Software Programmable DSP Platform Analysis

Episode 5, 5 April 2007, Ingredients

Liveness Analysis
- Control-Flow Graphs
- Definition & Use
- Calculation of Liveness
- Interference Graphs

Register Allocation
- Coloring by Simplification
- Spilling

Cl6x Compiler Intrinsics

Function Inlining

From Abstract To Concrete Registers

- Instruction selection has left us with an assembly program that uses abstract registers (unboundedly many).
- But target architecture only has a small fixed set of registers...
- We want to map numerous temporaries (TEMP) into as few concrete registers as possible.
- Obviously we can only assign the same register to two temporaries, if we do not need both of them at the same time.

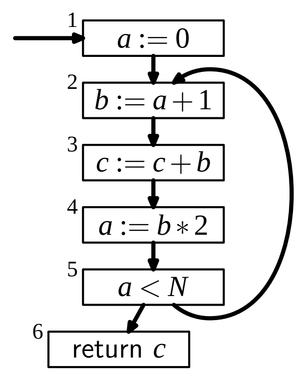
Liveness Analysis

- Identify temporaries that cannot be active at the same time.
- This is achieved by liveness analysis.
- Liveness analysis works on control flow graphs.
- In practice the flow graph is created from the abstract machine program,
- but for clarity of presentation we shall use simple language of expressions and assignments in this lecture.

Control-Flow Graphs

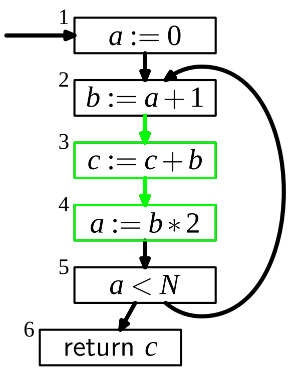
- Each statement is a node
- An edge from node x to y if statement x can be directly followed by y during execution.

$a \leftarrow 0$
$L_1: b \leftarrow a + 1$
$c \leftarrow c + b$
$a \leftarrow b * 2$
if $a < N$ goto L_1
return c

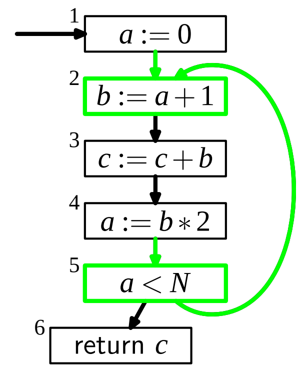


Live Variable

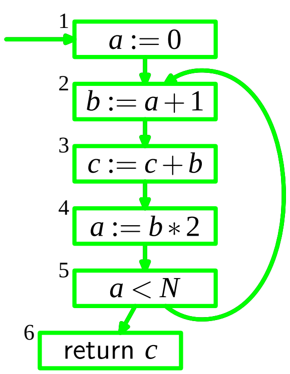
A variable is live at a given program point if its current value may be used in later execution.



- *b* is live in node 4
- so *b* is live on entry to 4
- 3 does not define *b* so *b* is live in 3 and on all edges incoming.
- 2 defines *b* and does not use it. *b* is not live in 2. Live range of *b* is $\{2 \to 3, 3 \to 4\}$.

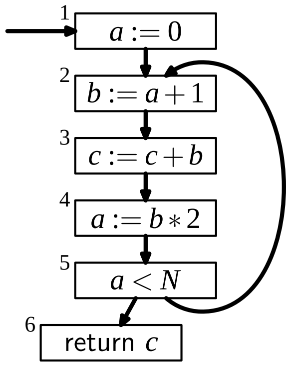


- *a* is live in nodes 2, 5.
- Take one step back.
- 4 and 1 kill *a*.
- Live range of *a* is $\{1 \to 2, 4 \to 5 \to 2\}$.
- Note: the value of *a* in node 3 is completely useless.



- *c* is used in 3, 6
- One step back.
- Another one back.
- Note that *c* is live both on entry and exit from 3, as it is both defined and used in 3.
- *c* is live on entry to 1. If *c* is not a parameter, then this is a bug (uninitialized variable).

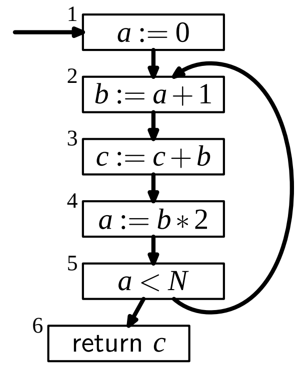
- *out-edges*[*n*]: all edges that lead to a successor node of *n*.
- *in-edges*[*n*]: all edges that lead from a predecessor node of *n*.
- *pred*[*n*]: set of all predecessors of *n*.
- *succ*[*n*]: set of all successors of *n*.



$$out\text{-}edges[5] = \{5 \to 6, 5 \to 2\} \qquad succ[5] = \{2,6\}$$
$$in\text{-}edges[2] = \{5 \to 2, 1 \to 2\} \qquad pred[2] = \{1,5\}$$

Definition & Use

- An assignment to a variable x **defines** x.
- An occurrence of x on the right hand side of the assignment is called a **use** of x.



- $def(3) = \{c\}$
- $use(3) = \{b,c\}$

Liveness

Variable x is **live** on the given edge if there exists a directed path from that edge to a use that does not go through any def.

X is **live-in** in node n if it is live on any of its *in-edges*.

X is **live-out** in node n if it is live on any of its *out-edges*.

Calculation of Liveness

$$in[n] = use[n] \cup (out[n] - def[n])$$
$$out[n] = \bigcup_{s \in succ[n]} in[s].$$

- initialize all $in[n]$ and $out[n]$ sets to be empty
- compute new sets interpreting equality like assignments
- repeat the previous step until no growth is observed in the sets.

The result for our running example is

node	*live-in*	*live-out*
1	c	ac
2	ca	bc
3	bc	bc
4	bc	ac
5	ac	ac
6	c	

Agenda

Interference Graphs

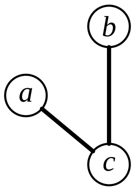
- Variables *a* and *b* are in interference if *a* and *b* cannot be allocated in the same memory space (a register).
- Overlapping live ranges cause interference.
- Architecture constraints may cause interferences (for example registers participating in some instruction cannot be from two different register files).

The following are our live ranges:

node	*live-in*	*live-out*
1	c	ac
2	ca	bc
3	bc	bc
4	bc	ac
5	ac	ac
6	c	

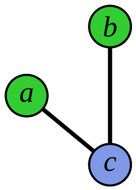
- We can see from this that *a* interferes with *c*
- and *b* interferes with *c*,
- but *a* does not interfere with *b*.

The same information presented as an *interference graph*:



Register Allocation

Assign as few platform registers to many temporaries: do this by assigning a minimal number of colors to nodes of interference graph, such that any neighboring vertices have different colors.



A and *b* have been allocated in the same register.

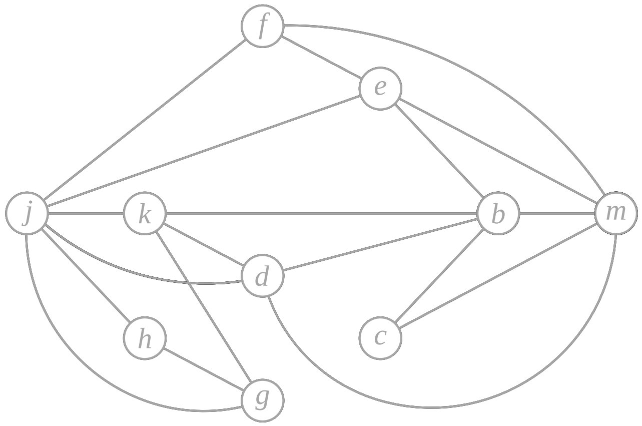
Coloring by Simplification

[Kempe 1879]

This is a coloring algorithm based on heuristics (i.e. does not guarantee optimality):

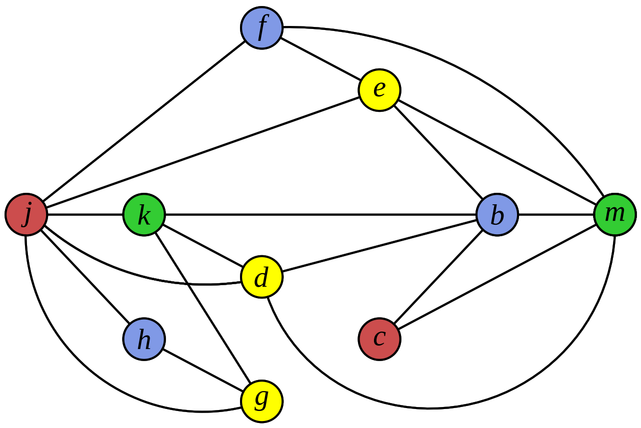
- Assume K registers (colors) are available.
- Find a node m with less than K neighbors.
- Remove m from the graph (it will be easy to add it and color, since it has less than K members).
- Repeat previous step until you end up with isolated nodes.
- Assign them the first color,
- and add nodes back to the graph in the reverse order, adding colors on the fly.

Simplifying



stack: g h k d j e f b c m (source: Appel, p. 237–238)

Selecting



stack: g h k d j e f b c m (source: Appel, p. 237–238)

Spilling

- Colouring by simplification may fail if the interference graph is not k-colourable.
- If all nodes left in the graph have degrees higher than k, an arbitrary node n has to be removed from the graph (potential spill).
- But since the algorithm cannot be really sure if this is a real spill, we put the node on the stack hoping that we can still colour this with just k colours during selection.
- If selection manages to colour n then fine.
- If neighbours of n already use k: **actual spill**.
- n has to be stored in memory.

- We ignore the spill during the main run and continue to find all other spills.
- Code is rewritten to fetch and store from memory for each definition and use.
- Then liveness analysis and colouring has to be rerun, as the interference graph has changed (the new code uses new temporaries).
- Usually this process succeeds after one or two iterations.

On Choosing Colors

- A local variable that is not live across the call should be allocated to the caller save registers (so only choose from a subsset of colours).
- Similarly a local variable that is live across several calls should be stored in a callee save register to avoid multiple saves.
- Register allocation for trees (side-effect free expressions) can be done much more efficiently, see Appel p. 257.

Register Allocation of cl6x

- TI's cl6x performs a *cost-based register allocation*
- Variables used within loops are weighted to have priority over others.
- Variables with non-overlapping ranges might be allocated to the same register.

[spru 187, p. 3-36]

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Cl6x Compiler Intrinsics

Function Inlining

Compiler Intrinsics [cl6x specific!]

- Intrinsics are special functions that map directly to inlined C67x instructions.
- They look like a function call.
- Name starts with an underscore.
- Instrinsics are directly compiled to special instructions.
- Exhaustive list available in section 2.4.1 of spru 198 (Programmer's Guide).

Saturated Addition in Standard C

```
int sadd(int a, int b) {
  int r;
  r = a + b;
  if (((a^b) & 0x80000000) == 0) {
    if ((r^a) & 0x80000000) {
      r = (a<0) ? 0x80000000:0x7fffffff;
    }
  }
  return r; }
```

Many, many cycles...

Saturated Addition Intrinsic

In Cl6x you can achieve the same effect with:

```
r = _sadd(a,b);
```

- translated directly to `SADD` instruction [spru189,3-108]
- no stack frame, entry code, exit code
- efficient execution (1 cycle)
- disadvantage: portability suffers (but C implementations are provided for workstation testing, profiling and compilations with other compilers).

Agenda

Inlining with cl6x

- Automatic inlining of small functions from optimization level -O3 and up
- Definition-control inlining (using the `inline` keyword), ignored if the optimizer is inactive.
- Intrinsics can also be understood as inlined functions implemented in assembly.

[source: spru 187 p. 2-38, 3-29]

- Appel describes the technology of inline expansion in section 15.4, but in the context of functional programming languages (which is somewhat too complex for our needs here).

Inlining pros and cons

- Saves overhead of function calls.
- Optimizer can optimize across the function call.
- Registers can be allocated better avoiding copying values to passing parameters, spilling, etc.
- Only useful for small functions or functions only called at one site (due to copying the function body).

Functions not inlined by cl6x

- Functions returning structures or unions.
- Functions containing static variables.
- Taking a structure or union as a parameter.
- Containing a volatile parameter/variable.
- Taking a variable number of arguments.
- Declaring a local struct, union or enum type.
- Recursive functions.
- Containing `#pragma` directives.
- With large stack frames (many local variables).

[spru 187, p. 2-42]