Unicode at gigabytes per second

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❗ many other contributors!

From characters to bits

Morse code

- A : 0 1
- B : 1 0 0 0
- C : 1 0 1 0

26 letters.

Fixed-length codes

- Baudot code (~1860). 5 bits.
- Hollerith code (~1896). 6 bits.
- American Standard-Code for Information Interchange or ASCII (~1961). 7 bits. 128 characters.

Dec	Hex	Chr
0	00	NUL
1	01	SOH
2	02	STX
3	03	ETX
4	04	EOT
5	05	ENQ
6	06	ACK
7	07	BEL
8	08	BS
9	09	HT
10	0A	LF
11	0B	VT
12	0C	FF
13	0D	CR
14	0E	SO
15	0F	SI
16	10	DLE
17	11	DC1
18	12	DC2
19	13	DC3
20	14	DC4
21	15	NAK
22	16	SYN
23	17	ETB
24	18	CAN
25	19	EM
26	1A	SUB
27	1B	ESC
28	1C	FS
29	1D	GS
30	1E	RS
31	1F	US

Dec	Hex	Chr
32	20	Space
33	21	!
34	22	"
35	23	#
36	24	$
37	25	%
38	26	&
39	27	'
40	28	(
41	29	)
42	2A	*
43	2B	+
44	2C	,
45	2D	-
46	2E	.
47	2F	/
48	30	0
49	31	1
50	32	2
51	33	3
52	34	4
53	35	5
54	36	6
55	37	7
56	38	8
57	39	9
58	3A	:
59	3B	;
60	3C	<
61	3D	=
62	3E	>
63	3F	?

Dec	Hex	Chr
64	40	@
65	41	A
66	42	B
67	43	C
68	44	D
69	45	E
70	46	F
71	47	G
72	48	H
73	49	I
74	4A	J
75	4B	K
76	4C	L
77	4D	M
78	4E	N
79	4F	O
80	50	P
81	51	Q
82	52	R
83	53	S
84	54	T
85	55	U
86	56	V
87	57	W
88	58	X
89	59	Y
90	5A	Z
91	5B	[
92	5C	\
93	5D	]
94	5E	^
95	5F	_

Dec	Hex	Chr
96	60	`
97	61	a
98	62	b
99	63	c
100	64	d
101	65	e
102	66	f
103	67	g
104	68	h
105	69	i
106	6A	j
107	6B	k
108	6C	l
109	6D	m
110	6E	n
111	6F	o
112	70	p
113	71	q
114	72	r
115	73	s
116	74	t
117	75	u
118	76	v
119	77	w
120	78	x
121	79	y
122	7A	z
123	7B	{
124	7C	|
125	7D	}
126	7E	~
127	7F	DEL

Too many fixed-length codes!

- IBM: Binary Coded Decimal Interchange Code. 6 bits.
- IBM: Extended Binary Coded Decimal Interchange Code or EBCDIC. 8 bits.
- ISO 8859 (~1987). 8 bits. European.
- Thai (TIS 620), Indian languages (ISCII), Vietnamese (VISCII) and Japanese (JIS X 0201).
- Windows character sets, Mac character sets.

Unicode (late 1980s)

- Extends ASCII.
- Universal.
- Replaces all other standards.
- Typography, full localisation, extensible.

Unicode: how many bits?

- 16 bits ought to be enough?
- Numerical range from 0x000000 to 0x10FFFF.
- Would need 20 to 21 bits.

UTF-16 and UTF-8

Two main formats.

UTF-16: Java, C#, Windows

UTF-8: XML, JSON, HTML, Go, Rust, Swift

UTF-16 and UTF-8

character range	UTF-8 bytes	UTF-16 bytes
ASCII (0000-007F)	1	2
latin (0080-07FF)	2	2
asiatic (0800-D7FF, E000-FFFF)	3	2
supplemental (010000-10FFFF)	4	4

UTF-16

- 16-bit words.
- characters in 0000-D7FF and E000-FFFF, stored as 16-bit values---using two bytes.
- characters in 010000-10FFFF are stored using a 'surrogate pair'.
- Comes in two flavours (little and big endian at the 16-bit level).

UTF-16 (surrogate pair)

- first word in D800-DBFF.
- second word in DC00-DFFF.
- character value is 10 least significant bits of each---second element is least significant.
- add 0x10000 to the result.

UTF-8

- 8-bit words (no endianess)
- One 'leading' byte followed by 0 to 3 bytes.

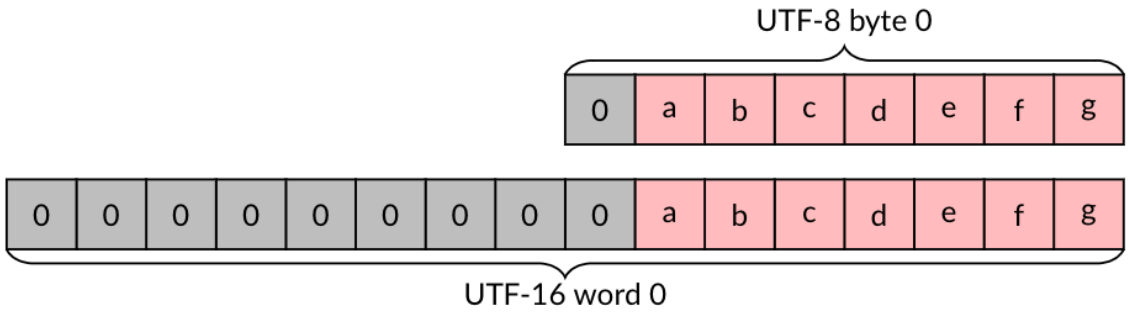
UTF-8 format

- Most significant bit of leading is zero, ASCII: [01000001].
- 3 most significant bits 110, two-byte sequence: [11000100] [10000101].
- 4 most significant bits 1100, three-byte sequence.
- 5 most significant bits 11000, four-byte sequence.
- Non-leading bytes have 10 as the two most significant bits.

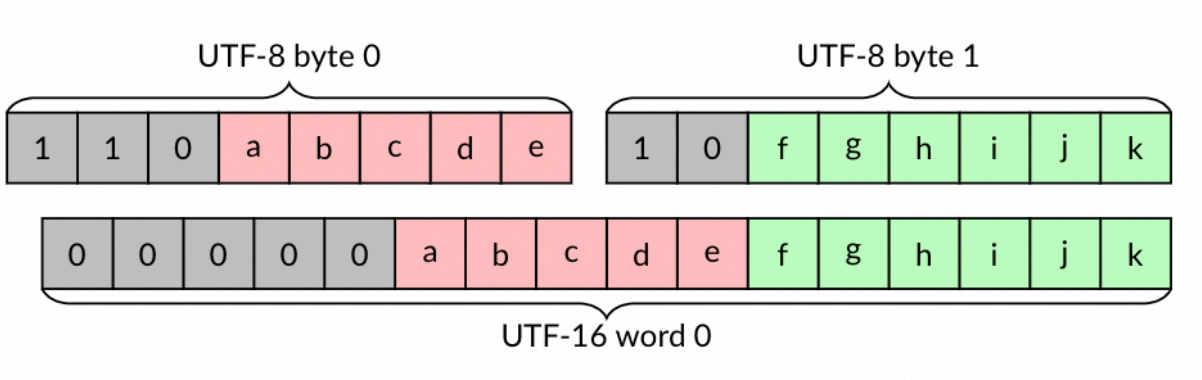
UTF-8 validation rules

- The five most significant bits of any byte cannot be all ones.
- The leading byte must be followed by the right number of continuation bytes.
- A continuation byte must be preceded by a leading byte.
- The decoded character must be larger than 7F for two-byte sequences, larger than 7FF for three-byte sequences, and larger than FFFF for four-byte sequences.
- The decoded code-point value must be less than 110000
- The code-point value must not be in the range D800-DFFF.

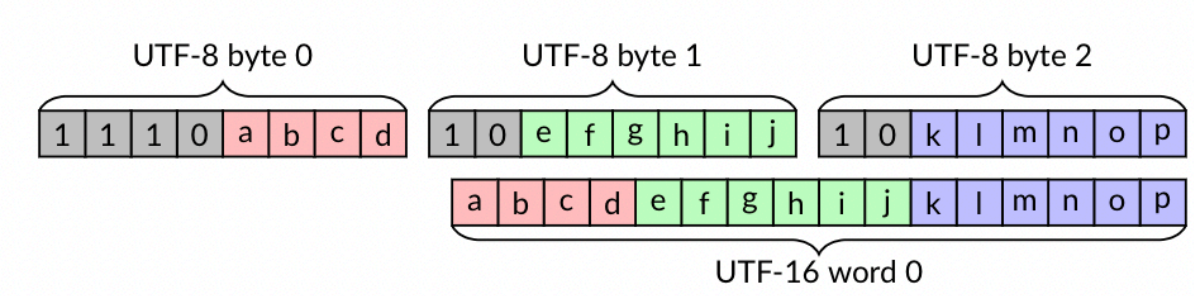
UTF-8/UTF-16 comparison (ASCII)



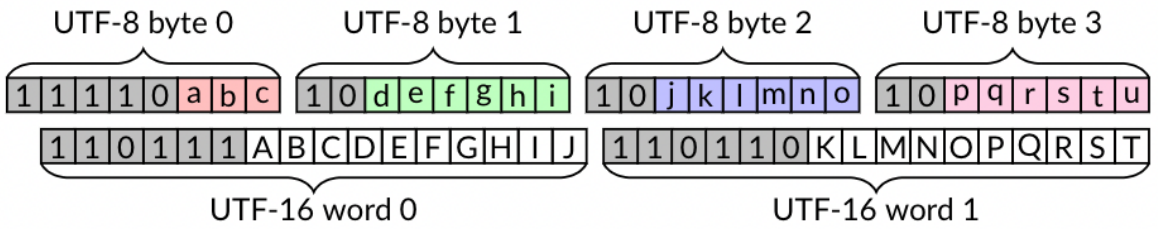
UTF-8/UTF-16 comparison (2-bytes)



UTF-8/UTF-16 comparison (3-bytes)



UTF-8/UTF-16 comparison (4-bytes)



UTF-8/UTF-16 transcoding

- Must convert (transcode) from one format to the other format, while validating the input.

Some numbers

- bandwidth between node instances: over 3 GB/s
- PCIe 4.0 disks (and PlayStation 5): over 5 GB/s
- Popular C++ trancoding library (ICU): ~1 GB/s

Gigabytes per second?

- x64, ARM, POWER: have SIMD instructions.

	UTF-8 to UTF-16	UTF-16 to UTF-8	validation	table size
Cameron's u8u16 (2008)	yes	no	yes	N/A
Inoue et al. (2008)	partial	no	no	105 kB
simdutf	yes	yes	yes	20 kB

Software implementations (no formal paper): Goffart (2012) and Gatilov (2019)

Vectorized permutation

- Can permute blocks of 16 bytes (or 32 bytes) using a single cheap instruction.
- Need a precomputed shuffle mask.
- data : [a b c d e f g]
- shuffle mask : [3 1 0 3 3 2 -1] (indexes)
- result : [d b a d d c 0]
- Conversely may be used as a form of vectorized table lookup.

UTF-8 to UTF-16 transcoding (core)

- Take a block of bytes.
- Continuation bytes (leading bits 10, less than -64)
- Non-continuation bytes are leading bytes
- Bytes before a leading byte end a character
- Build a bitmap
- Use the bitmap in a lookup table

UTF-8 to UTF-16 transcoding (example)

Start with...

[01000001] ([11000100] [10000101])
[01100011] ([11000011] [10000011]) [01101100] ([11000101] [10111010])

We have 9 bytes. Build a 9-bit bitmap where '1' means the end of a character

101101101

Use this as index in a table.

UTF-8 to UTF-16 transcoding (table)

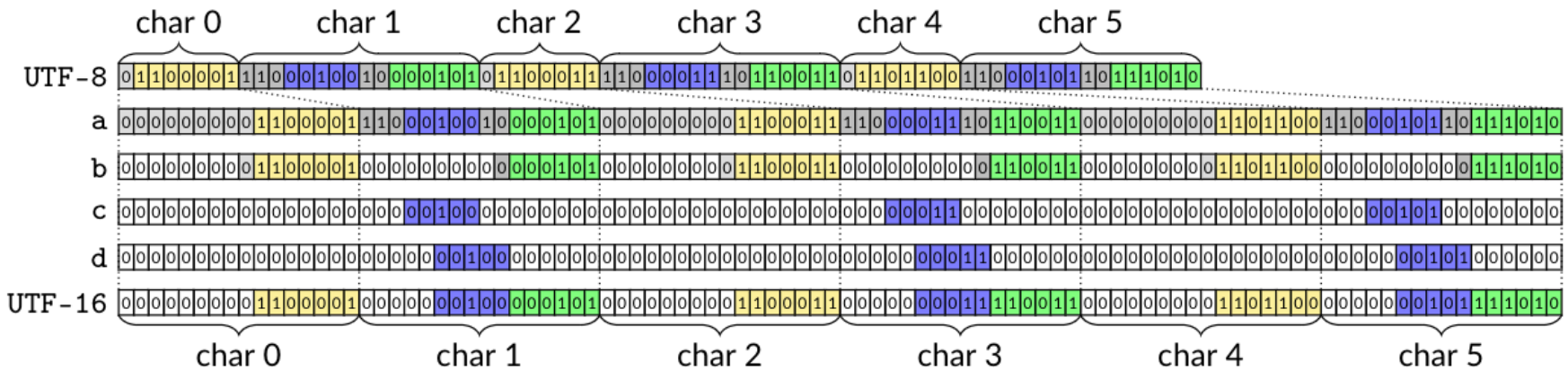
- If using 12-byte blocks, need 4096-long table.
- Each entry points to a shuffle mask and number of consumed bytes.

UTF-8 to UTF-16 transcoding (cases)

Shuffle masks are sorted into 'cases'.

1. First 64 cases correspond to 1-byte or 2-byte characters only.
2. Next 81 cases correspond to 1, 2 or 3 bytes per character.
3. Next 64 cases correspond to general case (1 to 4 bytes).

Each case corresponds to a code path.


char 0
char 1
char 2
char 3
char 4
char 5
UTF-8
a
b
c
d
UTF-16
char 0
char 1
char 2
char 3
char 4
char 5

UTF-8 to UTF-16 transcoding (more tricks)

1. Load blocks of 64 bytes.
2. Check for fast paths (e.g. all ASCII).
3. Eat 12 bytes at a time within 64 bytes.
4. Add a few fast path (e.g., all ASCII, all 2-byte, all 3-byte).

UTF-8 to UTF-16 transcoding (validation)

Given a 64-byte block, we can use a fast vectorized validation routine.

- Validating UTF-8 In Less Than One Instruction Per Byte, Software: Practice and Experience 51 (5), 2021

UTF-8 to UTF-16 transcoding (core algo)

- You can identify most UTF-8 errors by looking at sequences of 3 nibbles (4-bit).
- E.g., ASCII followed by continuation, leading not followed by continuation byte.

Do three lookups (using shuffe mask) and compute a bitwise AND. We call this vectorized classification.

Simplified vectorized classification

- Suppose you want to find all instances where value 3 is followed by value 1 or 2.
- Create two lookup tables.
- One for first nibble [0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0]
- second nibble [0,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0]
- Lookup first nibble in table, lookup second, compute bitwise AND.
- If result is 1, you have a match.
- Can do this in parallel over many values.

Fancier vectorized classification

- Suppose you want to find all instances where value 3 is followed by value 1 or 2. Value 5 followed by 0. Value 6 followed by 10.
- Create two lookup table2.
- One for first nibble [0,0,0,1,0,2,4,0,0,0,0,0,0,0,0,0]
- second nibble [2,1,1,0,0,0,0,0,0,0,4,0,0,0,0,0]
- Lookup first nibble in table, lookup second, compute bitwise AND.

Array of nibbles:

- original: [a0 a1 a2 a3 a4 ...]
- shift: [a1 a2 a3 a4 ...]
- shift: [a2 a3 a4 ...]
- f([a0 a1 a2 a3 a4 ...]) AND g([a1 a2 a3 a4 ...]) AND g([a2 a3 a4 ...])

UTF-16 to UTF-8

The other direction (from UTF-16 to UTF-8) is somewhat easier!

UTF-16 to UTF-8 (ASCII)

If all 16-bit words are ASCII (0000-007F), use a fast routine: 16 bytes into 8 'packed' bytes.

UTF-16 to UTF-8 (0000-07FF)

If all 16-bit words are in (0000-07FF)... build an 8-bit bitset indicating which 16-byte words are ASCII (0000-007F), load a shuffle mask, permute and patch.

UTF-16 to UTF-8 (0000-07FF, E000-FFFF)

If all 16-bit words are in the ranges 0000-D7FF, E000-FFFF, we use another similar specialized routine to produce sequences of one-byte, two-byte and three-byte UTF-8 characters.

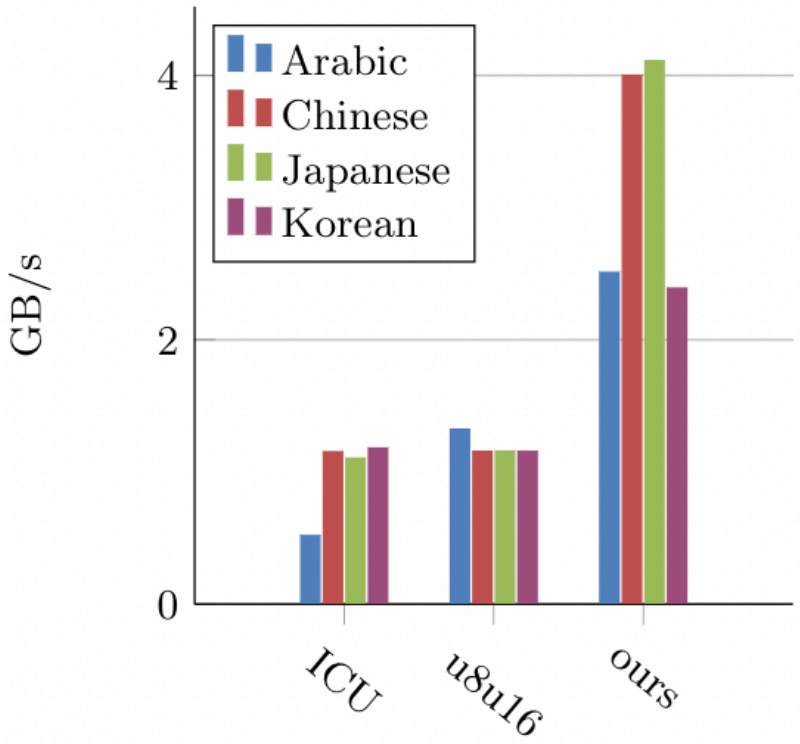
Otherwise, when we detect that the input register contains at least one part of a surrogate pair, we fall back to a conventional/scalar code path.

Experiments

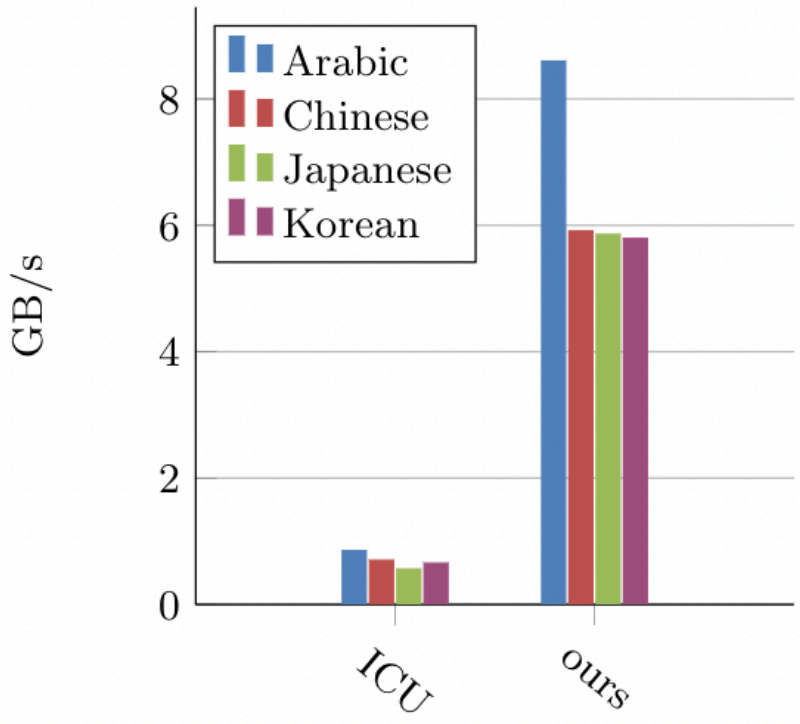
- AMD processor (AMD EPYC 7262, Zen 2 microarchitecture, 3.39 GHz) and GCC10.
- International Components for Unicode (UCI)
- u8u16 library
- lipsum text in various languages

ASCII transcoding

	UTF-8 to UTF-16	UTF-16 to UTF-8
simdutf	20 GB/s	36 GB/s
UCI	1 GB/s	2 GB/s



(a) UTF-8 to UTF-16 transcoding



(b) UTF-16 to UTF-8 transcoding

Software

https://github.com/simdutf/simdutf

- Open source, no patent.
- ARM NEON, SSE, AVX...
- Support runtime dispatch: adapts to your CPU.
- Easy to use: drop `simdutf.cpp` and `simdutf.h` in your project.
- Compiles to tens of kilobytes.

Further reading

- Lemire, Daniel and Wojciech Muła , Transcoding Billions of Unicode Characters per Second with SIMD Instructions, Software: Practice and Experience (to appear) https://r-libre.teluq.ca/2400/
- Blog: https://lemire.me/blog/