An Introduction to Digital Video Data Compression in Java

Fore June

Chapter 8 Huffman Encoding

8.1 Introduction

Rather than saving the 3D run-level tuples directly, people encode them using an entropy encoder which in general yields significant compression. Entropy encoding is a reversible or lossless process; exact data can be recovered in the decoding process from the encoded data. Arithmetic coding and Huffman coding are two popular methods of entropy encoding with the former giving slightly better results and consuming more computing power. This kind of encoding is also referred to as variable-length coding (VLC) because the codewords representing symbols are of varying lengths. We shall only discuss the Huffman encoding method here.

The commonly used generalized ASCII code uses 8 bits to represent a character and unicode uses 16 bits to do so; these are fixed-length codes, which are simple but inefficient in the representation. Huffman coding assigns a variable-length codeword to each symbol (or tuple here) based on the probability of the occurrence of the symbol. Frequently occurring symbols are represented with short codewords whilst less common symbols are represented with longer codewords; in this way we have a shorter average codeword length and thus saving space to store the codewords, leading to data compression.

We say that a code has the **prefix property** and is a prefix code if no codeword is the prefix, or start of the codeword for another symbol. A code with codewords $\{1, 01, 00\}$ has the prefix property; a code consisting of $\{1, 0, 01, 00\}$ does not, because "0" is a prefix of both "01" and "00". A non-prefix code like { 1, 0, 01, 00 } cannot be instantaneously decoded because when we receive a bitstream such as "001", we do not know whether it consists of { '0', '0', '1' }, or { '0', '01' } or { '00', '1' }. On the other hand, a prefix code can be instantaneously decoded. That is, a message can be transmitted as a sequence of concatenated codewords, without any out-of-band markers to frame the words in the message. The receiver can decode the message unambiguously, by repeatedly finding and removing prefixes that form valid codewords, which are impossible if the message is formed by a non-prefix code as shown in the above example. Prefix codes are also known as prefix-free codes, prefix condition codes, comma-free codes, and instantaneous codes.

Not only that Huffman codes are prefix codes, they are also optimal in the sense that no other prefix code can yield a shorter average codeword length than a corresponding Huffman code. It is the foundation of numerous compression applications, including text compression, audio compression, image compression, and video compression. It is a building block of many contemporary multi-media applications.

Huffman code was developed by David A. Huffman while he was a Ph.D. student at MIT, and published in the 1952 paper "A Method for the Construction of Minimum-Redundancy Codes." Huffman codes are easiest to understand and implement if we use trees to represent them though the tree concept was not used when Huffman first developed the code. Briefly, Huffman tree is a **binary tree** (an ordered 2-ary tree) with a weight associated with each node. Let us first consider some simple examples to understand its principles.

Consider the following two codes.

Symbol	Code 1	Code 2
a	000	000
b	001	11
c	010	01
d	011	001
e	100	10

Code 1 is a fixed-length code with codeword length 3 and Code 2 is a variable-length code. Both of them have the prefix property (note that a fixed-length code always has the prefix property). They can be represented by binary trees like those shown in Figure 8-1. Decoding a bitstream is simply a process of traversing the binary tree; we start from the root of the tree and go left or right based on whether the current bit examined is 0 or 1 until we reach a leaf, which is associated with a symbol; we then start from the root again and examine the next bit and so on. For example, Code 2 decodes the string "000100111" uniquely to "aecb". It is obvious that Code 2 always has a shorter average codeword length when compared to Code 1.

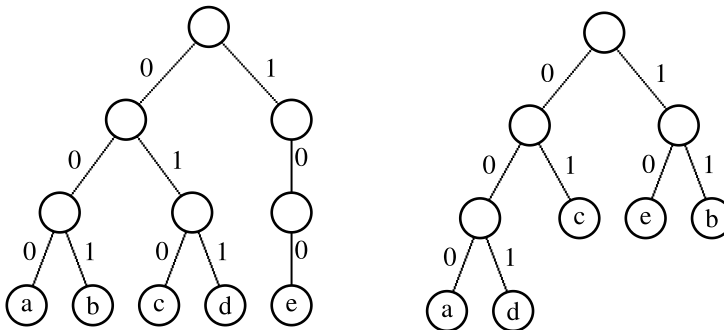


Figure 8-1. Binary Tree Representations of Code1 (left) and Code 2 (right)

8.2 Huffman Codes

Consider an example that the probabilities of the occurrence of symbols are known:

Symbol	Frequency	Code 1	Code 2
a	0.35	000	00
b	0.20	001	10
c	0.20	010	011
d	0.15	011	010
e	0.10	100	110

We can calculate the average lengths $\overline{L}$ of the codewords of the two codes. Obviously, Code 1 is a fixed-length code and the average length is 3. For Code 2, we need to take into

account the frequency of occurrence of each symbol:

$$\begin{aligned} \text{Code 1} : \overline{L} &= 3\ bits \\ \text{Code 2} : \overline{L} &= 0.35 \times 2 + 0.20 \times 2 + 0.20 \times 3 + 0.15 \times 3 + 0.10 \times 3 = 2.45\ (bits) \end{aligned} \tag{8.1}$$

Code 2 is a prefix code and has a significantly shorter average codeword length than that of Code 1. *But is Code 2 the best code for the given frequencies? Can we do better than Code 2, creating a code that has shorter* $\overline{L}$ *than Code 2?* This question can be answered by constructing a Huffman tree to obtain a Huffman code for the given symbols and frequencies. We start from a forest of trees, each of which has only one single node (which is a root as well as a leaf); each root consists of the symbol and the weight (probability) of it. In this example, we totally have five single-noded trees as shown in Figure 8-2:

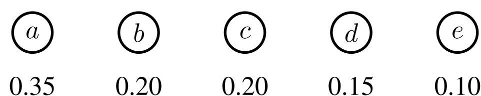


Figure 8-2. A Forest of Single-noded Trees

Next, we merge the two trees whose roots have lowest weights and calculate the sum of the two weights. We assign the sum as the weight to the root of the merged tree. The resulted forest is shown in Figure 8-3, where we have merged two pairs of roots that have the lowest weights.

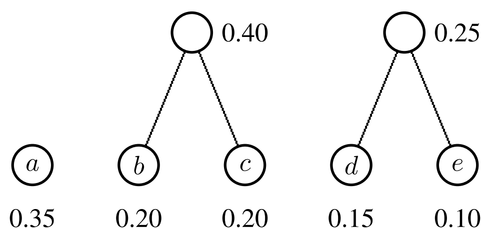


Figure 8-3. Merging Two Pairs of Roots with Lowest Weights

We repeat the above merging process until there is only one tree in the forest. Figure 8-4 and Figure 8-5 show two more iterations of the process. Note that for clarity of presentation, some node positions have been rearranged.

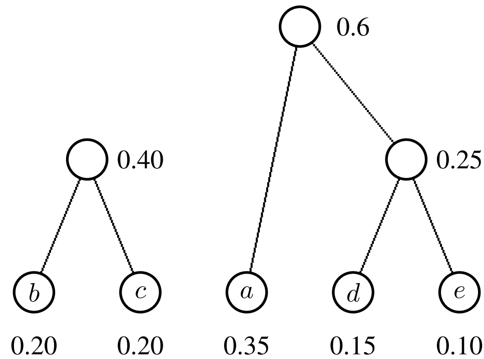


Figure 8-4. Merging Two More Roots with Lowest Weights

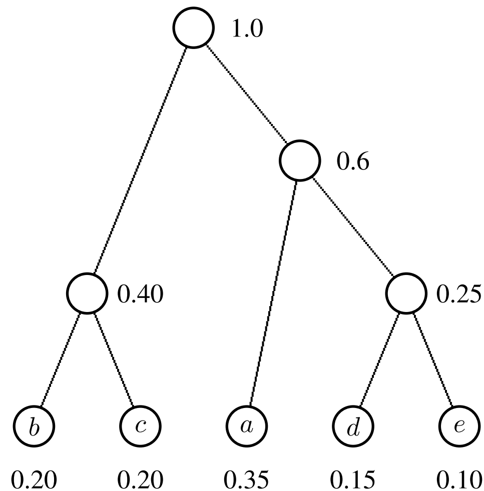


Figure 8-5. Merging All Trees Yields a Huffman Tree

As shown in Figure 8-5, the final single tree obtained is the Huffman tree that we need. To obtain the codeword for a symbol, we traverse the tree, starting from the root, until we arrive at a leaf, which contains the symbol; in the traversal, we generate a 0 on going left and a 1 on going right (it works just as well if we generate a 1 on going left and a 0 on right) as shown in Figure 8-6. The sequence of 1's and 0's parsed in the traversal from the root to the symbol is the codeword. The following table shows the Huffman code obtained from the Huffman tree of Figure 8-6.

Symbol	Codeword	Length
a	10	2
b	00	2
c	01	2
d	110	3
e	111	3

The average length of the Huffman code is

$$\overline{L} = 0.35 \times 2 + 0.20 \times 2 + 0.20 \times 2 + 0.15 \times 3 + 0.10 \times 3 = 2.25\ (bits) \tag{8.2}$$

which is shorter than that of Code 2 (2.45 bits) discussed above. Actually, one can prove that Huffman code is optimal. That is, a Huffman code always gives the shortest average code length of all prefix codes for a given set of probabilities of occurrences of symbols. (We'll skip the proof here.)

Note that the symbols are not limited to alphabets and letters. They can be any quantitative values or even abstract objects. Note also that a Huffman decoder does not need to know the probability distribution of the symbols in order to decode them. It only needs to know the Huffman tree to decode a bit-stream consisting of codewords encoded by a Huffman code. In the decoding process, we start from the root of the tree and traverse the tree according to the 0's and 1's we read from the bit-stream until we reach a leaf to recover the encoded symbol; we then start from the root again and read in further bits for traversal to obtain the next symbol and so on. For example, suppose the following is the output bit-stream resulted from encoding a sequence of symbols using the Huffman tree of Figure 8-6:

$$00101110110 \tag{8.3}$$

Upon decoding, we start from the tree root and first read in '0 0', reaching symbol 'b'; we then start from the root again and read in '1 0', reaching symbol 'a'; next, the bit sequence '1 1 1' gives symbol 'e'; next, '0 1' gives 'c' and finally '1 0' gives 'a'. Therefore, the encoded sequence of symbols of the bit-stream (8.3) is "b a e c a".

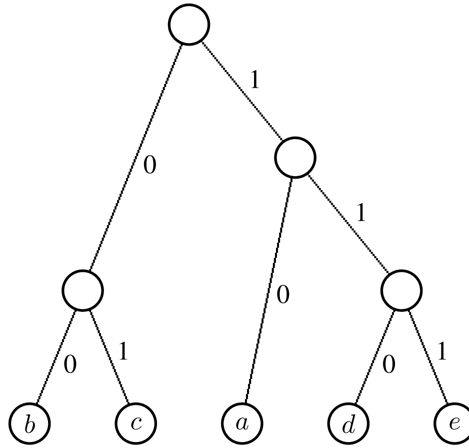


Figure 8-6. Traversing the Huffman Tree

8.3 Huffman Tree Properties

A Huffman tree can be conveniently constructed using a priority queue. A priority queue is a special queue that associates each element with a priority value. A general queue has the property of "First In First Out (FIFO)". That is, the first element that enters the queue is the first to be removed. In other words, the first entered-element is always at the front of the queue which is the next element to be deleted. This happens in a cashier station of a supermarket; the customer who arrives first at the cashier is the first one to be served. On the other hand, a priority queue does not follow the FIFO scenario; it is the element that has the highest priority in the queue that will be deleted first. This could happen when the president of a big company meets a number of visitors; she would first meet the most important visitor before meeting other less important people. Therefore, the element at the front of a priority queue always has the highest priority and is the first one to be deleted. In other words, when an element with a priority higher than the priorities of all the elements currently in the queue enters the queue, it will be moved to the front of the queue.

In our application, we can set the priority of a node (root of a tree) to be the reciprocal of its weight. That is, the lower the weight, the higher the priority. As an example, in Figure 8-2, node **e** has the highest priority, followed by node **d**, and node **a** has the lowest priority. With this association, a Huffman tree can be constructed by the following steps:

1. Start with a forest consisting of single-node trees; the root of a tree contains a symbol and its weight, which is the reciprocal of its priority value.
2. Insert the roots (nodes) of all trees of the forest into a priority queue.
3. Delete two nodes from the priority queue; the two deleted nodes always have the least weights (highest priorities).
4. Merge the deleted nodes to form a new root with combined weights; insert the new root back to the priority queue.
5. Repeat steps 3 - 4 until the priority queue is empty.

In the above steps, when the priority queue is empty, a single tree is formed and it is the

required Huffman tree. In the process, we assume that a root always links to the rest of the nodes of the tree.

The priority queue implementation is straightforward and intuitive. However, it is not the most efficient method. and we shall not use it here. To make more efficient or customized implementations, it is helpful to learn some properties of a Huffman tree.

Firstly, we have learned that a Huffman tree is optimal. However, it is not unique. Given a set of frequencies, we can have more than one Huffman tree that yields the optimal average codeword length; different trees can be constructed by interchanging the assignment of 0 and 1 to the left and right traversal or by merging roots with equal weights in different orders.

Secondly, all internal nodes (non-leaves) of a Huffman tree always have two children. The binary tree that represents Code 1 in Figure 8-1 will never occur in a Huffman tree regardless of the occurrence frequencies of the symbols.

Thirdly, if the weights of the symbols are changing, the Huffman tree needs to be recomputed dynamically. This can be done by utilizing the *Sibling Property*, which defines a binary tree to be a Huffman tree if and only if:

1. all leaf nodes have non-negative weights,
2. all internal nodes have exactly two children,
3. the weight of each parent node is the sum of its childrenś weights, and
4. the nodes are numbered in increasing order by non-decreasing weight so that siblings are assigned consecutive numbers or rank, and most importantly, their parent node must be higher in the numbering.

The *Sibling Property* is usually used in *Dynamic Huffman Coding*, where we encode a stream of symbols on the fly and the symbol statistics changes as we read in more and more symbols.

Finally, we shall prove a lemma concerning binary trees to help us simplify the implementation of a Huffman tree when we use an array to implement it. Consider a binary tree where

n_0 = number of leaves (nodes of degree 0)
n_1 = number of nodes of degree 1 (nodes having one child)
n_2 = number of nodes of degree 2 (nodes having two children)

Lemma:

For a non-empty binary tree,

$$n_0 = n_2 + 1 \tag{8.4}$$

Proof:

The total number of nodes in the tree is

$$n = n_0 + n_1 + n_2 \tag{8.5}$$

Except the root, a node always has a branch leading to it. Thus the total number of branches is

$$n_B = n - 1 \tag{8.6}$$

But all branches stem from nodes of degree 1 or 2, so

$$n_B = n_1 + 2 \times n_2 \tag{8.7}$$

Combining (8.6) and (8.7), we have

$$n - 1 = n_1 + 2 \times n_2 \tag{8.8}$$

yielding

$$n_0 + n_1 + n_2 - 1 = n_1 + 2 \times n_2 \tag{8.9}$$

Simplifying (8.9), we obtain

$$n_0 = n_2 + 1$$

which is the result we want to prove.

From Huffman tree properties discussed above, we know that a Huffman tree does not have any node of degree 1 (i.e. $n_1 = 0$) and thus the number of internal nodes is equal to n_2. Also, the number of symbols is equal to the number of leaves (n_0) in the tree. Therefore, if we have n symbols, from the Lemma, we know that the corresponding Huffman tree will have $n_2 = n_0 - 1 = n - 1$ internal nodes. To save a Huffman tree, we need an entry for each of the left and right child pointers and an entry for each symbol. The total number of entries N_T in the table that holds the Huffman Tree is equal to the number of pointers plus the number of symbols and is given by

$$N_T = 2 \times (n - 1) + n = 3 \times n - 2 \tag{8.10}$$

For instance, consider a Huffman tree consisting of five symbols: a, b, c, d, e as shown in Figure 8-7.

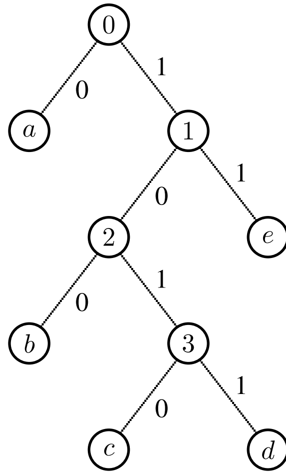


Figure 8-7. A Huffman Tree Consisting of Five Symbols

The following table shows the corresponding Huffman code of Figure 8-7.

Symbol	Codeword
a	0
b	100
c	1010
d	1011
e	11

In this example, the size of the table N_T that implements the Huffman tree is

$$N_T = 3 \times 5 - 2 = 13 \tag{8.11}$$

The Huffman tree is represented by the following table (Table 8-1), where traversing left gives a 0, and traversing right gives a 1 and $N_T = 13$. Note that in the table, the root is pointing at the highest table location ($N_T - 1$) and when traversing the tree we move from the top of the table down to a location that contains a symbol. When we reach a location whose index is smaller than N_T, we know that we have reached a terminal node (leaf) containing a symbol.

Table 8-1

Table Index	Table Content	Comments
12	0	left child of node 0 (root)
11	10	right child of node 0
10	8	left child of node 1
9	4	right child of node 1
8	1	left child of node 2
7	6	right child of node 2
6	2	left child of node 3
5	3	right child of node 3
4	'e'	symbol at leaf
3	'd'	symbol at leaf
2	'c'	symbol at leaf
1	'b'	symbol at leaf
0	'a'	symbol at leaf

The following piece of java-like pseudo code shows how we traverse the table to obtain the symbols; in the code, htree[] is the table containing the Huffman tree:

```
loc = 3 * N - 3;              //start from root, N = # of symbols
do {
  loc0 = loc;                 //in is data pointer pointing to
                              //  encoded data
  if ( read_one_bit( in ) == 0 ) //a 0, go left
      loc = htree[loc0];
  else
      loc =  htree[loc0+1];   //a 1, go right

} while ( loc >= N );         //traverse until reach leaf
return htree[loc];            //return
```

Table 8-1 can be simplified if we assert that the number of symbols n is smaller than a certain value and we associate each symbol with a value in the range 0 to $n-1$. For example, if we assert $n \leq 128$, which actually applies to many video compression applications, then

1. each pointer can be represented by a byte, with a left child denoted by the upper byte of a 16-bit word and right child by the lower byte,
2. table locations signify symbol values and do not need extra entries to hold the symbols, and
3. table size N_T is reduced to $n-1$.

The above Huffman tree example where the number of symbols is 5 can now be represented by a table with size of $5-1=4$ as shown below.

Table 8-2

Table Index (Symbol)	Left Child	Right Child	Comments
3 (8)	0 (a)	7	left, right children of node 0 (root)
2 (7)	6	4 (e)	left, right children of node 1
1 (6)	1 (b)	5	left, right children of node 2
0 (5)	2 (c)	3 (d)	left, right children of node 3

Table 8-2 only has 4 entries while Table 8-1 which has 13 entries. The symbols are represented by the table indices with 0 representing 'a', 1 representing 'b' and so on. To resolve the case whether a table entry holds a pointer or an actual symbol value, we've added the value N_T to all table indices before saving them as pointers. Therefore, in a table entry, if the pointer value is smaller than N_T, we know that it is a terminal node (symbol). The following piece of code shows how to decode such a table that represents a Huffman tree; a left mask and right mask are used to extract the correct pointer value.

```
                            //N = # of symbols
left_mask = 0xFF00;         //to extract upper byte(left child)
right_mask = 0x00FF;        //to extract lower byte(right child)
loc = ( N - 1 ) + N;        //start from root; add offset N to
                            // distinguish pointers from symbols
do {
  loc0 = loc - N;           //loc0 is real table location
  if ( read_one_bit( in ) == 0 ){  //a 0, go left
      loc = ( htree[loc0] & left_mask ) >> 8;
 } else{
      loc =  htree[loc0] & right_mask;
 }
} while ( loc >= N );       //traverse until reaches leaf
return loc;                 //symbol value = loc
```

8.4 Pre-calculated Huffman-based Tree Coding

The Huffman coding process has a disadvantage that the statistics of the occurrence of the symbols must be known ahead of the encoding process. Though we do not need to transmit the probability table to the decoder, we do need it before we can do any encoding. The probability table for a large video cannot be calculated until after the video data have been processed which may introduce unacceptable delay into the encoding process. Because of these, practical video coding standards define sets of codewords based on the probability distributions of generic video data. The following example is a pre-calculated Huffman table taken from MPEG-4 Visual (Simple Profile), which uses 3D run-level coding discussed before to encode quantized coefficients. A total of 102 specific combinations of (*run, level, last*) have variable-length codewords assigned to them and part of these are shown in Table 8-3. Each codeword can be up to 13 bits long and the last bit is the sign bit 's', which indicates if the decoded coefficient is positive (0) or negative (1). Any (*run, level, last*) combination that is not listed in the table is coded using an escape sequence; a special ESCAPE code of 0000011 is first transmitted followed by a 13-bit fixed-length codeword describing the values of *run, level*, and *last*. A valid codeword cannot contain more than eight consecutive zeros. Therefore, a sequence consisting of eight or more consecutive zeros, "00000000..." indicates an error in the encoded bitstream or possibly a start

code, which might contain a long sequence of zeros. We shall use Table 8-3 in our entropy-encoding stage shown in Figure 7-1. The full implementation of the Huffman encoding and decoding for our video codec is discussed in the next section.

Table 8-3

Run	Level	Last	Code
0	1	0	10s
1	1	0	110s
2	1	0	1110s
0	2	0	1111s
0	1	1	0111s
3	1	0	01101s
4	1	0	01100s
5	1	0	01011s
0	3	0	010101s
1	2	0	010100s
6	1	0	010011s
7	1	0	010010s
8	1	0	010001s
9	1	0	010000s
1	1	1	001111s
2	1	1	001110s
3	1	1	001101s
4	1	1	001100s
0	4	0	0010111s
10	1	0	0010110s
11	1	0	0010101s
12	1	0	0010100s
5	1	1	0010011s
6	1	1	0010010s
7	1	1	0010001s
8	1	1	0010000s
ESCAPE			0000011s
..	..	..	..

8.5 Huffman Coding Implementation

Because Huffman coding involve reading and writing one bit at a time, we need to first develop some functions that can process an arbitrary number of bits of a file. We provide the program "BitIO.java" which consists of two classes, namely, **BitInputStream** and **BitOuputStream** that has functions to process data on a bit-basis. The file can be downloaded from this book's web site at *http://www.forejune.com/jvcompress/*. We do not intend to discuss the details of these classes as they do not directly relate to video compression. All we need to know is how to use them, which is straightforward. The following is the class interface of BitInputStream class that can read data bits from an InputStream:

```
class BitInputStream
{
  private InputStream ins;
  ........
  public BitInputStream( InputStream in )
  {
      ins = in;
  }
  //read one bit
  synchronized public int readBit() throws IOException
  {
    .....
  }
  //read n bits
  synchronized public int readBits( int n ) throws IOException
  {
  }
};
```

The interface of the corresponding output class, BitOutputStream that sends data bits to an OutputStream is shown below:

```
class BitOutputStream
{
  private OutputStream outs;
  ........

  public BitOutputStream( OutputStream out )
  {
    outs = out;
  }
  synchronized public void writeBit(int bit) throws IOException
  {
    ........
  }
  synchronized public void writeBits(int data, int n)
                                    throws IOException
  {
    ........
  }
};
```

The main purpose of the Huffman code here is to encode the run-level codewords of the DCT coefficients after forward quantization and reordering. Recall that we have defined a class to represent a 3D run-level codeword:

```
class Run3D {
  byte  run;
  short level;
  byte  last;
};
```

Each Run3D object represents a run-level codeword, and the Huffman code is used to encode these codewords. We define a class called **RunHuff** that will help encode and decode run-level codewords. This class “has-a” run3D class. As you’ll see, we’ll insert

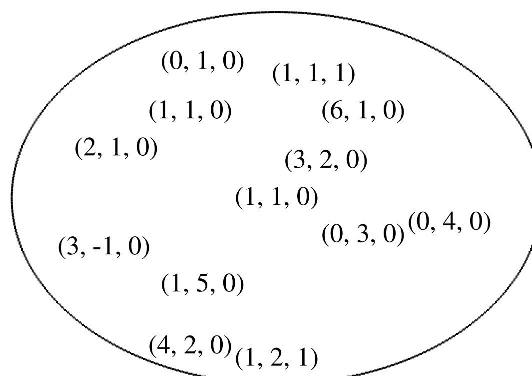
RunHuff objects into a **map**, which involves the ordering of nodes. **Maps** and **multimaps** are data structures that are useful in problems in which multiple collections naturally occur.

A **map**, sometimes also referred to as a dictionary or a table is an associative container where records (data) are specified by key values. It is an indexed collection; the key can be used to generate an index to access the corresponding record. A map can be considered as a collection of associations of key and value pairs. The key is used to find the value as shown below:

$$
\begin{aligned}
&key_1 \rightarrow value_1 \\
&key_2 \rightarrow value_2 \\
&key_3 \rightarrow value_3 \\
&.... \\
&key_n \rightarrow value_n
\end{aligned}
$$

For example, we can use the telephone number as the key to lookup the information of a person. The keys in a map must be ordered and unique. A multimap is similar to a map except that a multimap permits multiple entries to be accessed using the same key value. (i.e. The keys in a multimap do not need to be unique.)

In java, elements are found via the keys; we cannot use an iterator to traverse a map. To traverse all the elements (values) in a map, we have to put the elements in a set. Therefore, another data structure we need to use in our implementation is a **set**. A **set** is an unordered collection of elements in which each element is unique. It is also a container. A **bag** (also called a multiset) is similar to a set except that duplicated elements are allowed. Actually, the concept of a **set** underlies much of mathematics and is as well an integral part of many computing algorithms. The fundamental operations of a set include adding and removing elements, testing for inclusion of an element, and forming unions, intersections and differences of other sets. A set does not require ordering. Therefore, we cannot find an element in a set using a key like what a map does. On the other hand, we can traverse a set and perform the standard operations on sets. (Note that unlike java, the C++ Standard Template Library slightly modifies the concept of a set so that its elements are ordered.) The following figure shows a set of 3D run-level codewords:



Java provides several implementing classes of map interface, including HashMap, Hashtable, IdentityHashMap, RenderingHints, TreeMap, and WeakHashMap. We choose **TreeMap** in our implementation. The function "put(Object *key*, Object *value*)" associates the specified

value with the specified key and inserts them into the map. If the map previously contained a mapping for the key, the old value is replaced. On the other hand, the function "public Object get (Object key)" returns the value to which the map associated with the specified key.

In our implementation of the Huffman codec (encoder-decoder), we make both the **key** and the **value** to be RunHuff objects for the convenience of programming. Since the keys are ordered, to utilize a map properly, we must define the keys in a way that they can be compared with each other. Therefore, our class **RunHuff** implements **Comparable**$<$**RunHuff**$>$ as shown in Listing 8-1. The parameter inside the angular brackets $<>$ specifies the key type and in our case the key type is a RunHuff object. Actually, as a RunHuff object "has-a" Run3D object, we order the objects using the values of ($run, level, last$) of the Run3D objects. (Aternatively, one can specify the key type of Comparable as a Run3D object rather than a RunHuff object.) We first try to determine the "smaller" relation of two RunHuff objects by comparing the $runs$ of their Run3D objects; the one with smaller run values is the smaller RunHuff object and the comparison is done. If the $runs$ are equal, we compare the $levels$ and if the $levels$ are equal, we compare the the $lasts$. If the $runs$, $levels$ and $lasts$ of the two objects are equal, we assume that the keys are equal. This concept is presented in the compareTo function of Listing 8-1 shown below.

Program Listing 8-1: Class Containing Run-level Codewords

```
/*
 * RunHuff.java
 * For the use of constructing a pre-calculated Huffman tree.
 */

/*
 * Need to implement Comparable so that a RunHuff object
 * can be inserted into a TreeMap which will contain the
 * Huffman Table used for encoding.
 */
class RunHuff implements Comparable<RunHuff>
{
  Run3D r = new Run3D();
  int codeword;
  byte hlen; //length of Huffman code
  short index; //table index where codeword saved

  RunHuff() {} //constructors

  RunHuff ( Run3D a, int c, byte len, short idx )
  {
    r.run = a.run; r.level = a.level; r.last = a.last;
    codeword = c; hlen = len; index = idx;
  }

  //A run tuple is used as a key for comparison
  public int compareTo ( RunHuff right ) throws ClassCastException
  {
    if ( r.run < right.r.run )
      return 1;     //smaller
    if ( r.run > right.r.run )
      return -1;   //larger
    //run equals
    if ( r.level < right.r.level )
```

```
      return 1;
    if ( r.level > right.r.level )
      return -1;
   //both run and level equal
    if ( r.last < right.r.last )
      return 1;
    if ( r.last > right.r.last )
      return -1;
    return 0;   //The two objects equal
  }
};
```

We assume that a pre-calculated Huffman Table like the one shown in Table 8-3 is provided. Listing 8-2 presents the class **Hcodec** that makes use of a pre-calculated Huffman Table to build the encoder and decoder. We declare a variable *htable* to be a map to collect **RunHuff** objects, each of which contains a 3D run-level tuple and the corresponding Huffman codeword (Table 8-2). The statement

```
TreeMap<RunHuff,RunHuff>htable = new TreeMap<RunHuff,RunHuff>();
```

constructs a TreeMap object with *htable* pointing to this new object. The first and second argument enclosed by the anugular brackets $<>$ of TreeMap specify the key type and value tppe respectively. In our case, both the key type and value type are RunHuff objects.

The function **build_htable()** of the class Hcodec has all codewords and run-level tuples hard-coded in the code and saved in variables *hcode, runs, levels,* and *last* respectively. The function collects all these pre-calculated run-level tuples and Huffman codewords and saves them in the map *htable*. The TreeMap member function **put** is used to insert the RunHuff objects into the map. In the function, the special run value 127 is used to represent the ESC (escape) symbol:

Program Listing 8-2: Class for Building Huffman Coder Decoder

---

```
//Hcodec.java
//Building a Huffman Encoder-Decoder
import java.util.Set;
import java.util.Map;
import java.util.TreeMap;
import java.util.Iterator;
import java.io.*;

class Hcodec
{
  private final int NSymbols = 256;   //maximum symbols allowed
  private final short ESC = 0x60;     //Escape code
  private boolean tableNotBuilt = true;
  TreeMap<RunHuff, RunHuff>  htable = new TreeMap<RunHuff,RunHuff>();

  //use a map ( htable ) to collect all pre-calculated run-level
  //  and Huffman codewords
  void build_htable ()
  {
    //N = number of pre-calculated codewords with positive levels
    //In practice, N should be larger than 100
    short i, j, k, N = 10;
    //lengths of Huffman codewords (not including sign-bit)
```

```
    byte hlen[] = { 2, 3, 4, 4, 4, 5, 5, 5, 6, 7 };
    //Huffman codewords, 0x60 is ESC
    short hcode[] = {0x01,0x3,0x7,0xf,0xe, 0x16, 0x6, 0x1a, 0x2a, ESC};

    //data of 3D run-level tuples ( codewords )
    byte runs[] = {0, 1, 2, 0, 0, 3, 4, 5, 0, 127};  //127 signifies ESC
    short levels[] = {1, 1, 1, 2, 1, 1, 1, 1, 3, 0 };
    byte  lasts[] = {0, 0, 0, 0, 1, 0, 0, 0, 0, 0 };

    Run3D r = new Run3D();             //a 3D run-level codeword (tuple)
    RunHuff rf[] = new RunHuff[128];   //table containing RunHuff objects

    //inserting RunHuff objects into Map htable
    k = 0; j = 0;
    for ( i = 0; i < N-1; i++ ) {
      r.run = runs[i];
      r.level = levels[i];
      r.last = lasts[i];
      //construct a RunHuff object, positive level, so sign=0
      rf[k++] = new  RunHuff ( r, hcode[i] << 1,  hlen[i], j++ );
      //do the same thing for negative level, sign = 1
      r.level = (short) -r.level;
      rf[k++] = new RunHuff ( r, (hcode[i]<<1) | 1, hlen[i], j++ );
    }
    //special handling for ESC code
    r.run = runs[N-1];
    r.level = levels[N-1];
    r.last = lasts[N-1];
    rf[k] = new RunHuff ( r, hcode[N-1] << 1, hlen[N-1], j );
    //insert all (positive & negative levels) RunHuff objects into htable
    k = (short) ( 2 * N - 1 );     //2N - 1 RunHuff objects
    for ( i = 0; i < k; i++ )
      htable.put( rf[i], rf[i] );
    tableNotBuilt = false;
  }
  ........
};
```

As we mentioned earlier, we cannot use an iterator to traverse a map directly in java but TreeMap provides the function **entrySet**() to return a set view of the mappings in the map. Therefore, we can make use of the set's iterator and functions to process the map's data. The set's iterator returns the mappings in ascending key order. Each element in the returned set is a Map.Entry. The returned set is bound to this map, so changes to this map are reflected in the set, and vice-versa. The set supports element removal, which removes the corresponding mapping from the TreeMap, through the **Iterator.remove, Set.remove, removeAll, retainAll** and **clear** operations. Listing 8-3 shoows how to use the set view and functions to print all the entries of TreeMap *htable*. (In Java or C++, an iterator is an object that can access members of an array or a container class. It has the ability to traverse the elements in a certain range using certain operators. Very often, it is used in a manner similar to pointers.).

Program Listing 8-3: Print TreeMap Entries Using Set View and Functions

---

```
class Hcodec
```

```
{
  ....

  void print_htable()
  {
    // Use an Iterator to traverse the mappings in the TreeMap.  Note
    // that the mappings are in sorted order (with respect to the keys).
    Iterator itr = htable.entrySet().iterator();
    RunHuff rfs[] = new RunHuff[htable.size()];
    System.out.printf("\n(run,level,last),\tCodeword\tHCode Length,index");
     while ( itr.hasNext() )
     {
        Map.Entry entry = (Map.Entry) itr.next();
        RunHuff rhuf = (RunHuff) entry.getValue();
        rfs[rhuf.index] = rhuf;
     }
     for ( int i = 0; i < htable.size(); i++ ) {
        RunHuff rhuf = rfs[i];
        System.out.printf("\n(%4d, %4d, %d), \t%8x \t%x\t    %d, \t%4d",
            rhuf.r.run, rhuf.r.level, rhuf.r.last, rhuf.codeword,
            rhuf.codeword >> 1, rhuf.hlen, rhuf.index );
     }
  }
}
```

After we have collected all the pre-calculated run-level Huffman codewords in the **map** *htable*, the encoding of 3D run-levels tuples becomes simple. To encode a run-level codeword, all we need to do is to lookup the **map** *htable*; if the run-level codeword is in the map, we output the Huffman codeword along with the sign-bit; if it is not in the map, we "escape" and output the run-level codeword "directly".

Suppose the array *runs*[] contains all the run-level codewords of a macroblock; the following piece of code shows how to encode them using the pre-calculated Huffman codewords saved in *htable*. In the code, we use the member function **containsKey**() of TreeMap to determine if the run-level tuple is in *htable*. If yes, we retrieve the RunHuff object which contains the Huffman codeword from *htable* using the function **get**() and the run-level tuple as key. It then outputs the Huffman codeword and the sign-bit, otherwise it escape-encodes the run-level tuple by first outputting the ESCAPE code followed by a fixed-length codeword for the tuple:

Program Listing 8-4: Encode 3D run-level tuples with Huffman codewords

```
  /*
    Inputs:
      runs[] contains the 3D run-level tuples of a macroblock of quantized
      DCT coefficients
    Outputs:
      bitstreams of codewords ( Huffman + sign or ESCAPE + 3D run-level )
      to BitOutputStream outputs
    Note that data member htable contains all the pre-calculated Huffman
      codewords of 3D run-level tuples
  */
  void huff_encode ( Run3D runs[], BitOutputStream outputs )
  {
    short i, j, k;
```

```
    if ( tableNotBuilt )
      build_htable();
    k = 0;  i = 0;
    while ( i < 64 ) {          //a macroblock has at most 64 samples
      try {
        //construct a RunHuff object; only runs[k] is relevant as it is
        //  used for searching (we've defined CompareTo in RunHuff class)
        RunHuff rf = new RunHuff( runs[k], 0, (byte) 0, (short) 0 );
        if ( htable.containsKey ( rf ) ){
          RunHuff rhuf = htable.get( rf );
        } else {                          //not in table
          escape_encode( outputs, rf.r ); //need to 'escape encode' Run3D Object
       }
      } catch (IOException e) {
        e.printStackTrace();
        System.exit(0);
      }
      if ( runs[k].last != 0 ) break;   //end of run-level codewords
      i += ( runs[k].run + 1 );         //special case: whole run-block 0
      k++;
    }
  }
```

To encode a run-level tuple using the ESC symbol, we first check if the level is negative. If it is negative, we output a '1' bit otherwise we output a '0' bit. We then send the special code for the ESC symbol followed by the binary numbers representing the values of run, level and last. The following piece of code shows how to do this precisely.

```
  //Encode codeword unsing ESC
  void escape_encode ( BitOutputStream outputs, Run3D r )
  {
    try {
      if ( r.level < 0 ) {            //value of level negative
        outputs.writeBit ( 1 );       //output sign-bit first
        r.level = (short) -r.level;   //change level value to positive
      } else
        outputs.writeBit ( 0 );       //value of level positive
      outputs.writeBits ( ESC, 7 );   //ESCAPE code
      if ( r.run == 64 ) r.run = 63;  //r.level differentiates between
                                      //  if last element nonzero
      outputs.writeBits ( r.run, 6 );      //6 bits for run value
      outputs.writeBits ( r.level, 8 );    //8 bits for level value
      outputs.writeBit ( r.last );         //1 bit for last value
    } catch (IOException e) {
       e.printStackTrace();
       System.exit(0);
    }
  }
```

The functions **huff_encode**() and **escape_encode**() encode the 3D run-level tuples of a macroblock. In the encoding process, the Huffman tree is not needed. However, to decode the encoded bitstream, we have to use the Huffman tree to recover the 'symbols' (run-level tuples). We can easily construct the Huffman tree in the form of a table from the **map** *htable*. Note that here we build the Huffman tree from pre-calculated codewords,

not from symbol weights as people normally do. Therefore, the process is a lot simpler as Huffman codewords have been provided. The following function **build_huff_tree**() builds the Huffman tree from *htable* and saves it in the table (array) *huf_tree*[] of data type short. An entry of *huf_tree*[] holds a node's pointer to a child or an index ('symbol') if the node is a leaf; the index points to an entry of another table,*run_table*[], which contains the actual run-level tuple (see Table 8-3). For convenience of programming, we put *huf_tree*[] and *run_table*[] in a class called **Dtables**. Again we use the member function entrySet() of the class TreeMap to obtain a set view of the map *htable*; a set interator is used to traverse the set and obtain all the RunHuff objects of the set. Keep in mind that a RunHuff object contains a 3D run-level tuple and the associated Huffman codeword.

Program Listing 8-5: Constructing Huffman Tree

```
class Dtables {
  short huf_tree[] = new short[1024];   //table containing Huffman Tree
  Run3D run_table[] = new Run3D[512];  //table containing run-level codewords

  Dtables()
  {
    for ( int i = 0; i < 512; i++ )
      run_table[i] = new Run3D();
  }
};

class Hcodec
{
  ....

  void build_huff_tree ( Dtables d )
  {
    int i, j, n0, free_slot, loc, loc0, root, ntotal;
    int mask, hcode;

    n0 = NSymbols;        //number of symbols (=number of leaves in tree)
    ntotal = 2 * n0 - 1;  //Huffman tree has  n0 - 1  internal nodes
    root = 3 * n0 - 3;    //location of root, offset n0 has been added
    free_slot = root - 2; //next free table entry for filling in with a
                          //  pointer or an index
                          //  (note:root has root_left, root_right)
    for ( i = 0; i < ntotal; ++i )    //initialize the table
      d.huf_tree[i] = -1;             //all entries empty

    Iterator itr = htable.entrySet().iterator();
    RunHuff rfs[] = new RunHuff[htable.size()];
    while ( itr.hasNext() ) {
        Map.Entry entry = (Map.Entry) itr.next();
        RunHuff rhuf = (RunHuff) entry.getValue();
        rfs[rhuf.index] = rhuf;
    }
    for ( int ii = 0; ii < htable.size(); ii++ ) {
        RunHuff rhuf = rfs[ii];
        if ( rhuf.r.level < 0 ) continue;//only save positive levels
                                         //  of run-level codeword
        d.run_table[rhuf.index/2]=rhuf.r;//save run-level codeword;index
                           //  divided by 2 as only postive levels saved
        loc = root;                 //always start from root
        mask = 0x01;                //for examining bits of Huffman codeword
```

```
        hcode = rhuf.codeword >> 1;//rightmost bit is sign-bit,not Huffman
        for ( i = 0; i < rhuf.hlen; ++i ){ //traverse the Huffman codeword
          loc0 = loc - n0;         //everything shifted by offset n0
          if ( i == ( rhuf.hlen - 1 ) ){//last bit, should point to leaf
            if ( (mask & hcode) == 0 )  //a 0, save it at 'left' leaf
              d.huf_tree[loc0] = (short) (rhuf.index/2);
            else                         //a 1, save it at 'right' leaf
              d.huf_tree[loc0-1] = (short) (rhuf.index/2);
            continue;  //get out of for-i for loop, consider next codeword
          }
          if ( (mask & hcode) == 0 ){      //a 0 ( go left )
            if (d.huf_tree[loc0] == -1){  //slot empty
              d.huf_tree[loc0] = (short)free_slot;//point to left new child
              free_slot -= 2;              //next free table entry
            }                              //else : already has left child
            loc = d.huf_tree[loc0];        //follow the left child
          } else {                         //a 1 ( go right )
            if (d.huf_tree[loc0-1]== -1){ //slot empty
              d.huf_tree[loc0-1]= (short)free_slot;//point to right new kid
              free_slot -= 2;
            }                              //else: already has right child
            loc = d.huf_tree[loc0-1];      //follow the right child
          }
          mask <<= 1;                      //consider next bit
        } //for i
      } //while
  } //build_huff_tree()
}
```

After we have built the Huffman tree, decoding becomes simple. We read in a bitstream and traverse the tree starting from the root. If the bit read is a 0, we traverse left, otherwise we traverse right until we reach a leaf where we recover a symbol. If the symbol is an ESCAPE code, we need to further read in a fixed-number of bits to determine the 'symbol' (the run-level tuple). Then we read in another bit and start the tree-traversal from the root again. The details are shown in the function **huff_decode**() listed below.

Program Listing 8-6: Huffman Decoder

```
  /*
    Inputs: inputs, the encoded bitstream to be decoded
          d.huf_tree[], table containing the Huffman tree
          d.run_table[], table containing the actual run-level codewords
    Output: runs[], table containing the run-level tuples of a macroblock
  */
  short huff_decode( BitInputStream inputs,  Dtables d,  Run3D runs[] )
  {
    short n0, loc, loc0, root, k;
    int c, sign;
    boolean done = false;
    Run3D rp;
    n0 = NSymbols;                //number of symbols
    root = (short)(3 * n0 - 3);  //points to root of tree
    k = 0;
    try {
      while ( !done ) {
        loc = root;               //starts from root
```

```
        sign = inputs.readBit(); //sign-bit
        do {
          loc0 = (short) (loc - n0);
          c = inputs.readBit();              //read one bit
          if (c < 0) {done = true; break;}  //no more data, done
          if ( c == 0 )                     //a 0, go left
            loc = d.huf_tree[loc0];
          else                              //a 1, go right
            loc = d.huf_tree[loc0-1];
        } while ( loc >= n0 );              //traverse until reaches leaf
        if ( loc >= n0 ) break;             //done
        rp = d.run_table[loc];

        Run3D r3d = new Run3D();
        if ( rp.run == -1 ) {  //ESCAPE code, read actual run-level tuple
          r3d.run  = (byte) inputs.readBits ( 6 );  //read 6 bits for run
          r3d.level  = (byte) inputs.readBits ( 8 );//read 8 bits for level
          r3d.last = (byte) inputs.readBit();       //read 1 bit for last
          if ( sign == 1 )            //if sign is 1, level should be negative
            r3d.level = (byte) -r3d.level;
        } else {                      //not ESCAPE code
          r3d.run = rp.run;
          r3d.level = rp.level;
          r3d.last = rp.last;
          if ( sign == 1 )            //1 => negative
            r3d.level = (byte) -r3d.level;
        }
        if ((r3d.run == 63)&&(r3d.level == 0))
          r3d.run = 64;               //whole block 0
        runs[k++] = r3d;              //save tuple in table runs[]
        if ( r3d.last != 0 )          //end of macroblock
          break;
      } //while
    } catch (IOException e) {
       e.printStackTrace();
       System.exit(0);
    }

    if ( done ) return -1;            //if ( done ) => no more data
    else return 1;
  }
```

Putting all these together, we provide two driver programs,

```
Test_huf_encode.java, and
Test_huf_decode.java
```

for you to do the testing of the concepts discussed above. (The programs can be downloaded from the web site of this book, *http://www.forejune.com/jvcompress/*.) You can copy the files along with the ".dct" files and put them in the same directory. Since the classes discussed here need to use other classes discussed in previous chapters, you need to setup the CLASSPATH properly using a command like the following:

```
export CLASSPATH=$CLASSPATH:../5/:../6/:../7/
```

Then compile all the java programs in the current directory with the command "javac *.java". Java byte codes will be generated and you may use the command,

```
$java Test_huf_encode t.dct t.huf
```

to encode the DCT coefficients of the file “t.dct” and save the Huffman codeword bitstream in “t.huf”. The command

```
$java Test_huf_decode t.huf t.dec
```

decodes the Huffman codeword bitstream saved in “t.huf” and saves the decoded DCT coefficients in the file “t.dec”.

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