Data Structures & Algorithms in C++

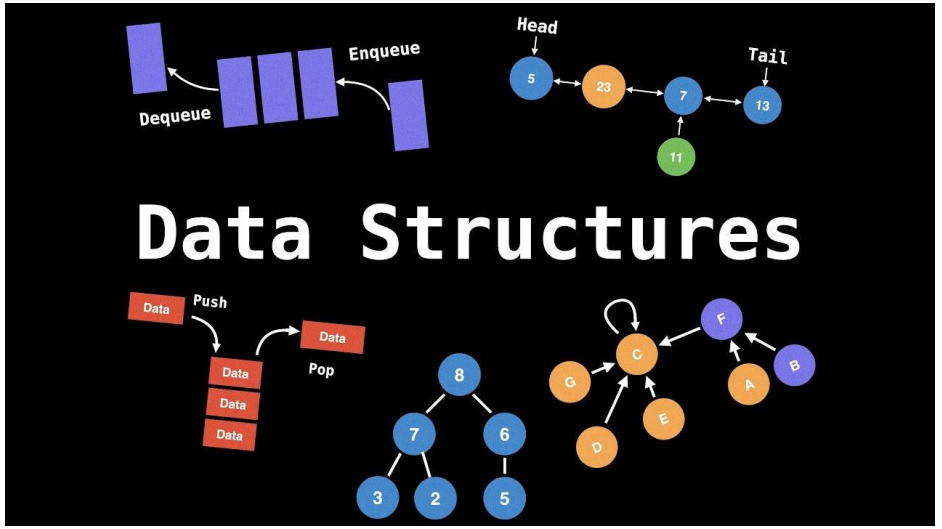
WEEK 01

Introduction

- Concept of Data Structures
- Data Structures and Algorithms
- Classification of Data Structures
- Data Expressions
- Control Flow, Functions, Classes

Data Structures ?

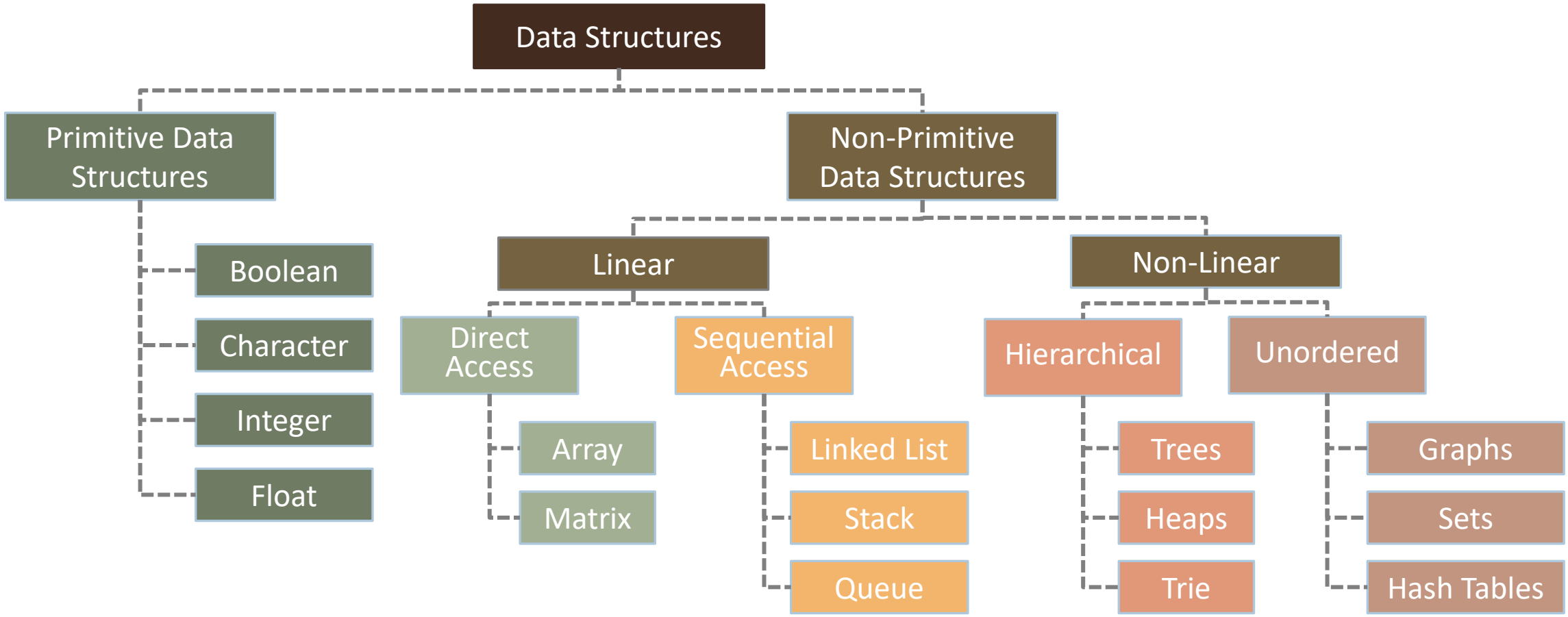
- A Data Structure is a specific way of organizing and storing data within a program, allowing for efficient access and manipulation of that data
  - Essential ingredients in creating fast and powerful algorithms
  - Help to manage and organize data
  - Make code cleaner and easier to understand



Data Structures and Algorithms

- An algorithm is a procedure used for solving a problem or performing a computation
  - A step-by-step procedure or formula for solving a problem
  - Examples: sorting, searching, traversal
- Data structures are containers for data, algorithms are tools for manipulating these structures
- Basic components of an **Algorithm**
  - Input, Output, Clearness, Finiteness, Effectiveness

List of Data Structures



Fundamental Data Types

- **Primitive Data Structures**
  - **bool** : boolean value, either true or false
  - **char** : character
  - **short** : short integer
  - **int** : integer
  - **long** : long integer
  - **float** : single-precision floating-point number
  - **double** : double-precision floating-point number
  - **enum** : a user-defined type that can hold any of a set of discrete values

Complex Data Types

- **Pointers**
  - a variable that holds the value of such an address
  - address-of operator : &
  - dereferencing : accessing an object's value from its address

```
char ch = 'Q';
char* p = &ch;          // p holds the address of ch
cout << *p;             // outputs the character 'Q'
ch = 'Z';               // ch now holds 'Z'
cout << *p;             // outputs the character 'Z'
*p = 'X';               // ch now holds 'X'
cout << ch;             // outputs the character 'X'
```

- **References**

```
string author = "Samuel Clemens";
string& penName = author;
penName = "Mark Twain";
```

Complex Data Types

- **Pointers vs. References**

Aspect	Pointer	Reference
Definition	A variable that stores the memory address of another variable	An alias (alternative name) for an already existing variable
Syntax	Uses the * operator to declare and dereference	Uses the & operator for declaration (not to be confused with the & in address-of)
Nullability	Can be assigned nullptr to indicate it points to no valid memory location	Must always reference a valid variable; cannot be null
Indirection	Must be dereferenced using * to access or modify the value it points to	Directly accesses the value of the variable it references, without requiring dereferencing
Usage	Commonly used for dynamic memory management and data structures	Simplifies syntax for passing variables by reference and aliasing objects

Complex Data Types

- **Arrays**
  - A collection of elements of the same type
  - Referenced by its index
  - No built-in run-time checking for out of bounds (vs. STL vector)

```
double f[5];          // array of 5 doubles: f[0], ..., f[4]
int m[10];            // array of 10 ints: m[0], ..., m[9]
f[4] = 2.5;
m[2] = 4;
cout << f[m[2]];      // outputs f[4], which is 2.5
```

  - The name of an array is equivalent to a pointer to the array's initial element

```
char c[] = {'c', 'a', 't'};
char* p = c;                  // p points to c[0]
char* q = &c[0];              // q also points to c[0]
cout << c[2] << p[2] << q[2]; // outputs "ttt"
```

Complex Data Types

- **Strings**
  - Fixed-length array of characters that ends with the null character (C-style strings)
  - C++ provides STL strings
    - Concatenated using "+" operator
    - Compared with each other using lexicographic order ("<", ">",…)

```
#include <string>
using std::string;
// ...
string s = "to be";
string t = "not " + s;
string u = s + " or " + t;
if (s > t)
  cout << u;
```

```
string s = "John";
int i = s.size();
char c = s[3];
s += " Smith";
```

Complex Data Types

- **C-Style Structures**
  - Useful for storing an aggregation of elements of the different type

```
enum MealType { NO_PREF, REGULAR, LOW_FAT, VEGETARIAN };

struct Passenger {
    string      name;          // passenger name
    MealType    mealPref;      // meal preference
    bool        isFreqFlyer;   // in the frequent flyer program?
    string      freqFlyerNo;   // the passenger's freq. flyer number
};

Passenger pass = { "John Smith", VEGETARIAN, true, "293145" };
```

- **C++** provides a much more powerful and flexible construct called a class with both data and functions

Complex Data Types

- Pointer and **dynamic memory allocation (new)**

```
Passenger *p;
// ...
p = new Passenger;                  // p points to the new Passenger
p->name = "Pocahontas";             // set the structure members
p->mealPref = REGULAR;
p->isFreqFlyer = false;
p->freqFlyerNo = "NONE";
```

  - Because C++ does not provide automatic garbage collection, all dynamically allocated objects should be explicitly deleted (cf. memory leak)

```
char* buffer = new char[500];       // allocate a buffer of 500 chars
buffer[3] = 'a';                    // elements are still accessed using []
delete [] buffer;                   // delete the buffer
```

Complex Data Types

- **Comparison between new and malloc**

Aspect	new (in C++)	malloc (in C)
Purpose	Used to allocate memory and automatically call the constructor of the object	Used to allocate memory, but does not call any constructors
Syntax	Type* pointer = new Type; ex) int* p = new int;	void *pointer = malloc(size_t size); ex) int *p = (int *)malloc(sizeof(int));
Memory deallocation	using delete ex) delete p;	using free ex) free(p);
Type safety	Type-safe; no need for explicit casting ex) int* p = new int;	Not type-safe; requires explicit casting ex) int *p = (int*)malloc(sizeof(int));

Complex Data Types

- **Namespaces and Using statements**
  - allow a group of related names to be defined in one space
  - fully qualified name : ex) myglobals::cat

```
namespace myglobals {
  int cat;
  string dog = "bow wow";
}
```

  - the using statement makes some or all of the names from the namespace accessible

```
using std::string;              // makes just std::string accessible
using std::cout;                // makes just std::cout accessible

using namespace myglobals;      // makes all of myglobals accessible
```

Expressions

- **Operator Precedence**

Type	*Operators*
scope resolution	namespace_name :: member
selection/subscripting function call postfix operators	class_name.member pointer–>member array[exp] function(args) var++ var––
prefix operators dereference/address	++var ––var +exp –exp ˜exp !exp *pointer &var
multiplication/division	* / %
addition/subtraction	+ –
shift	<< >>
comparison	< <= > >=
equality	== !=
bitwise and	&
bitwise exclusive-or	^
bitwise or	|
logical and	&&
logical or	||
conditional	bool_exp ? true_exp : false_exp
assignment	= += –= *= /= %= >>= <<= &= ^= |=

Expressions

- **Type casting**

```
int      i1  = 18;
int      i2  = 16;
double   dv1 = i1 / i2;                    // dv1 has value 1.0
double   dv2 = double(i1) / double(i2);    // dv2 has value 1.125
double   dv3 = double( i1 / i2 );          // dv3 has value 1.0
```

  - **Explicit** cast operators

```
double   d1 = 3.2;
double   d2 = 3.9999;
int      i1 = static_cast<int>(d1);        // i1 has value 3
int      i2 = static_cast<int>(d2);        // i2 has value 3
```

  - **Implicit** cast operators

```
int      i  = 3;
double   d  = 4.8;
double   d3 = i / d;          // d3 = 0.625 = double(i)/d
int      i3 = d3;             // i3 = 0 = int(d3)
                              // Warning! Assignment may lose information
```

Control Flow

- If Statement
- Switch Statement
- While/Do-While Loops
- For Loop

```
// Initialize an int array
int num[5] = {1,2,3,4,5};

// Ranged for loop
for (int n : num)
    std::cout << n << std::endl;

// Nested for loop
for  (int i=0; i<5; i++)
    std::cout << num[i] << std::endl;
```

Functions

- Argument Passing
  - Call by Reference, Call by Value

```
void f(int value, int& ref) {          // one value and one reference
  value++;                             // no effect on the actual argument
  ref++;                               // modifies the actual argument
  cout << value << endl;               // outputs 2
  cout << ref << endl;                 // outputs 6
}

int main() {
  int cat = 1;
  int dog = 5;
  f(cat, dog);                         // pass cat by value, dog by ref
  cout << cat << endl;                 // outputs 1
  cout << dog << endl;                 // outputs 6
  return EXIT_SUCCESS;
}
```

  - Array arguments : use pointer (T[] → T*)

Functions

- **Overloading**
  - **Function overloading** : same name with different argument lists

```
void print(int x)                          // print an integer
  { cout << x; }

void print(const Passenger& pass) {   // print a Passenger
  cout << pass.name << " " << pass.mealPref;
  if (pass.isFreqFlyer)
    cout << " " << pass.freqFlyerNo;
}
```

  - **Operator overloading** : +, *, +=, ==, <<, …

```
bool operator==(const Passenger& x, const Passenger& y) {
  return x.name          == y.name
      && x.mealPref      == y.mealPref
      && x.isFreqFlyer   == y.isFreqFlyer
      && x.freqFlyerNo   == y.freqFlyerNo;
}
```

Classes

- **Class Structure**
  - Data members (member variables) + member functions (methods)

```
class Counter {                    // a simple counter
public:
  Counter();                       // initialization
  int getCount();                  // get the current count
  void increaseBy(int x);          // add x to the count
private:
  int count;                       // the counter's value
};
```

  - Access control
    - “Private” means that they are accessible only from within the class
  - Member functions
    - Access functions, Update functions

Classes

Constructors

- Default constructors, copy constructors

```
class Passenger {
private:
  // ...
public:
  Passenger();                                  // default constructor
  Passenger(const string& nm, MealType mp, const string& ffn = "NONE");
  Passenger(const Passenger& pass);  // copy constructor
  // ...
};
```

- Initializer list

```
                                // constructor using an initializer list
Passenger::Passenger(const string& nm, MealType mp, string ffn)
  : name(nm), mealPref(mp), isFreqFlyer(ffn != "NONE")
  { freqFlyerNo = ffn; }
```

Destructors

```
class Vect {
public:
  Vect(int n);
  ~Vect();
  // ... other public members omitted
private:
  int*          data;
  int           size;
};

Vect::Vect(int n) {
  size = n;
  data = new int[n];
}

Vect::~Vect() {
  delete [] data;
}
```

Classes

- Every class that allocates its own objects using new should:
  - Define a destructor to free any allocated objects
  - Define a copy constructor, which allocates its own new member storage and copies the contents of member variables
  - Define an assignment operator, which deallocates old storage, allocates new storage, and copies all member variables

```
Vect& Vect::operator=(const Vect& a) {
  if (this != &a) {
    delete [] data;
    size = a.size;
    data = new int[size];
    for (int i=0; i < size; i++) {
      data[i] = a.data[i];
    }
  }
  return *this;
}
```

```
Vect a(100);
Vect b = a;
Vect c;
c = a;
```

Classes

- **Friend function**

```
class SomeClass {
private:
  int secret;
public:
  // ...                                  // give << operator access to secret
  friend ostream& operator<<(ostream& out, const SomeClass& x);
};

ostream& operator<<(ostream& out, const SomeClass& x)
  { cout << x.secret; }
```

- **Class friendship**

```
class Vector {                          // a 3-element vector
public: // ... public members omitted
private:
  double coord[3];                      // storage for coordinates
  friend class Matrix;                  // give Matrix access to coord
};

class Matrix {                          // a 3x3 matrix
public:
  Vector multiply(const Vector& v);     // multiply by vector v
  // ... other public members omitted
private:
  double a[3][3];                       // matrix entries
};

Vector Matrix::multiply(const Vector& v) {  // multiply by vector v
  Vector w;
  for (int i = 0; i < 3; i++)
    for (int j = 0; j < 3; j++)
      w.coord[i] += a[i][j] * v.coord[j];   // access to coord allowed
  return w;
}
```

Classes
- STL (Standard Template Library)

- A collection of useful classes for common data structures

STL	Descriptions
stack	Container with last-in, first-out access
queue	Container with first-in, first-out access
deque	Double-ended queue
vector	Resizable array
list	Double linked list
priority_ queue	Queue ordered by value
set	Set
map	Associated arry (Dictionaries)

- Vector (vs. Array)
  - A dynamic container from the STL that can resize itself as needed
  - Provide bounds checking with at() member function, throwing exceptions for out-of-bound access
  - Copying the contents of one vector to the other

```
int i = // ...
cout << scores[i];                    // index (range unchecked)
buffer.at(i) = buffer.at(2 * i);      // index (range checked)
vector<int> newScores = scores;       // copy scores to newScores
scores.resize(scores.size() + 10);    // add room for 10 more elements
```

Classes
- STL (Standard Template Library)

- STL string class

s.find(p)	Return the index of first occurrence of string *p* in *s*
s.find(p, i)	Return the index of first occurrence of string *p* in *s* on or after position *i*
s.substr(i,m)	Return the substring starting at position *i* of *s* and consisting of *m* characters
s.insert(i, p)	Insert string *p* just prior to index *i* in *s*
s.erase(i, m)	Remove the substring of length *m* starting at index *i*
s.replace(i, m, p)	Replace the substring of length *m* starting at index *i* with *p*
getline(is, s)	Read a single line from the input stream *is* and store the result in *s*

- Example

```
string s = "a dog";                          // "a dog"
s += " is a dog";                            // "a dog is a dog"
cout << s.find("dog");                       // 2
cout << s.find("dog", 3);                    // 11
if (s.find("doug") == string::npos) { }      // true
cout << s.substr(7, 5);                      // "s a d"
s.replace(2, 3, "frog");                     // "a frog is a dog"
s.erase(6, 3);                               // "a frog a dog"
s.insert(0, "is ");                          // "is a frog a dog"
if (s == "is a frog a dog") { }              // true
if (s < "is a frog a toad") { }              // true
if (s < "is a frog a cat") { }               // false
```

Classes
- An Example Program

- Header file

```
#ifndef CREDIT_CARD_H                       // avoid repeated expansion
#define CREDIT_CARD_H

#include <string>                           // provides string
#include <iostream>                         // provides ostream

class CreditCard {
public:
  CreditCard(const std::string& no,         // constructor
        const std::string& nm, int lim, double bal=0);
                                            // accessor functions
  std::string    getNumber() const    { return number; }
  std::string    getName() const      { return name; }
  double         getBalance() const   { return balance; }
  int            getLimit() const     { return limit; }

  bool chargeIt(double price);              // make a charge
  void makePayment(double payment);         // make a payment
private:                                    // private member data
  std::string    number;                    // credit card number
  std::string    name;                      // card owner's name
  int            limit;                     // credit limit
  double         balance;                   // credit card balance
};
                                            // print card information
std::ostream& operator<<(std::ostream& out, const CreditCard& c);
#endif
```

- Out-of-class member functions

```
#include "CreditCard.h"                     // provides CreditCard

using namespace std;                        // make std:: accessible
                                            // standard constructor
CreditCard::CreditCard(const string& no, const string& nm, int lim, double bal) {
  number = no;
  name = nm;
  balance = bal;
  limit = lim;
}
                                            // make a charge
bool CreditCard::chargeIt(double price) {
  if (price + balance > double(limit))
    return false;                           // over limit
  balance += price;
  return true;                              // the charge goes through
}

void CreditCard::makePayment(double payment) { // make a payment
  balance -= payment;
}
                                            // print card information
ostream& operator<<(ostream& out, const CreditCard& c) {
  out << "Number = "    << c.getNumber()    << "\n"
      << "Name = "      << c.getName()      << "\n"
      << "Balance = "   << c.getBalance()   << "\n"
      << "Limit = "     << c.getLimit()     << "\n";
  return out;
}
```

Classes
- An Example Program

- Test function

```
#include <vector>                       // provides STL vector
#include "CreditCard.h"                 // provides CreditCard, cout, string

using namespace std;                    // make std accessible

void testCard() {                       // CreditCard test function
  vector<CreditCard*> wallet(10);       // vector of 10 CreditCard pointers
                                        // allocate 3 new cards
  wallet[0] = new CreditCard("5391 0375 9387 5309", "John Bowman", 2500);
  wallet[1] = new CreditCard("3485 0399 3395 1954", "John Bowman", 3500);
  wallet[2] = new CreditCard("6011 4902 3294 2994", "John Bowman", 5000);

  for (int j=1; j <= 16; j++) {         // make some charges
    wallet[0]->chargeIt(double(j));     // explicitly cast to double
    wallet[1]->chargeIt(2 * j);         // implicitly cast to double
    wallet[2]->chargeIt(double(3 * j));
  }

  cout << "Card payments:\n";
  for (int i=0; i < 3; i++) {           // make more charges
    cout << *wallet[i];
    while (wallet[i]->getBalance() > 100.0) {
      wallet[i]->makePayment(100.0);
      cout << "New balance = " << wallet[i]->getBalance() << "\n";
    }
    cout << "\n";
    delete wallet[i];                   // deallocate storage
  }
}
```

- Main function & Output

```
int main() {
  testCard();
  return EXIT_SUCCESS;
}
```

```
Card payments:
Number = 5391 0375 9387 5309
Name = John Bowman
Balance = 136
Limit = 2500
New balance = 36

Number = 3485 0399 3395 1954
Name = John Bowman
Balance = 272
Limit = 3500
New balance = 172
New balance = 72

Number = 6011 4902 3294 2994
Name = John Bowman
Balance = 408
Limit = 5000
New balance = 308
New balance = 208
New balance = 108
New balance = 8
```