Object Support in an Array-based GPGPU Extension for Ruby

ARRAY '16

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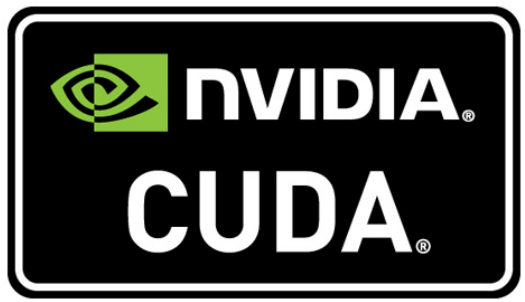
Overview

What is Ikra?



A Ruby-to-CUDA compiler . . .

- that allows programmers to use GPGPU easily
- with dynamic compilation
- supporting object-oriented programming and polymorphic expressions
- with a number of optimizations:
  kernel fusion, job reordering, structure-of-arrays data layout

Related Work

- **Related work**
  - *Frameworks similar to Ikra:* Accelerate, pyCUDA, ...
    Focus on high-level code generation/optimizations (kernel fusion, subexpr. elimination, ...)
  - *Application-level Optimizations:* Programming styles/best practices
    E.g., techniques for reducing branch divergence (e.g., job reordering), data layout optimizations (e.g., structure-of-arrays layout)
- **Focus of this work**
  - Support *object-oriented programming* in GPGPU code
  - Employ *language-level optimizations* to achieve good performance
  - Implement *low-level* code optimizations

Parallel Sections

- `peach`, `pmap`, `pnew`, (`pselect`, `preduce`)
- One thread per base array element
- **Input data:** iterator variables, lexical variables, instances variables of objects
- **Output data:** result of parallel section, changed objects (kernel code can have side effects)

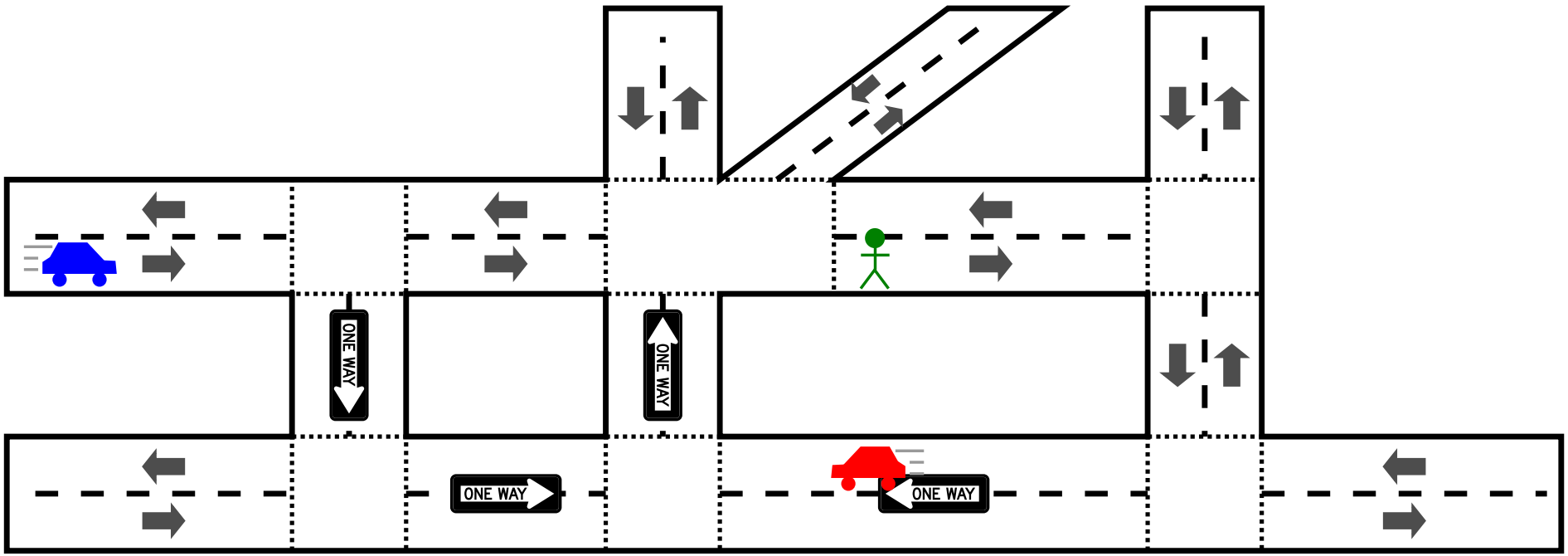
```
inc = 10 # lexical variable

[1, 2, 3].pmap do |v|
    v + inc
end
```

Overview

Example: Agent-based Traffic Simulation

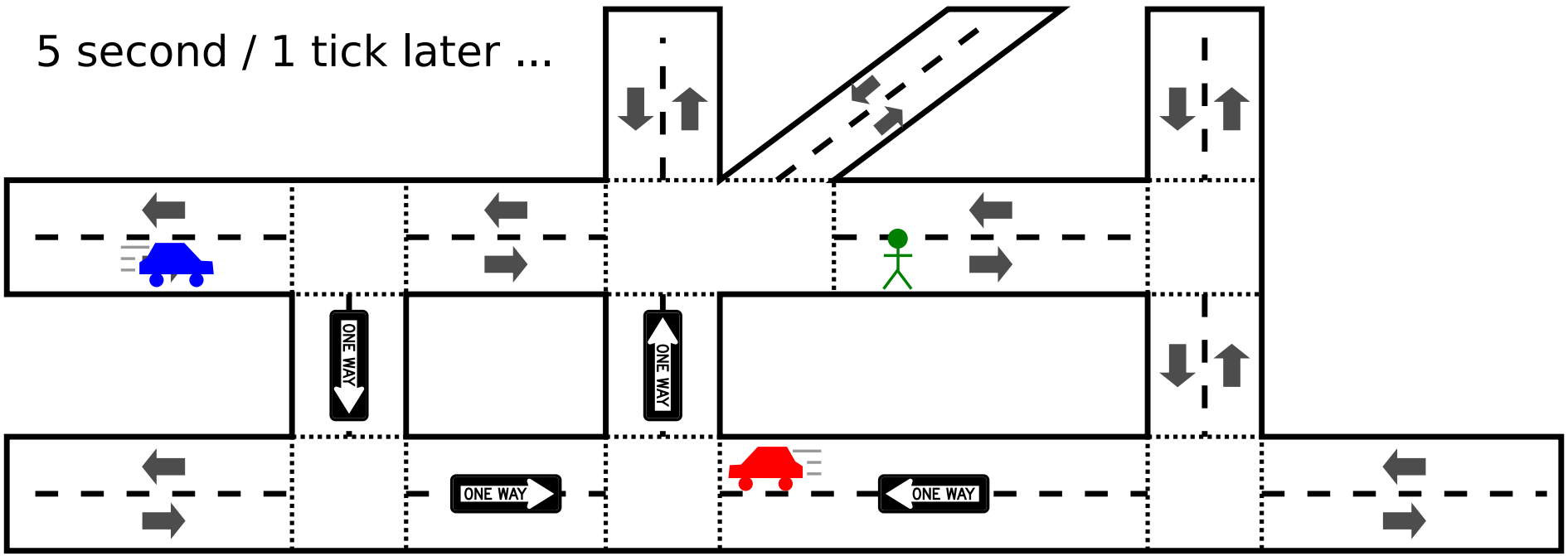
Problem Description [2]



- Simulate movement of agents (cars, etc.) on a street network
- Iteration-based, different behavior per *type/class*

Example: Agent-based Traffic Simulation

Problem Description [2]



- Simulate movement of agents (cars, etc.) on a street network
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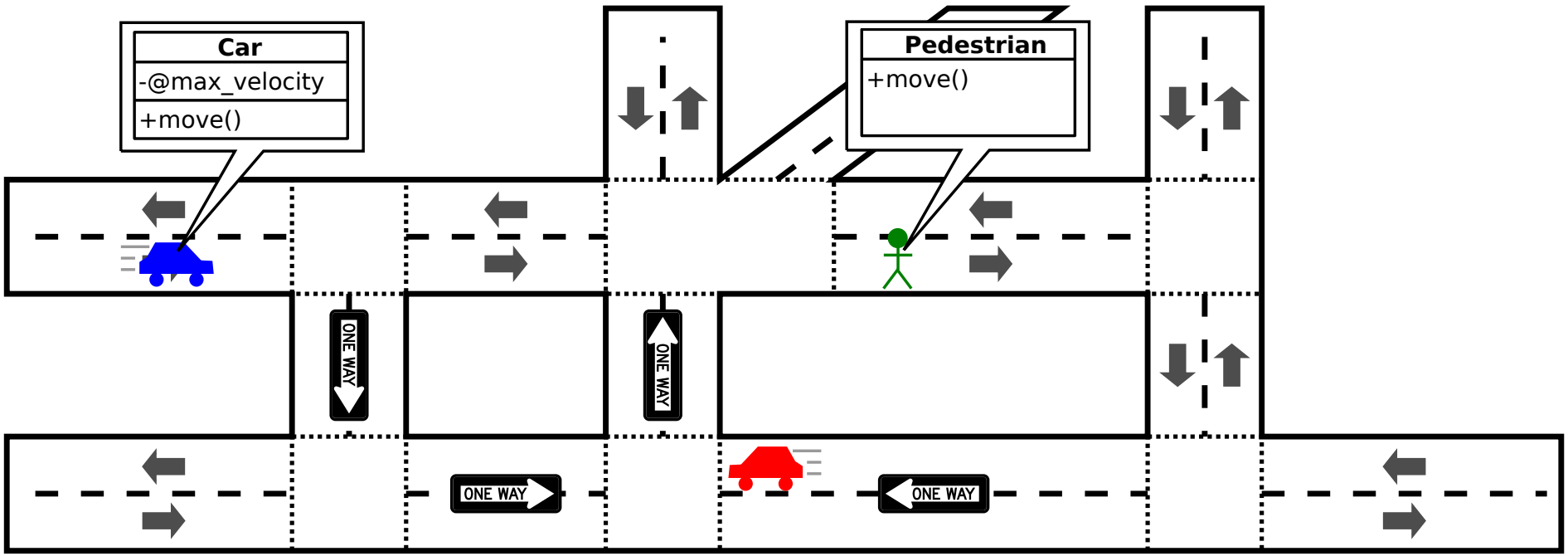
Example: Agent-based Traffic Simulation

Problem Description [2]



- Simulate movement of agents (cars, etc.) on a street network
- Iteration-based, different behavior per *type/class*

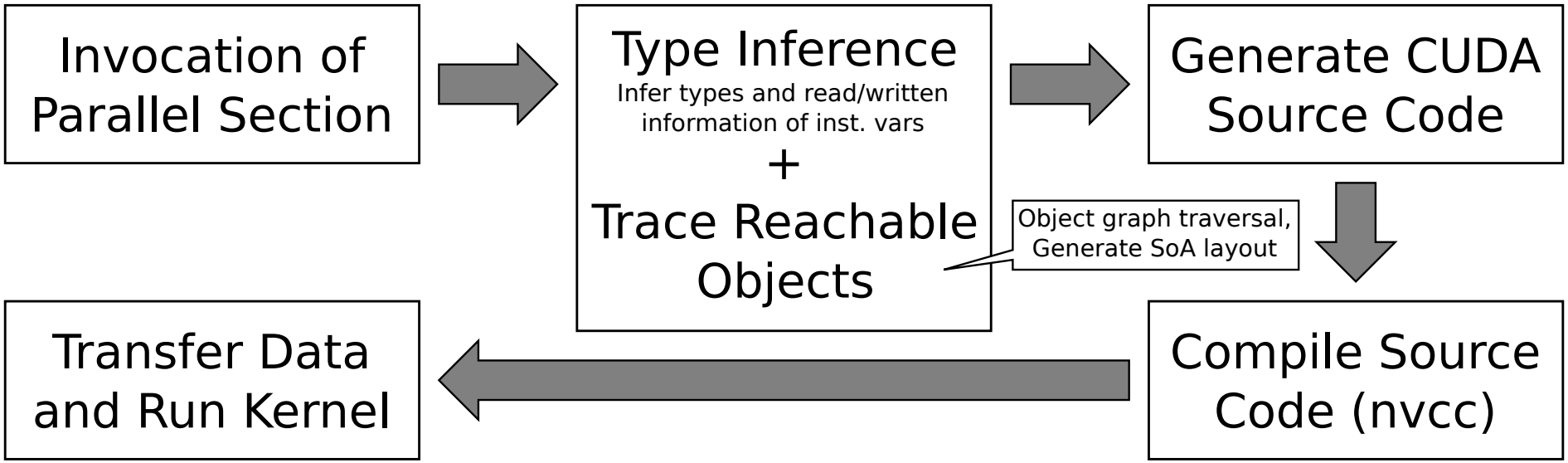
Iteration-based Simulation

```ruby
agents = # load scenario from file system
ticks = 1000
weather = Weather::Rainy

agents.peach(ticks) do |agent|
    agent.move(weather)
end
```

- One thread per agent
- Syntactical sugar (+synchronization)

Overview

Architecture: Compilation Process



- Code analysis at runtime (*dynamic compilation*)
- Metaprogramming, reflection allowed outside of parallel sections, but not inside them
- Support for object-oriented programming, Ruby classes, virtual method calls, dynamically-typed expressions

Translation Process

- Block → C++ CUDA function
- Instance method → C++ CUDA function
- Polymorphic expressions: union type struct [1]

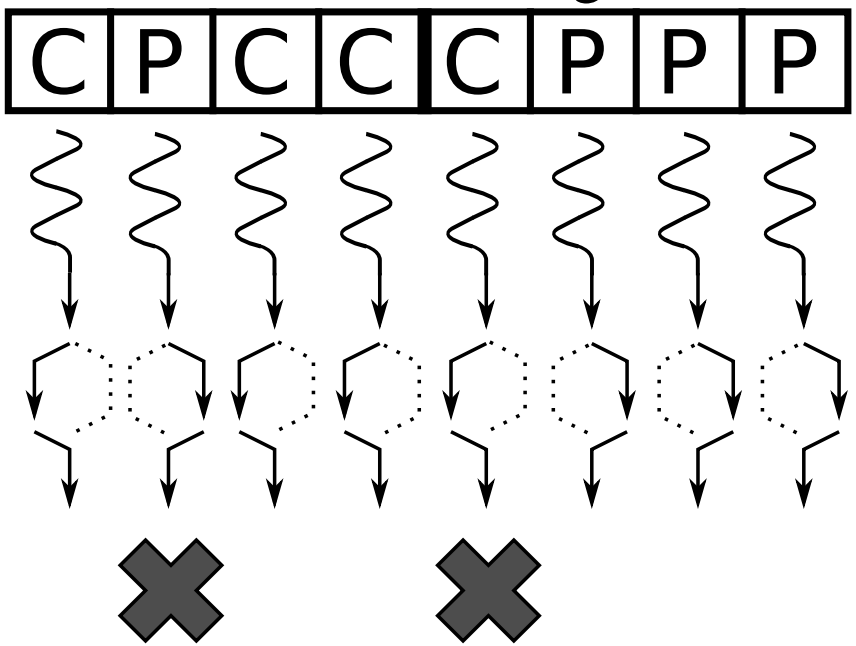
```
typedef struct union_type
{
    int object_id;
    int class_id;
} union_t;
```

Polymorphic Method Calls

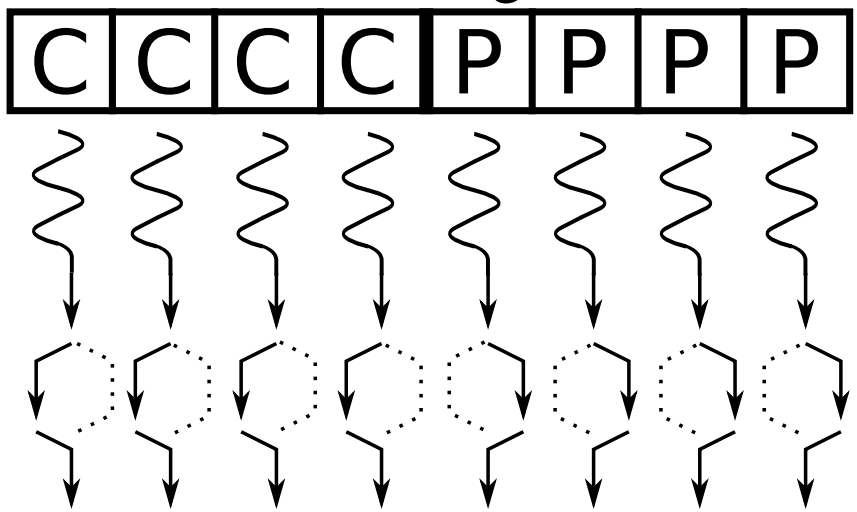
```
__global__ void kernel(union_t *agent, int weather, int ticks)
{
  int tid = blockIdx.x * blockDim.x + threadIdx.x;
  block(agent[tid], weather, ticks);
}

__device__ void block(union_t agent, int weather, int ticks)
{
  for (int i = 0; i <= ticks; i++)
  {
    switch (agent.class_id) # determined during type inference
    {
      case TAG_Car:
        method_Car_move(agent.id, weather); break;
      case TAG_Pedestrian:
        method_Pedestrian_move(agent.id, weather); break;
    }
  }
}
```

Job Reordering (1/2)

Without Job Reordering:



With Job Reordering:

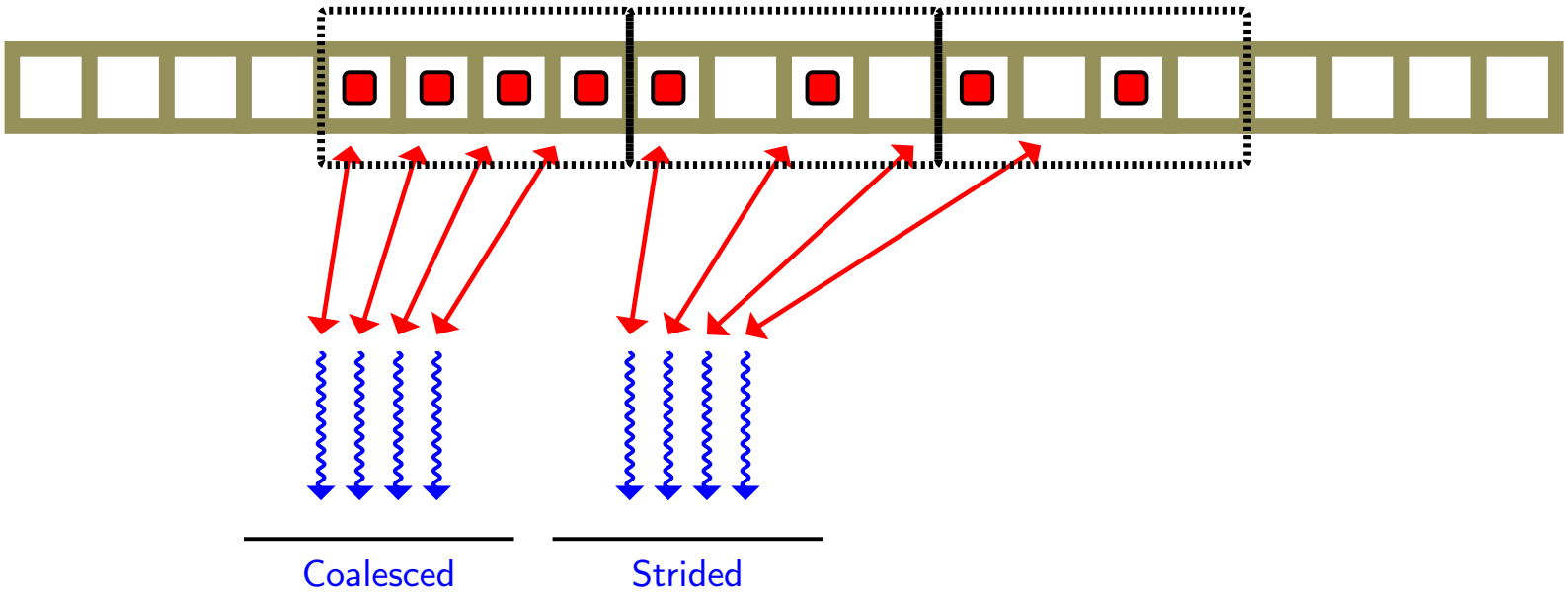


- **Purpose:** Avoid branch divergence (GPU is SIMD) [6]
- **Mechanism:** Reorder jobs according to runtime type information
- About 30% faster with job reordering

Job Reordering (2/2)

```
__global__
    void kernel(union_t *agent, int *jobs, int weather, int ticks)
{
  int tid = blockIdx.x * blockDim.x + threadIdx.x;
  block(agent[jobs[tid]], weather, ticks);
}

__device__ void block(union_t agent, int weather, int ticks)
{
  /* ...  */
}
```

Memory Coalescing

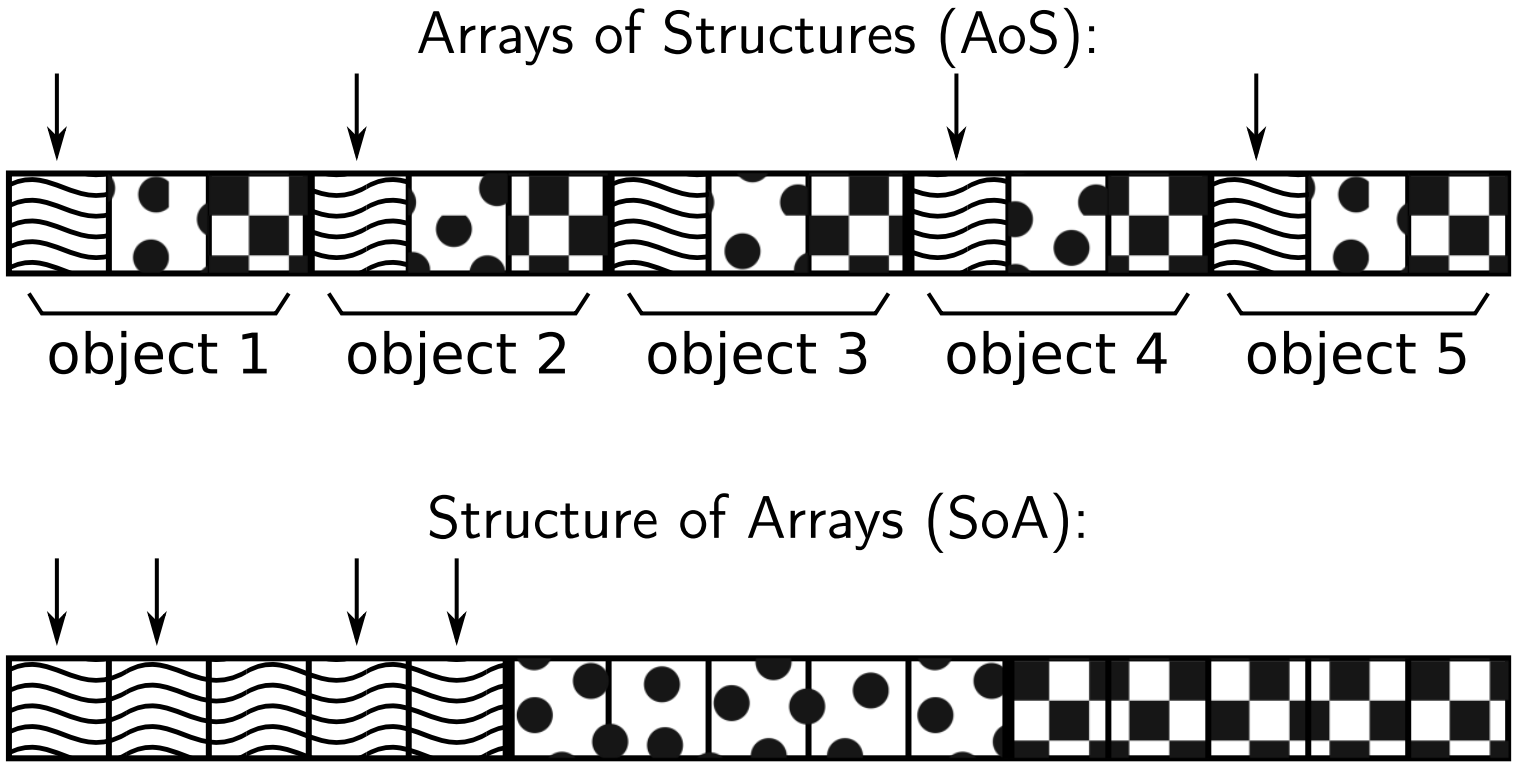


- **Memory Coalescing:** Process multiple global memory access requests in one transaction
- **Requirement:** Spatial locality of memory

Illustration: *realazthat* GitHub Gist (`https://goo.gl/tjPTZr`)

Structure-of-Arrays Representation

Overview (c.f. *Columnar Objects* [3, 4])



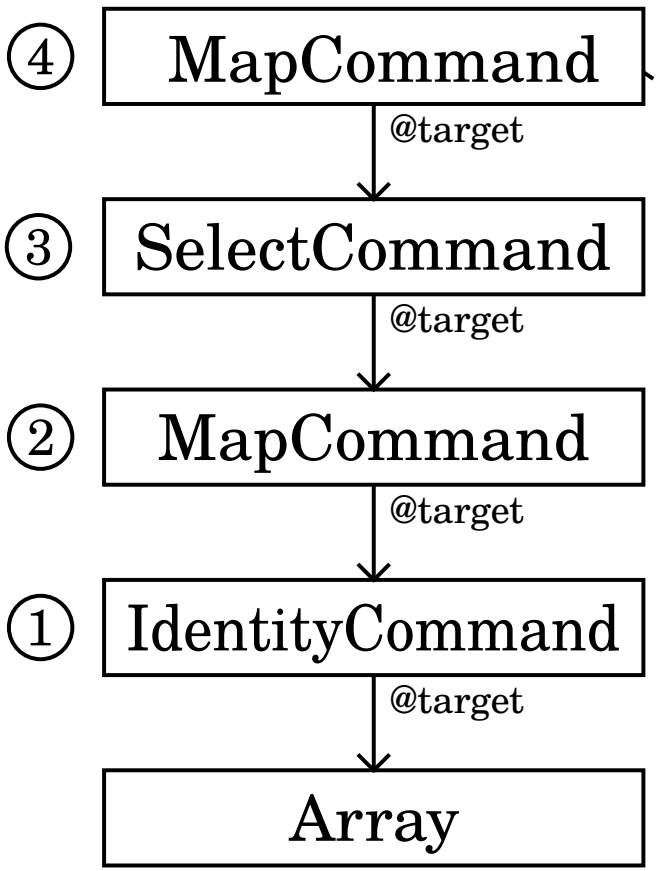
- **Purpose:** Increase memory coalescing
- **Mechanism:** Spatial locality of instance variables (group inst. vars.)

Structure-of-Arrays Representation

Type Inference and Generating Arrays: Object Tracer

1. **Object Tracing:** Generate set of objects reachable from *base array* and *lexical variables* (only those that have `Ikra::Entity` included)
2. **Inst. Var. Type Analysis:** Collect types of all instance variables
3. **Translation:** Infer types and generate CUDA program
4. **SoA Generation:** Generate arrays for Structure-of-Arrays representation
5. **Kernel Invocation:** Run kernel

Kernel Fusion




```
command[5]
command.size
command.
   execute
```

```
__device__ int block_1(int el) { return el; }
__device__ int block_2(int el) { return 2 * el; }
__device__ bool block_3(int el) { return el > 10; }
__device__ int block_4(int el) { return el + 1; }

__global__ void kernel(int *input, int *result, int *jobs) {
    int job = jobs[threadIdx.x + blockIdx.x * ...];
    int v2 = block_2(block_1(input[job]));
    if (block_3(v2)) result[job] = block_4(v2); }
```

- **Purpose:** Reduce global memory access for cascaded kernel operations
- **Mechanism:** Generate single kernel for multiple parallel sections [5]

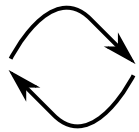
Kernel Fusion

Examples / Use Cases / Future Work

Embedded DSL for Database Queries

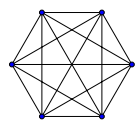
```
SELECT state, COUNT(*)
FROM employees
WHERE age > 25
GROUP BY state
```

```
employees.pselect do |empl|
    e.age > 25
end.preduce([:state]) do ↩
    |acc, empl|
    acc + 1
end
```



Iteration-based Simulations

```
agents = # load scenario
for i in 1..ticks
  agents = agents.pmap do ↩
      |agent|
    agent.move
  end
end
```

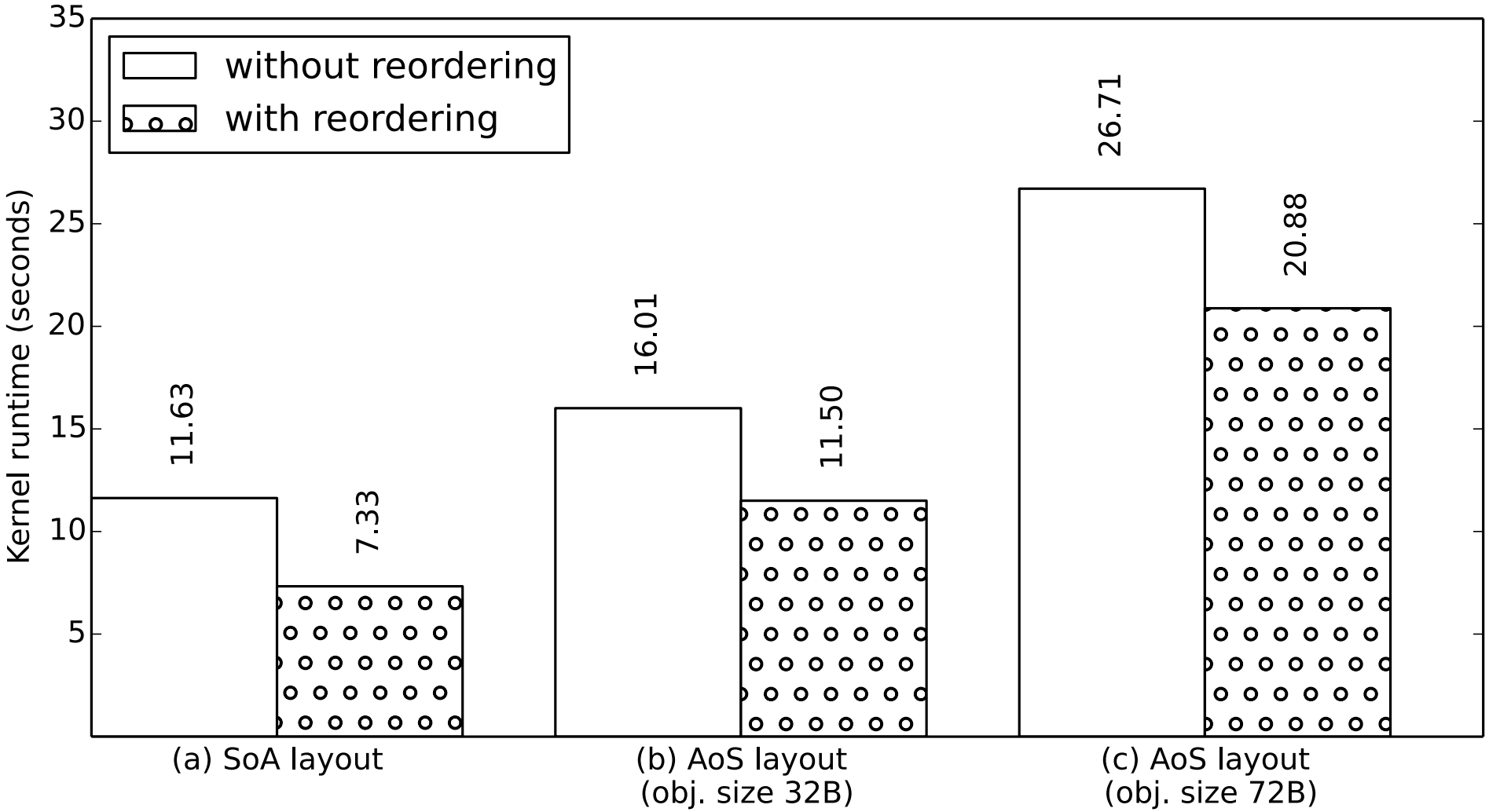


Algorithmic Primitives for Graph Algorithms

```
d_s1 = graph.dist_from(s1)
d_s2 = graph.dist_from(s2)
d_s1.join(d_s2) do |n1, n2|
  n1.dist = n2.dist
end
```

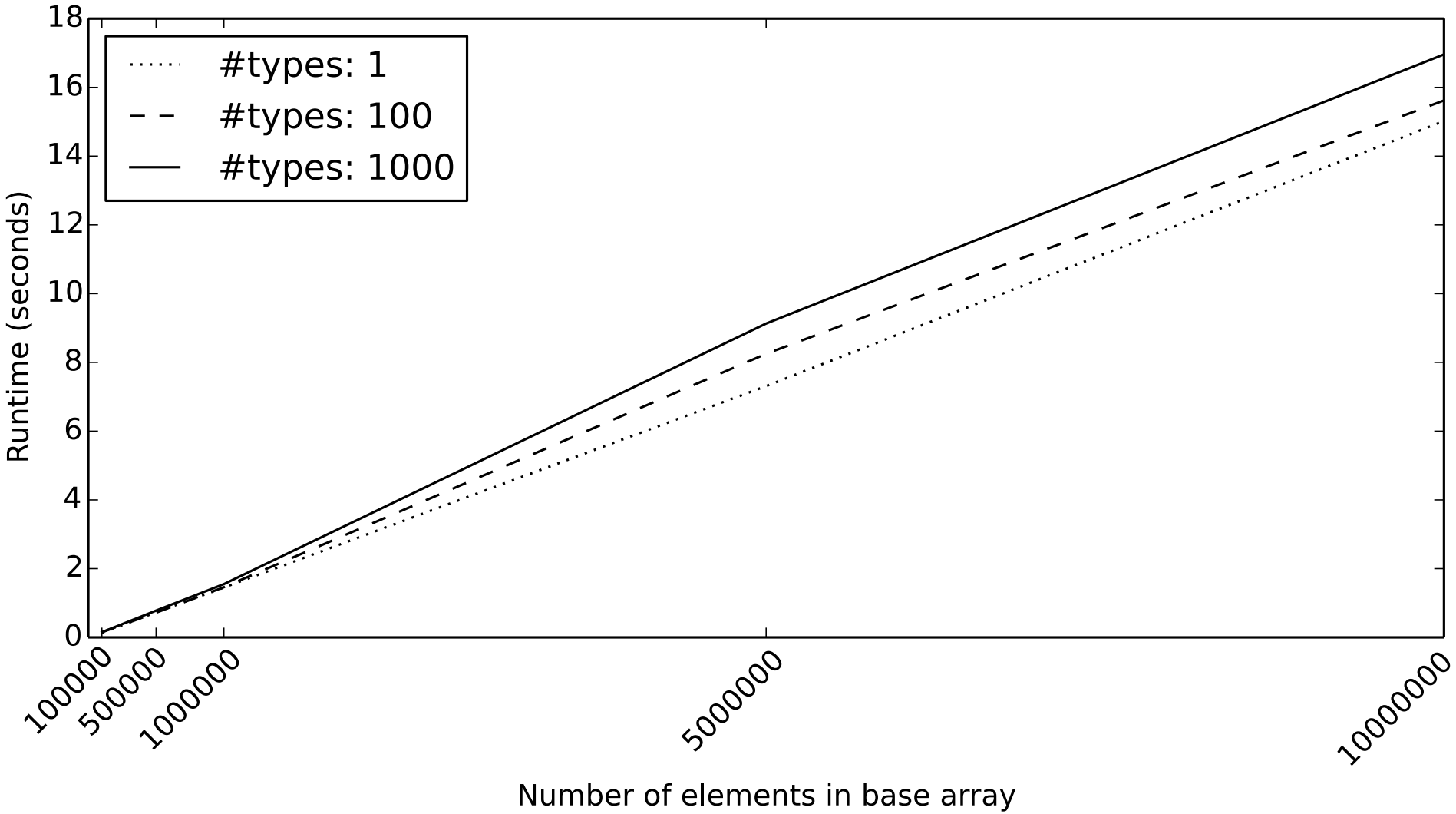
Overview

Kernel Running Time



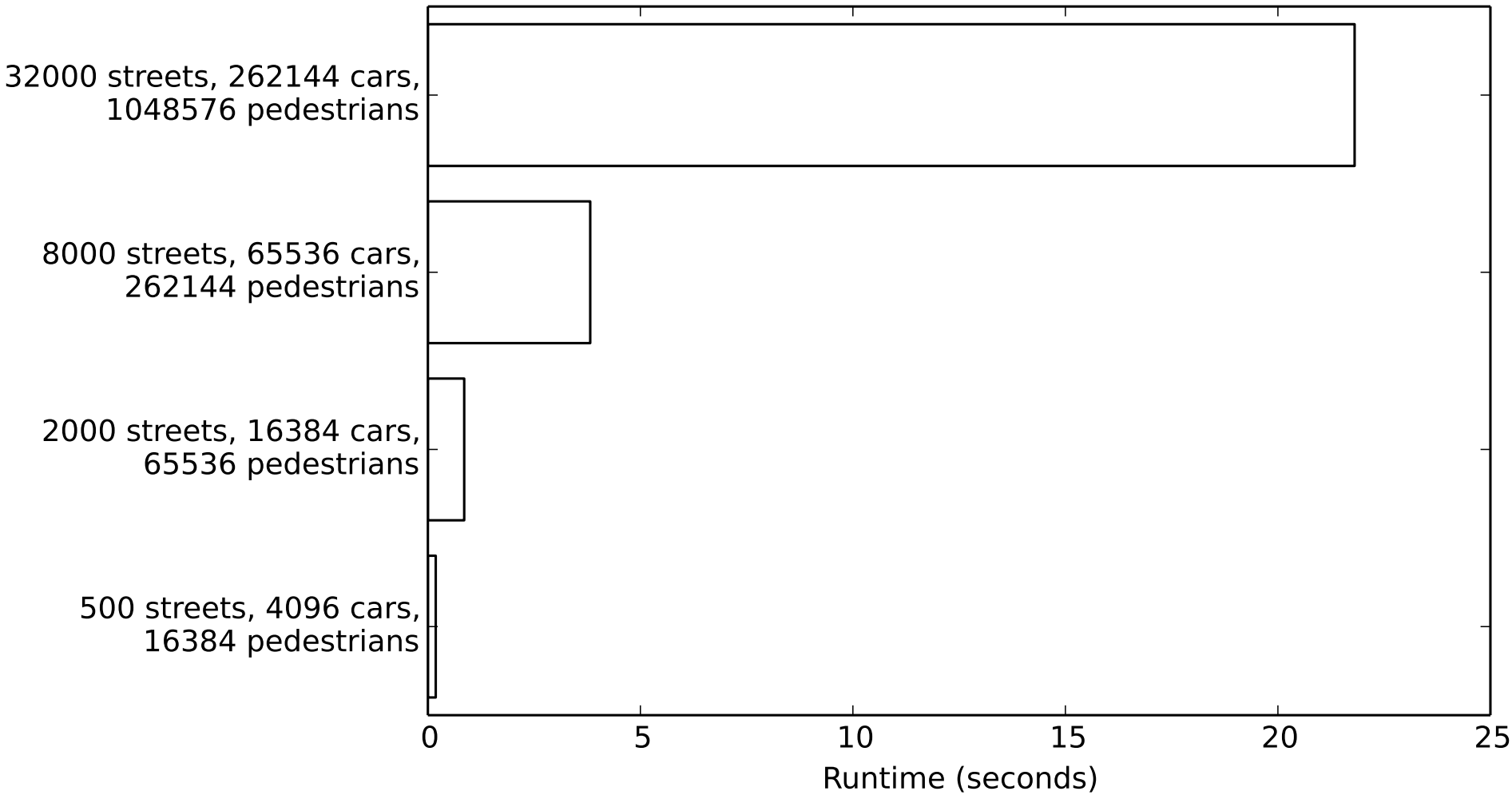
Setting: nVidia Tesla K20Xm, Ruby 1.9.3p448, Linux 3.0.76-0.11
Scenario: 4,096 cars, 16,384 pedestrians, 500 streets, 1,000,000 iterations

Job Reordering



Setting: Intel Xeon X5670 CPU (2.93 GHz), Ruby 1.9.3p448, Linux 3.0.76-0.11

Object Tracing and SoA Generation



Setting: Intel Xeon X5670 CPU (2.93 GHz), Ruby 1.9.3p448, Linux 3.0.76-0.11

Overview

Ideas for Future Work

- Full support for *object-oriented programming*: instance creation, etc.
- Job reordering: take into account *run-time types of expressions inside the kernel* (and reorder after a while)
- *Synchronization* primitives: block-level, global
- *Minimizing data transfers*: allocate data only in global memory
- More *low-level optimizations*: e.g., code unrolling for ILP

Summary

- **Ikra:** A GPGPU framework for Ruby
- Supports **object-oriented programming** including virtual method calls and dynamically-typed expressions
- Employs **low-level optimizations**: job reordering, structure-of-arrays data layout, kernel fusion

References

[1] M. Abadi, L. Cardelli, B. Pierce, G. Plotkin. Dynamic Typing in a Statically-Typed Language. POPL '89

[2] D. Helbing. Social Self-Organization: Agent-Based Simulations and Experiments to Study Emergent Social Behavior, chapter Agent-Based Modeling

[3] T. Mattis, J. Henning, P. Rein, R. Hirschfeld, M. Appeltauer. Columnar objects: Improving the Performance of Analytical Applications. Onward! 2015

[4] G. Mei, H. Tian. Impact of Data Layouts on the Efficiency of GPU-accelerated IDW Interpolation. SpringerPlus, 2016

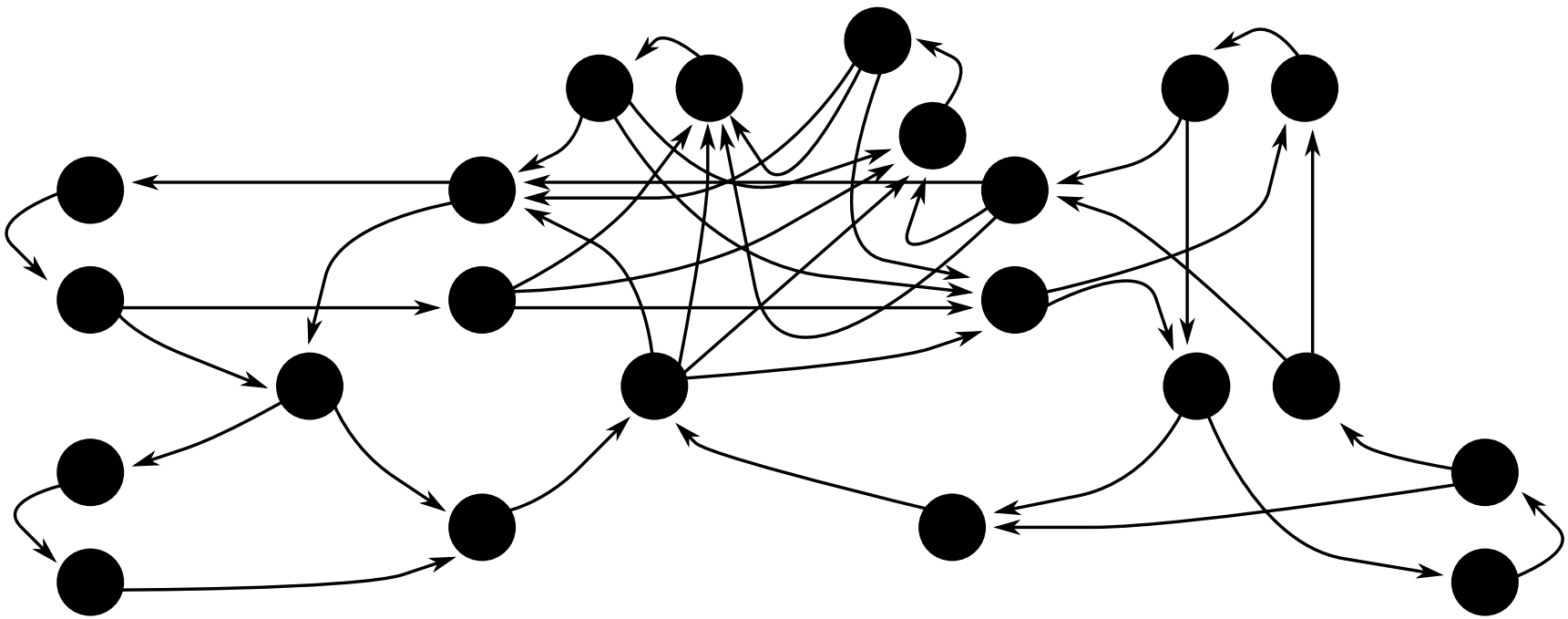
[5] M. Wahib, N. Maruyama. Scalable Kernel Fusion for Memory-bound GPU Applications. SC '14

[6] E. Z. Zhang, Y. Jiang, Z. Guo, X. Shen. Streamlining GPU Applications on the Fly: Thread Divergence Elimination through Runtime Thread-Data Remapping. ICS '10

Appendix

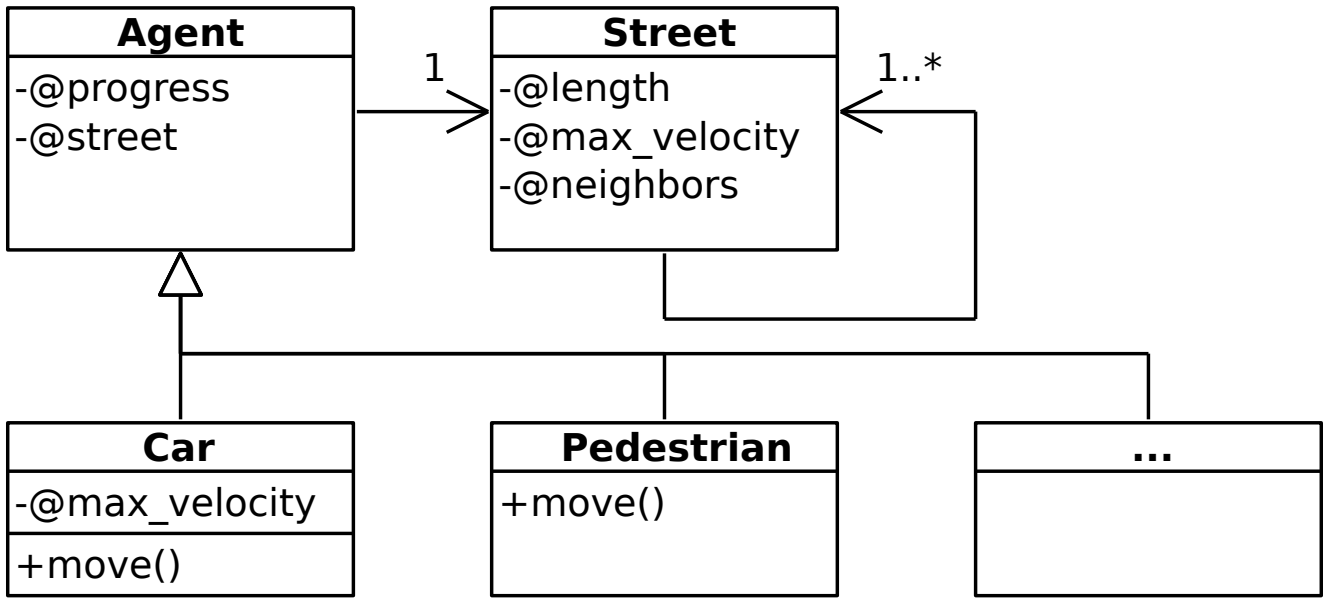
Example: Agent-based Traffic Simulation

Graph Representation



Example: Agent-based Traffic Simulation

UML Class Diagram



- Car moves with velocity $\min(S.max\_velocity, C.max\_velocity)$
- Pedestrian moves with random velocity between -2 mph and 4 mph
- Agent moves to random neighboring street when reaching end of street

Iteration-based Simulation (1/3)

First approach: Parallel inner section

```
agents = # load scenario from file system
ticks = 1000
weather = Weather::Rainy

for i in 1..ticks
    agents.peach do |agent|
        agent.move(weather)
    end
end
```

- One thread per agent
- Problem: Separate kernel launches for every iteration

Iteration-based Simulation (2/3)

Second approach: Parallel outer section with loop inversion

```
agents = # load scenario from file system
ticks = 1000
weather = Weather::Rainy

agents.peach do |agent|
    for i in 1..ticks
        agent.move(weather)
        # add synchronization here
    end
end
```

- One thread per agent

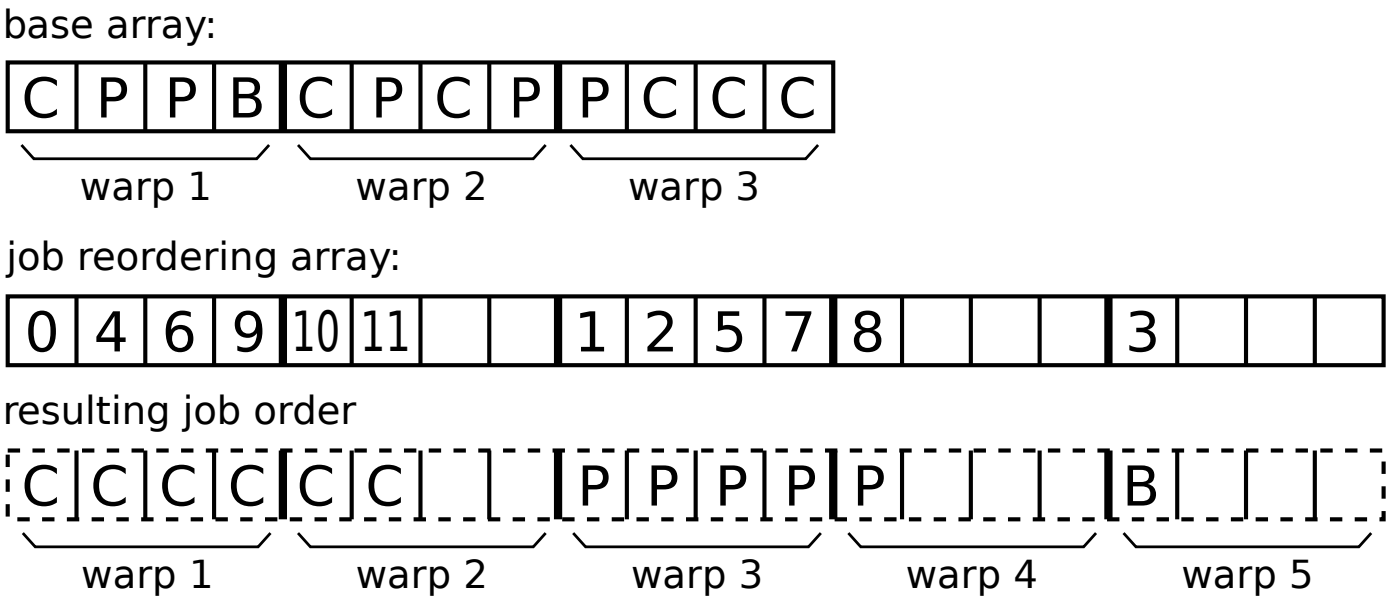
Iteration-based Simulation (3/3)

Third approach: Syntactical sugar

```
agents = # load scenario from file system
ticks = 1000
weather = Weather::Rainy

agents.peach(ticks) do |agent|
    agent.move(weather)
end
```

- One thread per agent
- Syntactical sugar for previous example (+synchronization)

Job Reordering



- **Purpose:** Avoid branch divergence (GPU is SIMD) [6]
- **Mechanism:** Reorder jobs according to runtime type information

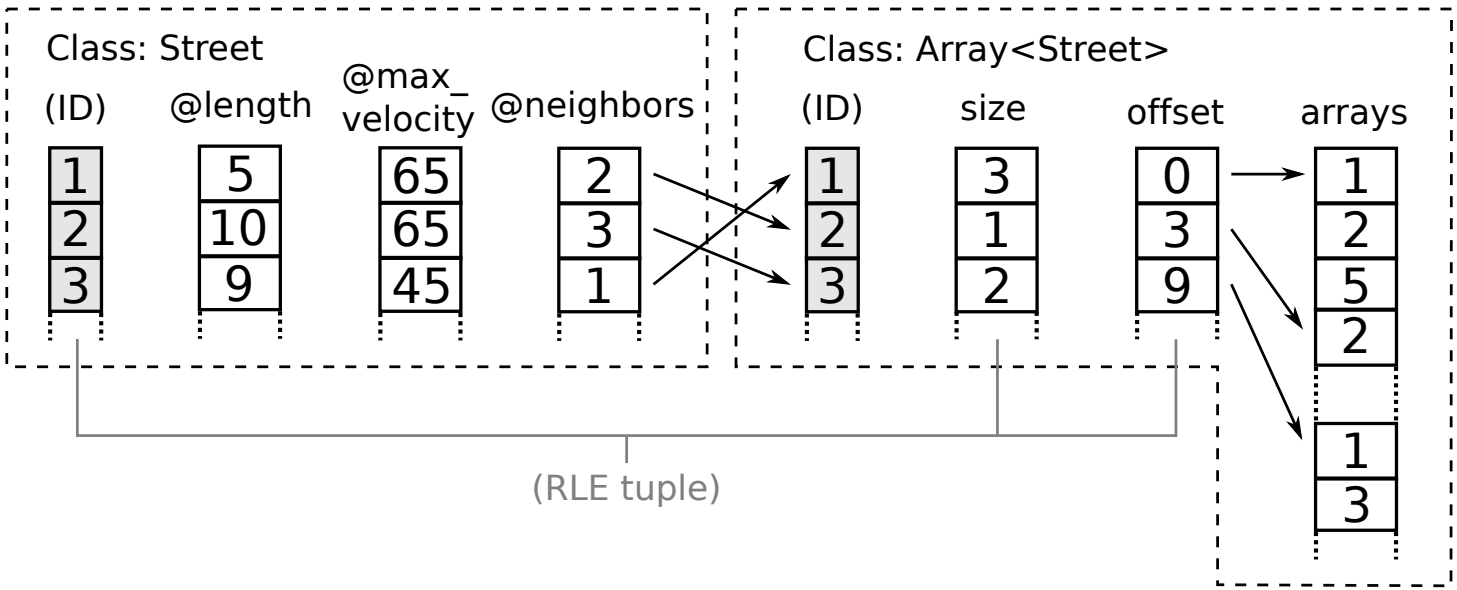
Structure-of-Arrays Representation

Code Example

```
__device__ float *d_Car_max_velocity;
__device__ float *d_Car_progress;
/* ...  */

__device__ void method_Car_move(int agent_id, int weather)
{
  /* ...  */

  // Due to SIMD, all threads execute this simultaneously:
  d_Car_progress[agent_id] += speed / 60.0;

  /* ...  */
}
```

Structure-of-Arrays Representation

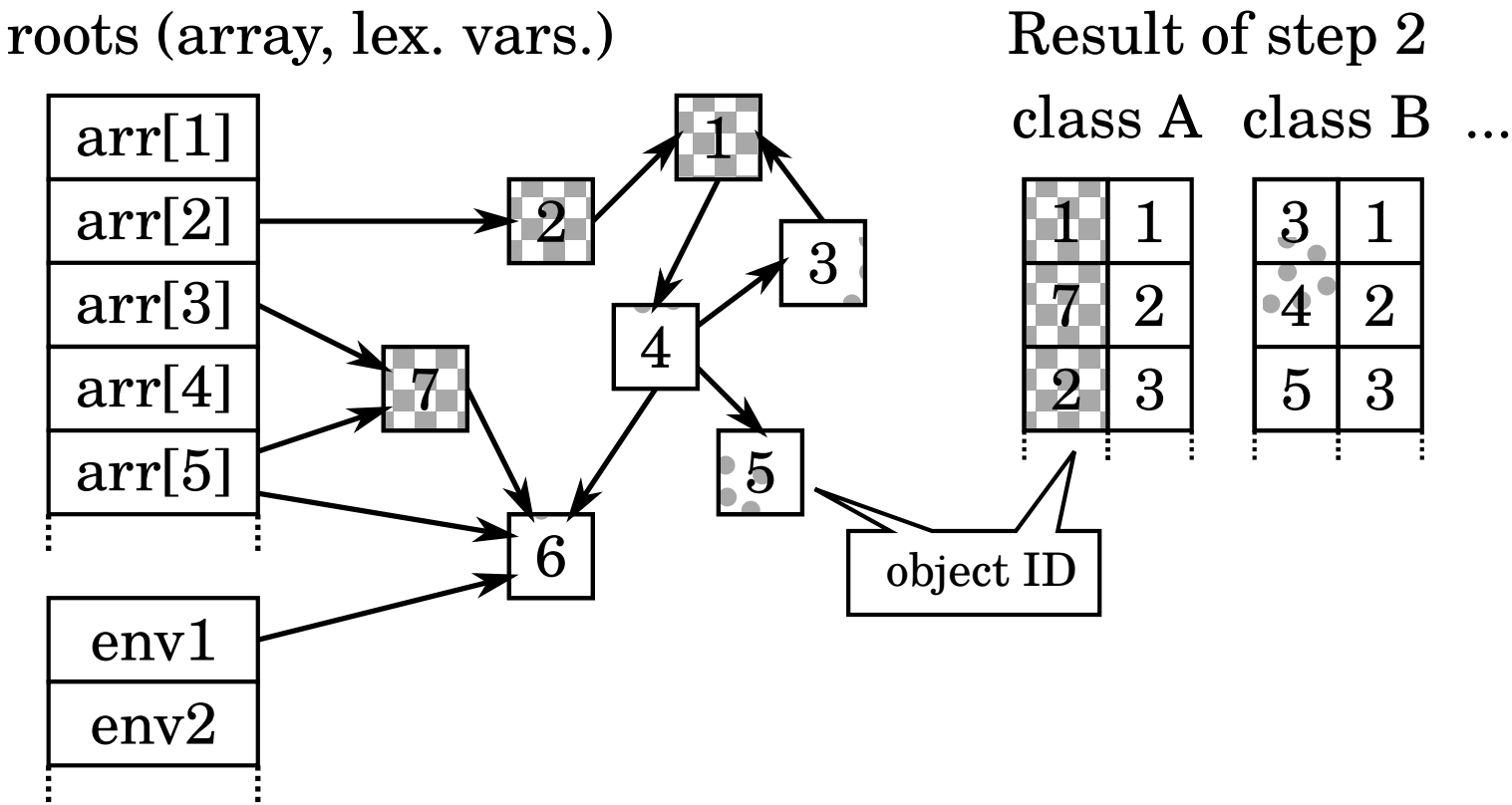
Arrays



- **Basic Idea:** Treat arrays like other classes, but distinguish between inner types
- **Implementation:** Store *size* and *offset* into *contents array* as if they were *instance variables*
- **Future Work:** Allow arrays to grow

Structure-of-Arrays Representation

SoA Generation (c.f. *system tracer* in Smalltalk systems)



- Pointers of object references must be replaced with array indices

1. Assign IDs to objects (grouped by class), build hash map object → ID
2. Build arrays, replace object references with IDs (or union type tuple)