PRINCETON UNIVERSITY iris hep

Alexander and the Ragged, Jagged, Nested, Indirected, Very Awkward Arrays

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Next week, I said,
I'm going to Australia.

In a data analysis, physicists need...

rich data structures

You can get that with C++ or Python, but C++ is verbose for analysis and Python is slow.

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interactivity

Data-oriented DSLs like NumPy and Pandas are convenient, but only for rectangular arrays of numbers.

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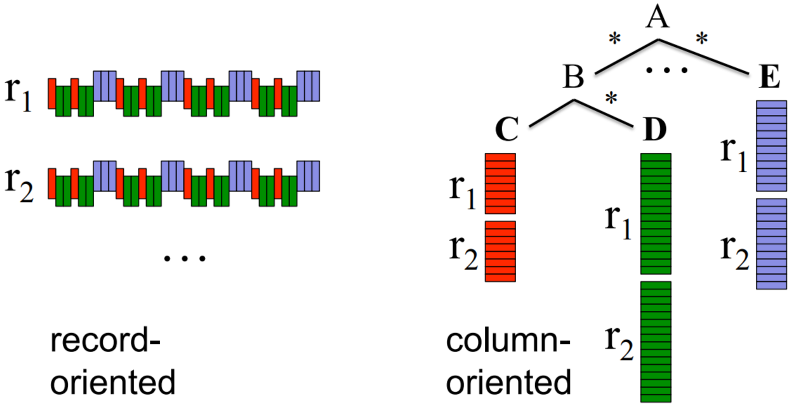
speed

Results should pop up quickly enough that you don't lose your train of thought.

Any data structure can be arranged as columnar arrays



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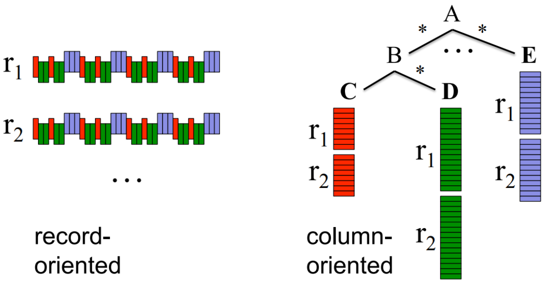
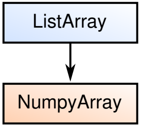


Clickable links to prior art:

- ROOT I/O with object splitting **(1997)**.
- M. Sergey et. al. (Google Dremel) *Proc. of the 36th Int'l Conf on Very Large Data Bases* **(2010)**, pp. 330–339.
- T. Mattis et. al., "Columnar Objects: Improving the Performance of Analytical Applications," in *ACM Int'l Symp. on New Ideas, New Paradigms, and Reflections on Programming and Software (Onward!)*, **(2015)**, pp. 197–210.
- Parquet file format **(2015)**.
- Apache Arrow in-memory format **(2016)**.
- Zarr data delivery system **(2015)**.
- XND vectorized math library **(2018)**.
- TensorFlow RaggedTensor **(2018)**.

An array of variable-length arrays ("ragged" or "jagged") can be built out of flattened contents and offsets specifying the beginning of each subarray.

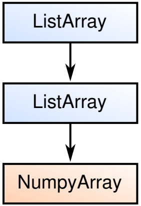



```
[[1.1, 2.2, 3.3],
 [],
 [4.4, 5.5],
 [6.6],
 [7.7, 8.8, 9.9]]
```

```
offsets    0,              3,   3,          5,   6,             9
content  1.1, 2.2, 3.3,      4.4, 5.5, 6.6, 7.7, 8.8, 9.9
```

Building columnar data structures from single-purpose parts

Multiple levels of variable-length arrays ("doubly jagged") can be built by using one jagged array as the content of the other.

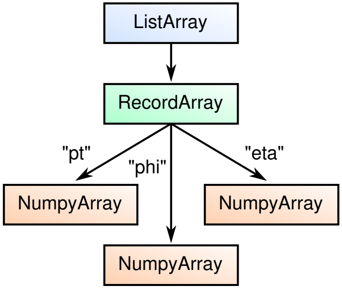



```
[[[1.1, 2.2, 3.3],
  [],
  [4.4, 5.5],
  [6.6]],
 [],
 [[7.7, 8.8, 9.9]]]
```

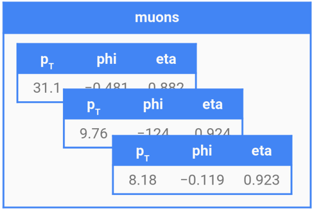
⇩

```
offsets1   0,                               4,   4,           5
offsets2   0,           3,   3,        5,   6,            9
content  1.1, 2.2, 3.3,    4.4, 5.5, 6.6, 7.7, 8.8, 9.9
```

Complex data structures can be built if you have enough columnar components, such as records with named fields, mixed data types, pointers, lazy loading...



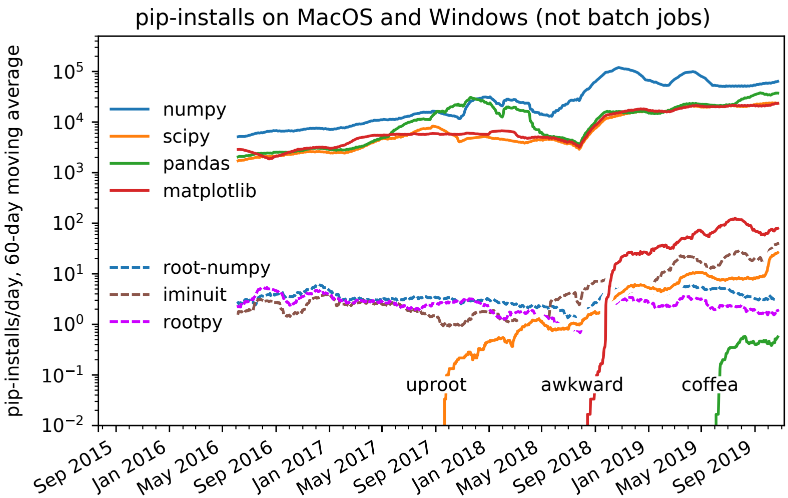

```
[[Muon(31.1, −0.481, 0.882),
      Muon(9.76, −0.124, 0.924),
      Muon(8.18, −0.119, 0.923)],
 [Muon(5.27, 1.246, −0.991)],
 [Muon(4.72, −0.207, 0.953)],
 [Muon(8.59, −1.754, −0.264),
      Muon(8.714, 0.185, 0.629)]
```

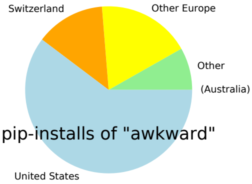


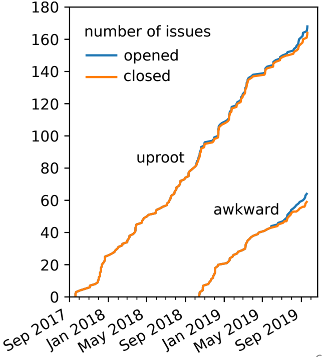

```
offsets      0,                          3,       4,       5,           7
     pt   31.1,    9.76,    8.18,    5.27,    4.72,    8.59, 8.714
    phi −0.481, −0.123, −0.119,   1.246, −0.207, −1.754, 0.185
    eta  0.882,   0.924,   0.923, −0.991,   0.953, −0.264, 0.629
```

Awkward Array

We now have 1 year of user feedback and maintainance experience







awkward has 100 downloads/day, 2 issues/week

What I've learned

From feedback and tutorials:

The interface needs to be simpler: a single `awkward.Array` class to hide the `ListArray` → `RecordArray` → `NumpyArrays` structure.

Separate structural operations (e.g. cross-join) from physics (e.g. cross-product).

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The interface needs to be simpler: a single `awkward.Array` class to hide the `ListArray` → `RecordArray` → `NumpyArrays` structure.

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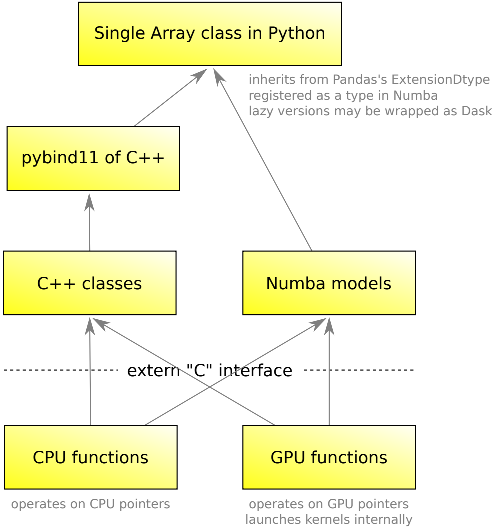
From maintenance:

Current implementation is entirely written in Python/Numpy.

For better flexibility, robustness, and uniformity, and in a few cases, speed, it should be rewritten in C++.

New architecture

Layer 1: Python user interface: a single `awkward.Array` class.



New architecture

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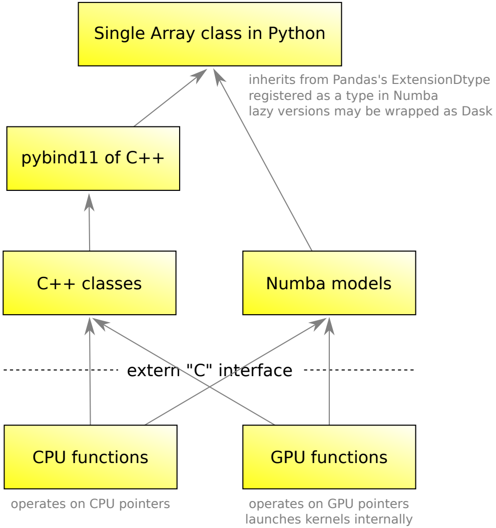
Layer 2: Structural classes in Python (e.g. `ListArray`/`RecordArray`).



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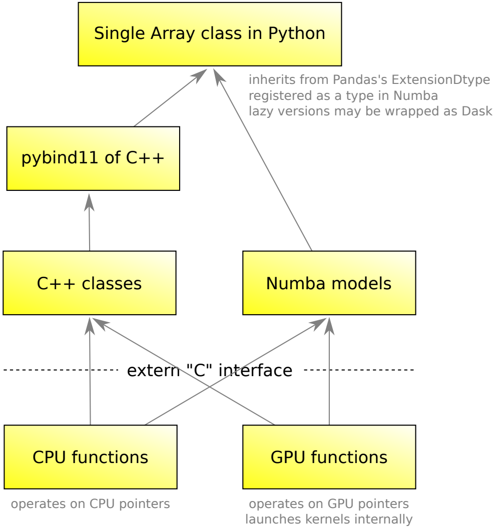
Layer 3: Array allocation and ownership; reference counting. Two languages: C++ and Numba (compiled Python).



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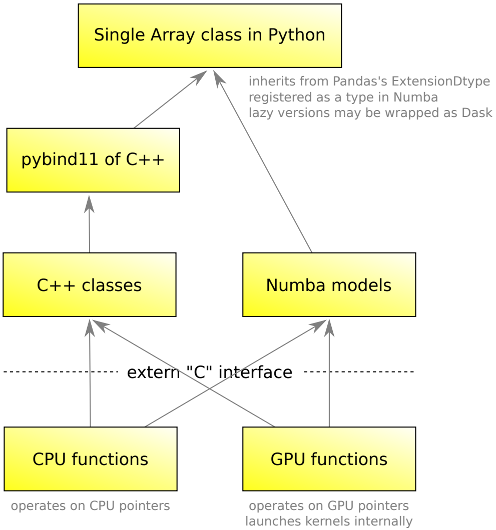
Layer 1: Python user interface: a single `awkward.Array` class.

Layer 2: Structural classes in Python (e.g. `ListArray`/`RecordArray`).

Layer 3: Array allocation and ownership; reference counting. Two languages: C++ and Numba (compiled Python).

Layer 4: Implementations, where we write **`for`** loops. The only layer that needs to be optimized for speed.

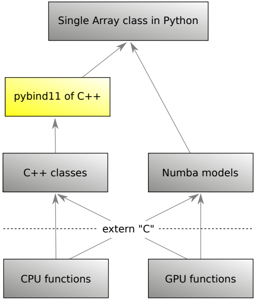


First benefit: greater generality

The current implementation has some hidden limitations, such as slicing in more than two jagged dimensions.

```
>>> import awkward     # awkward 0.x
>>> array = awkward.fromiter([[[0.0, 1.1, 2.2], [], [3.3, 4.4]],
...                           [[5.5]], [], [[6.6, 7.7, 8.8, 9.9]]])
>>> array[::-1, ::2, 1:].tolist()

NotImplementedError: this implementation cannot slice a JaggedArray
                     in more than two dimensions
```



But the new implementation is based on **for** loops and recursive procedures that can go arbitrarily deep.

```
>>> import awkward1    # awkward 1.0
>>> array = awkward1.fromiter([[[0.0, 1.1, 2.2], [], [3.3, 4.4]],
...                            [[5.5]], [], [[6.6, 7.7, 8.8, 9.9]]])
>>> awkward1.tolist(array[::-1, ::2, 1:])

[[[7.7, 8.8, 9.9]], [], [[]], [[1.1, 2.2], [4.4]]]
```

Full access in C++

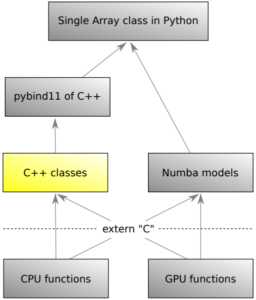
Everything is available in C++ except the convenient syntax.

```
namespace ak = awkward;
int main(int, char**) {
  std::vector<std::vector<std::vector<double>>> vector =
      {{{0.0, 1.1, 2.2}, {}, {3.3, 4.4}}, {{5.5}}, {},
       {{6.6, 7.7, 8.8, 9.9}}};

  ak::FillableArray builder(ak::FillableOptions(1024, 2.0));
  for (auto x : vector)
      builder.fill(x);
  std::shared_ptr<ak::Content> array = builder.snapshot();

  ak::Slice slice;
  slice.append(ak::SliceRange(ak::Slice::none(), ak::Slice::none(), -1));    // ::-1
  slice.append(ak::SliceRange(ak::Slice::none(), ak::Slice::none(), 2));     // ::2
  slice.append(ak::SliceRange(1, ak::Slice::none(), ak::Slice::none()));     // 1:

  if (array.get()->getitem(slice).get()->tojson(false, 1) !=
        "[[[7.7,8.8,9.9]],[],[[]],[[1.1,2.2],[4.4]]]")
      return -1;
  return 0;
}
```



Full access in Numba

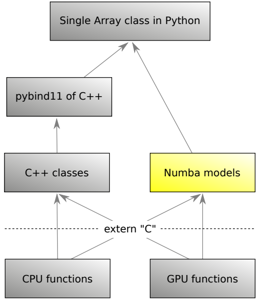
Similarly, everything is available in functions compiled by Numba.

```
>>> import numba
>>>
>>> @numba.jit(nopython=True)
... def compileme(a):
...     return a[::-1, ::2, 1:]
...
>>> compileme

CPUDispatcher(<function compileme at 0x7fd135e52ae8>)

>>> array = awkward1.fromiter([[[0.0, 1.1, 2.2], [], [3.3, 4.4]],
...                            [[5.5]], [], [[6.6, 7.7, 8.8, 9.9]]])
>>> awkward1.tolist(compileme(array))

[[[7.7, 8.8, 9.9]], [], [[]], [[1.1, 2.2], [4.4]]]
```



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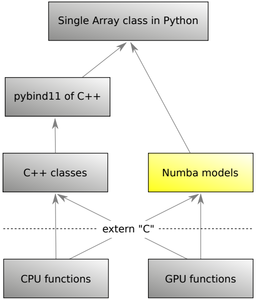

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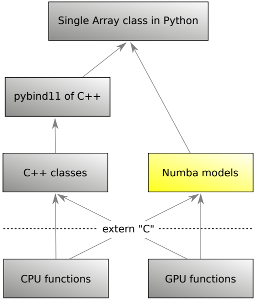

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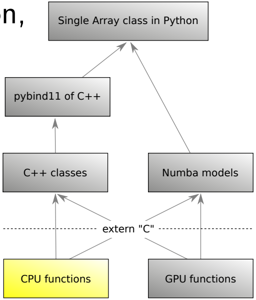
Data analysts can start with pure Python and only accelerate the functions that need it.

Single implementation

All interfaces—Python, C++, Numba—share the same implementation, a pure C library of functions on arrays.




```
extern "C" {
  Error awkward_listarray32_getitem_next_at_64(int64_t* tocarry,
      const int32_t* fromstarts, const int32_t* fromstops,
      int64_t lenstarts, int64_t startsoffset, int64_t stopsoffset,
      int64_t at) {
    // This is only only layer with loops over array elements.
    for (int64_t i = 0;  i < lenstarts;  i++) {
      int64_t length = fromstops[stopsoffset + i] -
                       fromstarts[startsoffset + i];
      int64_t regular_at = at;
      if (regular_at < 0) {
        regular_at += length;
      }
      if (!(0 <= regular_at  &&  regular_at < length)) {
        return failure("index out of range", i, at);
      }
      tocarry[i] = fromstarts[startsoffset + i] + regular_at;
    }
    return success();
}
```

Investigated toy languages with sets as a first-class concept

https://github.com/jpivarski/PartiQL

```
# "For events with at least three leptons (electrons or muons) and a same-flavor
# opposite-sign lepton pair, find the same-flavor opposite-sign lepton pair with a
# mass closest to 91.2 GeV; make a histogram of the pT of the leading other lepton."

leptons = electrons union muons

cut count(leptons) >= 3 named "three_leptons" {
    Z = electrons as (lep1, lep2) union muons as (lep1, lep2)
            where lep1.charge != lep2.charge
            min by abs(mass(lep1, lep2) - 91.2)

    third = leptons except [Z.lep1, Z.lep2] max by pt
    hist third.pt by regular(100, 0, 250) named "third_pt"
}
```

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    third = leptons except [Z.lep1, Z.lep2] max by pt
    hist third.pt by regular(100, 0, 250) named "third_pt"
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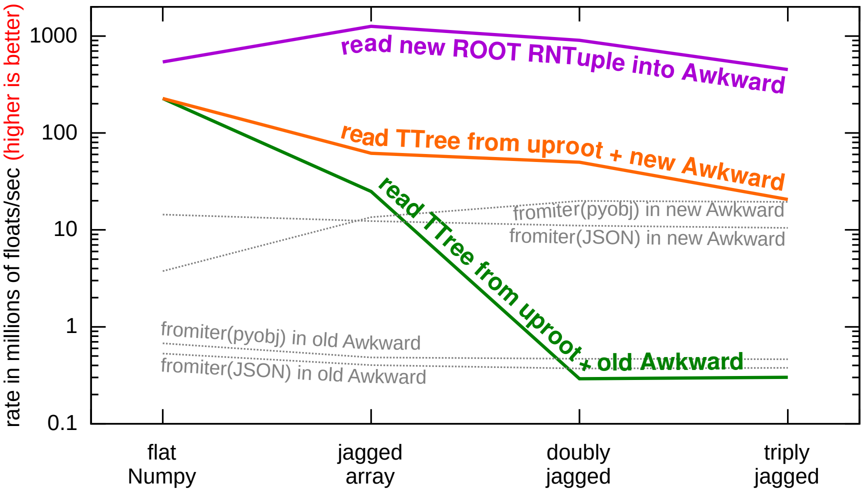
```

To define operations on sets, such as **join**, **cross**, **union**, and **except**, we need what SQL calls a surrogate-key index, so this has been added as an optional `Identity` array, passed through all operations in Awkward 1.0.

Converting record-oriented data into columnar data is much faster

Uncompressed data in warm cache; ∼5 GB samples in binary format; AWS r5ad.xlarge instance; measuring the wall time needed to copy from source into jagged^N arrays.



Multi-paradigm arrays

With a dataset in Awkward form (from TTrees, RNtuples, Arrow...), we want to

- perform vectorized operations with a Numpy-like syntax,
- pass data to and from a C++ library,
- enter a compiled Numba function to write fast for loops,
- evaluate a declarative expression on sets of particles,

interchangeably.

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Awkward 1.0 is intended as a solid foundation for that future.

When can I try it?

https://github.com/scikit-hep/awkward-1.0

Nowish: it is in a testable state (for Coffea and thrill-seekers).

Will be minimally usable for physics analysis in "early 2020."

Start an **`import awkward`** → **`import awkward0`**
`import awkward1` → **`import awkward`** transition by spring.