Assignment 5

Evolution in Action

Print out the assignment and make notes on it.

Don't just view it on screen!

W1–7 and C1–2 Due: 11:59 PM, Tuesday, October 31, 2006
C3–4 Due: 11:59 PM, Saturday, November 4, 2006

In this assignment, you gain experience in writing C++ iterators, applying STL algorithms (and function objects), performing benchmarking, and refactoring code. You will also develop a list class that can be used in place of the STL type *list<int>* in some (limited) circumstances.

Background — Genetic Algorithms

Genetic algorithms attempt to solve difficult problems by "evolving" a good solution. In real life, natural selection is the process by which members of a species that are well-suited to their environment tend to survive and breed and those that are ill-suited to that environment fare less well and are less likely to procreate. Future generations are made from the genes of those members of the species that are most fit for the environment in which that species lives. A genetic algorithm applies the mechanism of natural selection using a "fitness function" chosen by the programmer. For example, a simple fitness function might interpret the genes of an organism as the value of x in a complicated equation. The natural-selection process could then be tuned to prefer organisms that generate an output near zero, so that the survivors would eventually produce a solution to the equation.

Genetic algorithms were the first step in the current research area called "artificial life", and they have been used to successfully solve many otherwise intractable problems.

There are three basic processes in evolution: crossover, mutation and selection. Crossover involves taking copies of the genes of two parent organisms and splicing them together to form a child organism. Usually a randomly chosen genetic subsequence from one parent replaces the equivalent subsequence from the other parent. The crossover function lies at the heart of a genetic algorithm—a properly written crossover function will have some possibility of capturing good traits from both parents, but it does so in complete ignorance of whether one gene sequence or subsequence is good or bad. It is quite likely that a child will actually be less fit than either of its parents.

After crossover has produced a new organism, there is a random chance that this new organism will undergo a mutation. Mutation involves selecting a gene site and modifying it in some fashion, usually by replacing it with another gene. Mutation is very rare in real life, and in a genetic algorithms it should also occur rarely, otherwise too many fit organisms will be lost to harmful mutations.

The final step, selection, involves evaluating the organisms according to some criterion (the "fitness function") and choosing the ones that satisfy this criterion most successfully. In real life, selection is the harsh process of "survival of the fittest". In a genetic algorithm, the same method is used: the least fit organisms are discarded (i.e., "killed") without being allowed to reproduce. The fit organisms get a chance to reproduce before they die. As in real life, there is some randomness, so that a somewhat unfit organism has a chance of surviving to reproduce even though that may mean that a more fit organism is discarded. This randomness turns out to be important to the success of the method, because any two slightly unfit parents might (through crossover) generate an extremely fit child.

Scenario

To pay some bills over winter break, you're working at *Lamarkian Enterprises*, a bold new startup company whose eventual goal is to make programmers redundant by evolving algorithms to solve all the hardest problems in computer science. Their lead programmer, Dakota Winter, began exploring the problem space by writing a genetic algorithm to solve some "classic" graph problems, including the Traveling Salesrep Problem. However, Dakota is no longer with the company, due to an unfortunate incident better not talked about.

Management looked into what Dakota had left behind, and although there was no documentation file with the code, there were two printed pages in Dakota's cubicle (which have been reproduced on the following two pages) that give some description of the program, `natselpath`, that Dakota was working on.

Management took a look at Dakota's code and discovered that almost all of Dakota's code resided in a single file. Worse, the code defines very few C++ classes, choosing instead to implement most of its functionality via top-level functions, even though there are some obvious ways in which the code could be broken into classes.

In addition, one particularly pointy-haired manager expressed concern at Dakota's extensive use of the C++ Standard Template Library (STL); he had heard a rumor from his cousin-in-law's auto mechanic that the STL is inefficient, especially its *list* class template. According to this manager, *list* is wasteful because it uses templates and, worse, *list* is implemented as a doubly linked list while all `natselpath` needs is a singly-linked list.

Your manager has handed you Dakota's code to clean up. You will have to

- Write an *IntList* class (storing a singly linked list of integers) that can replace the uses of *list<int>* in the code
- Factor out logical components of the code into separate classes

The `natselpath` Program

The `natselpath` program attempts to solve two common graph problems, *shortest Hamiltonian path* (SHP) and the *shortest tour* problem (also known as the *traveling salesrep problem* (TSP)).

Shortest Hamiltonian path takes a set of nodes and internode distances (see the example in Figure 1(a) and (b)), and tries to find the shortest path that includes all the nodes exactly once (we do not require any particular start or end point). Figure 1(c) shows the shortest Hamiltonian path for our example, and, for contrast, Figure 1(d) shows the longest Hamiltonian path. The shortest tour problem is analogous, except that we return to our starting point.

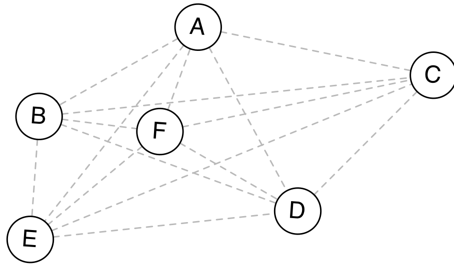
The examples shown in Figure 1 are easy to solve using a "brute force" method where we evaluate every possible path through the graph and find the best one. In the example, there are are only 6!/2 (i.e., 360) possible Hamiltonian paths, so it would be easy to check each one. But checking every possible path has *exponential* time complexity and quickly becomes intractable. For 36 nodes, there are 36!/2 possible paths (i.e., 185,996,663,394,950,608,733,999,724,075,417,600,000,000—if we could check one possibility every nanosecond, it would take about six septillion years to check them all).

These problems are *NP-complete*, which, in essence, means that *every* algorithm that guarantees to *always* find the correct answer to this problem is an exponential-time algorithm like the one above. Genetic algorithms like `natselpath` do not guarantee to always find the optimal solution, but they usually do converge on a good solution. Moreover, as a probabilistic algorithm, each run is different, and so even if you don't get an optimal solution on the first try, you may do better if you run the program again.

In `natselpath`, different paths through the graph constitute the different organisms in the ecosystem. The organisms' "DNA" is the path through the graph represented as a list of integers: an organism representing the winning path E, B, F, A, D, C (Figure 1(c)) would be represented as a list 4, 1, 5, 0, 3, 2.

Initially, the colony of organisms have DNA that corresponds to random paths, but their fitness is based on how short they are. Organisms representing shorter paths survive and breed with other "shorter" organisms. Over time the traits that make an organism good are reinforced and bad traits eliminated.

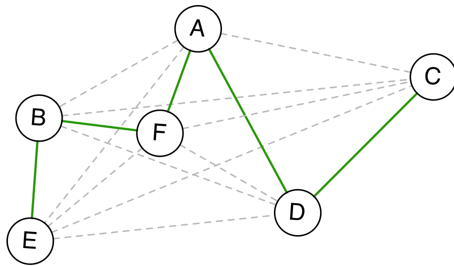
Figure 1: Path problems solved by `natselpath`



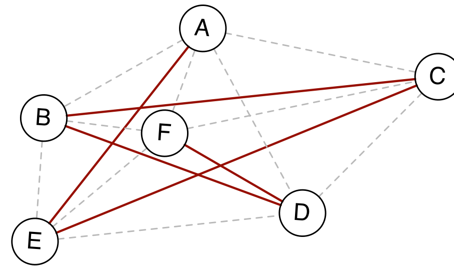
(a) Nodes & distances (graphically)

	A	B	C	D	E	F
A	0	66	87	76	98	40
B	66	0	144	100	45	44
C	87	144	0	70	158	101
D	76	100	70	0	97	58
E	98	45	158	97	0	61
F	40	44	101	58	61	0

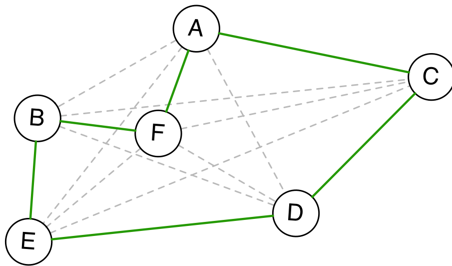
(a) Nodes & distances (matrix)



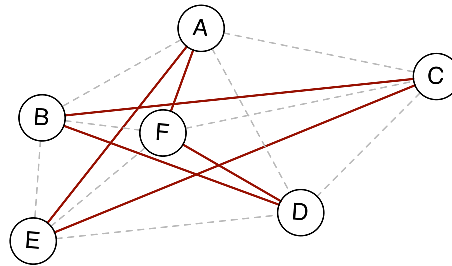
(c) Shortest Hamiltonian path



(d) Longest Hamiltonian path



(e) Shortest tour



(f) Longest tour

Current Data Structures

The program currently uses the following data structures:

Organism

An organism will be represented entirely by its gene sequence. Each element in the sequence will contain only a single integer from 0 to 9. In the current implementation of the code the gene sequence is represented using the type *list<int>*. The *Organism* type is simply a synonym for *list<int>* to make the code more readable.

Organism::iterator and *Organism::const_iterator*

At several places in the code, the program needs to cycle through the genes of the organism. The code uses *Organism::iterator* and *Organism::const_iterator* to perform these iteration tasks. In the current code, these types are equivalent to *list<int>::iterator* and *list<int>::const_iterator*, respectively.

Colony

The *Colony* type is used to represent the population of organisms. It is simply a container type that holds *Organism* objects—in the current code, *Colony* is a synonym for *vector<Organism>*. Like the organism type, it currently has iterators.

Preliminaries

Set up your assignment directory by running `svn update`. This command should check out the following files and directories:

```
Answers.txt
Design.txt
Makefile
natselpath-private.hpp
natselpath.cpp
data/abcdef.labels
data/abcdef.matrix
data/ca_cities.labels
data/ca_cities.matrix
data/uk_cities.labels
data/uk_cities.matrix
data/us_cities.labels
data/us_cities.matrix
```

Written Component

When answering the following questions, explain your answers clearly. Your answers should be placed in the file `Answers.txt` and submitted using Subversion in the usual way.

W1. Compile the code (with optimization) by running `make OPTFLAGS=-O2` and then run the command[1]

```
time ./natselpath -d -S 1 data/us_cities
```

(a) What does this command line mean? (You can find out about the `time` command by typing `man time`, and about the arguments to the `natselpath` program by looking at the initial comments in `natselpath.cpp`.)

(b) What output does it produce? (If you run the command on a machine other than knuth, indicate the processor and clock speed of the machine in question, and include the output from running `uname -a`.)

W2. Comment out line 71 in `natselpath.cpp`, which reads

typedef *list<int> Organism*;

and add each of the following (in turn):

(a) **typedef** *list<char> Organism*;

(b) **typedef** *vector<int> Organism*;

(c) **typedef** *vector<char> Organism*;

(d) **typedef** *string Organism*;

For each of the parts above, recompile the code (with optimization) and report the timings you get from running

```
time ./natselpath -d -S 1 data/us_cities
```

(When you are done, revert the definition of *Organism* to *list<int>*.)

W3. Lists and arrays have quite different representations. Why can we change *Organism* from being a synonym for *list<int>* to a synonym for *vector<char>* or *string* without causing compiler errors?

W4. The code uses a functor. What is a functor? Where is it created? (See Stroustrup, Section 18.4 for a discussion of functors.)

W5. Explain how findBest works (i.e., find out what the STL algorithm min_element is used for and explain why it is the right tool for this problem).

W6. There is a comment at the top of the naturalSelection function explaining that early versions of the code used sort, later versions used partial_sort, and the current version uses nth_element.

1. This command line causes `make` to run g++ with the compiler option `-O2` (which, incidentally, is "oh two", *not* "zero two") to turn on optimization, which is useful for doing the performance comparison questions. In general, you should *not* use optimization while you are actively doing development—it makes compilation slower and debugging with gdb more sketchy.

(a) Highlight the similarities and differences between the STL algorithms `sort`, `partial_sort`, and `nth_element`. (You will almost certainly need to look these functions up, either in Chapter 18 of Stroustrup or on the web—see the resources page on the class website.)

(b) Explain why the code evolved from `sort` to `partial_sort` to `nth_element`, including why the code is still correct and whether any efficiency gains are likely.

(c) Modify the code to use each of the other methods in turn and run the code to determine whether each change improves performance in practice. Summarize your findings. (Revert the code afterwards.)

W7. In the separate file `Design.txt`, list the two or more new classes you would recommend adding to the program — see Question C3 below. Describe the operations that each class will support. (For the October 31 submission, do not try to write code or header files for these classes!)

Coding Component

These coding questions are designed so that you can submit your code after completing each question. You will, however, only be graded on your final submission.

C1. Create the files `intlist.hpp` and `intlist.cpp`, implementing an *IntList* class and add them to your CS 70 repository. You should write your *IntList* class such that if the definition of the *Organism* type is changed to

```
#include "intlist.hpp"
typedef IntList Organism;
```

the program will still compile, run, and produce the same output as before.

Important: After adding new files, make sure you add them to your repository using `svn add`. Also, run `make clean` whenever you add files or perform major refactoring work—doing so will cause `make` to remove `Makefile.deps`, which describes which source files are used in building which object files.

The overall structure of your *IntList* class should be similar to the *StringStack* class seen during lectures (which you may use as a starting point). Thus, there will be three classes involved, *IntList*, *IntList::Node*, and *IntList::Iterator*. However, unlike the stack class, you will need both a head and a tail pointer in the header (in order to support `push_back` efficiently).

Your linked-list class must be named *IntList* and must support the following operations:

- A default constructor.
- A `swap` operation.
- A copy constructor.

- A destructor. The destructor must clean up properly; in other words, it must empty the list.
- An assignment operator.
- A size function returning the number of elements in the list (your implementation is allowed to take $O(n)$ time, where n is the size of the list)
- A push_back function that inserts a single integer at the tail of the list. This function should be declared as

  ```
  void push_back(int value);
  ```

  Your push_back function *must* operate in $O(1)$ time. You have already done a similar implementation in CS 60 when you examined queues.
- Two typedefs, defining the types *iterator* and *const_iterator* as synonyms for *Iterator*.[2]
- Two inner classes, *Iterator* and *Node*, where *Node* is private.
- A begin function that returns an iterator that refers to the start of the list. This function should be declared as

  ```
  iterator begin() const;
  ```
- An end function that returns an invalid/past-the-end iterator,

  ```
  iterator end() const;
  ```
- An equality test (**operator**==) and an inequality test (**operator**!=).

Note: You may not change the function and type names given above. You may, however, write additional member functions such as push_front, pop_front, front, back, and reverse if you wish. (If you have written your list class correctly, it will not be not possible to write pop_back efficiently, so there is little point in supplying this function.)

The *IntList::Iterator* class must provide at least the following operations:

- A copy constructor
- An assignment operator
- A destructor
- An equality test (**operator**==) and an inequality test (**operator**!=)
- A preincrement operator (**operator**++)
- An **operator*** that returns an *int&* (so that the integer in the current position can be modified if necessary)

2. In an industrial-strength implementation, we would define separate types for *iterator* and *const_iterator*, but in this assignment doing so is more trouble than it is worth. As a result, people will be able modify objects even when they only have a *const_iterator*.

Compile and test your code thoroughly. Your *IntList* class will be tested separately, so it is important that it works correctly.[3]

After you have created and tested your *IntList* class, you can either continue to use it in the genetic-algorithm code or switch that code back to using the STL's *list<int>* type. Using your *IntList* may result in more comprehensible error messages while you are working on coding the next part, whereas using *list<int>* will insulate your later code from any bugs in your list class.

C2. The code that has been provided to you uses many top-level functions and defines almost no classes. It could be argued that the code only provides the *NatSelEnv* class because it is very convenient to pass a function object to the STL algorithms.

Your primary job in this assignment is to refactor the code into a better more object-based style. Examine the code to discover the logical relationships between the functions and how they might be broken up into separate files and classes. Devise at least two new classes reflecting the logical structure of the program. (A solution involving four new classes is quite possible.)

Document your design in the file `Design.txt`. You should specify what the classes are and what the member functions are and should do.

. . . . End of the First Part of the Assignment . . . .

Before continuing, you should read the sample solution's `Design.txt` *file and perform self-assessment on your written answers and initial design. If you want to submit your code for the first part sooner so that you can start the second part in good time, send email and we'll provide it to you. You do not have to adopt our design, but you should only continue with your own design if you feel highly confident that your design is at least as good. If you don't understand the suggested design, ask questions of the graders or Prof. O'Neill.*

. . . . Start of the Second Part of the Assignment . . . .

C3. Refactor the code according to your chosen design. In your final code, you should find that the overall code looks simpler and is easier to follow. If you have done things properly many of the functions will have fewer arguments.

Note that the execution behavior of your code must be *exactly the same* as the existing code—this requirement means that you must take care when making changes involving the random-number generator to make sure that the same numbers are generated. (The random-number functions used by the code are described in the Unix manual pages—`man lrand48`).

3. You may find that your *IntList* class seems slower than the STL's *list<int>* class, even if you have written clean, elegant, and efficient code. The reasons behind this slowdown are curious indeed—a small reward is available to any student who can discover why the slowdown occurs and whether it can be prevented.

C4. Extend your `Design.txt` file to accurately and fully describe your final design. Guidance on writing an adequate `Design.txt` file is available on the course website.

Testing

Testing is your responsibility. You should test your program a number of times under different conditions. It may be a good idea to keep a copy of the program executable from the initial (unmodified) version to use for comparison purposes.

In its default condition, the program is nondeterministic (i.e., two successive runs may produce different results, especially if you use the `-d` switch to see the program's debugging output). To make testing easier, the program accepts a switch that makes it deterministic. If you use `-S` *n*, where *n* is an integer, the random seed will be set to that value. Specifying the random seed will allow you to control the program's behavior so that you can reproduce bugs.

You will also find it instructive to run the program with the `-d` switch, and to run it for many different values of the `-g`, `-m`, `-p`, `-r`, and `-s` switches. Judicious reading of the comments, together with experimentation, will reveal the purpose of these switches and how they interact.

Sample Runs

To make it clearer how the program is used, here are some sample runs from executing `natselpath` on knuth (if you run the code on Mac OS X you will probably see the same answer because they both use the same open-source BSD random number generator; but in general on different operating systems (or even different versions of the same operating system), you should expect similar *not* identical results).[4] Below are the results of planning a one-way trip through eighteen prominent US cities:

```
unix% ./natselpath -g 30 -S 42 data/us_cities
2       Boston (197)
12      New York City (235)
17      Washington D.C. (375)
4       Cleveland (173)
7       Detroit (288)
3       Chicago (410)
10      Minneapolis (625)
13      St. Louis (559)
1       Atlanta (653)
```

4. In fact, the only reason we use the `lrand48` generator instead of the more customary `random`, is that it gives the same results on the Macs and on knuth.

```
9       Miami (857)
11      New Orleans (509)
5       Dallas (654)
0       Albuquerque (457)
6       Denver (527)
14      Salt Lake City (703)
8       Los Angeles (384)
15      San Francisco (808)
16      Seattle

Total Distance: 8414
```

If we start with a different random seed, we get a different (worse) result:

```
unix% ./natselpath -g 30 -S 1 data/us_cities
16      Seattle (808)
15      San Francisco (384)
8       Los Angeles (703)
14      Salt Lake City (537)
6       Denver (457)
0       Albuquerque (654)
5       Dallas (509)
11      New Orleans (857)
9       Miami (653)
1       Atlanta (559)
13      St. Louis (302)
3       Chicago (410)
10      Minneapolis (671)
7       Detroit (173)
4       Cleveland (375)
17      Washington D.C. (235)
12      New York City (197)
2       Boston

Total Distance: 8484
```

(although if we removed the `-g 30` option—and thus ran with the default of fifty generations—we would again get an answer of 8414 miles).

Finally, in addition to controlling the number of generations (`-g`), we can control the mutation rate (`-m`), the population size (`-p`), the percentage survival rate (`-s`, which should be smaller than the population size), and the percentage of the survivors that survive through luck rather fitness (`-r`), and run with debugging (`-d`). The command line

```
./natselpath  -S 56 -d -s 2.5 -r 1 data/uk_cities
```

finds the shortest path through the thirty-six British cities listed in the `uk_cities` files. These parameters (the tiny percentage survival rate) lead the algorithm to converge quickly on an answer, but the colony is prone to lacking genetic diversity, different seed values reveal that most runs do not converge on the best path of 2190 miles.

Note:

You can think of the running time of the program as being $\mathrm{O}(population \times generations)$.[5] Don't use huge numbers or you' ll wait all day! If you don't specify the `-S` switch, you will get different results every time you run the program. That's a feature, not a bug.

Tricky Stuff

As usual, there are some tricky parts to this assignment. Some of them are

- Be sure to read the code in `natselpath.cpp` before you start, so that you understand the requirements placed on the *IntList* and *IntList::Iterator* classes.
- Before you try to write the iterator, it would be wise to debug the list code itself. To help with that task, you will probably want to write a special test driver program.
- Be sure your *IntList* destructor, copy constructor, and assignment operator are working before you try to run the main program. If you don't debug them in isolation, you will experience strange bugs that will be hard to find.
- Remember that the iterator access operator (**operator***) must return an integer by reference (*int&*). Otherwise you won't be able to get the mutation operator to work.
- Remember that `push_back` must run in $\mathrm{O}(1)$ time. You will be penalized if its complexity is $\mathrm{O}(n)$.
- Refactoring the code (breaking it up into separate files/classes) may seem daunting at first, but there are some fairly obvious lines you can draw between different parts of the code. Remember that you can plan things out in `Design.txt` or on paper first—you don't have to try to keep all the details in your head.
- If you save a copy of the original executable, you'll be able to test whether your revised version of the program always behaves the same way. Better yet, keep a copy of the entire original source.
- Work incrementally. It is hard to maintain *exactly* the same behavior. If you restructure the entire program and you get different output, it will be nearly impossible to track down the cause of the problem. If you make smaller changes and retest after each step, you're much more likely to pinpoint problems.

5. You might want to try to analyze the complexity yourself and determine whether this bound is actually correct.

- If you believe there may be bugs in your *IntList*, you can temporarily use the STL's *list<int>* and see whether the bug persists.
- The new classes you write need not exactly match the behavior of the types used in the current code. The operations you provide for each class need to be meaningful for that class. If, for example, you decided you needed a *Television* class, I would not be pleased to see it having a push_front() member function. Televisions don't "push front".

  Similarly, if you were refactoring code that had the typedef

  ```
  typedef vector<Food> Cupboard;
  ```

  and had decided that *Cupboard* would be better implemented as a class, you would then need to separate the code that used *Cupboard*s into two kinds, *external code* and *internal code*. External users of *Cupboard*s don't care about how *Cupboard*s are represented internally and don't try to do things like use array subscripting on them. Internal code implements the class, and does need to know and use whatever the underlying representation is (in this case *vector<Food>*). When you refactor the code, the different uses of *Cupboard* need to be reflected by *different types*. Thus, the external code would continue to use *Cupboard*s, but the internal code will now be accessing a different type (it will be using *vector<Food>* [if the implementation code needs to refer to the type more than once, it would be sensible to use a private typedef to define a handy synonym for this type, such as *Shelves*]). Similarly, internal functions will now access the data via a data member—thus code that used to read:

  ```
  mycupboard[++shelf] = fruit;
  ```

  would probably read

  ```
  mycupboard.shelves_[++shelf] = fruit;
  ```

  or, if mycupboard is now the object that this points to,

  ```
  shelves_[++shelf] = fruit;
  ```

- The behavior of the program is extremely sensitive to the random numbers it gets from the randomInt function. These random numbers in turn depend on the number of times randomInt has been called. If you have trouble matching the sample output or the behavior of the original code, check to see whether you're creating scratch organisms that cause extra calls to randomInt.

  If you're still having problems, add extra code to print out a large random number (e.g., randomInt(10000)) at the same key points in both your code and the original version. If both programs have the same random seed, initially they'll both print the same numbers. When they diverge, you'll know that your code did something different from original code.