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
- Lesson: You don't always have to solve the general problem!

Motivation

"Problems" with Modern High Level Languages

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

Solutions

- 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
- 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 modifier	Where can the field be assigned?
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();
```

Store of a field:

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

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

Example 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

`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 (*e.g.,* **`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

```
x = y.f;          x = y.f;
x.foo();   CSE?   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`

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

- Very simple
- Inexpensive to compute (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

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*)

- 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

A field, *f*, is encapsulated when

- `may_leak`(*f*) = false, and
- `source_type`(*f*) = new/null

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)`

Object Inlining

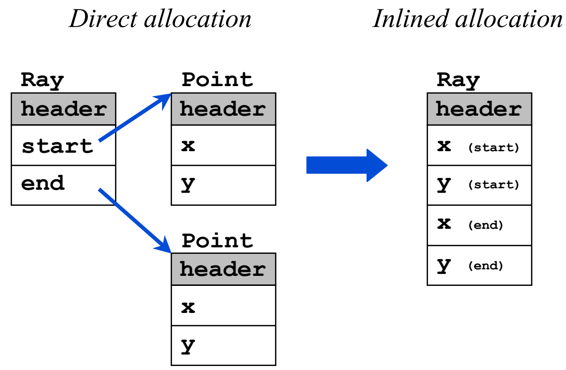
Idea

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

Example

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

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



Object Inlining (cont)

Benefits

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

Bottom line

- Object inlining produces code much like 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?

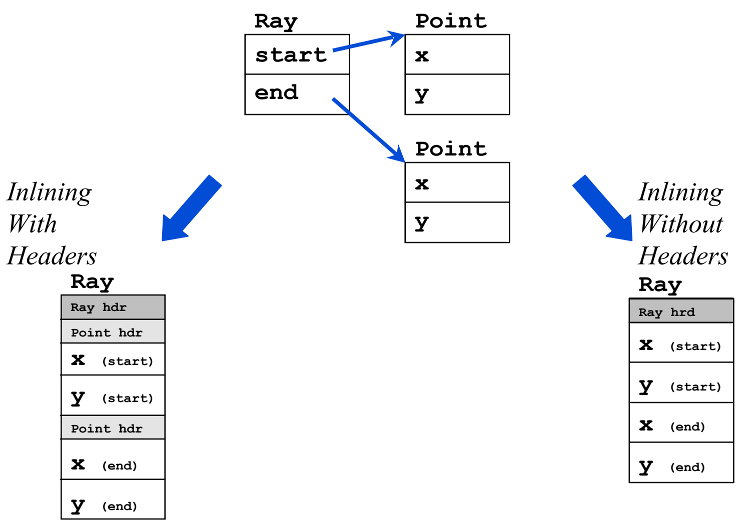
Answer: No, if the following hold:

- 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
– Garbage collector must be aware of this

Approaches

– In most systems, objects that may escape cannot be inlined
– Or...
  – Inlined objects may be tagged as such (in header), and
  – The garbage collector agrees not to collect enclosing object if 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 have static information about the candidate inlined object

Object Inlining with Field Analysis (cont)

Field Property: `uses_header`(*field*)

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

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

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

Idea

- These properties are used to determine whether the header for inlined objects must be preserved

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

References

`x = y.f;`	`x = y + offset(y, f);`

Initializations

`x = new T;`	if required, initialize header of `y.f`
	`x = y + offset(y, f);`
`y.f = x;`	deleted

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 and **`source_type`**(field) = new

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

Virtual method calls

- Significantly reduced (0-90%)

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%
- Cheap to compute

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
  - Register allocation