東京工業大学
Tokyo Institute of Technology

Ikra-Cpp: A C++/CUDA DSL for Object-oriented Programming with Structure-of-Arrays Layout

Matthias Springer, Hidehiko Masuhara
Tokyo Institute of Technology

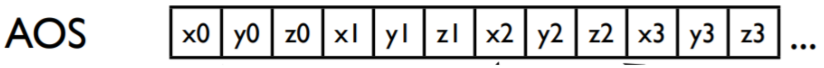
WPMVP 2018

Outline

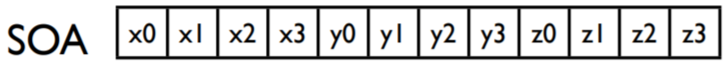
1. Introduction
2. Ikra-Cpp API and Example
3. Implementation Outline
4. Addressing Modes
5. Performance Evaluation
6. Related Work + Future Work
7. Summary

Introduction

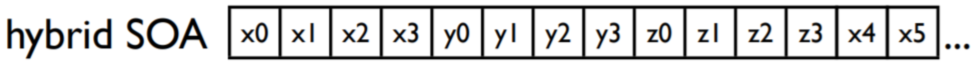
- AOS: Array of Structures
  `struct { float x, y, z; } arr[100];`



- SOA: Structure of Arrays
  `struct { float x[100], y[100], z[100]; } s;`
  - Good for caching, vectorization, parallelization



- Hybrid SOA (SoAoS)



- **Ikra-Cpp:** Embedded C++/CUDA DSL for SOA
  - Notation close to standard C++
  - *Support OOP features:*
    Member functions, pointers, constructors, virtual functions

Figures: ispc: A SPMD Compiler for High-Performance CPU Programming

Ikra-Cpp API

```
class Body : public SoaLayout<Body> {
  public: IKRA_INITIALIZE_CLASS
    float_ pos_x = 0.0;
    float_ pos_y = 0.0;
    float_ vel_x = 1.0;
    float_ vel_y = 1.0;

    Body(float x, float y) : pos_x(x), pos_y(y) {}

    void move(float dt) {
        pos_x = pos_x + vel_x * dt;
        pos_y = pos_y + vel_y * dt;
    }
};

IKRA_HOST_STORAGE(Body, 128);
```

Ikra-Cpp API

```
class Body : public SoaLayout<Body> {
  public: IKRA_INITIALIZE_CLASS
    float_ pos_x = 0.0;
    float_ pos_y = 0.0;
    float_ vel_x = 1.0;
    float_ vel_y = 1.0;

    Body(float x, float y) : pos_x(x), pos_y(y) {}

    void move(float dt) {
        pos_x = pos_x + vel_x * dt;
        pos_y = pos_y + vel_y * dt;
    }
};

IKRA_HOST_STORAGE(Body, 128);
```

Ikra-Cpp API

```
class Body : public SoaLayout<Body> {
  public: IKRA_INITIALIZE_CLASS
    float_ pos_x = 0.0;
    float_ pos_y = 0.0;
    float_ vel_x = 1.0;
    float_ vel_y = 1.0;

    Body(float x, float y) : pos_x(x), pos_y(y) {}

    void move(float dt) {
        pos_x = pos_x + vel_x * dt;
        pos_y = pos_y + vel_y * dt;
    }
};

IKRA_HOST_STORAGE(Body, 128);
```

Use this class like any other C++ class:

```
void create_and_move() {
    Body* b = new Body(1.0, 2.0);
    b->move(0.5);
    assert(b->pos_x == 1.5);
}
```

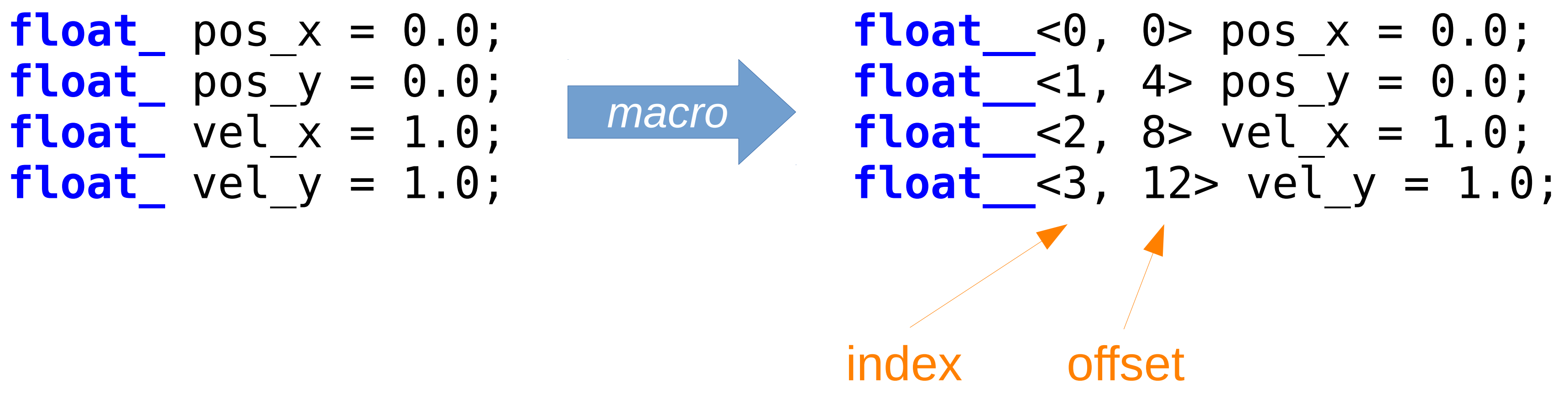
Ikra-Cpp “Executor” API

- A few extra functions to have a uniform API for CPU and GPU computation
- Construct multiple objects:
  ```
  Body* b = Body::make(10, /*x=*/ 1.0, /*y=*/ 2.0)
  ```
- for-all execution:
  ```
  ikra::execute(&Body::move, b, 10, /*dt=*/ 0.5);
  ```
- GPU versions: `cuda_make`, `cuda_execute`
- Automatic memory transfer between CPU/GPU

Implementation Outline

- Statically allocated storage buffer
- “Fake pointers” encode object IDs
- Special SOA field types (e.g., `float_`)
    - Overloaded Operators: Decode object ID, calculate location inside the storage buffer
- Implementation: preprocessor macros, template metaprogramming, operator overloading (achieving close to standard C++ notation without special tools/compilers)

Field Types



```
float_ pos_x = 0.0;
float_ pos_y = 0.0;
float_ vel_x = 1.0;
float_ vel_y = 1.0;
```

```
float__<0, 0> pos_x = 0.0;
float__<1, 4> pos_y = 0.0;
float__<2, 8> vel_x = 1.0;
float__<3, 12> vel_y = 1.0;
```

- Implicit conversion operator: `float x = body->pos_x;`
- Assignment operator: `body->pos_x = 10.5;`
- Member of pointer operator: `vertex->neighbor->visit();`

Addressing Modes

- Multiple techniques for encoding IDs

Zero Addressing.: &obj_{id} = id

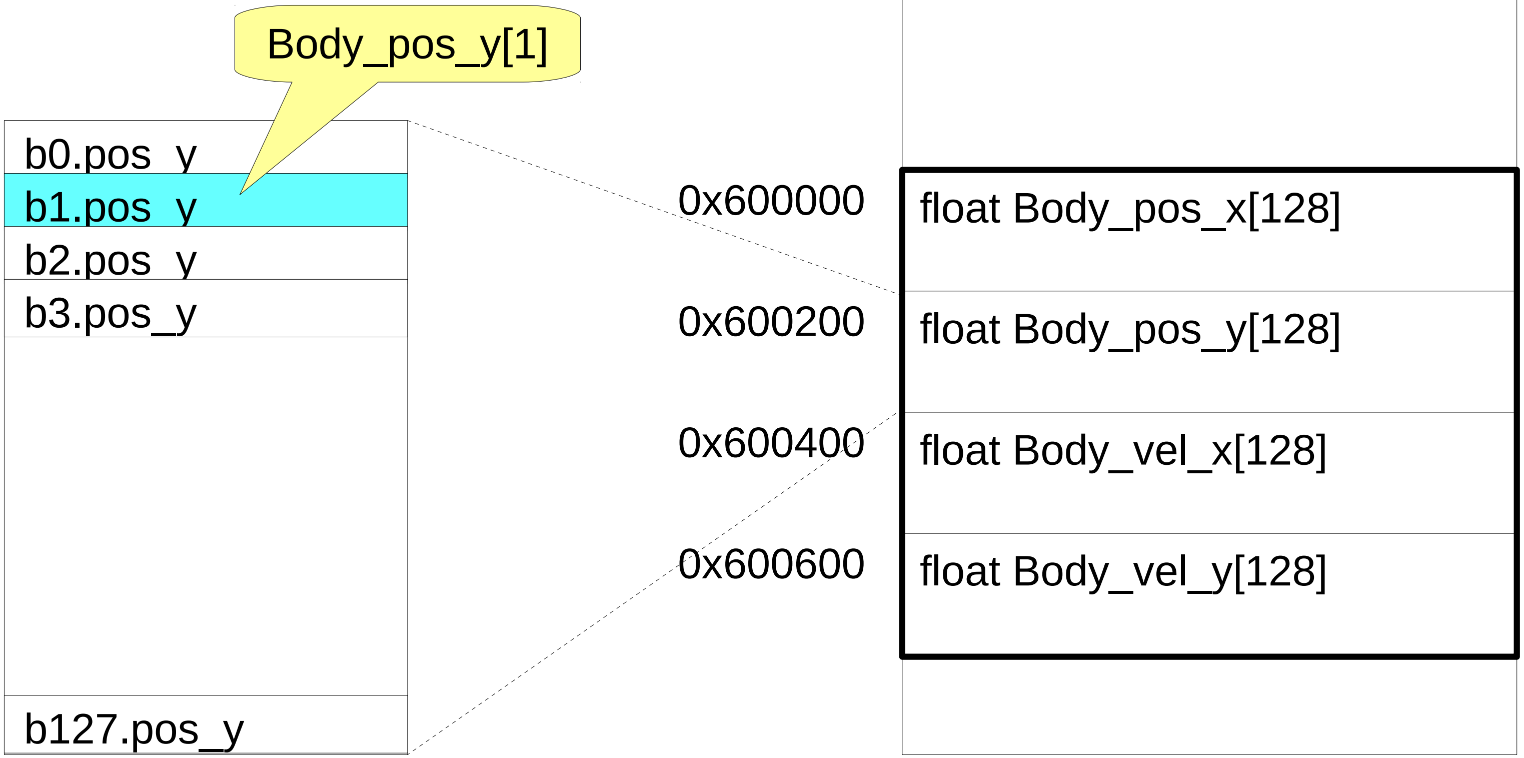
Storage-relative Zero Addr.: &obj_{id} = buffer + id

First Field Addr.: &obj_{id} = buffer + sizeof(T) * id

Zero Addressing Mode

Zero Addressing.: &obj$_{id}$ = id

```
(float) b1->pos_y
```



Body_pos_y[1]

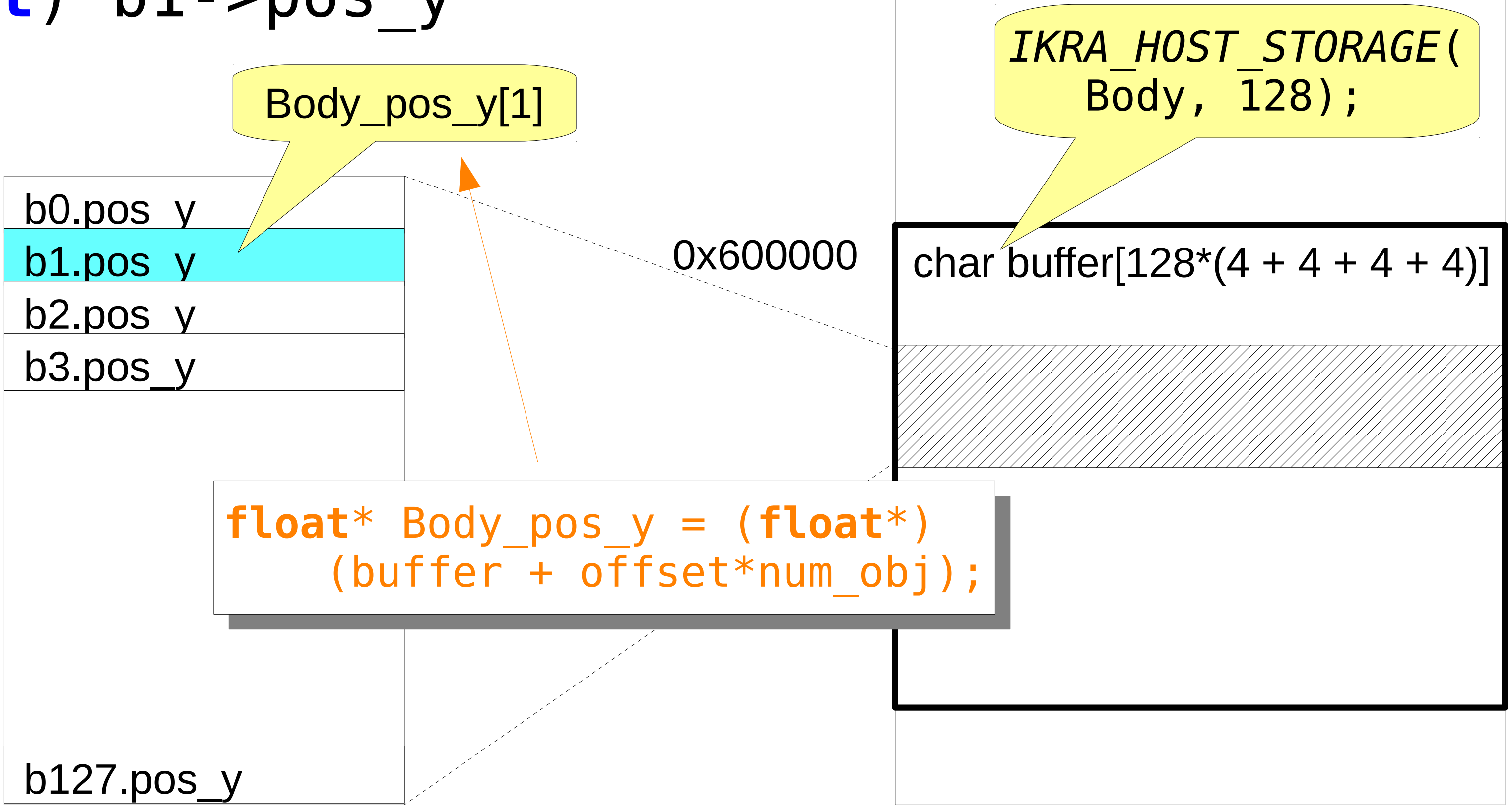
b0.pos_y
b1.pos_y
b2.pos_y
b3.pos_y
b127.pos_y

0x600000	float Body_pos_x[128]
0x600200	float Body_pos_y[128]
0x600400	float Body_vel_x[128]
0x600600	float Body_vel_y[128]

Zero Addressing Mode

Zero Addressing.: $\&obj_{id} = id$

```
(float) b1->pos_y
```



Body_pos_y[1]

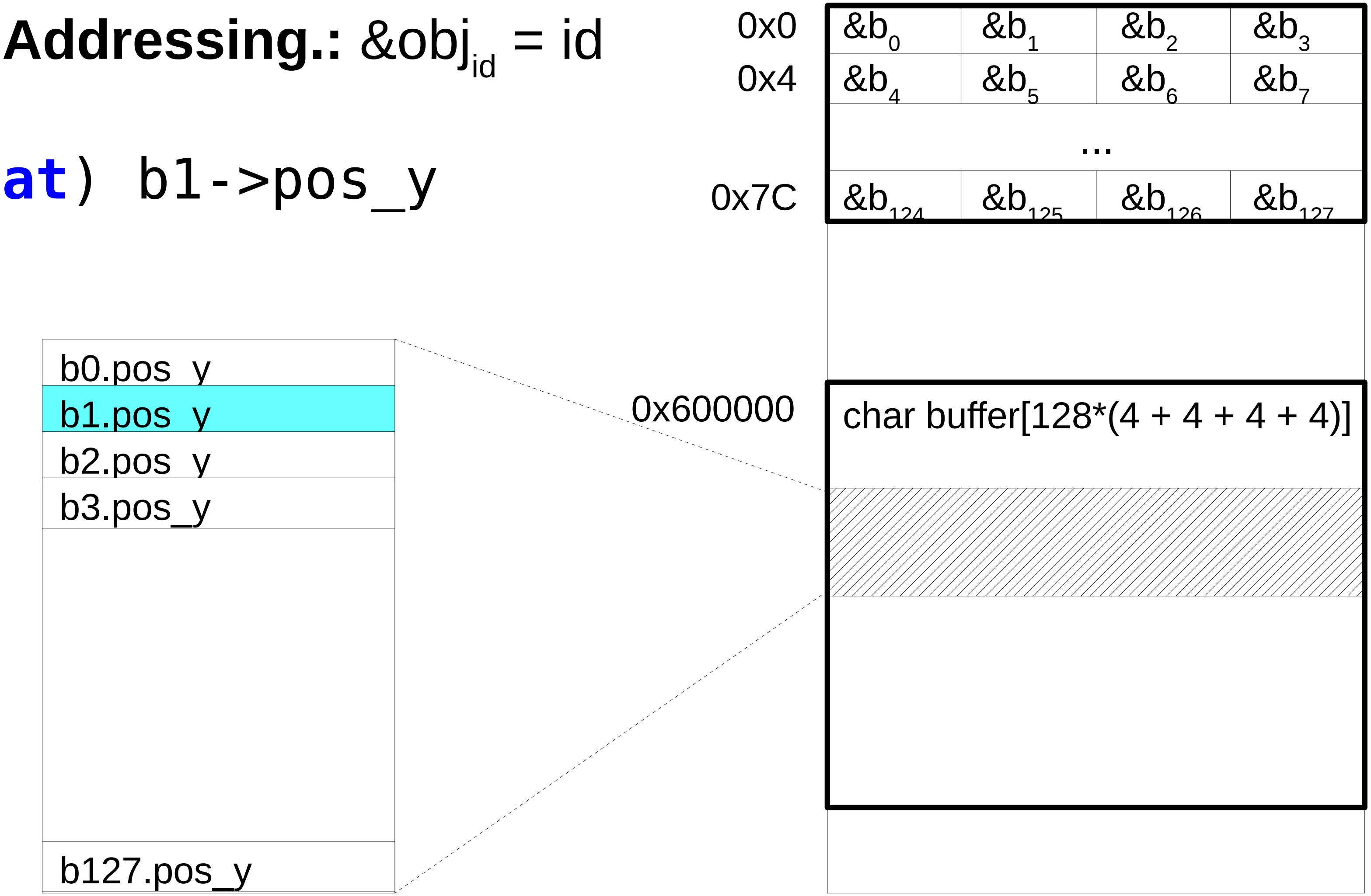
IKRA_HOST_STORAGE(
Body, 128);

```
float* Body_pos_y = (float*)
    (buffer + offset*num_obj);
```

Zero Addressing Mode

Zero Addressing.: $\&obj_{id} = id$

```
(float) b1->pos_y
```



0x0	$\&b_0$	$\&b_1$	$\&b_2$	$\&b_3$
0x4	$\&b_4$	$\&b_5$	$\&b_6$	$\&b_7$
	…			
0x7C	$\&b_{124}$	$\&b_{125}$	$\&b_{126}$	$\&b_{127}$

0x600000

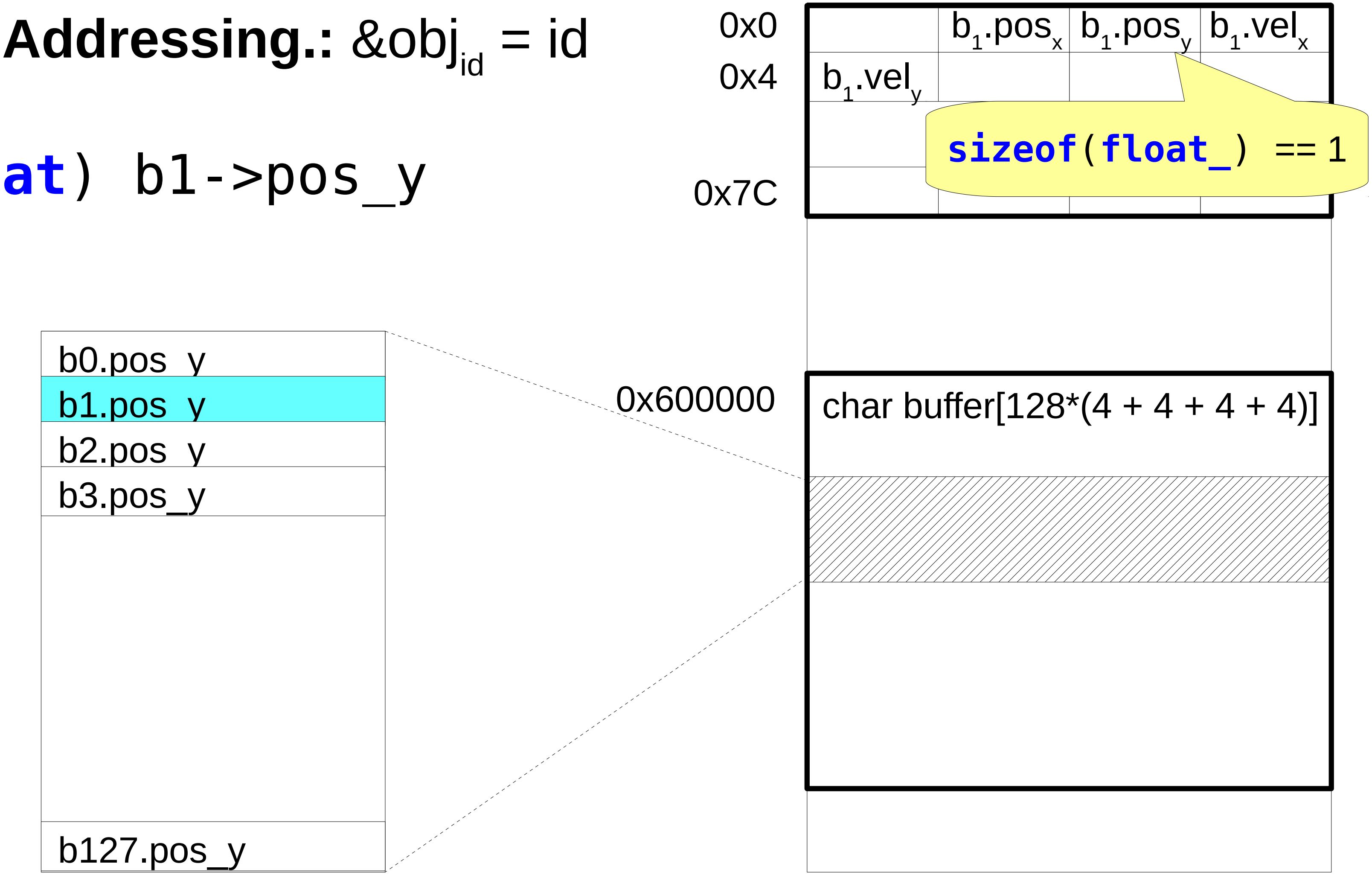
char buffer[128*(4 + 4 + 4 + 4)]

b0.pos_y
b1.pos_y
b2.pos_y
b3.pos_y
b127.pos_y

Zero Addressing Mode

Zero Addressing.: &obj$_{id}$ = id

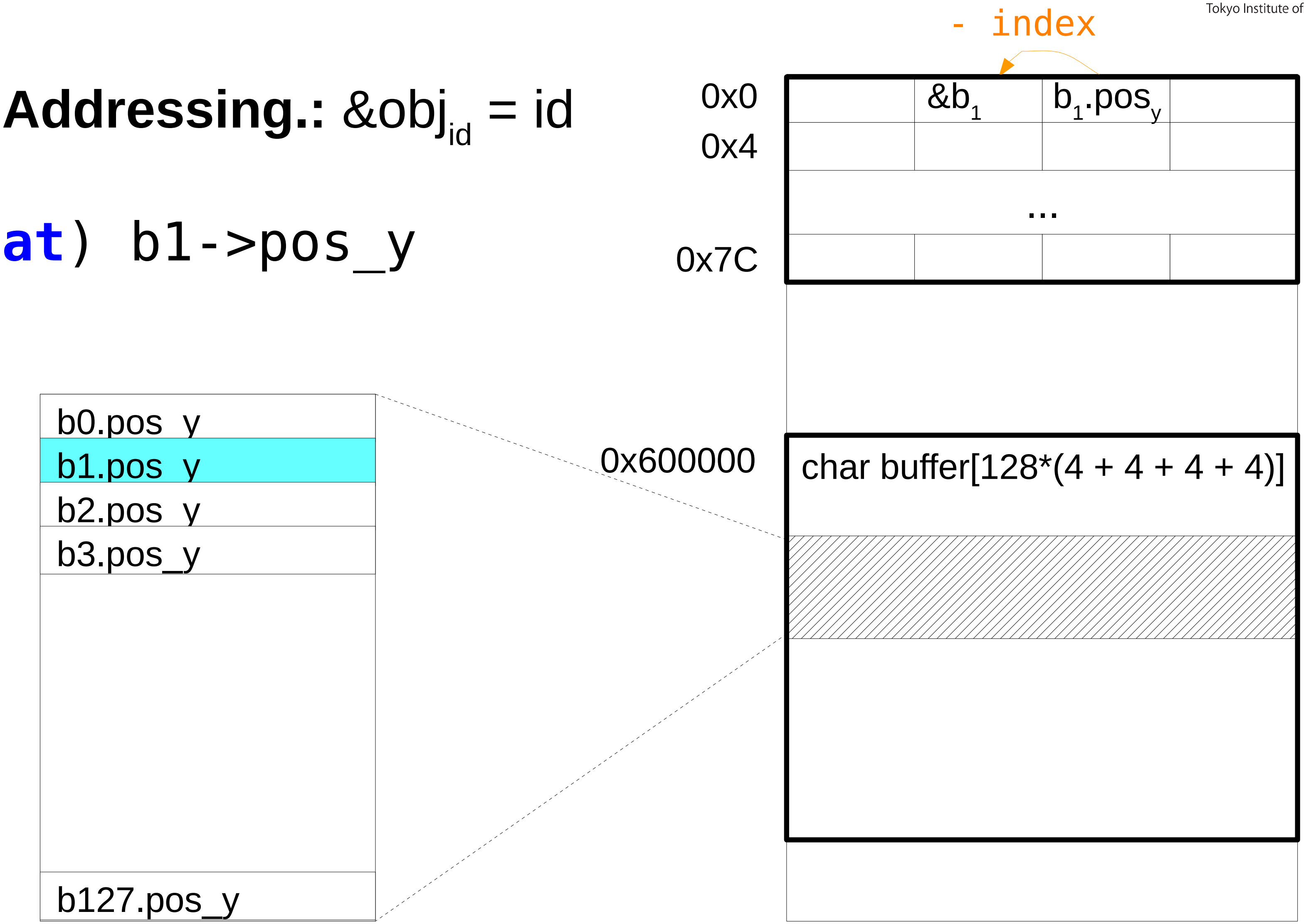
```
(float) b1->pos_y
```



Zero Addressing Mode

Zero Addressing.: $\&obj_{id} = id$

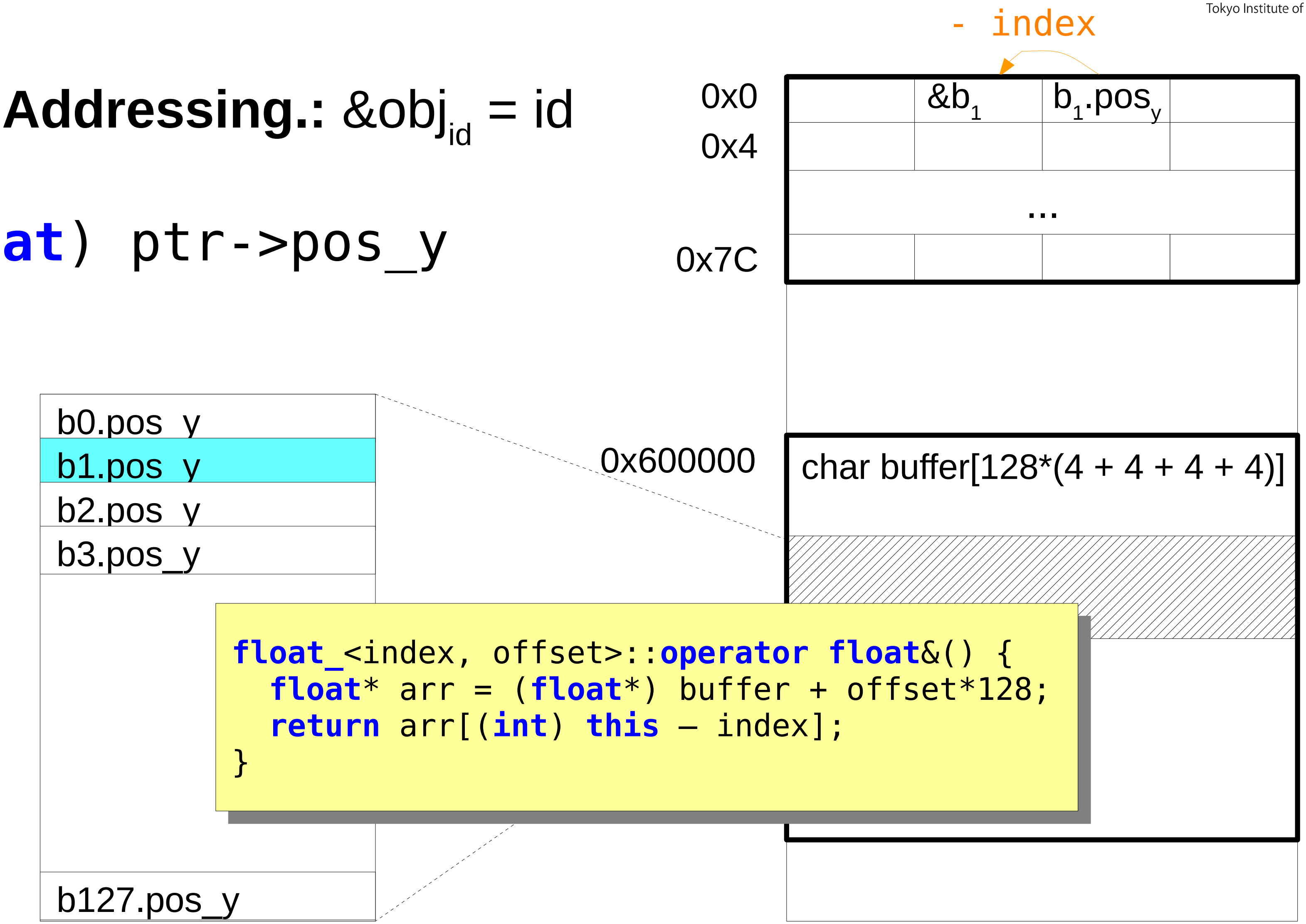
```
(float) b1->pos_y
```



Zero Addressing Mode

Zero Addressing.: $\&obj_{id} = id$

```
(float) ptr->pos_y
```

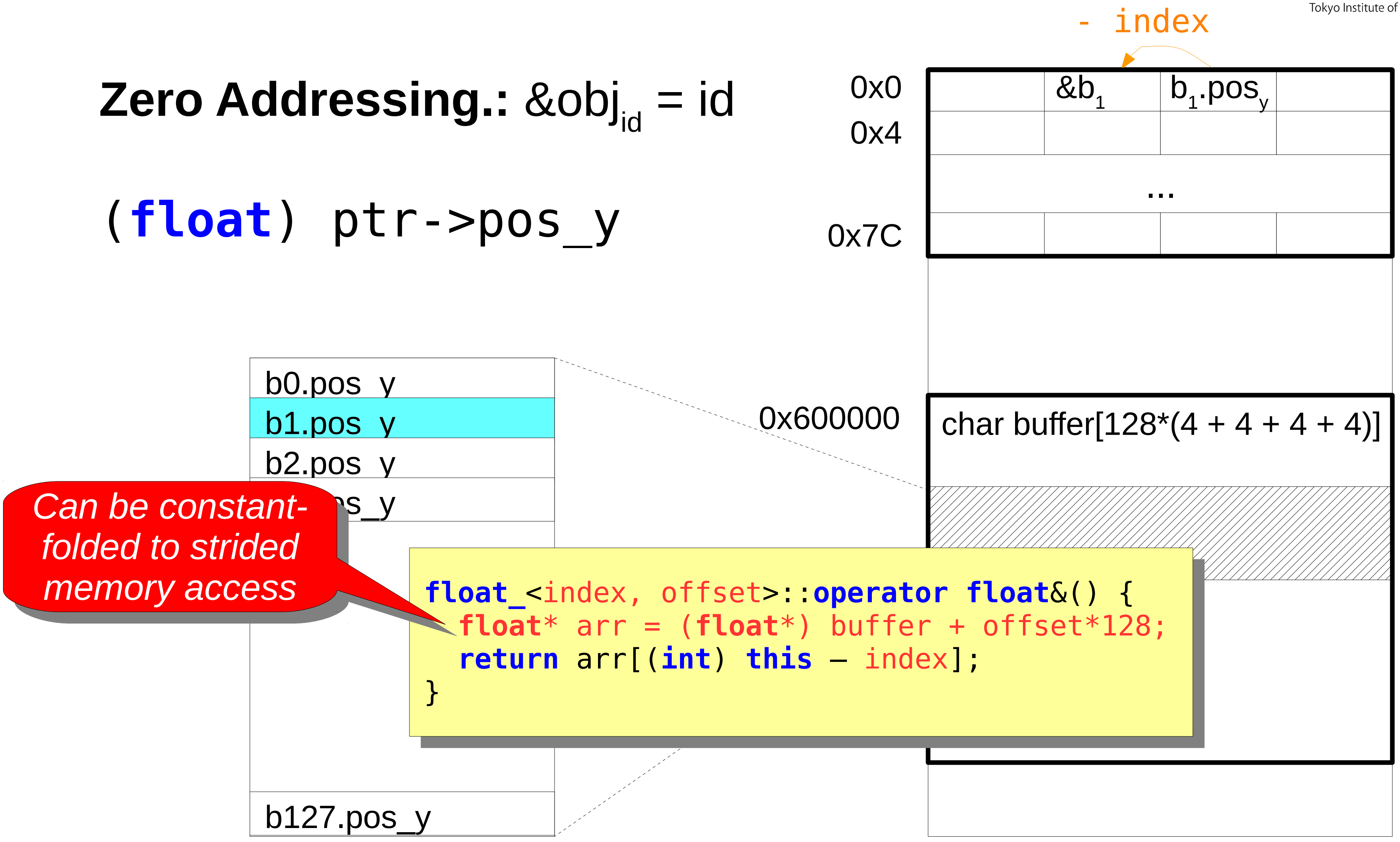


```
float_<index, offset>::operator float&() {
  float* arr = (float*) buffer + offset*128;
  return arr[(int) this – index];
}
```

Zero Addressing Mode

Zero Addressing.: &obj$_{id}$ = id

```
(float) ptr->pos_y
```



Can be constant-folded to strided memory access

```
float_<index, offset>::operator float&() {
  float* arr = (float*) buffer + offset*128;
  return arr[(int) this – index];
}
```

Addressing Modes

- Multiple techniques for encoding IDs

Zero Addressing.: $\&obj_{id} = id$

new keyword

Storage-relative Zero Addr.: $\&obj_{id} = buffer + id$

virtual member functions

First Field Addr.: $\&obj_{id} = buffer + sizeof(T) * id$

Performance Evaluation

- Reading/writing single field in zero addressing
  - Same assembly code as hand-written SOA code
  - Verified with gcc 5.4.0 and clang 3.8.0 / 5.0 in -O3

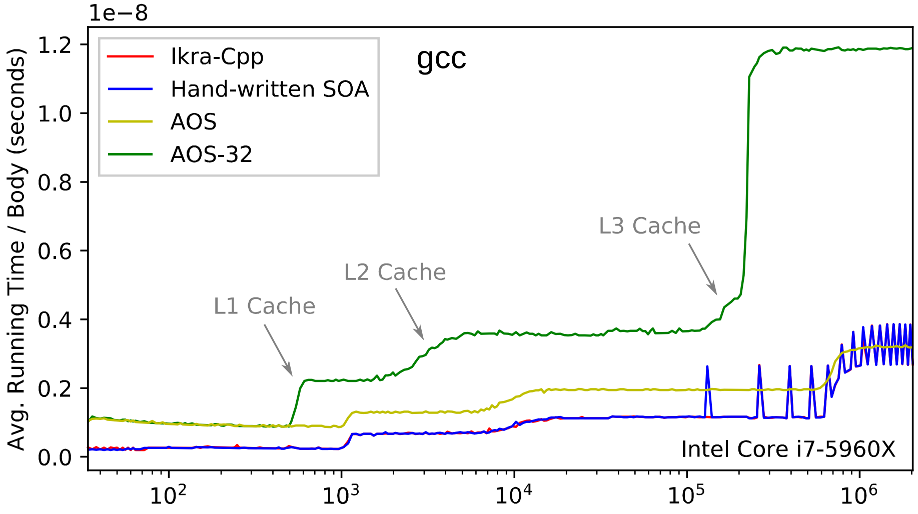
Performance Evaluation

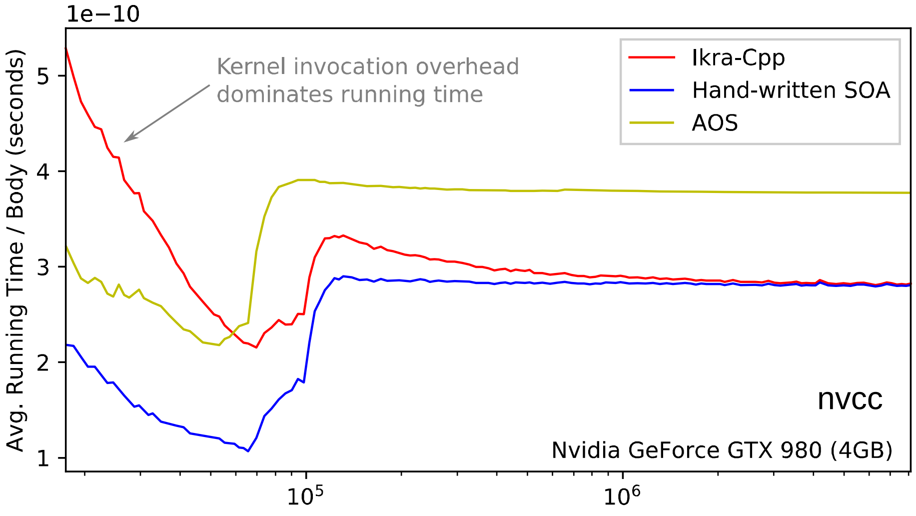
- Reading/writing single field in zero addressing
  - Same assembly code as hand-written SOA code
  - Verified with gcc 5.4.0

```
ikra::execute(&Body::move, 0.5);
```

- Consecutive field access in a loop
  - gcc: same performance as hand-written SOA (constexpr necessary in implementation)
  - clang: loop vectorization fails
  - nvcc: same performance as hand-written SOA, minus kernel invocation overhead (unoptimized)

Performance Evaluation





Related Work

東京工業大学
Tokyo Institute of Technology

Robert Strzodka. **Abstraction for AoS and SoA Layout in C++**.
In GPU Computing Gems Jade Edition, pp. 429-441, 2012.

```
template <ASX::ID t_id = ASX::ID_value>
struct Body {
  typedef ASX::ASAGroup<float, t_id> ASX_ASA;
  union { float pos_x; ASX_ASA dummy1; };
  union { float pos_y; ASX_ASA dummy2; };
  union { float vel_x; ASX_ASA dummy3; };
  union { float vel_y; ASX_ASA dummy4; };
};

typedef ASX::Array<Body, 100, ASX::SOA> Container;
Container container;

void move(Container::reference body, float dt) {
  body.pos_x = body.pos_x + body.vel_x * dt;
  body.pos_y = body.pos_y + body.vel_y * dt;
}
```

Must all have same size (or be combined in groups of same size)

Related Work

Holger Homann, Francois Laenen. **SoAx: A generic C++ Structure of Arrays for handling particles in HPC code**. In Comp. Phys. Comm., Vol. 224, pp. 325-332, 2018.

Layout specified with std::tuple

```
SOAX_ATTRIBUTE(pos, “position”);
SOAX_ATTRIBUTE(vel, “velocity”);

typedef std::tuple<pos<float, 2>, vel<float, 2>> Body;
Soax<Body> container(100);

void move(int id, float dt) {
  container.pos(id, 0) += container.vel(id, 0) * dt;
  container.pos(id, 1) += container.vel(id, 1) * dt;
}

void move_all(float dt) {
  container.posArr(0) += container.velArr(0) * dt;
  container.posArr(1) += container.velArr(1) * dt;
}
```

Related Work

Matt Pharr, William R. Mark. **ispc: A SPMD compiler for high-performance CPU programming**. In Innovative Parallel Computing (InPar), 2012.

```
struct Body {
  float pos_x, pos_y, vel_x, vel_y;
};

soa<100> struct Body bodies[100];

void move(uniform soa<100> Body* varying body,
          uniform float dt) {
  body->pos_x += body->vel_x * dt;
  body->pos_y += body->vel_y * dt;
}
```

AoSoA layout possible
(“hybrid layout”)

Related Work

- No support for object-oriented programming
  - Pointers instead of IDs
  - Member Functions
  - Constructors, Dynamic Allocation (**new** keyword)
- Support for multiple containers
- ASX and SoAx: non-standard C++ notation

Future Work

- Utilize ROSE Compiler
  - Powerful C++ preprocessor (source-to-source)
  - “Optimization of low-level abstractions can be (and frequently is) not handled well by the compiler” (ROSE Manual)
  - Use mixture of techniques shown today and ROSE code transformation rules
- Support more OOP features: subclassing, virtual function calls

Summary

- **Ikra-Cpp:** C++/CUDA DSL for OOP with SOA Data Layout
- Implementation in C++, no external tools required
- Notation close to standard C++
- Address computation is as easy as in normal array access, but can be difficult for compilers to optimize
- **Future work:** Reimplementation with ROSE, more OOP features

東京工業大学
Tokyo Institute of Technology

Appendix

Field Types

```
float_ pos_x = 0.0;
float_ pos_y = 0.0;
float_ vel_x = 1.0;
float_ vel_y = 1.0;
```

macro

```
Field<float, 0, 0> pos_x = 0.0;
Field<float, 1, 4> pos_y = 0.0;
Field<float, 2, 8> vel_x = 1.0;
Field<float, 3, 12> vel_y = 1.0;
```

index

offset

Storage Buffer

```
float_ pos_x = 0.0;
float_ pos_y = 0.0;
float_ vel_x = 1.0;
float_ vel_y = 1.0;
```

macro

```
Field<float, 0, 0> pos_x = 0.0;
Field<float, 1, 4> pos_y = 0.0;
Field<float, 2, 8> vel_x = 1.0;
Field<float, 3, 12> vel_y = 1.0;
```

Inside Field<float>:
Calculate address into storage buffer.

Large enough to store four float arrays of size 100

```
IKRA_HOST_STORAGE(Body, 100);
```

macro

```
char buffer[100 * Body::ObjectSize];
```

C++ Operators

```
float_ pos_x = 0.0;
float_ pos_y = 0.0;
float_ vel_x = 1.0;
float_ vel_y = 1.0;
```

```
Field<float, 0, 0> pos_x = 0.0;
Field<float, 1, 4> pos_y = 0.0;
Field<float, 2, 8> vel_x = 1.0;
Field<float, 3, 12> vel_y = 1.0;
```

```
pos_x = 1.0;          /* type error: cannot assign float to Field<float>*/
```

C++ Operators

```
float_ pos_x = 0.0;
float_ pos_y = 0.0;
float_ vel_x = 1.0;
float_ vel_y = 1.0;
```

```
Field<float, 0, 0> pos_x = 0.0;
Field<float, 1, 4> pos_y = 0.0;
Field<float, 2, 8> vel_x = 1.0;
Field<float, 3, 12> vel_y = 1.0;
```

```
pos_x = 1.0;

T* Field<T, Index, Offset>::data_ptr() {
  T* arr = (T*) buffer + 100*Offset;
  return arr + id();
}

void Field<T, Index, Offset>::operator=(float value) {
  *data_ptr() = value;
}
```

SOA field array

How to calculate ID? Later...

C++ Operators

```
float_ pos_x = 0.0;
float_ pos_y = 0.0;
float_ vel_x = 1.0;
float_ vel_y = 1.0;
```

```
Field<float, 0, 0> pos_x = 0.0;
Field<float, 1, 4> pos_y = 0.0;
Field<float, 2, 8> vel_x = 1.0;
Field<float, 3, 12> vel_y = 1.0;
```

```
float x = pos_x;          /* type error: cannot convert Field<float> to float*/
```

C++ Operators

```
float_ pos_x = 0.0;
float_ pos_y = 0.0;
float_ vel_x = 1.0;
float_ vel_y = 1.0;
```

macro

```
Field<float, 0, 0> pos_x = 0.0;
Field<float, 1, 4> pos_y = 0.0;
Field<float, 2, 8> vel_x = 1.0;
Field<float, 3, 12> vel_y = 1.0;
```

```
float x = pos_x;

T* Field<T, Index, Offset>::data_ptr() {
  T* arr = (T*) buffer + 100*Offset;
  return arr + id();
}

Field<T, Index, Offset>::operator T&() {
  return *data_ptr();
}
```

Encoding IDs in Pointers

- Object pointers do not point to meaningful addresses.

```
Body* b = new Body(/*x=*/ 1.0, /*y=*/ 2.0);
```

What is the value of b?
(Encoding ID in pointer)

```
T* Field<T, Index, Offset>::data_ptr() {
  T* arr = (T*) buffer + 100*Offset;
  return arr + id();
}
```

How to calculate ID?
(Decoding ID from `this`)

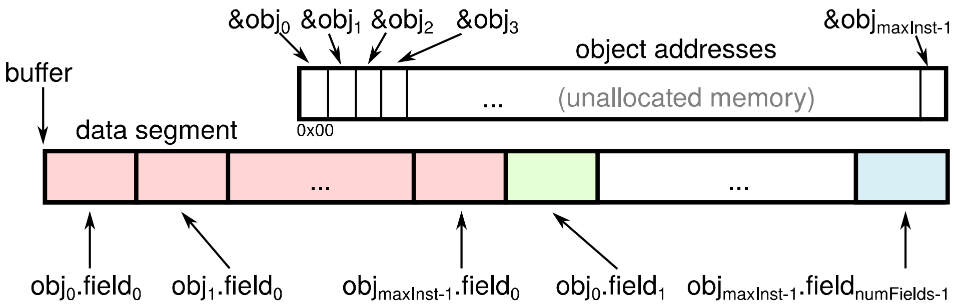
Zero Addressing Mode

- Multiple techniques for encoding IDs

Zero Addressing.: $\&obj_{id} = id$

```
int Field<T, Index, Offset>::id() {
  Body* ptr = (Body*) ((char*) this – Index*sizeof(Field<...>));
  return (int) ptr;
}
```

```
void* Body::operator new() {
  return (void*) size++;
}
```



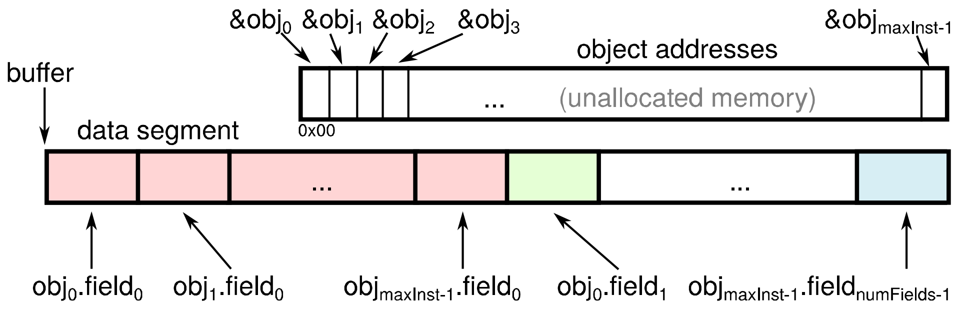
Zero Addressing Mode

- Multiple techniques for encoding IDs

Zero Addressing.: $\&obj_{id} = id$

```
int Field<T, Index, Offset>::id() {
  Body* ptr = (Body*) ((char*) this – Index);
  return (int) ptr;
}
```

```
void* Body::operator new() {
  return (void*) size++;
}
```



Example: Address Computation

東京工業大学
Tokyo Institute of Technology

Zero Addressing.: &obj_{id} = id

```
class TestClass : public SoaLayout<TestClass> {
  public: IKRA_INITIALIZE
    int_ field0;
    int_ field1;
};

IKRA_HOST_STORAGE(Body, 100);

int get_field1(TestClass* o) {
    return o->field1;
}
```

Example: Address Computation

Zero Addressing.: $\&obj_{id} = id$

```
class TestClass : public SoaLayout<TestClass> {
  public: IKRA_INITIALIZE
    int_ field0;
    int_ field1;
};

IKRA_HOST_STORAGE(Body, 100);

int get_field1(TestClass* o) {
    Field<int, 1, 4>& f = o->field1;
    return (int) f;
}
```

Example: Address Computation

Zero Addressing.: $\&obj_{id} = id$

```
class TestClass : public SoaLayout<TestClass> {
  public: IKRA_INITIALIZE
    int_ field0;
    int_ field1;
};

IKRA_HOST_STORAGE(Body, 100);

int get_field1(TestClass* o) {
    Field<int, 1, 4>& f = o->field1;
    int* data_ptr = f.data_ptr();
    return *data_ptr;
}
```

Example: Address Computation

Zero Addressing.: &obj$_{id}$ = id

```
class TestClass : public SoaLayout<TestClass> {
  public: IKRA_INITIALIZE
    int_ field0;
    int_ field1;
};

IKRA_HOST_STORAGE(Body, 100);

int get_field1(TestClass* o) {
    Field<int, 1, 4>& f = o->field1;
    int* arr = (int*) (buffer + 100*4);
    int* data_ptr = arr + f.id();
    return *data_ptr;
}
```

Example: Address Computation

Zero Addressing.: $\&obj_{id} = id$

```
class TestClass : public SoaLayout<TestClass> {
  public: IKRA_INITIALIZE
    int_ field0;
    int_ field1;
};

IKRA_HOST_STORAGE(Body, 100);

int get_field1(TestClass* o) {
    Field<int, 1, 4>& f = o->field1;
    int* arr = (int*) (buffer + 100*4);
    int* data_ptr = arr + (int) &f – 1;
    return *data_ptr;
}
```

Example: Address Computation

Zero Addressing.: &obj_{id} = id

```
class TestClass : public SoaLayout<TestClass> {
  public: IKRA_INITIALIZE
    int_ field0;
    int_ field1;
};

IKRA_HOST_STORAGE(Body, 100);

int get_field1(TestClass* o) {
    int* arr = (int*) (buffer + 100*4);
    int* data_ptr = arr + (int) o + 1 – 1;
    return *data_ptr;
}
```

Example: Address Computation

Zero Addressing.: $\&\mathrm{obj}_{id} = \mathrm{id}$

```
class TestClass : public SoaLayout<TestClass> {
  public: IKRA_INITIALIZE
    int_ field0;
    int_ field1;
};

IKRA_HOST_STORAGE(Body, 100);

int get_field1(TestClass* o) {
    int* data_ptr = (int*) (buffer + 400 + ((int) o)*4);
    return *data_ptr;
}
```

Strided memory access:
const + 4*var

Field access can be as efficient as in hand-written SOA layout!
If your compiler can optimize this...

gcc and clang: yes

Addressing Modes

- Multiple techniques for encoding IDs

Zero Addressing.: $\&obj_{id} = id$

a) Workaround: Set size of C++ object to 0

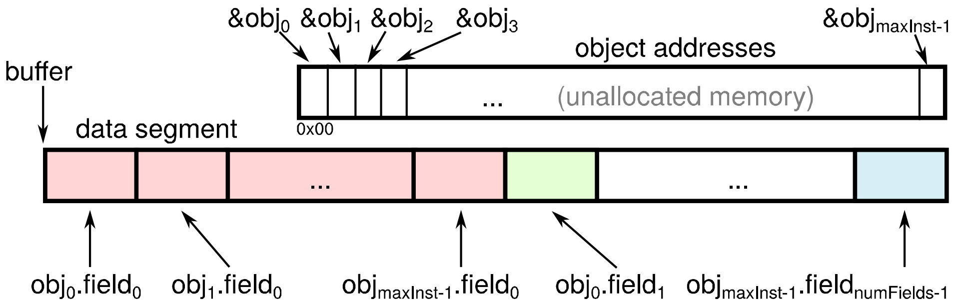
```
char _[0];
```

b) Use a different encoding scheme where pointers point to allocated memory

```
new Body(1.0, 2.0);
```

Problem with Zero-Initialization

```
void* Body::operator new() {
  return (void*) size++;
}
```



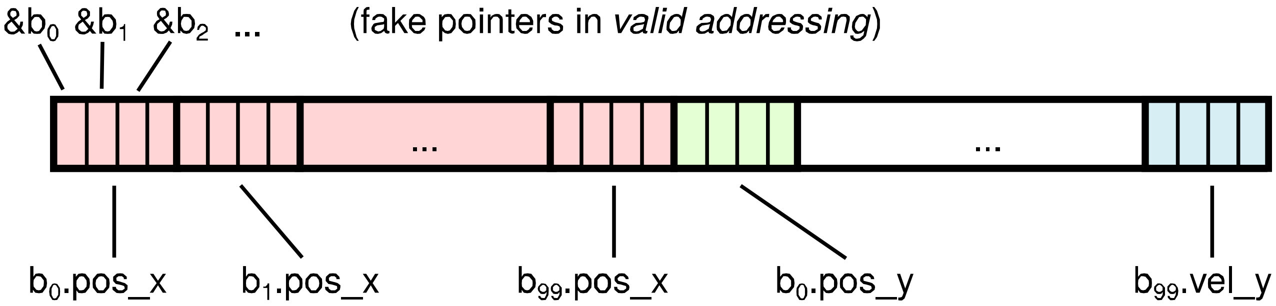
Addressing Modes

- Multiple techniques for encoding IDs

Storage-relative Zero Addr.: $\&obj_{id} = buffer + id$

```
int Field<T, Index, Offset>::id() {
  Body* ptr = (Body*) ((char*) this – Index);
  return (int) ptr – (int) buffer;
}


void* Body::operator new() {
  return (char*) buffer + size++;
}
```



Again, field access can be as efficient as in hand-written SOA layout!

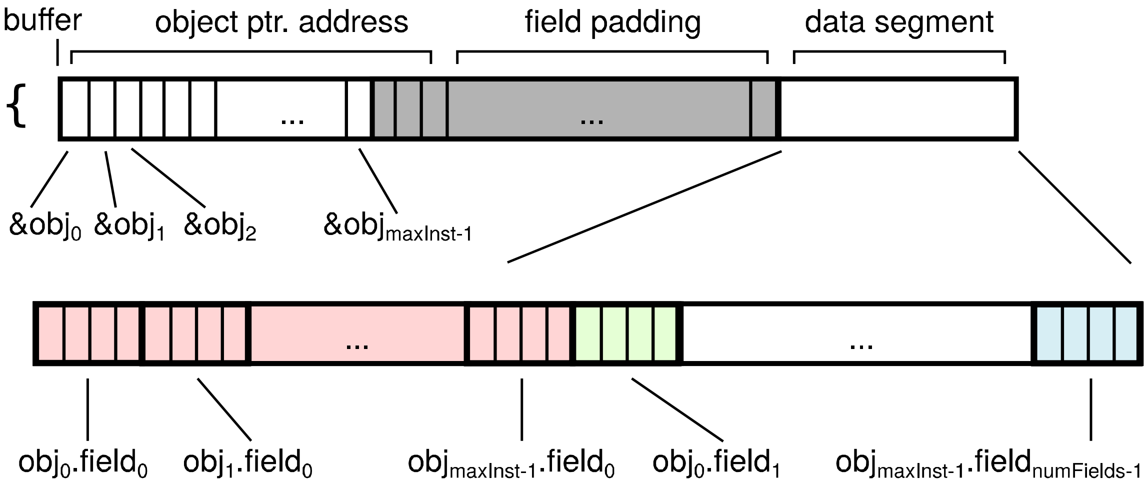
Addressing Modes

- Multiple techniques for encoding IDs

Storage-relative Zero Addr.: $\&obj_{id} = buffer + padding + id$

```
int Field<T, Index, Offset>::id() {
  Body* ptr = (Body*) ((char*) this – Index);
  return (int) ptr – (int) buffer – padding;
}
```

```
void* Body::operator new() {
  return (char*) buffer
    + padding + size++;
}
```



Again, field access can be as efficient as in hand-written SOA layout!