Chapter 8

Code Generation

- Code generation is the Final phase.
- Input is IR from the front end + symbol table.
- Back end = optimization + code generation.
- Optimization = IR to IR. Can be in multiple phases (does several passes). Optimization is optional!

Figure 8.1: Position of code generator

Objectives of code generation

- Correctness. Semantic meaning of the source program should be preserved.
- It should be of high quality; that is, it must make effective use of the available resources of the target machine.
- Moreover, the code generator itself must run efficiently.

Objectives of code generation…

- Important criteria for CG: CORRECTNESS.
- Others
  - Ease of implementation
  - Testing to ensure correctness
  - Ease of maintenance
- We assume
  - In IR there are no syntactic or semantic errors.
  - Type checking completed, type conversion operators are embedded (as needed).

Challenges

- The problem of generating an optimal target program for a given source program is hard.
  - Sub-problems like register allocation (to be done efficiently), itself is intractable.
- We must be content with heuristics (which evolved over time with experience). And this does a good job in practice.

Primary tasks of CG

- Instruction selection
  – Choosing appropriate one from available
- Register allocation and assignment
  – What values to keep in which registers
- Instruction ordering
  – Deciding in what order to schedule the execution of instructions.

Issues in the design of a CG

- Depends on the form of IR, the target language, and the run-time system.
- The tasks mentioned, instruction selection, register allocation and assignment, and instruction ordering are encountered in any CG design.

- Various IRs we consider are:
  - three-address code,
  - trees (syntax trees), and
  - DAGs.

The target program

- The most common target-machine architectures are **RISC** (reduced instruction set computer) , **CISC** (complex instruction set computer), and **stack based**.
- RISC
  - Many registers
  - Three-address instructions
  - Simple addressing modes
  - Simple instruction-set architecture.

- CISC
  - Few registers
  - Two-address instructions
  - A variety of addressing modes
  - Several register classes
  - Variable length instructions
  - Instructions with side effects.

- Stack-based machine
  - Push operands onto a stack
  - Perform operations on the operands at the top
  - Top of the stack is kept in registers for high performance
  - Stack-based machines, almost disappeared, since it demands too many swap and copy operations.
  - However, they are revived with JVM (Java Virtual Machine)

- The common alternatives to stack machines are **register machines**, in which each instruction explicitly names specific registers for its operands and result.
- JVM simulates stack machine.
- Recall, PDA with two stacks can simulate a Turing machine.

Absolute vs relocatable target code

- Absolute machine-language program need to be placed at a fixed location in memory.
- Compilation time, execution time can be lesser.
- For embedded programs, like in a car, which needs to run in real time, this approach is suitable.
- Entire source program needs to be compiled at once. {you can not compile one function at a time.}

- Relocatable machine-language program (called object module) allows subprograms to be compiled separately.
- Flexibility. You can use precompiled tools/libraries.

3^{rd} option

- Producing an assembly-language program as output makes the process of code generation easier.
- Price paid is: this is not target code. Assembler need to translate this to target code.
- We use this one, in our CG.

Instruction selection

- CG maps IR to a sequence of code of target m/c.
- Complexity of this depends on
  - The level of the IR
  - The nature of the instruction-set architecture
  - The desired quality of the generated code.

The level of the IR

- If IR is of high level, each IR statement can be translated into a sequence of m/c code using code templates.
- Such statement-by-statement CG is like interpretation and the resulting m/c code is slow.
  - M/c dependent code optimization is needed.
- If IR is closer to the target m/c, this results in efficient code.

- If each data type (basic data types) is supported in a uniform way, then it is easy …since we do not worry about type!
- In principle, assume there is only one data type, like int, then every three-address statement of the form $x = y+z$, can be translated :

```
LD  R0, y       // R0 = y        (load y into register R0)
ADD R0, R0, z   // R0 = R0 + z   (add z to R0)
ST  x, R0       // x = R0        (store R0 into x)
```

This strategy often produces redundant loads and stores. For example, the sequence of three-address statements

```
a = b + c
d = a + e
```

would be translated into

```
LD  R0, b        // R0 = b
ADD R0, R0, c    // R0 = R0 + c
ST  a, R0        // a = R0
LD  R0, a        // R0 = a
ADD R0, R0, e    // R0 = R0 + e
ST  d, R0        // d = R0
```

Here, the fourth statement is redundant since it loads a value that has just been stored, and so is the third if `a` is not subsequently used.

Quality of the generated code

- Speed (to complete one IR stmt) & Size (of the code sequence).
- On most machines, a given IR can be implemented by many different code sequences.
  - Each quite different from other, with significant speed and size differences.
- Eg: If INC instruction is available, then a = a+1 can be implemented more efficiently than

```
LD  R0, a        // R0 = a
ADD R0, R0, #1   // R0 = R0 + 1
ST  a, R0        // a = R0
```

Register allocation

- A key problem is, deciding what to store in which register.
- Registers are the fastest memory. But very few in number.
  - Some instructions, forces that its operands must be kept in the registers.

Register allocation

The use of registers is often subdivided into two subproblems:

1. *Register allocation*, during which we select the set of variables that will reside in registers at each point in the program.

2. *Register assignment*, during which we pick the specific register that a variable will reside in.

- Register allocation, in an optimal way, is NP-complete

Example 8.1: Certain machines require *register-pairs* (an even and next odd-numbered register) for some operands and results. For example, on some machines, integer multiplication and integer division involve register pairs. The multiplication instruction is of the form

```
M x, y
```

where `x`, the multiplicand, is the even register of an even/odd register pair and `y`, the multiplier, is the odd register. The product occupies the entire even/odd register pair.

The division instruction is of the form

```
D x, y
```

where the dividend occupies an even/odd register pair whose even register is `x`; the divisor is `y`. After division, the even register holds the remainder and the odd register the quotient.

Evaluation order

- The order in which computations are done can affect the efficiency
  - Some computation orders require fewer registers
- Picking the best order, in general, is NP-complete.
  - DAG analysis (we see this) can help.
- This is studied in detail in m/c dependent code optimization.

8.2 The Target Language

- Instruction set architecture of the target m/c is a must to be well understood by the compiler writer.
- But, we make many assumptions on the target m/c that simplifies the CG discussion.

A simple target m/c model

- We have n general-purpose registers, R0, R1,…,Rn-1.
- Limited set of instructions we consider.
  - We assume all operands are integers.

- *Load* operations:

LD $dst,\ addr$	$dst = addr$
LD r, x	loads the value in location x into register r.
LD r_1, r_2	*register-to-register copy*

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- *Store* operations:

  ST x, r $x = r$.
  stores the value in register r into the location x.

- *Load* operations:

LD $dst,\ addr$	$dst = addr$
LD r, x	loads the value in location x into register r.
LD r_1, r_2	*register-to-register copy*

- *Store* operations:

ST x, r	$x = r$. stores the value in register r into the location x.

- *Computation* operations $OP\ dst, src_1, src_2$

OP is a operator like ADD or SUB.

SUB r_1, r_2, r_3	$r_1 = r_2 - r_3$

Unary operators that take only one operand do not have a src_2.

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- *Conditional jumps* of the form `B`*cond* r, L, where r is a register, L is a label, and *cond* stands for any of the common tests on values in the register r.

For example, `BLTZ` r, L causes a jump to label L if the value in register r is less than zero, and allows control to pass to the next machine instruction if not.

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We can have other instructions, like BGTZ (greater than), BLEZ (less or equal), BGEZ (greater or equal), BEQZ (equal to).

Addressing modes, we assume are:

- In instructions, a location can be a variable name x referring to the memory location that is reserved for x (that is, the l-value of x).

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- Accessing array elements. *a(r)* is located at memory address *a+r* where a is the base address of an array and r is the index stored in a register.

For example, the instruction `LD R1, a(R2)` has the effect of setting $\texttt{R1} = contents(\texttt{a} + contents(\texttt{R2}))$, where $contents(x)$ denotes the contents of the register or memory location represented by x.

- A memory location can be an integer indexed by a register. For example, `LD R1, 100(R2)` has the effect of setting `R1` $= contents(100 + contents(\texttt{R2}))$, that is, of loading into `R1` the value in the memory location obtained by adding 100 to the contents of register `R2`.

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- We also allow two indirect addressing modes: $*r$ means the memory location found in the location represented by the contents of register r and $*100(r)$ means the memory location found in the location obtained by adding 100 to the contents of r. For example, `LD R1, *100(R2)` has the effect of setting `R1` $= contents(contents(100 + contents(\texttt{R2})))$

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- Finally, we allow an immediate constant addressing mode. The constant is prefixed by `#`. The instruction `LD R1, #100` loads the integer 100 into register `R1`, and `ADD R1, R1, #100` adds the integer 100 into register `R1`.

```
b = a[i]

    LD  R1, i            // R1 = i
    MUL R1, R1, 8        // R1 = R1 * 8
    LD  R2, a(R1)        // R2 = contents(a + contents(R1))
    ST  b, R2            // b = R2
```

That is, the second step computes $8i$, and the third step places in register `R2` the value in the ith element of `a` — the one found in the location that is $8i$ bytes past the base address of the array `a`.

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```
a[j] = c

   LD  R1, c          // R1 = c
   LD  R2, j          // R2 = j
   MUL R2, R2, 8      // R2 = R2 * 8
   ST  a(R2), R1      // contents(a +  contents(R2)) = R1
```

```
if x < y goto L
```

```
LD   R1, x          // R1 = x
LD   R2, y          // R2 = y
SUB  R1, R1, R2     // R1 = R1 - R2
BLTZ R1, M          // if R1 < 0 jump to M
```

Here, `M` is the label that represents the first machine instruction generated from the three-address instruction that has label `L`.

Exercise 8.2.1: Generate code for the following three-address statements assuming all variables are stored in memory locations.

a) `x = 1`

b) `x = a`

c) `x = a + 1`

d) `x = a + b`

e) The two statements

```
x = b * c
y = a + x
```

- The abbreviations like LD, ADD, R1, etc (which are discussed) should be used while answering these type of questions.

8.3 Addresses in the Target Code

- We skip this section.

8.4 Basic Blocks and Flow Graphs

- IR can be seen as a graph where nodes are basic blocks, arcs show the dependency (the flow ordering). {This graph may not be explicit}.
- This gives context that is needed & that must be preserved; this allows reordering of instructions; usage of principle of locality in a better way.

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   (b) Control will leave the block without halting or branching, except possibly at the last instruction in the block.

2. The basic blocks become the nodes of a *flow graph*, whose edges indicate which blocks can follow which other blocks.

8.4.1 Basic Blocks

- Partition a sequence of three-address code into basic blocks.
  - Algorithm 8.5 : Uses *leader* instructions to identify a block.
- Put arrows between them.

Algorithm 8.5: Partitioning three-address instructions into basic blocks.

INPUT: A sequence of three-address instructions.

OUTPUT: A list of the basic blocks for that sequence in which each instruction is assigned to exactly one basic block.

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- Identify instructions called leaders.
  1. The first three-address instruction is a leader.
  2. Any instruction that is the target of a conditional or unconditional jump is a leader.
  3. Any instruction that immediately follows a conditional or unconditional jump is a leader.
- Then, for each leader, its basic block is itself + all upto (but not) the next leader.

```
for i from 1 to 10 do
    for j from 1 to 10 do
        a[i, j] = 0.0;
for i from 1 to 10 do
    a[i, i] = 1.0;
```

Figure 8.8:

Source code that converts a 10 by 10 matrix a into an identity matrix.

```
 1)  i = 1
 2)  j = 1
 3)  t1 = 10 * i
 4)  t2 = t1 + j
 5)  t3 = 8 * t2
 6)  t4 = t3 - 88
 7)  a[t4] = 0.0
 8)  j = j + 1
 9)  if j <= 10 goto (3)
10)  i = i + 1
11)  if i <= 10 goto (2)
12)  i = 1
13)  t5 = i - 1
14)  t6 = 88 * t5
15)  a[t6] = 1.0
16)  i = i + 1
17)  if i <= 10 goto (13)
```

Intermediate code to set a 10×10 matrix to an identity matrix

Flow graphs

```
1)  i = 1
2)  j = 1
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6)  t4 = t3 - 88
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12) i = 1
13) t5 = i - 1
14) t6 = 88 * t5
15) a[t6] = 1.0
16) i = i + 1
17) if i <= 10 goto (13)
```
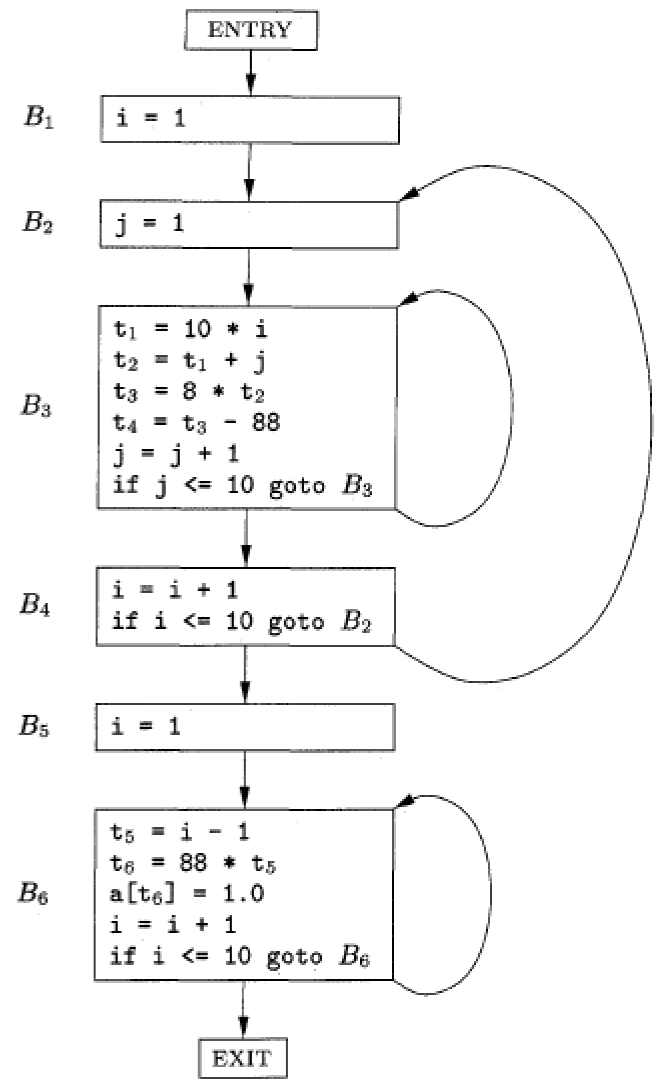
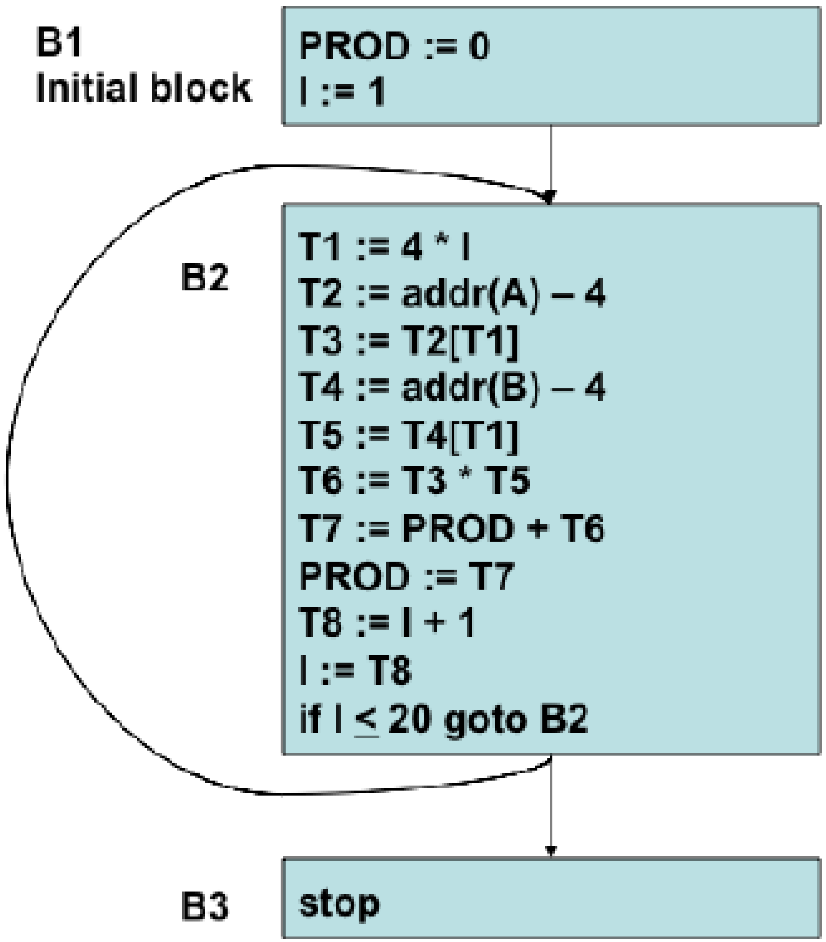

Intermediate code to set a 10×10 matrix to an identity matrix



Example of Basic Blocks and Control Flow Graph



High level language code:

```
{ PROD = 0;
  for ( I = 1; I <= 20; I++)
    PROD = PROD + A[I] * B[I];
}
```

```
PROD := 0
I := 1
T1 := 4 * I
T2 := addr(A) – 4
T3 := T2[T1]
T4 := addr(B) – 4
T5 := T4[T1]
T6 := T3 * T5
T7 := PROD + T6
PROD := T7
T8 := I + 1
I := T8
if I ≤ 20 goto B2
stop
```

8.4.2 Next-Use Information

- Knowing when the value of a variable is reused (without interleaving changes) will result in a good code.
- If the value of a variable in a register is reused within a few instructions, then it is good keep it there, otherwise one can keep it in main memory.

8.4.2 Next-Use Information..

- Statement i : $x = y + z;$
- Statement j: $a = x + b;$
- $j > i$ and in between x is not modified. There are no jumps or branching between i and j.
  - Then we say x is *live* at statement i; j *uses* the value of x at i.
- One can easily find the *live* variables and where they are *next used*.
- Basic blocks can be scanned for this purpose.

8.5 Optimization of basic blocks

- Often a substantial improvement can be achieved in the running time by analyzing a basic block by itself. {This is local optimization where flow is not taken in to account.}

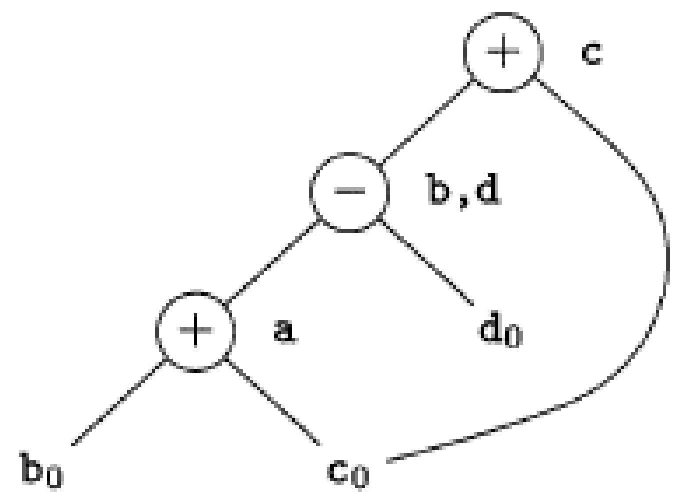
DAG representation of basic blocks

- DAG representation of basic blocks
  - We can eliminate local common sub-expressions.
  - Eliminate dead code.
  - Reorder statements.
  - Algebraic laws can be applied to simplify.

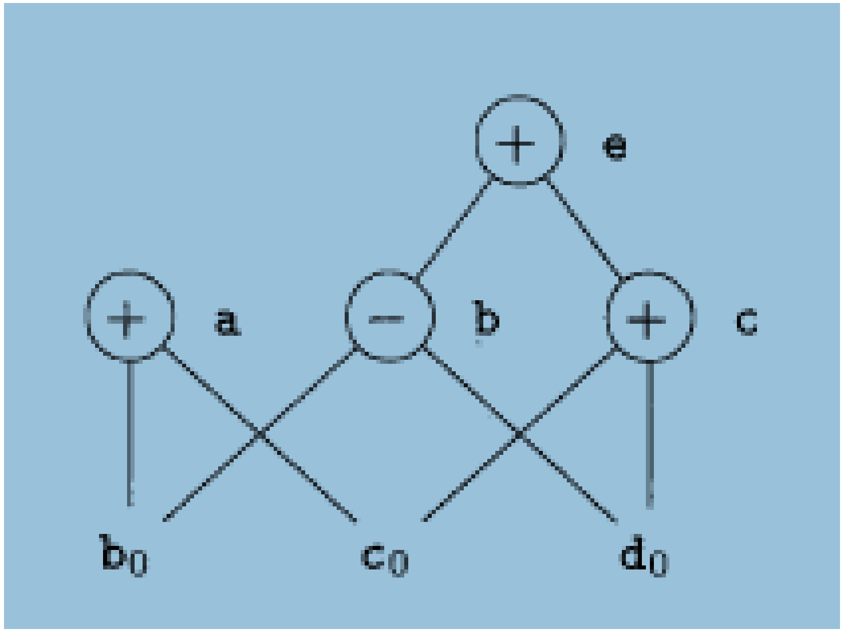
Example 8.10: A DAG for the block

```
a = b + c
b = a - d
c = b + c
d = a - d
```

3rd one is done last. Reordering is done.
Various versions of same variable are used.



```
a = b + c;
b = b - d
c = c + d
e = b + c
```



Other optimizations

Dead Code Elimination

Eliminates code that cannot be reached or where the results are not subsequently used.

For example, consider the following code fragment:

```
int count
void foo()  {
    int i;
    i = 1;      // dead code since it is not subsequently used
    count = 1; //dead code since it was overwritten
    count = 2;
    return;
    count = 3; //dead code(unreachable) since the function has returned
}
```

After applying dead code elimination we have the code below:

```
    int count
    void foo() {
        count = 2;
        return;
    }
```

Constant Folding

This refers to the technique of evaluating ate compile time, expressions whose operands are known to be constant.

It involves the determining that all of the operands in an expression are constant values, performing the evaluation of the expression at compile time and then replacing the expression by its value. For example, the expression

$$12 + 4 * 3$$

can be replaced by its result of **24** at compile time and omit the code as if the input contained the results rather than the original expression

Constant Propagation

In constant propagation, if a variable is assigned a constant value, then subsequent use of that variable can be replaced by a constant as long as no intervening assignment has changed the value of the variable.

For Example, consider the code:

```
int x = 12;
int y = 7 - x /2;
return y * (24 / x + 2)
```

Applying constant propagation to x, we have:

```
int x = 12;
int y = 7 - 12 / 2;
return y * (24 / 12 + 2);
```

Applying constant folding , we have:

```
int x = 12;
int y = 1;
return y * 4;
```

Strength Reduction

This is also called operator strength reduction is the replacement of expressions that are expensive with cheaper and simple ones.

Fore example an add instruction can be used to replace a multiply instruction.

The code:

T2 = T2 * 2

Can be replaced with:

T2 = T2 + T2

Algebraic identities can be used ..

$$x + 0 = 0 + x = x \qquad x - 0 = x$$
$$x \times 1 = 1 \times x = x \qquad x/1 = x$$

Expensive		Cheaper
x^2	$=$	$x \times x$
$2 \times x$	$=$	$x + x$
$x/2$	$=$	$x \times 0.5$

Code Motion

Also called loop-invariant code motion has to do with moving a block of code outside a loop if it wont have any difference if it is executed outside or inside the loop.

Consider the example:

```
for (int i = 0; i < n; i++) {
    x = y + z;
    a[i] = 6 * i;
}
```

In the code fragment, the expression x = y + z has no effect inside the loop and can safely be moved outside of the loop.

The resulting code would be:

```
x = y + z;
for (int i = 0; i < n; i++) {
    a[i] = 6 * i;
}
```

Inlining

This is also referred to as function inlining or inline expansion, is a technique of replacing a function call with the actual body of the function.

This technique eliminates the overhead associated with expanding the body of the function inline.

Consider the fragment:

```
int add ( int x, int y)
{
        z = x + y;
        return z;
}

int  sub (int x, int y) {
        return add(x, -y)
}
```

We can expand the second function without calling he add function, so we have:

```
int  sub (int x, int y) {
        return x + -y;
}
```

- Other things are not covered in this basic course.