Femtocode: query system for HEP

What's a query system?

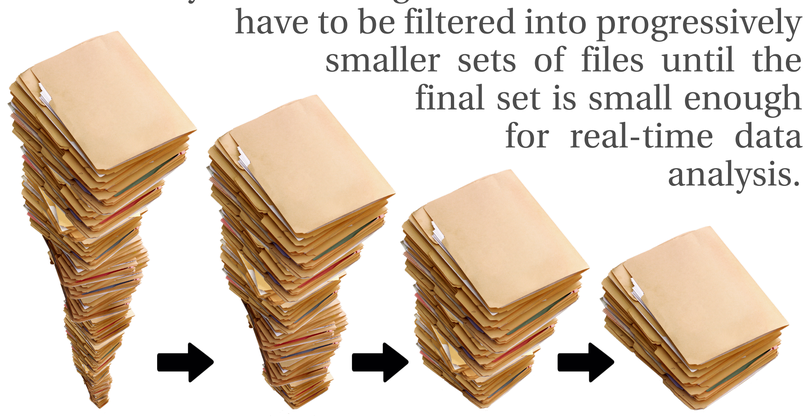
User asks a question, gets an answer quickly enough to *explore* the data.

Like a Google query, but aggregating HEP data, returning (e.g.) histograms.

Embedded within an analysis script: provides sliced projections of the data for users to fit/plot/analyze in any way they want.

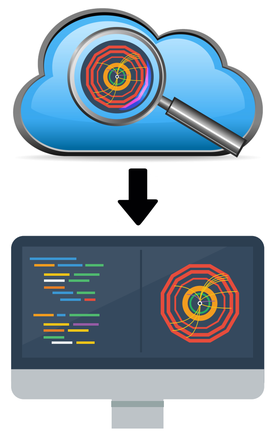
How it differs from what we do now

Physicists arrange data as sets of files that have to be filtered into progressively smaller sets of files until the final set is small enough for real-time data analysis.



Instead, we propose a service that serves aggregated views of analysis object data on demand.

Must be responsive to requests in real-time: ~1 sec for each scan over a dataset.



High-level language

User writes expressions that pick apart the structure of objects within arbitrary-length lists, to any depth of nesting.

Higher-order functions like `.map`, `.pairs`, `.filter`, `.reduce` instead of explicit `for` loops.

Femtocode query language is distributed in quoted snippets throughout a structured workflow and tree of aggregators.

(See `http://histogrammar.org` for histogram abstraction.)

```
workflow = session.source("b-physics")                    # pull from a named dataset
       .define(goodmuons = "muons.filter($1.pt > 5)")     # muons with pt > 5 are good
       .filter("goodmuons.size >= 2")                     # keep events with at least two
       .define(dimuon = """
           mu1, mu2 = goodmuons.maxby($1.pt, 2);          # pick the top two by pt
           energy = mu1.E + mu2.E;                        # compute imploded energy/momentum
           px = mu1.px + mu2.px;
           py = mu1.py + mu2.py;
           pz = mu1.pz + mu2.pz;

           rec(mass = sqrt(energy**2 - px**2 - py**2 - pz**2),
               pt = sqrt(px**2 + py**2),
               phi = atan2(py, px),
               eta = ln((energy + pz)/(energy - pz))/2)  # construct a record as output
           """)
       .bundle(                                           # make a bundle of plots
           mass = bin(120, 0, 12, "dimuon.mass"),         # using the variables we've made
           pt = bin(100, 0, 100, "dimuon.pt"),
           eta = bin(100, -5, 5, "dimuon.eta"),
           phi = bin(314, 0, 2*pi, "dimuon.phi + pi"),
           muons = loop("goodmuons", "mu", bundle(        # also make plots with one muon per entry
               pt = bin(100, 0, 100, "mu.pt"),
               eta = bin(100, -5, 5, "mu.eta"),
               phi = bin(314, -pi, pi, "mu.phi")
           ))
       )

pending = workflow.submit()                               # submit the query
pending["mass"].plot()                                    # and plot results while they accumulate
pending["muons"]["pt"].plot()                             # (they'll be animated)

blocking = pending.await()                                # stop the code until the result is in

massplot = blocking.plot.root("mass")                     # convert to a familiar format, like ROOT
massplot.Fit("gaus")                                      # and use that package's tools
```

No runtime errors:

Type system includes min/max ranges of numbers and collection lengths, so that out-of-domain errors are caught at compile-time.

Examples: `"x/y"` must be `"if y != 0: x/y else: None"`.

`filter("goodmuons.size >= 2")` above ensures that we can assign two of them as `mu1`, `mu2`.

Total functional language:

Every expression that compiles returns a result. (For simplicity, recursion is not allowed.)

Low-level execution

No objects at runtime:

All nested structures are represented as homogeneous arrays.

```
type          = collection(collection(record(a=integer, b=real)))
values        = [ [(1, 1.1)] [] [(2, 2.2) (3, 3.3)]] [ [(4, 4.4)]]
```

becomes

```
data[][]@size = 3 1          0  2          1 1
data[][]-a    =   1             2     3          4
data[][]-b    =       1.1           2.2   3.3        4.4
```

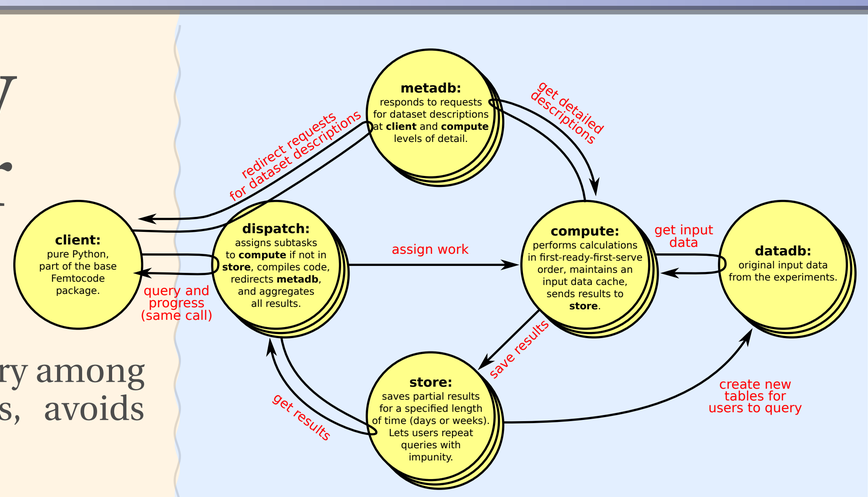
```
muons.map({mu1 =>
  muons.map({mu2 =>
    e1 = mu1.p**2 + 0.105658**2;
    e2 = mu2.p**2 + 0.105658**2;
    e1 + e2
    }).max
  }).max
```

```
#0       := **(muons[]-p, 2)
#1       := +(#0, 0.011164)
#2@size := $explodesize(muons[], muons[])
#2       := $explodedata(#1, #2@size, (muons[]))
#3       := $explodedata(#1, #2@size, (muons[], muons[]))
#4       := +(#2, #3)
#5       := $implode(#4, muons[], "max")
#6       := $implode(#5, None, "max")
```

Each statement may be a branchless, loopless GPU kernel or grouped by array size to minimize CPU passes over data.

Query server

Distributes query among compute nodes, avoids duplicate work.



Performance studies

- Typical analysis asks for ~10 TB of input data.
- Typical query touches < 1% of the *columns*.
- Disk read at 40 MB/sec ⇒ 2.6 sec for 1000 disks.
- Typical analysis touches < 10% of the *columns*.
- Therefore, fill 1 TB of a cluster's RAM as cache.
- Cache read at 1 GB/sec ⇒ 0.1 sec for 1000 cores.

Microbenchmarks:

Add a constant to an array of 64-bit floats on different systems. The first are disk limited, the last are memory bandwidth limited.

0.018 MHz	CMSSW EDAnalyzer (C++ event framework)
1.5 MHz	`TTree::Draw` in ROOT (HEP analysis toolkit)
2.8 MHz	minimal disk read and unzip
12 MHz	allocating C++ objects on heap, iterating, deleting
31 MHz	allocating C++ objects on stack and iterating
54 MHz	Femtocode loop, current implementation
250 MHz	minimal single-threaded loop in C (our goal)
8 000 MHz	same loop on 128 threads in KNL's MCDRAM
57 000 MHz	equivalent on Tesla P100-SXM2 GPU