CSc 453 — Compilers and Systems Software

21 : Code Generation II

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Next-Use Information

2 Overview

- We need to know, for each use of a variable in a basic block, whether the value contained in the variable will be used again later in the block.
- If a variable has no *next-use* we can reuse the register allocated to the variable.
- We also need to know whether a variable used in a basic block is *live-on-exit*, i.e. if the value contained in the variable has a use outside the block. The global data-flow analysis we talked about in the optimization unit can be used to this end.
- If no *live-variable* analysis has been done we assume all variable are live on exit from the block. This will mean that when the end of a basic block has been reached, all values kept only in registers will have to be stored back into their corresponding variables' memory locations.

3 Basic Block Code Generation

```
X := Y + Z
Z := Z * 5
T7 := Z + 1
Y := Z - T7
X := Z + Y
```

- Generate code one basic block at a time.
- We don't know which path through the flow-graph has taken us to this basic block. ⇒ We can't assume that any variables are in registers.

4 Basic Block Code Generation...

```
X := Y + Z
Z := Z * 5
T7 := Z + 1
Y := Z - T7
X := Z + Y
```

- We don't know where we will go from this block. ⇒ Values kept in registers must be stored back into their memory locations before the block is exited.

```
Load variables into registers.
        Compute....
Store register values back
into their memory locations.
```

5 Next-Use Information

```
X := Y + Z
Z := Z * 5
T7 := Z + 1
Y := Z - T7
X := Z + Y
```

- We want to keep variables in registers for as long as possible, to avoid having to reload them whenever they are needed.
- When a variable isn't needed any more we free the register to reuse it for other variables. ⇒ We must know if a particular value will be used later in the basic block.

6 Next-Use Information...

```
X := Y + Z
Z := Z * 5
T7 := Z + 1
Y := Z - T7
X := Z + Y
```

- If, after computing a value `X`, we will soon be using the value again, we should keep it in a register. If the value has no further use in the block we can reuse the register.

7 Next-Use Information...

X is live at (5)

```
(5)    X := ···
           ...  (no ref to X) ...
(14)   ··· := ··· X ···
```

- `X` is live at (5) because the value computed at (5) is used later in the basic block.
- `X`'s next_use at (5) is (14).
- It is a good idea to keep `X` in a register between (5) and (14).

8 Next-Use Information...

X is dead at (12)

```
(12)  ··· := ··· X ···
          ...  (no ref to X)  ...
(25)  X := ···
```

- X is dead at (12) because its value has no further use in the block.
- Don't keep `X` in a register after (12).

9 Next-Use Information – Example

Intermediate Code	Live/Dead				Next Use			
	x	y	z	t_7	x	y	z	t_7
(1) x := y+z	L	D	D		(2)	_	_	
(2) z := x*5	D		L		_		(3)	
(3) t_7 := z+1			L	L			(4)	(4)
(4) y := z-t_7		L	L	D		(5)	(5)	_
(5) x := z+y	D	D	D		_	_	_	

- `x, y, z` are live on exit, t_7 (a temporary) isn't.

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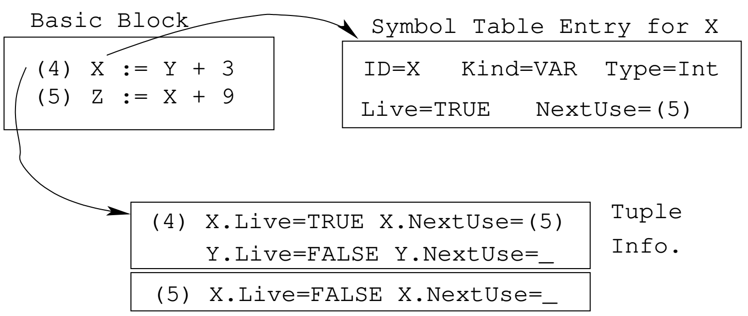
Algorithm

11 Next-Use Algorithm

- A two-pass algorithm computes next-use & liveness information for a basic block.
- In the first pass we scan over the basic block to find the end. Also:
  1. For each variable `X` used in the block we create fields `X.live` and `X.next_use` in the symbol table. Set `X.live:=FALSE; X.next_use:=NONE`.
  2. Each tuple $\boxed{\texttt{(i) X:=Y+Z}}$ stores next-use & live information. We set

`(i).X.live:=(i).Y.live:=(i).Z.live:=FALSE` and `(i).X.next_use:=(i).Y.next_use:= (i).Z.next_use:= NONE`.

12 Next-Use Algorithm...



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1. Scan forwards over the basic block:
   - Initialize the symbol table entry for each used variable, and the tuple data for each tuple.
2. Scan backwards over the basic block. For every tuple `(i): x := y op z` do:
   (a) Copy the live/next_use-info from `x, y, z`'s symbol table entries into the tuple data for tuple `(i)`.
   (b) Update `x, y, z`'s symbol table entries:

```
x.live      :=  FALSE;
x.next_use  :=  NONE;
y.live      :=  TRUE;
z.live      :=  TRUE;
y.next_use  :=  i;
z.next_use  :=  i;
```

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Example

15 Next-Use Example – Forward Pass

	SyTab-Info						Instr.-Info					
	live			next_use			live			next_use		
i	x	y	z	x	y	z	x	y	z	x	y	z
(1) x:=y+z	F	F	F				F	F	F			
(2) z:=x*5	F	F	F				F	F	F			
(3) y:=z-7	F	F	F				F	F	F			
(4) x:=z+y	F	F	F				F	F	F			

16 Next-Use Example – Backwards Pass

	SyTab-Info						Instr.-Info					
	live			next_use			live			next_use		
i	x	y	z	x	y	z	x	y	z	x	y	z
(4) x := z+y	F	T	T		4	4	F	F	F			
(3) y := z-7	F	F	T			3	F	T	T		4	4
(2) z := x*5	T	F	F	2			F	F	T			3
(1) x := y+z	F	T	T		1	1	T	F	F	2		

- The data in each row reflects the state in the symbol table and in the data section of instruction `i` after `i` has been processed.

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Register & Address Descriptors

18 Register & Address Descriptors

- During code generation we need to keep track of what's in each register (a Register Descriptor).
- One register may hold the values of several variables (e.g. after `x:=y`).
- We also need to know where the values of variables are currently stored (an Address Descriptor).
- A variable may be in one (or more) register, on the stack, in global memory; all at the same time.

19 Register & Address Descriptors...

Address Descriptor		
Id	Memory	Regs.
x	fp(16)	{r0}
y	fp(20)	{}
z	0x2020	{r1, r3}
t1		{r0}

Register Descriptor	
Reg	Contents
r0	{x, t1}
r1	{z}
r2	{}
r3	{z}

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A Simple Code Generator

21 A Simple Code Generator

A flowgraph: We generate code for each individual basic block.

An Address Descriptor (AD): We store the location of each variable: in register, on the stack, in global memory.

A Register Descriptor (RD): We store the contents of each register.

Next-Use Information: We know for each point in the code whether a particular variable will be referenced later on.

We need:

GenCode(i: x := y op z): Generate code for the i:th intermediate code instruction.

GetReg(i: x := y op z): Select a register to hold the result of the operation.

22 Machine Model

- We will generate code for the address-register machine described in the book. It is a CISC, not a RISC; it is similar to the x86 and MC68k.
- The machine has n general purpose registers `R0, R1, ..., R`n.

`MOV M, R`	Load variable `M` into register `R`.
`MOV R, M`	Store register `R` into variable `M`.
OP `M, R`	Compute `R := R` *OP* `M`, where *OP* is one of `ADD, SUB, MUL, DIV`.
OP `R2, R1`	Compute `R1 := R1` *OP* `R2`, where *OP* is one of `ADD, SUB, MUL, DIV`.

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GenCode((i): X := Y OP Z)

- `L` is the location in which the result will be stored. Often a register.
- Y' is the most favorable location for Y. I.e. a register if Y is in a register, Y's memory location otherwise.

GenCode((i): X := Y)

- Often we won't have to generate any code at all for the tuple `X := Y`; instead we just update the address and register descriptors (AD & RD).

GetReg(i: X := Y op Z)

- If we won't be needing the value stored in `Y` after this instruction, we can reuse `Y`'s register.

24 GenCode((i): X := Y OP Z)

1. `L := GetReg(i: X := Y op Z).`
2. `Y' :=` "best" location for `Y`. `IF Y` is not in `Y' THEN gen(MOV Y', L).`
3. `Z' :=` "best" location for `Z`.
4. `gen(OP Z', L)`
5. Update the address descriptor: `X` is now in location `L`.
6. Update the register descriptor: `X` is now only in register `L`.
7. `IF (i).Y.next_use=NONE THEN` update the register descriptor: `Y` is not in any register. Same for `Z`.

25 GenCode((i): X := Y)

- `IF Y` only in mem. location `L THEN`
  - `R := GetReg(); gen(MOV Y, R);`
  - `AD: Y` is now only in reg `R`.
  - `RD: R` now holds `Y`.
- `IF Y` is in register `R THEN`
  - `AD: X` is now only in register `R`.
  - `RD: R` now holds `X`.
  - `IF (i).Y.next_use=NONE THEN RD:` No register holds `Y`.
- At the end of the basic block store all live variables (that are left in registers) in their memory locations.

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Register Allocation

27 GetReg(i: X := Y op Z)

1. IF
   - Y is in register R and R holds only Y
   - (i).Y.next_use=NONE

   THEN RETURN R;
2. ELSIF there's an empty register R available THEN RETURN R;
3. ELSIF
   - X has a next use and there exists an occupied register R

   THEN Store R into its memory location and RETURN R;
4. OTHERWISE RETURN the memory location of X.

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Code Generation Example

29 Code Generation Example

- The state in RD and AD is after the operation has taken place.
- Only two registers are available, r0 and r1.
- In the last instruction we select r0 for spilling.
- Note that x and y are kept in registers until the end of the basic block. At the end of the block, they are returned to their memory locations.

30 Code Generation Example...

	Interm. Code	Machine
(1)	x := y + z	MOV y, r0 ADD z, r0
(2)	z := x * 5	MUL 5, r0
(3)	y := z - 7	MOV r0, r1 SUB 7, r1
(4)	x := z + y	MOV r0, z ADD r1, r0
		MOV r1, y MOV r0, x

31 Code Generation Example...

Interm.	Machine	RD	AD	Live		
				x	y	z
x := y + z	MOV y, r0 ADD z, r0	r0 $\equiv$ x	x $\equiv$ r0	T	F	T
z := x ∗ 5	MUL 5, r0	r0 $\equiv$ z	z $\equiv$ r0	F		T
y := z - 7	MOV r0, r1 SUB 7, r1	r0 $\equiv$ z r1 $\equiv$ y	z $\equiv$ r0 y $\equiv$ r1		T	T

32 Code Generation Example...

Interm.	Machine	RD	AD	Live		
x := z + y	MOV r0, z	r0 $\equiv$ z r1 $\equiv$ y	z $\equiv$ mem z $\equiv$ r0 y $\equiv$ r1	T	T	T
	ADD r1, r0	r0 $\equiv$ x r1 $\equiv$ y	x $\equiv$ r0 y $\equiv$ r1 z $\equiv$ mem			
	MOV r1, y MOV r0, x		y $\equiv$ mem x $\equiv$ mem			

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Summary

34 Readings and References

- Read Louden:

  Generation of Intermediate Code 407–442

  Machine Code Generation 453–467

- This lecture is taken from the Dragon book:

  Next-Use Information 534–535

  Simple Code Generation 535–541.

  Address & Register Descriptors 537

35 Summary

- Register allocation requires next-use information, i.e. for each reference to x we need to know if x's value will be used further on in the program.
- We also need to keep track of what's in each register. This is sometimes called register tracking.
- We need a register allocator, a routine that picks registers to hold the contents of intermediate computations.