Approachable Error Bounded Lossy Compression

Robert Underwood, Ph.D. Candidate, School of Computing

SC20 Everywhere we are | more than hpc.

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CLEMSON UNIVERSITY

About Me – Robert Underwood

- Ph.D. Candidate
- Computer Science
- Research Interests:
  - Lossy Compression
  - Reliability and Fault Tolerance
  - High Performance Computing

Personal Website

My CV

Exascale HPC Needs to Process Big Data

- Exascale Apps:
  - CESM-LE – 300TB/instance
  - HACC – 2000PB storage
- Exascale Instruments
  - LCLS-II – >250GB/s steaming

System	Disk Storage	Peak Disk Bandwidth	Memory
Bebop	< 2PB	n/a	0.3 PB
Mira	24 PB	n/a	~ 1 PB
Theta	11PB	n/a	~ 1 PB
Summit	250PB	2.5 TB/s	10PB
Aroura	230PB	25 TB/s	10PB
Projected Exascale	500 PB		

Franck Cappello et al. “Use Cases of Lossy Compression for Floating Point Data in Scientific Datasets”. 2018
Machine Characteristics from respective websites accessed 17 September 2020

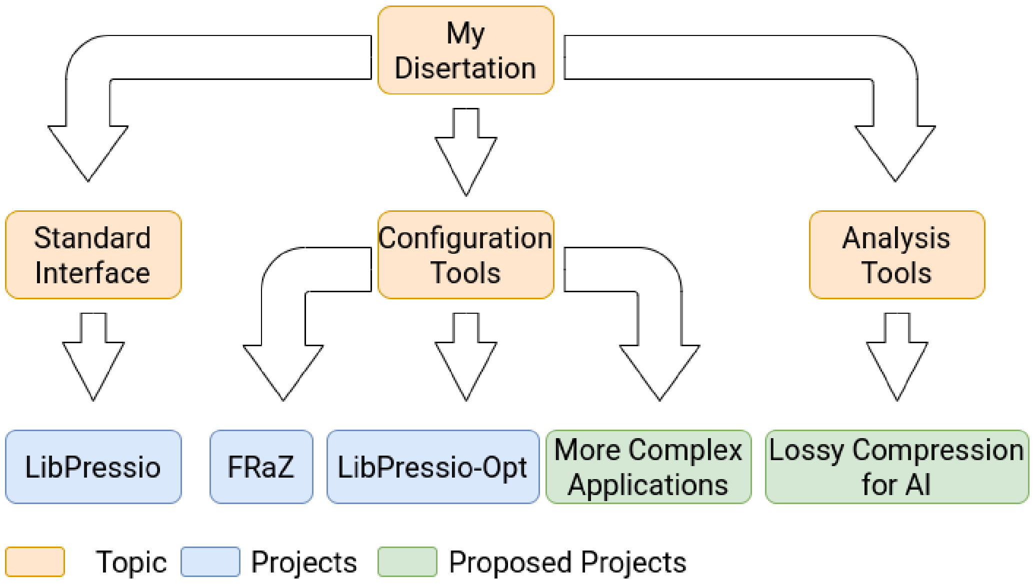
Compression is the Solution

Compression represents data in a more compact fashion

	Lossless	Lossy	Error Bounded Lossy Compression
Examples	ZIP	JPEG	SZ/ZFP/MGARD
Compression Ratio	☹	☺	☺
Ease of Use	☺	☹	??
Data Integrity	☺	☹	☺

Lossy Compression Is Not Approachable

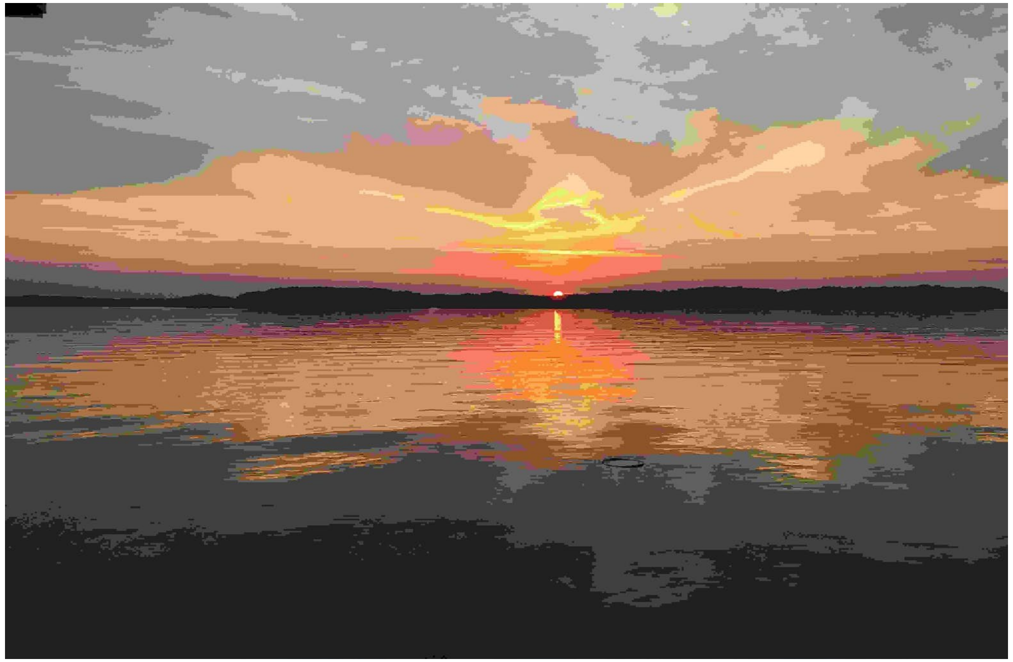
- Too many interfaces
- Too difficult to configure
- Few tools to understand
- **My dissertation provides a single interface to use, configure, understand compression**



Outline

1. Introduction to Compression Principles
2. LibPressio
3. Automated Configuration of Compressors
4. Understanding the Effects of Compression
5. Conclusions and Future Work

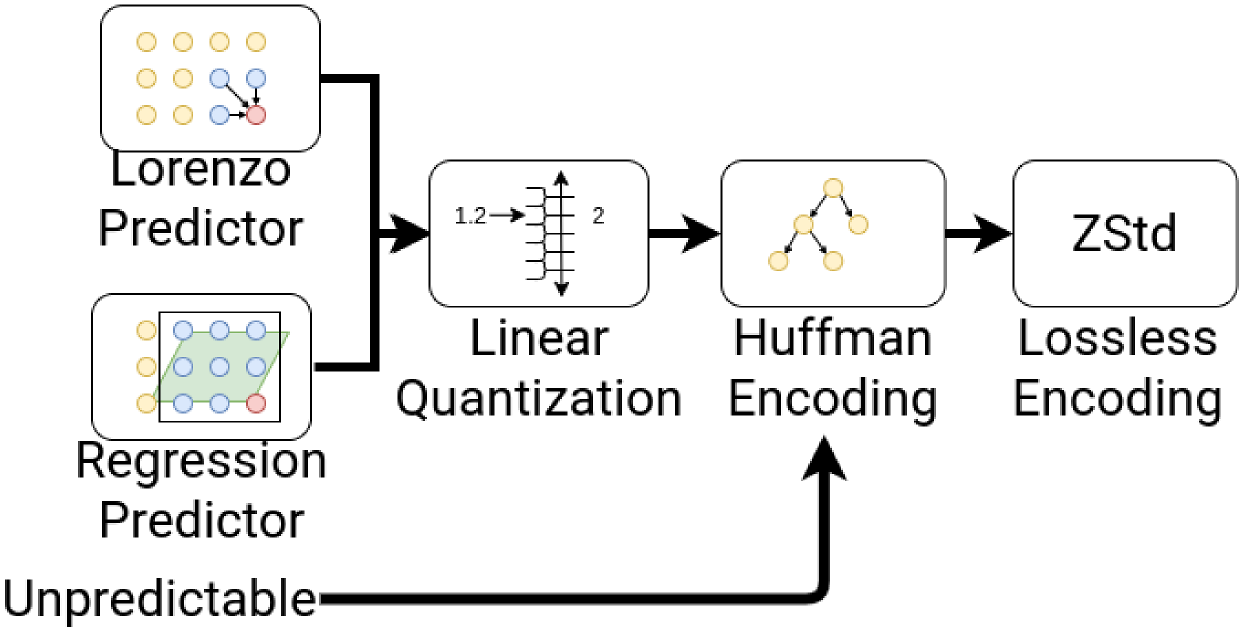
Introduction to Error-Bounded Compression Principles



Lake Hartwell – Lossless (left), Lossy (right). The image on the right is 17 times smaller

SZ

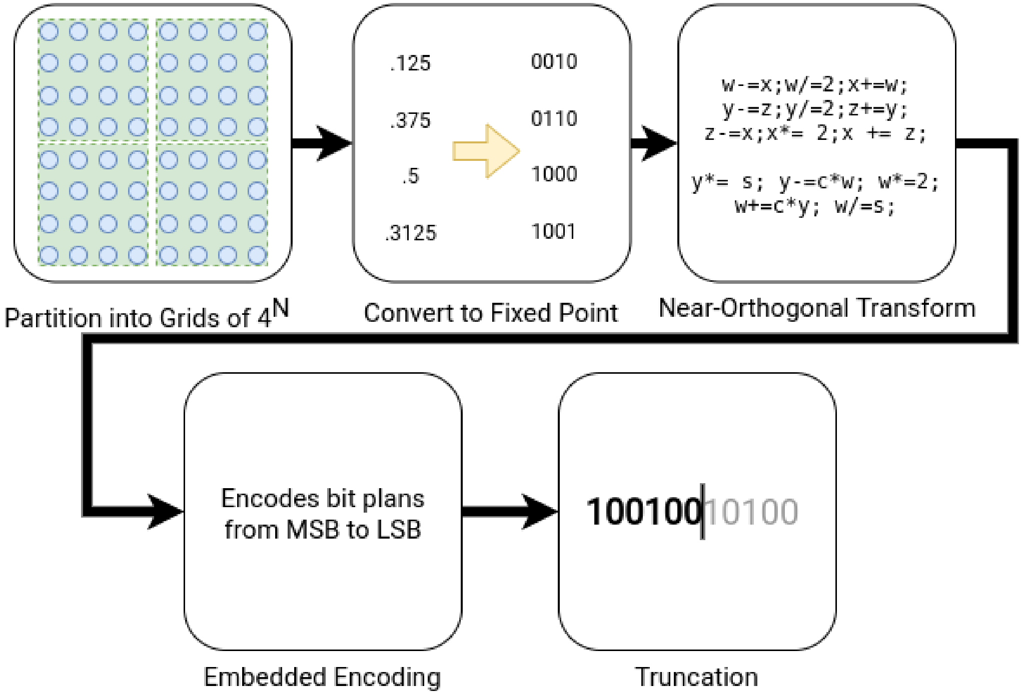
- Prediction Based Compressor
  1. Data Prediction
  2. Linear Quantization
  3. Entropy Encoding
  4. Lossless Encoding



Di, Sheng and Cappello, Franck “Fast Error Bounded Lossy Compression with SZ” 2016

ZFP

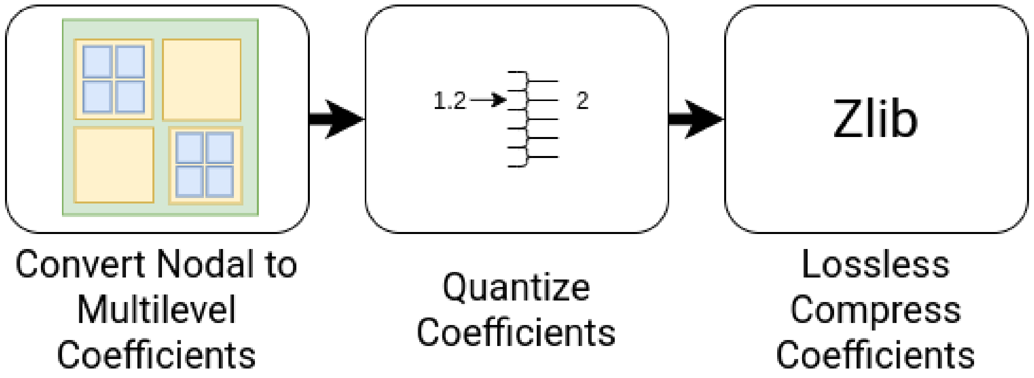
- Transform Based Compressor
  1. Partition into grids of 4^n
  2. Convert to fixed point by block
  3. Near Orthogonal Transform
     - Similar to JPEG Compression
  4. Bit manipulation



Lindstrom, Peter. “Fixed Rate Compressed Floating Point Arrays” 2012

MGARD

- Multi-Grid Method
  1. Determine Multi-grid coefficients
  2. Quantize “binding” coefficients
  3. Losslessly encode quantized coefficients



Whitney, Ben E. “Multilevel Techniques for Compression and Reduction of Scientific Data” 2018

LibPressio

A Generic Abstraction for the Compression of Dense Tensors

LibPressio Provides a Common Interface

- Common Abstractions for:
  - Loading compressors
  - Configuration
  - Compression/Decompression
  - Representing Data
  - Error Reporting
  - Computing Metrics

Get LibPressio

```c
//get the compressor
struct pressio* library = pressio_instance();
struct pressio_compressor* sz = pressio_get_compressor(library,
↪  "sz");

//configure, validate, and assign the options
struct pressio_options* config =
↪  pressio_compressor_get_options(sz);
pressio_options_set_integer(config, "sz:error_bound_mode",
↪  REL);
pressio_options_set_double(config, "sz:rel_err_bound", 0.01);
pressio_compressor_set_options(sz, config);

//read in an input buffer
size_t dims[] = {500,500,100};
struct pressio_data* description =
↪  pressio_data_new_empty(pressio_float_dtype, 3, dims);
struct pressio_data* input_data =
↪  pressio_io_data_path_read(description, "CLOUDf48.bin.f32");

//create output buffers
struct pressio_data* compressed_data =
↪  pressio_data_new_empty(pressio_byte_dtype, 0, NULL);
struct pressio_data* decompressed_data =
↪  pressio_data_new_owning(pressio_float_dtype, 3, dims);

//compress and decompress the data
pressio_compressor_compress(sz, input_data, compressed_data);
pressio_compressor_decompress(sz, compressed_data,
↪  decompressed_data);
```

Current Plugins and Tools

Compressors

- blosc
- imagemagick
- **fpzip**
- **mgard**
- **sz**
- **zfp**

Meta-Compressors

- linear_quantizer
- many_dependent
- many_independent
- resize
- transpose
- opt
- no-op
- **fault_injector**
- **random_errors**

Metrics

- composite (lua)
- error_stat
- time
- size
- no-op
- **kl_divergence**
- **ks_test**
- **pearson**
- **spatial_error**
- **ftk_critical_points**
- **external**

IO

- posix
- csv
- hdf5
- select
- empty
- no-op

Tools

- LibPressio-Tools
- LibPressio-Predict
- LibPressio.jl
- **LibPressio.py**
- **Z-Checker**

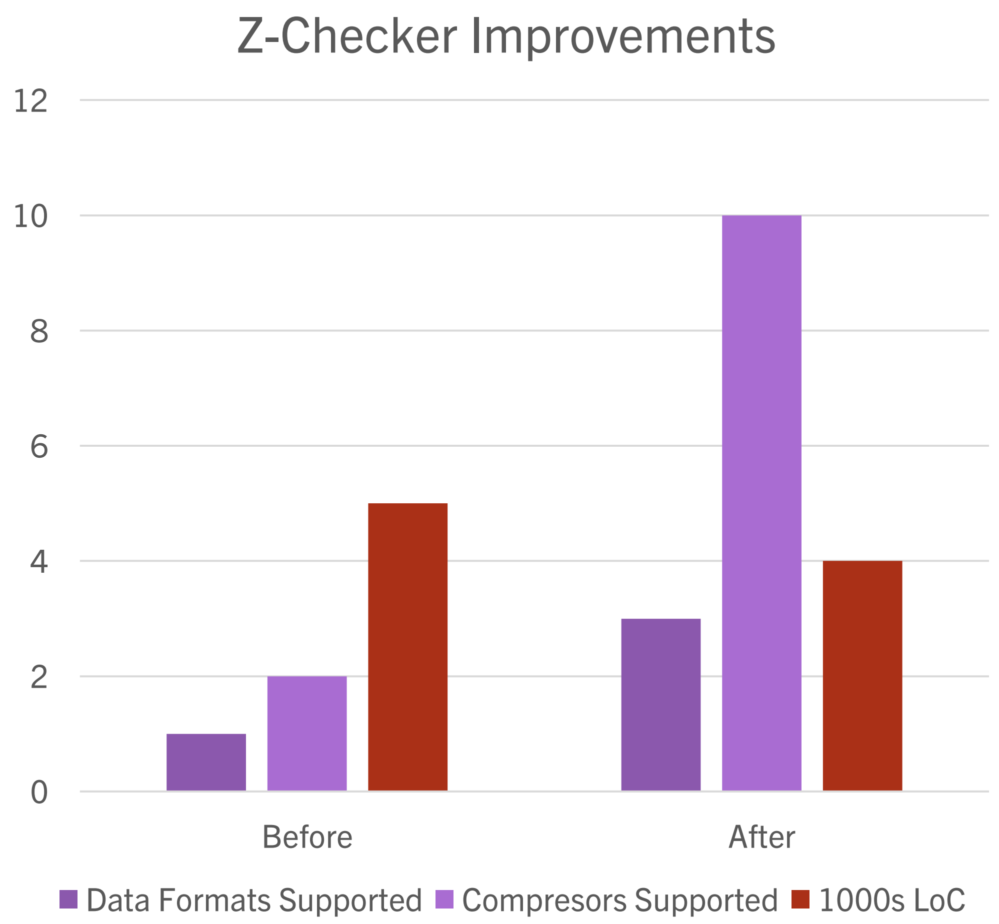
Bolded plugins developed in collaboration with others

Meta Compressors Boost Productivity

- Not a compressor themselves
- Provide common services:
  - Auto Configuration tools
  - Pre/Post Processors
  - Parallel Runtimes

LibPressio Solves Problems

- Writing for multiple compressors is hard: over 100 bugs fixed to date
- Case Study: Z-Checker
  - Save over 1000 LoC (≈21%)
  - Better:
    - Over 10 new compressors
    - Over 3 new data formats
  - NEW Faster: with MPI parallelism
  - Future proof: New compressors just need a recompile



Future Work on LibPressio

- Support for accelerator sharing
  - GPUs
  - Threads
  - FPGAs
- Support for asynchrony/streams
- Support for sparse problems

Automated Configuration of Compressors

Automated Configuration Timeline

IPDPS 2020

FRaZ

- Bounding Compression Ratio

LibPressio-Opt

- Bounding User Metrics
- Performance Improvements

More Complex Apps

- Bounding Complex, Multi-faceted Metrics

1 - FRaZ: Fixed Ratio Compression

Can we tune compression using a control loop to bound the compression ratio?

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FRaZ: Approach

Formulate compressor configuration as an optimization problem

$$\max_{\vec{c} \in U} Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right)\right)$$

FRaZ: Approach

Formulate compressor configuration as an optimization problem

Compression Ratio

$$\max_{\vec{c} \in U} Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right)\right)$$

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Compression Ratio

$$\max_{\vec{c} \in U} Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right)\right)$$

Error Bound

FRaZ: Approach

Formulate compressor configuration as an optimization problem

Compression Ratio

$$\max_{\vec{c}\in U} Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right)\right)$$

Error Bound

Allowed Error Bounds

FRaZ: Approach

Formulate compressor configuration as an optimization problem

Compression Ratio

Data for a Field and Timestep

$$\max_{\vec{c}\in U} Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right)\right)$$

Error Bound

Allowed Error Bounds

FRaZ: Approach

Formulate compressor configuration as an optimization problem

Compression Ratio

Data for a Field and Timestep

$$\max_{\vec{c}\in U} Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right)\right)$$

Error Bound

Compression Function

Allowed Error Bounds

FRaZ: Approach

Formulate compressor configuration as an optimization problem

Compression Ratio

Data for a Field and Timestep

Error Bound Mode

$$\max_{\vec{c}\in U} Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right)\right)$$

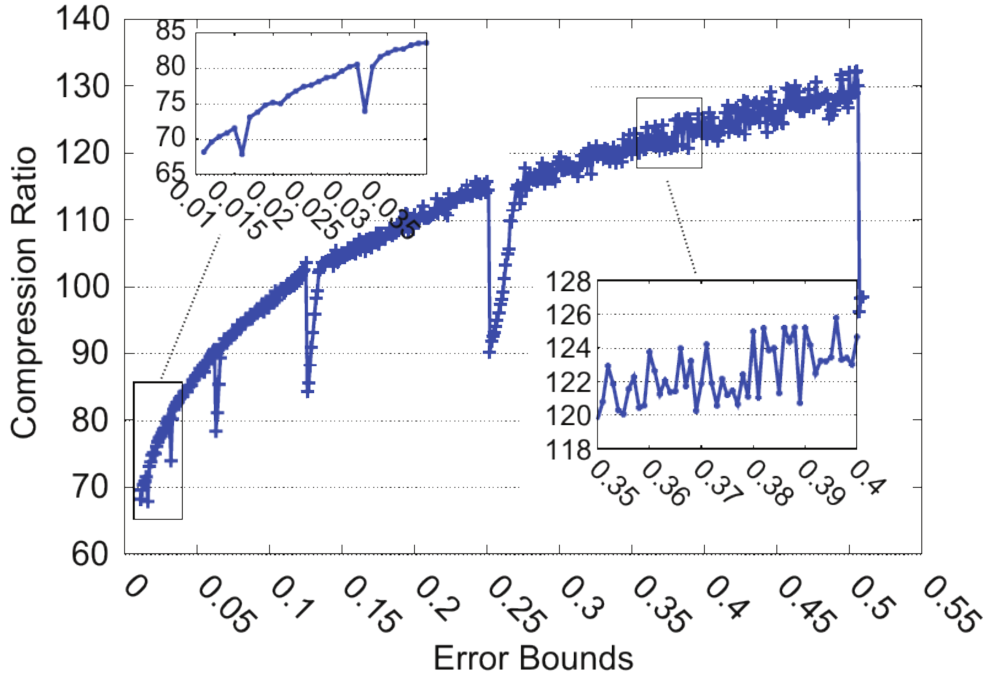
Error Bound

Compression Function

Allowed Error Bounds

FRaZ: Approach

- Why not use binary search?
  - It doesn't work
  - The relationship between error bounds and compression ratios is not monotonic
- What can we use?
  - Optimization
    - Derivative Based Methods
      - Analytic Derivatives
      - Numerical Derivatives
    - Derivative Free Optimization



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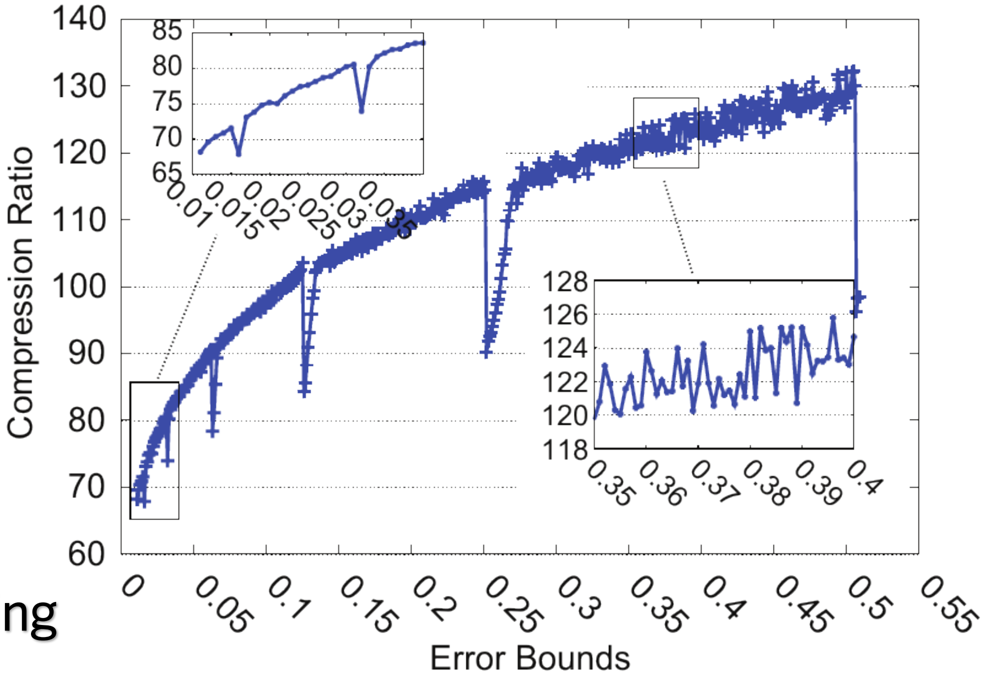

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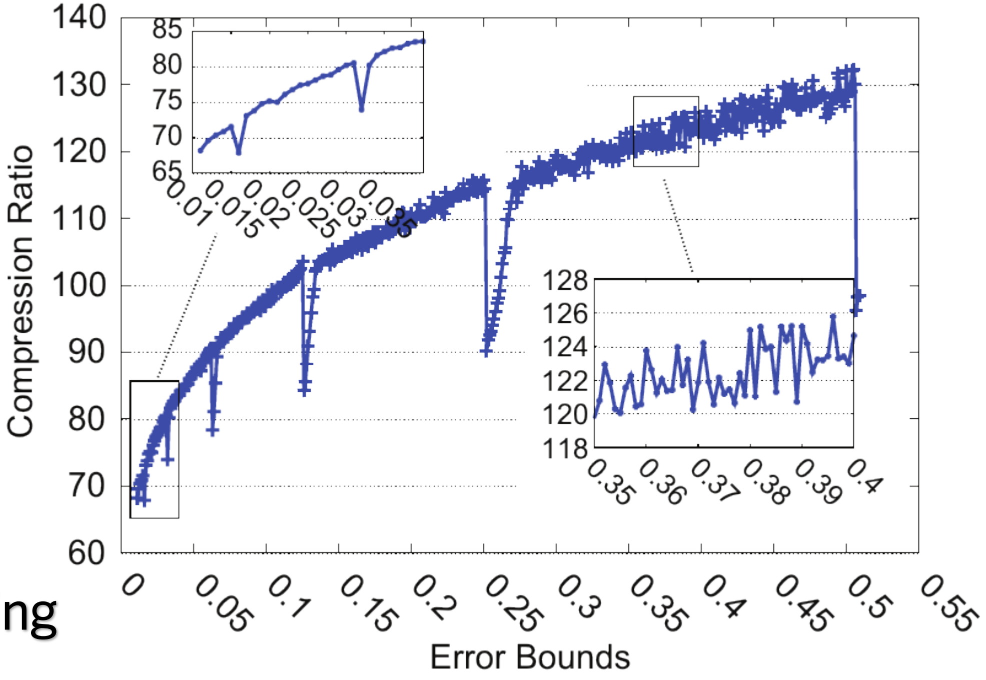

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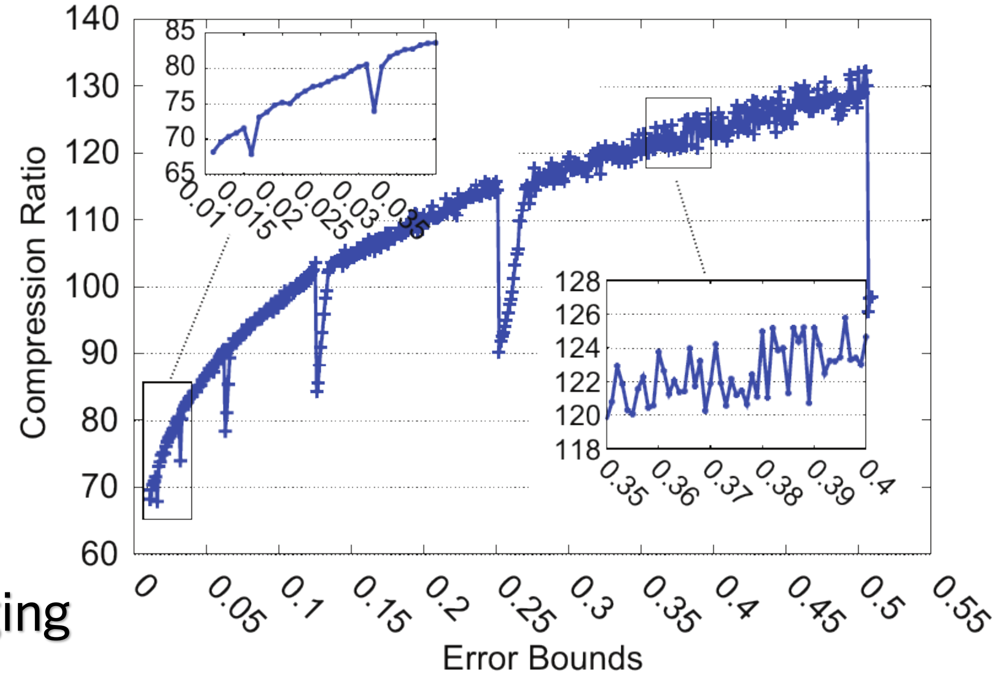
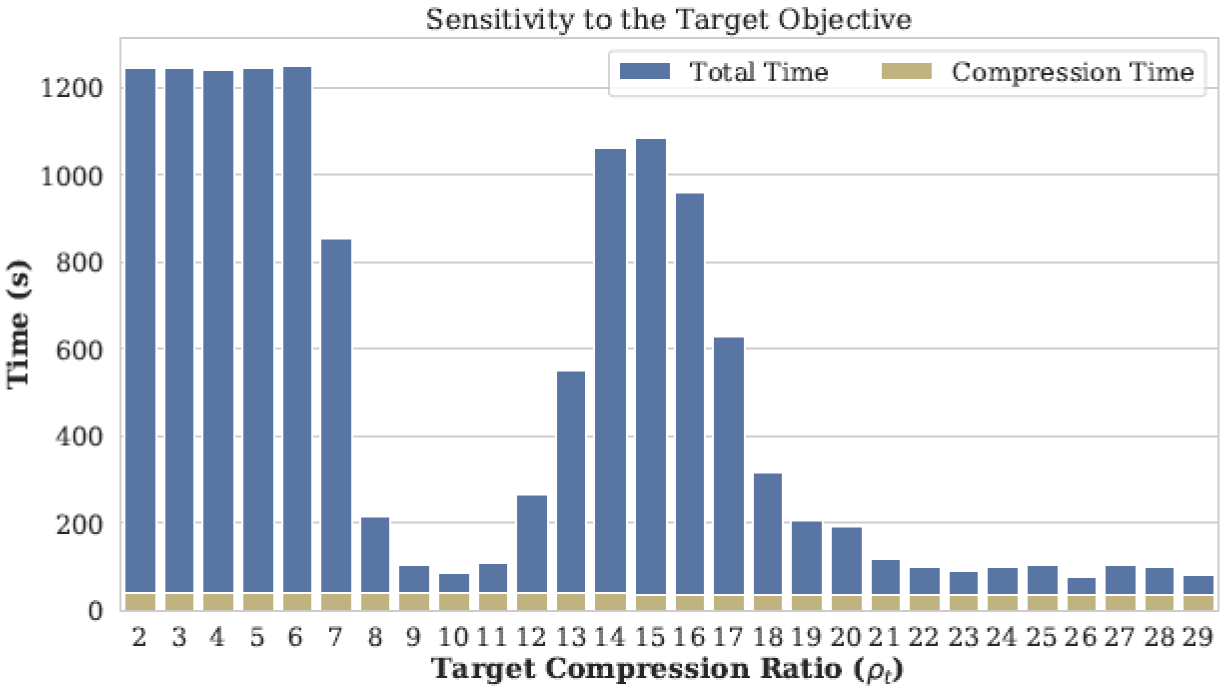
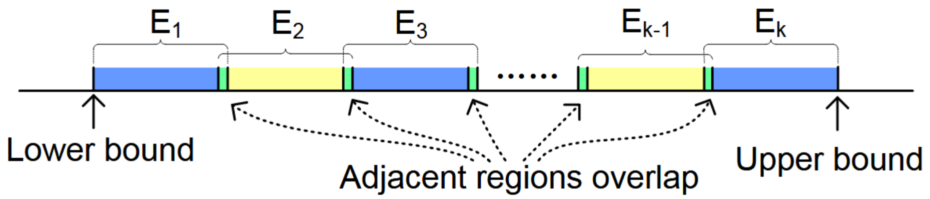


FRaZ: Key Findings

- Tuning takes only 2x longer than an oracle in the feasible case
- Some targets are faster because more error bounds meet some targets
- How do we get there?
  - Parallelize by
    1. Field – run each field independently
    2. Timestep – try reusing prior timesteps configuration
    3. Error Bound Range – run ranges independently, stopping early if a solution is found





Automated Configuration Timeline

In Submission

FRaZ

- Bounding Compression Ratio

LibPressio-Opt

- Bounding User Metrics
- Performance Improvements

More Complex Apps

- Bounding Complex, Multi-faceted Metrics

2 – LibPressio-Opt: Bound User Metrics

Can we extend FRaZ to bound simple user metrics and improve performance?

LibPressio-Opt: Approach

Formulate compressor configuration as an optimization problem

Compression Ratio

Data for a Field and Timestep

Error Bound Mode

$$\max_{\vec{c}\in U} Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right)\right)$$

Error Bound

Compression Function

Allowed Error Bounds

LibPressio-Opt: Approach

Formulate compressor configuration as an optimization problem

Compression Ratio

Data for a Field and Timestep

Error Bound Mode

$$\max_{\vec{c}\in U} Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right); \overrightarrow{\boldsymbol{\theta}_{\boldsymbol{m}}}\right)$$

Error Bound

Compression Function

Allowed Error Bounds

LibPressio-Opt: Approach

Formulate compressor configuration as an optimization problem

$$\max_{\vec{c}\in U} Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right); \overrightarrow{\theta_m}\right)$$

Compression Ratio

Data for a Field and Timestep

Error Bound Mode

Error Bound

Allowed Error Bounds

Compression Function

Fixed Metric Parameters

LibPressio-Opt: Approach

Formulate compressor configuration as an optimization problem

User Error Bound

Data for a Field and Timestep

Error Bound Mode

$$\max_{\vec{c}\in U} Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right); \overrightarrow{\theta_m}\right)$$

Compression Function

Fixed Metric Parameters

Error Bound

Allowed Error Bounds

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Data for a Field and Timestep

Error Bound Mode

$$\max_{\vec{c}\in U} Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right); \overrightarrow{\theta_m}\right)$$

Compression Function

Fixed Metric Parameters

Non-fixed Compressor Settings

Allowed Error Bounds

LibPressio-Opt: Approach

Formulate compressor configuration as an optimization problem

User Error Bound

Data for a Field and Timestep

Error Bound Mode

$$\max_{\vec{c}\in U} Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right); \overrightarrow{\theta_m}\right)$$

Non-fixed Compressor Settings

Compression Function

Fixed Metric Parameters

Feasible Compressor Settings

LibPressio-Opt: Approach

Formulate compressor configuration as an optimization problem

User Error Bound

Data for a Field and Timestep

Compressor Fixed-Parameters

$$\max_{\vec{c} \in U} Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right); \overrightarrow{\theta_m}\right)$$

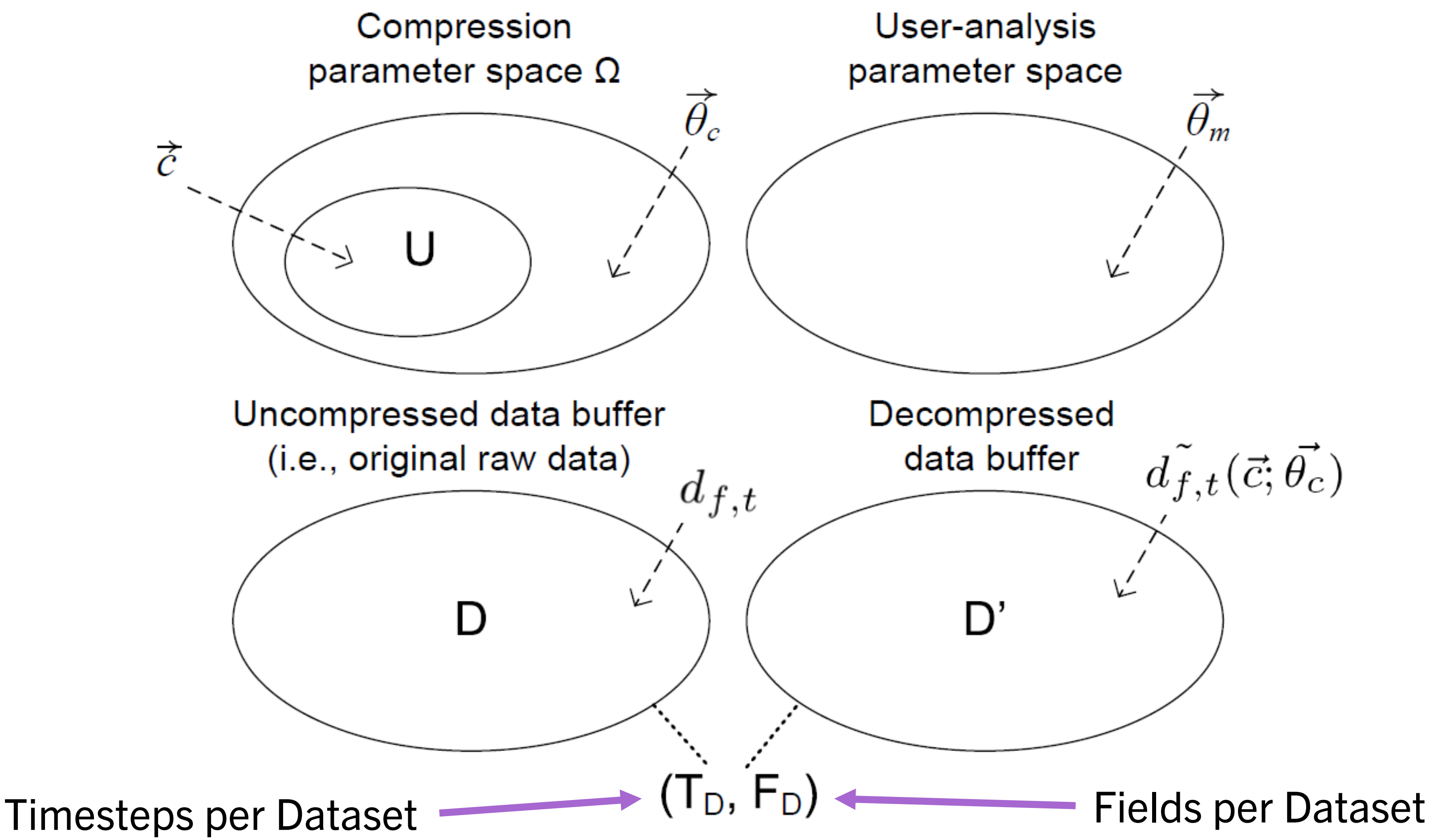
Non-fixed Compressor Settings

Compression Function

Fixed Metric Parameters

Feasible Compressor Settings

Illustration of Relationship among Notations



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What about constraints on objectives?

For any, $Q_i\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right)\right)$ and τ_i

i^{th} metric

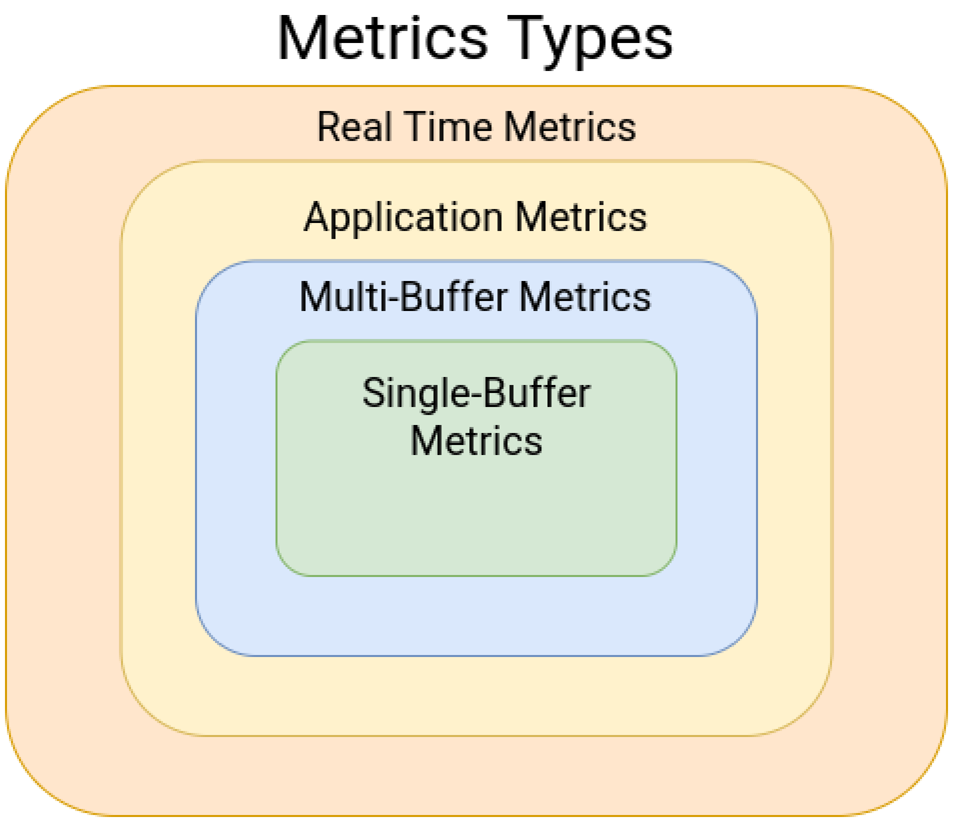
threshold for i^{th} metric

We can construct:

$$Q\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right)\right) = \begin{cases} Q_0\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right)\right) \ if\ \forall_i, Q_i\left(d_{f,t}, \widetilde{d_{f,t}}\left(\vec{c};\ \overrightarrow{\theta_c}\right)\right) \leq \tau_i \\ -\infty\ , otherwise \end{cases}$$

What do we mean by “Metrics”?

- Requirements
  - “Sufficiently” Deterministic
  - Have a fixed number of Real valued inputs and outputs
  - Can be modeled as having a single objective



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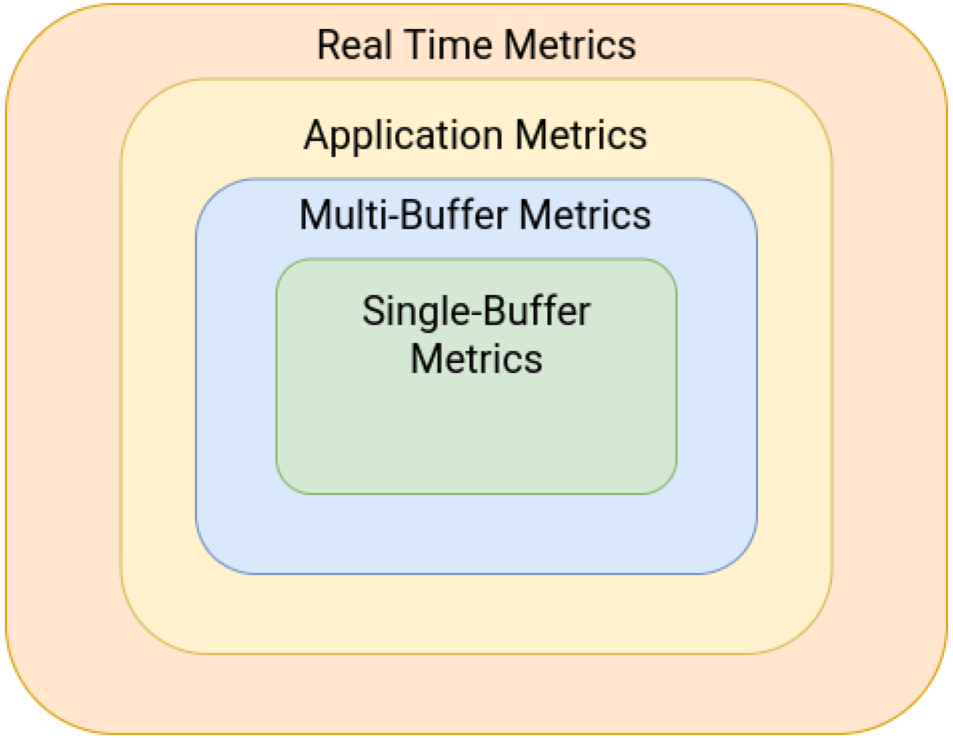
- Types

Real Time – Can only be computed at runtime (i.e. compression_time)

Metrics Types



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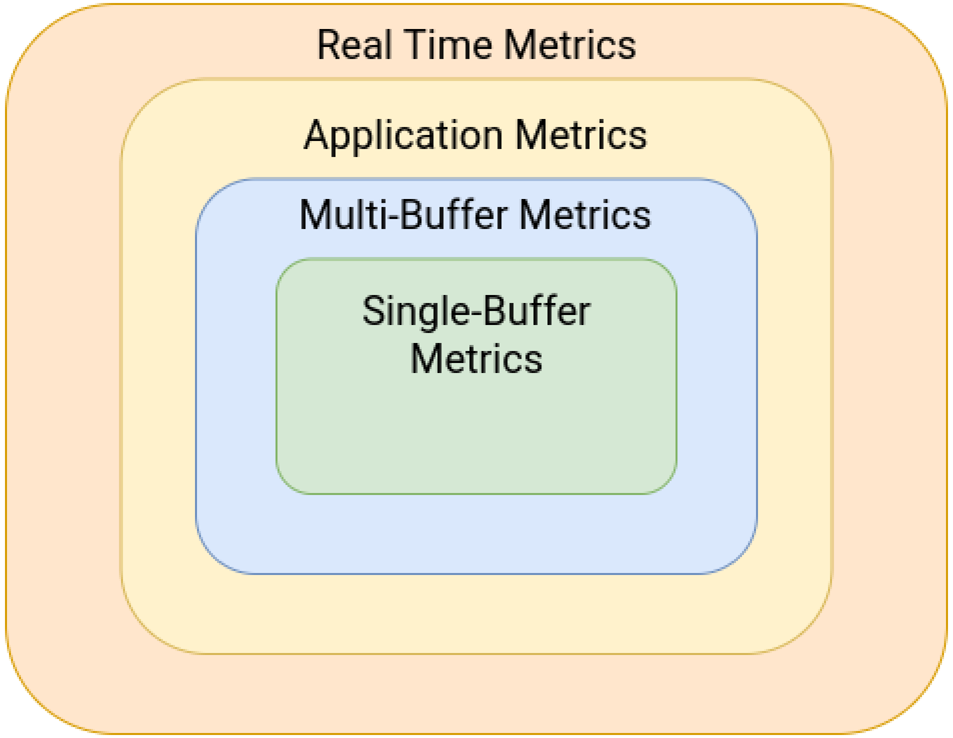
Application – Needs a specific collection of buffers to compute (Anything "app" specific)

Metrics Types



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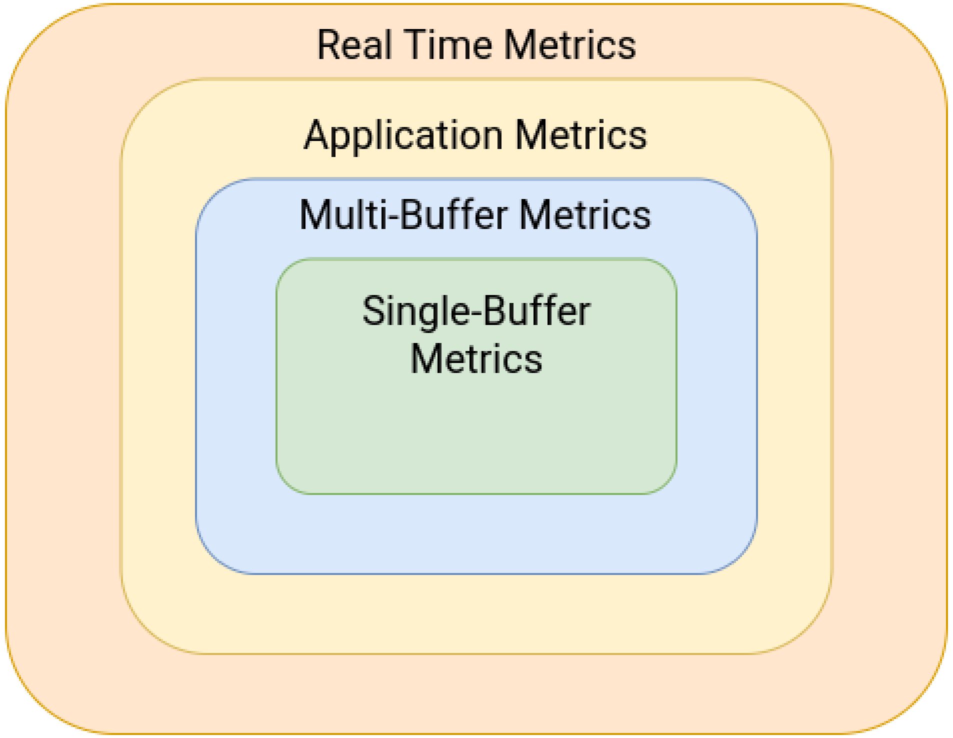
Multi-Buffer – Can be computed with any number of buffers (i.e. compression_ratio)

Metrics Types



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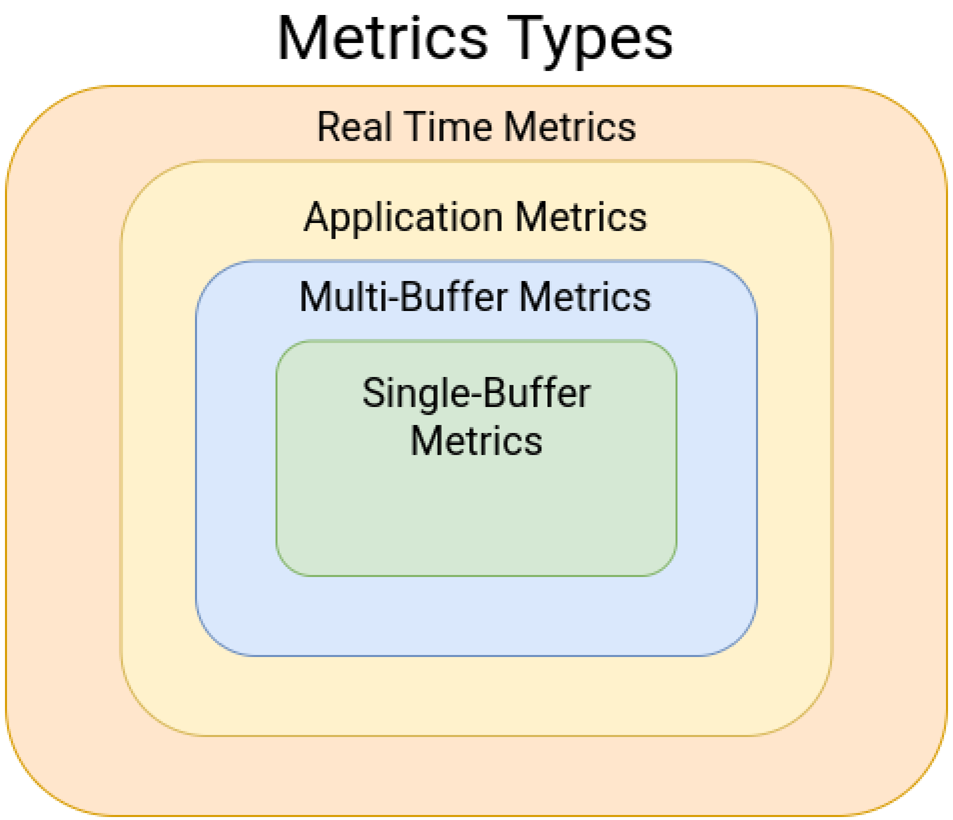
Single-Buffer – Computed from any single buffer



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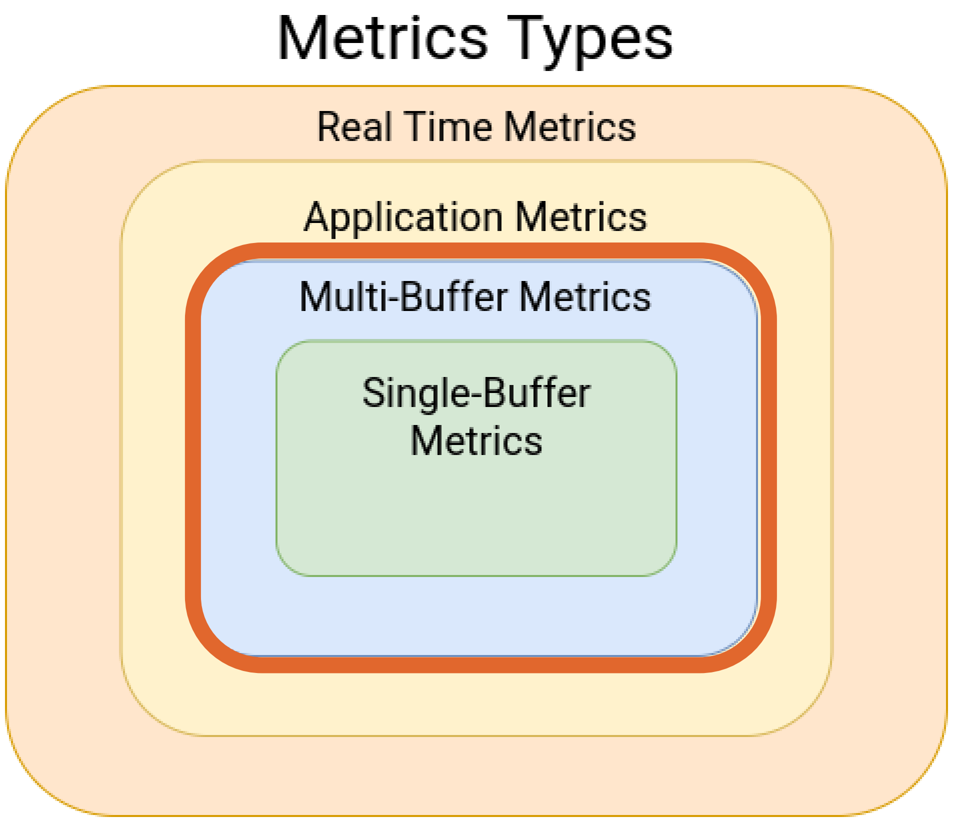


MGARD Quantity of Interest Mode

- Requirements
  - Q is a bounded linear functional
    - iff: $Q(\alpha x + \beta y) = \alpha Q(x) + \beta Q(y)$
  - $d_{f,t}$ represents a regular grid
    - This includes many simulations
- Procedure
  - Precompute scaling factor $\Upsilon_{L^s}(Q)$
  - Use bound $\Upsilon_{L^s}(Q) \left\| d_{f,t} - \widetilde{d_{f,t}} \right\|_{L^s}$
  - Details in the paper cited below

Ainsworth, Mark; Tugluk, Ozan; Whitney, Ben; Klasky, Scott . "Multilevel techniques for compression and reduction of scientific data-quantitative control of accuracy in derived quantities. 2019

VS. MGARD Quantity of Interest Mode

- Relative to MGARD-QOI mode
  - LibPressio-Opt+SZ is much faster for one-off tasks
  - Even if precomputation is not required, it can still be faster

VS. FRaZ

- Relative to FRaZ
  - Inter-iteration early termination
  - Multi-threaded searches
  - Embeddable
  - Supports user-defined objectives
  - Supports multiple input parameters
  - Extendable Search methods

Automated Configuration Timeline

Current Work

FRaZ
- Bounding Compression Ratio

LibPressio-Opt
- Bounding User Metrics
- Performance Improvements

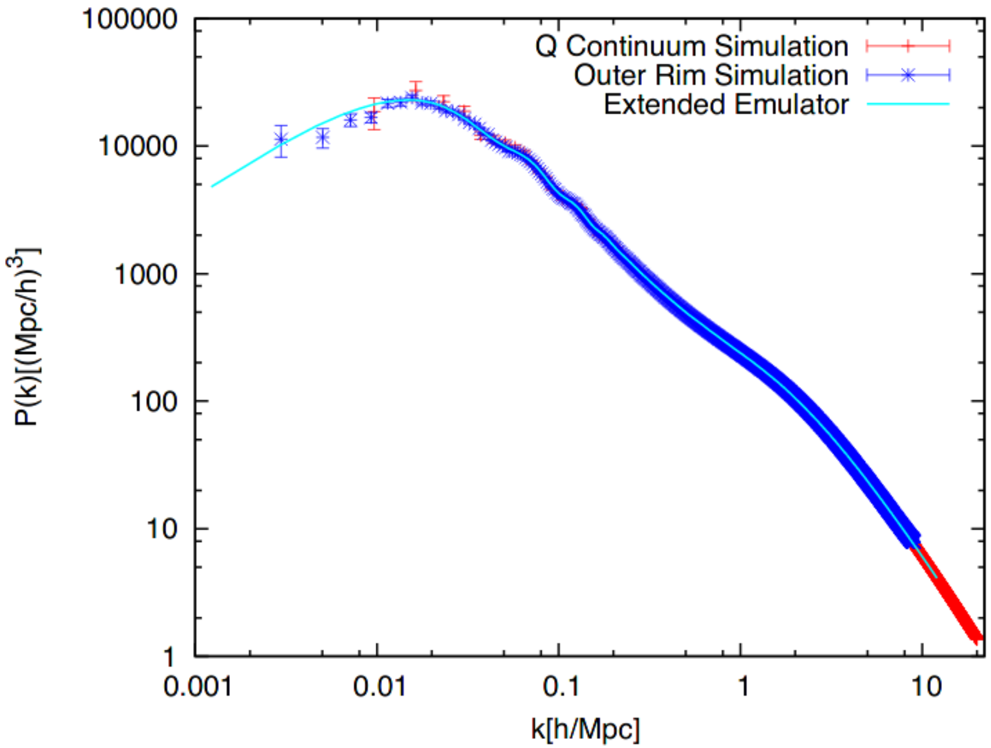
More Complex Apps
- Bounding Complex, Multi-faceted Metrics

3 – More Complex Applications

Can we adapt LibPressio-Opt to bound complex , multi-faceted metrics that use multiple buffers such as Hardware/Hybrid Accelerated Cosmology Code (HACC)'s power spectrum?

Background

- HACC – ECP astrophysics particle application
- No compressors bound spectral error



Matter Fluctuation Power Spectra from Outer Rim and Q Continuum simulation at z=0.26. [3]

Approach

1. Implement the spectra as a LibPressio metric of type vector<double>
2. Explore metrics to compare spectra
3. Solve maximum compression ratio such that differences between spectra are acceptable

Future Work

- True Multi-Objective Compression
- Improve the search algorithm
- Better Compression task scheduling

Understanding the Effects of Compression on ML/AI

Lossy Compression for AI

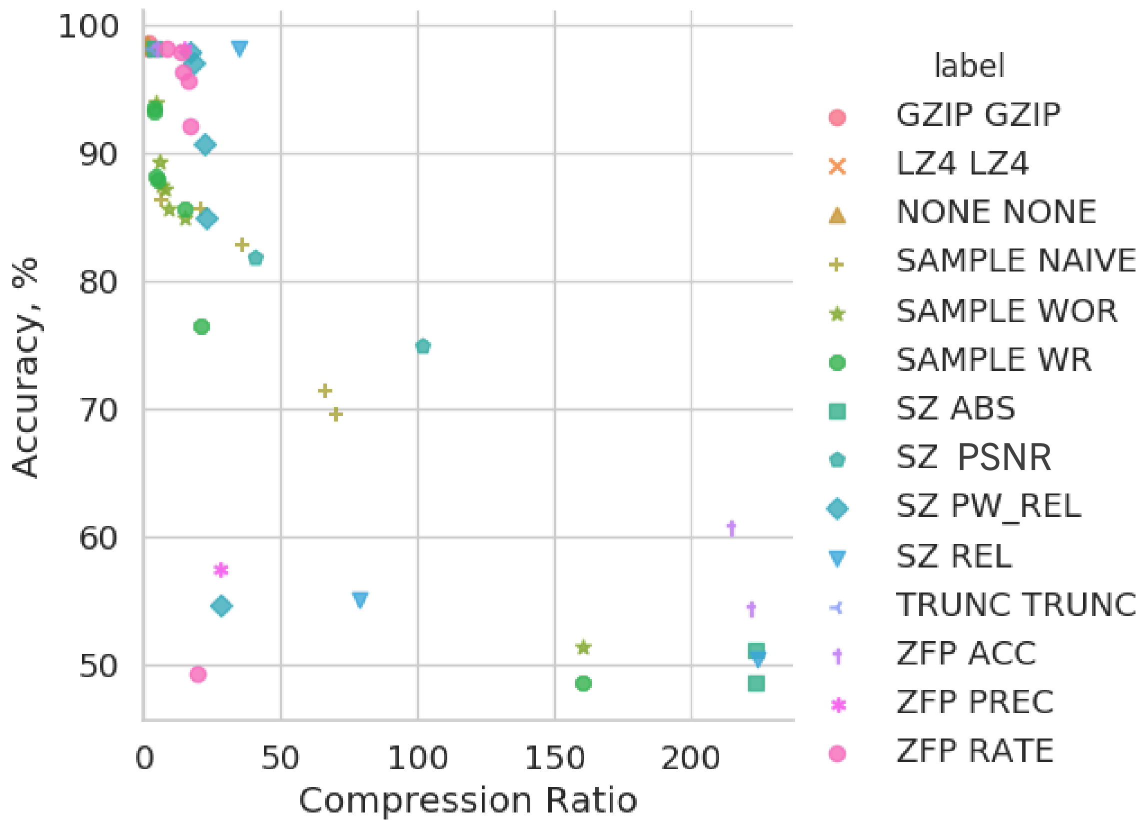
What are the trade-offs for compressing training and testing data to save storage space?

Approach

- Use LibPressio External Metrics on training data to collect pareto-optimal points
  - External Metrics run scripts to collect data.
  - In this case: here a known-good AI based model

Key Findings

- Prediction-Based EBLC works best (SZ)
  - Even better than sampling!
  - Even on imbalanced datasets!
- Sometimes EBLC improves performance!
- Compress tabular data relatively by feature



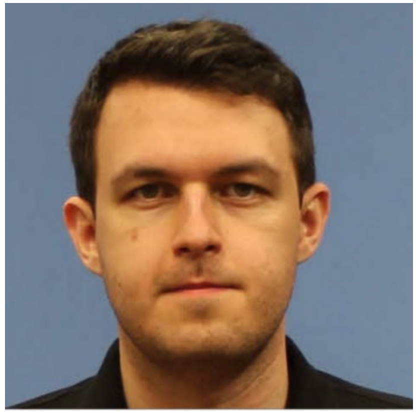
Conclusion

- Error Bounded Lossy Compression has the potential to be transformative
  - Especially with an interface to unify, tools to configure, and tools to understand

Thank You!










Thank You!

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CLEMSON UNIVERSITY

ECP EXASCALE COMPUTING PROJECT

NSF

Argonne NATIONAL LABORATORY

School of COMPUTING Clemson University

Questions?

Approachable Error Bounded Lossy Compression

Robert Underwood

robertu@g.clemson.edu

Clemson University

October 8, 2020

My Curriculum Vita

Papers I Worked On

- R. Underwood, S. Di, J. C. Calhoun and F. Cappello, "FRaZ: A Generic High-Fidelity Fixed-Ratio Lossy Compression Framework for Scientific Floating-point Data," 2020 (IPDPS)
- Jiannan Tian et al. "cuSZ: An Efficient GPU Based Error-Bounded Lossy Compression Framework for Scientific Data". In: Proceedings of 29th International Conference on Parallel Architectures and Compilation Techniques. Co-Author. ACM. Atlanta, Georgia (virtual), Oct. 2020.
- A. Gok et al. "Metrics for the Preservation of the Error In Derivatives" 2020 (In Preparation)
- R. Underwood, S. Di, J. C. Calhoun and F. Cappello, "LibPressio-Opt: Fast User Error Bounds for Loss Compression" 2020 (In Submission)
- R. Underwood et al. "Machine Learning and AI with Error Bounded Lossy Compression" (In Preparation)

References

- Ainsworth, Mark; Tugluk, Ozan; Whitney, Ben; Klasky, Scott . "Multilevel techniques for compression and reduction of scientific data-quantitative control of accuracy in derived quantities. 2019
- Di, Sheng and Cappello, Franck "Fast Error Bounded Lossy Compression with SZ" 2016
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