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On Performance of Sparse Fast Fourier Transform Algorithms Using the Flat Window Filter

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ABSTRACT The problem of computing the Sparse Fast Fourier Transform(sFFT) of a K-sparse signal of size N has received significant attention for a long time. The first stage of sFFT is hashing the frequency coefficients of $\hat{x}$ into $B(\approx K)$ buckets named frequency bucketization. The process of frequency bucketization is achieved through the use of filters: Dirichlet kernel filter, aliasing filter, flat filter, etc. The frequency bucketization through these filters can decrease runtime and sampling complexity in low dimensions. It is a hot topic about the sFFT Algorithms using the flat filter because of its convenience and efficiency since its emerge and widely application. The next stage of sFFT is the spectrum reconstruction by identifying frequencies that are isolated in their buckets. Up to now, there are more than thirty different sFFT algorithms using the sFFT idea as mentioned above by their unique methods. An important question now is how to analyze and evaluate the performance of these algorithms in theory and practice. In this article, it is mainly discussed about the algorithms using the flat filter. In the first part, the article introduces the techniques in detail including two types of frameworks, five different methods to reconstruct spectrum and corresponding algorithms. We get the conclusion of the performance of these five algorithms including runtime complexity, sampling complexity and robustness in theory. In the second part, we make three categories of experiments for computing the signals of different SNR, different N, and different K by a standard testing platform and record the run time, percentage of signal sampled and L_0, L_1, L_2 error both in exactly sparse case and general sparse case. The result of experiments is consistent with the inferences obtained in theory. It can help us to optimize these algorithms and use them correctly in the right areas.

INDEX TERMS Sparse Fast Fourier Transform(sFFT), flat window filter, sub-linear algorithms

I. INTRODUCTION

The Discrete Fourier Transform(DFT) is one of the most important and widely used techniques in signal processing and mathematical computing. The most popular algorithm to compute the DFT is the fast Fourier transform(FFT) invented by Cooly and Tukey. The algorithm can compute the DFT of a signal of size N in $O(N\log N)$ time and use $O(N)$ samples. FFT greatly simplifies the operation process, however, with the emergence of big data problems, the FFT is no longer fast enough. Furthermore, sometimes it is hard to acquire a sufficient amount of data to compute the DFT. These two problems become the the major computational bottleneck in many applications. It motivates the need for the algorithms that can compute the Fourier transform in sublinear time and that use only a subset of the input data. People thought of many ideas in order to realize such an algorithm. Later, they focused on the study of the characteristics of the signal itself. The research found that a large number of signals are sparse in the frequency domain, only K frequencies are non-zeros or are significantly large. This feature is common and inherent in signals covers many fields (e.g. audio, video data, medical image, etc). In this case, when $K << N$,one can retrieve the information with high accuracy using only the coefficients of the K most significant frequencies. So the sparse fast

Fourier transform(sFFT) has been proposed and achieved good results. The research of sparse fast Fourier transform has been a hot topic in signal processing research since its birth, it was named one of the 10 Breakthrough Technologies in MIT Technology Review in 2012.

The firsts stage of sFFT algorithm is hashing the frequency coefficients of $\hat{x}$ into buckets such that the value of the bucket is the sum of the values of the frequency coefficients that hash into the bucket. The number of buckets is denoted by B and the size of one bucket is denoted by L. The process of frequency bucketization is achieved through the use of filters. The effect of Dirichlet kernel filter is to make the signal convoluted a rectangular window in the time domain, it can be equivalent to the signal multiply a Dirichlet kernel window of size $L(L << N)$ in the frequency domain. The typical application using the Dirichlet kernel filter is AAFFT algorithm. The effect of aliasing filter is to make the signal multiply a comb window in the time domain, it can be equivalent to the signal convoluted a comb window of size $B(\approx K)$ in the frequency domain. The typical application using the aliasing filter is FFAST algorithm. The effect of flat filter is to make the signal multiply a mix window in the time domain, it can be equivalent to the signal convoluted a flat window of size $L(L << N)$ in the frequency domain. The typical application using the flat filter is sFFT1.0 algorithm. After frequency bucketization, the algorithm then focuses on the non-empty buckets and computes the positions and values of the large frequency coefficients in those buckets in what we call the spectrum reconstruction or identifying frequencies. As we can see as follows, there are more than thirty algorithms using the sFFT idea and more than ten sFFT algorithms using the flat filter. A central question now is how to analyze and evaluate the performance of these algorithms for computing the different SNR, different N, and different K signals by the compare of themselves or other types of algorithms. It should be proved whether the runtime complexity, sampling complexity and robustness performance are consistent with the theory or not. Are there any better ways to improve these algorithms when using it in practice? The results of these performance analysis is the guide for us to optimize these algorithms and use them correctly in the different areas.

The first sFFT algorithm with sub-linear runtime and sub-sampling property was given in [1], which gave a randomized algorithm with runtime and sampling complexity $O(K^2 poly(\log N))$. This was later improved to $O(K poly(\log N))$ [2],[3,][4] through the use of binary search technique for spectrum reconstruction and the use of unequally-spaced FFTs. The algorithm is so called Ann Arbor fast Fourier transform (AAFFT), the version of them are AAFFT0.5 and AAFFT0.9.

In[14],[15], an algorithm so called FFAST(Fast Fourier Aliasing-based Sparse Transform) which focuses on exactly K-sparse signals was given. Their approach is based on downsampling of the input signal using a constant number of co-prime downsampling factors guided by CRT. These aliasing patterns of different downsampled signals are formulated as parity-check constraints of good erasure-correcting sparse-graph codes. FFAST costs $O(K\log K)$ to compute the exactly signals and only use $O(K)$ samples. In[16],[17], the author adapt the FFAST framework to the case where the time-domain samples are corrupted by a white Gaussian noise. The author show that the extended noise robust algorithm R-FFAST computes DFT using $O(K\log^3 N)$ samples, in $O(K\log^4 N)$ runtime. These two algorithms perform well when N is a product of some smaller prime numbers.

In[18][19], an algorithm is proposed and so called sFFT-DT(sFFT by downsampling in the time domain). The idea behind sFFT-DT is to downsample the original input signal first and then all subsequent operations are conducted on the downsampled signals. To overcome aliasing problem, the author consider the locations and values of K non-zero entries as variables and the aliasing problem is found to be equivalent to MPP problem, which can be solved via orthogonal polynomials or syndrome decoding with a CS(compressive sensing) based solver.

In[5], a deterministic algorithm so called GFFT(Gopher Fast Fourier Transform) which based on CRT was given. The GFFT is a aliasing-based search algorithm. The approximation error bounds in[5] are further improved in[6] . Later, an algorithm so called CLW-SFT (Christlieb Lawlor Wang Sparse Fourier Transform), which used phase encoding method was given in [7]. The noiseless version[8] of this algorithm is an adaptive algorithm which has running time $O(K\log K)$. In[7], the author developed this algorithm by using the multiscale error-correcting method to cope with high-level noise with runtime $O(K^2\log K)$. In [9], the author evaluate the performance of DMSFT (generated from GFFT) and CLW-DSFT (generated from CLW-SFT) and compare their runtime and robustness characteristics with other algorithms. These four algorithms all have a hypothesis that the algorithms can sample anywhere they want.

In[60] , an algorithm is proposed and so called DSFFT (Deterministic Sparse FFT). In the algorithm K needs not to be known in advance but will be determined during the algorithm. The method is based on the divide-and-conquer approach and may require the solution of a Vandermonde system of size at most $K \times K$ at each iteration step j if $K^2 < 2^j$.

In this article, we mainly focus on the sFFT algorithms using the flat window filter. These algorithms so called Sparse Fast Fourier Transform (sFFT1.0-sFFT4.0) that can compute the exactly K-sparse signals in time $O(K\log N)$ and general K-sparse signals in time $O(K\log N\log(N/K))$ were given in[10],[11]. The algorithms leverage techniques from digital signal processing(flat window filter). Unlike other randomized algorithms, the algorithm sFFT1.0 and sFFT2.0 are not iterative. These two algorithms identify and estimate the K largest coefficients in one shot. The algorithm sFFT3.0 can estimate the position by using only two samples of the filtered signal inspired by the frequency offset estimation in OFDM in the exactly sparse case. Later, a new robust algorithm so called MPFFT (Matrix Pencil FFT) was proposed in [12] on the basic of sFFT3.0 algorithm. The major new ingredient is a mode collision detector based on the matrix pencil method. This method enables the algorithm to use fewer samples of the input signal.

In[20], the article propose an overview of sFFT and summarize a three-step approach in the stage of spectrum reconstruction: 1) identification of frequencies whose coefficients are large; 2) accurate estimation of the Fourier coefficients identified; and 3) subtraction of the contribution of the partial Fourier representation computed by the first two steps and go back to stage one. In[20], it also provides a standard testing platform[34] that can be used to evaluate different sFFT algorithms. There are also some researches try to conquer the sFFT problem from other aspects ,e.g. from runtime complexity[32],[35], robustness[25],[28], determination[24],[28],[29],[50], software[23],[34],[53],[49], sampling complexity [21],[22],[37],[42],[44], higher dimensions[21],[30],[37],[44], implementation [38],, hardware [33][50] and special setting such as for real non-negative vectors[27] , for structured fourier sparsity signal[29] , for vectors with small support[29] .. perspectives.

II. UNITS

Use either SI (MKS) or CGS as primary units. (SI units are strongly encouraged.) English units may be used as secondary units (in parentheses). This applies to papers in data storage. For example, write "15 Gb/cm^2 (100 Gb/in^2)." An exception is when English units are used as identifiers in trade, such as "3½-in disk drive." Avoid combining SI and CGS units, such as current in amperes and magnetic field in oersteds. This often leads to confusion because equations do not balance dimensionally. If you must use mixed units, clearly state the units for each quantity in an equation.

The SI unit for magnetic field strength H is A/m. However, if you wish to use units of T, either refer to magnetic flux density B or magnetic field strength symbolized as $\mu_0 H$. Use the center dot to separate compound units, e.g., "A·m^2."

III. SOME COMMON MISTAKES

The word "data" is plural, not singular. The subscript for the permeability of vacuum μ_0 is zero, not a lowercase letter "o." The term for residual magnetization is "remanence"; the adjective is "remanent"; do not write "remnance" or "remnant." Use the word "micrometer" instead of "micron." A graph within a graph is an "inset," not an "insert." The word "alternatively" is preferred to the word "alternately" (unless you really mean something that alternates). Use the word "whereas" instead of "while" (unless you are referring to simultaneous events). Do not use the word "essentially" to mean "approximately" or "effectively." Do not use the word "issue" as a euphemism for "problem." When compositions are not specified, separate chemical symbols by en-dashes; for example, "NiMn" indicates the intermetallic compound $Ni_{0.5}Mn_{0.5}$ whereas "Ni–Mn" indicates an alloy of some composition Ni_xMn_{1-x}.

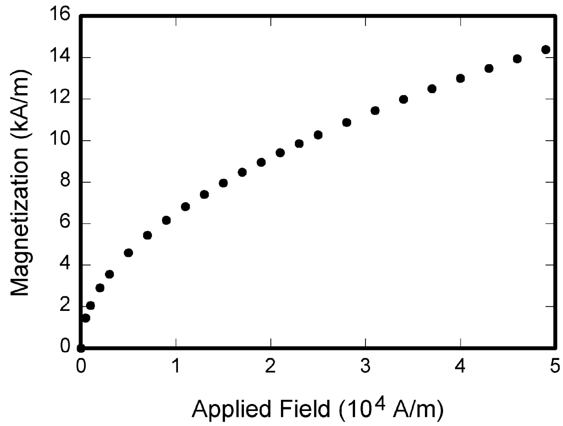

FIGURE 1. Magnetization as a function of applied field. It is good practice to explain the significance of the figure in the caption.

IV. SOME COMMON MISTAKES

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Be aware of the different meanings of the homophones "affect" (usually a verb) and "effect" (usually a noun), "complement" and "compliment," "discreet" and "discrete," "principal" (e.g., "principal investigator") and "principle" (e.g., "principle of measurement"). Do not confuse "imply" and "infer."

Prefixes such as "non," "sub," "micro," "multi," and "ultra" are not independent words; they should be joined to the words they modify, usually without a hyphen. There is no period after the "et" in the Latin abbreviation "et al." (it is also italicized). The abbreviation "i.e.," means "that is," and the abbreviation "e.g.," means "for example" (these abbreviations are not italicized).

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V. GUIDELINES FOR GRAPHICS PREPARATION AND SUBMISSION

A. TYPES OF GRAPHICS

The following list outlines the different types of graphics published in IEEE journals. They are categorized based on

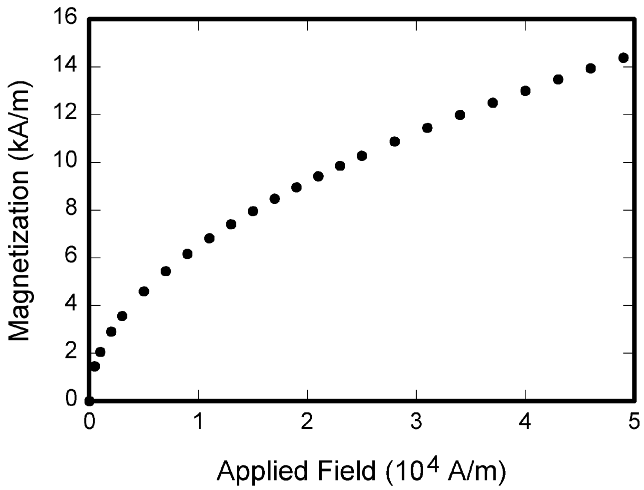

FIGURE 2. Magnetization as a function of applied field. It is good practice to explain the significance of the figure in the caption.

their construction, and use of color/shades of gray:

1) Color/Grayscale figures

Figures that are meant to appear in color, or shades of black/gray. Such figures may include photographs, illustrations, multicolor graphs, and flowcharts.

2) Line Art figures

Figures that are composed of only black lines and shapes. These figures should have no shades or half-tones of gray, only black and white.

3) Author photos

Head and shoulders shots of authors that appear at the end of our papers.

4) Tables

Data charts which are typically black and white, but sometimes include color.

B. MULTIPART FIGURES

Figures compiled of more than one sub-figure presented side-by-side, or stacked. If a multipart figure is made up of multiple figure types (one part is lineart, and another is grayscale or color) the figure should meet the stricter guidelines.

C. FILE FORMATS FOR GRAPHICS

Format and save your graphics using a suitable graphics processing program that will allow you to create the images as PostScript (PS), Encapsulated PostScript (.EPS), Tagged Image File Format (.TIFF), Portable Document Format (.PDF), Portable Network Graphics (.PNG), or Metapost (.MPS), sizes them, and adjusts the resolution settings. When submitting your final paper, your graphics should all be submitted individually in one of these formats along with the manuscript.

TABLE 1. Units for Magnetic Properties

Symbol	Quantity	Conversion from Gaussian and CGS EMU to SI [a]
Φ	magnetic flux	1 Mx $\rightarrow 10^{-8}$ Wb $= 10^{-8}$ V·s
B	magnetic flux density, magnetic induction	1 G $\rightarrow 10^{-4}$ T $= 10^{-4}$ Wb/m^2
H	magnetic field strength	1 Oe $\rightarrow 10^3/(4\pi)$ A/m
m	magnetic moment	1 erg/G = 1 emu $\rightarrow 10^{-3}$ A·m$^2 = 10^{-3}$ J/T
M	magnetization	1 erg/(G·cm^3) = 1 emu/cm^3 $\rightarrow 10^3$ A/m
$4\pi M$	magnetization	1 G $\rightarrow 10^3/(4\pi)$ A/m
σ	specific magnetization	1 erg/(G·g) = 1 emu/g $\rightarrow$ 1 A·m^2/kg
j	magnetic dipole moment	1 erg/G = 1 emu $\rightarrow 4\pi \times 10^{-10}$ Wb·m
J	magnetic polarization	1 erg/(G·cm^3) = 1 emu/cm^3 $\rightarrow 4\pi \times 10^{-4}$ T
χ, κ	susceptibility	$1 \rightarrow 4\pi$
χ_ρ	mass susceptibility	1 cm^3/g $\rightarrow 4\pi \times 10^{-3}$ m^3/kg
μ	permeability	$1 \rightarrow 4\pi \times 10^{-7}$ H/m $= 4\pi \times 10^{-7}$ Wb/(A·m)
μ_r	relative permeability	$\mu \rightarrow \mu_r$
w, W	energy density	1 erg/cm^3 $\rightarrow 10^{-1}$ J/m^3
N, D	demagnetizing factor	$1 \rightarrow 1/(4\pi)$

Vertical lines are optional in tables. Statements that serve as captions for the entire table do not need footnote letters.

[a]Gaussian units are the same as cg emu for magnetostatics; Mx = maxwell, G = gauss, Oe = oersted; Wb = weber, V = volt, s = second, T = tesla, m = meter, A = ampere, J = joule, kg = kilogram, H = henry.

D. SIZING OF GRAPHICS

Most charts, graphs, and tables are one column wide (3.5 inches/88 millimeters/21 picas) or page wide (7.16 inches/181 millimeters/43 picas). The maximum depth a graphic can be is 8.5 inches (216 millimeters/54 picas). When choosing the depth of a graphic, please allow space for a caption. Figures can be sized between column and page widths if the author chooses, however it is recommended that figures are not sized less than column width unless when necessary.

There is currently one publication with column measurements that do not coincide with those listed above. Proceedings of the IEEE has a column measurement of 3.25 inches (82.5 millimeters/19.5 picas).

The final printed size of author photographs is exactly 1 inch wide by 1.25 inches tall (25.4 millimeters $\times$ 31.75 millimeters/6 picas $\times$ 7.5 picas). Author photos printed in editorials measure 1.59 inches wide by 2 inches tall (40 millimeters $\times$ 50 millimeters/9.5 picas $\times$ 12 picas).

E. RESOLUTION

The proper resolution of your figures will depend on the type of figure it is as defined in the "Types of Figures" section. Author photographs, color, and grayscale figures should be at least 300dpi. Line art, including tables should be a minimum of 600dpi.

F. VECTOR ART

In order to preserve the figures' integrity across multiple computer platforms, we accept files in the following formats: .EPS/.PDF/.PS. All fonts must be embedded or text converted to outlines in order to achieve the best-quality results.

G. COLOR SPACE

The term color space refers to the entire sum of colors that can be represented within the said medium. For our purposes, the three main color spaces are Grayscale, RGB (red/green/blue) and CMYK (cyan/magenta/yellow/black). RGB is generally used with on-screen graphics, whereas CMYK is used for printing purposes.

All color figures should be generated in RGB or CMYK color space. Grayscale images should be submitted in Grayscale color space. Line art may be provided in grayscale OR bitmap colorspace. Note that "bitmap colorspace" and "bitmap file format" are not the same thing. When bitmap color space is selected, .TIF/.TIFF/.PNG are the recommended file formats.

H. ACCEPTED FONTS WITHIN FIGURES

When preparing your graphics IEEE suggests that you use of one of the following Open Type fonts: Times New Roman, Helvetica, Arial, Cambria, and Symbol. If you are supplying EPS, PS, or PDF files all fonts must be embedded. Some fonts may only be native to your operating system; without the fonts embedded, parts of the graphic may be distorted or missing.

A safe option when finalizing your figures is to strip out the fonts before you save the files, creating "outline" type. This converts fonts to artwork what will appear uniformly on any screen.

I. USING LABELS WITHIN FIGURES

1) Figure Axis labels

Figure axis labels are often a source of confusion. Use words rather than symbols. As an example, write the quantity "Magnetization," or "Magnetization M," not just "M." Put units in parentheses. Do not label axes only with units. As in Fig. 1, for example, write "Magnetization (A/m)" or "Magnetization ($A{\cdot}m^{-1}$)," not just "A/m." Do not label axes with a ratio of quantities and units. For example, write "Temperature (K)," not "Temperature/K."

Multipliers can be especially confusing. Write "Magnetization (kA/m)" or "Magnetization (10^3 A/m)." Do not write "Magnetization (A/m) $\times$ 1000" because the reader would not know whether the top axis label in Fig. 1 meant 16000 A/m or 0.016 A/m. Figure labels should be legible, approximately 8 to 10 point type.

2) Subfigure Labels in Multipart Figures and Tables

Multipart figures should be combined and labeled before final submission. Labels should appear centered below each subfigure in 8 point Times New Roman font in the format of (a) (b) (c).

J. FILE NAMING

Figures (line artwork or photographs) should be named starting with the first 5 letters of the author's last name. The next characters in the filename should be the number that represents the sequential location of this image in your article. For example, in author "Anderson's" paper, the first three figures would be named ander1.tif, ander2.tif, and ander3.ps.

Tables should contain only the body of the table (not the caption) and should be named similarly to figures, except that '.t' is inserted in-between the author's name and the table number. For example, author Anderson's first three tables would be named ander.t1.tif, ander.t2.ps, ander.t3.eps.

Author photographs should be named using the first five characters of the pictured author's last name. For example, four author photographs for a paper may be named: oppen.ps, moshc.tif, chen.eps, and duran.pdf.

If two authors or more have the same last name, their first initial(s) can be substituted for the fifth, fourth, third... letters of their surname until the degree where there is differentiation. For example, two authors Michael and Monica Oppenheimer's photos would be named oppmi.tif, and oppmo.eps.

K. REFERENCING A FIGURE OR TABLE WITHIN YOUR PAPER

When referencing your figures and tables within your paper, use the abbreviation "Fig." even at the beginning of a sentence. Do not abbreviate "Table." Tables should be numbered with Roman Numerals.

L. CHECKING YOUR FIGURES: THE IEEE GRAPHICS ANALYZER

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Because IEEE will do the final formatting of your paper, you do not need to position figures and tables at the top and bottom of each column. In fact, all figures, figure captions, and tables can be placed at the end of your paper. In addition to, or even in lieu of submitting figures within your final manuscript, figures should be submitted individually, separate from the manuscript in one of the file formats listed above in Section V-C. Place figure captions below the figures; place table titles above the tables. Please do not include captions as part of the figures, or put them in "text boxes" linked to the figures. Also, do not place borders around the outside of your figures.

N. COLOR PROCESSING/PRINTING IN IEEE JOURNALS

All IEEE Transactions, Journals, and Letters allow an author to publish color figures on IEEE Xplore® at no charge, and automatically convert them to grayscale for print versions. In most journals, figures and tables may alternatively be printed in color if an author chooses to do so. Please note that this service comes at an extra expense to the author. If you intend to have print color graphics, include a note with your final paper indicating which figures or tables you would like to be handled that way, and stating that you are willing to pay the additional fee.

VI. CONCLUSION

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

.

Appendixes, if needed, appear before the acknowledgment.

ACKNOWLEDGMENT

The preferred spelling of the word "acknowledgment" in American English is without an "e" after the "g." Use the singular heading even if you have many acknowledgments. Avoid expressions such as "One of us (S.B.A.) would like to thank . . . ." Instead, write "F. A. Author thanks . . . ." In most cases, sponsor and financial support acknowledgments are placed in the unnumbered footnote on the first page, not here.

REFERENCES AND FOOTNOTES

A. REFERENCES

References need not be cited in text. When they are, they appear on the line, in square brackets, inside the punctuation. Multiple references are each numbered with separate brackets. When citing a section in a book, please give the relevant page numbers. In text, refer simply to the reference number. Do not use "Ref." or "reference" except at the beginning of a sentence: "Reference [3] shows . . . ." Please do not use automatic endnotes in Word, rather, type the reference list at the end of the paper using the "References" style.

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B. FOOTNOTES

Number footnotes separately in superscript numbers.[1] Place the actual footnote at the bottom of the column in which it is cited; do not put footnotes in the reference list (endnotes). Use letters for table footnotes (see Table 1).

APPENDIX A SUBMITTING YOUR PAPER FOR REVIEW

A. FINAL STAGE

When you submit your final version (after your paper has been accepted), print it in two-column format, including figures and tables. You must also send your final manuscript on a disk, via e-mail, or through a Web manuscript submission system as directed by the society contact. You may use Zip for large files, or compress files using Compress, Pkzip, Stuffit, or Gzip.

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