Femtocode: querying HEP data

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Reminder of motivation

(I last talked about this on December 12.)

Query systems

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Femtocode

I'm developing a query system whose performance permits real-time analysis, but is capable of complex manipulations, such as filtering tracks, picking pairs to compute invariant masses, etc.

Three interrelated parts

Language/compiler

- As familiar to the user as possible (objects, nested loops).
- But constrained to allow restructuring for fast execution (map/filter/reduce instead of for loops, total-functional).
- Extra-strength type system to eliminate runtime errors.

Execution engine

- Operate on contiguous columns of data (like "TLeaf"), not objects. Restructuring becomes changes in arrays of integers.
- No memory allocation at runtime, vectorizable loops.
- JIT-compiled. CPU target for now, but GPU is possible.

Distributed server

- Vending machine: queries go in, histograms (etc.) come out.
- Referential transparency eliminates the need for "sessions."

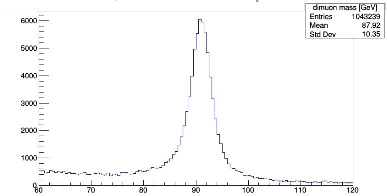
```
pending = session.source("ZZ_13TeV_pythia8")
    .define(mumass = "0.105658")      # chain of operations on source
    .toPython(mass = """
muons.map(mu1 => muons.map({mu2 =>    # doubly nested loop over muons
  p1x = mu1.pt * cos(mu1.phi);
  p1y = mu1.pt * sin(mu1.phi);        # shares scope with other steps
  p1z = mu1.pt * sinh(mu1.eta);       # in the chain (see "mumass")
  E1 = sqrt(p1x**2 + p1y**2 + p1z**2 + mumass**2);

  p2x = mu2.pt * cos(mu2.phi);
  p2y = mu2.pt * sin(mu2.phi);
  p2z = mu2.pt * sinh(mu2.eta);
  E2 = sqrt(p2x**2 + p2y**2 + p2z**2 + mumass**2);

  px = p1x + p2x; py = p1y + p2y;
  pz = p1z + p2z; E = E1 + E2;

  # "if" is required to avoid sqrt(-x)
  if E**2 - px**2 - py**2 - pz**2 >= 0:
    sqrt(E**2 - px**2 - py**2 - pz**2)
  else:
    None   # output type is nullable
}))
""").submit()                         # asynchronous submission to
final = pending.await()               # watch result accumulate
```

Yes, we see the Z peak.



Taking this example apart (1/3)

- Femtocode always appears in quotes (like SQL). It is a big-data aggregation step in the midst of a traditional analysis.
- A query is a "workflow" from source to aggregation, compiled and submitted as one unit.

  e.g. `source("dataset").define(X).define(Y).histogrammar(Z)`
- Most Femtocode expressions are tiny (hence "femto"), scattered throughout a Histogrammar aggregation:

```
session.source("dataset")
    .define(goodmuons = """...""")   # define good muons
    .filter("goodmuons.size >= 2")   # cut on them
    .define(dimuon = """..."""       # define dimuons
    .bundle(                         # plot their attributes
        mass = bin(120, 0, 12, "dimuon.mass"),
        pt = bin(100, 0, 100, "dimuon.pt"),
        eta = bin(100, -5, 5, "dimuon.eta"),
        phi = bin(314, 0, 2*pi, "dimuon.phi + pi"),
                                     # also plot the muons
        muons = explode("goodmuons", "mu", bundle(
            pt = bin(100, 0, 100, "mu.pt"),
            eta = bin(100, -5, 5, "mu.eta"),
            phi = bin(314, -pi, pi, "mu.phi"))))
```

Taking this example apart (2/3)

- Doubly nested loop by nesting functionals:
  `muons.map(mu1 => muons.map(mu2 => f(mu1, mu2)))`
  is equivalent to

  ```
  list_of_lists = []
  for mu1 in muons:
      list_of_numbers = []
      for mu2 in muons:
          list_of_numbers.append(f(mu1, mu2))
      list_of_lists.append(list_of_numbers)
  ```

- There will someday be more convenient forms: `pairs`, `table`, `filter`, `flatten`, `flatMap`, `zip`, `permutations`, etc.

  (This example would ideally use `pairs`, to avoid double-counting, and `flatten` to destructure the list-of-lists.)

Taking this example apart (3/3)

- Type system requires domain of `sqrt` to be guarded:

```
sqrt(E**2 - px**2 - py**2 - pz**2)
```

```
FemtocodeError: Function "sqrt" does not accept arguments with
the given types:

    sqrt(real)

    The sqrt function can only be used on non-negative numbers.

Check line:col 19:2 (pos 401):
      sqrt(E**2 - px**2 - py**2 - pz**2)
------^
```

But this works:

```
if E**2 - px**2 - py**2 - pz**2 >= 0:
    sqrt(E**2 - px**2 - py**2 - pz**2)
else:
    None
```

- The compiler tracks each subexpression's interval of validity:

`E**2 - px**2 - py**2 - pz**2` is limited to `real(min=0, max=inf)`.

In the future, we could use SymPy to discover this algebraically.

Another thing to notice

```
muons.map(mu1 => muons.map({mu2 =>
  p1x = mu1.pt * cos(mu1.phi);
  p1y = mu1.pt * sin(mu1.phi);
  p1z = mu1.pt * sinh(mu1.eta);
  E1 = sqrt(p1x**2 + p1y**2 + p1z**2 + mumass**2);
```

only uses `mu1`

```
  p2x = mu2.pt * cos(mu2.phi);
  p2y = mu2.pt * sin(mu2.phi);
  p2z = mu2.pt * sinh(mu2.eta);
  E2 = sqrt(p2x**2 + p2y**2 + p2z**2 + mumass**2);
```

only uses `mu2`

```
  px = p1x + p2x;
  py = p1y + p2y;
  pz = p1z + p2z;
  E = E1 + E2;

  if E**2 - px**2 - py**2 - pz**2 >= 0:
    sqrt(E**2 - px**2 - py**2 - pz**2)
  else:
    None
}))
```

uses both.

Femtocode minimizes computation

In most compilers, at least one of the two stanzas would be needlessly recomputed for every *pair* of muons. Physicists have learned to move these expressions out of the loop, possibly at the expense of readability.

Femtocode's compiler turns every loop over objects into vectorized functions on individual fields. A by-product of this is that the functions depending on `mu1` and `mu2` decouple from the functions depending on `(mu1, mu2)`.

In fact, all duplicate expressions are computed exactly once. The *only* reason to use assignment is for clarity.

What the dimuon example expands to

```
Sized by muons[]@size:
    #0       := cos(muons[]-phi)
    #1       := *(muons[]-pt, #0)
    #2       := **(#1, 2)
    #3       := sin(muons[]-phi)
    #4       := *(muons[]-pt, #3)
    #5       := **(#4, 2)
    #6       := sinh(muons[]-eta)
    #7       := *(muons[]-pt, #6)
    #8       := **(#7, 2)
    #9       := +(#2, #5, #8, 0.011164)
    #10      := sqrt(#9)
type(#10) == real(0.105658, almost(inf))

Sized by #11@size:
    #11@size := $explodesize(muons[], muons[])
    #11      := $explodedata(#10, #11@size, (muons[]))
    #12      := $explodedata(#10, #11@size, (muons[], muons[]))
    #13      := +(#11, #12)
    #14      := **(#13, 2)
    #15      := $explodedata(#1, #11@size, (muons[]))
    #16      := $explodedata(#1, #11@size, (muons[], muons[]))
    #17      := +(#15, #16)
    #18      := **(#17, 2)
    #19      := -(#14, #18)
    #20      := $explodedata(#4, #11@size, (muons[]))
    #21      := $explodedata(#4, #11@size, (muons[], muons[]))
    #22      := +(#20, #21)
    #23      := **(#22, 2)
    #24      := -(#19, #23)
    #25      := $explodedata(#7, #11@size, (muons[]))
    #26      := $explodedata(#7, #11@size, (muons[], muons[]))
    #27      := +(#25, #26)
    #28      := **(#27, 2)
    #29      := -(#24, #28)
    #30      := >=(#29, 0)
    #31      := <(#29, 0)
    #32      := -(#24, #28)
    #33      := sqrt(#32)
    #34      := if(#30, #31, #33, None)
type(#34) == union(null, real(0, almost(inf)))
```

`muons[]-pt`, `muons[]-phi`, `muons[]-eta`, `muons[]@size`, and everything that starts with a # is (at least conceptually) a big array of values.

All functions except `$explode*` are ideally suited to GPU acceleration.