

# On-Demand JSON: A Better Way to Parse Documents?

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JSON is a popular standard for data interchange on the Internet. Ingesting JSON documents can be a performance bottleneck. A popular parsing strategy consists in converting the input text into a tree-based data structure—sometimes called a Document Object Model or DOM. We designed and implemented a novel JSON parsing interface—called On-Demand—that appears to the programmer like a conventional DOM-based approach. However, the underlying implementation is a pointer iterating through the content, only materializing the results (objects, arrays, strings, numbers) lazily. On recent commodity processors, an implementation of our approach provides superior performance in multiple benchmarks. To ensure reproducibility, our work is freely available as open source software.

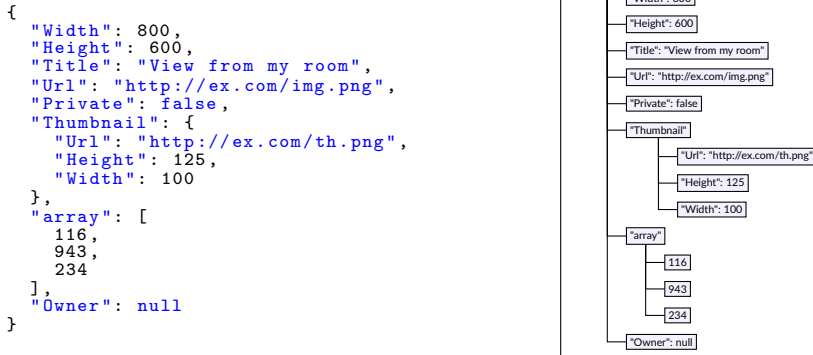
**KEYWORDS**

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## 1 | INTRODUCTION

There are several text-based semi-structured document formats (e.g., HTML, XML, JSON). JSON is maybe the most popular format online for data interchange [1]. Several database systems such as CouchDB, RethinkDB, MongoDB, SimpleDB and JSON Tiles [2] use JSON as their primary exchange format.

A JSON document must be stored in a valid Unicode (UTF-8) string. The JSON syntax is nearly a strict subset of the popular programming language JavaScript. It has four primitive types (string, number, Boolean, null) and two composed types (arrays and objects). An object takes the form of a series of key-value pairs between braces where keys are strings and values can be primitive or composed types (e.g., `{"name": "Jack", "age": 22}`). An array is a



**FIGURE 1** JSON example with corresponding tree form

list of comma-separated values (either primitive or composed) between brackets (e.g., `[1, "abc", null]`). The JSON specification has six *structural characters* (`'[', '{', '}', '}', ':', ','`) to delimit the location and structure of objects and arrays.

Programmers rarely work directly on text-based semi-structured document formats: they prefer to work with a software interface—a *parser*—providing automated validation and text-to-data conversion. There are two popular general-purpose parsing strategies [3]:

- Many parsers process the input document (e.g., JSON, HTML, XML) immediately into an in-memory data structure. Most web browsers use such an approach under the name Document Object Model (DOM): web pages (HTML) are loaded in memory into an ordered tree, accessible as a data structure from a programming language such as JavaScript [4]. Fig. 1 illustrates how a JSON document might be viewed as an ordered tree. A DOM-like approach is convenient, but it requires that the original document be materialized in memory. If the programmer is only interested in a subset of the document, they must still construct the whole tree. Further, even when the programmer needs to ingest the whole document, they may need to copy the data into their own data structures and data types. Hence the materialization of the tree might be unnecessary and wasteful.
- There are also event-based or *streaming* strategies. The document is processed from the beginning, and each newly encountered component is an event: e.g., the beginning of a string, the beginning of an array, the end of an array, etc. In some instances, the programmer may provide functions corresponding to each event. E.g., a programmer might have a function that is triggered each time a string is encountered. One of the most popular families of such parsers might be Simple API for XML (SAX) [5]. Streaming approaches can be efficient: if the programmer only needs to capture part of the input document, they can ignore everything else. The programmer may also write the data to their own data structures directly, without the need to materialize a full tree in a temporary memory buffer. We may use these efficient strategies for specific tasks such as well-defined queries (e.g., JSONPath [6]). We may also apply them to the deserialisation of specific data structures: a popular framework that serves this purpose in Rust is called *serde* [7]. For general-purpose tasks, streaming strategies might be challenging to the programmer. For example, the programmer may need to write their own code to track their logical location within the document. Without help, the programmer may end up with streaming code that is not highly efficient.

It is possible to parse JSON at high speed with DOM-like approaches. The *simdjson* DOM parser [8] can construct an ordered tree at a speed of over  $2\text{ GiBs}^{-1}$  on realistic inputs. However, we might be able to go even faster if

```

auto doc = parser.iterate(json);
for (object point_object : doc["coordinates"]) {
    x += double(point_object["x"]);
    y += double(point_object["y"]);
    z += double(point_object["z"]);
}

```

**FIGURE 2** On-Demand C++ source code used by the kostya JSON benchmark

we skip the in-memory construction of the ordered tree. The conventional approach to avoid the materialization of the document as an in-memory data structure is to adopt a streaming strategy. However, even when it would provide superior performance (e.g.,  $2\times$  or  $3\times$  faster), we believe that many programmers would still prefer the DOM-like approach for convenience.

For high-efficiency and convenience, we want to offer to the programmer a lazily evaluated tree [9]: if the programmer only needs one number out of a larger document, we allow the programmer to navigate to this one number using as little effort as possible, and to only materialize this one number. When the input document is an array (e.g., `[1, 2, 3]`), we propose to offer to the programmer what appears to be an array data structure, but is just an iterator over the values in the array. For objects (e.g., `{"one": 1, "two": 2, "three": 3}` in JSON), we iterate over key-value pairs. The parsing of the values is delayed until it is needed: the programmer may choose to skip unneeded values. Furthermore, we seek to provide as much flexibility to the programmer as possible. A given value appearing in JSON as a number may be parsed by the programmer as an integer, a floating-point number, or a string; a string (e.g., `"3.1416"`) can be parsed as number; and so forth. We call this lazy parsing strategy *On-Demand*. We refer to On-Demand as a *front-end*: it is a programming interface for the programmer that serves to abstract much of the complexity necessary for correct and efficient parsing.

An open-source implementation of our proposal (simdjson On-Demand) provides high speed. A long-standing benchmark of several JSON parsers<sup>1</sup> (henceforth Kostya) starts with a 10 000-long array of coordinates in JSON (e.g., `{"coordinates": [{"x": 2.0, "y": 0.5, "z": 0.25}, ...]}`) and requires that the parser sums all 'x' values, all 'y' values and all 'z' values. The On-Demand source code specific to this benchmark is provided in Fig. 2. The results are updated regularly, but the On-Demand approach is often ranked in first position among  $\approx 75$  competitors. We present some of the results in Table 1 for July 2022. The nearest competitor which does not sacrifice floating-point accuracy is Serde in the Rust programming language. A highly efficient C++ approach (DAW JSON Link) is practically on par with On-Demand in performance and it offers a functionality similar to Serde, with other specialized compile-time constructions, although without exact number parsing [8, 10].

We believe that the Kostya benchmark illustrates that an On-Demand front-end may achieve high performance with a software interface that is both expressive—our code is generic—and accessible: our users' code resembles that of a DOM interface.

<sup>1</sup><https://github.com/kostya/benchmarks>

Library and Language	Time (s)	Energy Usage (J)
C++/g++ (simdjson On-Demand)	0.067	2.8
Rust (Serde)	0.11	5.6
C++/g++ (RapidJSON)	0.25	6.9
C++/g++ (Boost.JSON)	0.40	16
Go	0.86	36
C++/clang++ (Nlohmann)	1.3	53
Python	1.5	60

**TABLE 1** Sample of the kostya JSON benchmark results (July 2022), after excluding techniques that fail to provide exact number parsing. The benchmark is reported to run on an Intel Xeon E-2324G processor (Rocket Lake), using a Debian distribution with GCC 12.1, Go 1.18.2, Rust 1.61 and Python 3.10.4. The test file is 115 GB, the timing excludes the time requires to load the file from disk.

## 2 | RELATED WORK

Our work builds on simdjson [8], specifically on its indexing stage. The simdjson parser was the first standard-compliant JSON parser to process gigabytes of data per second on a single core using commodity processors. Given an input JSON document, the simdjson parser identifies the starting location of all JSON nodes (e.g., numbers, strings, null, true, false, arrays, objects) as well as all JSON structural characters ('[', '{', ']', '}', ':', ','). The parser stores these locations as integer indexes in a separate array. For example, given the array {"abc":2000}, we might have the indexes 0, 1, 6, 7, 11. During this indexing stage, we must distinguish the characters that are between quotes, and thus inside a string value, from other characters. For example, the JSON document "[1,2]\\"" is a single string and we only need to locate the first quote character. During the indexing phase, the simdjson parser also checks the Unicode encoding using an efficient SIMD-based algorithm [11]. It also checks other rules such that we only find the ASCII space, the horizontal tab, the line feed, the carriage return and the JSON structural characters ('[', '{', ']', '}', ':', ',') outside strings. The entirety of the indexing is done with in bit-parallel manner, and leveraging SIMD instructions when available. It reads blocks of 64 bytes one after the other. From the 64 bytes, it generates a 64-bit word which acts as a bitset: the location of each 1-bit indicates the potential location of a JSON structural character or the start of a value. From this 64-bit word, we extract index locations to an array of integers, each 64-byte block generating between zero to 32 index values. The software relies on runtime dispatching, first identifying the features supported by the CPU and then calling on the appropriate function. The simdjson library is used by popular database systems such as ClickHouse and StarRocks.

Though the simdjson parser provides state-of-the-art speed on single-core commodity processors, there are faster JSON parsers on more specialized hardware. Using field-programmable gate arrays (FPGA), Dann et al. [12] designed PipeJSON, the first standard-compliant JSON parser to process tens of gigabytes of data per second. It consists in a JSON parser prototype with a simdjson-compatible interface, and it can serve as a drop-in replacement for the simdjson parser. Hahn et al. [13] present a fast FPGA JSON filtering parser than can locate relevant components with high accury and high speed. Peltenburg et al. [14] convert JSON to the Arrow format at the rate of tens of gigabytes per second on an FPGA. Stehle and Jacobsen similarly achieve high speeds, using a graphical processing unit (GPU) [15]. It is also possible to accelerate JSON parsing with multicore parallelism [16, 17].

One of the advantages of our On-Demand approach is that the programmer can quickly skip irrelevant JSON data. Consuming JSON faster by skipping irrelevant sections is a common strategy. Alagiannis et al. [18] query JSON without loading it in their database—parsing only what is necessary. Bonetta and Brantner use just-in-time (JIT) compilation and selective data access [19]. Jiang and Zhao [3] implemented a JSON streaming framework (JSONSki) to fast-forward over different cases of irrelevant substructures. Li et al. present their fast parser, Mison which can jump directly to a queried field without parsing intermediate content [20]. Mison uses SIMD instructions to quickly identify some structural characters but otherwise works by processing bit-vectors in general purpose registers with branching loops. Mison preceded `simdjson` and it is broadly similar to `simdjson`'s indexing. FishStore [21] parses JSON data and selects subsets of interest, storing the result in a fast key-value store [22]. Though built originally on Mison, FishStore has adopted `simdjson`<sup>2</sup>. Palkar et al. present Sparser: it filters quickly an unprocessed document to find mostly just the relevant information [23], and then relies on a parser.

### 3 | ON-DEMAND FRONT-END

Conceptually, parsing with On Demand begins with the creation of a parser instance (`ondemand::parser`). The parser is responsible for memory allocation and it can be reused from document to document. Given a parser instance, the user calls the `iterate` method on a string input which returns a document instance (`ondemand::document`). The method calls the `simdjson` indexing routine, and writes an index in the parser instance. Afterward, the front-end consists essentially in a pointer over the document which we call internally a `json_iterator`: the iterator resides within the document instance.

We typically traverse the document sequentially from the beginning to the end, always pointing at one pseudo-structural character at a time. The `json_iterator` has also a reference to a pre-allocated string buffer—owned by the parser instance—where we may decode JSON strings: strings in JSON may contain escaped characters (e.g., `\n` or `\u0030`) and we provide the user with an unescaped version stored in our own buffer.

During the processing of a valid JSON document, we point at a structural character ('[', '{', ']', '}', ':', ',', ') or at the beginning of a value:

- A quote character ('"') marking the beginning of either a string value or an object key.
- A digit or minus character ('-', '0', ..., '9') marking the beginning of number.
- The letters 'n', 't' or 'f' for the start of a `null`, `true`, or `false` token.

However not all of these states are accessible to the programmer: in the normal course of operation, the code points at the beginning of an array ('['), at the beginning of an object ('{') or at the beginning of a value (number, string, Boolean, null).

The On-Demand front-end validates the content that it parses. We may choose to skip a value (e.g., a string or a number) and in which case the content of the value is not fully validated. For example, the JSON string `[1,1b]` is invalid—because `1b` is not a valid number string—but if it is not accessed (i.e., it is skipped), then no error may be reported.

To help us keep track of the structure of the JSON document, our pointer instance (`json_iterator`) contains a depth counter. When we enter an array or an object, the depth is incremented by one, and decremented by one when we exit the object or the array. In case of an error or when we have consumed the whole document, the depth is set to zero. Table 2 illustrates the depth model for the document from Fig. 1.

<sup>2</sup><https://github.com/microsoft/FishStore>

From the point of view of the programmer, we may create arrays and objects (`ondemand::array` and `ondemand::object`). Yet these instances are mere thin wrappers and the creation of the instance translates into a check for the presence of the right structural characters ('[', '{', ']', '}'). They record their starting position and their document depth. They provide access to corresponding iterators over the elements of the arrays or the fields of the object.

When reading an object's key-value pair, the key's location is accessed and the pointer is moved to the associated value. We return to the user a `field` structure containing a pointer to the key that was just read, and a reference to the value. We may also seek a key within an object: when doing so, we scan for the presence of string instances (recognized by a quote character '"') preceded by a colon character (':') at the depth of the current object. The programmer might seek different key values as in Fig. 2: each time we advance through the content, with a possible restart from the beginning if we arrive at the end of the object. We know that a key cannot be found if we have scanned through the object entirely, with a possible restart from the beginning, arriving back to our starting point. We always scan for keys from our current position, instead of systematically starting from the beginning. If the key is not found then we are left pointing at either the start of the object or at a comma. We are at the depth of the object itself. When searching for a key, if the key is found then we are left pointing at the colon, and we are one depth below the object itself. We then immediately advance to the value.

As much as possible, we rely on `std::string_view` instances. Unlike the conventional C++ `std::string` which allocate their own memory, the `std::string_view` instances are thin wrappers around a character pointer. Thus when we return a string value, we do not need to allocate a new buffer and to copy the content. Given a JSON value (string, number, Boolean or null), the `raw_json_token()` method provides a direct (unprocessed) `std::string_view` instance mapped to the original JSON string. Because the document is indexed, such a method can be implemented using few instructions. Given an array or an object, a programmer can have direct access to the corresponding memory region in the original document: the `raw_json()` method returns a `std::string_view` instance representing the unprocessed string representation of the array or object.

Most functions may return an error. To provide flexible error handling, our functions often return a value of a type corresponding to the template `simdjson_result`. This template contains a pair of value: an error code and the actual value. Hence, a `get_double()` method might return a structure containing an error code and a 64-bit floating-point value of the type `double`. A `simdjson_result` instance throws an exception when we attempt to cast it to its value type (e.g., `double`) if the error condition indicates an error. For users who prefer to avoid exception handling, we make it possible to recover the value from a `simdjson_result` instance after checking the error condition. Most of our methods (`get_array()`, `get_object()`, `get_bool()`, ...) return `simdjson_result` instances. For convenience, we can cast values directly to a given type (e.g., `double`) without explicitly creating a `simdjson_result` instance.

Fig. 3 illustrates how the On Demand front-end might work with a non-trivial example. Given a JSON document made of an array of objects, we initiate a loop, accessing each element of the array as an object (`car`). Given such an object, we may query some fields (e.g., `model`) but not others (e.g., `make`): unqueried fields are skipped as much as possible. We may cast a value to a string, to an integer or to a floating-point value. In this particular example, if the value does not match the desired type, then a C++ exception would be thrown. We also support arbitrary schema through the `type()` method: it indicates whether the current node is potentially a number, a string, a Boolean, an array, an object, etc.

data type	pointed text (prefix)	depth
+document	{ "Width": 800, "Height": 60	1
+object	{ "Width": 800, "Height": 60	1
double	800, "Height": 600, "Title":	2
double	600, "Title": "View from my r	2
string	"View from my room", "Url": "	2
string	"http://ex.com/img.png", "Pri	2
bool	false, "Thumbnail": { "Url"	2
bool	false, "Thumbnail": { "Url"	2
+object	{ "Url": "http://ex.com/th.p	2
string	"http://ex.com/th.png", "Hei	3
double	125, "Width": 100 }, "arra	3
double	100 }, "array": [ 116, 9	3
-object	}, "array": [ 116, 943,	2
+array	[ 116, 943, 234 ], "Ow	2
double	116, 943, 234 ], "Owner"	3
double	943, 234 ], "Owner": null	3
double	234 ], "Owner": null }	3
-array	], "Owner": null }	2
skip	null }	2
-object	}	1

**TABLE 2** Representation of the state of our On-Demand pointer as we move through the document. The '+' and '-' prefix on the data types indicate the beginning and end of arrays and objects respectively.

## 4 | EXPERIMENTS

We benchmark our On-Demand front-end on a recent Intel architecture. We use a non-virtual (*metal*) server from Amazon Web Services (`c6i.metal`) configured with Ubuntu 22.04. These servers use 32-core Intel Xeon 8375C (Ice Lake) processors having 41 MiB of L3 memory: the cores have 48 kB of L1 data cache memory and 1.25 MiB of L2 cache memory. They are rated with a base clock frequency of 2.9 GHz and a maximal frequency of 3.5 GHz. The servers have 256 GiB of main memory (DDR4, 3200 MHz). The benchmarks are single-threaded and we exclude disk and network accesses from our tests.

The software is written in C++ and compiled with GCC 12 using the default CMake setting for a release build: `-O3 -DNDEBUG`. We do not compile for a specific processor architecture. The benchmarks are written using the Google Benchmark (v1.6.0) framework.<sup>3</sup>

<sup>3</sup><https://github.com/google/benchmark>

```

ondemand::parser parser;
auto cars_json = R"([
  {"make": "Toyota", "model": "Camry", "year": 2018,
  "tire_pressure": [40.1, 39.9, 37.7, 40.4]},
  {"make": "Kia", "model": "Soul", "year": 2012,
  "tire_pressure": [30.1, 31.0, 28.6, 28.7]},
  {"make": "Toyota", "model": "Tercel", "year": 1999,
  "tire_pressure": [29.8, 30.0, 30.2, 30.5]}
])"_padded;
// Iterating through an array of objects
for (ondemand::object car : parser.iterate(cars_json)) {
  // Accessing a field by name
  cout << "Model:_" << std::string_view(car["model"]) << endl;
  // Casting a JSON element to an integer
  uint64_t year = car["year"];
  cout << "-_This_car_is_" << 2020 - year << "years_old." << endl;
  // Iterating through an array of numbers
  double total_tire_pressure = 0;
  for (double tire_pressure : car["tire_pressure"]) {
    total_tire_pressure += tire_pressure;
  }
  cout << "-_Average_tire_pressure:_" << (total_tire_pressure / 4) << endl;
}

```

**FIGURE 3** On-Demand C++ example: it illustrates how we access key-value elements, handle integers and strings.

Our benchmarking code is *instrumented*: we use the performance counters of the processors to record the number instructions retired, the number of cycles and the number of mispredicted branches. It allows us to compute the actual average processor frequency: we verify that it can reach 3.5 GHz as expected.

To benchmark and validate our work, we need various tasks. Our goal is to compare On-Demand with existing generic JSON parsers. We choose to compare against the following state-of-the-art C++ standard-compliant parsers.

- The yyjson parser is a C library that was released shortly after the first release of the simdjson library. According to the author (private communication), the goal of the yyjson was to get as close as possible to simdjson, while using only generic C code. We use the version 0.5.1, released on June 17, 2022.
- In earlier work, Langdale and Lemire selected RapidJSON and sajson as references. In 2018, RapidJSON was described as the fastest traditional state-machine-based parser available [23]. Though they both have similar performance, sajson only does partial UTF-8 validation. Given the introduction of yyjson, we keep only RapidJSON (version 1.1.0, released in September 2018).
- We also include JSON for Modern C++ (version 3.10.5, from January 2022)—it is also known as Nlohmann/json. It is a popular parser.

Though there are many other libraries, in different programming languages, we believe that these three choices rep-



resent a good sample of competitive solutions. To test On-Demand, we use the `simdjson` library version 3.0 (released in October 2022<sup>4</sup>).

We use the JSON input as a database, and we seek to resolve some queries. We load all JSON documents in memory prior to running the benchmark; we omit disk and network accesses. Our main test document is the `twitter.json` file [8]: it is the result of a search for the character one in Japanese and Chinese using the Twitter API. It contains 631 515 bytes, 2108 integers, 18 099 strings, 1264 objects and 1050 arrays. We picked the following tasks.

- *json2msgpack*: We must validate and convert the `twitter.json` file into a binary MessagePack (MsgPack for short) equivalent. MessagePack is a binary format comparable to JSON [24]. We use a simple conversion: all numbers are mapped to double types, all strings are prefixed by a 32-bit counter, and so forth. All our implementations rely on a recursive function call where the type of the current document node is queried and used as part of a switch/case query. When an array or an object is encountered, its content is processed recursively. It is an instance where the entire content of the file is consumed.
- *partial tweets*: The `twitter.json` file consists of an object containing a field with the key `statuses` having as a value an array. Each element of the array is a tweet as a JSON object. We seek to extract from each tweet the fields `created_at`, `id`, `text`, `in_reply_to_status_id`, `retweet_count`, `favorite_count` and from a subobject associated with the key `user`, we want to acquire the user's `id` and the user's `screen_name`. We expect that such partial extraction of the content of a JSON document is common in practice.
- *distinct user*: In the `twitter.json` file, we seek to find all user identifiers (`id`) as 64-bit identifiers and store them in an array implemented as a `std::vector<uint64_t>` instance. They are found as part of tweets (`user/id`) or within retweet metadata (keys `retweeted_status/user/id`).
- *find tweet*: We seek the textual content (`text`) of the tweet having identifier 505874901689851904. There is only one such tweet.
- *top tweet*: We scan all tweets and report the most retweeted one (according to `retweet_count`), returning the `screen_name` of the author and the textual content (`text`).
- *kostya*: We reproduce the Kostya benchmark (see § 1 and Fig. 2), with less overhead and in a more controlled setting (Google Benchmark). We use 524 288 triples stored in memory. The benchmark computes the sums of the `x`, `y`, and `z` values.
- *large random*: We proceed with a task similar to the Kostya benchmark except that instead of summing up the values, we construction three-value vectors and we append them to an array. We create, in memory, a temporary JSON document made of 1 000 000 triples of floating-point values within objects (e.g., `"x":0.14323412321`, `"y":0.931321111`, `"z":0.0111141232312`).

Table 3 presents the processing speed for various tasks. We define the speed as the size of the input divided by the estimated elapsed time. Performance timings are heavily skewed toward the minimum; they do not follow a normal distribution [25]. Accordingly, we present the best processing speed (out of all runs) and the average processing speed. Except for the `json2msgpack` task, the On-Demand front-end is more than twice as fast as any competitor, except maybe for the DOM version of `simdjson`.

Table 4 presents the number of CPU instructions retired by input byte. The number of instructions required is stable in our tests (within 1%). We find that the On-Demand front-end requires far fewer instructions than the competitors.

<sup>4</sup><https://github.com/simdjson/simdjson>

**TABLE 3** Best and average processing speed in GiB s<sup>-1</sup> for various tasks and implementations.

task	simdjson (On Demand)	simdjson (DOM)	yyjson	RapidJSON	JSON for Modern C++
json2msgpack	2.5–2.7	1.8–2.0	0.81–1.3	0.41–0.45	0.025–0.027
partial tweets	5.3–5.8	3.2–3.4	1.0–2.0	0.40–0.49	0.096–0.11
distinct user	5.5–5.9	3.2–3.5	1.0–1.9	0.40–0.49	0.10–0.12
find tweet	9.0–9.8	3.4–3.7	1.0–2.1	0.41–0.51	0.12–0.13
top tweet	5.5–6.0	3.3–3.6	1.0–1.9	0.41–0.50	0.088–0.093
kostya	2.7–3.0	1.6–1.8	0.73–0.77	0.54–0.57	0.096–0.10
large random	0.94–0.99	0.53–0.56	0.37–0.39	0.24–0.26	0.045–0.048

**TABLE 4** Instructions per input byte for various task and JSON implementations.

task	simdjson (On Demand)	simdjson (DOM)	yyjson	RapidJSON	JSON for Modern C++
json2msgpack	4.4	5.7	6.6	24.9	391.
partial tweets	2.3	3.5	4.7	23.0	110.
distinct user	2.2	3.4	4.7	23.0	102.
find tweet	1.3	3.3	4.6	22.8	84.7
top tweet	2.2	3.4	4.6	22.9	121.
kostya	3.7	5.9	7.0	19.3	111.
large random	11.5	20.1	19.4	44.3	260.

## 5 | CONCLUSION

Our work suggests that On-Demand might be a better approach for parsing semi-structured text documents when high efficiency and high expressivity are important. To ensure reproducibility, our work is freely available as open source software.

Future work should assess the generality of On-Demand. We should write On-Demand front-end in other programming languages (e.g., Java, Rust, Go). We should apply it to other data sources (e.g., XML, CSV).

There are implementation design strategies that warrant further investigation. For example, our implementation relies on a precomputed index, giving us the location of structural characters: it makes our implementation convenient and the construction of the index is fast, but an On-Demand front-end may not require an index. Yet an even richer document index might prove more beneficial in some cases: instead of merely indexing the location of the objects, arrays and values, the index could be built with more information about the schema: e.g., the index could inform us that we have encountered an array made of  $n$  integers.

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