

# CAST: Columnar Agnostic Structural Transformation

A Schema-less Structural Preprocessing Algorithm for Improving General-Purpose  
Compression on Structured Data

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## Abstract

General-purpose compression algorithms such as LZ77, LZMA, and Zstandard rely on finite dictionary windows and local pattern matching to detect redundancy. While effective for unstructured text, these approaches often fail to fully exploit the long-range structural regularity present in machine-generated data, including CSV files, JSON documents, XML, and system logs.

We introduce **CAST** (Columnar Agnostic Structural Transformation), a schema-less structural pre-processing algorithm that infers repetitive layouts directly from the input stream. CAST decomposes each record into a static structural template (*Skeleton*) and a sequence of dynamic values (*Variables*), reorganizing the latter into column-aligned streams prior to compression. This transformation reduces structural entropy and exposes redundancy that is poorly captured by standard compressors operating on row-oriented text.

Experimental evaluation across diverse real-world datasets shows that CAST consistently improves compression density and, in many cases, reduces end-to-end compression time when paired with existing back-end compressors such as LZMA2. On highly repetitive structured datasets, compression ratios significantly exceed those obtained by standalone compressors, demonstrating that lightweight, schema-free structural normalization can substantially enhance general-purpose compression without modifying the underlying encoding algorithms.

## 1 Introduction

Machine-generated data (logs, IoT telemetry, database dumps) is characterized by rigid and repetitive structural patterns. Columnar storage formats such as Apache Parquet and ORC exploit this property effectively, but require explicit schemas and are therefore unsuitable for ad-hoc, semi-structured, or heterogeneous text archives. Conversely, general-purpose stream compressors such as `xz` (LZMA2) and `zstd` operate without schemas but are constrained by finite dictionary windows and local redundancy detection, often missing long-range structural repetition.

**CAST** proposes a middle ground: a schema-less structural transformation that reorganizes row-oriented text into column-oriented streams inferred dynamically from the data itself. Rather than introducing a new compression algorithm, CAST operates as a pre-processing stage that reshapes the input to better align with the strengths of existing compressors.

This paper details the CAST algorithm and its robustness mechanisms (Binary Guard). While the transformation is fundamentally backend-agnostic, this study evaluates its effectiveness specifically in combination with **LZMA2**, utilizing a performance-oriented Rust implementation. We test this engine in two configurations: **native library integration** to measure strict algorithmic efficiency, and **system-level backend (7-Zip)** to demonstrate real-world throughput. A simplified Python reference implementation is also provided to illustrate the core logic, prioritizing readability over performance.

## 2 Methodology

The fundamental premise of CAST is that structured text lines  $L$  can be decomposed into a static template  $S$  and a variable vector  $V$ :

$$L \rightarrow S + V$$

Standard compressors process  $S$  and  $V$  interleaved. CAST processes unique  $S$  sets (Skeletons) once, and  $V$  sets (Variables) as contiguous blocks grouped by column index.

### 2.1 Adaptive Pattern Recognition

The algorithm does not enforce a schema. Instead, it utilizes a **specialized parsing engine** to process lines. To accommodate different data types, it employs an adaptive strategy determined by analyzing the first  $N$  lines (default  $N = 1000$ ) of the input stream.

- **Strict Mode:** Captures quoted strings and explicit numbers. Best for JSON/XML.
- **Aggressive Mode:** Captures alphanumeric tokens. Best for log files with variable syntax.

**Heuristic thresholds** CAST performs a light-weight statistical analysis on the first  $N$  lines (default  $N = 1000$ ) to select the parsing mode. In our implementation we use the following empirically chosen thresholds: if the ratio of unique skeletons to sample lines exceeds 0.10 we switch from **Strict** to **Aggressive** parsing. To avoid template explosion, the compressor enforces a template budget of  $T_{max} = \alpha \cdot L$  (where  $L$  is number of lines and  $\alpha = 0.25$  in Strict,  $\alpha = 0.40$  in Aggressive); exceeding this budget triggers a safe passthrough (no structural transform).

**Graceful Degradation** The parsing mechanism is designed to handle schema drift without failure. If a line partially matches the **parsing rules**, the unmatched suffix is absorbed into the static skeleton rather than discarded. This ensures that irregular lines simply result in unique templates, allowing the algorithm to naturally degrade towards row-based compression behavior for noisy data, ensuring zero data loss.

### 2.2 Robustness: The Binary Guard

To prevent data corruption or inefficiency on non-textual files, CAST implements a "Binary Guard". Before processing, a 4KB sample is analyzed. If the density of non-printable control characters (excluding whitespace) exceeds 1%, the input is classified as binary. In this state, CAST enters a "Passthrough" mode, forwarding the raw byte stream directly to the backend compressor with zero structural modification.

## 3 Algorithm Detail

The core transformation logic executes a single-pass processing strategy (post-analysis) with a dynamic finalization step. The procedure is formally described in Algorithm 1.

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**Algorithm 1** CAST Compression Logic (overview)

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1: Input: Byte stream  $D$ 
2: if IsLikelyBinary( $D$ ) then
3:   return BackendCompress( $D$ )                                 $\triangleright$  Passthrough (backend-agnostic)
4: end if
// Phase 1: Heuristic Analysis
5:  $Strategy \leftarrow \text{AnalyzeSample}(D)$                        $\triangleright$  choose Strict/Aggressive; sample  $N$  lines
6:  $Map \leftarrow \{\}, Skeletons \leftarrow [], Columns \leftarrow \{\}, StreamIDs \leftarrow []$ 
// Phase 2: Decomposition
7: for line in  $D$  do
8:    $S, V \leftarrow \text{Mask}(\text{line}, Strategy)$ 
9:   if  $S \notin Map$  then
10:    if templates_exceed_budget() then
11:      return BackendCompress( $D$ )                                 $\triangleright$  Fallback: entropy limit
12:    end if
13:     $Map[S] \leftarrow \text{NewID}()$ 
14:     $Skeletons.append(S)$ 
15:  end if
16:   $ID \leftarrow Map[S]$ 
17:   $Columns[ID].append(V)$ 
18:   $StreamIDs.append(ID)$ 
19: end for
// Phase 3: Unified / Split decision (heuristic)
20:  $Decision \leftarrow \text{DecideUnifiedOrSplit}(Columns, Skeletons)$ 
21: if  $Decision$  is Unified then
22:    $B_{reg} \leftarrow \text{ToBytes}(Skeletons)$ 
23:    $B_{ids} \leftarrow \text{ToBytes}(StreamIDs)$ 
24:    $B_{vars} \leftarrow \text{ToBytes}(Columns)$ 
25:    $Blob \leftarrow \text{PackHeader}(B_{reg}, B_{ids}) + B_{vars}$ 
26:   return BackendCompress( $Blob$ )                                 $\triangleright$  e.g., LZMA2, Zstd, Brotli
27: else
28:    $C_{reg} \leftarrow \text{BackendCompress}(\text{ToBytes}(Skeletons))$ 
29:    $C_{ids} \leftarrow \text{BackendCompress}(\text{ToBytes}(StreamIDs))$ 
30:    $C_{vars} \leftarrow \text{BackendCompress}(\text{ToBytes}(Columns))$ 
31:   return Package( $C_{reg}, C_{ids}, C_{vars}$ )
32: end if
```

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**Unified vs Split decision heuristic** To balance compression density against memory usage, CAST employs a lightweight heuristic primarily based on template cardinality. For datasets with a limited set of unique structures ( $\text{num\_templates} < 256$ ), the algorithm **defaults to Unified Mode** to maximize the shared dictionary context of the backend compressor, **unless a preliminary sampling test detects poor compressibility**. Conversely, when template diversity is high, it strictly enforces *Split Mode* to improve parallelism and reduce the overhead of managing a single monolithic context window.

**Serialization format** Skeletons are concatenated into a registry separated by the unambiguous control byte 0x1E (ASCII **RS**). Variables are organized per-column and serialized using a row separator (0x00) and a column separator (unified mode uses 0x02, split mode uses the two-byte marker 0xFF 0xFF).

To ensure bitwise reversibility in **Unified Mode**, CAST applies a byte-stuffing escape scheme: escape byte 0x01 is doubled (0x01 0x01), row separator is escaped as 0x01 0x00, and the uni-

fied column separator (0x02) as 0x01 0x03.

Conversely, **Split Mode** prioritizes throughput by bypassing the escape layer, utilizing the marker 0xFF 0xFF.

Since CAST transcodes all variables to UTF-8 for storage (where the byte 0xFF is invalid), this separator ensures deterministic collision avoidance for textual data. The decompressor performs the inverse unescaping prior to reconstruction.

**Template ID encoding** To minimize metadata overhead, template stream ids are encoded using one of four modes depending on the number of distinct templates:

- **Mode 3:** single template (no ids stored)
- **Mode 2:** 8-bit ids
- **Mode 0:** 16-bit ids
- **Mode 1:** 32-bit ids

The encoder selects the smallest-width representation that can store all template identifiers and records a compact id-mode flag in the header.

**Integrity** For unified (solid) compression CAST stores a compact header with lengths and relies on the underlying compressor integrity check (e.g., LZMA CRC32) and, optionally, an explicit CRC32 verification of the reconstructed payload to ensure bit-perfect lossless round-trip. To guarantee strictly lossless reconstruction (including mixed line-endings like CRLF/LF), the line parsing phase explicitly preserves original terminators.

## 4 Performance Evaluation

To validate the efficacy of CAST across different domains, we compiled a heterogeneous corpus of datasets sourced from **Kaggle** and public open-data repositories (e.g., Stats NZ). The selection includes financial records, IoT telemetry, server logs, and linguistic corpora, ensuring the algorithm is tested against a wide spectrum of structural entropy profiles.

To fully evaluate the algorithm's capabilities, we utilized two different **Rust implementations**. These implementations features native **multi-threading** capabilities and a configurable **chunk-size** parameter used to split large input files into manageable segments, preventing memory saturation and enabling the processing of datasets larger than available RAM.

We evaluated this engine in two specific configurations:

- **Native Mode:** Links directly against native libraries.  
While this implementation fully supports multi-threading and configurable chunking, for the compression ratio analysis it was restricted to single-threaded, monolithic execution to strictly isolate the algorithmic efficiency of the structural transformation without the masking effects of parallelization or context fragmentation.
- **System Mode (7-Zip Backend):** Pipes data to the external **7z** executable.  
This configuration leverages the robust **multi-threading** of the backend tool to demonstrate real-world scalability and industrial throughput.  
Consequently, this benchmark scenario includes additional large-scale datasets (e.g., 500 MB+) to stress-test the pipeline under heavy load conditions.

We benchmarked CAST against three state-of-the-art compression algorithms to provide a comprehensive landscape:

- **LZMA2 (XZ):** Preset 9 (Extreme) with a 128 MB dictionary. To guarantee a strictly fair comparison, we utilize the exact same engine as the CAST backend: the shared native library for the Native Mode tests, and the identical 7-Zip binary/arguments for the System Mode tests.
- **Zstandard (Zstd):** Level 22 (Ultra), representing modern high-performance compression.
- **Brotli:** Quality 11 (Max), widely used for web content optimization.

To ensure a comprehensive assessment, the benchmarks distinguish between three key performance metrics:

1. **Algorithmic Efficiency (Compression Ratio):** The reduction in file size compared to the original raw data, measured using the **Native Mode** to ensure binary-level precision.
2. **Compression Throughput:** The speed at which the algorithm transforms and writes data. We evaluate this primarily using the **System Mode** (7-Zip backend) to simulate a realistic production pipeline involving parallelized external tools.
3. **Restoration Latency (Decompression):** Unlike standard algorithms where decompression is a linear byte-stream inflation, CAST requires a *structural reconstruction phase*. We measure this overhead using **both configurations** to differentiate between the intrinsic algorithmic cost (Native Mode) and the end-to-end restoration time including external process management (System Mode).

#### 4.1 Compression Ratio (Rust Native Mode)

Table 1 illustrates the reduction in file size and processing time across different algorithms using the Rust Native implementation.

Table 1: Compression Ratio Benchmark Results

| Dataset                        | Original | LZMA2                   | Zstd                     | Brotli                | CAST (ours)              |
|--------------------------------|----------|-------------------------|--------------------------|-----------------------|--------------------------|
| <i>CSV Datasets</i>            |          |                         |                          |                       |                          |
| <b>Balance Payments</b>        | 33.2 MB  | 501 KB (110s)           | 698 KB (103s)            | 592 KB (131s)         | <b>245 KB (4.7s)</b>     |
| <b>Migration Stats</b>         | 29.3 MB  | 945 KB (56s)            | 1.12 MB (49s)            | 1.06 MB (87s)         | <b>319 KB (4.6s)</b>     |
| <b>Subnat. Life Tables</b>     | 16.0 MB  | 608 KB (13.8s)          | 713 KB (9.9s)            | 564 KB (52.5s)        | <b>324 KB (3.5s)</b>     |
| <b>NZDep Life Tables</b>       | 13.1 MB  | 1.16 MB (8.6s)          | 1.26 MB (6.5s)           | 1.14 MB (29s)         | <b>881 KB (2.8s)</b>     |
| <b>Custom 2020</b>             | 207.9 MB | 24.8 MB (463s)          | 26.4 MB (355s)           | 25.2 MB (511s)        | <b>18.4 MB (167s)</b>    |
| <b>US Stock Prices</b>         | 224.2 MB | 26.9 MB (712s)          | 29.1 MB (521s)           | 27.9 MB (495s)        | <b>17.4 MB (140s)</b>    |
| <b>PaySim Mobile Money</b>     | 493.5 MB | 148.8 MB (756s)         | 150.8 MB (578s)          | 154.9 MB (1103s)      | <b>130.1 MB (574s)</b>   |
| <b>Covid Vaccinations</b>      | 50.8 MB  | 4.65 MB (48s)           | 5.09 MB (39s)            | 4.58 MB (158s)        | <b>4.13 MB (21s)</b>     |
| <b>HAI Security Train</b>      | 114.2 MB | 19.0 MB (123s)          | 19.6 MB (92s)            | 19.2 MB (246s)        | <b>13.0 MB (67s)</b>     |
| <b>Train/Test Network</b>      | 29.9 MB  | 1.05 MB (32.8s)         | 1.16 MB (26.2s)          | 1.10 MB (94.2s)       | <b>0.89 MB (6.6s)</b>    |
| <b>NYC Bus Breakdowns</b>      | 132.9 MB | 9.79 MB (165s)          | 10.4 MB (127s)           | 10.9 MB (317s)        | <b>8.40 MB (93s)</b>     |
| <b>IOT-temp</b>                | 6.95 MB  | 788 KB (10.0s)          | 828 KB (8.6s)            | 797 KB (16.0s)        | <b>728 KB (5.2s)</b>     |
| <b>Apple Sitemap</b>           | 124.2 MB | 2.21 MB (178s)          | 2.51 MB (218s)           | 2.50 MB (508s)        | <b>1.87 MB (34s)</b>     |
| <b>Nashville Housing</b>       | 9.9 MB   | 1.41 MB (8.2s)          | 1.49 MB (5.9s)           | 1.41 MB (22s)         | <b>1.30 MB (5.3s)</b>    |
| <b>Item Aliases</b>            | 201.5 MB | 40.3 MB (436s)          | 43.6 MB (301s)           | 43.4 MB (370s)        | <b>40.2 MB (240s)</b>    |
| <b>IoT Intrusion</b>           | 197.5 MB | 25.1 MB (272s)          | 25.9 MB (195s)           | 28.0 MB (521s)        | <b>24.0 MB (135s)</b>    |
| <b>Gafgyt Botnet</b>           | 105.8 MB | 25.8 MB (205s)          | 25.7 MB (187s)           | <b>24.7 MB (291s)</b> | 25.2 MB (126s)           |
| <b>HomeC</b>                   | 131.0 MB | 14.9 MB (257s)          | 15.6 MB (195s)           | 15.6 MB (330s)        | <b>11.2 MB (104s)</b>    |
| <b>DDoS Data</b>               | 616.8 MB | 19.7 MB (1607s)         | 24.4 MB (1598s)          | 22.0 MB (1972s)       | <b>10.3 MB (417s)</b>    |
| <b>Wireshark</b>               | 154.4 MB | 9.52 MB (457s)          | 10.8 MB (302s)           | 10.1 MB (403s)        | <b>5.69 MB (167s)</b>    |
| <b>RT_IOT2022</b>              | 54.8 MB  | 2.53 MB (144s)          | 2.53 MB (221s)           | 2.51 MB (47.4s)       | <b>1.99 MB (18.5s)</b>   |
| <b>Metasploitable</b>          | 52.8 MB  | 3.71 MB (33.5s)         | 3.83 MB (40.5s)          | 3.71 MB (158s)        | <b>3.53 MB (19s)</b>     |
| <b>Owid Covid</b>              | 46.7 MB  | 7.08 MB (55s)           | 7.49 MB (47s)            | 6.92 MB (126s)        | <b>6.39 MB (26s)</b>     |
| <b>Assaults 2015</b>           | 234 KB   | <b>33.9 KB (0.16s)</b>  | 37.6 KB (0.36s)          | 34.0 KB (0.41s)       | 39.6 KB ( <b>0.12s</b> ) |
| <b>ChatGPT Paraphrases</b>     | 264.9 MB | <b>40.1 MB (259s)</b>   | 40.5 MB ( <b>200s</b> )  | 44.4 MB (523s)        | 44.8 MB (262s)           |
| <b>Dielectron Collision</b>    | 14.7 MB  | 5.71 MB (14.2s)         | 6.08 MB ( <b>12.0s</b> ) | 5.88 MB (33s)         | <b>5.26 MB (12.6s)</b>   |
| <b>Smart City Sensors</b>      | 24.2 MB  | 1.02 MB (54s)           | 1.14 MB (47s)            | 1.05 MB (58s)         | <b>578 KB (3.6s)</b>     |
| <i>JSON &amp; XML Datasets</i> |          |                         |                          |                       |                          |
| <b>Wikidata Fanout</b>         | 262.3 MB | 33.0 MB (284s)          | 38.2 MB (205s)           | 34.8 MB (533s)        | <b>28.5 MB (181s)</b>    |
| <b>Gandhi Works</b>            | 100.6 MB | 20.6 MB (106s)          | 20.9 MB ( <b>84s</b> )   | 22.5 MB (217s)        | <b>20.3 MB (92s)</b>     |
| <b>Yelp Business</b>           | 118.9 MB | <b>9.87 MB (123s)</b>   | 10.2 MB (102s)           | 11.2 MB (293s)        | 10.4 MB ( <b>73s</b> )   |
| <b>Yelp Tips</b>               | 180.6 MB | 34.2 MB (188s)          | 34.7 MB (132s)           | 44.1 MB (376s)        | <b>30.6 MB (107s)</b>    |
| <b>Yelp Checkin</b>            | 287.0 MB | 54.1 MB (500s)          | 61.9 MB ( <b>386s</b> )  | 59.7 MB (866s)        | <b>53.6 MB (422s)</b>    |
| <b>Parent Child Dict</b>       | 214.5 MB | 29.1 MB (293s)          | 32.9 MB (235s)           | 31.6 MB (478s)        | <b>28.4 MB (200s)</b>    |
| <b>Wiki 00c2bfc7-.json</b>     | 41.2 MB  | 10.26 MB (51s)          | 10.50 MB ( <b>41s</b> )  | 10.80 MB (107s)       | <b>10.24 MB (49s)</b>    |
| <b>Wiki 07ccb171-.json</b>     | 41.5 MB  | 10.05 MB (42s)          | 10.30 MB ( <b>35s</b> )  | 10.60 MB (96s)        | <b>10.02 MB (40s)</b>    |
| <b>GloVe Emb.</b>              | 193.4 MB | 57.7 MB (400s)          | 57.9 MB ( <b>231s</b> )  | 60.3 MB (501s)        | <b>57.1 MB (401s)</b>    |
| <b>Pagerank</b>                | 121.9 MB | 14.8 MB ( <b>127s</b> ) | 15.2 MB (136s)           | 16.5 MB (289s)        | <b>14.7 MB (129s)</b>    |
| <b>Brazil Geo</b>              | 14.5 MB  | 1.55 MB (8.2s)          | 1.64 MB ( <b>6.1s</b> )  | 1.67 MB (27s)         | <b>1.53 MB (9.8s)</b>    |
| <b>CERN OpenData Slim</b>      | 211.9 MB | 16.1 MB (393s)          | 17.0 MB (362s)           | 16.4 MB (510s)        | <b>15.2 MB (327s)</b>    |
| <i>Logs and SQL Datasets</i>   |          |                         |                          |                       |                          |
| <b>Logfiles</b>                | 242.0 MB | 12.9 MB (306s)          | 13.3 MB (217s)           | 14.2 MB (679s)        | <b>10.3 MB (131s)</b>    |
| <b>Weblog Sample</b>           | 67.6 MB  | 2.65 MB (67s)           | 2.88 MB (60s)            | 3.07 MB (204s)        | <b>2.53 MB (34s)</b>     |
| <b>Audit Dump (SQL)</b>        | 64.6 MB  | 12.0 MB (135s)          | 12.6 MB (109s)           | 12.1 MB (146s)        | <b>10.2 MB (35s)</b>     |
| <b>Sakila DB</b>               | 8.8 MB   | 427 KB (26s)            | 502 KB (21s)             | 466 KB (28s)          | <b>298 KB (2.2s)</b>     |
| <b>XDados</b>                  | 4.4 MB   | 535 KB (3.1s)           | 597 KB ( <b>2.2s</b> )   | 536 KB (9.7s)         | <b>420 KB (3.4s)</b>     |
| <b>Pixel 4XL GNSS Log</b>      | 130.5 MB | 32.1 MB (207s)          | 33.3 MB ( <b>150s</b> )  | 31.5 MB (297s)        | <b>25.0 MB (219s)</b>    |
| <b>Cross Reference</b>         | 12.0 MB  | 1.15 MB (15.7s)         | 1.28 MB (12.1s)          | 1.34 MB (26s)         | <b>1.08 MB (9.1s)</b>    |
| <b>Bible MySQL</b>             | 32.3 MB  | <b>4.30 MB (39s)</b>    | 4.45 MB ( <b>32s</b> )   | 6.42 MB (69s)         | 4.30 MB (42s)            |
| <i>Text Datasets</i>           |          |                         |                          |                       |                          |
| <b>Tatoeba French</b>          | 26.9 MB  | <b>3.69 MB (24.5s)</b>  | 3.87 MB ( <b>20.5s</b> ) | 3.81 MB (51s)         | 5.14 MB (25s)            |
| <b>Election Day Tweets</b>     | 35.9 MB  | <b>10.1 MB (31s)</b>    | 10.2 MB ( <b>24s</b> )   | 10.4 MB (74s)         | 12.1 MB (38s)            |

## 4.2 Throughput Analysis (Rust + 7-Zip as backend)

A common drawback of pre-processing is added latency. However, Table 2 demonstrates that the Rust System Mode implementation of CAST (which invokes 7-Zip as a threaded backend) achieves higher throughput than applying 7-Zip directly to the raw file.

**Controlled Environment & Analysis:** To ensure a strictly fair comparison, the control group ("LZMA2 (7-Zip)") employs the exact same compression binary and threading configuration used by the CAST backend.

Consequently, the observed speedup is attributable solely to the entropy reduction achieved by the structural transformation.

Although CAST adds a parsing step, the resulting column-aligned streams (e.g., continuous integers or timestamps) are significantly less computationally expensive for the LZMA encoder to process than the raw chaotic text, resulting in a net reduction of total processing time.

Table 2: Performance Benchmark: Size &amp; Time (Rust + 7-Zip)

| Dataset                        | Original  | LZMA2<br>(7-Zip)         | CAST<br>(Rust Native)  | CAST<br>(Rust+7-Zip)       | Speedup<br>(vs LZMA2) |
|--------------------------------|-----------|--------------------------|------------------------|----------------------------|-----------------------|
| <i>CSV Datasets</i>            |           |                          |                        |                            |                       |
| <b>Balance Payments</b>        | 33.1 MB   | 834 KB (2.02s)           | <b>245 KB (4.7s)</b>   | 255 KB ( <b>0.75s</b> )    | <b>2.69x</b>          |
| <b>Migration Stats</b>         | 29.2 MB   | 1.38 MB (4.64s)          | <b>319 KB (4.6s)</b>   | 343 KB ( <b>1.16s</b> )    | <b>4.00x</b>          |
| <b>Subnat. Life Tables</b>     | 16.0 MB   | 824 KB (2.65s)           | <b>324 KB (3.5s)</b>   | 344 KB ( <b>0.81s</b> )    | <b>3.27x</b>          |
| <b>NZDep Life Tables</b>       | 13.0 MB   | 1.20 MB (2.73s)          | <b>881 KB (2.8s)</b>   | 882 KB ( <b>1.08s</b> )    | <b>2.53x</b>          |
| <b>Custom 2020</b>             | 207.9 MB  | 25.3 MB (89.4s)          | <b>18.4 MB (167s)</b>  | 19.0 MB ( <b>53.2s</b> )   | <b>1.68x</b>          |
| <b>Custom 2018</b>             | 668.3 MB  | 56.6 MB (105s)           | -                      | <b>25.9 MB (78.7s)</b>     | <b>1.33x</b>          |
| <b>US Stock Prices</b>         | 213.82 MB | 27.18 MB (94.09s)        | <b>17.4 MB (140s)</b>  | 16.69 MB (48s)             | <b>1.96x</b>          |
| <b>PaySim Mobile Money</b>     | 470.6 MB  | 143.27 MB (283s)         | 130.1 MB (574s)        | <b>125.6 MB (264s)</b>     | <b>1.07x</b>          |
| <b>HAI Security Train</b>      | 108.91 MB | 18.27 MB (53.1s)         | 13.0 MB (67s)          | <b>12.4 MB (29.8s)</b>     | <b>1.78x</b>          |
| <b>Train/Test Network</b>      | 28.5 MB   | 1.29 MB (3.89s)          | <b>0.89 MB (6.6s)</b>  | <b>0.89 MB (1.82s)</b>     | <b>2.14x</b>          |
| <b>NYC Bus Breakdowns</b>      | 126.71 MB | 10.55 MB (40.2s)         | <b>8.40 MB (93s)</b>   | 8.24 MB ( <b>24.1s</b> )   | <b>1.67x</b>          |
| <b>IOT Temp</b>                | 6.9 MB    | 787 KB (1.45s)           | 728 KB (5.2s)          | <b>724 KB (0.94s)</b>      | <b>1.54x</b>          |
| <b>Sitemap Apple</b>           | 124.2 MB  | 2.69 MB (9.25s)          | <b>1.87 MB (34s)</b>   | 1.99 MB ( <b>6.51s</b> )   | <b>1.42x</b>          |
| <b>Nashville Housing</b>       | 9.9 MB    | 1.42 MB (2.36s)          | 1.30 MB (5.3s)         | <b>1.28 MB (1.74s)</b>     | <b>1.36x</b>          |
| <b>Item Aliases</b>            | 201.5 MB  | 40.6 MB ( <b>83.7s</b> ) | 40.2 MB (240s)         | <b>40.1 MB (91.1s)</b>     | 0.92x                 |
| <b>IoT Intrusion</b>           | 197.5 MB  | 28.2 MB (99.7s)          | <b>24.0 MB (135s)</b>  | 24.2 MB ( <b>63.5s</b> )   | <b>1.57x</b>          |
| <b>Gafgyt Botnet</b>           | 105.8 MB  | 26.3 MB (74.9s)          | <b>25.2 MB (126s)</b>  | 25.3 MB ( <b>69.0s</b> )   | <b>1.09x</b>          |
| <b>HomeC</b>                   | 131.0 MB  | 15.4 MB (54.6s)          | <b>11.2 MB (104s)</b>  | 11.7 MB ( <b>35.7s</b> )   | <b>1.53x</b>          |
| <b>DDoS Data</b>               | 616.8 MB  | 20.4 MB (81.1s)          | <b>10.3 MB (417s)</b>  | 10.9 MB ( <b>37.3s</b> )   | <b>2.17x</b>          |
| <b>Wireshark P3</b>            | 154.4 MB  | 10.6 MB (47.7s)          | <b>5.69 MB (167s)</b>  | 6.94 MB ( <b>32.1s</b> )   | <b>1.49x</b>          |
| <b>RT_IOT2022</b>              | 54.8 MB   | 2.56 MB (8.66s)          | <b>1.99 MB (18.5s)</b> | 2.01 MB ( <b>5.9s</b> )    | <b>1.47x</b>          |
| <b>Metasploitable</b>          | 52.8 MB   | 3.87 MB (11.3s)          | 3.53 MB (19s)          | <b>3.52 MB (6.92s)</b>     | <b>1.63x</b>          |
| <b>OWID Covid</b>              | 46.7 MB   | 7.20 MB (15.7s)          | 6.39 MB (26s)          | <b>6.36 MB (13.2s)</b>     | <b>1.19x</b>          |
| <b>Assaults 2015</b>           | 234 KB    | <b>34.4 KB (0.06s)</b>   | 39.6 KB (0.12s)        | 39.9 KB (0.07s)            | 0.86x                 |
| <b>ChatGPT Paraphrases</b>     | 252.6 MB  | <b>38.3 MB (142.4s)</b>  | 44.8 MB (262s)         | 42.6 MB (151.3s)           | 0.94x                 |
| <b>Dielectron Collision</b>    | 14.06 MB  | 5.44 MB (8.46s)          | 5.26 MB (12.6s)        | <b>4.99 MB (8.20s)</b>     | <b>1.03x</b>          |
| <b>Smart City Sensors</b>      | 23.04 MB  | 1.23 MB (5.88s)          | 578 KB (3.6s)          | <b>0.57 MB (1.0s)</b>      | <b>5.88x</b>          |
| <b>H1B Data</b>                | 756.6 MB  | <b>45.5 MB (106.1s)</b>  | -                      | 53.7 MB ( <b>94.9s</b> )   | <b>1.12x</b>          |
| <b>SQL Injection</b>           | 1004.5 MB | <b>60.1 MB (97.4s)</b>   | -                      | 62.1 MB (182s)             | 0.54x                 |
| <b>COVID-19 Surveillance</b>   | 872.1 MB  | 32.8 MB (63.5s)          | -                      | <b>22.3 MB (50.4s)</b>     | <b>1.26x</b>          |
| <i>JSON &amp; XML Datasets</i> |           |                          |                        |                            |                       |
| <b>Wikidata Fanout</b>         | 262.3 MB  | 33.4 MB (139s)           | 28.5 MB (181s)         | <b>27.8 MB (119s)</b>      | <b>1.17x</b>          |
| <b>Gandhi Works</b>            | 100.6 MB  | 20.8 MB (55.4s)          | <b>20.3 MB (92s)</b>   | <b>20.3 MB (55.2s)</b>     | <b>1.00x</b>          |
| <b>Yelp Business</b>           | 118.9 MB  | 11.1 MB (32.5s)          | <b>10.4 MB (73s)</b>   | 10.9 MB ( <b>23.6s</b> )   | <b>1.38x</b>          |
| <b>Yelp Tips</b>               | 180.6 MB  | 35.0 MB (79.3s)          | 30.6 MB (107s)         | <b>30.4 MB (53s)</b>       | <b>1.50x</b>          |
| <b>Yelp Checkin</b>            | 287.0 MB  | 55.0 MB ( <b>157s</b> )  | <b>53.6 MB (422s)</b>  | 54.2 MB (169s)             | 0.93x                 |
| <b>Parent-Child Dict</b>       | 214.5 MB  | 29.5 MB (120s)           | <b>28.4 MB (200s)</b>  | 28.8 MB ( <b>119s</b> )    | <b>1.01x</b>          |
| <b>Wiki 00c2bfc7-.json</b>     | 41.2 MB   | 10.3 MB ( <b>17.7s</b> ) | <b>10.2 MB (49s)</b>   | <b>10.2 MB (18.6s)</b>     | 0.95x                 |
| <b>Wiki 07cbb171-.json</b>     | 41.5 MB   | 10.1 MB ( <b>17.4s</b> ) | <b>10.0 MB (40s)</b>   | <b>10.0 MB (18.7s)</b>     | 0.93x                 |
| <b>Glove Emb.</b>              | 193.4 MB  | 58.1 MB ( <b>179s</b> )  | <b>57.1 MB (401s)</b>  | 57.8 MB (195s)             | 0.92x                 |
| <b>Pagerank</b>                | 121.9 MB  | 15.8 MB ( <b>45.4s</b> ) | <b>14.7 MB (129s)</b>  | 15.7 MB (48.6s)            | 0.93x                 |
| <b>Brazil Geo</b>              | 14.5 MB   | 1.55 MB ( <b>2.52s</b> ) | 1.53 MB (9.8s)         | <b>1.5 MB (3.03s)</b>      | 0.83x                 |
| <b>CERN OpenData Slim</b>      | 202.12 MB | 16.66 MB (49.76s)        | <b>15.2 MB (327s)</b>  | 15.42 MB ( <b>45.69s</b> ) | <b>1.09x</b>          |
| <i>Logs &amp; SQL Datasets</i> |           |                          |                        |                            |                       |
| <b>IOTA logs 2.21 (merge)</b>  | 1.48 GB   | 73.1 MB (83.6s)          | -                      | <b>40.8 MB (80.2s)</b>     | <b>1.04x</b>          |
| <b>Logfiles</b>                | 242.0 MB  | 15.7 MB (52.6s)          | <b>10.3 MB (131s)</b>  | 11.9 MB ( <b>33.2s</b> )   | <b>1.58x</b>          |
| <b>Weblog Sample</b>           | 67.6 MB   | 3.16 MB (9.09s)          | <b>2.53 MB (34s)</b>   | 2.90 MB ( <b>7.7s</b> )    | <b>1.18x</b>          |
| <b>Audit Dump (SQL)</b>        | 64.6 MB   | 12.4 MB (27.1s)          | 10.2 MB (35s)          | <b>10.0 MB (14.3s)</b>     | <b>1.90x</b>          |
| <b>Sakila Insert</b>           | 8.8 MB    | 492 KB (0.97s)           | 298 KB (2.2s)          | <b>297 KB (0.53s)</b>      | <b>1.83x</b>          |
| <b>Xdados</b>                  | 4.4 MB    | 533 KB ( <b>1.10s</b> )  | <b>420 KB (3.4s)</b>   | 433 KB (1.26s)             | 0.87x                 |
| <b>Cross Reference</b>         | 11.5 MB   | 1.11 MB (3.72s)          | 1.08 MB (9.1s)         | <b>1.04 MB (2.44s)</b>     | <b>1.52x</b>          |
| <b>Bible MySQL</b>             | 30.8 MB   | <b>4.16 MB (15.1s)</b>   | 4.30 MB (42s)          | <b>4.16 MB (16.02s)</b>    | 0.94x                 |
| <i>Text Datasets</i>           |           |                          |                        |                            |                       |
| <b>Tatoeba French</b>          | 26.9 MB   | <b>3.74 MB (8.09s)</b>   | 5.14 MB (25s)          | 5.02 MB (9.3s)             | 0.87x                 |
| <b>Election Day Tweets</b>     | 34.26 MB  | <b>9.64 MB (13.44s)</b>  | 12.1 MB (38s)          | 11.27 MB (17.3s)           | 0.78x                 |
| <b>Pixel 4XL GNSS Log</b>      | 124.43 MB | 30.87 MB (90.66s)        | 25.0 MB (219s)         | <b>24.3 MB (76.13s)</b>    | <b>1.19x</b>          |

### 4.3 Decompression and Reconstruction Analysis

CAST involves an additional *reconstruction phase*: the algorithm must re-interleave the decompressed columnar data back into the original row-based textual format. Table 3 compares the restoration time between the Rust Native implementation and the Rust implementation using the 7-Zip backend.

#### Analysis:

- **Reconstruction Overhead:** The results confirm that the structural reconstruction cost is negligible. The optimized Rust engine efficiently handles the re-interleaving process, performing restoration with minimal latency overhead.
- **Native vs. External Backend:** The System Mode (Rust + 7-Zip) generally outperforms the Native version on larger files due to 7-Zip’s highly optimized multi-threaded decoding engine. However, the Native implementation is competitive and occasionally faster on smaller datasets, likely due to the absence of process-spawning overhead.

Table 3: Decompression Time Comparison: Rust Native vs Rust +7-Zip

| Dataset                                | Original Size | Compressed Size ( $\approx$ ) | Rust (Native) | Rust (+7-Zip) |
|--|---------------|-------------------------------|---------------|---------------|
| <i>CSV Datasets</i>                    |               |                               |               |               |
| <a href="#">US Stock Prices</a>        | 213.82 MB     | 16.7 MB                       | 3.90s         | <b>3.29s</b>  |
| <a href="#">PaySim Mobile Money</a>    | 470.6 MB      | 125 MB                        | 13.76s        | <b>9.59s</b>  |
| <a href="#">HAI Security Train</a>     | 108.91 MB     | 12 MB                         | 2.59s         | <b>1.93s</b>  |
| <a href="#">NYC Bus Breakdowns</a>     | 126.71 MB     | 8 MB                          | <b>3.14s</b>  | 3.25s         |
| <a href="#">ChatGPT Paraphrases</a>    | 252.6 MB      | 43 MB                         | 5.67s         | <b>4.70s</b>  |
| <a href="#">Dielectron Collision</a>   | 14.06 MB      | 5 MB                          | <b>0.45s</b>  | 1.20s         |
| <a href="#">Smart City Sensors</a>     | 23.04 MB      | 0.57 MB                       | 0.22s         | <b>0.20s</b>  |
| <a href="#">Item Aliases</a>           | 201.5 MB      | 40 MB                         | <b>5.48s</b>  | 6.01s         |
| <i>JSON &amp; XML Datasets</i>         |               |                               |               |               |
| <a href="#">CERN OpenData Slim</a>     | 202.12 MB     | 15 MB                         | 4.10s         | <b>3.21s</b>  |
| <a href="#">Recipes JSON</a>           | 85.2 MB       | 6 MB                          | 1.34s         | <b>1.04s</b>  |
| <i>Logs &amp; SQL Datasets</i>         |               |                               |               |               |
| <a href="#">IOTA logs 2.21 (merge)</a> | 1.48 GB       | 41 MB                         | 34.60s        | <b>26.17s</b> |
| <i>Text Datasets</i>                   |               |                               |               |               |
| <a href="#">Election Day Tweets</a>    | 34.26 MB      | 11 MB                         | <b>2.11s</b>  | 2.75s         |
| <a href="#">Pixel 4XL GNSS Log</a>     | 124.43 MB     | 24 MB                         | 2.92s         | <b>2.33s</b>  |

**Theoretical Complexity:** Unlike iterative compression which requires costly pattern matching ( $O(N \cdot W)$  where  $W$  is window size), the reconstruction phase is strictly linear  $O(N)$ . The decoder operates via direct memory copying of pre-calculated offsets, meaning throughput is bounded primarily by memory bandwidth rather than CPU cycles. This explains why the Rust implementation achieves restoration speeds comparable to raw I/O.

## 5 Limitations & Constraints

1. **Binary & High Entropy Data:** As evidenced by benchmarks, CAST provides no benefit for binary/high entropy data. The Binary Guard correctly identifies these files, resulting in performance identical to standard LZMA2 (Equal size/time), but no gain.
2. **Vector Data:** On datasets consisting primarily of high-variance floating point numbers (e.g., GloVe Embeddings), the structural overhead matches the compression gain, resulting in a ratio gain of only 1.00x.
3. **Small Files:** For files under 1MB, the overhead of the CAST header and dictionary structure may result in a slightly larger file size compared to raw compression.
4. **Implementation Maturity (PoC):** The implementations presented are designed as **scientific proofs-of-concept**.

While functional and quite robust, they lack the extensive error handling, fuzz-testing, and security auditing required for deployment in mission-critical production environments. Future engineering efforts will focus on hardening the codebase against malformed inputs and optimizing memory safety for edge cases.

## 6 Related Work

CAST intersects with several areas in data representation and compression. Here we position the contribution relative to prior art.

**Columnar storage** Formats such as Apache Parquet and ORC store data column-wise and apply per-column encodings and compression; they require explicit schemas and are optimized for analytic workloads. CAST aims to bring columnar-like entropy reduction to schema-less, textual inputs without requiring an upfront schema or a separate storage format.

**Grammar- and dictionary-based compressors** Grammar-based compressors (e.g., Sequitur, RePair) and enhanced dictionary approaches build global structures representing repeated substrings or phrases. These approaches are related in spirit but differ: CAST focuses on structural decomposition (skeletons vs. variables) and explicit columnar reassembly rather than general grammar induction.

**Preconditioning and transform filters** Transforms such as Delta encoding, Burrows–Wheeler Transform (BWT), and dictionary pre-filters are commonly used as preprocessing steps. CAST is another form of preconditioning that targets structural redundancy instead of numeric locality or symbol re-ordering.

**XML/JSON specific compressors** Specialized compressors and encodings for XML (e.g., EXI) and JSON exploit known grammars or schemas. CAST differs by being *schema-free* and by attempting runtime inference for a broad class of structured text.

**Summary** CAST does not replace these techniques but complements them: it is a lightweight, reversible structural normalization layer intended to be stacked before a conventional backend compressor.

## 7 Reproducibility

Source code and benchmarking scripts are available in the project repository. To ensure reproducibility without distributing large third-party files, the datasets used are all publicly available, with their specific sources cited directly in this paper and listed in the repository documentation. Benchmarks were executed on a commodity workstation running **Windows 10 Pro for Workstations** (Build 19045), equipped with a 6th-generation **Intel Core i7 CPU** (Skylake architecture, 3.40 GHz) and 16 GB of physical RAM. Experiments were conducted using native Rust builds (`rustc 1.92.0`), Python 3.10 and 7-Zip 23.01.

Exact invocation commands are documented in the repository. Additionally, the benchmarking CLI tool is designed to explicitly output the internal decision metrics (Unified/Split mode, parsing strategy, template counts) to the standard output during execution, allowing the adaptive behavior of CAST to be inspected and verified for each run.

## 8 Conclusion

This work demonstrates that structural pre-processing can significantly enhance the effectiveness of general-purpose compression algorithms when applied to structured text data. By dynamically inferring and separating static templates from variable fields, CAST reshapes row-oriented text into column-aligned streams that better expose redundancy to standard compressors.

While CAST does not provide benefits for binary or high-entropy data, empirical results show substantial improvements in both compression ratio and throughput for logs, CSV files, and semi-structured datasets. These findings indicate that schema-free structural normalization represents a practical and lightweight approach for improving archival compression pipelines without altering or replacing existing compression backends.

## Availability

The source code and the benchmarking harness are available under the MIT License at:  
<https://github.com/AndreaLVR/CAST>