Machine Code Generation - 3

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Outline of the Lecture

- Mach. code generation – main issues (in part 1)
- Samples of generated code (in part 2)
- Two Simple code generators (in part 2)
- Optimal code generation
  - Sethi-Ullman algorithm
  - Dynamic programming based algorithm
  - Tree pattern matching based algorithm
- Code generation from DAGs
- Peephole optimizations

Optimal Code Generation - The Sethi-Ullman Algorithm

- Generates the shortest sequence of instructions
  - Provably optimal algorithm (w.r.t. length of the sequence)
- Suitable for expression trees (basic block level)
- Machine model
  - All computations are carried out in registers
  - Instructions are of the form *op R,R* or *op M,R*
- **Always computes the left subtree into a register and reuses it immediately**
- Two phases
  - Labelling phase
  - Code generation phase

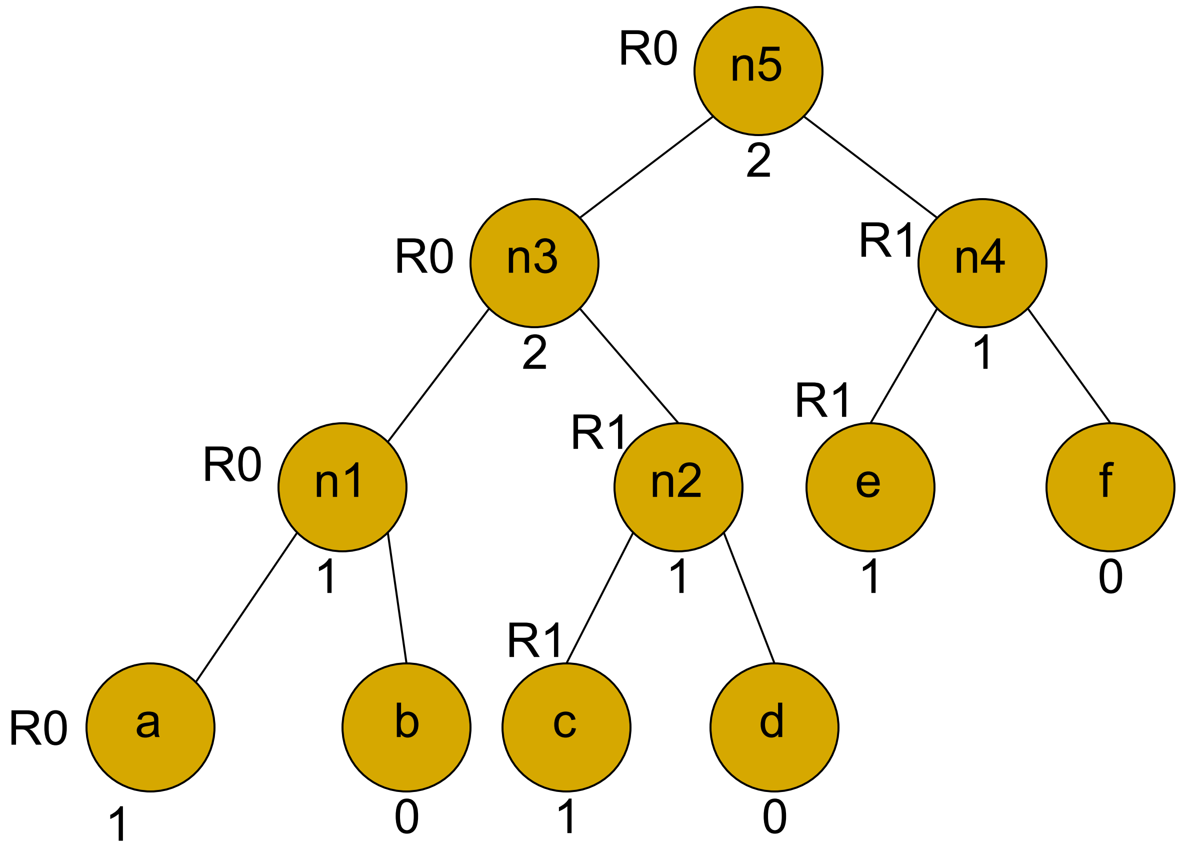
The Labelling Algorithm

- Labels each node of the tree with an integer:
  - fewest no. of registers required to evaluate the tree with no intermediate stores to memory
  - Consider binary trees
- For leaf nodes
  - ***if*** **n** is the leftmost child of its parent ***then***

    label(n) := 1 ***else*** **label(n) := 0**
- For internal nodes
  - **label(n) = max (l_1, l_2), if l_1 <> l_2**

    = l_1 + 1, if $l_1 = l_2$

Labelling - Example



Code Generation Phase – Procedure GENCODE(n)

- RSTACK – stack of registers, $R_0,\ldots,R_{(r-1)}$
- TSTACK – stack of temporaries, $T_0,T_1,\ldots$
- A call to Gencode(n) generates code to evaluate a tree T, rooted at node n, into the register top (RSTACK) ,and
  - the rest of RSTACK remains in the same state as the one before the call
- A swap of the top two registers of RSTACK is needed at some points in the algorithm to ensure that a node is evaluated into the same register as its left child.

The Code Generation Algorithm (1)

Procedure gencode(n);

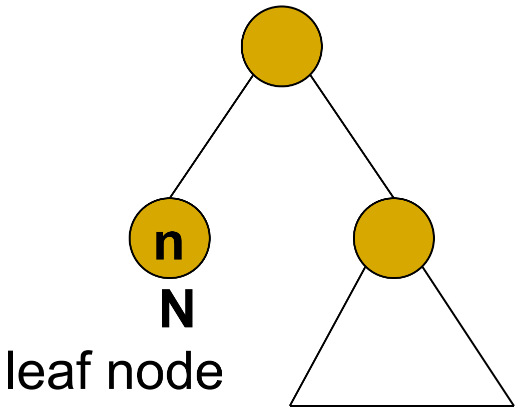
{ /* case 0 */

if

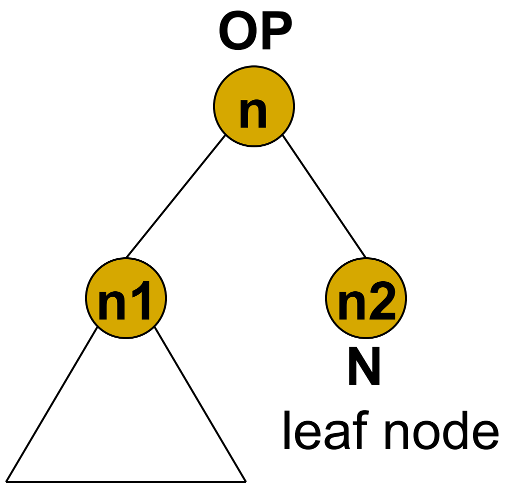
n is a leaf representing operand N and is the leftmost child of its parent

then

print(LOAD N, top(RSTACK))



The Code Generation Algorithm (2)



/* case 1 */

else if

n is an interior node with operator OP, left child n1, and right child n2

then

if label(n2) == 0 ***then*** **{**

let N be the operand for n2;

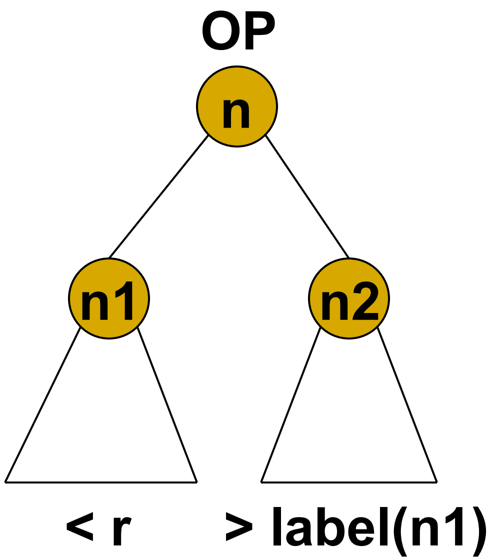
gencode(n1);

print(OP N, top(RSTACK));

}

The Code Generation Algorithm (3)

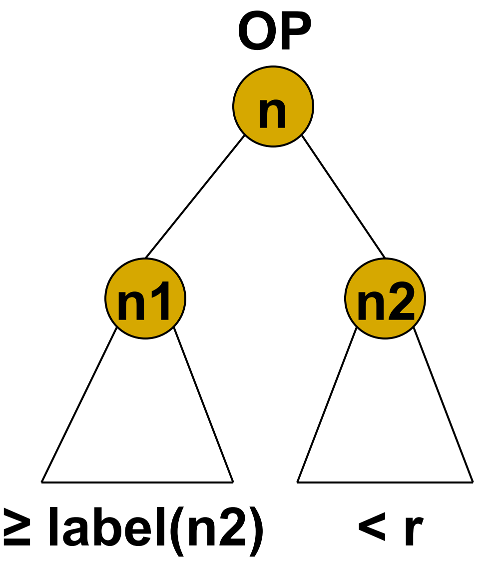
```
/* case 2 */
else if ((1 ≤ label(n1) < label(n2))
            and( label(n1) < r))
then {
   swap(RSTACK); gencode(n2);
   R := pop(RSTACK); gencode(n1);
   /* R holds the result of n2 */
   print(OP R, top(RSTACK));
   push (RSTACK,R);
   swap(RSTACK);
   }
```



The swap() function ensures that a node is evaluated into the same register as its left child

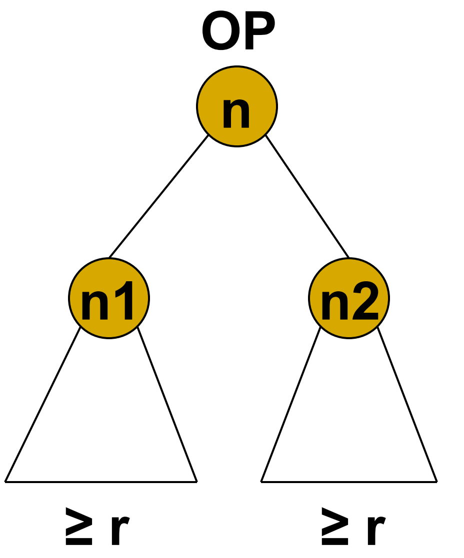
The Code Generation Algorithm (4)

```
/* case 3 */
else if ((1 ≤ label(n2) ≤ label(n1))
           and( label(n2) < r))
then {
  gencode(n1);
  R := pop(RSTACK); gencode(n2);
  /* R holds the result of n1 */
  print(OP  top(RSTACK), R);
  push (RSTACK,R);
  }
```



The Code Generation Algorithm (5)

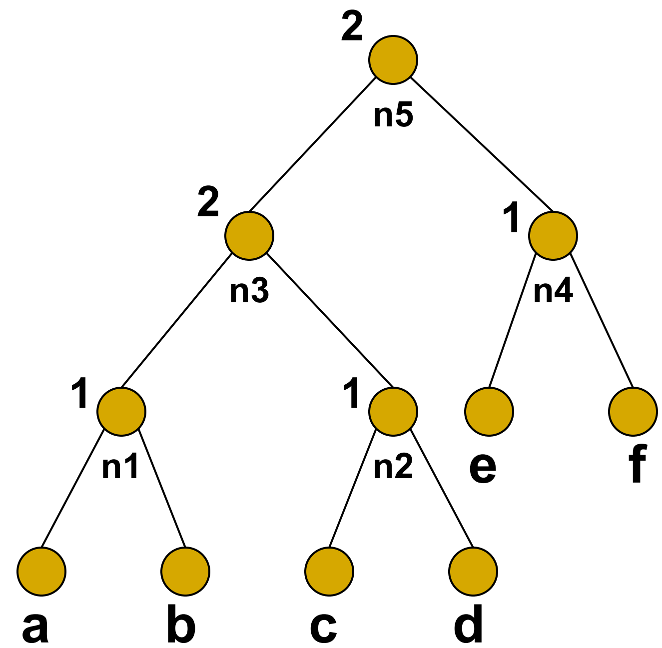
```
/* case 4, both labels are ≥ r */
else {
    gencode(n2); T:= pop(TSTACK);
    print(LOAD top(RSTACK), T);
    gencode(n1);
    print(OP T, top(RSTACK));
    push(TSTACK, T);
    }
}
```



Code Generation Phase – Example 1

No. of registers = r = 2

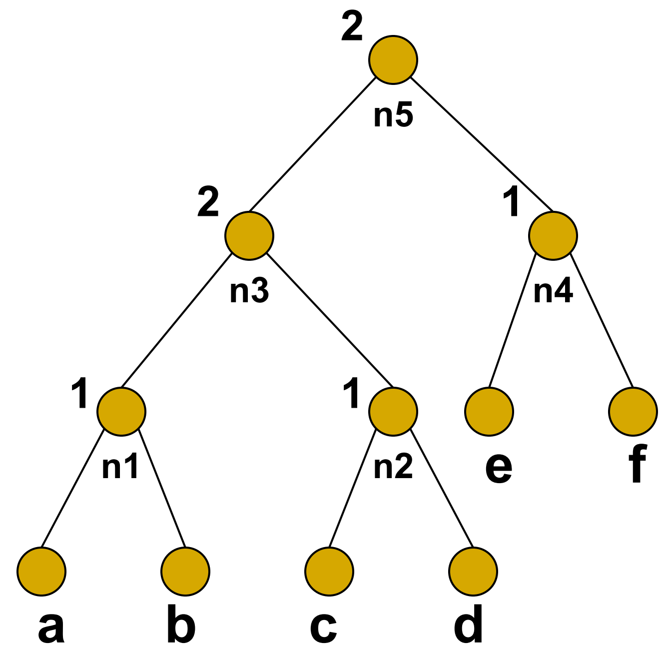
n5 → n3 → n1 → a → Load a, R0
→ op_{n1} b, R0
→ n2 → c → Load c, R1
→ op_{n2} d, R1
→ op_{n3} R1, R0
→ n4 → e → Load e, R1
→ op_{n4} f, R1
→ op_{n5} R1, R0



Code Generation Phase – Example 2

No. of registers = r = 1.
Here we choose *rst* first so that *lst* can be computed into R0 later (case 4)

n5 → n4 → e → Load e, R0
→ op_{n4} f, R0
→ Load R0, T0 {release R0}
→ n3 → n2 → c → Load c, R0
→ op_{n2} d, R0
→ Load R0, T1 {release R0}
→ n1 → a → Load a, R0
→ op_{n1} b, R0
→ op_{n3} T1, R0 {release T1}
→ op_{n5} T0, R0 {release T0}

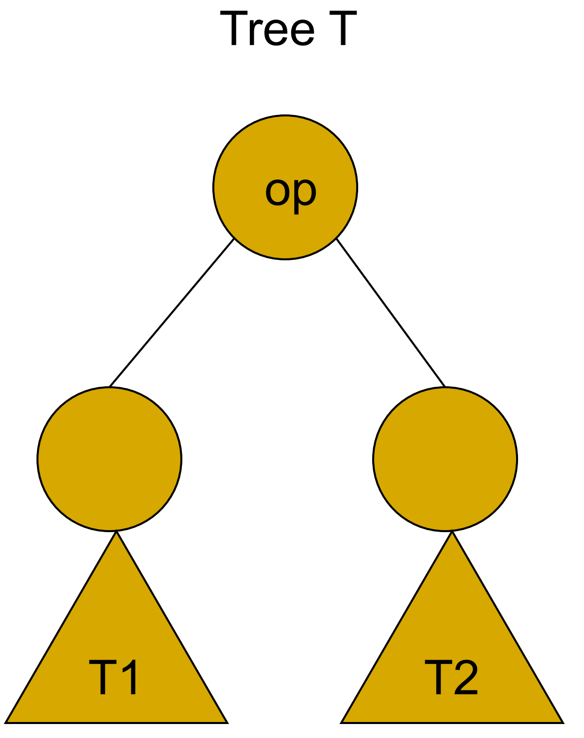


Dynamic Programming based Optimal Code Generation for Trees

- Broad class of register machines
  - r interchangeable registers, $R_0,\ldots,R_{r-1}$
  - Instructions of the form $R_i := E$
    - If E involves registers, R_i must be one of them
    - $R_i := M_j$, $R_i := R_i \; op \; R_j$, $R_i := R_i \; op \; M_j$, $R_i := R_j$, $M_i := R_j$
- Based on principle of contiguous evaluation
- Produces optimal code for trees (basic block level)
- Can be extended to include a different cost for each instruction

Contiguous Evaluation

- First evaluate subtrees of *T* that need to be evaluated into memory. Then,
  - Rest of *T1, T2, op*, in that order, *OR,*
  - Rest of *T2, T1, op*, in that order
- Part of *T1*, part of *T2*, part of *T1* again, etc., is *not* contiguous evaluation
- Contiguous evaluation is optimal!
  - No higher cost and no more registers than optimal evaluation



The Algorithm (1)

1. Compute in a bottom-up manner, for each node *n* of *T*, an array of costs, *C*
   - *C[i]* = *min* cost of computing the complete subtree rooted at *n*, assuming *i* registers to be available
     - Consider each machine instruction that matches at *n* and consider all possible contiguous evaluation orders (using dynamic programming)
     - Add the cost of the instruction that matched at node *n*

The Algorithm (2)

- Using *C*, determine the subtrees that must be computed into memory (based on cost)
- Traverse *T*, and emit code
  - memory computations first
  - rest later, in the order needed to obtain optimal cost
- Cost of computing a tree into memory = cost of computing the tree using all registers + 1 (store cost)

An Example

Max no. of registers = 2

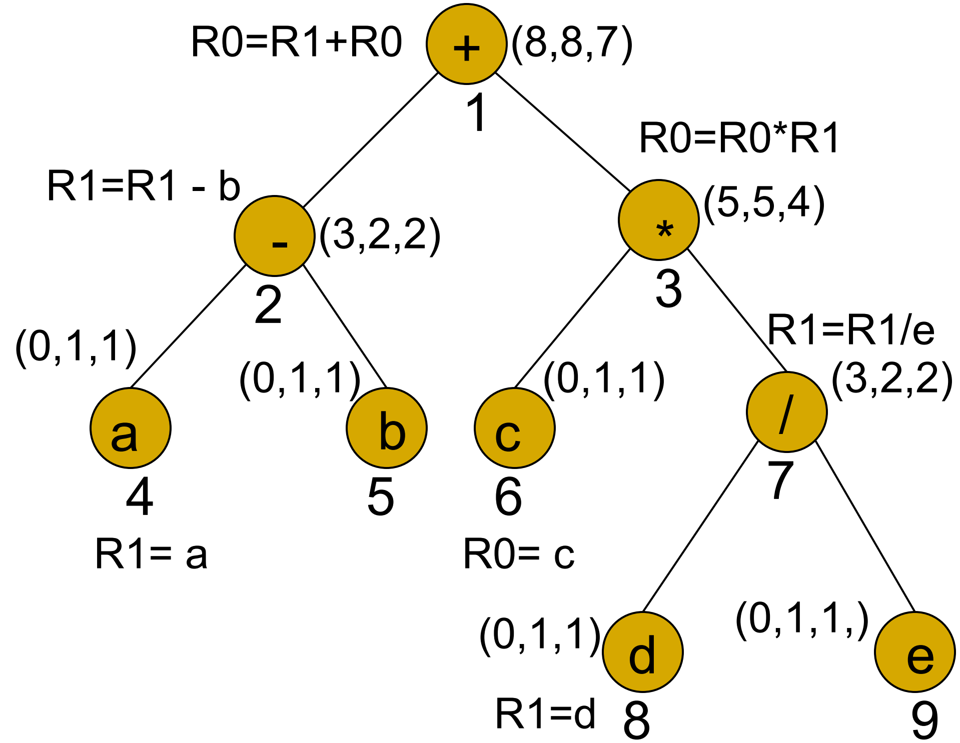
Node 2: matching instructions

R*i* = R*i* – M (*i* = 0,1) and
R*i* = R*i* – R*j* (*i,j* = 0,1)

C2[1] = C4[1] + C5[0] + 1
= 1+0+1 = 2

C2[2] = Min{ C4[2] + C5[1] + 1,
C4[2] + C5[0] + 1,
C4[1] + C5[2] + 1,
C4[1] + C5[1] + 1,
C4[1] + C5[0] + 1}
= Min{1+1+1,1+0+1,1+1+1,
1+1+1,1+0+1}
= Min{3,2,3,3,2} = 2

C2[0] = 1+ C2[2] = 1+2 = 3



R0 = c
R1 = d
R1 = R1 / e
R0 = R0 * R1
R1 = a
R1 = R1 – b
R0 = R1 + R0

Generated sequence of instructions

Example – continued
Cost of computing node 3 with 2 registers

#regs for node 6	#regs for node 7	cost for node 3
2	0	1+3+1 = 5
2	1	1+2+1 = 4
1	0	1+3+1 = 5
1	1	1+2+1 = 4
1	2	1+2+1 = 4
	min value	4

Cost of computing with 1 register = 5 (row 4, red)
Cost of computing into memory = 4 + 1 = 5

Triple = (5,5,4)

Example – continued
Traversal and Generating Code

Min cost for node 1=7, Instruction: R0 := R1+R0

Compute RST(3) with 2 regs into R0

Compute LST(2) into R1

For node 3, instruction: R0 := R0 * R1

Compute RST(7) with 2 regs into R1

Compute LST(6) into R0

For node 7, instruction: R1 := R1 / e

Compute RST(9) into memory (already available)

Compute LST(8) into R1

For node 8, instruction: R1 := d

For node 6, instruction: R0 := c

For node 2, instruction: R1 := R1 – b

Compute RST(5) into memory (available already)

Compute LST(4) into R1

For node 4, instruction: R1 := a