## Modern Uses of Compilers

**Last time**

– Pointer analysis

**Today**

– Compiling object-oriented languages



## What is an Object-Oriented Programming Language?

**Objects**

– Encapsulate code and data

**Inheritance**

– Supports code reuse and software evolution (kind of)

**Subtype polymorphism**

– Can use a subclass wherever a parent class is expected

**Dynamic binding** *(message sends)*

– Binding of method name to code is done dynamically based on the dynamic type of the (receiver) object

**Person**

**Student** **Teacher**

```
PrintName(Person p);
```

```
Person p = new Person;
Student s = new Student;

PrintName(p);
PrintName(s);
```

```
p.reprimand();
```

## Implementation: Inheritance of Instance Variables

**Goal**

– Lay out object for type-independent instance variable access

**Solution**

– Prefixing: super-class fields are at beginning of object

**Example**

| Person |
|---|
| Name |

| Student |
|---|
| Name<br>ID |

| Teacher |
|---|
| Name<br>Salary |

**Multiple inheritance?**

– May need to leave blanks

– Use graph coloring (one node for each distinct field, edge between coexistent fields, color indicates layout position)



## Implementation: Dynamic Binding

**Problem**

– The appropriate method depends on the dynamic type of the object e.g., `p.reprimand()`

**Solution**

– Create descriptor for each class (*not* each object) encoding available methods

– Store a pointer to a class descriptor in each object

– Lay out methods in class descriptor just like instance variables

| Person |
|---|
| getName |

| Student |
|---|
| getName<br>reprimand<br>workhard |

| Teacher |
|---|
| getName<br>reprimand<br>party |

**Usage summary**

– Load class descriptor pointer from object

– Load method address from descriptor

– Jump to method

## What is a Pure Object-Oriented Programming Language?

***Everything* is an object**
- Even numbers, strings, constants, *etc*.

**All work achieved by sending messages to objects**
- Even simple arithmetic and control flow

**Example**

Invoke **x**'s equal method

```
if (  &{x.eq(3)},
      &{a.set(a.plus(1))},
      &{a.set(a.minus(1))}
   );
```

Pass closures to the **if** method to create a control flow construct

Pass **then** computation

Pass **else** computation

**Very clean and simple**
- But very inefficient if naively implemented



## Why are Object-Oriented Languages Slow?

**Dynamism**
- Code
- Data

**Style**
- Granularity (lots of small objects)
- Exploit dynamism

**High-level (modern) features**
- Closures & non-LIFO activation records
- Safety, *etc*.

**Garbage collection**

## Dynamism: Code

**Dynamic binding**

– What code gets executed at a particular static message send?
– It depends, and it may change

**Example**

```
class rectangle extends shape {   ?             ?
    int length() { ... }
    int width() { ... }
    int area() { return (length() * width()); }
}

class square extends rectangle {
    int size;
    int length() { return(size); }
    int width() { return(size); }
}
```

What happens with the following?

```
rect.area();
sq.area();
```



## Cost of Dynamic Binding

**Direct cost**

– Overhead of performing dynamic method invocation

**Indirect cost**

– Inhibits static analysis of the code

**Example**

Want to inline and assign to registers, *etc.*

```
class rectangle:shape {
      int length() { ... }
      int width() { ... }
      int area() { return (length() * width()); }
}
```

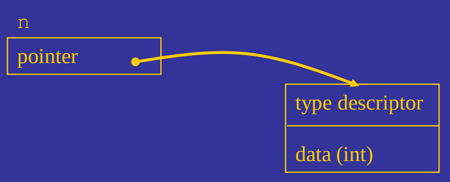
## Dynamism: Data

**Object instance types are not statically apparent**

- Need to be able to manipulate all objects uniformly
- Boxing: wrap all data and reference it with a pointer

**Example**

```
Integer n = new Integer(33);
```






## Cost of Dynamism: Data

**Direct cost**

- Overhead of actually extracting data
- *e.g.*, 2 loads versus 0 (if data already in a register)

**Indirect cost**

- More difficult to statically reason about data

## Style

**Sometimes programmers write C-style code in OO languages**
- Easy: just "optimize" it away

**Sometimes programmers actually exploit dynamism**
- Hard: it can't just be "optimized away"

**Programmers create many small objects**
- Thwarts local analysis
- Exacerbates dynamism problem
- Huge problem for pure OO languages

**Programmers create many small methods**
- Methods to encapsulate data
- *e.g.* Methods to get and set member fields



## Modern High-level Features

**Closures and non-LIFO activation records**
- Leads to much heap allocation of data

**Example**

```
foo (Integer i) {
    Integer n;
    ...
    return (&{n+i});

}
```

## A Concrete Example: Java

**High-level and modern**

- Object-oriented (not pure, but more pure than C++)
  - Granularity of objects and methods can be large or small
- Mobile (standard bytecode IR)
- Multithreaded (great for structuring distributed and UI programs)
- Garbage collected
- Dynamic class loading
- Reasonable exception system
- Rich standard libraries



## Why is Java Slow?

**Bytecode interpretation?**

- Not a good answer

## Approaches to Implementing Java

**Interpretation**

- Extremely portable
  - Simple stack machine
- Performance suffers
  - Interpretation overhead
  - Stack machine (no registers)

**Direct compilation**

- Compile the source or bytecodes to native code
- Sacrifices portability
- Can have very good performance



## Approaches to Implementing Java (cont)

**JIT compilation**

- Still supports mobile code (with more effort)
- Can have very good performance
  - Compilation time is critical
- Compiler can exploit dynamic information

**JIT/Dynamic compilation**

- Compiler gets several chances on the same code
- Compiler can exploit changes in dynamic information
- These systems are now quite sophisticated and effective

## Approaches to Implementing Java (cont)

**Custom processor**

- Direct hardware support of Java bytecodes
- This has proven to be an impractical approach
  - See "Retrospective on High-Level Language Computer Architecture" by Ditzel and Patterson (ISCA 1980)
- But maybe some hardware support (*e.g.*, for GC) is a good idea?

**Hybrids**

- JIT and Interpretation
- Direct compilation and interpretation

**Same-context translation**

- Source-to-source or bytecode-to-bytecode



## Why is Java Slow?

**Impediments to performance**

- Dynamic class loading thwarts optimization
  - Even the class hierarchy is dynamic
- Flexible array semantics
- Run-time checks (null pointers, array bounds, types)
- Precise exception semantics thwart optimization
- Multithreading introduces synchronization overhead
- Lots of memory references (poor cache performance)

. . . and all the usual OO challenges

## Analysis with a Dynamic Class Hierarchy

**Approaches**

- Ignore it (*i.e.*, disable dynamic class loading)
- Exploit final classes & methods
- Conservative optimization (*e.g.*, guarded devirtualization)
- Track validity of current code fragments and rebuild as necessary
  - *e.g.*, Resolution dependence graph
  - Necessitates JIT/dynamic compilation



## Scientific Programming and Java

**Consider matrix multiplication**

```
for (i=0; i<m; i++)
    for (j=0; j<p; j++)
        for (k=0; k<n; k++)
            C[i][j] += A[i][k] * B[k][j];
```

**Why is this Java code slow?**

- 6 null pointer checks (with just 2 floating point operations!)
- 6 index checks

**Can we optimize this code?**

- Precise exception model
  - Exception semantics inhibit removal or reordering
- No multidimensional arrays
  - Rows may alias

## More on Matrix Multiplication

**Why can't we just do this. . . ?**

```
if (m <= C.size(0) && p <= C.size(1) &&
    m <= A.size(0) && n <= A.size(1) &&
    n <= B.size(0) && p <= B.size(1)) {
    for (i=0; i<m; i++)
        for (j=0; j<p; j++)
            for (k=0; k<n; k++)
                C[i][j] += A[i][k] * B[k][j];
} else {
    raise exception
}
```

**No out-of-bounds checks, right?**



## Exceptions in Java

**Exceptions in Java are precise**

- The effects of all statements and expressions before a thrown exception must appear to have taken place, and
- The effects of all statements or expressions after a thrown exception must appear not to have taken place

**Implications**

- Must be very careful or clever when
  - Eliminating checks or
  - Reordering statements

## **Safe Regions** [Moreira *et al.* TOPLAS 2000]

**Idea**

- Create two versions of a block of code
- One is guaranteed not to except and is optimized accordingly
- The other is used when the code might except

```
if (m <= C.size(0) && p <= C.size(1) &&
     m <= A.size(0) && n <= A.size(1) &&
    n <= B.size(0) && p <= B.size(1)) {
    for (i=0; i<m; i++)                    // safe region
        for (j=0; j<p; j++)
            for (k=0; k<n; k++)
                C[i][j] += A[i][k] * B[k][j];
} else {
    for (i=0; i<m; i++)                    // unsafe region
        for (j=0; j<p; j++)
            for (k=0; k<n; k++)
                C[i][j] += A[i][k] * B[k][j];
}
```



## **Java Arrays and Loop Transformations**

**Java arrays**

- No multidimensional arrays
  - Instead use arrays of arrays (can be ragged)
  - Requires one memory reference for each array dimension
- Rows may alias with one another

**Arrays are common in scientific applications**

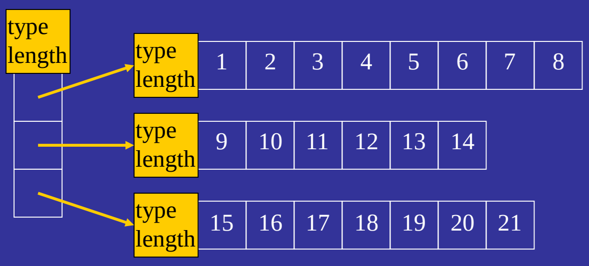
- Their use requires optimization for good performance
- Large body of work on loop transformations makes assumptions
  - Arrays stored in contiguous memory
  - No aliasing among array elements
  - (Arrays are not ragged)

## Comparing Arrays

**A 2D array in C**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |

**An array of arrays in Java**






## Java Arrays

**Elements within an array can alias with one another**

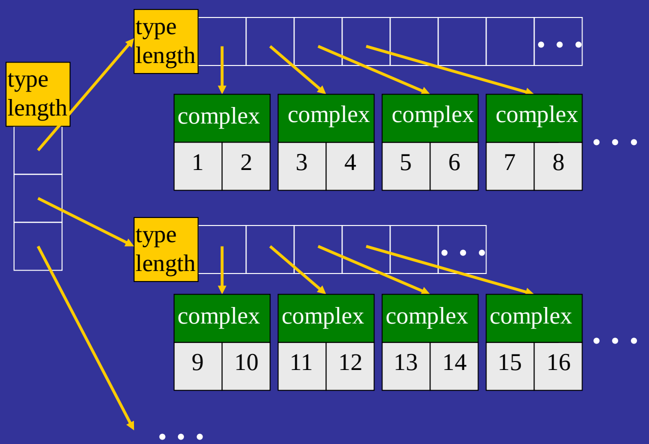

A[1][i] aliases to A[2][i]

**Implications?**

– Complicates dependence testing

## Java Arrays (cont)

**An array of arrays of complex numbers**




What are the implications of this structure?



## Semantic Expansion [Artigas *et al.* LCPC ’99]

**Idea**

– Introduce a new final array class with simpler semantics

– Treat the new class as a primitive in the compiler

```
doubleArray2D C = new doubleArray2D(m,p);
doubleArray2D A = new doubleArray2D(m,n);
doubleArray2D B = new doubleArray2D(n,p);

for (i=0; i<m; i++)
   for (j=0; j<p; j++)
      for (k=0; k<n; k++)
         C.set(i,j,C.get(i,j)+A.get(i,k)*B.get(k,j));
```

Look at this ugly syntax

## Semantic Expansion (cont)

**Pros**

- Yields good performance
- Doesn't officially change the language
- Can be used for other pseudo primitive classes (*e.g.*, Complex)

**Cons**

- Inelegant (ugly syntax)
- Not general
- Does in fact change the language
- Loses syntactic benefits of true primitives
- At odds with the spirit of the language
- Can't extend these special classes

**Are there more elegant and general solutions?**



## Concepts

**Dynamism**

- Direct costs
- Indirect costs

**Exception semantics**

**Array semantics**

**Object overhead**