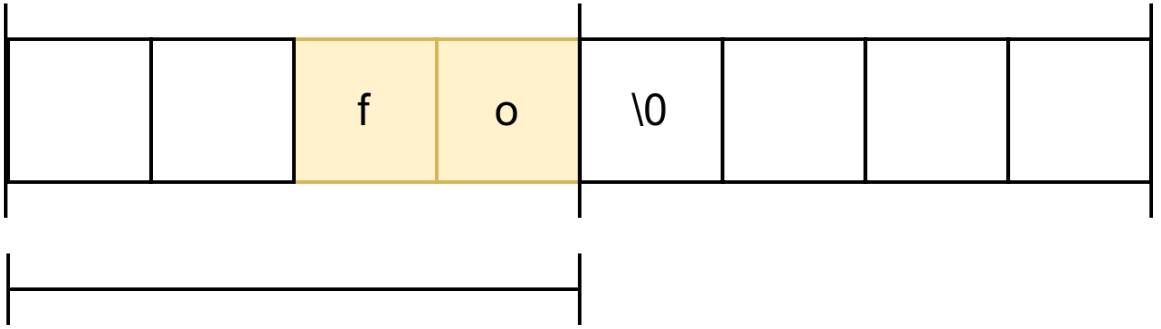

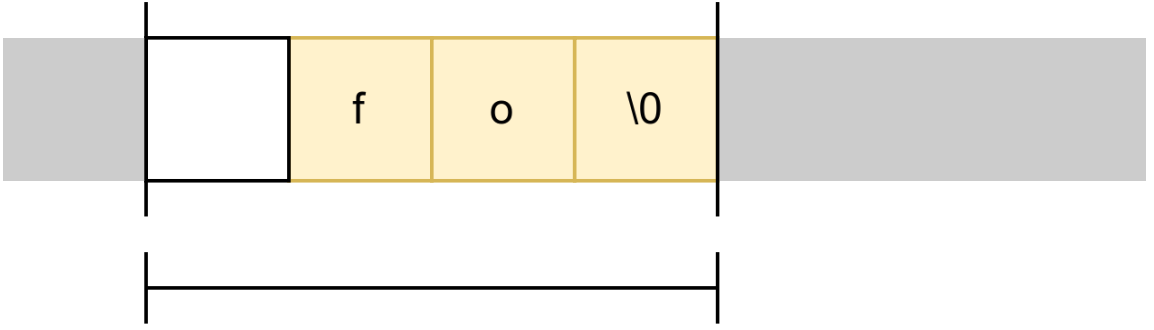

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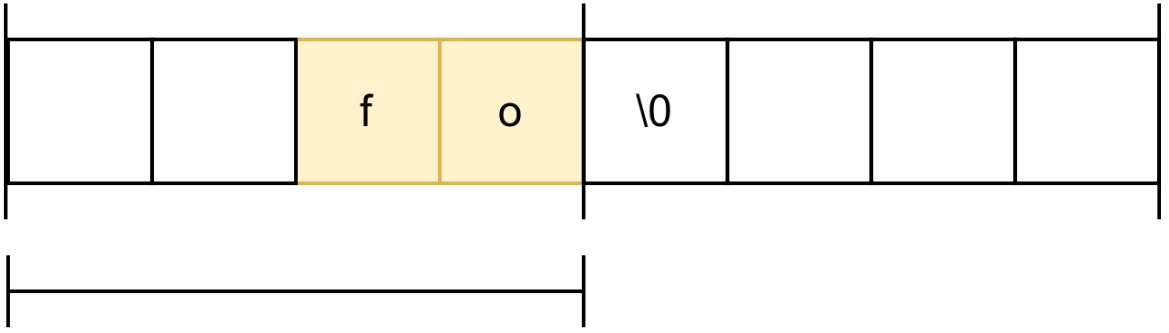
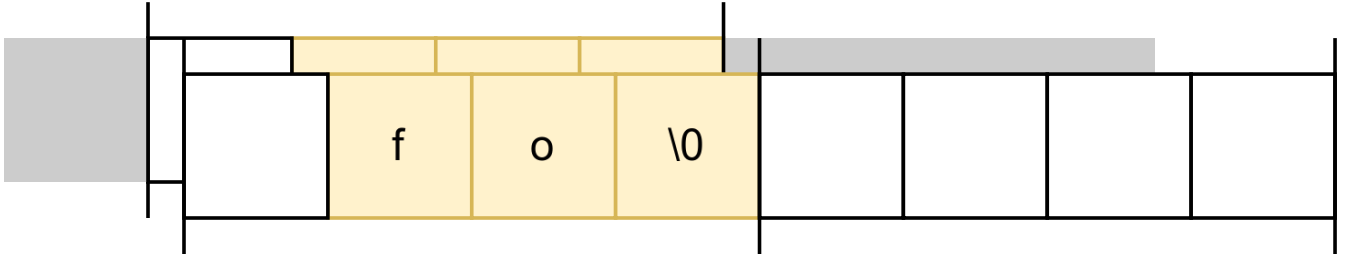


copy to bounce buffer on stack



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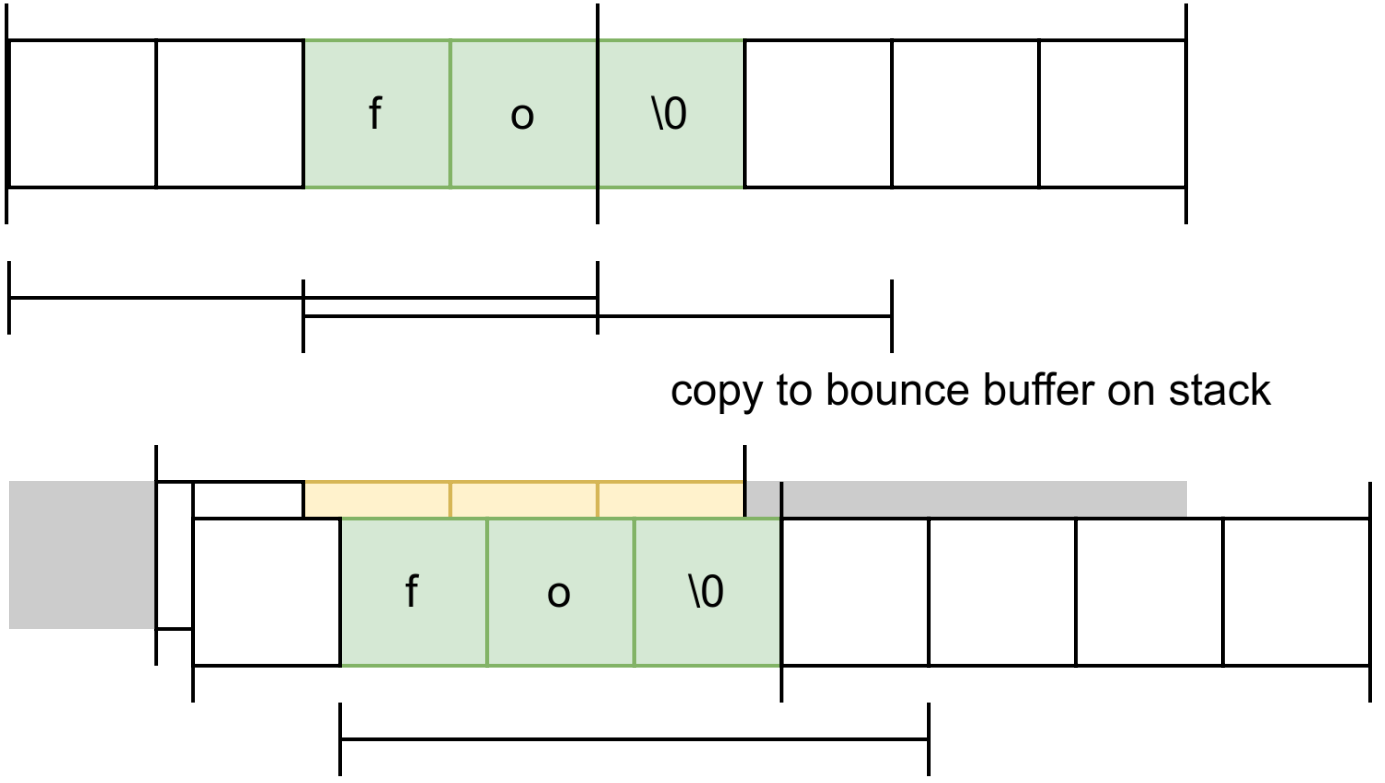


Set Matching

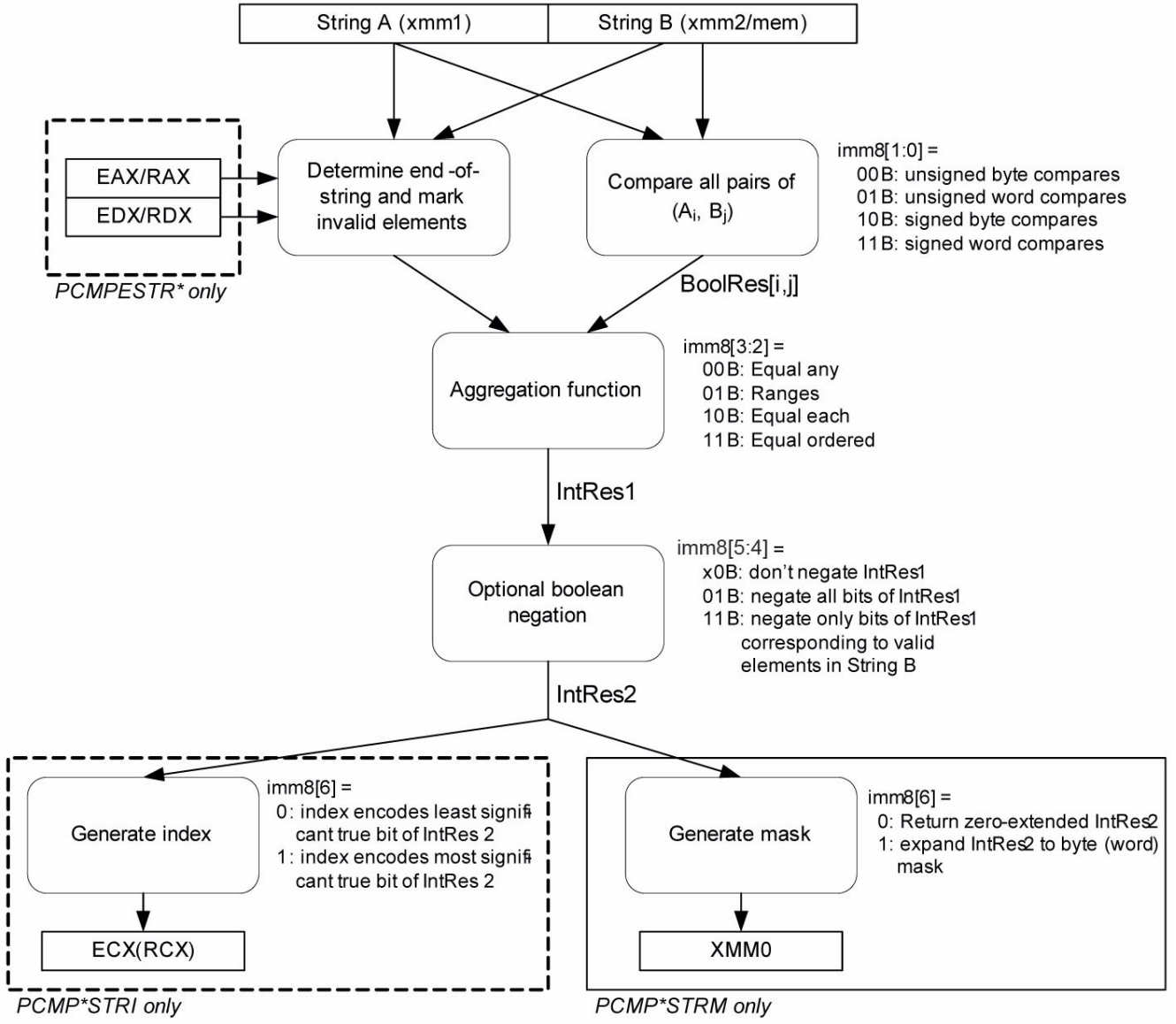
strcspn("foo bar", " \t\n");

- 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

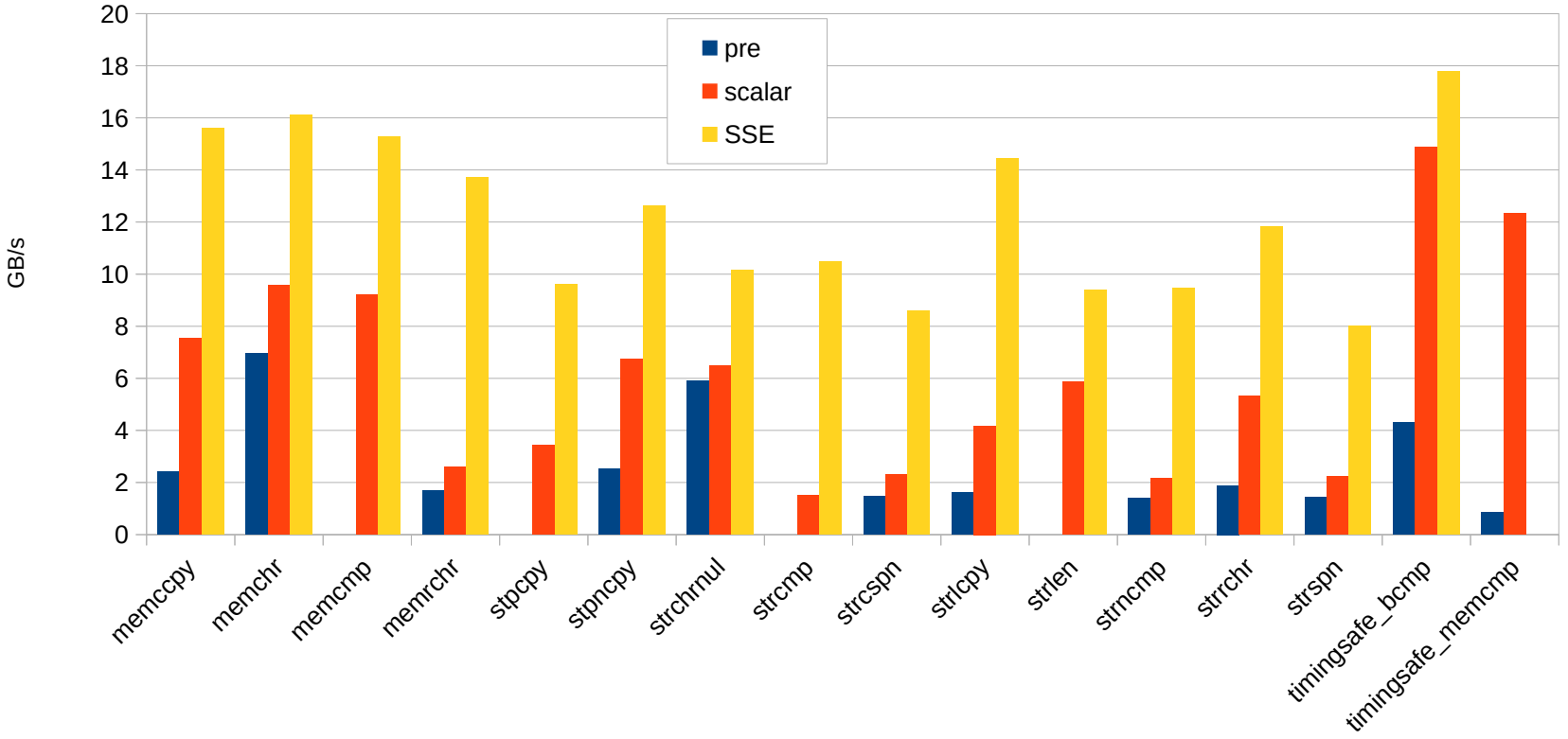
That means *strstr()*, *memmem()*

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

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@ (acceptance testing in progress)
  - riscv64 by strajabot@ (work in progress)

Results (amd64)



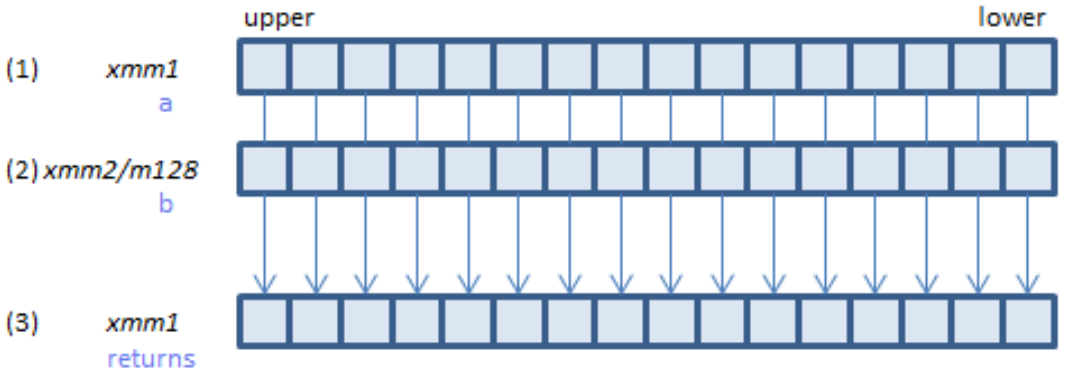
AMD64 <-> Aarch64

Background

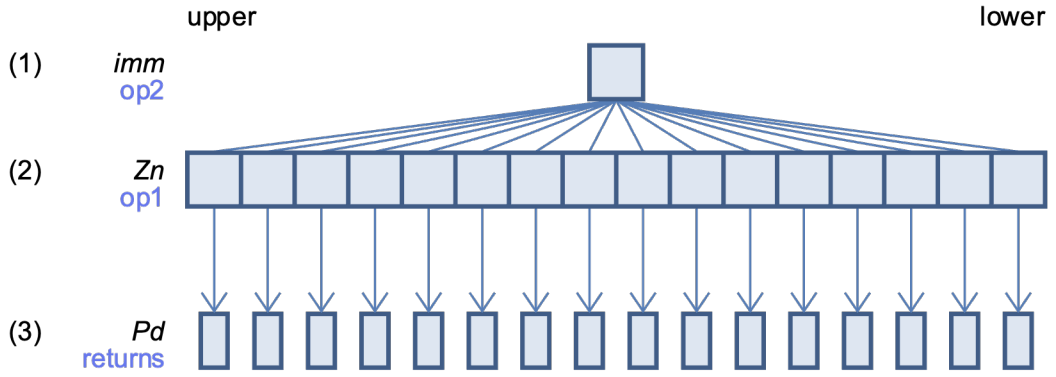
- Project as part of Google Summer of Code 2024
- Port amd64 SIMD libc optimizations to Aarch64
- Another contributor ported to RISC-V
- Several functions already had efficient implementations as part of the Arm Optimized Routines repository in src/contrib
- Several functions had less efficient implementations.
- Some functions missing
- Write all the string functions!

Most common instructions are available

- Bit scanning instructions (minor variations) Performed in a GPR after a match is found.
- Bytewise comparisons



PCMPEQB (**p**acked **com**pare for **eq**uality **b**ytes)



CMEQ (**com**pare bitwise **eq**ual)

Some require extra fiddling

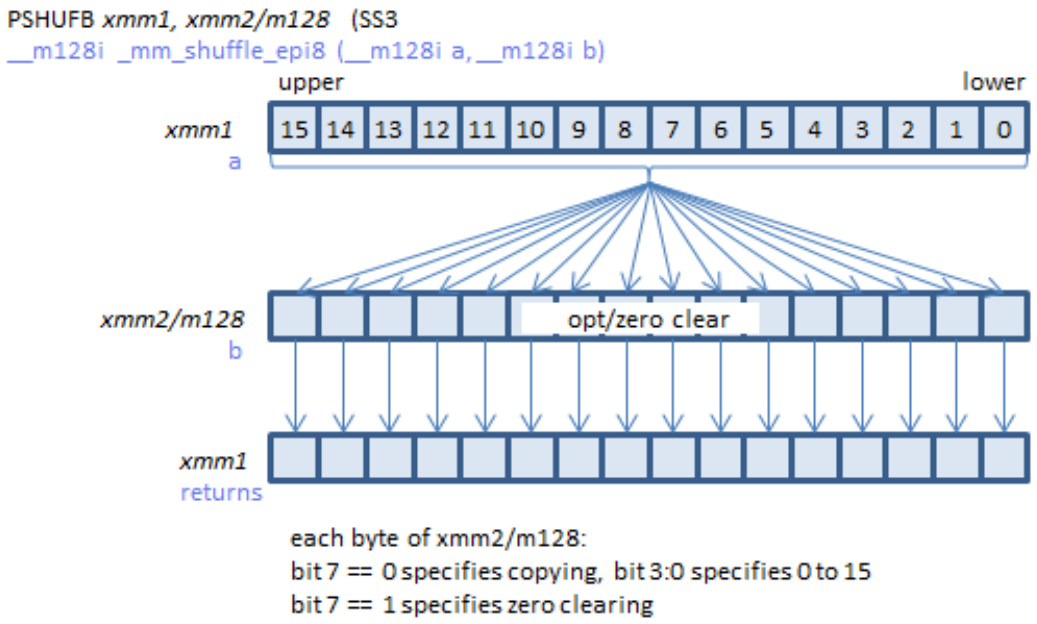
- For counted string functions we avoid branches by inducing a “fake” match in the match mask where the buffer ends.

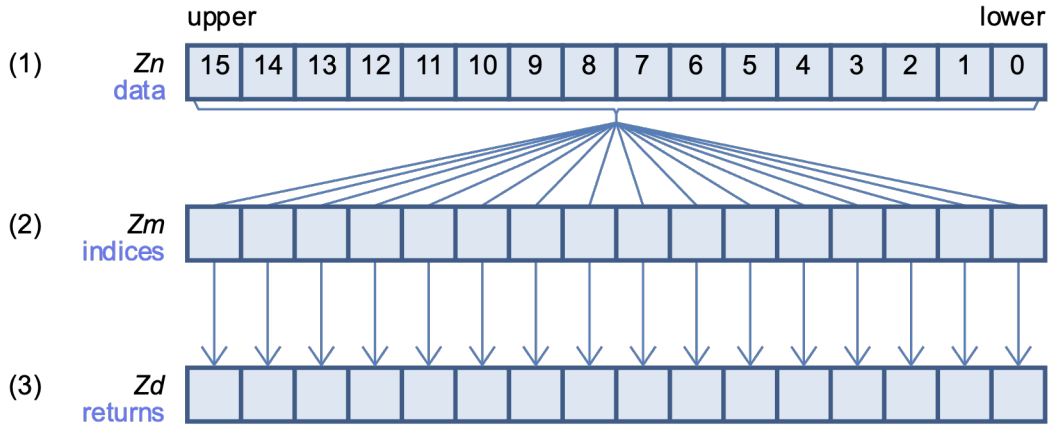
```
/* end of buffer will occur in next 32 bytes */
.Ltail:
          movdqu    (%rdi, %rbx, 1), %xmm0
          pxor      %xmm1, %xmm1
          pcmpeqb   (%rdi, %rsi, 1), %xmm1
          pcmpeqb   (%rdi), %xmm0
          pmovmskb  %xmm1, %r8d
          pmovmskb  %xmm0, %r9d
          bts       %edx, %r8d
          test      %r8w, %r8w
          jnz       .Lnul_found
          xor       $0xffff, %r9d
          jnz       .Lmismatch
```

```
.Ltail:
          ldr       q0, [x8, x11]
          ldr       q1, [x8, x10]
          ldr       q2, [x8]

          cmeq      v1.16b, v1.16b, #0
          cmeq      v0.16b, v0.16b, v2.16b

          shrn      v1.8b, v1.8h, #4
          shrn      v0.8b, v0.8h, #4
          fmov      x6, d1
          fmov      x5, d0

          mov       x13, #0xf
          lsl       x4, x2, #2
          lsl       x4, x13, x4
          orr       x3, x6, x4
          cmp       x2, #16
          csel      x6, x3, x6, lo

          cbnz      x6, .Lnulfound
          cbz       x5, .Lmismatch
```

How to be careful not to step into the void

- When buffer located at end of a page
- No variable shift for SIMD registers





```
movdqa          (%rdi), %xmm0
movdqa          (%rsi), %xmm2
mov             $-1, %r8d
mov             $-1, %r9d
mov             %eax, %ecx
shl             %cl, %r8d
mov             %edx, %ecx
shl             %cl, %r9d
movdqa          %xmm0, -40(%rsp)
movdqa          %xmm2, -24(%rsp)
pcmpeqb         %xmm1, %xmm0
pcmpeqb         %xmm1, %xmm2
pmovmskb        %xmm0, %r10d
pmovmskb        %xmm2, %r11d
test            %r8d, %r10d
lea             -40(%rsp), %r8
cmovz           %rdi, %r8
test            %r9d, %r11d
lea             -24(%rsp), %r9
cmovz           %rsi, %r9
movdqu          (%r8, %rax, 1), %xmm0
movdqu          (%r9, %rdx, 1), %xmm4
```

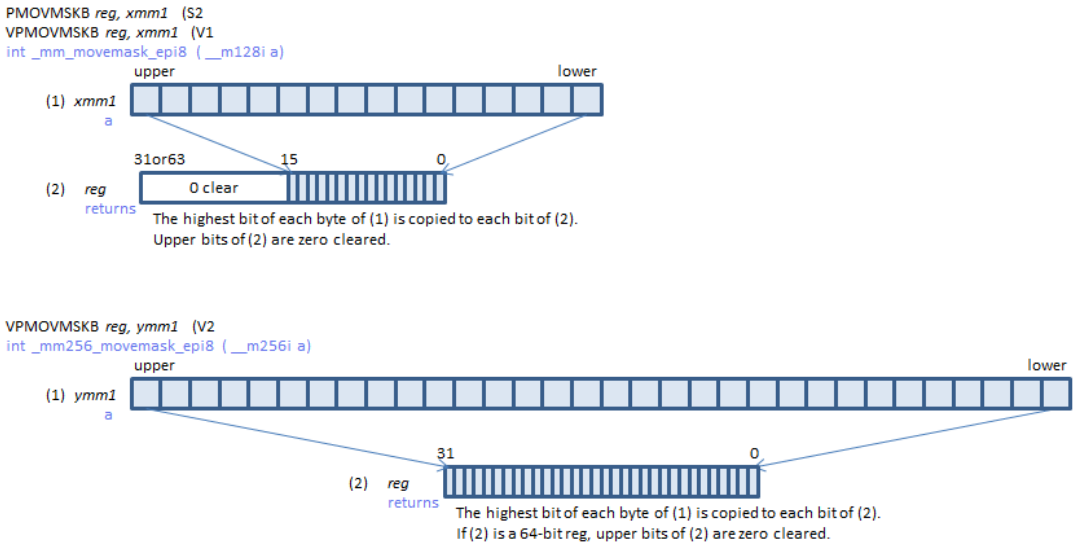
amd64

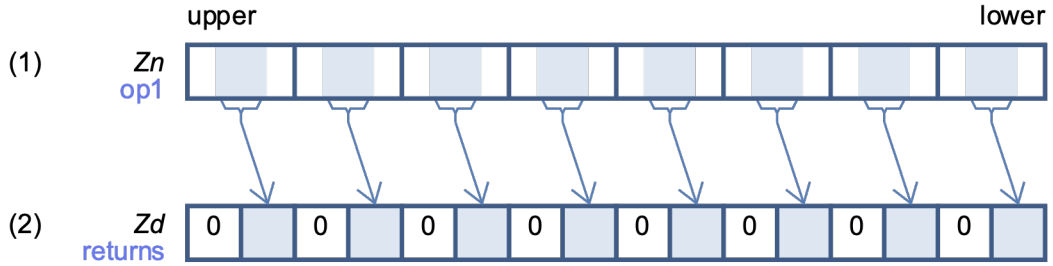
```
        bic     x8, x0, #0xf
        and     x9, x0, #0xf
        ldr     q0, [x8]
        ldr     q1, [x10]
        adrp    x14, shift_data
        add     x14, x14, :lo12:shift_data

        /* heads may cross page boundary, avoid
        unmapped loads */
        tst     x5, x3
        b.eq    0f

        ldr     q4, [x14, x9]
        tbl     v0.16b, {v0.16b}, v4.16b

        .section .rodata
        .p2align 4
shift_data:
        .byte 0, 1, 2, 3, 4, 5, 6, 7
        .byte 8, 9, 10, 11, 12, 13, 14, 15
        .fill 16, 1, -1
        .size shift_data, .-shift_data
```

Aarch64

Some require imagination

- Reducing the match from 128 -> 64 bits
- No pmovmskb in Aarch64 but shrn is a good enough substitute
- Several solutions available





Simple strlen(3)

```
1:      pxor            %xmm1, %xmm1
        pcmpeqb         (%rdi), %xmm1
        pmovmskb        %xmm1, %eax
        test            %eax, %eax
        add             $16, %rdi
        jz              1b

        /* match found in loop body */
        tzcnt  %eax, %eax
        sub    %rsi, %rdi
        lea    -16(%rdi, %rax, 1), %rax
        ret
```

```
.Lloop:
        ldr    q0, [x10, #16]!
        cmeq   v0.16b, v0.16b, #0
        shrn   v0.8b, v0.8h, #4
        fcmp   d0, #0.0
        b.eq   .Lloop
        fmov   x1, d0
.Ldone:
        sub    x0, x10, x0
        rbit   x1, x1
        clz    x3, x1
        lsr    x3, x3, #2
        add    x0, x0, x3
```

Notable Alternatives

- UMAXV for the hot path then SHRN on exit
  beneficial for long strings

- PCMEQ to turn matches into 0xff, then ORR with 0, 1, ..., 15, and finally UMINV to find the index of the first mismatch (or -1 if there is none)
  beneficial for very short strings

Some require a lot of imagination

- str(c)spn(3) greatly benefits from the SSE4.2 PCMPISTRI instruction
- Really tricky to port, heavy use of *slow* tbl instruction
- Current implementation with a lookup table (LUT) for >2 byte sets
- Empty set degrades to strlen(3), 1 char set degrades to strchrnul(3)

Future work

- Implement the Muła / Langdale algorithm for Aarch64
- SVE support D43306
- Add an ARCHLEVEL flag for Aarch64
- Port to AVX2/AVX-512, SVE
- Locale stuff (nasty)
- strstr(3)
- Possible other areas that could benefit from SIMD optimizations