Lecture 21

CIS 341: COMPILERS

Announcements / Plan

- HW5: OAT – typechecking, structs, function pointers
  - Due: Thursday, April 13

- HW6: LLVM Optimization: analysis and register allocation
  - Due: Wednesday, April 26

- FINAL EXAM: Thursday, May 4th noon – 2:00p.m.

MULTIPLE INHERITANCE

Multiple Inheritance

- C++: a class may declare more than one superclass.
- Semantic problem: Ambiguity

```
class A { int m(); }
class B { int m(); }
class C extends A,B {…}     // which m?
```

  - Same problem can happen with fields.
  - In C++, fields and methods can be duplicated when such ambiguity arises (though explicit sharing can be declared too)

- Java: a class may implement more than one interface.
  - No semantic ambiguity: if two interfaces contain the same method declaration, then the class will implement a single method

```
interface A { int m(); }
interface B { int m(); }
class C implements A,B {int m() {…}}     // only one m
```

Dispatch Vector Layout Strategy Breaks

```
interface Shape {                                   D.V.Index
  void setCorner(int w, Point p);                        0
}

interface Color {
  float get(int rgb);                                    0
  void set(int rgb, float value);                        1
}

class Blob implements Shape, Color {
  void setCorner(int w, Point p) {…}                     0?
  float get(int rgb) {…}                                 0?
  void set(int rgb, float value) {…}                     1?
}
```

General Approaches

- Can't directly identify methods by position anymore.

- Option 1: Use a level of indirection:
  - Map method identifiers to code pointers (e.g. index by method name)
  - Use a hash table
  - May need to do search up the class hierarchy

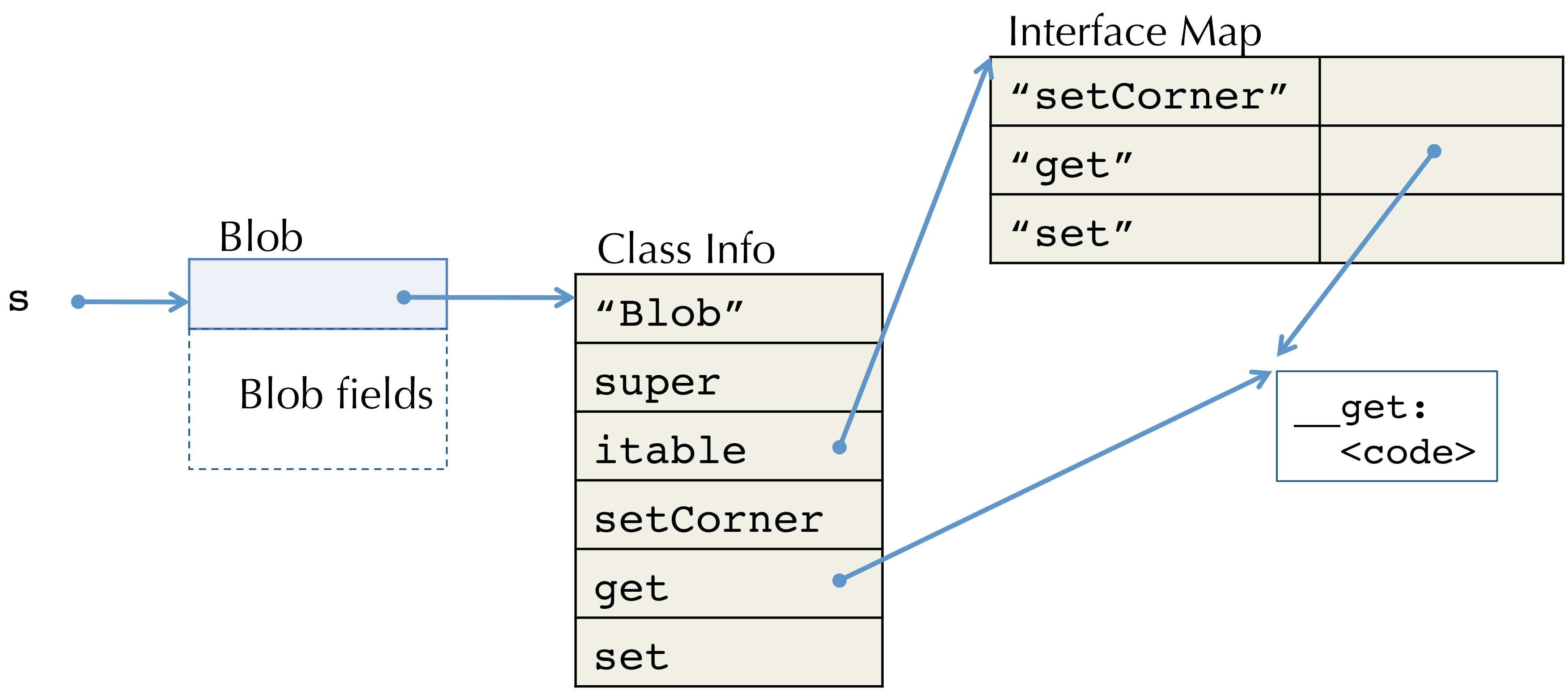
- Option 2: Give up separate compilation
  - Use "sparse" dispatch vectors, or binary decision trees
  - Must know then entire class hierarchy

- Option 3: Allow multiple D.V. tables (C++)
  - Choose which D.V. to use based on static type
  - Casting from/to a class may require run-time operations

- Note: many variations on these themes
  - Different Java compilers pick different approaches to options1 and 2…

Option 1: Search + Inline Cache

- For each class & interface keep a table mapping method names to method code
  - Recursively walk up the hierarchy looking for the method name
- Note: Identifiers are in quotes are not strings; in practice they are some kind of unique identifier.



Inline Cache Code

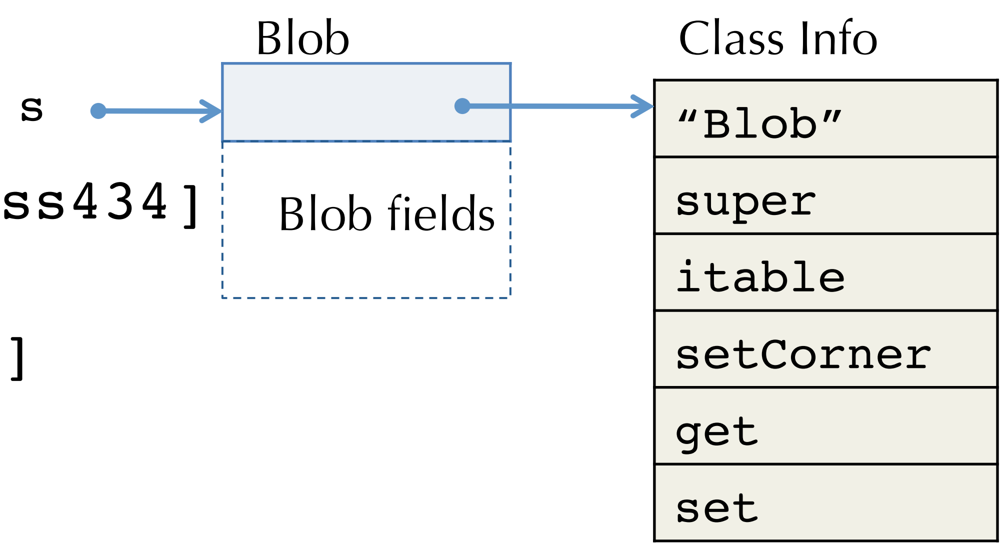
- Optimization: At call site, store class and code pointer in a cache
  - On method call, check whether class matches cached value
- Compiling: `Shape s = new Blob(); s.get();`
  Call site 434

Table in data seg.

```
cacheClass434:
  "Blob"
cacheCode434:
  <ptr>
```

- Compiler knows that s is a Shape
  - Suppose `%rax` holds object pointer
- Cached interface dispatch:

```
// set up parameters
   movq [%rax], tmp
   cmpq tmp, [cacheClass434]
   Jnz __miss434
   callq [cacheCode434]
__miss434:
  // do the slow search
```



Option 1 variant 2: Hash Table

- Idea: don't try to give all methods unique indices
  - Resolve conflicts by checking that the entry is correct at dispatch
- Use hashing to generate indices
  - Range of the hash values should be relatively small
  - Hash indices can be pre computed, but passed as an extra parameter

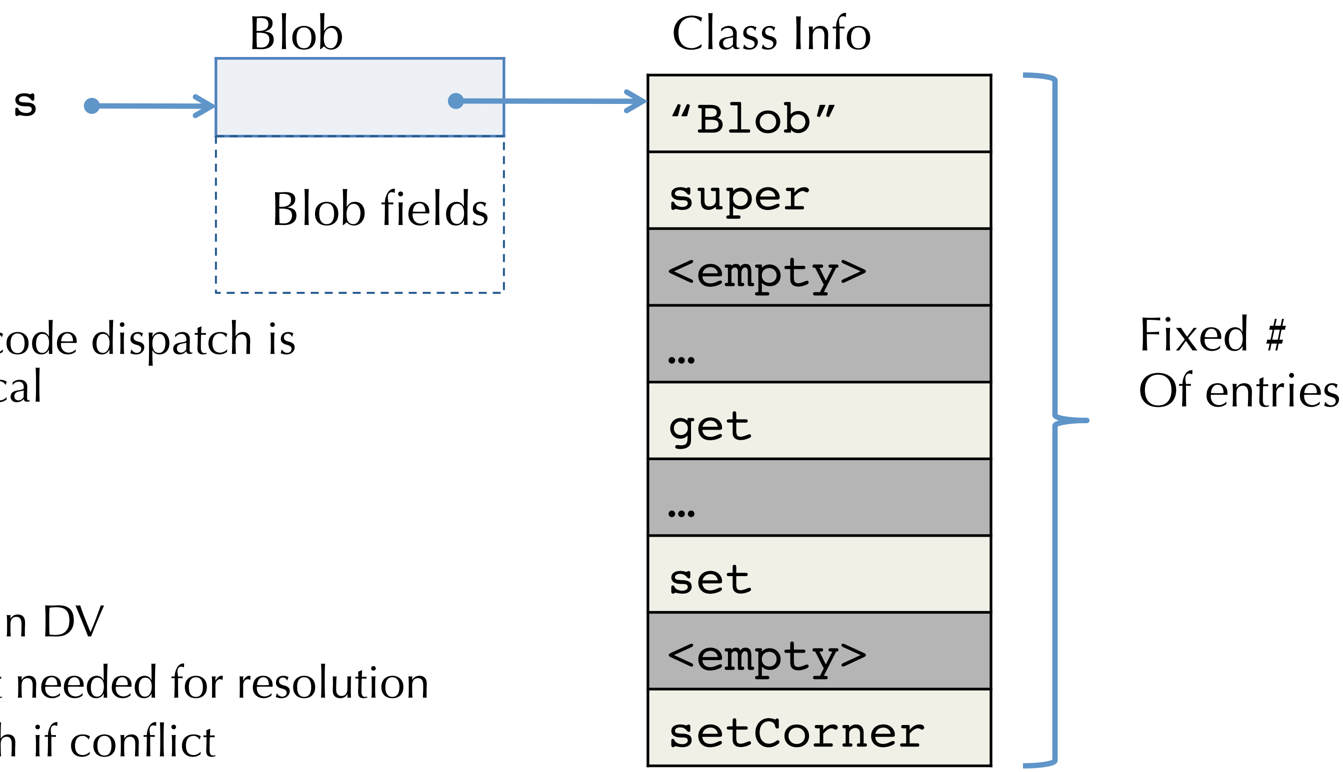
```
interface Shape {                          D.V.Index
  void setCorner(int w, Point p);          hash("setCorner") = 11
}

interface Color {
  float get(int rgb);                      hash("get") = 4
  void set(int rgb, float value);          hash("set") = 7
}

class Blob implements Shape, Color {
  void setCorner(int w, Point p) {…}             11
  float get(int rgb) {…}                         4
  void set(int rgb, float value) {…}             7
}
```

Dispatch with Hash Tables

- What if there is a conflict?
  - Entries containing several methods point to code that resolves conflict (e.g. by searching through a table based on class name)



- Advantage:
  - Simple, basic code dispatch is (almost) identical
  - Reasonably efficient
- Disadvantage:
  - Wasted space in DV
  - Extra argument needed for resolution
  - Slower dispatch if conflict

Option 2 variant 1: Sparse D.V. Tables

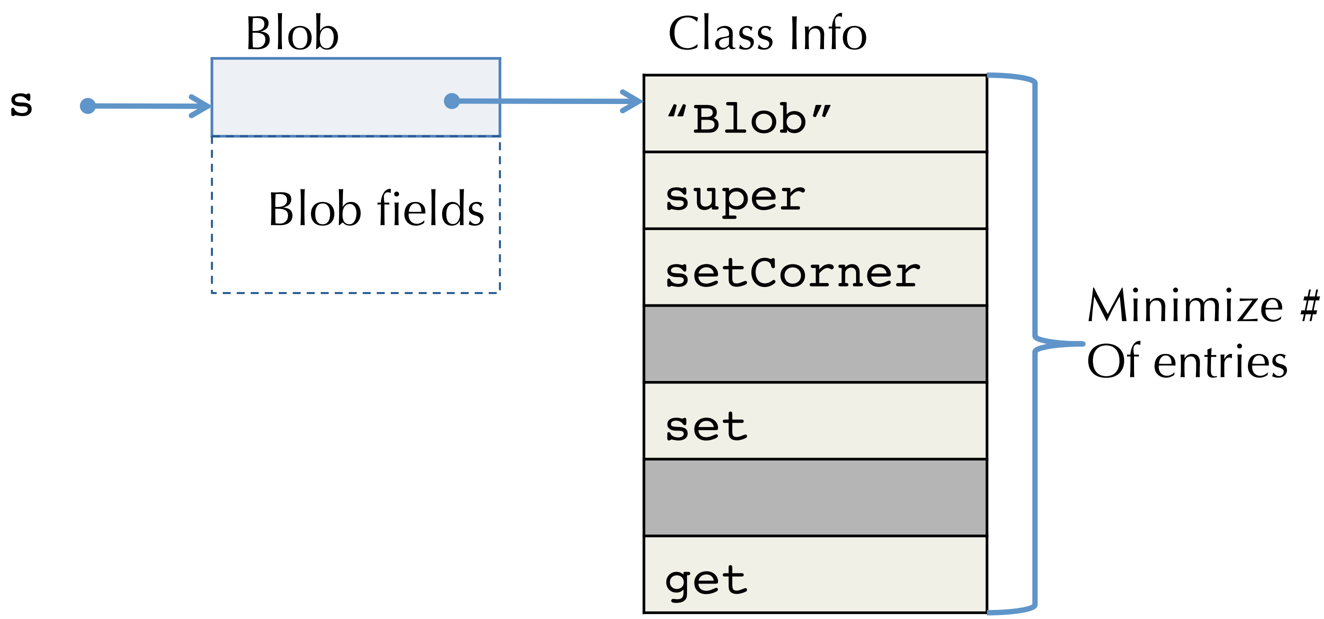
- Give up on separate compilation…
- Now we have access to the whole class hierarchy.

- So: ensure that no two methods in the same class are allocated the same D.V. offset.
  - Allow holes in the D.V. just like the hash table solution
  - Unlike hash table, there is never a conflict!

- Compiler needs to construct the method indices
  - Graph coloring techniques can be used to construct the D.V. layouts in a reasonably efficient way (to minimize size)
  - Finding an optimal solution is NP complete!

Example Object Layout

- Advantage: Identical dispatch and performance to single-inheritance case
- Disadvantage: Must know entire class hierarchy

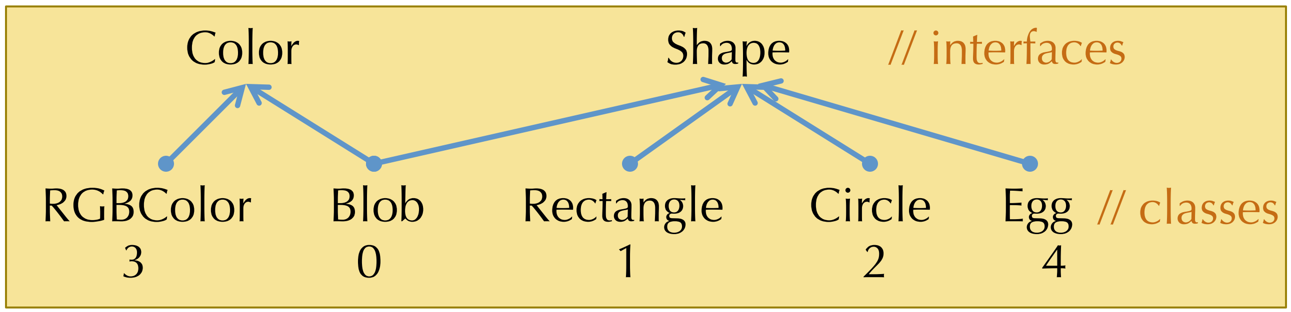


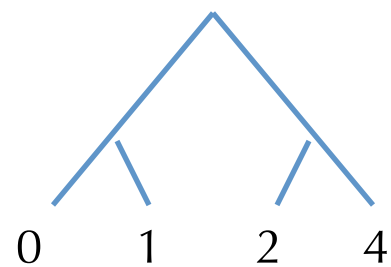
Option 2 variant 2: Binary Search Trees

- Idea: Use conditional branches not indirect jumps
- Each object has a class index (unique per class) as first word
  - Instead of D.V. pointer (no need for one!)
- Method invocation uses range tests to select among *n* possible classes in *lg n* time
  - Direct branches to code at the leaves.

```
Shape x;
x.SetCorner(…);
```

```
  Mov eax, ⟦x⟧
  Mov ebx, [eax]
  Cmp ebx, 1
  Jle  __L1
  Cmp ebx, 2
  Je __CircleSetCorner
  Jmp __EggSetCorner
__L1:
  Cmp ebx, 0
  Je __BlobSetCorner
  Jmp __RectangleSetCorner
```





Decision tree

Search Tree Tradeoffs

- Binary decision trees work well if the distribution of classes that may appear at a call site is skewed.
  - Branch prediction hardware eliminates the branch stall of ~10 cycles (on X86)
- Can use profiling to find the common paths for each call site individually
  - Put the common case at the top of the decision tree (so less search)
  - 90%/10% rule of thumb: 90% of the invocations at a call site go to the same class
- Drawbacks:
  - Like sparse D.V.'s you need the whole class hierarchy to know how many leaves you need in the search tree.
  - Indirect jumps can have better performance if there are >2 classes (at most one mispredict)

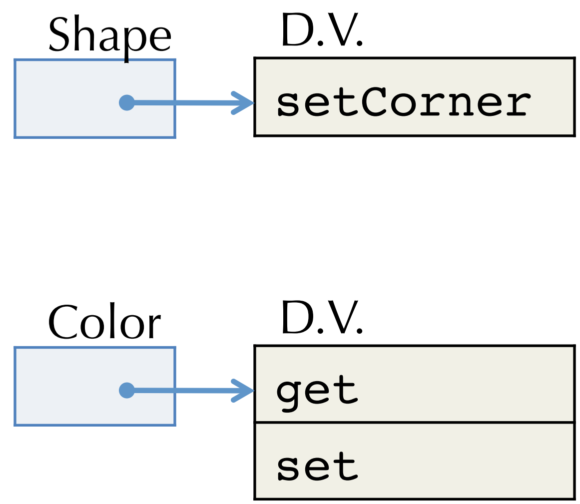
Option 3: Multiple Dispatch Vectors

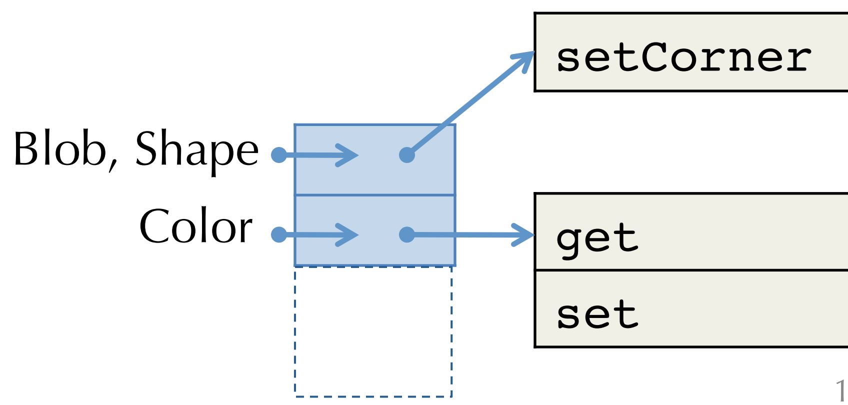
- Duplicate the D.V. pointers in the object representation.
- Static type of the object determines which D.V. is used.

```
interface Shape {                       D.V.Index
  void setCorner(int w, Point p);               0
}

interface Color {
  float get(int rgb);                           0
  void set(int rgb, float value);               1
}

class Blob implements Shape, Color {
  void setCorner(int w, Point p) {…}
  float get(int rgb) {…}
  void set(int rgb, float value) {…}
}
```





Multiple Dispatch Vectors

- A reference to an object might have multiple "entry points"
  - Each entry point corresponds to a dispatch vector
  - Which one is used depends on the statically known type of the program.

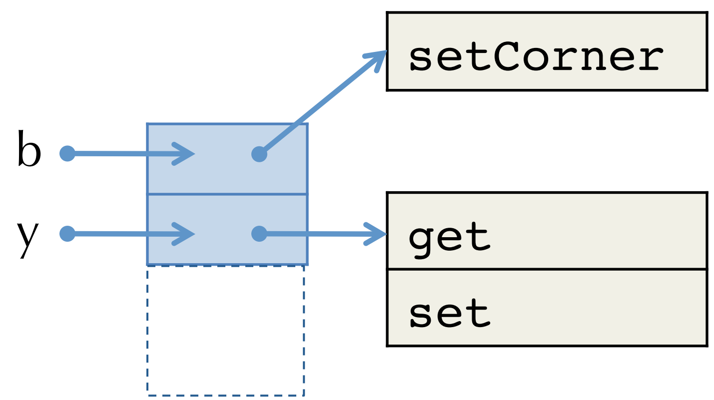
```
Blob b = new Blob();
Color y = b;      // implicit cast!
```

- Compile

```
Color y = b;
```

As

```
Movq ⟦b⟧ + 8 , y
```



Multiple D.V. Summary

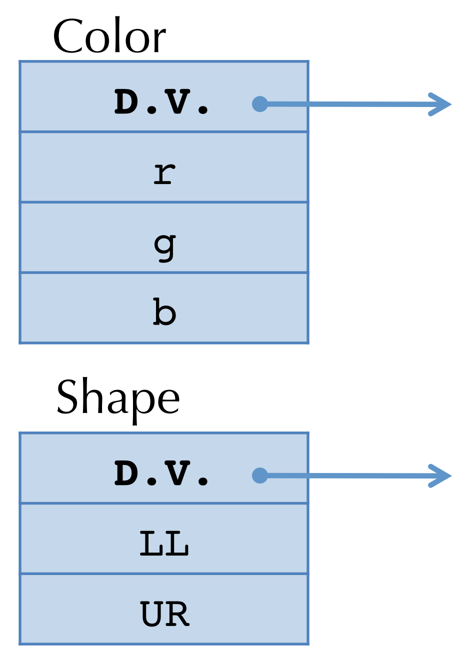
- Benefit: Efficient dispatch, same cost as for multiple inheritance
- Drawbacks:
  - Cast has a runtime cost
  - More complicated programming model… hard to understand/debug?

- What about multiple inheritance and fields?

Multiple Inheritance: Fields

- Multiple supertypes (Java): methods conflict (as we saw)
- Multiple inheritance (C++): fields can also conflict
- Location of the object's fields can no longer be a constant offset from the start of the object.

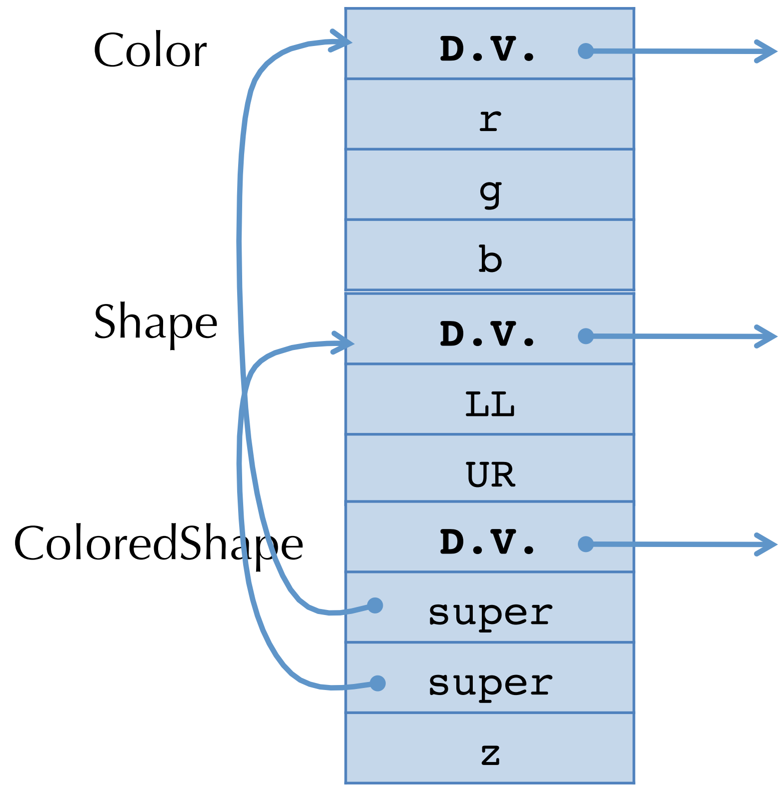
```
class Color {
  float r, g, b; /* offsets: 4,8,12 */
}
class Shape {
  Point LL, UR; /* offsets: 4, 8 */
}
class ColoredShape extends
Color, Shape {
  int z;
}
```



ColoredShape ??

C++ approach:

- Add pointers to the superclass fields
  - Need to have multiple dispatch vectors anyway (to deal with methods)
- Extra indirection needed to access superclass fields
- Used even if there is a single superclass
  - Uniformity

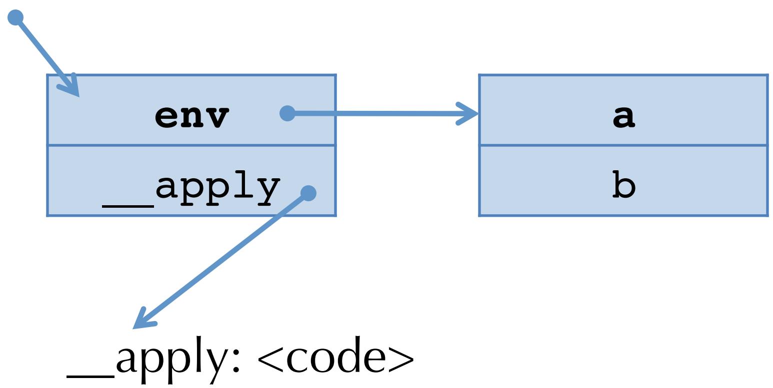


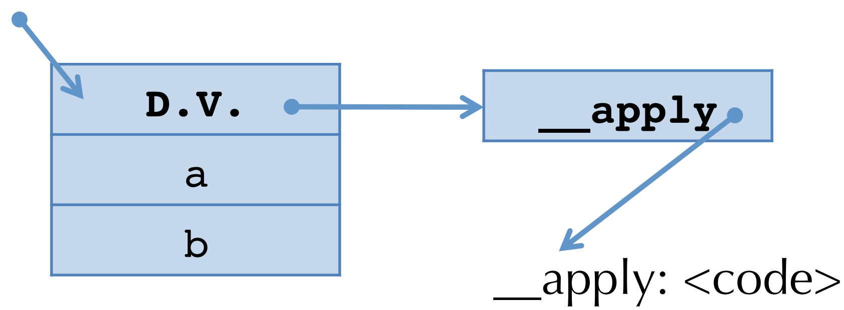
Observe: Closure ≈ Single-method Object

- Free variables ≈ Fields
- Environment pointer ≈ "this" parameter
- Closure for function: ≈ Instance of this class:

```
fun (x,y) ->
  x + y + a + b
```

```
class C {
  int a, b;
  int apply(x,y) {
    x + y + a + b
  }
}
```





A high-level tour of a variety of optimizations.

OPTIMIZATIONS

Optimizations

- The code generated by our OAT compiler so far is pretty inefficient.
  – Lots of redundant moves.
  – Lots of unnecessary arithmetic instructions.

- Consider this OAT program:

```
int foo(int w) {
  var x = 3 + 5;
  var y = x * w;
  var z = y - 0;
  return z * 4;
}
```

- See opt.c, opt-oat.oat

Unoptimized vs. Optimized Output

```
.globl _foo
_foo:
        pushl %ebp
        movl %esp, %ebp
        subl $64, %esp
__fresh2:
        leal -64(%ebp), %eax
        movl %eax, -48(%ebp)
        movl 8(%ebp), %eax
        movl %eax, %ecx
        movl -48(%ebp), %eax
        movl %ecx, (%eax)
        movl $3, %eax
        movl %eax, -44(%ebp)
        movl $5, %eax
        movl %eax, %ecx
        addl %ecx, -44(%ebp)
        leal -60(%ebp), %eax
        movl %eax, -40(%ebp)
        movl -44(%ebp), %eax
        movl %eax, %ecx
        movl -40(%ebp), %eax
        movl %ecx, (%eax)
        movl -40(%ebp), %eax
        movl (%eax), %ecx
        movl %ecx, -36(%ebp)
        movl -48(%ebp), %eax
        movl (%eax), %ecx
        movl %ecx, -32(%ebp)
        movl -36(%ebp), %eax
        movl %eax, -28(%ebp)
        movl -32(%ebp), %eax
        movl %eax, %ecx
        movl -28(%ebp), %eax
        imull %ecx, %eax
        movl %eax, -28(%ebp)
        leal -56(%ebp), %eax
        movl %eax, -24(%ebp)
        movl -28(%ebp), %eax
        movl %eax, %ecx
        movl -24(%ebp), %eax
        movl %ecx, (%eax)
        movl -24(%ebp), %eax
        movl (%eax), %ecx
        movl %ecx, -20(%ebp)
        movl -20(%ebp), %eax
        movl %eax, -16(%ebp)
        movl $0, %eax
        movl %eax, %ecx
        subl %ecx, -16(%ebp)
        leal -52(%ebp), %eax
        movl %eax, -12(%ebp)
        movl -16(%ebp), %eax
        movl %eax, %ecx
        movl -12(%ebp), %eax
        movl %ecx, (%eax)
        movl -12(%ebp), %eax
        movl (%eax), %ecx
        movl %ecx, -8(%ebp)
        movl -8(%ebp), %eax
        movl %eax, -4(%ebp)
        movl $4, %eax
        movl %eax, %ecx
        movl -4(%ebp), %eax
        imull %ecx, %eax
        movl %eax, -4(%ebp)
        movl -4(%ebp), %eax
        movl %ebp, %esp
        popl %ebp
        ret
```

?

Hand optimized code:

```
_foo:
    shlq    $5, %rdi
    movq    %rdi, %rax
    ret
```

- Function foo may be inlined by the compiler, so it can be implemented by just one instruction!

Why do we need optimizations?

- To help programmers…
  - They write modular, clean, high-level programs
  - Compiler generates efficient, high-performance assembly

- Programmers don't write optimal code
- High-level languages make avoiding redundant computation inconvenient or impossible
  - e.g. `A[i][j] = A[i][j] + 1`
- Architectural independence
  - Optimal code depends on features not expressed to the programmer
  - Modern architectures *assume* optimization

- Different kinds of optimizations:
  - Time: improve execution speed
  - Space: reduce amount of memory needed
  - Power: lower power consumption (e.g. to extend battery life)

Some caveats

- Optimization are code transformations:
  - They can be applied at any stage of the compiler
  - They must be *safe* – they shouldn't change the meaning of the program.
- In general, optimizations require some program analysis:
  - To determine if the transformation really is safe
  - To determine whether the transformation is cost effective
- This course: most common and valuable performance optimizations
  - See Muchnick (optional text) for ~10 chapters about optimization

When to apply optimization

High level

- AST
- IR

Mid level

- Canonical IR

Low level

- Abstract assembly
- Assembly

* Inlining
* Function specialization
* Constant folding
* Constant propagation
* Value numbering
* Dead code elimination
* Loop-invariant code motion
* Common sub-expression elimination
* Strength Reduction
* Constant folding & propagation
* Branch prediction / optimization
* Register allocation
* Loop unrolling
* Cache optimization

Where to Optimize?

- Usual goal: improve time performance
- Problem: many optimizations trade space for time
- Example: *Loop unrolling*
  - Idea: rewrite a loop like:
    ```
    for(int i=0; i<100; i=i+1) {
      s = s + a[i];
    }
    ```
  - Into a loop like:
    ```
    for(int i=0; i<99; i=i+2){
      s = s + a[i];
      s = s + a[i+1];
    }
    ```
- Tradeoffs:
  - Increasing code space slows down whole program a tiny bit (extra instructions to manage) but speeds up the loop a lot
  - For frequently executed code with long loops: generally a win
  - Interacts with instruction cache and branch prediction hardware
- Complex optimizations may never pay off!

Writing Fast Programs In Practice

- Pick the right algorithms and data structures.
  - These have a much bigger impact on performance that compiler optimizations.
  - Reduce # of operations
  - Reduce memory accesses
  - Minimize indirection – it breaks working-set coherence
- *Then* turn on compiler optimizations
- Profile to determine program hot spots
- Evaluate whether the algorithm/data structure design works
- …if so: "tweak" the source code until the optimizer does "the right thing" to the machine code

Safety

- Whether an optimization is *safe* depends on the programming language semantics.
  - Languages that provide weaker guarantees to the programmer permit more optimizations, but have more ambiguity in their behavior.
  - e.g. In Java tail-call optimization (that turns recursive function calls into loops) is not valid.
  - e.g. In C, loading from initialized memory is undefined, so the compiler can do anything.
- Example: *loop-invariant code motion*
  - Idea: hoist invariant code out of a loop

```
while (b) {
  z = y/x;
  …             // y, x not updated
}
```

⇒

```
z = y/x;
while (b) {
  …             // y, x not updated
}
```

- Is this more efficient?
- Is this safe?

Constant Folding

- Idea: If operands are known at compile type, perform the operation statically.

```
int x = (2 + 3) * y   ➔  int x = 5 * y
b  & false            ➔  false
```

- Performed at every stage of optimization…
- Why?
  - Constant expressions can be created by translation or earlier optimizations
- Example: `A[2]` might be compiled to:
  `MEM[MEM[A] + 2 * 4]` ➔ `MEM[MEM[A] + 8]`

Constant Folding Conditionals

```
if (true) S              → S
if (false) S             → ;
if (true) S else S'      → S
if (false) S else S'     → S'
while (false) S          → ;

if (2 > 3) S             → ;
```

Algebraic Simplification

- More general form of constant folding
  - Take advantage of mathematically sound simplification rules
- Identities:
  - `a * 1 → a`   `a * 0 → 0`
  - `a + 0 → a`   `a – 0 → a`
  - `b | false → b`   `b & true → b`
- Reassociation & commutativity:
  - `(a + 1) + 2 → a + (1 + 2) → a + 3`
  - `(2 + a) + 4 → (a + 2) + 4 → a + (2 + 4) → a + 6`
- Strength reduction: (replace expensive op with cheaper op)
  - `a * 4 → a << 2`
  - `a * 7 → (a << 3) – a`
  - `a / 32767 → (a >> 15) + (a >> 30)`
- Note 1: must be careful with floating point (due to rounding) and integer arithmetic (due to overflow/underflow)
- Note 2: iteration of these optimizations is useful… how much?

Constant Propagation

- If the value is known to be a constant, replace the use of the variable by the constant
- Value of the variable must be propagated forward from the point of assignment
  - This is a substitution operation

- Example:

```
int x = 5;
int y = x * 2; ➔ int y = 5 * 2; ➔ int y = 10;  ➔
int z = a[y];     int z = a[y];     int z = a[y];  int z = a[10];
```

- To be most effective, constant propagation should be interleaved with constant folding

Copy Propagation

- If one variable is assigned to another, replace uses of the assigned variable with the copied variable.
- Need to know where copies of the variable propagate.
- Interacts with the scoping rules of the language.

- Example:

```
x = y;
if (x > 1) {
  x = x * f(x – 1);
}
```

➔

```
~~x = y;~~
if (y > 1) {
  x = y * f(y – 1);
}
```

- Can make the first assignment to x *dead* code (that can be eliminated).

Dead Code Elimination

- If a side-effect free statement can never be observed, it is safe to eliminate the statement.

```
x  = y * y  // x is dead!
…           // x never used   ➔      …
x = z * z                            x = z * z
```

- A variable is *dead* if it is never used after it is defined.
  - Computing such *definition* and *use* information is an important component of compiler

- Dead variables can be created by other optimizations…

Unreachable/Dead Code

- Basic blocks not reachable by any trace leading from the starting basic block are *unreachable* and can be deleted.
  - Performed at the IR or assembly level
  - Improves cache, TLB performance

- Dead code: similar to unreachable blocks.
  - A value might be computed but never subsequently used.
- Code for computing the value can be dropped
- But only if it's *pure*, i.e. it has *no externally visible side effects*
  - Externally visible effects: raising an exception, modifying a global variable, going into an infinite loop, printing to standard output, sending a network packet, launching a rocket
  - Note: Pure functional languages (e.g. Haskell) make reasoning about the safety of optimizations (and code transformations in general) easier!

Inlining

- Replace a call to a function with the body of the function itself with arguments rewritten to be local variables:
- Example in OAT code:

```
int g(int x) { return x + pow(x); }
int pow(int a) { int b = 1; int n = 0;
   while (n < a) {b = 2 * b}; return b; }
```

➔

```
int g(int x) { int a = x; int b = 1; int n = 0;
    while (n < a) {b = 2 * b}; tmp = b; return x + tmp;
}
```

- May need to rename variable names to avoid *name capture*
  - Example of what can go wrong?
- Best done at the AST or relatively high-level IR.
- When is it profitable?
  - Eliminates the stack manipulation, jump, etc.
  - Can increase code size.
  - Enables further optimizations

Code Specialization

- Idea: create specialized versions of a function that is called from different places with different arguments.
- Example: specialize function `f` in:

```
class A implements I { int m() {…} }
class B implements I { int m() {…} }
int f(I x) { x.m(); }          // don't know which m
A a = new A(); f(a);           // know it's A.m
B b = new B(); f(b);           // know it's B.m
```

- `f_A` would have code specialized to dispatch to `A.m`
- `f_B` would have code specialized to dispatch to `B.m`
- You can also inline methods when the run-time type is known statically
  - Often just one class implements a method.

Common Subexpression Elimination

- In some sense it's the opposite of inlining: fold redundant computations together
- Example:

`a[i] = a[i] + 1` compiles to:

```
[a + i*4] = [a + i*4] + 1
```

Common subexpression elimination removes the redundant add and multiply:

```
t = a + i*4; [t] = [t] + 1
```

- For safety, you must be sure that the shared expression always has the same value in both places!

Unsafe Common Subexpression Elimination

- Example: consider this OAT function:

```
unit f(int[] a, int[] b, int[] c) {
  int j = …; int i = …; int k = …;
  b[j] = a[i] + 1; c[k] = a[i]; return;
}
```

- The following optimization that shares the expression `a[i]` is unsafe… why?

```
unit f(int[] a, int[] b, int[] c) {
  int j = …; int i = …; int k = …;
  t = a[i];
  b[j] = t + 1; c[k] = t; return;
}
```

LOOP OPTIMIZATIONS

Loop Optimizations

- Program hot spots often occur in loops.
  - Especially inner loops
  - Not always: consider operating systems code or compilers vs. a computer game or word processor

- Most program execution time occurs in loops.
  - The 90/10 rule of thumb holds here too. (90% of the execution time is spent in 10% of the code)

- Loop optimizations are very important, effective, and numerous
  - Also, concentrating effort to improve loop body code is usually a win

Loop Invariant Code Motion (revisited)

- Another form of redundancy elimination.
- If the result of a statement or expression does not change during the loop *and* it's pure, it can be hoisted outside the loop body.
- Often useful for array element addressing code
  - Invariant code not visible at the source level

```
for (i = 0; i < a.length; i++) {
    /* a not modified in the body */
}
```

```
t = a.length;
for (i =0; i < t; i++) {
  /* same body as above */
}
```

Hoisted loop-invariant expression

Strength Reduction (revisited)

- Strength reduction can work for loops too
- Idea: replace expensive operations (multiplies, divides) by cheap ones (adds and subtracts)
- For loops, create a *dependent induction variable*:

- Example:

```
for (int i = 0; i<n; i++) { a[i*3] = 1; }  // stride by 3
```

```
int j = 0;
for (int i = 0; i<n; i++) {
  a[j] = 1;
  j = j + 3;   // replace multiply by add
}
```

Loop Unrolling (revisited)

- Branches can be expensive, unroll loops to avoid them.

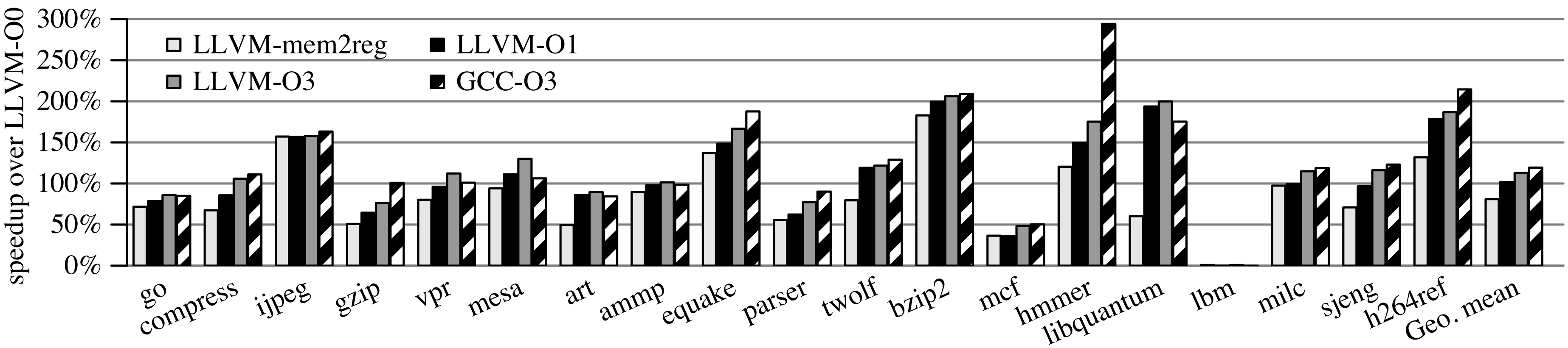
```
for (int i=0; i<n; i++) { S }
```

```
for (int i=0; i<n-3; i+=4) {S;S;S;S};
for (       ; i<n; i++) { S } // left over iterations
```

- With k unrollings, eliminates (k-1)/k conditional branches
  - So for the above program, it eliminates ¾ of the branches
- Space-time tradeoff:
  - Not a good idea for large S or small n
- Interacts with instruction caching, branch prediction

EFFECTIVENESS?

Optimization Effectiveness?



$$\%\text{speedup} = \left[\frac{\text{base time}}{\text{optimized time}} - 1\right] \times 100\%$$

Example:

base time = 2s

optimized time = 1s ⇒ 100% speedup

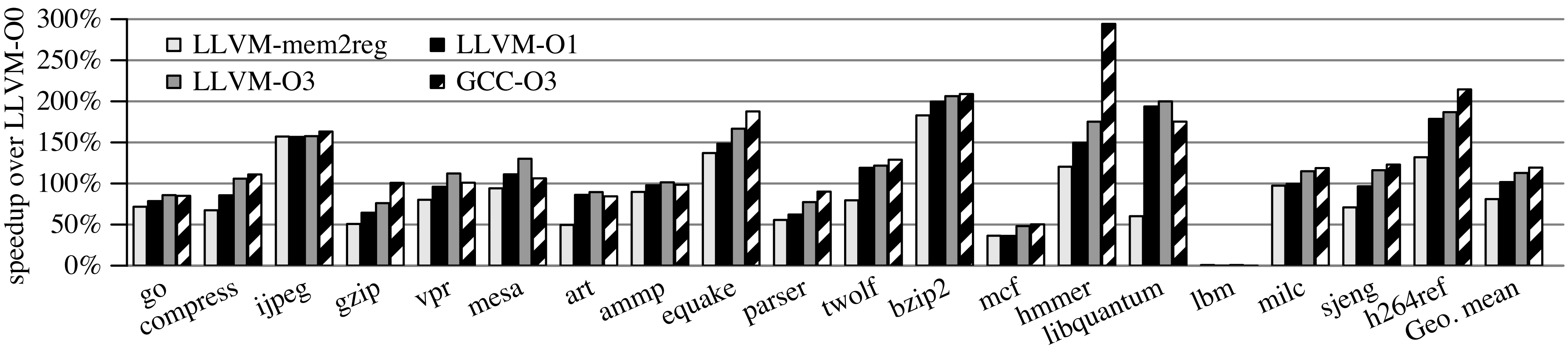
Example:

base time = 1.2s

optimized time = 0.87s ⇒ 38% speedup

Graph taken from:
Jianzhou Zhao, Santosh Nagarakatte, Milo M. K. Martin, and Steve Zdancewic.
Formal Verification of SSA-Based Optimizations for LLVM.
In Proc. 2013 ACM SIGPLAN Conference on Programming Languages Design and Implementation (PLDI), 2013

Optimization Effectiveness?



- mem2reg: promotes alloca'ed stack slots to temporaries to enable register allocation
- Analysis:
  - mem2reg alone (+ back-end optimizations like register allocation) yields ~78% speedup on average
  - -O1 yields ~100% speedup
    (so all the rest of the optimizations combined account for ~22%)
  - -O3 yields ~120% speedup
- Hypothetical program that takes 10 sec. (base time):
  - Mem2reg alone: expect ~5.6 sec
  - -O1: expect ~5 sec
  - -O3: expect ~4.5 sec