Module 10: Compilers: Simple Code Generators

Profs. Pralay Mitra and Partha Pratim Das

pralay@cse.iitkgp.ac.in, ppd@cse.iitkgp.ac.in

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Department of Computer Science & Engineering

Outline of the Lecture

- Code generation – main issues
- Samples of generated code
- Two Simple code generators
- Optimal code generation
  - Sethi-Ullman algorithm
- Peephole optimizations

Code Generation – Main Issues (1)

- Transformation:
  - Intermediate code → m/c code (binary or assembly)
  - We assume quads, CFG and ST to be available
- Which instructions to generate?
  - For the quadruple A = A+1, we may generate
    - Inc A *or*
    - Load A, R1
      Add #1, R1
      Store R1, A
  - One sequence is faster than the other
    - cost implication

Code Generation – Main Issues (2)

- In which order?
  - Some orders may use fewer registers and/or may be faster
- Which registers to use?
  - Optimal assignment of registers to variables is difficult to achieve
- Optimize for memory, time or power?
- Is the code generator easily retargetable to other machines?
  - Can the code generator be produced automatically from specifications of the machine?

Samples of Generated Code

- B = A[i]
```
Load   i, R1 // R1 = i
Mult   R1,4,R1// R1 = R1*4
// each element of array
// A is 4 bytes long
Load   A(R1), R2// R2=(A+R1)
Store  R2, B// B = R2
```
- X[j] = Y
```
Load  Y, R1// R1 = Y
Load  j, R2// R2 = j
Mult   R2, 4, R2// R2=R2*4
Store  R1, X(R2)// X(R2)=R1
```
- X = *p
```
Load   p, R1
Load   0(R1), R2
Store  R2, X
```
- *q = Y
```
Load   Y, R1
Load   q, R2
Store   R1, 0(R2)
```
- if X < Y goto L
```
Load  X, R1
Load  Y, R2
Cmp   R1, R2
Bltz     L // Branch on less than 0
```

A Simple Code Generator – Scheme A

- Treat each quadruple as a 'macro'
  - Example: The quad *A := B + C* will result in

```
Load B, R1   OR   Load B, R1
Load C, R2
Add R2, R1        Add C, R1
Store R1, A       Store R1, A
```

  - Results in inefficient code
    - Repeated load/store of registers
  - Very simple to implement

A Simple Code Generator – Scheme B

- Track values in registers and reuse them
  - If any operand is already in a register, take advantage of it
  - Register descriptors
    - Tracks <register, variable name> pairs
    - A single register can contain values of multiple names, if they are all copies
  - Address descriptors
    - Tracks <variable name, location> pairs
    - A single name may have its value in multiple locations, such as, memory, register, and stack

A Simple Code Generator – Scheme B

- Leave computed result in a register as long as possible
- Store only at the end of a basic block or when that register is needed for another computation
  - On exit from a basic block, store only live variables which are not in their memory locations already (use address descriptors to determine the latter)
  - If liveness information is not known, assume that all variables are live at all times

Example

- A := B+C
  - If B and C are in registers R1 and R2, then generate
    - *ADD R2,R1* (cost = 1, result in R1)
      - legal only if B is *not live* after the statement
  - If R1 contains B, but C is in memory
    - *ADD C,R1* (cost = 2, result in R1) **or**
    - *LOAD C, R2*

      ADD R2,R1 (cost = 3, result in R1)
      - legal only if B is *not live* after the statement
      - attractive if the value of C is subsequently used
        - It can be taken from R2

Next Use Information

- Next use info is used in code generation and register allocation
- Next use of *A* in quad *i* is *j* if

Quad *i* : A = ... (assignment to A)

$\Downarrow$ (control flows from *i* to *j* with no assignments to A)

Quad *j* : = A op B (usage of A)

- In computing next use, we assume that on exit from the basic block
  - All temporaries are considered non-live
  - All programmer defined variables (and non-temps) are live
- Each procedure/function call is assumed to start a basic block
- Next use is computed on a backward scan on the quads in a basic block, starting from the end
- Next use information is stored in the symbol table

Example of computing Next Use

3	T1 := 4 * I	T1 – (nlv, lu 0, nu 5), I – (lv, lu 3, nu 10)
4	T2 := addr(A) – 4	T2 – (nlv, lu 0, nu 5), A – (lv, lu 4, nnu)
5	T3 := T2[T1]	T3 – (nlv, lu 0, nu 8), T2 – (nlv, lu 5, nnu), T1 – (nlv, lu 5, nu 7)
6	T4 := addr(B) – 4	T4 – (nlv, lu 0, nu 7), B – (lv, lu 6, nnu)
7	T5 := T4[T1]	T5 – (nlv, lu 0, nu 8), T4 – (nlv, lu 7, nnu), T1 – (nlv, lu 7, nnu)
8	T6 := T3 * T5	T6 – (nlv, lu 0, nu 9),T3 – (nlv, lu 8, nnu), T5 – (nlv, lu 8, nnu)
9	PROD := PROD + T6	PROD – (lv, lu 9, nnu), T6 – (nlv, lu 9, nnu)
10	I := I + 1	I – (lv, lu 10, nu 11)
11	if I ≤ 20 goto 3	I – (lv, lu 11, nnu)

nlv: not live **lv**: live **lu**: last use **nu**: next use **nnu**: no next use **lu 0**: no last use

Scheme B – The algorithm

- We deal with one basic block at a time
- We assume that there is no global register allocation
- For each quad *A := B op C* do the following
  - Find a location *L* to perform *B op C*
    - Usually a register returned by *GETREG*() (could be a mem loc)
  - Where is *B*?
    - *B*' , found using address descriptor for *B*
    - Prefer register for *B*', if it is available in memory and register
    - Generate *Load B' , L* (if *B*' is not in *L*)
  - Where is *C*?
    - *C*' , found using address descriptor for *C*
    - Generate *op C' , L*
  - Update descriptors for *L* and *A*
  - If *B/C* have no next uses, update descriptors to reflect this information

Function *GETREG*( )

Finds *L* for computing *A := B op C*

1. If *B* is in a register (say *R*), R holds no other names, and
   - *B* has no next use, and *B* is not live after the block, then return *R*
2. Failing (1), return an empty register, if available
3. Failing (2)
   - If *A* has a next use in the block, OR
     if *B op C* needs a register (*e.g.*, *op* is an indexing operator)
     - Use a *heuristic* to find an occupied register R
       - **a register whose contents are referenced farthest in future, or**
       - **the number of next uses is smallest etc.**
     - *Spill* it by generating an instruction, *MOV R, mem*
       - ***mem* is the memory location for the variable in *R***
       - **That variable is not already in *mem***
     - Update *Register* and *Address* descriptors
4. If *A* is not used in the block, or no suitable register can be found
   - Return a memory location for *L*

Example

T,U, and V are temporaries – not live at the end of the block
W is a non-temporary – live at the end of the block, 2 registers

Statements	Code Generated	Register Descriptor	Address Descriptor
T := A * B	Load A,R0 Mult B, R0	R0 contains T	T in R0
U := A + C	Load A, R1 Add C, R1	R0 contains T R1 contains U	T in R0 U in R1
V := T - U	Sub R1, R0	R0 contains V R1 contains U	U in R1 V in R0
W := V * U	Mult R1, R0	R0 contains W	W in R0
	Store R0, W		W in memory (restored)

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_s,R_t or *op* M_s,R_t
- Always computes the left subtree into a register and reuses it immediately
- Two phases
  - Labelling phase
  - Code generation phase

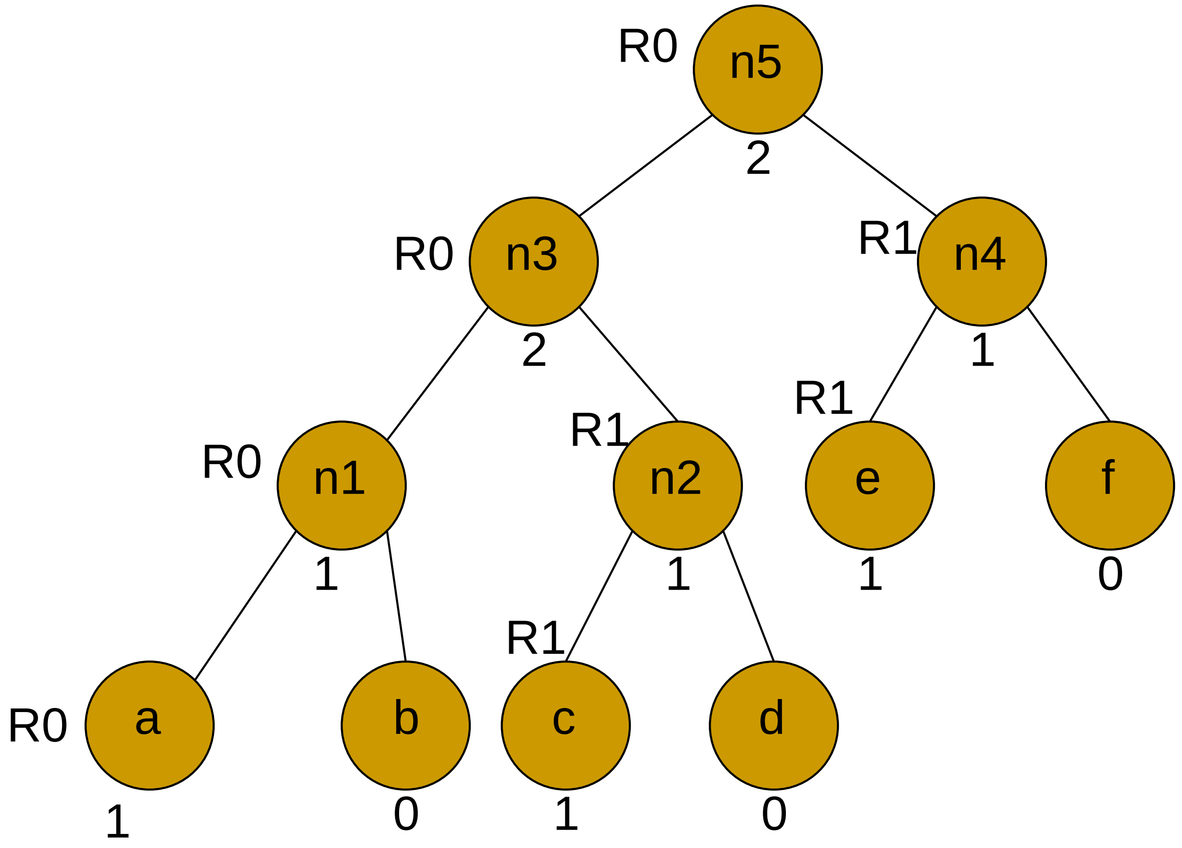
The Labelling Algorithm

- Label each node of the tree with an integer:
  - Consider binary trees
  - Fewest no. of registers required to evaluate the tree with no intermediate stores to memory
- 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

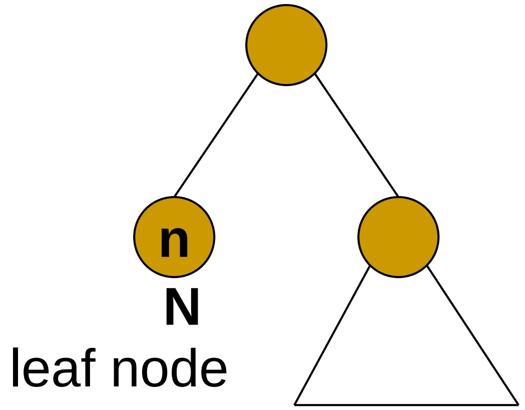


Code Generation Phase – Procedure GENCODE(n)

- RSTACK – stack of registers, R_0,...,$R_{(r-1)}$
- TSTACK – stack of temporaries, T_0,T_1,...
- 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.

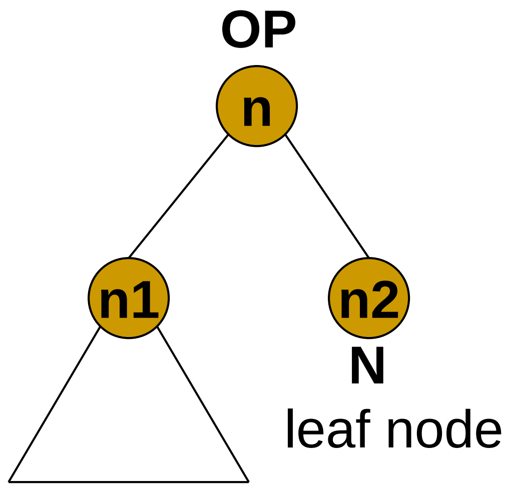
The Code Generation Algorithm (1)

```
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))
```



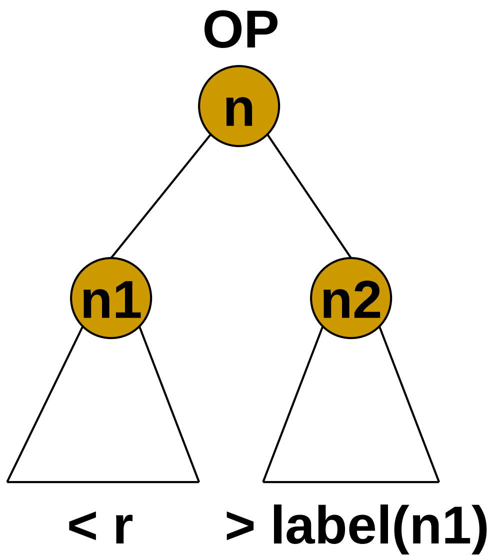
The Code Generation Algorithm (2)

```
/* 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)

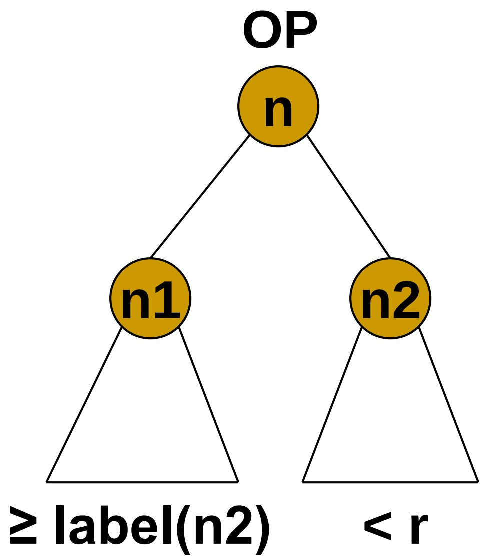
```
/* case 2 */
else if ((1 ≤ label(n1) < label(n2))
            and (label(n1) < r))
then {
   swap(RSTACK); gencode(n2);
   R := pop(RSTACK); gencode(n1);
   /* R holds the result of n2 */
   print(OP R, top(RSTACK));
   push (RSTACK,R);
   swap(RSTACK);
   }
```



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

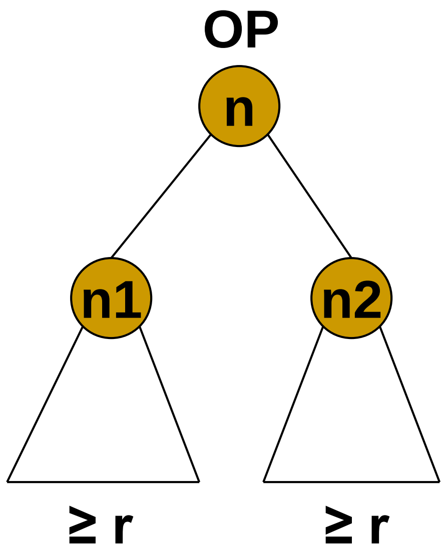
The Code Generation Algorithm (4)

```
/* 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

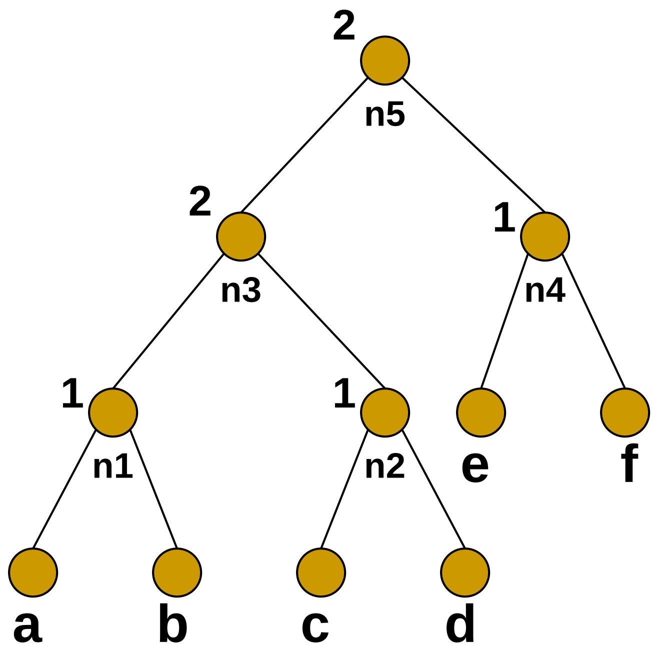
No. of registers = r = 2

n5 → n3 (case 3)

- n1 → a (case 3)
- 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

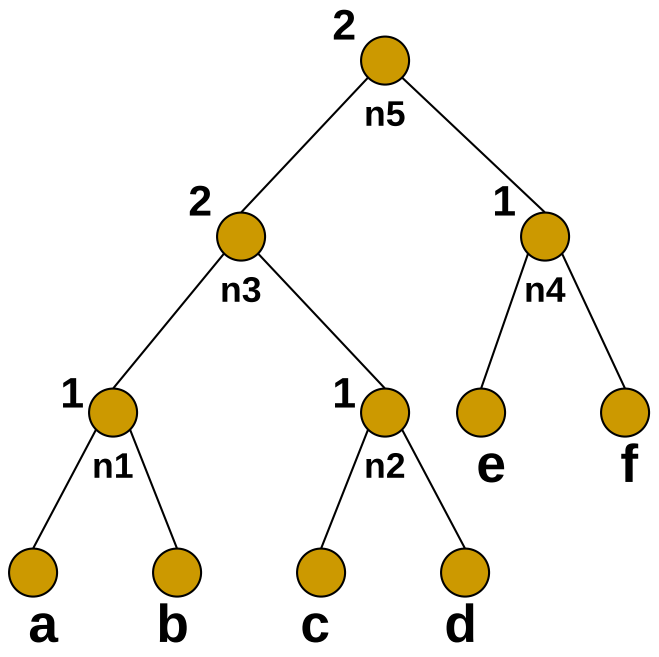
→ op$_{n5}$ R1, R0



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}



Peephole Optimizations

- Simple but effective local optimization
- Usually carried out on machine code, but intermediate code can also benefit from it
- Examines a sliding window of code (peephole), and replaces it by a shorter or faster sequence, if possible
- Each improvement provides opportunities for additional improvements
- Therefore, repeated passes over code are needed

Peephole Optimizations

- Some well known peephole optimizations
  - eliminating redundant instructions
  - eliminating unreachable code
  - eliminating jumps over jumps
  - algebraic simplifications
  - strength reduction
  - use of machine idioms

Elimination of Redundant Loads and Stores

Basic block B

```
Load X, R0
{no modifications
to X or R0 here}
Store R0, X
```

Store instruction can be deleted

Basic block B

```
Load X, R0
{no modifications
to X or R0 here}
Load X, R0
```

Second Load instr can be deleted

Basic block B

```
Store R0, X
{no modifications
to X or R0 here}
Load X, R0
```

Load instruction can be deleted

Basic block B

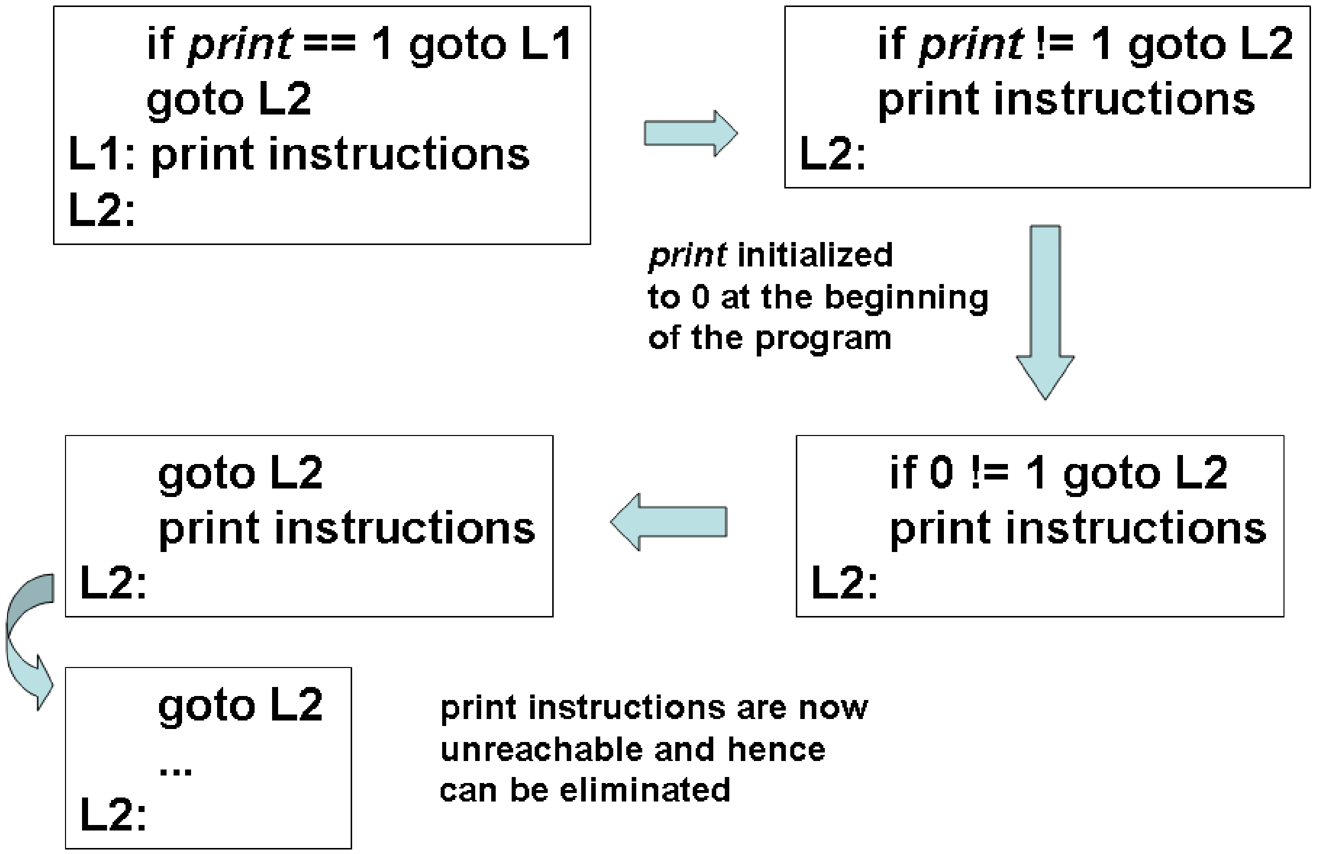
```
Store R0, X
{no modifications
to X or R0 here}
Store R0, X
```

Second Store instr can be deleted

Eliminating Unreachable Code

- An unlabeled instruction immediately following an unconditional jump may be removed
  - May be produced due to debugging code introduced during development
  - Or due to updates to programs (changes for fixing bugs) without considering the whole program segment

Eliminating Unreachable Code



```
      if print == 1 goto L1
      goto L2
L1: print instructions
L2:
```

```
      if print != 1 goto L2
      print instructions
L2:
```

print initialized
to 0 at the beginning
of the program

```
      if 0 != 1 goto L2
      print instructions
L2:
```

```
      goto L2
      print instructions
L2:
```

```
      goto L2
      ...
L2:
```

print instructions are now
unreachable and hence
can be eliminated

Flow-of-Control Optimizations

```
    goto L1
      ...
L1: goto L2
      ...
```

```
    goto L2
      ...
L1: goto L2
      ...
```

No jumps to L1

```
    goto L2
      ...
      ...
```

Statement L1: ... can be removed only if it is preceded by an unconditional jump

```
if a<b goto L1
      ...
L1: goto L2
      ...
```

```
if a<b goto L2
      ...
L1: goto L2
      ...
```

always executes "goto L1"

```
    goto L1
      ...
L1: if a<b goto L2
L3:
      ...
```

Only one jump to L1, L1 is preceded by an unconditional goto

sometimes skips "goto L3"

```
    if a<b goto L2
    goto L3
      ...
L3:
      ...
```

Reduction in Strength and Use of Machine Idioms

- x^2 is cheaper to implement as x*x, than as a call to an exponentiation routine
- For integers, $x*2^3$ is cheaper to implement as x << 3 (x left-shifted by 3 bits)
- For integers, $x/2^2$ is cheaper to implement as x >> 2 (x right-shifted by 2 bits)

Reduction in Strength and Use of Machine Idioms

- Floating point division by a constant can be approximated as multiplication by a constant
- Auto-increment and auto-decrement addressing modes can be used wherever possible
  - Subsume INCREMENT and DECREMENT operations (respectively)
- Multiply and add is a more complicated pattern to detect