Lecture 21

CIS 341: COMPILERS

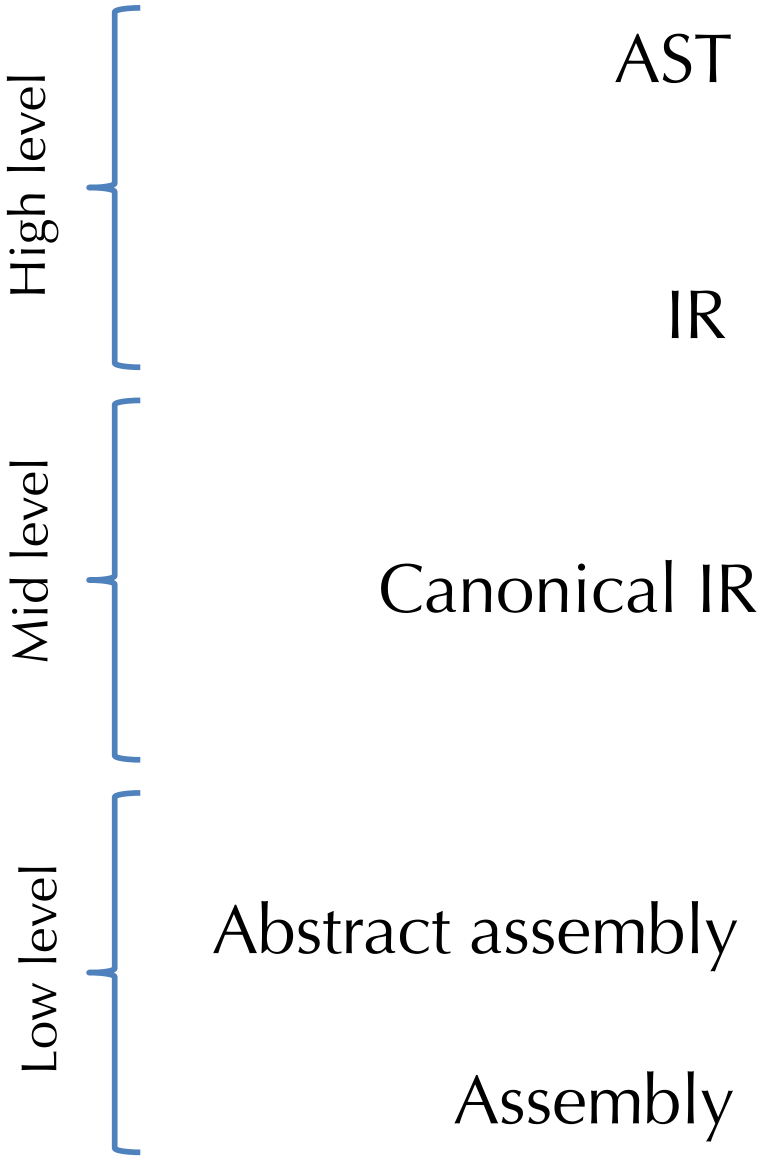
Announcements

- HW5: Oat v. 2.0
  - records, function pointers, type checking, array-bounds checks, etc.
  - typechecker & safety
  - Due: Wednesday, April 13th

Why optimize?

OPTIMIZATIONS, GENERALLY

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

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 C, loading from initialized memory is undefined, so the compiler can do anything if a program reads uninitalized data.
  - *e.g.*, In Java tail-call optimization (which turns recursive function calls into loops) is not valid because of "stack inspection".
- 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?

A high-level tour of a variety of optimizations.

BASIC OPTIMIZATIONS

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         ➔
  if (false) S       ➔ ;
```

Algebraic Simplification

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

- ***Mathematical 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?
- *Note 3:* must be sure that rewrites terminate:
  - commutativity apply like: `(x + y)` → `(y + x)` → `(x + y)` → `(y + x)` → …

Constant Propagation

- If a variable 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 z = a[y];
```

➔

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

➔

```
int y = 10;
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 program analysis

- 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: inline `pow` into `g`

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

➔

note: renaming

```
int g(int x) {
    int a = x;
    int b = 1; int x2 = 0;
    while (x2 < a) {b = 2 * b; x2 = x2 + 1};
    tmp = b;
    return x + tmp;
}
```

- May need to rename variables to avoid *capture*
  - See lecture about ***capture avoiding substitution*** for lambda calculus
- 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

- *fold redundant computations together*
  - in some sense, it's the opposite of inlining
- 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) {
  var j = …; var i = …; var k = …;
  b[j] = a[i] + 1;
  c[k] = a[i];
  return;
}
```

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

```
unit f(int[] a, int[] b, int[] c) {
  var j = …; var i = …; var 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.

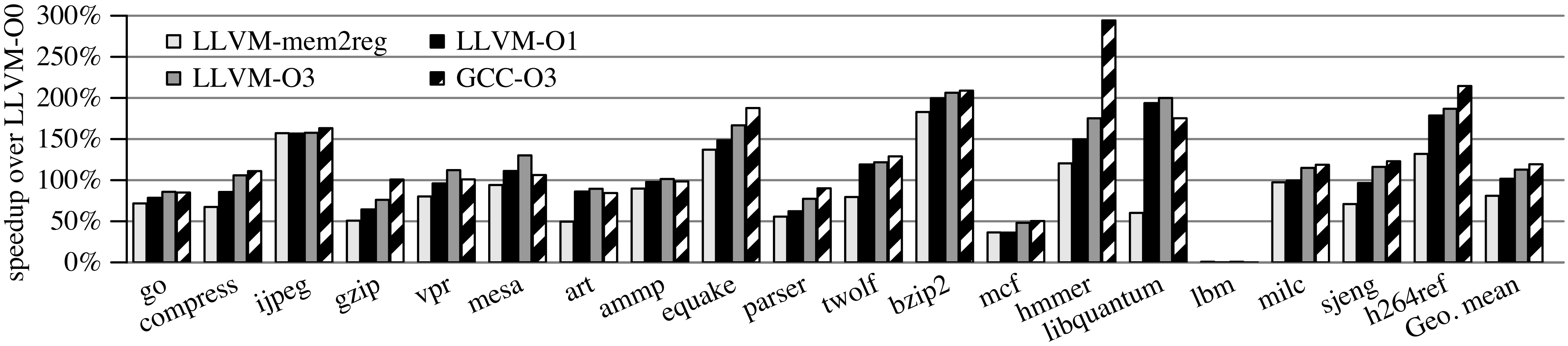
```
for (int i=0; i<n; i++) { S }
```

```
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

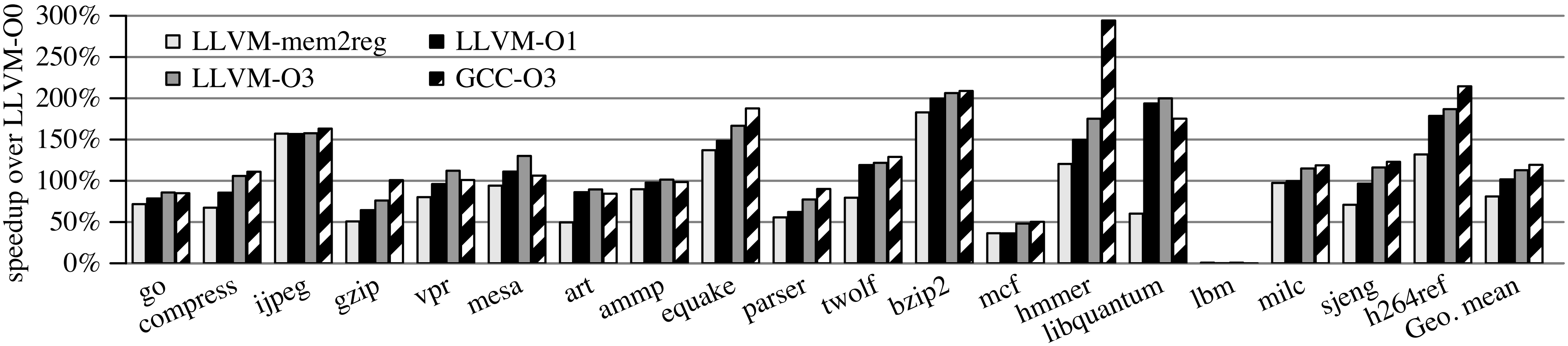
Example:

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

CODE ANALYSIS

Motivating Code Analyses

- There are lots of things that might influence the safety/applicability of an optimization
  - What algorithms and data structures can help?

- How do you know what is a loop?
- How do you know an expression is invariant?
- How do you know if an expression has no side effects?
- How do you keep track of where a variable is defined?
- How do you know where a variable is used?
- How do you know if two reference values may be aliases of one another?

Moving Towards Register Allocation

- The OAT compiler currently generates as *many* temporary variables as it needs
  - These are the `%uids` you should be very familiar with by now.

- Current compilation strategy:
  - Each %`uid` maps to a stack location.
  - This yields programs with many loads/stores to memory.
  - Very inefficient.

- Ideally, we'd like to map as many `%uid`'s as possible into registers.
  - Eliminate the use of the `alloca` instruction?
  - Only 16 max registers available on 64-bit X86
  - %rsp and %rbp are reserved and some have special semantics, so really only 10 or 12 available
  - This means that a register must hold more than one slot
- When is this safe?

Liveness

- Observation: `%uid1` and `%uid2` can be assigned to the same register if their values will not be needed at the same time.
  - What does it mean for an `%uid` to be "needed"?
  - Ans: its contents will be used as a source operand in a later instruction.
- Such a variable is called "*live*"
- Two variables can share the same register if they are *not* live at the same time.

Scope vs. Liveness

- We can already get some coarse liveness information from variable scoping.
- Consider the following OAT program:

```
int f(int x) {
  var a = 0;
  if (x > 0) {
      var b = x * x;
      a = b + b;
  }
  var c = a * x;
  return c;
}
```

- Note that due to OAT’s scoping rules, variables `b` and `c` can never be live at the same time.
  - `c`’s scope is disjoint from `b`’s scope
- So, we could assign `b` and `c` to the same alloca’ed slot and potentially to the same register.

But Scope is too Coarse

- Consider this program:

```
int f(int x) {
  int a = x + 2;
  int b = a * a;
  int c = b + x;
  return c;
}
```

x is live

a and x are live

b and x are live

c is live

- The scopes of a,b,c,x all overlap – they're all in scope at the end of the block.
- But, a, b, c are never live at the same time.
  - So they can share the same stack slot / register

Live Variable Analysis

- A variable v is *live* at a program point if v is defined before the program point and used after it.
- Liveness is defined in terms of where variables are *defined* and where variables are *used*

- Liveness analysis: Compute the live variables between each statement.
  - May be *conservative* (i.e. it may claim a variable is live when it isn't) so because that's a safe approximation
  - To be useful, it should be more *precise* than simple scoping rules.

- Liveness analysis is one example of *dataflow analysis*
  - Other examples: Available Expressions, Reaching Definitions, Constant-Propagation Analysis, …

Control-flow Graphs Revisited

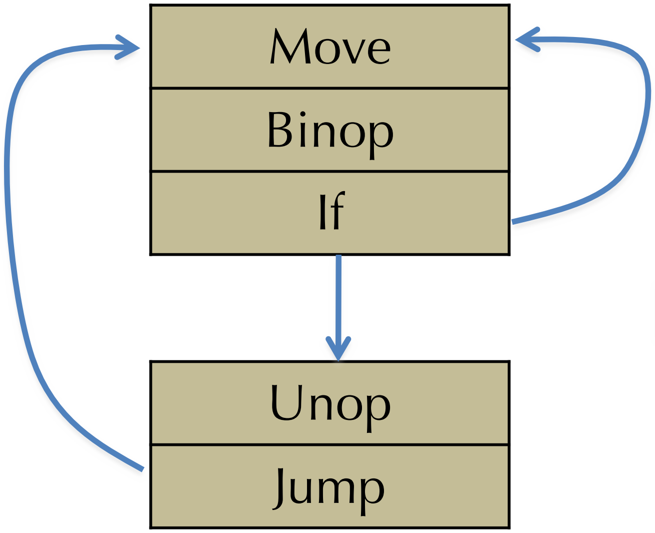
- For the purposes of dataflow analysis, we use the *control-flow graph* (CFG) intermediate form.
- Recall that a basic block is a sequence of instructions such that:
  - There is a distinguished, labeled entry point (no jumps into the middle of a basic block)
  - There is a (possibly empty) sequence of non-control-flow instructions
  - The block ends with a single control-flow instruction (jump, conditional branch, return, etc.)

- A *control flow graph*
  - Nodes are blocks
  - There is an edge from B1 to B2 if the control-flow instruction of B1 might jump to the entry label of B2
  - There are no "dangling" edges – there is a block for every jump target.

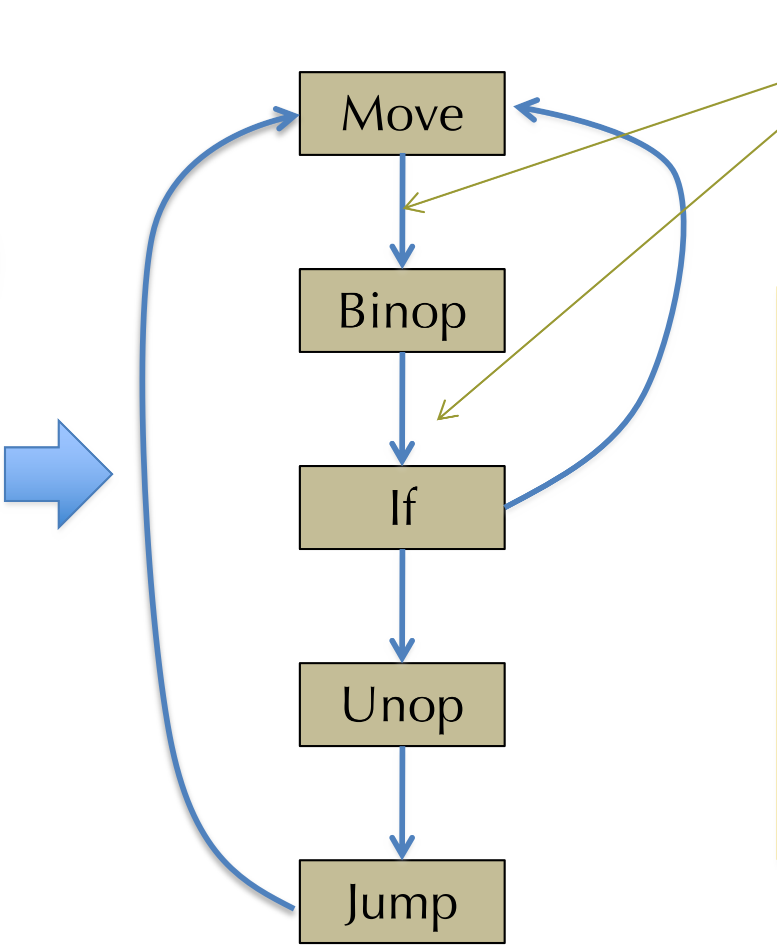
- Note: the following slides are intentionally a bit ambiguous about the exact nature of the code in the control flow graphs:
  - at the x86 assembly level
  - an "imperative" C-like source level
  - at the LLVM IR level
  - Same general idea, but the exact details will differ
    - e.g. LLVM IR doesn't have "imperative" update of %uid temporaries.
    - In fact, the SSA structure of the LLVM IR makes some of these analyses simpler.

Dataflow over CFGs

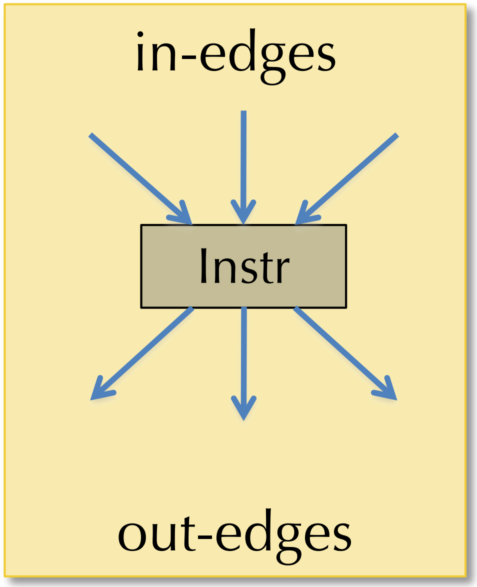
- For precision, it is helpful to think of the “fall through” between sequential instructions as an edge of the control-flow graph too.
  - Different implementation tradeoffs in practice…



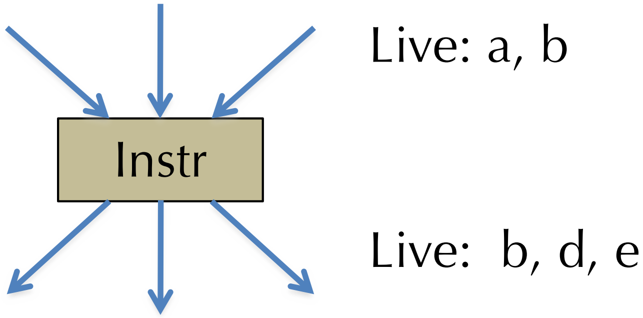
Basic block CFG



“Exploded” CFG



Liveness is Associated with *Edges*

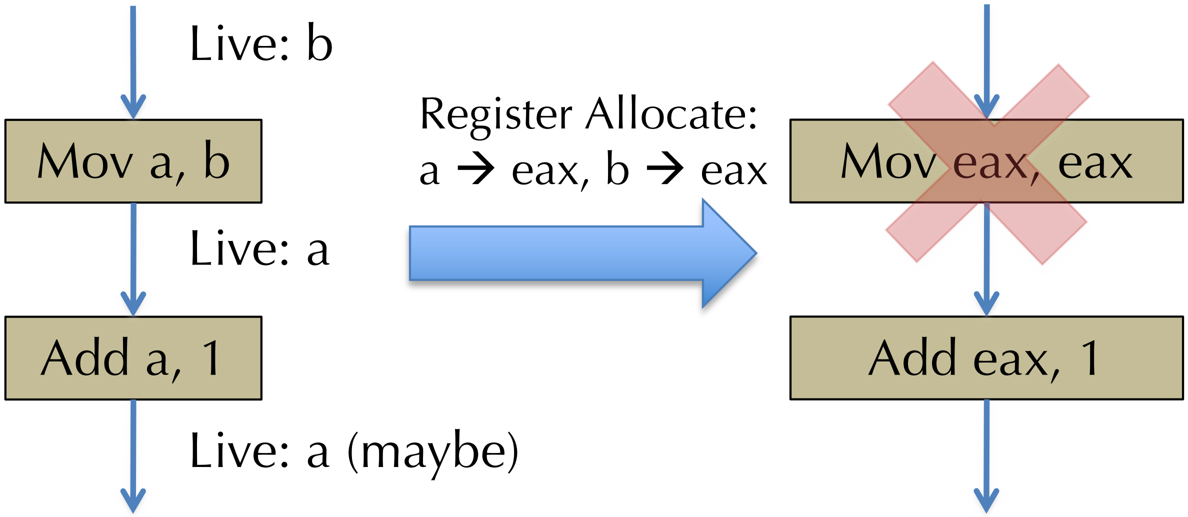


Live: a, b

Instr

Live: b, d, e

- This is useful so that the same register can be used for different temporaries in the same statement.
- Example: `a = b + 1`
- Compiles to:



Live: b

Mov a, b

Live: a

Add a, 1

Live: a (maybe)

Register Allocate:
a → eax, b → eax

Mov eax, eax

Add eax, 1

Uses and Definitions

- Every instruction/statement *uses* some set of variables
  - i.e. reads from them
- Every instruction/statement *defines* some set of variables
  - i.e. writes to them

- For a node/statement s define:
  - use[s] : set of variables used by s
  - def[s] : set of variables defined by s

- Examples:

– `a = b + c`	use[s] = {b,c}	def[s] = {a}
– `a = a + 1`	use[s] = {a}	def[s] = {a}

Liveness, Formally

- A variable v is *live* on edge e if:
  There is
  - a node n in the CFG such that use[n] contains v, *and*
  - a directed path from e to n such that for every statement s′ on the path, def[s′] does not contain v

- The first clause says that v will be used on some path starting from edge e.
- The second clause says that v won't be redefined on that path before the use.

- Questions:
  - How to compute this efficiently?
  - How to use this information (e.g. for register allocation)?
  - How does the choice of IR affect this? (e.g. LLVM IR uses SSA, so it doesn't allow redefinition ⇒ simplify liveness analysis)

Simple, inefficient algorithm

- "A variable v is live on an edge e if there is a node n in the CFG using it *and* a directed path from e to n pasing through no def of v."

- Backtracking Algorithm:
  - For each variable v…
  - Try all paths from each use of v, tracing backwards through the control-flow graph until either v is defined or a previously visited node has been reached.
  - Mark the variable v live across each edge traversed.

- Inefficient because it explores the same paths many times (for different uses and different variables)