

Code generation and local optimization

Generating assembly

- How do we convert from three-address code to assembly?
 - Seems easy! But easy solutions may not be the best option
- What we will cover:
 - Instruction selection
 - Peephole optimizations
 - “Local” common subexpression elimination
 - “Local” register allocation

Naïve approach

- “Macro-expansion”
- Treat each 3AC instruction separately, generate code in isolation

ADD A, B, C → LD A, R1
LD B, R2
ADD R1, R2, R3
ST R3, C

MUL A, 4, B → LD A, R1
MOV 4, R2
MUL R1, R2, R3
ST R3, B

Why is this bad? (I)

MUL A, 4, B



LD A, R1
MOV 4, R2
MUL R1, R2, R3
ST R3, B

Why is this bad? (I)

MUL A, 4, B



LD A, R1
MOV 4, R2
MUL R1, R2, R3
ST R3, B

Too many instructions
Should use a different instruction type

Why is this bad? (I)

MUL A, 4, B →
LD A, R1
MOV 4, R2
MUL R1, R2, R3
ST R3, B

MUL A, 4, B →
LD A, R1
MULI R1, 4, R3
ST R3, B

Too many instructions
Should use a different instruction type

Why is this bad? (II)

ADD A, B, C → LD A, R1
LD B, R2
ADD R1, R2, R3
ST R3, C

ADD A, B, C → LD A, R1
ADD C, A, E → LD B, R2
LD C, R4
LD A, R5
ADD R4, R5, R6
ST R6, E

Why is this bad? (II)

ADD A, B, C



LD A, R1
LD B, R2
ADD R1, R2, R3
ST R3, C

ADD A, B, C
ADD C, A, E



LD A, R1
LD B, R2
ADD R1, R2, R3
ST R3, C
LD C, R4
LD A, R5
ADD R4, R5, R6
ST R6, E

Redundant load of C
Redundant load of A
Uses a lot of registers

Why is this bad? (II)

ADD A, B, C



LD A, R1
LD B, R2
ADD R1, R2, R3
ST R3, C

ADD A, B, C
ADD C, A, E



LD A, R1
LD B, R2
ADD R1, R2, R3
ST R3, C
LD C, R4
LD A, R5
ADD R4, R5, R6
ST R6, E

Redundant load of C
Redundant load of A
Uses a lot of registers

Why is this bad? (III)

ADD A, B, C →
LD A, R1
LD B, R2
ADD R1, R2, R3
ST R3, C

ADD A, B, C
ADD A, B, D →
LD A, R1
LD B, R2
ADD R1, R2, R3
ST R3, C
LD A, R4
LD B, R5
ADD R4, R5, R6
ST R6, D

Why is this bad? (III)

ADD A, B, C →
LD A, R1
LD B, R2
ADD R1, R2, R3
ST R3, C

ADD A, B, C
ADD A, B, D →
LD A, R1
LD B, R2
ADD R1, R2, R3
ST R3, C
LD A, R4
LD B, R5
ADD R4, R5, R6
ST R6, D

Wasting instructions recomputing A + B

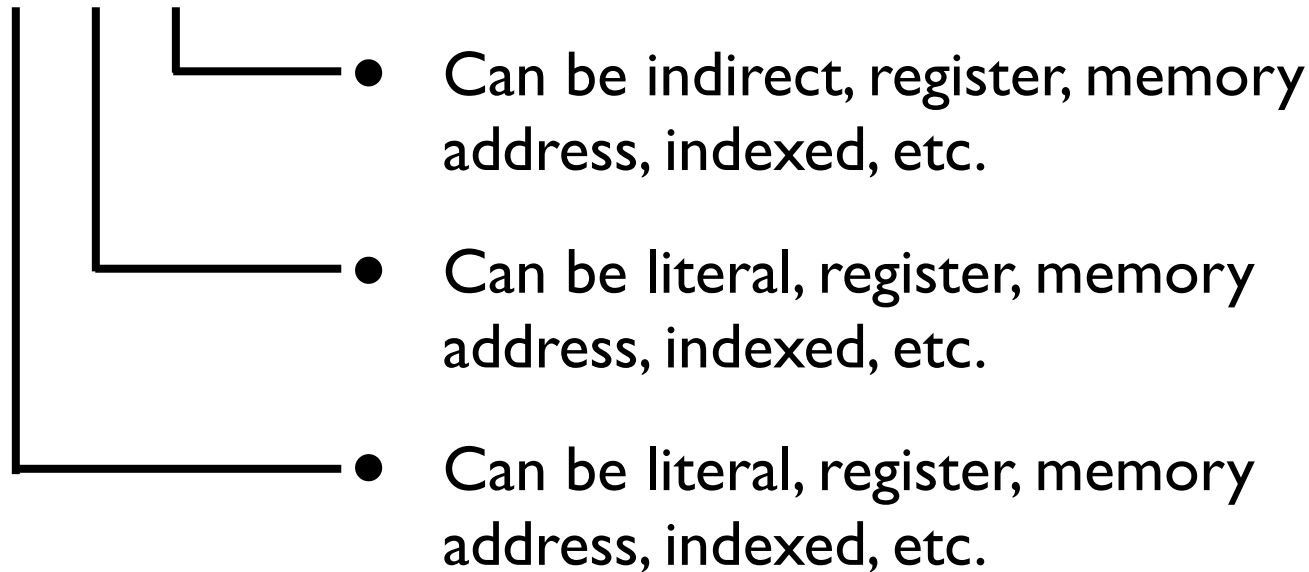
How do we address this?

- Several techniques to improve performance of generated code
 - *Instruction selection* to choose better instructions
 - *Peephole optimizations* to remove redundant instructions
 - *Common subexpression elimination* to remove redundant computation
 - *Register allocation* to reduce number of registers used

Instruction selection

- Even a simple instruction may have a large set of possible address modes and combinations

+ A B C



- Dozens of potential combinations!

More choices for instructions

- Auto increment/decrement (especially common in embedded processors as in DSPs)
 - e.g., load from this address and increment it
 - Why is this useful?
- Three-address instructions
- Specialized registers (condition registers, floating point registers, etc.)
- “Free” addition in indexed mode
MOV (R1)offset R2
 - Why is this useful?

Peephole optimizations

- Simple optimizations that can be performed by pattern matching
- Intuitively, look through a “peephole” at a small segment of code and replace it with something better
- Example: if code generator sees `ST R X; LD X R`, eliminate load
- Can recognize sequences of instructions that can be performed by single instructions

`LDI R1 R2; ADD R1 4 R1` replaced by

`LDINC R1 R2 4` //load from address in R1 then inc by 4

Peephole optimizations

- Constant folding

`ADD lit1, lit2, Rx` → `MOV lit1 + lit2, Rx`
`MOV lit1, Rx`
`ADD li2, Rx, Ry` → `MOV lit1 + lit2, Ry`

- Strength reduction

`MUL operand, 2, Rx` → `SHIFTL operand, 1, Rx`
`DIV operand, 4, Rx` → `SHIFTR operand, 2, Rx`

- Null sequences

`MUL operand, 1, Rx` → `MOV operand, Rx`
`ADD operand, 0, Rx` → `MOV operand, Rx`

Peephole optimizations

- Combine operations

```
JEQ L1  
JMP L2  
L1: ...
```

→ JNE L2

- Simplifying

SUB operand, 0, Rx → NEG Rx

- Special cases (taking advantage of ++/--)

ADD 1, Rx, Rx → INC Rx

SUB Rx, 1, Rx → DEC Rx

- Address mode operations

```
MOV A R1  
ADD 0(R1) R2 R3
```

→ ADD @A R2 R3

Superoptimization

- Peephole optimization/instruction selection writ large
- Given a sequence of instructions, find a different sequence of instructions that performs the same computation in less time
- Huge body of research, pulling in ideas from all across computer science
 - Theorem proving
 - Machine learning

Common subexpression elimination

- Goal: remove redundant computation, don't calculate the same expression multiple times

1: $A = B * C$

2: $E = B * C$

Keep the result of statement 1 in a temporary and reuse for statement 2

- Difficulty: how do we know when the same expression will produce the same result?

1: $A = B * C$

2: $B = \langle \text{new value} \rangle$

3: $E = B * C$

B is "killed." Any expression using B is no longer "available," so we cannot reuse the result of statement 1 for statement 3

- This becomes harder with pointers (how do we know when B is killed?)

Common subexpression elimination

- Two varieties of common subexpression elimination (CSE)
- Local: within a single basic block
 - Easier problem to solve (why?)
- Global: within a single procedure or across the whole program
 - Intra- vs. inter-procedural
 - More powerful, but harder (why?)
 - Will come back to these sorts of “global” optimizations later

CSE in practice

- Idea: keep track of which expressions are “available” during the execution of a basic block
 - Which expressions have we already computed?
 - Issue: determining when an expression is no longer available
 - This happens when one of its components is assigned to, or “killed.”
- Idea: when we see an expression that is already available, rather than generating code, copy the temporary
 - Issue: determining when two expressions are the same

Maintaining available expressions

- For each 3AC operation in a basic block
 - Create name for expression (based on lexical representation)
 - If name not in available expression set, generate code, add it to set
 - Track register that holds result of and any variables used to compute expression
 - If name in available expression set, generate move instruction
 - If operation assigns to a variable, kill all dependent expressions

Example

Three address code

```
+ A B T1
+ T1 C T2
+ A B T3
+ T1 T2 C
+ T1 C T4
+ T3 T2 D
```

Generated code

Available expressions:

Example

Three address code

```
+ A B T1
+ T1 C T2
+ A B T3
+ T1 T2 C
+ T1 C T4
+ T3 T2 D
```

Generated code

```
ADD A B R1
```

Available expressions: "A+B"

Example

Three address code

+ A B T1
+ T1 C T2
+ A B T3
+ T1 T2 C
+ T1 C T4
+ T3 T2 D

Generated code

ADD A B R1
ADD R1 C R2

Available expressions: "A+B" "T1+C"

Example

Three address code

- + A B T1
- + T1 C T2
- + A B T3
- + T1 T2 C
- + T1 C T4
- + T3 T2 D

Generated code

```
ADD A B R1
ADD R1 C R2
MOV R1 R3
```

Available expressions: "A+B" "T1+C"

Example

Three address code

+ A B T1
+ T1 C T2
+ A B T3
+ T1 T2 C
+ T1 C T4
+ T3 T2 D

Generated code

```
ADD A B R1
ADD R1 C R2
MOV R1 R3
ADD R1 R2 R5; ST R5 C
```

Available expressions: "A+B" "~~T1+C~~" "T1+T2"

Example

Three address code

+ A B T1
+ T1 C T2
+ A B T3
+ T1 T2 C
+ T1 C T4
+ T3 T2 D

Generated code

ADD A B R1
ADD R1 C R2
MOV R1 R3
ADD R1 R2 R5; ST R5 C
ADD R1 C R4

Available expressions: "A+B" "T1+T2" "T1+C"

Example

Three address code

```
+ A B T1
+ T1 C T2
+ A B T3
+ T1 T2 C
+ T1 C T4
+ T3 T2 D
```

Generated code

```
ADD A B R1
ADD R1 C R2
MOV R1 R3
ADD R1 R2 R5; ST R5 C
ADD R1 C R4
ADD R3 R2 R6; ST R6 D
```

Available expressions: "A+B" "T1+T2" "T1+C" "T3+T2"

Downsides

- What are some downsides to this approach? Consider the two highlighted operations

Three address code

+ A B T1
+ T1 C T2
+ A B T3
+ T1 T2 C
+ T1 C T4
+ T3 T2 D

Generated code

```
ADD A B R1
ADD R1 C R2
MOV R1 R3
ADD R1 R2 R5; ST R5 C
ADD R1 C R4
ADD R3 R2 R6; ST R6 D
```

Downsides

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Three address code

+ A B T1
+ T1 C T2
+ A B T3
+ T1 T2 C
+ T1 C T4
+ T3 T2 D

Generated code

```
ADD A B R1
ADD R1 C R2
MOV R1 R3
ADD R1 R2 R5; ST R5 C
ADD R1 C R4
ST R5 D
```

- This can be handled by an optimization called *value numbering*, which we will not cover now (although we may get to it later)

Aliasing

- One of the biggest problems in compiler analysis is to recognize aliases – different names for the same location in memory
- Aliases can occur for many reasons
 - Pointers referring to same location, arrays referencing the same element, function calls passing the same reference in two arguments, explicit storage overlapping (unions)
- Upshot: when talking about “live” and “killed” values in optimizations like CSE, we’re talking about particular variable names
- In the presence of aliasing, we may not know which variables get killed when a location is written to

Memory disambiguation

- Most compiler analyses rely on *memory disambiguation*
 - Otherwise, they need to be too conservative and are not useful
- Memory disambiguation is the problem of determining whether two references point to the same memory location
 - *Points-to* and *alias* analyses try to solve this
 - Will cover basic pointer analyses in a later lecture

Register allocation

- Simple code generation: use a register for each temporary, load from a variable on each read, store to a variable at each write
- Problems
 - Real machines have a limited number of registers – one register per temporary may be too many
 - Loading from and storing to variables on each use may produce a lot of redundant loads and stores
- Goal: allocate temporaries and variables to registers to:
 - Use only as many registers as machine supports
 - Minimize loading and storing variables to memory (keep variables in registers when possible)
 - Minimize putting temporaries on stack

Global vs. local

- Same distinction as global vs. local CSE
 - Local register allocation is for a single basic block
 - Global register allocation is for an entire function (but not interprocedural – why?)
- Will cover some local allocation strategies now, global allocation later

Top-down register allocation

- For each basic block
 - Find the number of references of each variable
 - Assign registers to variables with the most references
- Details
 - Keep some registers free for operations on unassigned variables and spilling
 - Store *dirty* registers at the end of BB (i.e., registers which have variables assigned to them)
 - Do not need to do this for temporaries (why?)

Bottom-up register allocation

- Smarter approach:
 - Free registers once the data in them isn't used anymore
- Requires calculating *liveness*
 - A variable is live if it has a value that *may* be used in the future
- Easy to calculate if you have a single basic block:
 - Start at end of block, all local variables marked dead
 - If you have multiple basic blocks, all local variables defined in the block should be *live* (they may be used in the future)
 - When a variable is used, mark as live, record use
 - When a variable is defined, record def, variable dead above this
 - Creates chains linking uses of variables to where they were defined
- We will discuss how to calculate this across BBs later

Liveness example

- What is live in this code?

```
1:  A = B + C
2:  C = A + B
3:  T1 = B + C
4:  T2 = T1 + C
5:  D = T2
6:  E = A + B
7:  B = E + D
8:  A = C + D
9:  T3 = A + B
10: WRITE(T3)
```

Liveness example

- What is live in this code?

```
1:  A = B + C
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6:  E = A + B
7:  B = E + D
8:  A = C + D
9:  T3 = A + B
10: WRITE(T3)
```

```
1:  {A, B}
2:  {A, B, C}
3:  {A, B, C, T1}
4:  {A, B, C, T2}
5:  {A, B, C, D}
6:  {C, D, E}
7:  {B, C, D}
8:  {A, B}
9:  {T3}
10: {}
```

Bottom-up register allocation

For each tuple $op\ A\ B\ C$ in a BB, do

$R_x = \text{ensure}(A)$

$R_y = \text{ensure}(B)$

if A *dead* after this tuple, $\text{free}(R_x)$

if B *dead* after this tuple, $\text{free}(R_y)$

$R_z = \text{allocate}(C)$ //could use R_x or R_y

generate code for op

mark R_z *dirty*

At end of BB, for each dirty register

generate code to store register into appropriate variable

- We will present this as if A, B, C are variables in memory. Can be modified to assume that A, B and C are in virtual registers, instead

Bottom-up register allocation

ensure(opr)

```
if opr is already in register r
    return r
else
    r = allocate(opr)
    generate load from opr into r
    return r
```

free(r)

```
if r is marked dirty and variable is live
    generate store
mark r as free
```

allocate(opr)

```
if there is a free r
    choose r
else
    choose r to free
    free(r)
mark r associated with opr
return r
```

Example

- Perform register allocation for this code:

```
1:  A = B + C
2:  C = A + B
3:  T1 = B + C
4:  T2 = T1 + C
5:  D = T2
6:  E = A + B
7:  B = E + D
8:  A = C + D
9:  T3 = A + B
10: WRITE(T3)
```

Example

1: $A = B + C$	1: {A, B}
2: $C = A + B$	2: {A, B, C}
3: $T1 = B + C$	3: {A, B, C, T1}
4: $T2 = T1 + C$	4: {A, B, C, T2}
5: $D = T2$	5: {A, B, C, D}
6: $E = A + B$	6: {C, D, E}
7: $B = E + D$	7: {B, C, D}
8: $A = C + D$	8: {A, B}
9: $T3 = A + B$	9: {T3}
10: WRITE(T3)	10: {}

Inst	R1	R2	R3
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

Example

1: $A = B + C$	1: {A, B}
2: $C = A + B$	2: {A, B, C}
3: $T1 = B + C$	3: {A, B, C, T1}
4: $T2 = T1 + C$	4: {A, B, C, T2}
5: $D = T2$	5: {A, B, C, D}
6: $E = A + B$	6: {C, D, E}
7: $B = E + D$	7: {B, C, D}
8: $A = C + D$	8: {A, B}
9: $T3 = A + B$	9: {T3}
10: WRITE(T3)	10: {}

Inst	R1	R2	R3
1	B		A
2	B	C	A
3	B	C	T1
4	B	C	T2
5	B	C	D
6	E		D
7	B		D
8	B		A
9	T3		
10	F		

Aliasing, as usual, is a problem

- What happens with this code?

//a and b are aliased

LD a R1

LD b R2

ADD R1 R2 R3

ST R3 c // c = a + b

R1 = 7 //a = 7

ADD R1 R2 R4

ST R4 d // d = a + b

Dealing with aliasing

- Immediately before loading a variable x
 - For each variable aliased to x that is already in a dirty register, save it to memory (i.e., perform a store)
 - This ensures that we load the right value
- Immediately before writing to a register holding x
 - For each register associated with a variable aliased to x , mark it as invalid
 - So next time we use the variable, we will reload it
- Conservative approach: assume all variables are aliased (in other words, reload from memory on each read, store to memory on each write)
 - Better alias analysis can improve this
 - At subroutine boundaries, still often use conservative analysis

Allocation considerations

- Use *register coloring* to perform global register allocation
 - Will see this next
- Find right order of optimizations and register allocation
 - Peephole optimizations can reduce register pressure, can make allocation better
 - CSE can actually *increase* register pressure
 - Different orders of optimization produce different results
- Register allocation still an open research area
 - For example, how to do allocation for JIT compilers