

Lec 21 - Apache Arrow

Statistical Computing and Computation

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Apache Arrow

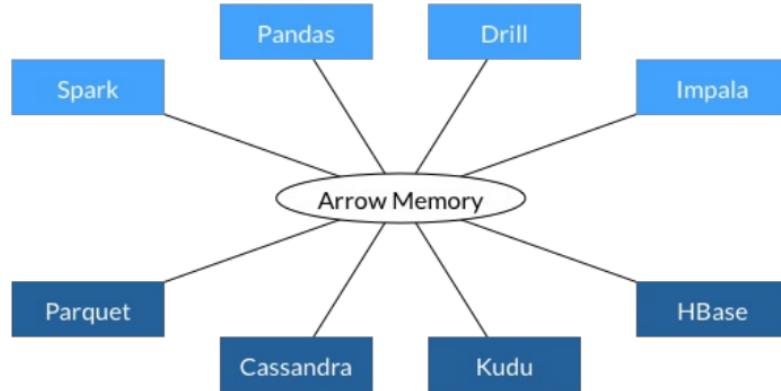
Apache Arrow is a software development platform for building high performance applications that process and transport large data sets. It is designed to both improve the performance of analytical algorithms and the efficiency of moving data from one system or programming language to another.

A critical component of Apache Arrow is its in-memory columnar format, a standardized, language-agnostic specification for representing structured, table-like datasets in-memory. This data format has a rich data type system (included nested and user-defined data types) designed to support the needs of analytic database systems, data frame libraries, and more.

Language support

Core implementations in:

- C
- C++
- C#
- go
- Java
- JavaScript
- Julia
- Rust
- MATLAB
- Python



pyarrow

```
import pyarrow as pa
```

The basic building blocks of Arrow are array and table^{*} objects, arrays are collections of data of a uniform type.

```
num = pa.array([1, 2, 3, 2], type=pa.int8())
num
```

```
## <pyarrow.lib.Int8Array object at 0x294c02fa0>
## [
##   1,
##   2,
##   3,
##   2
## ]
```

```
year = pa.array([2019, 2020, 2021, 2022])
year
```

```
## <pyarrow.lib.Int64Array object at 0x294c151c0>
## [
```

```
name = pa.array(
    ["Alice", "Bob", "Carol", "Dave"],
    type=pa.string()
)
name
```

```
## <pyarrow.lib.StringArray object at 0x294c15220>
## [
##   "Alice",
##   "Bob",
##   "Carol",
##   "Dave"
## ]
```

Tables

A table is created by combining multiple arrays together to form the columns while also attaching names for each column.

```
t = pa.table(  
    [num, year, name],  
    names = ["num", "year", "name"]  
)  
  
t
```

```
## pyarrow.Table  
## num: int8  
## year: int64  
## name: string  
## ----  
## num: [[1,2,3,2]]  
## year: [[2019,2020,2021,2022]]  
## name: [["Alice","Bob","Carol","Dave"]]
```

table is part of pyarrow but not part of the arrow standard, more on this in a bit

Array indexing

Elements of an array can be selected using [] with an integer index or a slice, the former returns a typed scalar the latter an array.

name[0]

```
## <pyarrow.StringScalar: 'Alice'>
```

name[0:3]

```
## <pyarrow.lib.StringArray object at 0x294c15340>
```

```
## [  
##   "Alice",  
##   "Bob",  
##   "Carol"  
## ]
```

name[:]

```
## <pyarrow.lib.StringArray object at 0x294c152e0>
```

```
## [  
##   "Alice",  
##   "Bob",
```

Arrow arrays are immutable and as such do not allow for element assignment.

name[-1]

```
## <pyarrow.StringScalar: 'Dave'>
```

name[::-1]

```
## <pyarrow.lib.StringArray object at 0x294c15400>
```

```
## [  
##   "Dave",  
##   "Carol",  
##   "Bob",  
##   "Alice"  
## ]
```

name[4]

```
## IndexError: index out of bounds
```

Data Types

The following types are language agnostic for the purpose of portability, however because of these some differ slightly from what is available from Numpy and Pandas,

- **Fixed-length primitive types:** numbers, booleans, date and times, fixed size binary, decimals, and other values that fit into a given number
 - Examples: `bool_()`, `uint64()`, `timestamp()`, `date64()`, and many more
- **Variable-length primitive types:** binary, string
- **Nested types:** list, map, struct, and union
- **Dictionary type:** An encoded categorical type

Schemas

A data structure that contains information on the names and types of columns for a table (or record batch),

```
t.schema
```

```
## num: int8
## year: int64
## name: string
```

```
pa.schema([
    ('num', num.type),
    ('year', year.type),
    ('name', name.type)
])
```

```
## num: int8
## year: int64
## name: string
```

Schema metadata

Schemas can also store additional metadata about the columns (e.g. codebook like textual descriptions)

```
new_schema = t.schema.with_metadata({  
    'num': "Favorite number",  
    'year': "Year expected to graduate",  
    'name': "First name"  
})  
new_schema
```

```
## num: int8  
## year: int64  
## name: string  
## -- schema metadata --  
## num: 'Favorite number'  
## year: 'Year expected to graduate'  
## name: 'First name'
```

```
t.cast(new_schema).schema
```

```
## num: int8  
## year: int64  
## name: string
```

Missing values / None / NaNs

```
pa.array([1,2,None,3])
```

```
## <pyarrow.lib.Int64Array object at 0x294c15400>
## [
##   1,
##   2,
##   null,
##   3
## ]
```

```
pa.array([1.,2.,None,3.])
```

```
## <pyarrow.lib.DoubleArray object at 0x294c152e0>
## [
##   1,
##   2,
##   null,
##   3
## ]
```

```
pa.array([1,2,None,3])[2]
```

```
pa.array(["alice","bob",None,"dave"])
```

```
## <pyarrow.lib.StringArray object at 0x294c15400>
## [
##   "alice",
##   "bob",
##   null,
##   "dave"
## ]
```

```
pa.array([1,2,np.nan,3])
```

```
## <pyarrow.lib.DoubleArray object at 0x294c15280>
## [
##   1,
##   2,
##   nan,
##   3
## ]
```

```
pa.array(["alice","bob",None,"dave"])[2]
```

Nest type arrays

list type:

```
pa.array([[1,2], [3,4], None, [5,None]])  
  
## <pyarrow.lib.ListArray object at 0x294c152e0>  
## [  
##   [  
##     1,  
##     2  
##   ],  
##   [  
##     3,  
##     4  
##   ],  
##   null,  
##   [  
##     5,  
##     null  
##   ]  
## ]
```

See also map and union arrays.

struct type:

```
pa.array([  
  {'x': 1, 'y': True, 'z': "Alice"},  
  {'x': 2, 'y': False, 'z': "Bob"},  
  {'x': 3, 'y': False }  
])  
  
## <pyarrow.lib.StructArray object at 0x294c15400>  
## -- is_valid: all not null  
## -- child 0 type: int64  

```

Dictionary array

A dictionary array is the equivalent to a factor in R or pd.Categorical in Pandas,

```
levels = pa.array(['sun', 'rain', 'clouds', 'snow'])
values = pa.array([0,0,2,1,3,None])
dict_array = pa.DictionaryArray.from_arrays(values, levels)
dict_array
```

```
## <pyarrow.lib.DictionaryArray object at 0x294a22d60>
##
## -- dictionary:
##   [
##     "sun",
##     "rain",
##     "clouds",
##     "snow"
##   ]
## -- indices:
##   [
##     0,
##     0,
##     2,
##     1,
```

```
dict_array.dictionary_decode()
```

```
## <pyarrow.lib.StringArray object at 0x294c15520>
## [
##   "sun",
##   "sun",
##   "clouds",
##   "rain",
##   "snow",
##   null
## ]
```

```
levels.dictionary_encode()
```

```
## <pyarrow.lib.DictionaryArray object at 0x294a22d60>
## 
## -- dictionary:
##   [
##     "sun",
##     "rain",
##     "clouds",
```

Record Batches

In between a table and an array Arrow has the concept of a Record Batch - which represents a chunk of the larger table. They are composed of a named collection of equal-length arrays.

```
batch = pa.RecordBatch.from_arrays(  
    [num, year, name],  
    ["num", "year", "name"]  
)  
  
batch
```

```
## pyarrow.RecordBatch  
## num: int8  
## year: int64  
## name: string
```

```
batch.num_columns
```

```
## 3
```

```
batch.num_rows
```

```
## 4
```

```
batch.nbytes
```

```
## 69
```

```
batch.schema
```

```
## num: int8
```

Batch indexing

[] can be used with a Record Batch to select columns (by name or index) or rows (by slice), additionally the slice() method can be used to select rows.

batch[0]

```
## <pyarrow.lib.Int8Array object at 0x294c155e0>
## [
##   1,
##   2,
##   3,
##   2
## ]
```

batch["name"]

```
## <pyarrow.lib.StringArray object at 0x294c15580>
## [
##   "Alice",
##   "Bob",
##   "Carol",
##   "Dave"
## ]
```

batch[0:2].to_pandas()

```
##     num  year   name
## 0     1  2019 Alice
## 1     2  2020 Bob
```

batch.slice(0,2).to_pandas()

```
##     num  year   name
## 0     1  2019 Alice
## 1     2  2020 Bob
```

Tables vs Record Batches

As mentioned previously in a footnote, `table` objects are not part of the Arrow specification - rather they are a convenience tool provided to help with the wrangling of multiple Record Batches.

```
table = pa.Table.from_batches([batch] * 3)
table
```

```
## pyarrow.Table
## num: int8
## year: int64
## name: string
## -----
## num: [[1,2,3,2],[1,2,3,2],[1,2,3,2]]
## year: [[2019,2020,2021,2022],[2019,2020,2021,2022],[2019,2020,2021,2022]]
## name: [["Alice","Bob","Carol","Dave"],["Alice","Bob","Carol","Dave"],["Alice","Bob","Carol","Dave"]]
```

table.num_columns

```
## 3
```

table.num_rows

table.to_pandas()

```
##     num   year   name
## 0      1  2019  Alice
## 1      2  2020   Bob
## 2      3  2021  Carol
```

Chunked Array

The columns of `table` are therefore composed of the columns of each of the batches, these are stored as `ChunkedArrays` instead of `Arrays` to reflect this.

```
table["name"]
```

```
## <pyarrow.lib.ChunkedArray object at 0x294c55400
## [
##   [
##     "Alice",
##     "Bob",
##     "Carol",
##     "Dave"
##   ],
##   [
##     "Alice",
##     "Bob",
##     "Carol",
##     "Dave"
##   ],
##   [
##     "Alice",
##     "Bob",
```

```
table[1]
```

```
## <pyarrow.lib.ChunkedArray object at 0x294c554f0>
## [
##   [
##     2019,
##     2020,
##     2021,
##     2022
##   ],
##   [
##     2019,
##     2020,
##     2021,
##     2022
##   ],
##   [
##     2019,
##     2020,
```

Arrow + NumPy

Conversion between NumPy arrays and Arrow arrays is straight forward,

```
np.linspace(0,1,11)

## array([0. , 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1. ])

pa.array( np.linspace(0,1,11) )

## <pyarrow.lib.DoubleArray object at 0x294c15f40>
## [
##   0,
##   0.1,
##   0.2,
##   0.3000000000000004,
##   0.4,
##   0.5,
##   0.6000000000000001,
##   0.7000000000000001,
##   0.8,
##   0.9,
##   1
## ]
```

NumPy & data copies

```
pa.array(["hello", "world"]).to_numpy()  
  
## ArrowInvalid: Needed to copy 1 chunks with 0 nulls, but zero_copy_only was True  
  
pa.array(["hello", "world"]).to_numpy(zero_copy_only=False)  
  
## array(['hello', 'world'], dtype=object)
```

```
pa.array([1,2,None,4]).to_numpy()  
  
## ArrowInvalid: Needed to copy 1 chunks with 1 nulls, but zero_copy_only was True  
  
pa.array([1,2,None,4]).to_numpy(zero_copy_only=False)  
  
## array([ 1.,  2., nan,  4.])
```

```
pa.array([[1,2], [3,4], [5,6]]).to_numpy()
```

Arrow + Pandas

We've already seen some basic conversion of Arrow table objects to Pandas, the conversions here are a bit more complex than with NumPy due in large part to how Pandas handles missing data.

Source (Pandas)	Destination (Arrow)
bool	BOOL
(u)int{8,16,32,64}	(U)INT{8,16,32,64}
float32	FLOAT
float64	DOUBLE
str / unicode	STRING
pd.Categorical	DICTIONARY
pd.Timestamp	TIMESTAMP(unit=ns)
datetime.date	DATE
datetime.time	TIME64

Source (Arrow)	Destination (Pandas)
BOOL	bool
BOOL with nulls	object (with values True, False, None)
(U)INT{8,16,32,64}	(u)int{8,16,32,64}
(U)INT{8,16,32,64} with nulls	float64
FLOAT	float32
DOUBLE	float64
STRING	str
DICTIONARY	pd.Categorical
TIMESTAMP(unit=*)	pd.Timestamp

From [Type differences documentation](#)

Series & data copies

Due to these discrepancies it is much more likely that converting from Arrow array to a Panda series will require a type to be changed in which case the data will need to be copied. Like `to_numpy()` the `to_pandas()` method also accepts the `zero_copy_only` argument, however it defaults to `False`.

```
pa.array([1,2,3,4]).to_pandas()
```

```
## 0      1
## 1      2
## 2      3
## 3      4
## dtype: int64
```

```
pa.array(["hello", "world"]).to_pandas()
```

```
## 0    hello
## 1   world
## dtype: object
```

Note that Arrow arrays are converted to Series while tables & batches are converted to DataFrames

```
pa.array([1,2,3,4]).to_pandas(zero_copy_only=True)
```

```
## 0      1
## 1      2
## 2      3
## 3      4
## dtype: int64
```

```
pa.array(["hello", "world"]).to_pandas(zero_copy_=
```

```
## ArrowInvalid: Needed to copy 1 chunks with 0 nulls,
```

```
pa.array(["hello", "world"]).dictionary_encode()
```

Zero Copy Series Conversions

Zero copy conversions from `Array` or `ChunkedArray` to NumPy arrays or pandas Series are possible in certain narrow cases:

- The Arrow data is stored in an integer (signed or unsigned `int8` through `int64`) or floating point type (`float16` through `float64`). This includes many numeric types as well as timestamps.
- The Arrow data has no null values (since these are represented using bitmaps which are not supported by pandas).
- For `ChunkedArray`, the data consists of a single chunk, i.e. `arr.num_chunks == 1`. Multiple chunks will always require a copy because of pandas's contiguousness requirement.

In these scenarios, `to_pandas` or `to_numpy` will be zero copy. In all other scenarios, a copy will be required.

DataFrame & data copies

```
table.to_pandas()
```

```
##      num  year   name
## 0      1  2019 Alice
## 1      2  2020  Bob
## 2      3  2021 Carol
## 3      2  2022 Dave
## 4      1  2019 Alice
## 5      2  2020  Bob
## 6      3  2021 Carol
## 7      2  2022 Dave
## 8      1  2019 Alice
## 9      2  2020  Bob
## 10     3  2021 Carol
## 11     2  2022 Dave
```

```
table.to_pandas(zero_copy_only=True)
```

```
## ArrowInvalid: Cannot do zero copy conversion into multi-column DataFrame block
```

```
table.drop(['name']).to_pandas(zero_copy_only=True)
```

```
## ArrowInvalid: Cannot do zero copy conversion into multi-column DataFrame block
```

Source

Pandas -> Arrow

To convert from a Pandas DataFrame to an Arrow Table we can use the `from_pandas()` method
(schemas can also be inferred from DataFrames)

```
df = pd.DataFrame({  
    'x': np.random.normal(size=5),  
    'y': ["A", "A", "B", "C", "C"],  
    'z': [1, 2, 3, 4, 5]  
})  
  
pa.Table.from_pandas(df)
```

```
## pyarrow.Table  
## x: double  
## y: string  
## z: int64  
## ----  
## x: [[-0.06485733164818355, -1.162152671617057, 0.24439260563508308, 0.9930845082160399, 0.4866059430117967]]  
## y: [["A", "A", "B", "C", "C"]]  
## z: [[1, 2, 3, 4, 5]]  
  
pa.Schema.from_pandas(df)
```

The import of Pandas indexes is governed by the `preserve_index` argument

An aside on tabular file formats

Comma Separated Values

This and other text + delimiter based file formats are the most common and generally considered the most portable, however they have a number of significant draw backs

- no explicit schema or other metadata
- column types must be inferred from the data
- numerical values stored as text (efficiency and precision issues)
- limited compression options

(Apache) Parquet

... provides a standardized open-source columnar storage format for use in data analysis systems. It was created originally for use in Apache Hadoop with systems like Apache Drill, Apache Hive, Apache Impala, and Apache Spark adopting it as a shared standard for high performance data IO.

Core features:

The values in each column are physically stored in contiguous memory locations and this columnar storage provides the following benefits:

- Column-wise compression is efficient and saves storage space
- Compression techniques specific to a type can be applied as the column values tend to be of the same type
- Queries that fetch specific column values need not read the entire row data thus improving performance

Feather

... is a portable file format for storing Arrow tables or data frames (from languages like Python or R) that utilizes the Arrow IPC format internally. Feather was created early in the Arrow project as a proof of concept for fast, language-agnostic data frame storage for Python (pandas) and R.

Core features:

- Direct columnar serialization of Arrow tables
- Supports all Arrow data types and compression
- Language agnostic
- Metadata makes it possible to read only the necessary columns for an operation

Example - File Format Performance

Building a large dataset

```
np.random.seed(1234)

df = (
    pd.read_csv("https://sta663-sp22.github.io/slides/data/penguins.csv")
        .sample(1000000, replace=True)
        .reset_index(drop=True)
)

num_cols = ["bill_length_mm", "bill_depth_mm", "flipper_length_mm",      "body_mass_g"]
df[num_cols] = df[num_cols] + np.random.normal(size=(df.shape[0],len(num_cols)))

df
```

##	species	island	bill_length_mm	bill_depth_mm	flipper_length_mm	body_mass_g	sex	year
## 0	Chinstrap	Dream	48.519017	17.136138	200.642256	3800.527739	male	2008
## 1	Gentoo	Biscoe	49.819091	15.317831	223.507723	5550.240852	male	2008
## 2	Chinstrap	Dream	45.174882	17.558060	188.966751	3449.851303	female	2007
## 3	Adelie	Biscoe	43.043647	18.630037	201.280925	4048.906267	male	2008
## 4	Gentoo	Biscoe	44.926619	13.633214	209.714220	4400.958077	female	2008
##
## 999995	Chinstrap	Dream	48.692352	18.184983	200.579977	3799.702510	male	2009
## 999996	Adelie	Biscoe	43.046500	20.182105	197.283516	4776.263332	male	2009
## 999997	Adelie	Torgersen	43.192871	17.278273	196.408173	4251.476411	male	2008
## 999998	Gentoo	Biscoe	53.208097	16.119915	230.537089	5498.259372	male	2009

Create output files

```
import os
os.makedirs("scratch/", exist_ok=True)

df.to_csv("scratch/penguins-large.csv")
df.to_parquet("scratch/penguins-large.parquet")

import pyarrow.feather

pyarrow.feather.write_feather(
    pa.Table.from_pandas(df),
    "scratch/penguins-large.feather"
)

pyarrow.feather.write_feather(
    pa.Table.from_pandas(df.dropna()),
    "scratch/penguins-large_nona.feather"
)
```

File Sizes

```
def file_size(f):
    x = os.path.getsize(f)
    print(f, "\t\t", round(x / (1024 * 1024),2), "MB")

file_size( "scratch/penguins-large.csv" )

## scratch/penguins-large.csv           100.91 MB

file_size( "scratch/penguins-large.parquet" )

## scratch/penguins-large.parquet       32.44 MB

file_size( "scratch/penguins-large.feather" )

## scratch/penguins-large.feather      48.93 MB

file_size( "scratch/penguins-large_nona.feather" )

## scratch/penguins-large_nona.feather 50.93 MB
```

Read Performance

```
%timeit pd.read_csv("scratch/penguins-large.csv")  
## 566 ms ± 11.9 ms per loop (mean ± std. dev. of 7 runs, 1 loop each)
```

```
%timeit pd.read_parquet("scratch/penguins-large.parquet")  
## 116 ms ± 3.43 ms per loop (mean ± std. dev. of 7 runs, 1 loop each)
```

```
%timeit pyarrow.csv.read_csv("scratch/penguins-large.csv")  
## 34.2 ms ± 99 µs per loop (mean ± std. dev. of 7 runs, 10 loops each)  
  
%timeit pyarrow.parquet.read_table("scratch/penguins-large.parquet")  
## 55.8 ms ± 104 µs per loop (mean ± std. dev. of 7 runs, 10 loops each)
```

```
%timeit pyarrow.feather.read_table("scratch/penguins-large.feather")
```

Read Performance (Arrow -> Pandas)

```
%timeit pyarrow.csv.read_csv("scratch/penguins-large.csv").to_pandas()
```

```
## 88.9 ms ± 1.45 ms per loop (mean ± std. dev. of 7 runs, 10 loops each)
```

```
%timeit pyarrow.parquet.read_table("scratch/penguins-large.parquet").to_pandas()
```

```
## 109 ms ± 153 µs per loop (mean ± std. dev. of 7 runs, 10 loops each)
```

```
%timeit pyarrow.feather.read_feather("scratch/penguins-large.feather")
```

```
## 61.5 ms ± 333 µs per loop (mean ± std. dev. of 7 runs, 10 loops each)
```

```
%timeit pyarrow.feather.read_feather("scratch/penguins-large_nona.feather")
```

```
## 60.6 ms ± 70.6 µs per loop (mean ± std. dev. of 7 runs, 10 loops each)
```

Column subset calculations - CSV & Parquet

```
%timeit pd.read_csv("scratch/penguins-large.csv")["flipper_length_mm"].mean()  
## 568 ms ± 9.43 ms per loop (mean ± std. dev. of 7 runs, 1 loop each)  
  
%timeit pd.read_parquet("scratch/penguins-large.parquet", columns=["flipper_length_mm"]).mean()  
## 9.74 ms ± 53.9 µs per loop (mean ± std. dev. of 7 runs, 100 loops each)  
  
%timeit pyarrow.parquet.read_table("scratch/penguins-large.parquet", columns=["flipper_length_mm"]).to_pandas()  
## 8.46 ms ± 183 µs per loop (mean ± std. dev. of 7 runs, 100 loops each)  
  
%timeit pyarrow.parquet.read_table("scratch/penguins-large.parquet")["flipper_length_mm"].to_pandas().mean()  
## 60.7 ms ± 1.04 ms per loop (mean ± std. dev. of 7 runs, 10 loops each)
```

Column subset calculations - Feather

```
%timeit pyarrow.feather.read_table("scratch/penguins-large.feather", columns=["flipper_length_mm"]).to_pa
```

```
## 8.1 ms ± 53.1 µs per loop (mean ± std. dev. of 7 runs, 100 loops each)
```

```
%timeit pyarrow.feather.read_table("scratch/penguins-large.feather")["flipper_length_mm"].to_pandas().mea
```

```
## 14.4 ms ± 403 µs per loop (mean ± std. dev. of 7 runs, 100 loops each)
```

```
%timeit pyarrow.feather.read_table("scratch/penguins-large_nona.feather", columns=["flipper_length_mm"]).
```

```
## 4.5 ms ± 76.9 µs per loop (mean ± std. dev. of 7 runs, 100 loops each)
```

```
%timeit pyarrow.feather.read_table("scratch/penguins-large_nona.feather")["flipper_length_mm"].to_pandas(
```

```
## 10 ms ± 21.9 µs per loop (mean ± std. dev. of 7 runs, 100 loops each)
```