CS412/CS413

Introduction to Compilers

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Lecture 33: Register Allocation

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Variables vs. Registers/Memory

- Difference between IR and assembly code:
  - IR (and abstract assembly) manipulate data in local and temporary variables
  - Assembly code manipulates data in memory/registers
- During code generation, compiler must account for this difference
- Compiler backend must allocate variables to memory or registers in the generated assembly code

Simple Approach

- Straightforward solution:
  - Allocate each variable in activation record
  - At each instruction, bring values needed into registers, perform operation, then store result to memory

```
x = y + z
```

⇒

```
mov 16(%ebp), %eax
mov 20(%ebp), %ebx
add %ebx, %eax
mov %eax, 24(%ebx)
```

- Problem: program execution very inefficient
  - moving data back and forth between memory and registers

Register Allocation

- Better approach = register allocation: keep variable values in registers as long as possible
- Best case: keep a variable's value in a register throughout the lifetime of that variable
  - In that case, we don't need to ever store it in memory
  - We say that the variable has been allocated in a register
  - Otherwise allocate variable in activation record
  - We say that variable is spilled to memory
- Which variables can we allocate in registers?
  - Depends on the number of registers in the machine
  - Depends on how variables are being used
- Main Idea: cannot allocate two variables to the same register if they are both live at some program point

Register Allocation Algorithm

Hence, basic algorithm for register allocation is:

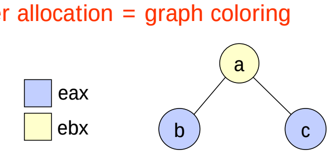
1. Perform live variable analysis (over abstract assembly code!)
2. Inspect live variables at each program point
3. If two variables are in same live set, they\` can't be allocated to the same register – they *interfere* with each other
4. Conversely, if two variables do not interfere with each other, they can be assigned the same register.

Interference Graph

- Nodes = program variables
- Edges = connect variables that interfere with each other

Code	Live set
	{a}
b = a + 2;	{a,b}
c = b*b;	{a,c}
b = c + 1;	{a,b}
return b*a;	

- Register allocation = graph coloring

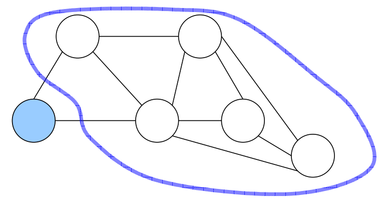


Graph Coloring

- Questions:
  - Can we efficiently find a coloring of the graph whenever possible?
  - Can we efficiently find the optimum coloring of the graph?
  - Can we assign registers to avoid move instructions?
  - What do we do when there aren't enough colors (registers) to color the graph?

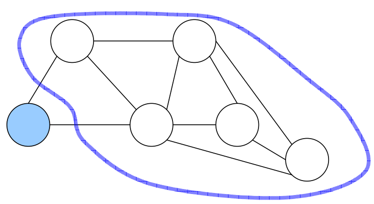
Coloring a Graph

- Assume K = number of registers (take K=3)
- Try to color graph with K colors
- Key operation = Simplify: find some node with at most K-1 edges and cut it out of the graph



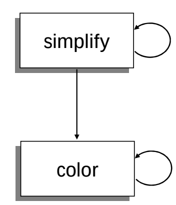
Coloring a Graph

- Idea: once coloring is found for simplified graph, removed node can be colored using free color
- Algorithm: simplify until graph contain no nodes
- Unwind stack, adding nodes back & assigning colors



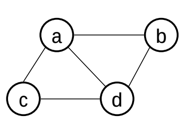
Stack Algorithm

- Phase 1: Simplification
  - Repeatedly simplify graph
  - When a variable (i.e., graph node) is removed, push it on a stack
- Phase 2: Coloring
  - Unwind stack and reconstruct the graph as follows:
  - Pop variable from the stack
  - Add it back to the graph
  - Color the node for that variable with a color that it doesn't iterfere with

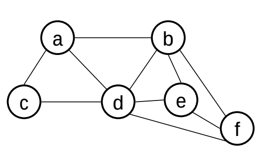


Stack Algorithm

- Example:

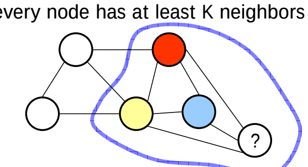


- ...how about:

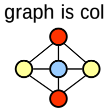


Failure of Heuristic

- If graph cannot be colored, it will reduce to a graph in which every node has at least K neighbors



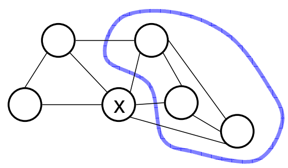
- May happen even if graph is colorable in K!



- Finding K-coloring is NP-hard problem (requires search)

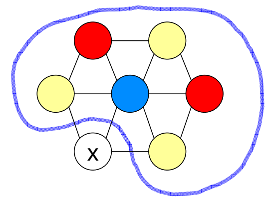
Spilling

- Once all nodes have K or more neighbors, pick a node and mark it for possible spilling (storage in activation record).
- Remove it from graph, push it on stack
- Try to pick node not used much, not in inner loop



Optimistic Coloring

- Spilled node may be K-colorable
- Try to color it when popping the stack
- If not colorable, actual spill: assign it a location in the activation record



Accessing Spilled Variables

- Need to generate additional instructions to get spilled variables out of activation record and back in again
- Simple approach: always keep extra registers handy for shuttling data in and out
- Better approach: rewrite code introducing a new temporary, rerun liveness analysis and register allocation

Rewriting Code

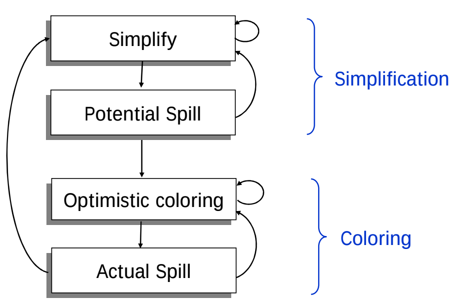
- Example: add v1, v2
- Suppose that v2 is selected for spilling and assigned to activation record location [ebp-24]
- Add new variable (say t35) for just this instruction, rewrite:

  mov –24(%ebp), t35
  add v1, t35

Advantage: t35 has short lifetime and doesn't interfere with other variables as much as v2 did.

- Now rerun algorithm; fewer or no variables will spill.

Putting Pieces Together



Precolored Nodes

- Some variables are pre-assigned to registers
  - mul instruction has use[I] = eax, def[I] = { eax, edx }
  - result of function call returned in eax
- To properly allocate registers, treat these register uses as special temporary variables and enter into interference graph as precolored nodes

Precolored Nodes

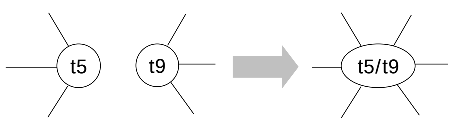
- Simplify. Never remove a pre-colored node --- it already has a color, i.e., it is a given register
- Coloring. Once simplified graph is all colored nodes, add other nodes back in and color them using precolored nodes as starting point

Optimizing Move Instructions

- Code generation produces a lot of extra mov instructions
  - mov t5, t9
- If we can assign t5 and t9 to same register, we can get rid of the mov --- effectively, copy elimination at the register allocation level.
- Idea: if t5 and t9 are not connected in inference graph, coalesce them into a single variable; the move will be redundant.

Coalescing

- When coalescing nodes, take union of edges
- Hence, coalescing results in high-degree nodes
- Problem: coalescing nodes can make a graph uncolorable



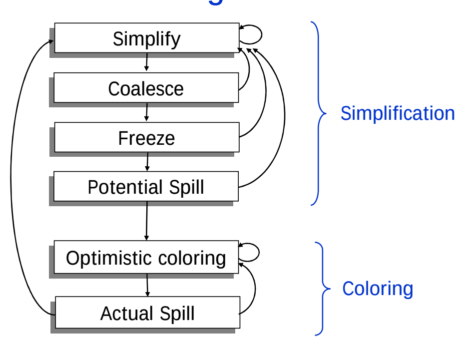
Conservative Coalescing

- Conservative = ensure that coalescing doesn't make the graph non-colorable (if it was colorable before)
- Approach 1: coalesce a and b if resulting node ab has less than K neighbors of significant degree
  - Safe because we can simplify graph by removing neighbors with insignificant degree, then remove coalesced node and get the same graph as before
- Approach 2: coalesce a and b if for every neighbor t of a: either t already interferes with b; or t has insignificant degree
  - Safe because removing insignificant neighbors with coalescing yields a subgraph of the graph obtained by removing those neighbors without coalescing

Simplification + Coalescing

- Consider M = set of move-related nodes (which appear in the source or destination of a move instruction) and N = all other variables
- Start by simplifying as many nodes as possible from N
- Coalesce some pairs of move-related nodes using conservative coalescing; delete corresponding mov instruction(s)
- Coalescing gives more opportunities for simplification: coalesced nodes may be simplified
- If can neither simplify nor coalesce, take a node f in M and freeze all the move instructions involving that variable; i.e., move all f-related nodes from M to N; go back to simplify.
- If all nodes frozen, no simplify possible, spill a variable

Full Algorithm



Overall Code Generation Process

- Start with low-level IR code
- Build DAG of the computation
  - Access global variables using static addresses
  - Access function arguments using frame pointer
  - Assume all local variables and temporaries are in registers (assume unbounded number of registers)
- Generate abstract assembly code
  - Perform tiling of DAG
- Register allocation
  - Live variable analysis over abstract assembly code
  - Assign registers and generate assembly code

Example

Program

```
array[int] a

function f:(int x) {
   int i;
   ...
   a[x+i] = a[x+i] + 1;
   ...
}
```

Low IR

```
t1 = x+i
t1 = t1*4
t1 = $a+t1
t2 = *t1
t2 = t2+1
t3 = x+i
t3 = t3*4
t3 = $a+t3
*t3 = t2
```

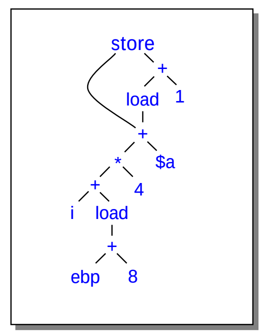

Accesses to Function Arguments

```
t1 = x+i
t1 = t1*4
t1 = $a+t1
t2 = *t1
t2 = t2+1
t3 = x+i
t3 = t3*4
t3 = $a+t3
*t3 = t2
```

```
t4 = ebp+8
t5 = *t4
t1 = t5+i
t1 = t1*4
t1 = $a+t1
t2 = *t1
t2 = t2+1
t6=ebp+8
t7 = *t6
t3 = t7+i
t3 = t3*4
t3 = $a+t3
*t3 = t2
```

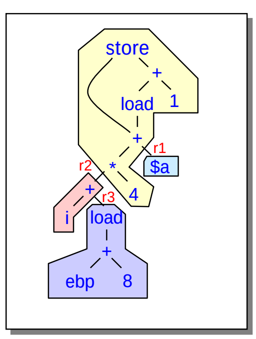

DAG Construction

```
t4 = ebp+8
t5 = *t4
t1 = t5+i
t1 = t1*4
t1 = $a+t1
t2 = *t1
t2 = t2+1
t6=ebp+8
t7 = *t6
t3 = t7+i
t3 = t3*4
t3 = $a+t3
*t3 = t2
```

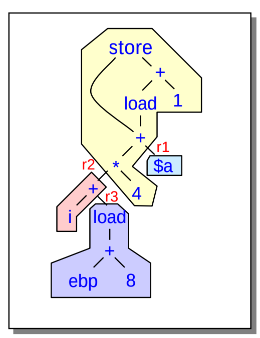


Tiling

- Find tiles
  - Maximal Munch
  - Dynamic programming
- Temporaries to transfer values between tiles
- No temporaries inside any of the tiles



Abstract Assembly Generation



Abstract Assembly

```
mov $a, r1
mov 8(%ebp), r3
mov i, r2
add r3, r2
add $1, (r1,r2,4)
```

Register Allocation

Abstract Assembly

```
mov $a, r1
mov 8(%ebp), r3
mov i, r2
add r3, r2
add $1, (r1,r2,4)
```

Live Variables

```
                  {%ebp, i}
mov $a, r1
                  {%ebp,r1,i}
mov 8(%ebp), r3
                  {r1, r3, i}
mov i, r2
                  {r1,r2,r3}
add r3, r2
                  {r1,r2}
add $1, (r1,r2,4)
                  {}
```


Register Allocation

Live Variables

```
                  {%ebp, i}
mov $a, r1
                  {%ebp,r1,i}
mov 8(%ebp), r3
                  {r1, r3, i}
mov i, r2
                  {r1,r2,r3}
add r3, r2
                  {r1,r2}
add $1, (r1,r2,4)
                  {}
```

- Build interference graph

```
         i — r3
       /  \  /  \
%ebp— r1 — r2
```

- Allocate registers:
  eax: r1, ebx: r3
  i, r2 spilled to memory

Assembly Code Generation

Abstract Assembly

```
mov $a, r1
mov 8(%ebp), r3
mov i, r2
add r3, r2
add $1, (r1,r2,4)
```

Assembly Code

```
mov $a, %eax
mov 8(%ebp), %ebx
mov –12(%ebp), %ecx
mov %ecx, -16(%ebp)
add %ebx, -16(%ebp)
mov –16(%ebp), %ecx
add $1, (%eax,%ecx,4)
```

Register allocation results:
eax: r1; ebx: r3; i, r2 spilled to memory

Where We Are

Source Program

↓ ✓

Optimized Assembly Code