Announcements

- HW5: OAT v. 2.0
  - records, function pointers, type checking, array-bounds checks, etc.
  - Due: Wednesday, April 11th
MULTIPLE INHERITANCE
Multiple Inheritance

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

```cpp
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

```java
interface A { int m(); }
interface B { int m(); }
class C implements A,B {int m() {...}} // only one m
```
interface Shape {
    void setCorner(int w, Point p);
}

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

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 options 1 and 2…
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.

```java
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) {...}
}
```
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 Dispatch Vectors
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;
}
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
- Environment pointer
- Closure for function:
  fun (x,y) ->
  x + y + a + b

≈ Fields
≈ “this” parameter
≈ Instance of this class:
  class C {
    int a, b;
    int apply(x,y) {
      x + y + a + b
    }
  }

≈ Fields
≈ “this” parameter
≈ Instance of this class:
  class C {
    int a, b;
    int apply(x,y) {
      x + y + a + b
    }
  }

CIS 341: Compilers
A high-level tour of a variety of 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:

```plaintext
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

Hand optimized code:

```assembly
_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

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

\[
\text{int } x = (2 + 3) \times y \Rightarrow \text{int } x = 5 \times y
\]

\[
b \& \text{false} \Rightarrow \text{false}
\]

• Performed at every stage of optimization…
• Why?
  – Constant expressions can be created by translation or earlier optimizations

• Example: \( A[2] \) might be compiled to:

\[
\text{MEM}[\text{MEM}[A] + 2 \times 4] \Rightarrow \text{MEM}[\text{MEM}[A] + 8]
\]
Constant Folding Conditionals

if (true) S \implies S
if (false) S \implies ;
if (true) S \text{ else } S' \implies S
if (false) S \text{ else } S' \implies S'
while (false) S \implies ;
if (2 > 3) S \implies ;
Algebraic Simplification

• More general form of constant folding
  – Take advantage of mathematically sound simplification rules

• Identities:
  – \( a * 1 \rightarrow a \)
  – \( a * 0 \rightarrow 0 \)
  – \( a + 0 \rightarrow a \)
  – \( a - 0 \rightarrow a \)
  – \( b \land \text{false} \rightarrow b \)
  – \( b \land \text{true} \rightarrow b \)

• Reassociation & commutativity:
  – \( (a + 1) + 2 \rightarrow a + (1 + 2) \rightarrow a + 3 \)
  – \( (2 + a) + 4 \rightarrow (a + 2) + 4 \rightarrow a + (2 + 4) \rightarrow a + 6 \)

• Strength reduction: (replace expensive op with cheaper op)
  – \( a * 4 \rightarrow a << 2 \)
  – \( a * 7 \rightarrow (a << 3) - a \)
  – \( a / 32767 \rightarrow (a >> 15) + (a >> 30) \)

• 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:

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

```plaintext
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:
    ```c
    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; }
    }
    ```

→

    ```c
    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:

```java
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:

\[ a[i] = a[i] + 1 \quad \text{compiles to:} \]
\[ [a + i \times 4] = [a + i \times 4] + 1 \]

Common subexpression elimination removes the redundant add and multiply:
\[ t = a + i \times 4; \quad [t] = [t] + 1 \]

• 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:

```c
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?

```c
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

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

// Hoisted loop-invariant expression

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

```
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 \(3/4\) 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?

%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 allocated 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