Module 07: CS31003: Compilers: Target Code Generation (TAC $\rightarrow$ TC)

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Target Code Generation Overview

Target Code Generation

Target Code Generation – Scope

- Target Machine: `x86-32 bits`
- Input
  - Symbol Tables
  - Table of Labels
  - Table of Constants
  - Quad Array of TAC
- Output
  - List of Assembly Instructions
  - External Symbol Table and Link Information
- No Error / Exception Handling

Target Code Generation Steps - Summary

1. TAC Optimization
2. Memory Binding
   - Generate AR from ST – memory binding for local variables
   - Generate Static Allocation from ST.gbl – memory binding for global variables
   - Generate Constants from Table of Constants
   - Register Allocations & Assignment
3. Code Translation
   - Generate Function Prologue
   - Generate Function Epilogue
   - Map TAC to Assembly – Function Body
4. Target Code Optimization
5. Target Code Management
   - Integration into an Assembly File
   - Link Information Generation – for multi-source build

TC Generation Steps – TAC Optimization

- Optimize TAC
- Peep-hole Optimization
  - Elimination of Useless Temporary
  - Eliminating Unreachable Code
  - Flow of Control Optimization
  - Algebraic Simplification & Reduction of Strength
- Common Sub-expression Elimination
- Constant Folding
- Dead-code Elimination

Example: Vector Product

```
int a[5], b[5], c[5];
int i, n = 5;

for(i = 0; i < n; i++) {
    if (a[i] < b[i])
        c[i] = a[i] * b[i];
    else
        c[i] = 0;
}
return;
```

```
//  int i, n = 5;
100: t1 = 5
101: n = t1
// for(i = 0; i < n; i++) {
102: t2 = 0
103: i = t2
104: if i < n goto 109 // T
105: goto 129 // F
106: t3 = i
107: i = i + 1
108: goto 104
// if (a[i] < b[i]) {
109: t4 = 4 * i
110: t5 = a[t4]
111: t6 = 4 * i
112: t7 = b[t6]
113: if t5 < t7 goto 115 // T
114: goto 124 // F
```

```
// c[i] = a[i] * b[i];
115: t8 = 4 * i
116: t9 = c + t8
117: t10 = 4 * i
118: t11 = a[t10]
119: t12 = 4 * i
120: t13 = b[t12]
121: t14 = t11 * t13
122: *t9 = t14
123: goto 106 // next
// c[i] = 0;
124: t15 = 4 * i
125: t16 = c + t15
126: t17 = 0
127: *t16 = t17
// }
128: goto 106 // for
// return;
129: return
```

Example: Vector Product: Peep-hole Optimization

Peep-hole optimization and potential removals are marked. Recomputed quad numbers are shown:

```
     // int i, n = 5;
     100: t1 = 5 XXX
100: 101: n = 5 <=== def-use
     // for(i = 0; i < n; i++) {
     102: t2 = 0 XXX
101: 103: i = 0 <=== def-use
102: 104: if i < n goto 109 // true exit
103: 105: goto 129 // false exit
     106: t3 = i <=== Unused XXX
104: 107: i = i + 1
105: 108: goto 104
     // if (a[i] < b[i]) {
106: 109: t4 = 4 * i // strength reduction
107: 110: t5 = a[t4]
108: 111: t6 = 4 * i // strength reduction
109: 112: t7 = b[t6]
110: 113: if t5 >= t7 goto 124 <=== Jmp-over-Jmp
     114: goto 115 XXX
```

```
     // c[i] = a[i] * b[i];
111: 115: t8 = 4 * i // strength reduction
112: 116: t9 = c + t8
113: 117: t10 = 4 * i // strength reduction
114: 118: t11 = a[t10]
115: 119: t12 = 4 * i // strength reduction
116: 120: t13 = b[t12]
117: 121: t14 = t11 * t13
118: 122: *t9 = t14
119: 123: goto 106 // next exit
     // c[i] = 0;
120: 124: t15 = 4 * i // strength reduction
121: 125: t16 = c + t15
     126: t17 = 0 XXX
122: 127: *t16 = 0 <=== def-use
     // } // End of for loop
123: 128: goto 106
     // return;
124: 129: return
```

Example: Vector Product: Peep-hole Optimization

On removal and reduction:

```
100: n = 5
101: i = 0
102: if i < n goto 106
103: goto 124
104: i = i + 1
105: goto 102
106: t4 = i << 2
107: t5 = a[t4]
108: t6 = i << 2
109: t7 = b[t6]
110: if t5 >= t7 goto 120
```

```
111: t8 = i << 2
112: t9 = c + t8
113: t10 = i << 2
114: t11 = a[t10]
115: t12 = i << 2
116: t13 = b[t12]
117: t14 = t11 * t13
118: *t9 = t14
119: goto 104
120: t15 = i << 2
121: t16 = c + t15
122: *t16 = 0
123: goto 104
124: return
```

TC Generation Steps – Memory Binding

- Generate AR from ST – memory binding for local variables

```
int Sum(int a[], int n) {
    int i, s = 0;
    for(i = 0; i < n; ++i) {
        int t;
        t = a[i];
        s += t;
    }
    return s;
}
```

```
Sum:    s = 0
        i = 0
L0:     if i < n goto L2
        goto L3
L1:     i = i + 1
        goto L0
L2:     t1 = i * 4
        t_1 = a[t1]
        s = s + t_1
        goto L1
L3:     return s
```

Symbol Table

a	int[]	param	4	0
n	int	param	4	4
i	int	local	4	8
s	int	local	4	12
t_1	int	local	4	16
t1	int	temp	4	20

Activation Record

t1	int	temp	4	−16
t_1	int	local	4	−12
s	int	local	4	−8
i	int	local	4	−4
a	int[]	param	4	+8
n	int	param	4	+12

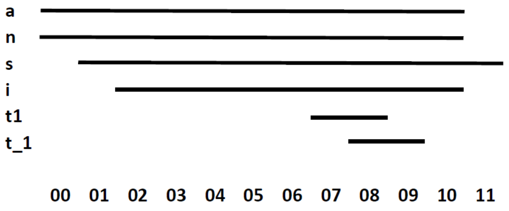
TC Generation Steps – Memory Binding

- Generate Static Allocation from ST.gbl – memory binding for global variables
  - Use DATA SEGMENT
- Generate Constants from Table of Constants
  - Use CONST SEGMENT
- Create memory binding for variables – register allocations
  - After a load / store the variable on the activation record and the register have identical values
  - Register allocations are often used to pass `int` or pointer parameters
  - Register allocations are often used to return `int` or pointer values

TC Generation Steps – Register Allocation & Assignment

- DEF-USE / Liveness Analysis / Interval Graph

```
000:                          // a, n
001:     s = 0                // a, n, s
002:     i = 0                // a, n, s, i
003: L0: if i < n goto L2     // a, n, s, i
004:     goto L3              // a, n, s, i
005: L1: i = i + 1            // a, n, s, i
006:     goto L0              // a, n, s, i
007: L2: t1 = i * 4           // a, n, s, i, t1
008:     t_1 = a[t1]          // a, n, s, i, t1, t_1
009:     s = s + t_1          // a, n, s, i, t_1
010:     goto L1              // a, n, s, i
011: L3: return s             // s
```



TC Generation Steps – Register Allocation & Assignment

Using a linear scan algorithm one can allocate and assign registers:

1. Perform DFA to gather liveness information. Keep track of all variables' live intervals, the interval when a variable is live, in a list sorted in order of increasing start point (this ordering is free if the list is built when computing liveness). We consider variables and their intervals to be interchangeable in this algorithm.
2. Iterate through liveness start points and allocate a register from the available register pool to each live variable.

TC Generation Steps – Register Allocation & Assignment

3. At each step maintain a list of active intervals sorted by the end point of the live intervals. (Note that insertion sort into a balanced binary tree can be used to maintain this list at linear cost). Remove any expired intervals from the active list and free the expired interval's register to the available register pool.
4. In the case where the active list is size R we cannot allocate a register. In this case add the current interval to the active pool without allocating a register. Spill the interval from the active list with the furthest end point. Assign the register from the spilled interval to the current interval or, if the current interval is the one spilled, do not change register assignments.

TC Generation Steps – Code Translation

- Generate Function Prologue – few lines of code at the beginning of a function, which prepare the stack and registers for use within the function
  - Pushes the old base pointer onto the stack, such that it can be restored later.

    ```
    push ebp
    ```
  - Assigns the value of stack pointer (which is pointed to the saved base pointer and the top of the old stack frame) into base pointer such that a new stack frame will be created on top of the old stack frame.

    ```
    mov ebp, esp
    ```
  - Moves the stack pointer further by decreasing its value to make room for variables (i.e. the function's local variables).

    ```
    sub esp, 12
    ```
  - Save the registers on the stack by push

    ```
    push esi
    ```

TC Generation Steps – Code Translation

- Generate Function Epilogue – appears at the end of the function, and restores the stack and registers to the state they were in before the function was called
  - Restore the registers from the stack by pop

    ```
    pop esi
    ```
  - Replaces the stack pointer with the current base (or frame) pointer, so the stack pointer is restored to its value before the prologue

    ```
    mov esp, ebp
    ```
  - Pops the base pointer off the stack, so it is restored to its value before the prologue

    ```
    pop ebp
    ```
  - Returns to the calling function, by popping the previous frame's program counter off the stack and jumping to it

    ```
    ret 0
    ```

TC Generation Steps – Code Translation

- Map TAC to Assembly
  - Choose optimized assembly instructions
  - Algebraic Simplification & Reduction of Strength
  - Use of Machine Idioms

TC Generation Steps – Target Code Optimization

- Optimize Target Code
  - Eliminating Redundant Load-Store
  - Eliminating Unreachable Code
  - Flow of Control Optimization

TC Generation Steps – Target Code Management

- Integration into an Assembly File
- Link Information Generation – for multi-source build

TAC to Target Assembly Mapping

Code Mapping

Code Mapping – Unary, Binary & Copy Assignment

int a, b, c;

TAC	x86	Remarks
`a = 5`	`mov DWORD PTR _a$[ebp], 5`	**mov r/m32,imm32**: Move imm32 to r/m32.

`a = b`	`mov eax, DWORD PTR _b$[ebp]`
	`mov DWORD PTR _a$[ebp], eax`
		mov r32,r/m32: Move r/m32 to r32.
		mov r/m32,r32: Move r32 to r/m32.

`a = -b`	`mov eax, DWORD PTR _b$[ebp]`
	`neg eax`
	`mov DWORD PTR _a$[ebp], eax`
		neg r/m32: Two's complement negate r/m32.

`a = b + c`	`mov eax, DWORD PTR _b$[ebp]`
	`add eax, DWORD PTR _c$[ebp]`
	`mov DWORD PTR _a$[ebp], eax`
		add r32, r/m32: Add r/m32 to r32

`a = b - c`	`mov eax, DWORD PTR _b$[ebp]`
	`sub eax, DWORD PTR _c$[ebp]`
	`mov DWORD PTR _a$[ebp], eax`
		sub r32,r/m32: Subtract r/m32 from r32.

`a = b * c`	`mov eax, DWORD PTR _b$[ebp]`
	`imul eax, DWORD PTR _c$[ebp]`
	`mov DWORD PTR _a$[ebp], eax`
		imul r/m32: EDX:EAX = EAX * r/m doubleword.

`a = b / c`	`mov eax, DWORD PTR _b$[ebp]`
	`cdq`
	`idiv DWORD PTR _c$[ebp]`
	`mov DWORD PTR _a$[ebp], eax`
		cdq: EDX:EAX = sign-extend of EAX. Convert Doubleword to Quadword
		idiv r/m32: Signed divide EDX:EAX by r/m32, with result stored in EAX = Quotient, EDX = Remainder.

`a = b % c`	`mov eax, DWORD PTR _b$[ebp]`
	`cdq`
	`idiv DWORD PTR _c$[ebp]`
	`mov DWORD PTR _a$[ebp], edx`	

Code Mapping – Unconditional & Conditional Jump

TAC	x86	Remarks
`goto L1`	`jmp  SHORT $L1$1017`	**jmp rel8**: Jump short, relative, displacement relative to next instruction. Mapped target address for L1 is $L1$1017.

`if a < b goto L1`	`mov eax, DWORD PTR _a$[ebp]`
	`cmp eax, DWORD PTR _b$[ebp]`
	`jge SHORT $LN1@main`
	`jmp SHORT $L1$1018`
	`$LN1@main:`
		cmp r32,r/m32: Compare r/m32 with r32. Compares the first operand with the second operand and sets the status flags in the EFLAGS register according to the results.
		jge rel8: Jump short if greater or equal (SF=OF).
		Input label L1 transcoded to $L1$1018 and new temporary label $LN1@main used.

`if a == b goto L1`	`mov`
	`eax, DWORD PTR _a$[ebp]`
	`cmp`
	`eax, DWORD PTR _b$[ebp]`
	`jne  SHORT $LN1@main`
	`jmp  SHORT $L1$1018`
	`$LN1@main:`
		jne rel8: Jump short if not equal (ZF=0).

`if a goto L1`	`cmp  DWORD PTR _a$[ebp], 0`
	`je  SHORT $LN1@main`
	`jmp  SHORT $L1$1018`
	`$LN1@main:`
		je rel8: Jump short if equal (ZF=1).

`ifFalse a goto L1`	`cmp  DWORD PTR _a$[ebp], 0`
	`jne  SHORT $LN1@main`
	`jmp  SHORT $L1$1018`
	`$LN1@main:`	

Code Mapping – Function Call & Return

int f(int x, int y, int z) { int m = 5; return m; }
...
int a, b, c, d;
d = f(a, b, c);

TAC	x86	Remarks
`param a` `param b` `param c` `d = call f, 3`	`mov eax, DWORD PTR _c$[ebp]` `push eax` `mov eax, DWORD PTR _b$[ebp]` `push eax` `mov eax, DWORD PTR _a$[ebp]` `push eax` `call _f`	**push r32**: Push r32. Decrements the stack pointer and then stores the source operand on the top of the stack. **call rel32**: Call near, relative, displacement relative to next instruction. Saves procedure linking information on the stack and branches to the procedure (called procedure) specified with the destination (target) operand.
	`add esp, 12 ; 0000000cH`	Adjust the stack pointer back (for parameters)
	`mov DWORD PTR _c$[ebp], eax`	Return value passed through eax
`In f()`	`push ebp` `mov ebp, esp`	Save base pointer & set new base pointer
`return m`	`mov eax, DWORD PTR _m$[ebp]` `mov esp, ebp` `pop ebp` `ret 0`	**pop r/m32**: Pop top of stack into m32; increment stack pointer. **ret imm16**: Near return to calling procedure and pop imm16 bytes from stack..

Code Mapping – Indexed Copy, Address & Pointer Assignment

int a, x[10], i = 0, b, *p = 0;

TAC	x86	Remarks

`a = x[i]`	`mov edx, DWORD PTR _i$[ebp]`
	`mov eax, DWORD PTR _x$[ebp+edx*4]`
	`mov DWORD PTR _a$[ebp], eax`	

`x[i] = b`	`mov edx, DWORD PTR _i$[ebp]`
	`mov eax, DWORD PTR _b$[ebp]`
	`mov DWORD PTR _x$[ebp+edx*4], eax`	

`p = &a`	`lea eax, DWORD PTR _a$[ebp]`
	`mov DWORD PTR _p$[ebp], eax`
		lea r32,m: Store effective address for m in register r32. Computes the effective address of the second operand (the source operand) and stores it in the first operand (destination operand). The source operand is a memory address (offset part) specified with one of the processors addressing modes; the destination operand is a general-purpose register.

`a = *p`	`mov eax, DWORD PTR _p$[ebp]`
	`mov ecx, DWORD PTR [eax]`
	`mov DWORD PTR _a$[ebp], ecx`	

`*p = b`	`mov eax, DWORD PTR _p$[ebp]`
	`mov ecx, DWORD PTR _b$[ebp]`
	`mov DWORD PTR [eax], ecx`	

Code Mapping – Unary, Binary & Copy Assignment: double

double a = 1, b = 7, c = 2;
CONST SEGMENT
__real@40140000 DQ 040140000r ; 5
__real@40000000 DQ 040000000r ; 2
__real@401c0000 DQ 0401c0000r ; 7
__real@3ff00000 DQ 03ff00000r ; 1

TAC	x86	Remarks

`a = 5`	`fld  QWORD PTR __real@40140000`
	`fstp QWORD PTR _a$[ebp]`
		fld m32fp: Push m32fp onto the FPU register stack. **fstp m32fp**: Copy ST(0) to m32fp and pop register stack.

`a = b`	`fld  QWORD PTR _b$[ebp]`
	`fstp QWORD PTR _a$[ebp]`	

`a = -b`	`fld  QWORD PTR _b$[ebp]`
	`fchs`
	`fstp QWORD PTR _a$[ebp]`
		fchs: Change Sign. Complements the sign bit of ST(0). This operation changes a positive value into a negative value of equal magnitude or vice versa.

`a = b + c`	`fld  QWORD PTR _b$[ebp]`
	`fadd QWORD PTR _c$[ebp]`
	`fstp QWORD PTR _a$[ebp]`
		fadd m32fp: Add m32fp to ST(0) and store result in ST(0).

`a = b - c`	`fld  QWORD PTR _b$[ebp]`
	`fsub QWORD PTR _c$[ebp]`
	`fstp QWORD PTR _a$[ebp]`
		fsub m32fp: Subtract m32fp from ST(0) and store result in ST(0).

`a = b * c`	`fld  QWORD PTR _b$[ebp]`
	`fmul QWORD PTR _c$[ebp]`
	`fstp QWORD PTR _a$[ebp]`
		fmul m32fp: Multiply ST(0) by m32fp and store result in ST(0).

`a = b / c`	`fld  QWORD PTR _b$[ebp]`
	`fdiv QWORD PTR _c$[ebp]`
	`fstp QWORD PTR _a$[ebp]`
		fdiv m32fp: Divide ST(0) by m32fp and store result in ST(0).