Example. Consider the following code fragment.

```plaintext
for (i = 0; i < n; i++)
    for (j = 0; j < i; j=j+10)
        print ("run time analysis")
```

Give a tight bound on the running time of this code fragment.

**Solution.** For each value of $i$, the inner loop executes $i/10$ times. Thus the running time of the body of the outer loop is at most $c(i/10)$, for some positive constant $c$. Hence the total running time of the code fragment is given by

$$
\sum_{i=0}^{n-1} c \left\lceil \frac{i}{10} \right\rceil \leq \sum_{i=0}^{n-1} c \left( \frac{i}{10} + 1 \right) = \frac{c(n-1)n}{20} + cn \leq 2cn^2 = O(n^2)
$$

We will now show that $\sum_{i=0}^{n-1} c \left\lceil \frac{i}{10} \right\rceil = \Omega(n^2)$. Note that

$$
\sum_{i=0}^{n-1} c \left\lceil \frac{i}{10} \right\rceil \geq \sum_{i=0}^{n-1} \frac{ci}{10} = c(n-1)n/20
$$

We want to find positive constants $c'$ and $n_0$, such that for all $n \geq n_0$,

$$
\frac{c(n-1)n}{20} \geq c'n^2
$$

This is equivalent to showing that $n(c - 20c') \geq c$. This is true when $c' = c/40$ and $n \geq 2$. Thus, the running time of the code fragment is $\Omega(n^2)$.

Example. Consider the following code fragment.

```plaintext
i = n
while (i >= 10) do
    i = i/3
for j = 1 to n do
    print ("Inner loop")
```

What is an upper-bound on the running time of this code fragment? Is there a matching lower-bound?
Solution. The running time of the body of the inner loop is $O(1)$. Thus the running time of the inner loop is at most $c_1n$, for some positive constant $c_1$. The body of the outer loop takes at most $c_2n$ time, for some positive constant $c_2$ (note that the statement $i = i/3$ takes $O(1)$ time). Suppose the algorithm goes through $t$ iterations of the while loop. At the end of the last iteration of the while loop, the value of $i$ is $n/3^t$. We know that the code fragment surely finishes when $n/3^t \leq 1$, solving which gives us $t \geq \log_3 n$. This means that the number of iterations of the while loop is at most $O(\log n)$. Thus the total running time is $O(n \log n)$.

We will now show that the running time is $\Omega(n \log n)$. We will lower-bound the number of iterations of the outer loop. Note that when the value of $i$ is more than 10 (say, $3^3$), the outer loop has not terminated. Solving $n/3^t \geq 3^3$, gives us that $\log_3 n - 3$ is a lower bound on the number of iterations of the outer loop. For each iteration of the outer loop, the inner loop runs $n$ times. Thus the total running time is at least $cn(\log_3 n - 3)$, for some positive constant $c$. Note that $cn(\log_3 n - 3) \geq c' n \log n$, when $c' = c/2$ and $n \geq 3^6$. Thus the running time is $\Omega(n \log n)$.

Example. Consider the following code fragment.

```plaintext
for i = 0 to n do
  for j = n down to 0 do
    for k = 1 to j-i do
      print (k)
```

What is an upper-bound on the running time of this algorithm? What is the lower bound?

Solution. Note that for a fixed value of $i$ and $j$, the innermost loop goes through $\max\{0, j - i\} \leq n$ times. Thus the running time of the above code fragment is $O(n^3)$.

To find the lower bound on the running time, consider the values of $i$, such that $0 \leq i \leq n/4$ and values of $j$, such that $3n/4 \leq j \leq n$. Note that for each of the $n^2/16$ different combinations of $i$ and $j$, the innermost loop executes at least $n/2$ times. Thus the running time is at least

$$(n^2/16)(n/2) = \Omega(n^3)$$

Example. Consider the following code fragment.

```plaintext
for i = 1 to n do
  for j = 1 to i*i do
    for k = 1 to j do
      print (k)
```

Give a tight-bound on the running time of this algorithm? We will assume that $n$ is a power of 2.

Solution. Note that the value of $j$ in the second for-loop is upper bounded by $n^2$ and the value of $k$ in the innermost loop is also bounded by $n^2$. Thus the outermost for-loop iterates for $n$ times, the second for-loop iterates for at most $n^2$ times, and the innermost loop iterates for at most $n^2$ times. Thus the running time of the code fragment is $O(n^5)$.

We will now argue that the running time of the code fragment is $\Omega(n^5)$. Consider the following code fragment.
for $i = n/2$ to $n$ do
  for $j = (n/4) \cdot (n/4)$ to $(n/2) \cdot (n/2)$ do
    for $k = 1$ to $(n/4) \cdot (n/4)$ do
      print ($k$)

Note that the values of $i, j, k$ in the above code fragment form a subset of the corresponding values in the code fragment in question. Thus the running time of the new code fragment is a lower bound on the running time of the code fragment in question. Thus the running time of the code fragment in question is at least $n/2 \cdot 3n^2/16 \cdot n^2/16 = \Omega(n^5)$.

Thus the running time of the code fragment in question is $\Theta(n^5)$.

**Example.** Consider the following code fragment. We will assume that $n$ is a power of 2.

```for (i = 1; i <= n; i = 2*i) do
  for j = 1 to i do
    print (j)
```

Give a tight-bound on the running time of this algorithm?

**Solution.** Observe that for $0 \leq k \leq \log_2 n$, in the $k^{th}$ iteration of the outer loop, the value of $i = 2^k$. Thus the running time $T(n)$ of the code fragment can be written as follows.

$$T(n) = \sum_{k=0}^{\log_2 n} 2^k$$
$$= 2^{\log_2 n + 1} - 1$$
$$= 2n - 1$$
$$= \Theta(n) \quad (c_1 = 1, c_2 = 2, n_0 = 1)$$

What is wrong with the following argument that the running time of the above code fragment is $\Omega(n \log n)$?

```for (i = n/128; i <= n; i = 2*i) do
  for j = 1 to n/128 do
    print (j)
```

The outer loop runs $\Omega(\log n)$ times and the inner loop runs $\Omega(n)$ times and hence the running time is $\Omega(n \log n)$.

**Discussion:** Consider a problem $X$ with an algorithm $A$.

- Algorithm $A$ runs in time $O(n^2)$. This means that the worst case asymptotic running time of algorithm $A$ is upper-bounded by $n^2$. Is this bound tight? That is, is it possible that the run-time analysis of algorithm $A$ is loose and that one can give a tighter upper-bound on the running time?
- Algorithm $A$ runs in time $\Theta(n^2)$. This means that the bound is tight, that is, a better (tighter) bound on the worst case asymptotic running time for algorithm $A$ is not possible.
- Problem $X$ takes time $O(n^2)$. This means that there is an algorithm that solves problem $X$ on all inputs in time $O(n^2)$. 

• Problem $X$ takes $\Theta(n^{1.5})$. This means that there is an algorithm to solve problem $X$ that takes time $O(n^{1.5})$ and no algorithm can do better.