MAHARISHI UNIVERSITY of MANAGEMENT

Engaging the Managing Intelligence of Nature

Computer Science Department

CS390 Fundamental Programming Practices (FPP)
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Lecture 11: Hashtables

Wholeness of the Lesson

Hashtables provide even faster access to elements in a collection than a BST, but at the price of losing the sorted status of the elements. If maintaining order among the elements of a collection is not required, hashtables are the most efficient data structure for storing elements in memory, when insertion, deletion, and lookup operations are needed. Hashtables give concrete expression to the ability of pure intelligence to know any one thing instantaneously.

The Hashtable ADT

- A Hashtable is a generalization of an array in which any object can be used as a key instead of just integers. A Hashtable has *keys* which are used to look up corresponding *values.* A typical example is to store records from a database in memory. A key field from the database is often used as a key in the hashtable, and the corresponding record is the value in the hashtable.

- Basic operations:

```
void put(Object key, Object value)
Object get(Object key)
Object remove(Object key)
```

Simple Example: Character Table

Char key	String value
'a'	"Adam"
'b'	"Bob"
'c'	"Charlie"
'w'	"William"

```
//insert into table
table.put('c', "Charlie");
//retrieve from table
table.get('c');  //returns "Charlie"
```

Implementation:

put(c, s):
- c   → (int)c   [convert key to a number -- a *hash code*]
        → i = (int)c - 'a'   [convert hash code to an array index -- a *hash value*]
- insert new Entry(c, s) into table[i]

get(c):
- c   → (int)c   [convert key to a hash code]
        → i = (int)c - 'a'   [convert hash code to hash value]
- Entry e = table[i]; return e.value
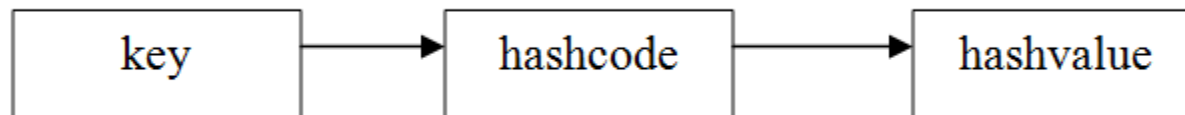
Pattern:

KEY (non-number) → HASHCODE (number) → HASH VALUE (array index)

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Creating a Hashtable

- First Steps:
  - a. *Convert Keys to Integers (hash codes).* Devise a way of converting keys to integers so that different keys are mapped to different integers. This is what Java's `hashCode()` function (in `Obect`) is for.

  - b. *Convert Hash Codes to Indices in an Array (hash values).* Devise a way of converting hashcodes to smaller integers (called *hash values*) that will be the indices of a smaller array, called the *table*. To do this, you first decide the `tableSize`, which is the length of the array. A typical way (note: Java does it differently) of making hash value from hashcode is by the formula

    ```
    hashvalue = Math.abs(hashcode % tableSize)
    ```

| key | → | hashcode | → | hashvalue |

<u>put</u> **operation**: `put(k, val)`

```
put("10110", jRecord);
put("21013", kRecord);
put("33536", mRecord);
```

<u>Step 1</u>: Compute index in table where data will be placed
- `Entry e = [k, val]`
- `hashcode = hashCode(k)`
- `h = hashvalue(hashcode)`
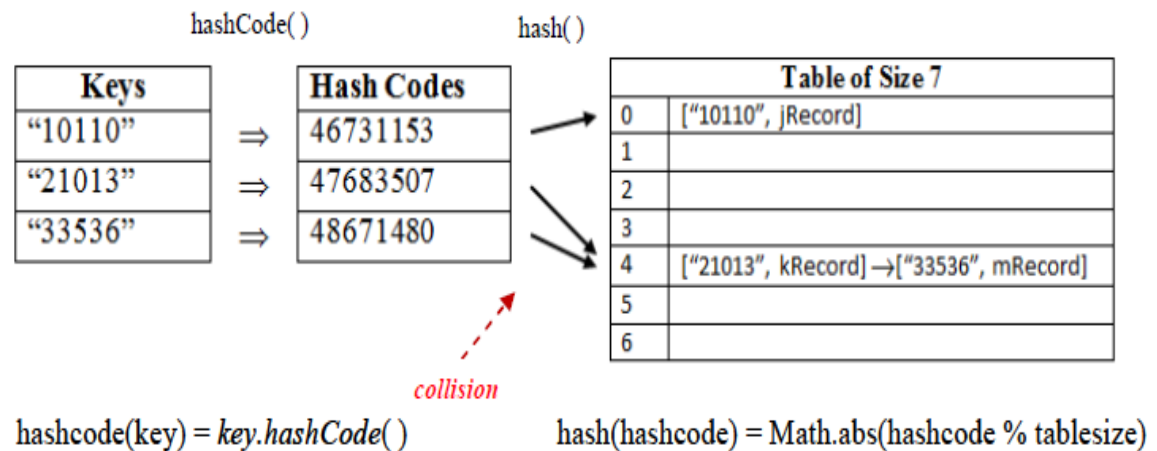   `= Math.abs(hashcode % tableSize)` (typically)

<u>Step 2</u>: Place the `Entry` object in the table in slot h.

- Would like to store `e` *directly* in `table[h]` but cannot because of potential collisions.

- <mark>*Solution*</mark>: Each table slot stores a `LinkedList`.*
  Store `e` by:

  `table[h].add(e)`

* In Java's HashMap, if the size of one of these linked lists gets to be too large (default = 8), the linked list is converted to a red-black tree.

Keys		Hash Codes
"10110"	⇒	46731153
"21013"	⇒	47683507
"33536"	⇒	48671480

hashCode( )   hash( )

Table of Size 7	
0	["10110", jRecord]
1	
2	
3	
4	["21013", kRecord]→["33536", mRecord]
5	
6	

collision

hashcode(key) = *key.hashCode( )*   hash(hashcode) = Math.abs(hashcode % tablesize)
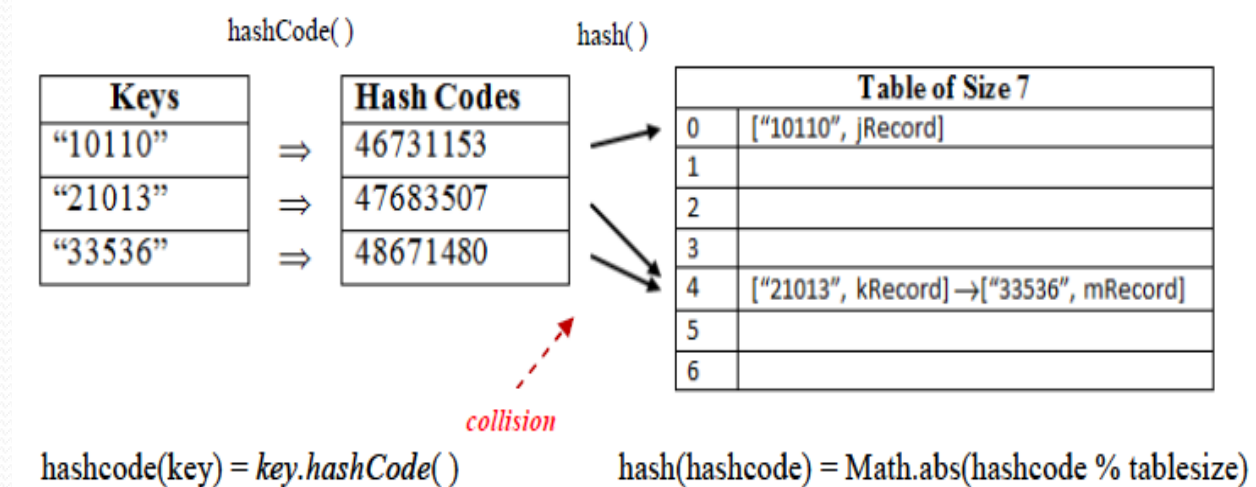
<u>get</u> <u>operation</u> `get(k)`

<u>Step 1</u>: Compute index in table where data will be found
- `hashcode = hashcode(k)`
- `h = hashvalue(hashcode)`
    `= Math.abs(hashcode % tableSize)` (typically)

<u>Step 2</u>: Read the `Entry` object from the table and return its value.

- `LinkedList l = table[h]`
- `Entry e = l.find(k)`
- `return e.val`

Hashtable Implementation

Demo: lesson11.myhashtable.MyHashtable

```
public class MyHashtable {
    private static final int INITIAL_SIZE = 20;
    private int tableSize;
    private LinkedList[] table;
    public MyHashtable(){
        this(INITIAL_SIZE);
    }
    public MyHashtable(int tableSize) {
        this.tableSize = tableSize;
        table = new LinkedList[tableSize];
    }
```

//Inner class in MyHashtable

```java
private class Entry {
    private Object key;
    private Object value;
    Entry(Object key, Object value) {
        this.key = key;
        this.value = value;
    }
    public String toString() {
        return key.toString() + "->"
                + value.toString();
    }
}
```

```
// FIRST TRY (needs to be fixed -- see SECOND TRY BELOW)

public void put(Object key, Object value){
        //disallow null keys
        if(key==null) return;

        //convert key to an integer – assumes key not null
        int hashcode = key.hashCode();

        //convert hashcode to a hashvalue – an array index
        int h = hash(hashcode);

        //put the value and the key into an Entry object
        //which will be placed in the table in the
        //slot (namely, h) – note: null value is allowed
        Entry e = new Entry(key,value);

        // now place it in the table
        if(table[h] == null){
                table[h] = new LinkedList();
        }
        table[h].add(e);
}
```

Problem: *Handling Duplicate Keys.* Our implementation does not handle duplicate keys in a good way.

Example: Suppose a client class attempts these `put` operations:

```
put(key, "Bob")
put(key, "Dave")
```

Suppose the hashvalue for `key` is 5. In the approach above, there will be two `Entries` placed in the list in slot 5 – [`key`, "Bob"] and [`key`, "Dave"]. Then (depending on the linked list's add method), the "Dave" entry will not be accessible when a `get(key)` operation is performed.

```java
// SECOND_TRY
public void put(Object key, Object value){
    //disallow null keys
    if(key==null) return;

    //convert key to an integer - assumes key not null
    int hashcode = key.hashCode();

    //convert hashcode to a hashvalue - an array index
    int h = hash(hashcode);

    //create the entry
    Entry e = new Entry(key, value);

    boolean keyAlreadyInUse = false;
    if(table[h] != null) {
      for(Object ob : table[h]) {
          Entry ent = (Entry)ob;
          if (ent.key.equals(key)) {
              keyAlreadyInUse = true;
              ent.value = value; //update value for this Entry
          }
      }
    }
    //we handled case keyAlreadyInUse==true in loop
    if(!keyAlreadyInUse) {
        // now place it in the table
        if(table[h] == null){
            table[h] = new LinkedList();
        }
        table[h].add(e);
    }
}
```

```java
public Object get(Object key){

    //null key not allowed
    if(key==null) return null;

     //convert key to an integer
    int hashcode = key.hashCode();

    //convert hashcode to a hashvalue – an array index
    int hash = hash(hashcode);

    //if slot given by hash not yet in use, return null
    if(table[hash] == null) return null;

    //now look for the desired Entry
    Entry e = null;
    Iterator it = table[hash].iterator();
    while(it.hasNext()){
        e = (Entry)it.next();
        if(e.key.equals(key)) {
            return e.value;
        }
    }
    return null;

}
```

Overriding the hashCode() Method

- Any implementation of the Hashtable ADT in Java will make use of the `hashCode()` function as the first step in producing a hash value (or table index) for an object that is being used as a key.

- Default implementation of `hashCode()` provided in the `Object` class is not generally useful – gives a numeric representation of the memory location of an object. See package `lesson11.defaulthashcode`

- **Example**: We wish to use pairs (`firstName`, `lastName`) as keys for `Person` objects in a hashtable.
  (See package `lesson11.needoverridehashcode`)

  Demo shows default `hashCode` method is not useful. If two `Pair` objects, created at different times, are equal (using the `equals` method), we would expect them to have the same `hashCodes,` so that after hashing they are sent to the same table slot. But default `hashCode` method does not take into account the fields used by `equals` method, so equal `Pair` objects are almost always assigned different slots in the table.

First Rule About Creating Keys for a Hashtable: *To use an object as a key in hashtable, you must override* `equals()` *and* `hashCode()`

Creating Good Hash Codes When Overriding hashCode()

- There are two general rules for creating hash codes (i.e. for overriding `hashCode()`):

    I. (Primary Hashing Rule) Equal keys must be given the same hash code (otherwise, the same key could be mapped to different slots in the table)

    If `k1.equals(k2) then k1.hashCode() == k2.hashCode()`

    II. (Secondary Hashing Guideline) Different keys should be given different hash codes (if not, then many different keys may be sent to the same slot in the table, thereby degrading hashtable performance).

    Best Practice: The hash codes should be distributed as evenly as possible (this means that one integer occurs as a hash code approximately just as frequently as any other)

Exercise 11.1 – What Happens When hashCode Is Not Overridden Carefully?

- In the InClassExercises project, a `MyHashtable` class is provided, and a class `MyClass` is also provided.
- Try overriding `hashCode` in `MyClass` as follows:

```
public void hashCode() {
    return 2;
}
```

- In the `main` method, create 10 instances of `MyClass`, passing into the constructor values 1, 2, …, 10 in succession
- Put these 10 instances into a new instance of `MyHashtable`, using each `MyClass` instance as a key and its integer value as the value:
  `myHashtable.put(myClass1, 1)`, etc
- Use the `printTable` method provided in this version of `MyHashtable` to print the underlying table, including the indices.
- What does the `printTable` output tell you about this way of overriding `hashCode` in `MyClass`?

Creating Hash Codes from Object Data (Legacy Approach)

You are trying to define `hashCode()` for your class and you want to build the hash code from the hash codes of each variable in the class. First step is to assign hash code values to each of these instance variables.

```
class MyClass {
     boolean val;
     double d;
     <type> f;
     String name;
      . . .
     public int hashCode() {
          //implement
     }
}
```

Suppose `f` is an instance variable in your class

- If `f` is `boolean`, compute `(f ? 1 : 0)`
- If `f` is a `byte`, `char`, `short`, or `int`, compute `(int) f`.
- If `f` is a `long`, compute `(int) (f ^ (f >>> 32))`
- If `f` is a `float`, compute `Float.floatToIntBits(f)`
- If `f` is a `double`, compute `Double.doubleToLongBits(f)` which produces a long `f1`, then return `(int) (f1 ^ (f1 >>> 32))`
- If `f` is an object, use `f.hashCode()` (best if implementation of `f` has overridden `hashCode()` already)

Combining HashCodes of Instance Variables to Produce a Final HashCode (Legacy Approach)

- Suppose your class has instance variables u, v, w and corresponding hashCodes `hash_u`, `hash_v`, `hash_w` (obtained as in the previous slide). Then:

```
@Override
public int hashCode() {
  int result = 17;
  result += 31 * result + hash_u;
  result += 31 * result + hash_v;
  result += 31 * result + hash_w;
  return result;
}
```

Combining HashCodes of Instance Variables to Produce a Final HashCode (Modern Approach)

- Use the following method in the `Objects` class to compute hash code.

```
public static int hash(Object... values)
```

- For example, if an object has three fields, x, y, and z, we could compute hash code in this way:

```
@Override
public int hashCode() {
  return Objects.hash(x, y, z);
}
```

Overriding HashCode for Pair class

Example. *Overriding hashCode in the Person-Pair example.* We must take in account the same fields in computing `hashCode` as those used in overriding `equals`. The fields in `Pair` are `String`s, and Java already provides `hashCodes` for `Strings`. So we make use of these and combine them to produce a complex `hashCode` for `Pair`. (See the solution in lesson11.needoverridehashcode)

```java
public class Pair {
    String first;
    String second;
    public Pair(String f, String s) {
        first = f;
        second = s;
    }
}
```

```java
//legacy approach
public int hashCode() {
    int result = 17; //seed
    int hashFirst = first.hashCode();
    int hashSecond = second.hashCode();
    result += 31 * result + hashFirst;
    result += 31 * result + hashSecond;
    return result;
}

//modern way
public int hashCode() {
    return Objects.hash(first, second);
}
```

HashCode in Java's String Class

Example. *How Java overrides hashCode in the String class*: Any Java String is converted to an integer via `hashCode()` by this formula:

Given a `String s` of length `k+1`

$$s.hashCode() \text{ equals } 31^k * s.charAt(0) +$$
$$31^{k-1} * s.charAt(1) +$$
$$31^{k-2} * s.charAt(2) +...+$$
$$31^0 * s.charAt(k)$$

Since every character in the `String` is taken into account, equal `Strings` must have equal `hashCodes`. Because of the formula, it is highly unlikely that two distinct `Strings` will be assigned the same `hashCode` (though it's possible)

Java's Implementation of Hashtables

- HashMap and Hashtable (HashMap is preferred; Hashtable is "legacy")

Feature	java.util.HashMap	java.util.Hashtable	MyHashtable
Allows null key	Yes	No	No
Allows null values	Yes	No	Yes
Allows duplicate keys	No	No	No (after correction)
Synchronized (for safe multithreading)	No	Yes	No

Java's Implementation of Hashtables

- Pre-j2se5.0

```
HashMap map = new HashMap();
map.put("Bob", new Employee("Bob",40000,1996,10,2));
Employee emp = (Employee)map.get("Bob");
```

- j2se5.0 version is parametrized:

```
HashMap<String, Employee> map =
        new HashMap<String,Employee>();
map.put("Bob", new Employee("Bob",40000,1996,10,2));
//no downcasting required
Employee emp = map.get("Bob");

map.put("Bob", new Employee("Bob",50000,1996, 10, 2));
//The Employee Bob with salary 50000 will be returned.
emp = map.get("Bob");
```

Main Point

The most common implementation of hashtables uses separate chaining; each hashvalue is an index in an array of Lists; all objects with colliding hashvalue i are stored in the ith list in the array. The solution to the problem of avoiding hashvalue collisions (namely, by using a List in each of the array slots) illustrates the principle of the second element: Using a List in each array slot provides a way to "harmonize" objects that were apparently in conflict because of identical hashvalues.

Hashtable Application #1: Removing Duplicates

- The most common use of hashtables is as in-memory look-up tables. For example, `Employee` records from a database could be stored by using `Employee` ID as key and the entire `Employee` record as value.

- Another application of hashtables is for "bookkeeping" purposes. A simple example is an efficient procedure for removing duplicates from a list. The "naïve" way to remove duplicates is to use nested loops: For each element `e` in the list, use an inner loop to look at all elements preceding `e` in the list to see if `e` has occurred before; if so, remove this second occurrence of `e`.

- A more efficient approach is to do the following: Create an auxiliary hashtable `h`. For each `e` in the list, check to see if `e` is a key in `h`. If so, remove `e` from the list. If not, add the entry `<e,e>` to `h`.

- See `package lesson11.removedups`

Exercise 11.2

Use a hashtable as a fast way to solve the following problem:

> You are given two arrays `arr1`, `arr2`, of `String`s Determine whether every `String` contained in `arr1` is also contained in `arr2`. You may not use nested loops.

See the method `isSubArray` in the `Subarray` class, in the InClassExercises.

Solution

```java
public static boolean isSubArray(String[] arr1, String[] arr2) {
    var h = new HashMap<String, String>();
    for(String s : arr2) {
        h.put(s, s);
    }
    for(String s: arr1) {
        if(!h.containsKey(s)) return false;
    }
    return true;
}
```

Hashtable Application #2:
The Set ADT

1. Mathematically, a ***set*** is (roughly) a collection of objects. Two sets are said to be equal if they have the same elements.

2. **Question**: Are the following sets equal?
   `{1, 1, 3}, {1, 3}, {3, 1}`

3. **Solution**: Yes, because all have the same elements.

   Note: A set does not impose an ordering of elements (the set may contain elements that have their own natural order, like integers, but the set itself does not impose an order)

We can represent the mathematical notion of a set as an ADT called `Set`. In order to faithfully represent the properties of the mathematical idea, the `Set` ADT must have the following characteristics:

- It does not allow duplicate elements

- Iterating through a set does not guarantee any special order on its elements (in particular, there is no guarantee that the order in which an Iterator will provide elements corresponds to the order in which the elements were added in the first place)

- Its overridden `equals()` method declares two `Sets` to be equal if and only if they have the same elements

Java provides a `Set` interface (and in j2se5.0, the parametrized version `Set<E>`) as part of the Collections API.

The Set Interface for Strings

```java
public interface Set<String> {

    //adds a String to the Set
    //do not allow null and prevent duplicates
    public boolean add(String ob);

    //removes a String
    public boolean remove(String ob);

    //returns true if ob is an element
    public boolean contains(String ob);

    //returns true if the set has no element
    public boolean isEmpty();

    //returns the number of elements in the set
    public int size();
}
```

Two implementations of the `Set` interface in Java:

- `HashSet` Using a `HashMap` to implement Sets prevents duplicate elements from being added in the `Set`. Does not guarantee order in which elements are stored

- `TreeSet`. Uses a red-black tree (a very efficient BST) to store elements, so when they are output, they are in sorted order

- Demo: `lesson11.sets`

Sample Implementation of Set

```java
public class MySetImpl implements MySet {
    private MyHashtable table;

    public MySetImpl(){
        table = new MyHashtable();
    }
    public boolean add(Object ob){
        if(ob == null || isUnmodifiable) {
            return false;
        }
        if(table.containsKey(ob)){
            return false;
        }
        table.put(ob,ob);
        return true;
    }
    public boolean contains(Object ob){
        if(ob == null) return false;
        return table.containsKey(ob);
    }
    public boolean remove (Object ob){
        if(ob == null || isUnmodifiable) {
            return false;
        }
        if(table.containsKey(ob)){
            Object obj = table.remove(ob);
            return (obj != null);
        }
        return false;
    }
```

Main Point

The Hashtable ADT is a generalization of the concept of an array. It supports (nearly) random access of table elements by looking up with a (possibly) non-integer key. In the usual implementations, objects used as keys in a hashtable are "hashed", producing hashcode (a numeric value) and hashvalue (numeric value reduced in size to be less than the table size). The hashvalue is an index in an array that can be used to locate or insert an object. Hashtables illustrate the principle of Do less and accomplish more – they provide an incredibly fast implementation of the main List operations.

Guidelines for Use of Common Data Structures

1. **Array List**
   - <u>Use When</u>: Main need for a list is random access reads, relatively infrequent adds (beyond initial capacity) and/or number of list elements is known in advance. Sorting routines run faster on an ArrayList than on a Linked List.
   - <u>Avoid When</u>: Many inserts and removes will be needed and/or when many adds expected, but number of elements unpredictable. Also: Maintaining data in sorted order is very inefficient.

2. **Linked List**
   - <u>Use When</u>: Insertions and deletions are frequent, and/or many elements need to be added, but total number is unknown in advance. There is no faster data structure for repeatedly adding new elements than a Linked List (since elements are always added to the front).
   - <u>Avoid When</u>: There is a need for repeated access to element by index, as in binary search – random access is not supported.

3. **Binary Search Tree**
   - <u>Use When</u>: Data needs to be maintained in sorted order. Faster than Linked Lists for insertions and deletions, but ordinary adds are slower. Provides very fast search for keys.
   - <u>Avoid When</u>: The extra benefit of keeping data in sorted order is not needed and rapid read access is needed (Array List provides faster read access by index and hashtables provide faster read access by key)

4. **Hashtable/Hashmap**
   - <u>Use When</u>: Random access to objects is needed but array indexing is not practical. Provides fastest possible insertion and deletion (faster than BSTs).
   - <u>Avoid When</u>: The order of data must be preserved (example: you want to find all employees whose salaries are in the range 60000..65000) or "find Max" or "find Min" operations are needed.

5. **Sets**
   - <u>Use When</u>: Duplicates should be disallowed, and there is no need for rapid lookup of individual set elements. Example: `keySet()` in `HashMap` returns a `Set`. To order the elements, use `TreeSet`.

Connecting the Parts of Knowledge With the Wholeness of Knowledge

Random access expanded from integer index to arbitrary index,
from "point" to "infinity"

1. Arrays and ArrayLists provide highly efficient index-based access to a collection of elements.

2. The Hashtable ADT generalizes the behavior of an array by allowing non-integer keys (in fact, any object type can be used for a key), while retaining nearly random access efficiency for insertions, deletions, and lookups.

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3. **Transcendental Consciousness:** TC is the home of all knowledge. The Upanishads declare "Know that by which all else is known" – this is the field of pure consciousness.

4. **Wholeness moving within itself**: In Unity Consciousness, one sees that the "key" to accessing complete knowledge of any object is the infinite value of that object, pure consciousness, which is known in this state to be one's own Self. Knowing that level of the object, it then becomes possible to know any more relative level of the object as well.