Arrow Street: Semi-automatic SOA / AOSOA

Pascal Costanza

ExaScience Lab, Intel, Belgium

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Overview

- Manual AOS, SOA, and AOSOA representations.
- Semi-automatic SOA and AOSOA representations.
- Early results.

Example Class

```
struct C {
    double x;
    double y;
    double z;

    C () {}

    C (double x, double y, double z) :
        x(x), y(y), z(z)
    {}
};
```

Different representations for “many” objects

	0	1	2	3	4	5	6	7	8	9	10	11	…
Standard AOS	x_0	y_0	z_0	x_1	y_1	z_1	x_2	y_2	z_2	x_3	y_3	z_3	…

Different representations for “many” objects

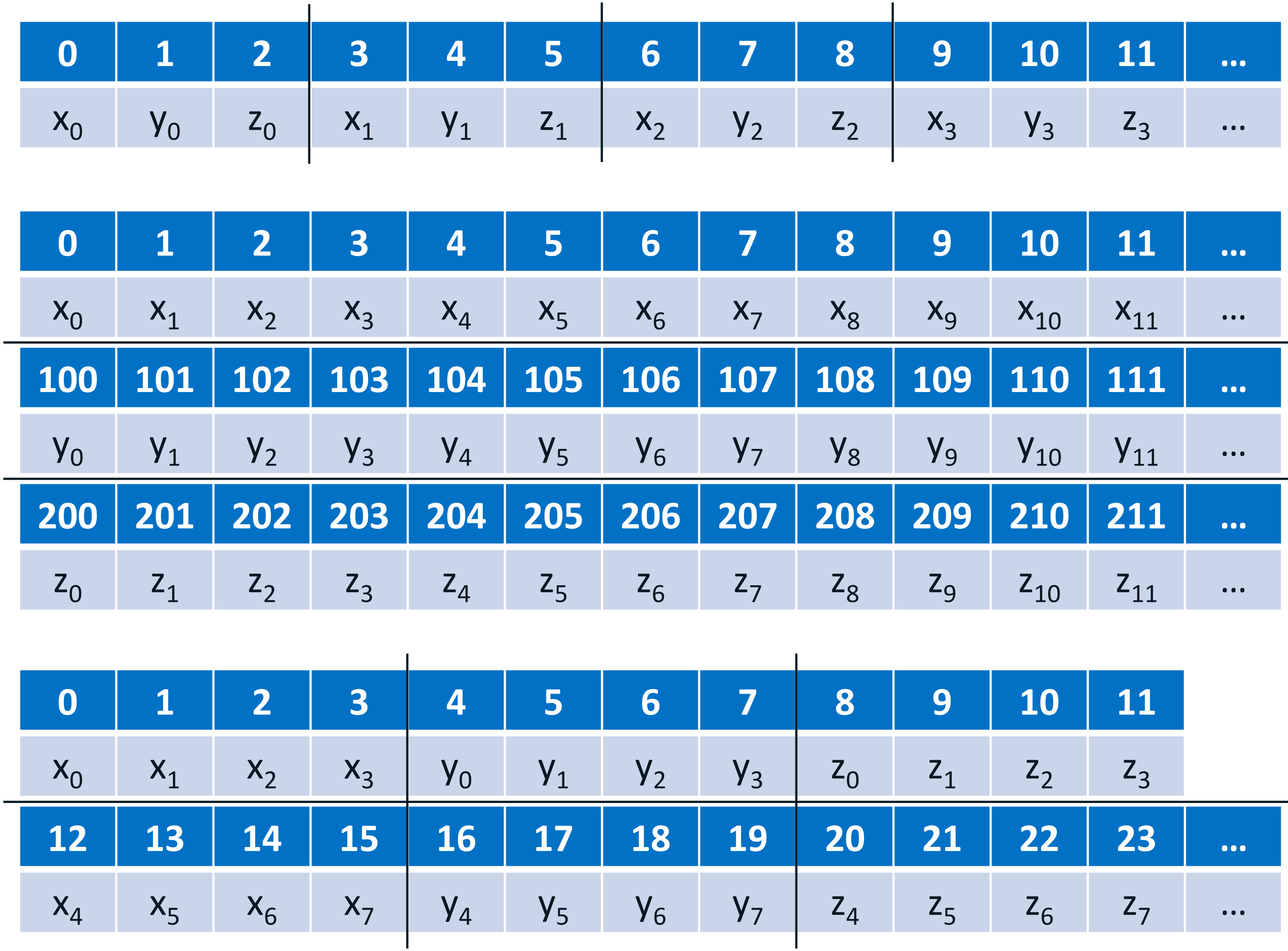
Standard AOS

0	1	2	3	4	5	6	7	8	9	10	11	…
x_0	y_0	z_0	x_1	y_1	z_1	x_2	y_2	z_2	x_3	y_3	z_3	…

SOA

0	1	2	3	4	5	6	7	8	9	10	11	…
x_0	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	…
100	101	102	103	104	105	106	107	108	109	110	111	…
y_0	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}	…
200	201	202	203	204	205	206	207	208	209	210	211	…
z_0	z_1	z_2	z_3	z_4	z_5	z_6	z_7	z_8	z_9	z_{10}	z_{11}	…

Different representations for “many” objects



Standard AOS

0	1	2	3	4	5	6	7	8	9	10	11	…
x_0	y_0	z_0	x_1	y_1	z_1	x_2	y_2	z_2	x_3	y_3	z_3	…

SOA

0	1	2	3	4	5	6	7	8	9	10	11	…
x_0	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	…
100	101	102	103	104	105	106	107	108	109	110	111	…
y_0	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}	…
200	201	202	203	204	205	206	207	208	209	210	211	…
z_0	z_1	z_2	z_3	z_4	z_5	z_6	z_7	z_8	z_9	z_{10}	z_{11}	…

AOSOA

0	1	2	3	4	5	6	7	8	9	10	11	
x_0	x_1	x_2	x_3	y_0	y_1	y_2	y_3	z_0	z_1	z_2	z_3	
12	13	14	15	16	17	18	19	20	21	22	23	…
x_4	x_5	x_6	x_7	y_4	y_5	y_6	y_7	z_4	z_5	z_6	z_7	…

Advantages and disadvantages of different representations

- AOS
  - All member of each instance next to each other.
  - Good for data locality, less good for vectorization.
  - Not good when only a subset of the members is needed.

- SOA
  - Each member of all instances next to each other.
  - Good for vectorization, less good for data locality. (SSE2, AVX, ...)
  - Good when only a subset of the members is needed.

- AOSOA
  - Balances advantages and disadvantages of AOS and SOA.

Standard AOS representation

```
C arr[len];
double result = 0;

for (auto i=0; i<len; ++i) {
  arr[i].x += arr[i].y * arr[i].z;
  result += arr[i].x;
}
```

Manual SOA representation

```
struct Cv {
  double* x;
  double* y;
  double* z;

  Cv (int len) :
    x(new double[len]), y(new double[len]), z(new double[len])
  {}

  ~Cv () {delete x[]; delete y[]; delete z[];}
};
```

Manual SOA representation

```
Cv arr(len);
double result = 0;

for (auto i=0; i<len; ++i) {
   arr.x[i] += arr.y[i] * arr.z[i];
   result += arr.x[i];
}
```

Manual SOA representation

- The user has to write the new class.
  (but that may be ok, because it could even be generated)

- The user has to recode all accesses to array members.
  (arr[i].x ⇔ arr.x[i])

- This requires invasive changes to the code.
  - Cumbersome and annoying,
    especially if it turns out that SOA is not better than AOS after all.
  - Developers are not willing to do this,
    and give up on the performance opportunity!

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- This requires invasive changes to the code.
  - Cumbersome and annoying,
    especially if it turns out that SOA is <u>not</u> better than AOS after all.
  - Developers are not willing to do this,
    and give up on the performance opportunity!
- Manual AOSOA representation is even more complicated!

Arrow Street

- A library for semi-automatic SOA/AOSOA data layouts. ("array / structures" => "arrow street")
- Based on modern C++11 language constructs, specifically:
  - std::tuple
  - variadic templates
  - type_traits
  - lambda expressions
- Available at https://github.com/ExaScience/arrow-street

Semi-automatic SOA representation with Arrow Street

```
struct Cr {
  double& x;
  double& y;
  double& z;

  typedef reference_type<double, double, double> reference;

  Cr (const reference::type& ref) :
    x(reference::get<0>(ref)),
    y(reference::get<1>(ref)),
    z(reference::get<2>(ref))
  {}
};
```

Semi-automatic SOA representation with Arrow Street

```
table<Cr,len> array;
double result = 0;

for (auto i=0; i<len; ++i) {
  arr[i].x += arr[i].y * arr[i].z;
  result += arr[i].x;
}
```

Semi-automatic SOA representation with Arrow Street

- The user has to write the new class.
  (but that may be ok, because it could even be generated)

- The user does not have to recode accesses to array members.
  (arr[i].x ⇔ arr[i].x)
  - Only variable and parameter declarations have to be changed, or can be turned into template parameters.
  - The accesses themselves can stay the same.
  - This allows for switching back and forth between AOS & SOA.

Semi-automatic AOSOA representation with Arrow Street

```
table_array<Cr,256> array(len);
double result  = 0;

for_each(array, [&] (Cr& element) {
   element.x += element.y * element.z;
   result += element.x;
});
```

Flexible representations with Arrow Street

-
  ```
  table_vector<Cr,tablesize> v(len);
  table_vector<Cr,len> v(len);
  table_vector<Cr,1> v(len);
  std::vector<C> v(len);
  ```

-
  ```
  table_array<Cr,tablesize,len> a;
  table_array<Cr,len,len> a;
  table_array<Cr,1,len> a;
  std::array<C,len> a;
  ```

First results (on Core i7 860 @ 2.80 GHz)

len: 100000
repeat: 1000000

flat AOS array:	171 sec
flat SOA array:	63 sec
std::array:	171 sec
nested SOA array, tablesize 1:	182 sec
nested SOA array, tablesize max:	63 sec
nested SOA array, tablesize 256:	70 sec
std::vector:	167 sec
nested SOA vector, tablesize 1:	212 sec
nested SOA vector, tablesize max:	64 sec
nested SOA vector, tablesize 256:	70 sec

First results: N-body kernel, original code

```
static float xx[N], yy[N], zz[N], mass[N], vx1[N], vy1[N], vz1[N];

for (i=0; i<M; ++i) {
    step(n, xx[i], yy[i], zz[i], c0, c1, xx, yy, zz, mass,
             &dx1, &dx2, &dx3);

    vx1[i] += dx1 * f;
    vy1[i] += dy1 * f;
    vz1[i] += dz1 * f;
}
```

N-body: New code

```
struct body {
   float xx, yy, zz, mass, vx1, vy1, vz1;
};

static body bodies[N];

for (i=0; i<M; ++i) {
  d1  = step(bodies, n, i, c0, c1);

  bodies[i].vx1  += d1.x * f;
  bodies[i].vy1  += d1.y * f;
  bodies[i].vz1  += d1.z * f;
}
```

N-body: Arrow Street code

```
struct body {
   float &xx, &yy, &zz, &mass, &vx1, &vy1, &vz1;
... };

static soa::table<body,N> bodies;

for (i=0; i<M; ++i) {
  d1  = step(bodies, n, i, c0, c1);

  bodies[i].vx1  += d1.x * f;
  bodies[i].vy1  += d1.y * f;
  bodies[i].vz1  += d1.z * f;
}
```

N-body: Arrow Street code

```
struct body {
   float &xx, &yy, &zz, &mass, &vx1, &vy1, &vz1;
... };

static soa::table<body,N> bodies;

for (i=0; i<M; ++i) {
  d1 = step(bodies, n, i, c0, c1);

  bodies[i].vx1 += d1.x * f;
  bodies[i].vy1 += d1.y * f;
  bodies[i].vz1 += d1.z * f;
}
```

Only declarations change.

Client code remains the same
as in traditional AOS code.

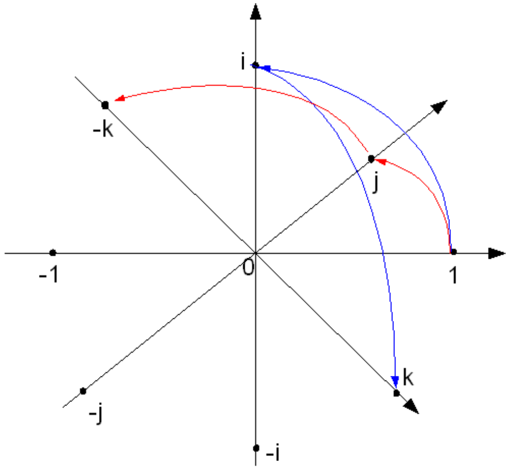
Performance of Arrow Street code is the
same as manually optimized data layout!!!

Other early results

- Helsim
  - 3D Electromagnetic Particle-In-Cell Simulation with In-Situ Visualization.
  - Developed at Intel ExaScience Lab, Belgium.
  - Arrow Street improves performance in charge/current deposition and particle moving.

Other early results

- Quaternion benchmark
  - Data representation used for animation and gaming systems.
  - Case study on Arrow Street performed at Intel.
  - Performance improvements in compute-intensive algorithms, competitive with Cilk Extended Array Notation.



Graphical representation of quaternion units product as 90°-rotation in 4D-space

Additional features

- Support for nested AOSOA representations.
- Support for complex data structures (composition/inheritance)
- Support for standard containers, especially iterators
- Parallel iteration using Cilk and TBB
  - ...including support for TBB range concept.
- No support for std::deque and OpenMP yet,
  but should be easy to add.
- Open source release at https://github.com/ExaScience/arrow-street

Conclusions

- SOA and AOSOA data representations are beneficial for SIMD instructions (SSE2, AVX).

- Current compilers do not support SOA/AOSOA well.

- Manual SOA/AOSOA is cumbersome and invasive, and developers give up on performance opportunity.

- Arrow Street is a pure library solution for C++11 that makes semi-automatic SOA/AOSOA substantially easier to express.

Thank You

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