Field Analysis

Last time

- Exploit encapsulation to improve memory system performance

This time

- Exploit encapsulation to simplify analysis
- Two uses of field analysis
  - Escape analysis
  - Object inlining

Motivation

Performance Problems with Modern High Level Languages

– Bounds and type checks for safety
– Virtual method calls to support object-oriented semantics
– Heap allocation to provide uniform view of objects

Solution

– Prove facts about array bounds and about types to tighten assumptions

e.g. To devirtualize a call, prove that the call has exactly one target class

– Such analysis typically requires interprocedural analysis
  – Costly
  – Sometimes impossible: dynamic class loading, unavailable source code

Field Analysis

A Cheap Form of Interprocedural Analysis

- Exploits encapsulation to limit the scope of analysis

  e.g. If an array is indexed by a private variable that is only set by one method, then only that one method needs to be analyzed to determine the index's value
- Deduce properties about fields based on the properties of all accesses to that field

Benefits

- Efficient (10% overhead in compilation time)
- Does not require access to the entire program
- Works well with dynamic class loading
- Can be applied to any language that supports encapsulation
  - Java, C++, Modula-3, etc.

Field Analysis for Java

Today: A specific solution [Ghemawat, Randall, & Scales, PLDI'00]

- Implemented in the context of Compaq's Swift optimizing Java compiler
- Swift translates bytecode to native Alpha code
- Swift performs a number of aggressive optimizations
- This implementation focuses on **reference types**
  - Ignores scalar fields

Field Modifiers Dictate Scope of Analysis

Java field modifiers

Class	**Field**	**Where can the field be modified?**
public	private	containing class
public	package	containing package
public	protected	containing package and subclasses
non-public	private	containing class
non-public	non-private	containing package
public	public	entire program

Example

```
public class Plane {
   private Point[] points;

   public Plane() {
      points = new Point[3];
   }

   public int GetAverageColor() {
      return (points[0].GetColor() +
              points[1].GetColor() +
              points[2].GetColor())/3;
   }
}
```

Since `points` is private

- Its properties can be determined by analyzing only the `Plane` class
- We can determine the exact type of `points`
- So we can inline the `GetColor()` method

Idea: Create an Enhanced Type System

Introduce special types

- A value is an object of exactly class T (and not a subclass of T)
- A value is an array of some constant size
- The value is known to be non-null
- . . .

Type analysis begins by determining types of

- Method arguments
- Loads of fields of objects
- Loads of global variables
- Non-null exact types assigned to newly allocated objects

Use type propagation to determine types of other nodes in the SSA graph

Basic Approach

1. Initialize

– Build SSA graph and gather type information

SSA provides flow-sensitivity

2. Incrementally update properties

– Consider all loads and stores and update properties associated with each field

Load of a field:

Analyze all uses of the load

```
x = y.f;
. . .
x.z();
```

Type of `x`?

Store of a field:

Analyze the value stored into the field and all other uses of the value

```
x = new T;
. . .
y.f = x;
```

Type of `y.f`?

Examples of Useful Properties

exact_type(*field*)

– The field is always assigned a value of the specified type

always_init(*field*)

– The field is always initialized

only_init(*field*)

– The field is only modified by constructors

Example Analysis

```
public class Plane {
   private Point[] points;

   public Plane() {
      points = new Point[3];
   }

   public void SetPoint(Point p, int i) {
      points[i] = p;
   }

   public Point GetPoint(int i) {
      return points[i];
   }
}
```

`points` is private, so its properties can be determined by only scanning the Plane class

`exact_types(points)` indicates a non-null array with base type `Point` and a constant size of 3

`only_init(points)` is true

`always_init(points)` is true

Example Optimizations

Precise type information supports a form of constant folding

`exact_type(`*`field`*`)`

- If the type is precisely known, we can convert a virtual method call to a static method call

- Precise type information can be used to statically evaluate type-inclusion tests such as **instanceof** or **array store checks**

- If the type is an array of constant size, some bounds checks can be eliminated and expressions that use the array length (eg. **`a.length()`**) can be statically evaluated

Example Optimizations (cont)

```
public class Plane {
   private Point[] points;

   public Plane() {
      points = new Point[3];
   }

   public void SetPoint(Point p, int i) {
      points[i] = p;
   }

   public Point GetPoint(int i) {
      return points[i];
   }
}
```

What optimizations are possible in this example?

Can eliminate null checks on `points`

Can use the constant 3 in bounds checks on `points`

Can eliminate the array store check for `points`

Example Optimizations (cont)

These properties can enhance other optimizations

CSE?

```
x = y.f;          x = y.f;
x.foo();    →     x.foo();
z = y.f;          z = x;
```

CSE is possible if x.foo does not modify **`y.f`**.

We know that **`y.f`** is only modified by a constructor if **`only_init`**`(f) = true`

Outline

Last time

– Exploit encapsulation to improve memory system performance

This time

– Exploit encapsulation to simplify analysis

– Two uses of field analysis

  – Escape analysis

  – Object inlining

Escape Analysis

Idea

- Does an object escape the method in which it is allocated?
- *E.g.*, return, assign to global/heap, pass to another method

```
f() {
    Point p = new Point();
    Stack s = new Stack(100);
    s.push(p);           /* p escapes */
    . . .
    return p;            /* p escapes */
}
```

Escape Analysis

Uses

- Objects that do not escape can be allocated on the stack

```
f() {
    Point p = new Point();
    return;              /* Allocate p on the stack */
}
```

- Why is this desirable?
  - Less overhead than heap allocation
  - Less work for garbage collector
  - Usually has better cache behavior

- Synchronization elimination
  - Escape from a thread: Can another thread access the object?
  - If an object cannot escape a thread, it need not be synchronized

Escape Analysis (cont)

Heavyweight escape analysis

- Many proposed variations [Aldrich'99, Blanchet'99, Bogda'99, Choi'99, Whaley'99]
- Typically expensive interprocedural data-flow analysis
- Large flow values
  - **Connection Graphs** represent "points-to" relationship among objects

Simple escape analysis

- Simplifying assumption: Any object that is assigned into the heap or returned from a method escapes that method

Evaluation of Simple Escape Analysis

Pros

- Extremely simple
- Inexpensive (analysis time is linear in code size)

Cons

- Inaccurate
- Assignment to heap does not necessarily imply escape

Limitations of Simple Escape Analysis

Consider the following code

```
class Pair {
    private Object first;
    private Object second;
}

Pair p = new Pair();
Integer x = new Integer(5);
p.first = x;
```

Questions

- Is `x` assigned to the heap?
- Does `x` escape?
  - Only if `p` escapes, since `x` is only assigned to an encapsulated field of `p`

Escape Analysis with Field Analysis

Idea

- Identify encapsulated fields
- If an object does not escape, then the contents of its encapsulated fields do not escape
- Escape from a thread can be handled similarly by focusing on thread creation routines

Conditions for identifying encapsulated fields

(1) The value of the field does not escape through a method that accesses the field, and

(2) Any value assigned to the field has not already escaped

- This is trivially true for newly-allocated objects

Field Properties for Escape Analysis

Field Property: `may_leak`(*field*)

– Indicates whether the object in the field might escape the containing object

Field Property: `source_type`(*field*)

– Describes the kind of values assigned to the field:

– new	*only assigned newly allocated objects*
– new/null	*. . . or null*
– new/null/param	*. . . or method parameters*
– other	

A field, *f*, is encapsulated when

– `may_leak`(*f*) = false	Condition (1)
– `source_type`(*f*) = new/null	Condition (2)

Limitations of Simple Escape Analysis (reprise)

Consider the following code

```
class Pair {
    private Object first;
    private Object second;
}

Pair p = new Pair();
Integer x = new Integer(5);
p.first = x;
```

Questions

- Is `x` assigned to the heap? Yes
- Does `x` escape?
  - Only if `p` escapes, since `x` is only assigned to an encapsulated field of `p`
  - Check `may_leak(p)`, `source_type(p)`

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Object Inlining

Idea

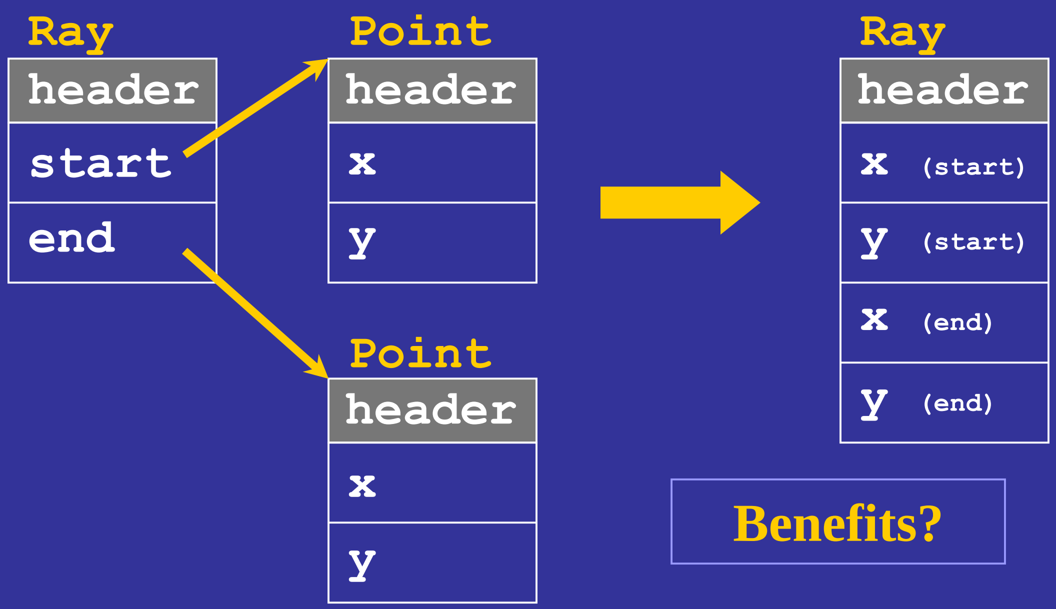
– Allocate storage for an object **inside** its containing object

Example

Direct allocation *Inlined allocation*

```
class Point {
      int x,y;
      ...
}

class Ray {
      Point start;
      Point end;
      ...
}
```



Benefits?

Object Inlining (cont)

Benefits

- Allows inlined objects to be accessed directly (*i.e.*, without following pointers)
- Reduces the size of objects
- Reduces allocation/garbage-collection overheads
- May improve data cache performance (Inlined objects are likely to be accessed together)

Bottom line

- Object inlining produces code closer to hand-tuned C

Object Representation and Inlining

Objects contain headers

- Type of object
- Method table
- Synchronization state

Needed for type checking, virtual method calls, synchronization

Question: Does the header need to be preserved for inlined objects?

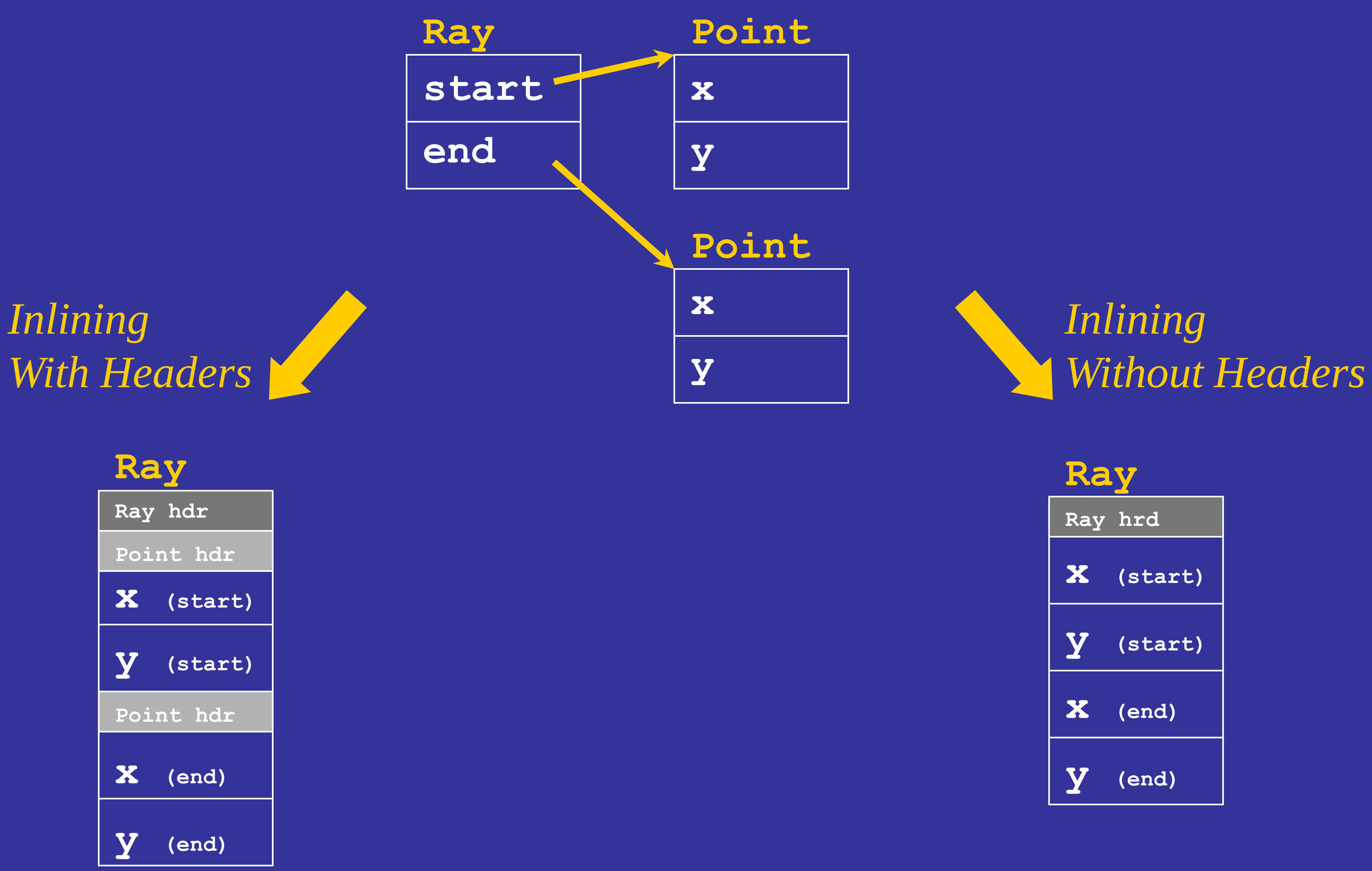
Answer: No, if the following hold:

- There are no virtual method invocations, no synchronization, and no type inclusion checks on the object (*i.e.*, we don't need it), and
- The object does not escape (*i.e*, no one else will need it)
- Otherwise, **`uses_header`**(*field*) = true

Question: Can a compiler do this type of inlining in C++?

Answer: No

Object Representation and Inlining (cont)



Object Inlining and Garbage Collection

Question: What if an inlined object escapes and its enclosing object does not?

Answer:

- Problem: the garbage collector might reclaim the enclosing object, which would also implicitly reclaim the inlined object

Two approaches

- Do not inline objects that may escape
- Tag inlined objects (in their header) and make sure that the garbage collector does not collect the enclosing object if the inlined object is live

Object Inlining with Field Analysis

Recall Field Property: `source_type`(*field*)

- Indicates the kind of values assigned to the field:
  - new *only assigned newly allocated objects*
  - new/null *. . . or null*
  - new/null/param *. . . or method parameters*
  - other

For inlining we are interested in the first case

- We need to know the exact type of an object before we can inline it

Object Inlining with Field Analysis (cont)

Do we need headers?

– Use the following properties to determine whether the header for inlined objects must be preserved

Field Property: `uses_header`(*field*)

– Indicates whether the header for the object in the field might ever be used

Field Property: `may_leak`(*field*)

– Indicates whether the object in the field might escape the containing object

Exploiting Field Analysis Properties

A field *f* can be inlined with a header when

- `always_init`(*f*) = true,
- `only_init`(*f*) = true,
- `source_type`(*f*) = new, and
- `exact_type`(*f*) = `static_type`(*f*)

The field is always initialized exactly once by a newly allocated object

The final condition is a simplification

- It makes object layout easier for the JVM
- One layout for all inlined objects of the same static type

Exploiting Field Analysis (cont)

A field *f* can be inlined without a header when

- It is can be inlined **with** a header,
- **`uses_header`**(*f*) = false, and
- **`may_leak`**(*f*) = false

Can also inline arrays when

- The array satisfies the above constraints, and
- The array has a constant size

Object Inlining Transformation

Transforming references to inlined objects

`pt = myRay.start;` → `pt = myRay + offset(myRay, start);`

Initializations

```
pt = new Point;
myRay.start = pt;
```

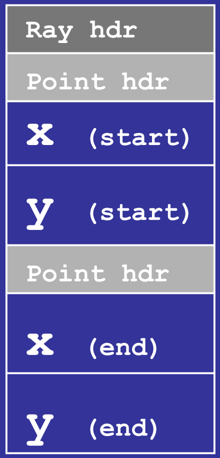
→ No allocation needed

Possibly initialize header of **`myRay.start`**

`pt = myRay + offset(myRay, start);`

Inlined Object

`myRay`



Limitations of Field Analysis

Native methods

- Cannot analyze native methods
- Conservative assumption: Assume the native methods read and write all fields that they can access

Weak consistency

- Some optimizations are not legal under weak consistency models on multiprocessors
- Race conditions may allow a thread to see a null value even if the `always_init`(field) is true

Reflection

- Field properties can be modified through reflection (`setAccessible()`)
- Disable field analysis on such fields

Impact on Performance

Run-time check elimination

- Many null-checks eliminated (0-50%)
- Some array bounds checks eliminated (0-60%)
- Not many cast checks eliminated (0-1%)

Virtual method calls

- Significantly reduced

Object inlining

- 0-11% performance improvement

Stack allocation

- Escape information does not significantly assist stack allocation (for the benchmarks considered)

Impact on Performance (cont)

Synchronization removal

– 0-90% reduction in dynamic synchronization

– Either helps a lot or helps very little

Bottom line

– 0-27% performance improvement

– Average improvement of 7%

Concepts

Escape analysis

- Useful for optimizing the allocation of objects
- Useful for removing unnecessary synchronization

Object inlining

- Remove object overhead
- Improve data locality

Field analysis

- Exploit encapsulation to simplify analysis
- Many uses
  - De-virtualization
  - Remove runtime checks
  - Perform escape analysis
  - Perform object inlining

Next Time

Lecture

– Traditional uses of compilers