

# **GAlib: A C++ Library of Genetic Algorithm Components**

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GAlib is a C++ library of genetic algorithm objects. The library includes tools for using genetic algorithms to do optimization in any C++ program using any representation and any genetic operators. This documentation includes an extensive overview of how to implement a genetic algorithm, the programming interface for GAlib classes, and examples illustrating customizations to the GAlib classes.



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## Features

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### General Features

- Many examples are included illustrating the use of various GAlib features, class derivations, parallelization, deterministic crowding, travelling salesman, DeJong, and Royal Road problems.
- The library has been used on various DOS/Windows, Windows NT/95, MacOS, and UNIX configurations. GAlib compiles without warnings on most major compilers.
- Templates are used in some genome classes, but GAlib can be used without templates if your compiler does not understand them.
- Four random number generators are included with the library. You can select the one most appropriate for your system, or use your own.

### Algorithms, Parameters, and Statistics

- GAlib can be used with PVM (parallel virtual machine) to evolve populations and/or individuals in parallel on multiple CPUs.
- Genetic algorithm parameters can be configured from file, command-line, and/or code.
- Overlapping (steady-state GA) and non-overlapping (simple GA) populations are supported. You can also specify the amount of overlap (% replacement). The distribution includes examples of other derived genetic algorithms such as a genetic algorithm with sub-populations and another that uses deterministic crowding.
- New genetic algorithms can be quickly tested by deriving from the base genetic algorithm classes in the library. In many cases you need only override one virtual function.
- Built-in termination methods include convergence and number-of-generations. The termination method can be customized for any existing genetic algorithm class or for new classes you derive.
- Speciation can be done with either DeJong-style crowding (using a replacement strategy) or Goldberg-style sharing (using fitness scaling).
- Elitism is optional for non-overlapping genetic algorithms.
- Built-in replacement strategies (for overlapping populations) include replace parent, replace random, replace worst. The replacement operator can be customized.
- Built-in selection methods include rank, roulette wheel, tournament, stochastic remainder sampling, stochastic uniform sampling, and deterministic sampling. The selection operator can be customized.
- "on-line" and "off-line" statistics are recorded as well as max, min, mean, standard deviation, and diversity. You can specify which statistics should be recorded and how often they should be flushed to file.

### Genomes and Operators

- Chromosomes can be built from any C++ data type. You can use the types built-in to the library (bit-string, array, list, tree) or derive a chromosome based on your own objects.

## Features: Genomes and Operators

- Built-in chromosome types include real number arrays, list, tree, 1D, 2D, and 3D arrays, 1D, 2D, and 3D binary string. The binary strings, strings, and arrays can be variable length. The lists and trees can contain any object in their nodes. The array can contain any object in each element.
- All chromosome initialization, mutation, crossover, and comparison methods can be customized.
- Built-in initialization operators include uniform random, order-based random, and initialize-to-zero.
- Built-in mutation operators include random flip, random swap, Gaussian, destructive, swap subtree, swap node.
- Built-in crossover operators include partial match, ordered, cycle, single point, two point, even, odd, uniform, node- and subtree-single point.
- Dominance and Diploidy are not explicitly built in to the library, but any of the genome classes in the library can easily be extended to become diploid chromosomes.
- Objective function
- Objective functions can be population- or individual-based.
- If the built-in genomes adequately represent your problem, a user-specified objective function is the only problem-specific code that must be written.

## Overview

---

This document outlines the contents of the library and presents some of the design philosophy behind the implementation. Some source code samples are provided at the end of the page to illustrate basic program structure, operator capabilities, operator customization, and derivation of new genome classes.

When you use the library you will work primarily with two classes: a genome and a genetic algorithm. Each genome instance represents a single solution to your problem. The genetic algorithm object defines how the evolution should take place. The genetic algorithm uses an objective function (defined by you) to determine how 'fit' each genome is for survival. It uses the genome operators (built into the genome) and selection/replacement strategies (built into the genetic algorithm) to generate new individuals.

There are three things you must do to solve a problem using a genetic algorithm:

1. Define a representation
2. Define the genetic operators
3. Define the objective function

GAlib helps you with the first two items by providing many examples and pieces from which you can build your representation and operators. In many cases you can use the built-in representations and operators with little or no modification. The objective function is completely up to you. Once you have a representation, operators, and objective measure, you can apply any genetic algorithm to find better solutions to your problem.

When you use a genetic algorithm to solve an optimization problem, you must be able to represent a single solution to your problem in a single data structure. The genetic algorithm will create a population of solutions based on a sample data structure that you provide. The genetic algorithm then operates on the population to evolve the best solution. In GAlib, the sample data structure is called a GAGenome (some people refer to it as a chromosome). The library contains four types of genomes: GAListGenome, GATreeGenome, GAArrayGenome, and GABinaryStringGenome. These classes are derived from the base GAGenome class and a data structure class as indicated by their names. For example, the GAListGenome is derived from the GAList class as well as the GAGenome class. Use a data structure that works with your problem definition. For example, if you are trying to optimize a function that depends on 5 real numbers, then use as your genome a 1-dimensional array of floats with 5 elements.

There are many different types of genetic algorithms. GAlib includes three basic types: 'simple', 'steady-state', and 'incremental'. These algorithms differ in the way that they create new individuals and replace old individuals during the course of an evolution.

GAlib provides two primary mechanisms for extending the capabilities of built-in objects. First of all (and most preferred, from a C++ point of view), you can derive your own classes and define new member functions. If you need to make only minor adjustments to the behavior of a GAlib class, in most cases you can define a single function and tell the existing GAlib class to use it instead of the default.

Genetic algorithms, when properly implemented, are capable of both exploration (broad search) and exploitation (local search) of the search space. The type of behavior you'll get depends on how the operators work and on the 'shape' of the search space.

## The Genetic Algorithm

The genetic algorithm object determines which individuals should survive, which should reproduce, and which should die. It also records statistics and decides how long the evolution should continue. Typically a genetic algorithm has no obvious stopping criterion. You must tell the algorithm when to stop. Often the number-of-generations is used as a stopping measure, but you can use goodness-of-best-solution, convergence-of-population, or any problem-specific criterion if you prefer.

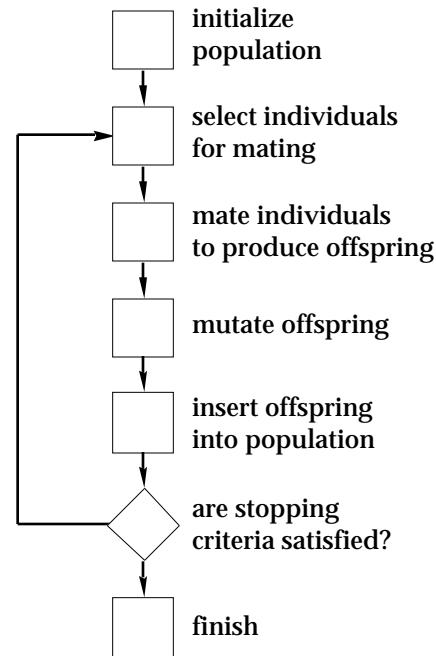
The library contains four flavors of genetic algorithms. The first is the standard 'simple genetic algorithm' described by Goldberg in his book. This algorithm uses non-overlapping populations and optional elitism. Each generation the algorithm creates an entirely new population of individuals. The second is a 'steady-state genetic algorithm' that uses overlapping populations. In this variation, you can specify how much of the population should be replaced in each generation. The third variation is the 'incremental genetic algorithm', in which each generation consists of only one or two children. The incremental genetic algorithms allow custom replacement methods to define how the new generation should be integrated into the population. So, for example, a newly generated child could replace its parent, replace a random individual in the population, or replace an individual that is most like it. The fourth type is the 'deme' genetic algorithm. This algorithm evolves multiple populations in parallel using a steady-state algorithm. Each generation the algorithm migrates some of the individuals from each population to one of the other populations.

In addition to the basic built-in types, GAlib defines the components you'll need to derive your own genetic algorithm classes. The examples include a few of these derivations including (1) a genetic algorithm that uses multiple populations and 'migration' between populations on multiple CPUs, and (2) a genetic algorithm that does 'deterministic crowding' to maintain different species of individuals during the evolution.

The base genetic algorithm class contains operators and data common to most flavors of genetic algorithms. When you derive your own genetic algorithm you can use these member data and functions to keep track of statistics and monitor performance.

The genetic algorithm contains the statistics, replacement strategy, and parameters for running the algorithm. the population object, a container for genomes, also contains some statistics as well as selection and scaling operators. A typical genetic algorithm will run forever. The library has built in functions for specifying when the algorithm should terminate. These include terminate-upon-generation, in which you specify a certain number of generations for which the algorithm should run, and terminate-upon-convergence, in which you specify a value to which the best-of-generation score should converge. You can customize the termination function to use your own stopping criterion.

The number of function evaluations is a good way to compare different genetic algorithms with various other search methods. The GAlib genetic algorithms keep track of both the number of genome evaluations and population evaluations.



## Defining a Representation

Use a data structure that is appropriate for your problem. If you are optimizing a function of real numbers, use real numbers in your genome. If a solution to your problem can be represented with some imaginary numbers and some integer values, define a genome with these characteristics.

Defining an appropriate representation is part of the art of using genetic algorithms (and at this point, it is still an art, not a science). Use a representation that is minimal but completely expressive. Your representation should be able to represent any solution to your problem, but if at all possible you should design it so that it cannot represent infeasible solutions to your problem. Remember that if the genome can represent infeasible solutions then the objective function must be designed to give partial credit to infeasibles.

The representation should not contain information beyond that needed to represent a solution to the problem. Although there may be merit in using a representation that contains 'extra' genetic material, unless properly implemented (in concert with the objective function and in full consideration of the type and characteristics of the search space), this tends to increase the size of the search space and thus hinder the performance of the genetic algorithm.

The number of possible representations is endless. You may choose a purely numeric representation such as an array of real numbers. These could be implemented as real numbers, or, in the Goldberg-style of a string of bits that map to real numbers (beware that using real numbers directly far outperforms the binary-to-decimal representation for most problems, especially when you use reasonable crossover operators). Your problem may depend on a sequence of items, in which case an order-based representation (either list or array) may be more appropriate. In many of these cases, you must choose operators that maintain the integrity of the sequence; crossover must generate reordered lists without duplicating any element in the list. Other problems lend themselves to a tree structure. Here you may want to represent solutions explicitly as trees and perform the genetic operations on the trees directly. Alternatively, many people encode trees into an array or parsable string, then operate on the string. Some problems include a mix of continuous and discrete elements, in which case you may need to create a new structure to hold the mix of information. In these cases you must define genetic operators that respect the structure of the solution. For example, a solution with both integer and floating parts might use a crossover that crosses integer parts with integer parts and floating parts with floating parts, but never mixes floating parts with integer parts.

Whichever representation you choose, be sure to pick operators that are appropriate for your representation.

## The Genome Operators

Each genome has three primary operators: initialization, mutation, and crossover. With these operators you can bias an initial population, define a mutation or crossover specific to your problem's representation, or evolve parts of the genetic algorithm as your population evolves. GALib comes with these operators pre-defined for each genome type, but you can customize any of them.

The initialization operator determines how the genome is initialized. It is called when you initialize a population or the genetic algorithm. This operator does not actually create new genomes, rather it 'stuffs' the genomes with the primordial genetic material from which all solutions will evolve. The population object has its own initialization operator. By default this simply calls the initialization operators of the genomes in the population, but you can customize it to do whatever you want.

The mutation operator defines the procedure for mutating each genome. Mutation means different things for different data types. For example, a typical mutator for a binary string genome flips the bits in the string with a given probability. A typical mutator for a tree, on the other hand, would swap subtrees with a given probability. In general, you should define a mutation that can do both exploration

## Overview: The Population Object

and exploitation; mutation should be able to introduce new genetic material as well as modify existing material. You may want to define multiple types of mutation for a single problem.

The crossover operator defines the procedure for generating a child from two parent genomes. Like the mutation operator, crossover is specific to the data type. Unlike mutation, however, crossover involves multiple genomes. In GAlib, each genome 'knows' its preferred method of mating (the default crossover method) but it is incapable of performing crossover itself. Each genetic algorithm 'knows' how to get the default crossover method from its genomes then use that method to perform the mating. With this model it is possible to derive new genetic algorithm classes that use mating methods other than the defaults defined for a genome.

Each of these methods can be customized so that it is specific not only to the data type, but also to the problem type. This is one way you can put some problem-specific 'intelligence' into the genetic algorithm (I won't go into a discussion about whether or not this is a good thing to do...)

In addition to the three primary operators, each genome must also contain an objective function and may also contain a comparator. The objective function is used to evaluate the genome. The comparator (often referred to as a 'distance function') is used to determine how different one genome is from another. Every genetic algorithm requires that an objective function is defined - this is how the genetic algorithm determines which individuals are better than others. Some genetic algorithms require a comparator.

The library has some basic data types built in, but if you already have an array or list object, for example, then you can quickly build a genome from it by multiply inheriting from your object and the genome object. You can then use this new object directly in the GAlib genetic algorithm objects.

In general, a genetic algorithm does not need to know about the contents of the data structures on which it is operating. The library reflects this generality. You can mix and match genome types with genetic algorithms. The

genetic algorithm knows how to clone genomes in order to create populations, initialize genomes to start a run, cross genomes to generate children, and mutate genomes. All of these operations are performed via the genome member functions.

## The Population Object

The population object is a container for genomes. Each population object has its own initializer (the default simply calls the initializer for each individual in the population) and evaluator (the default simply calls the evaluator for each individual in the population). It also keeps track of the best, average, deviation, etc for the population. Diversity can be recorded as well, but since diversity calculations often require a great deal of additional computation, the default is to not record diversity.

The selection method is also defined in the population object. This method is used by the genetic algorithms to choose which individuals should mate.

Each population object has a scaling scheme object associated with it. The scaling scheme object converts the objective score of each genome to a fitness score that the genetic algorithm uses for selection. It also caches fitness information for use later on by the selection schemes.

## Objective Functions and Fitness Scaling

Genetic algorithms are often more attractive than gradient search methods because they do not require complicated differential equations or a smooth search space. The genetic algorithm needs only a single measure of how good a single individual is compared to the other individuals. The objective function provides this measure; given a single solution to a problem, how good is it?

## Overview: So what does it look like in C++?

It is important to note the distinction between fitness and objective scores. The objective score is the value returned by your objective function; it is the raw performance evaluation of a genome. The fitness score, on the other hand, is a possibly-transformed rating used by the genetic algorithm to determine the fitness of individuals for mating. The fitness score is typically obtained by a linear scaling of the raw objective scores (but you can define any mapping you want, or no transformation at all). For example, if you use linear scaling then the fitness scores are derived from the objective scores using the fitness proportional scaling technique described in Goldberg's book. The genetic algorithm uses the fitness scores, not the objective scores, to do selection.

You can evaluate the individuals in a population using an individual-based evaluation function (which you define), or a population-based evaluator (also which you define). If you use an individual-based objective, then the function is assigned to each genome. A population-based objective function can make use of individual objective functions, or it can set the individual scores itself.

## So what does it look like in C++?

A typical optimization program has the following form. This example creates a one-dimensional binary string genome with the default operators then uses a simple genetic algorithm to do the evolution.

```
float Objective(GAGenome&);

main(){
    GA1DBinaryStringGenome genome(length, Objective);      // create a genome
    GASimpleGA ga(genome);                      // create the genetic algorithm
    ga.evolve();                                // do the evolution
    cout << ga.statistics() << endl;           // print out the results
}

float Objective(GAGenome&) {
    // your objective function goes here
}
```

You can very easily change the behaviour of the genetic algorithm by setting various parameters. Some of the more common ones are set like this:

```
ga.populationSize(popszie);
ga.nGenerations(ngen);
ga.pMutation(pmut);
ga.pCrossover(pcross);
GASigmaTruncationScaling sigmaTruncation;
ga.scaling(sigmaTruncation);
```

Alternatively you can have GALib read the genetic algorithm options from a file or from the command line. This snippet creates a genetic algorithm, reads the parameters from a file, reads parameters (if any) from the command line, performs the evolution, then prints out the statistics from the run.

```
GASTeadyStateGA ga(genome);
ga.parameters("settings.txt");
ga.parameters(argc, argv);
ga.evolve();
cout << ga.statistics() << endl;
```

A typical (albeit simple) objective function looks like this (this one gives a higher score to a binary string genome that contains all 1s):

```
float
Objective(GAGenome & g) {
    GA1DBinaryStringGenome & genome = (GA1DBinaryStringGenome &)g;
    float score=0.0;
    for(int i=0; i<genome.length(); i++)
        score += genome.gene(i);
    return score;
```

## Overview: What can the operators do?

}

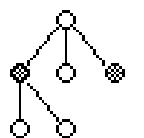
You can define the objective function as a static member of a derived class, or just define a function and use it with the existing GAlib genome classes.

When you write an objective function, you must first cast the generic genome into the type of genome that your objective function is expecting. From that point on you can work with the specific genome type. Each objective function returns a single value that represents the objective score of the genome that was passed to the objective function.

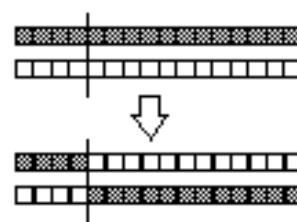
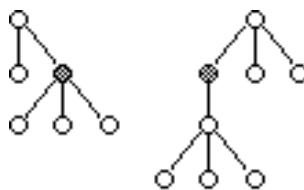
Please see the examples for more samples of the library in action. And see the programming interface page for a complete list of member functions and built-in operators.

### What can the operators do?

Here are some examples of the types of mutation and crossover that can be done using GAlib. Traditional crossover generates two children from two parents, and mutation is typically applied to a single individual. However, many other types of crossover and mutation are possible, such as crossover using three or more parents, asexual crossover or population-based mutation. The following examples illustrate some of the standard, sexual crossover and individual mutation methods in GAlib.



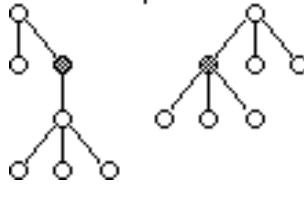
tree node swap mutation



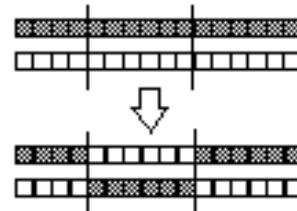
array one point crossover



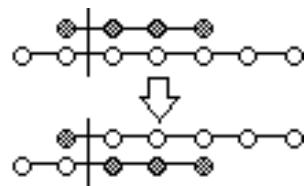
tree sub-tree swap mutation



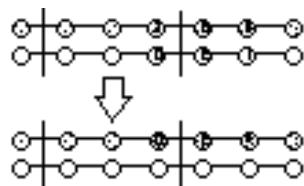
tree one point crossover



array two point crossover



list one point crossover



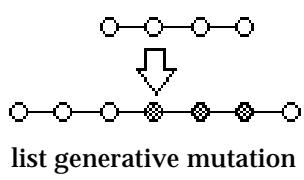
list order crossover



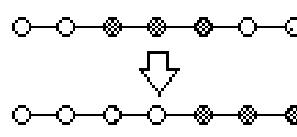
list destructive mutation



list node swap mutation



list generative mutation



list sequence swap mutation

## Overview: How do I define my own operators?

### How do I define my own operators?

Defining the operators is only as difficult as figuring out the algorithm you want to implement. As far as the actual implementation goes, there's not much to it. To assign an operator to a genome, just use the appropriate member function. For example, the following code snippet assigns 'MyInitializer' as the initialization function and 'MyCrossover' as the crossover function for a binary string genome.

```
GALDBinaryStringGenome genome(20);
genome.initializer(MyInitializer);
genome.crossover(MyCrossover);
```

If you do this to the first genome (the one you use to create the genetic algorithm) then all of the ones that the GA clones will have the same operators defined for them.

When you derive your own genome class you will typically hard-code the operators into the genome like this:

```
class MyGenome : public GAGenome {
public:
    static void RandomInitializer(GAGenome&);
    static int JuggleCrossover(const GAGenome&, const GAGenome&, GAGenome*, GAGenome*);
    static int KillerMutate(GAGenome&, float);
    static float ElementComparator(const GAGenome&, const GAGenome&);
    static float ThresholdObjective(GAGenome&);

public:
    MyGenome() {
        initializer(RandomInitializer);
        crossover(JuggleCrossover);
        mutator(KillerMutate);
        comparator(ElementComparator);
        evaluator(ThresholdObjective);
    }

    // remainder of class definition here
};

};
```

Notice how easy it becomes to change operators. You can very easily define a multitude of operators for a single representation and experiment with them to see which performs better.

Why are the genome operators GALib not member functions? The primary reason is so that you do not have to derive a new class in order to change the behaviour of one of the built-in genome types. In addition, the use of function pointers rather than member functions lets us change operators at run-time (unlike member functions or templated classes). And they are faster than virtual functions (OK, so this the virtual/non-virtual component is a pretty small fraction of actual execution time compared to most objective functions...). On the down side, they permit you to make some ugly mistakes by improperly casting.

The definition for the List1PtCrossover looks like this:

*This crossover picks a single point in the parents then generates one or two children from the two halves of each parent.*

```
template <class T> int
OnePointCrossover(const GAGenome& p1, const GAGenome& p2, GAGenome* c1, GAGenome* c2){
    GAListGenome<T> &mom=(GAListGenome<T> &)p1;
    GAListGenome<T> &dad=(GAListGenome<T> &)p2;
    int nc=0;
    unsigned int a = GARandomInt(0, mom.size());
    unsigned int b = GARandomInt(0, dad.size()); GAList<T> * list;
```

## Overview: How do I define my own operators?

```

// first do the sister...
if(c1){
    GAListGenome<T> &sis=(GAListGenome<T> &)*c1;
    sis.GAList<T>::copy(mom);
    list = dad.GAList<T>::clone(b);
    if(a < mom.size()){
        T *site = sis.warp(a);
        while(sis.tail() != site)
            sis.destroy(); // delete the tail node
        sis.destroy(); // trash the trailing node (list[a])
    }
    else{
        sis.tail(); // move to the end of the list
    }
    sis.insert(list); // stick the clone onto the end
    delete list;
    sis.warp(0); // set iterator to head of list
    nc += 1;
}

// ...now do the brother
if(c2){
    GAListGenome<T> &bro=(GAListGenome<T> &)*c2;
    bro.GAList<T>::copy(dad);
    list = mom.GAList<T>::clone(a);
    if(b < dad.size()){
        T *site = bro.warp(b);
        while(bro.tail() != site)
            bro.destroy(); // delete the tail node
        bro.destroy(); // trash the trailing node (list[a])
    }
    else{
        bro.tail(); // move to the end of the list
    }
    bro.insert(list); // stick the clone onto the end
    delete list;
    bro.warp(0); // set iterator to head of list
    nc += 1;
}
return nc;
}

```

The definition for FlipMutator for 1DArrayAlleleGenomes looks like this:

*This mutator flips the value of a single element of the array to any of the possible allele values.*

```

int
FlipMutator(GAGenome & c, float pmut) {
    GA1DArrayAlleleGenome<T> &child=(GA1DArrayAlleleGenome<T> &)c;
    register int n, i;
    if(pmut <= 0.0) return(0);
    float nMut = pmut * (float)(child.length());
    if(nMut < 1.0){ // we have to do a flip test on each bit
        nMut = 0;
        for(i=child.length()-1; i>=0; i--){
            if(GAFlipCoin(pmut)){
                child.gene(i, child.alleleset().allele());
                nMut++;
            }
        }
    }else{ // only flip the number of bits we need to flip
        for(n=0; n<nMut; n++){
            i = GARandomInt(0, child.length()-1);
            child.gene(i, child.alleleset().allele());
        }
    }
}

```

## Overview: What about deriving my own genome class?

```
        }
    }
    return((int)nMut);
}
```

And the definition for a typical initializer looks like this:

*This initializer creates a tree of bounded random size and forkiness.*

```
void
TreeInitializer(GAGenome & c) {
    GATreeGenome<Point> &tree=(GATreeGenome<Point> &)c;
    tree.root();
    tree.destroy(); // destroy any pre-existing tree
    Point p(0,0,0);
    tree.insert(p,GATreeBASE::ROOT);
    int n = GARandomInt(0,MAX_CHILDREN); // limit number of children
    for(int i=0; i<n; i++)
        DoChild(tree, 0);
}

void
DoChild(GATreeGenome<Point> & tree, int depth) {
    if(depth >= MAX_DEPTH) return; // limit depth of the tree
    int n = GARandomInt(0,MAX_CHILDREN); // limit number of children
    Point p(GARandomFloat(0,25), GARandomFloat(0,25), GARandomFloat(0,25));
    tree.insert(p,GATreeBASE::BELOW);
    for(int i=0; i<n; i++)
        DoChild(tree, depth+1);
    tree.parent(); // move the iterator up one level
}
```

## What about deriving my own genome class?

Here is the definition of a genome that contains an arbitrary number of lists. It could easily be modified to become a diploid genome. It is used in exactly the same way that the built-in genomes are used. For a simpler example, see the GNU example which integrates the GNU BitString object with GALib to form a new genome class.

```
class RobotPathGenome : public GAGenome {
public:
    GADefineIdentity("RobotPathGenome", 251);
    static void Initializer(GAGenome&);
    static int Mutator(GAGenome&, float);
    static float Comparator(const GAGenome&, const GAGenome&);
    static float Evaluator(GAGenome&);
    static void PathInitializer(GAGenome&);

public:
    RobotPathGenome(int nrobots, int pathlength);
    RobotPathGenome(const RobotPathGenome & orig);
    RobotPathGenome& operator=(const GAGenome & arg);
    virtual ~RobotPathGenome();
    virtual GAGenome *clone(GAGenome::CloneMethod) const ;
    virtual void copy(const GAGenome & c);
    virtual int equal(const GAGenome& g) const ;
    virtual int read(istream & is);
    virtual int write(ostream & os) const ;
    GAListGenome<int> & path(int i){ return *list[i]; }
    int npaths() const { return n; }
    int length() const { return l; }

protected:
```

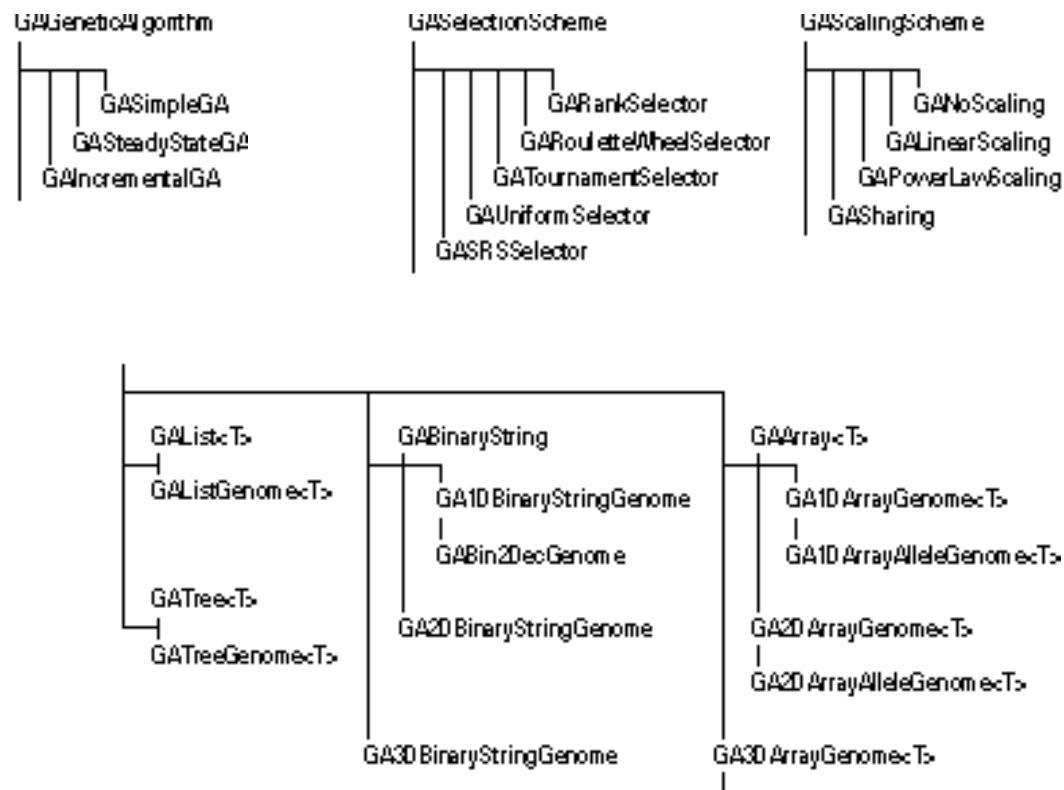
## Overview: What about deriving my own genome class?

```
int n, l;
GAListGenome<int> **list;
};
```

## Class Hierarchy

Here is an outline of the GAlib class hierarchy. The first section is a graphic map, the second section contains an outline of the hierarchy.

## GAlib Class Hierarchy - Pictorial



## GAlib Class Hierarchy - Outline

GAGeneticAlgorithm

- GASteadyStateGA (overlapping populations)
- GASimpleGA (non-overlapping populations)
- GAIIncrementalGA (overlapping with custom replacement)
- GADemeGA (parallel populations with migration)

GAStatistics

GAParallelList

GAPopulation

GAScalingScheme

- GANoScaling
- GALinearScaling
- GASigmaTruncationScaling
- GAPowerLawScaling
- GASHaring

GASelectionScheme

- GARankSelector
- GARouletteWheelSelector
- GATournamentSelector
- GAUniformSelector
- GASRSSelector
- GADSSelector

GAGenome

- GA1DBinaryStringGenome
- GABin2DecGenome
- GA2DBinaryStringGenome
- GA3DBinaryStringGenome
- GA1DArrayGenome<>
- GA1DArrayAlleleGenome<>
- GAStringGenome (same as GA1DArrayAlleleGenome<char>)
- GARealGenome (same as GA1DArrayAlleleGenome<float>)
- GA2DArrayGenome<>
- GA2DArrayAlleleGenome<>
- GA3DArrayGenome<>
- GA3DArrayAlleleGenome<>
- GATreeGenome<>
- GAListGenome<>

GAArray<>

GAAlleleSetArray<>

GAAlleleSet<>

GABinaryString

GABin2DecPhenotype

GATree<>

GATreeIter<>

GAList<>

GAListIter<>

## Programming Interface

---

This document describes the programming interface for the library. The section for each class contains a description of the object's purpose followed by the creator signature and member functions. There are also sections for library constants, typedefs, and function signatures.

### Global Typedefs and Enumerations

```
typedef float GAProbability, GAProb
typedef enum _GABoolean {gaFalse, gaTrue} GABoolean, GABool
typedef enum _GASuccess {gaSuccess, gaFailure} GASuccess
typedef unsigned char GABit
```

### Global Variables and Global Constants

```
char* gaErrMsg; // globally defined pointer to current error message
int gaDefScoreFrequency1 = 1; // for non-overlapping populations
int gaDefScoreFrequency2 = 100; // for overlapping populations
float gaDefLinearScalingMultiplier = 1.2;
float gaDefSigmaTruncationMultiplier = 2.0;
float gaDefPowerScalingFactor = 1.0005;
float gaDefSharingCutoff = 1.0;
```

### Function Prototypes

```
GABoolean (*GAGeneticAlgorithm::Terminator)(GAGeneticAlgorithm&)
GAGenome& (*GAIncrementalGA::ReplacementFunction)(GAGenome&, GAPopulation&)
void (*GAPopulation::Initializer)(GAPopulation &)
void (*GAPopulation::Evaluator)(GAPopulation &)
void (*GAGenome::Initializer)(GAGenome &)
float (*GAGenome::Evaluator)(GAGenome &)
int (*GAGenome::Mutator)(GAGenome &, float)
float (*GAGenome::Comparator)(const GAGenome &, const GAGenome&)
int (*GAGenome::SexualCrossover)(const GAGenome&, const GAGenome&, GAGenome*, GAGenome*)
int (*GAGenome::AsexualCrossover)(const GAGenome&, GAGenome*)
int (*GABinaryEncoder)(float& value, GABit* bits, unsigned int nbits, float min, float max)
int (*GABinaryDecoder)(float& value, const GABit* bits, unsigned int nbits, float min, float max)
```

### Parameter Names and Command-Line Options

Parameters may be specified using the full name strings (for example in parameter files), short name strings (for example on the command line), or explicit member functions (such as those of the genetic algorithm objects). All of the #defined names are simply the full names declared as #defined strings; you can use either the string (e.g. number\_of\_generations) or the #defined name (e.g. gaNnGenerations), but if you use the #defined name then the compiler will be able to catch your spelling mistakes.

When you specify GAlib arguments on the command line, they must be in name-value pairs. You can use either the long or short name. For example, if my program is called optimizer, the command line for running the program with a population size of 150, mutation rate of 10%, and score filename of evolve.txt would be:

```
optimizer popsize 150 pmut 0.1 sfile evolve.txt
```

#define name	full name short name	data type and default value
gaNminimaxi	minimaxi mm	int gaDefMiniMaxi = 1
gaNnGenerations	number_of_generations ngen	int gaDefNumGen = 250
gaNpConvergence	convergence_percentage pconv	float gaDefPConv = 0.99
gaNnConvergence	generations_to_convergence nconv	int gaDefNConv = 20
gaNpCrossover	crossover_probability pcross	float gaDefPCross = 0.9
gaNpMutation	mutation_probability pmut	float gaDefPMut = 0.01
gaNpopulationSize	population_size popsize	int gaDefPopSize = 30
gaNnPopulations	number_of_populations npop	int gaDefNPop = 10
gaNpReplacement	replacement_percentage prep1	float gaDefPRepl = 0.25
gaNnReplacement	replacement_number nrep1	int gaDefNRepl = 5
gaNnBestGenomes	number_of_best nbest	int gaDefNumBestGenomes = 1
gaNsScoreFrequency	score_frequency sfreq	int gaDefScoreFrequency1 = 1
gaNflushFrequency	flush_frequency ffreq	int gaDefFlushFrequency = 0

## Programming Interface: Parameter Names and Command-Line Options

#define name	full name short name	data type and default value
gaNscoreFilename	score_filename sfile	char* gaDefScoreFilename = "generations.dat"
gaNselectScores	select_scores sscores	int gaDefSelectScores = GAStatistics::Maximum
gaNelitism	elitism el	GABoolean gaDefElitism = gaTrue
gaNnOffspring	number_of_offspring noffspr	int gaDefNumOff = 2
gaNrecordDiversity	record_diversity recdiv	GABoolean gaDefDivFlag = gaFalse
gaNpMigration	migration_percentage pmig	float gaDefPMig = 0.1
gaNnMigration	migration_number nmig	int gaDefNMig = 5

## Error Handling

Exceptions are not used in GALib version 2.x. However, some GALib functions return a status value to indicate whether or not their operation was successful. If a function returns an error status, it posts its error message on the global GALib error pointer, a global string called gaErrMsg.

By default, GALib error messages are sent immediately to the error stream. You can disable the immediate printing of error messages by passing gaFalse to the ::GAResults function. Passing a value of gaTrue enables the behavior.

If you would like to redirect the error messages to a different stream, use the ::GASetErrorStream function to assign a new stream. The default stream is the system standard error stream, cerr.

Here are the error control functions and variables:

```
extern char gaErrMsg[];
void GAREportResults(GABoolean flag);
void GASetErrorStream(ostream&);
```

## Random Number Functions

GAlib includes the following functions for generating random numbers:

```
void GARandomSeed(unsigned s = 0)

int GARandomInt()
int GARandomInt(int low, int high)

double GARandomDouble()
double GARandomDouble(double low, double high)

float GARandomFloat()
float GARandomFloat(float low, float high)

int GARandomBit()

GABoolean GAFlipCoin(float p)

int GAGaussianInt(int stddev)
float GAGaussianFloat(float stddev)
double GAGaussianDouble(double stddev)
double GAUnitGaussian()
```

If you call it with no argument, the GARandomSeed function uses the current time multiplied by the process ID (on systems that have PIDs) as the seed for a psuedo-random number generator. On systems with no process IDs it uses only the time. You can specify your own random seed if you like by passing a value to this function. Once a seed has been specified, subsequent calls to GARandomSeed with the same value have no effect. Subsequent calls to GARandomSeed with a different value will re-initialize the random number generator using the new value.

The functions that take low and high as argument return a random number from low to high, inclusive. The functions that take no arguments return a value in the interval [0,1]. GAFlipCoin returns a boolean value based on a biased coin toss. If you give it a value of 1 it will return a 1, if you give it a value of 0.75 it will return a 1 with a 75% chance.

The GARandomBit function is the most efficient way to do unbiased coin tosses. It uses the random bit generator described in Numerical Recipes in C.

The Gaussian functions return a random number from a Gaussian distribution with deviation that you specify. The GAUnitGaussian function returns a number from a unit Gaussian distribution with mean 0 and deviation of 1.

GAlib uses a single random number generator for the entire library. You may not change the random number generator on the fly - it can be changed only when GAlib is compiled. See the config.h and random.h header files for details. By default, GAlib uses the ran2 generator described in Numerical Recipes in C.

## GAGeneticAlgorithm

This is an abstract class that cannot be instantiated. Each genetic algorithm, when instantiated, will have default operators defined for it. See the documentation for the specific genetic algorithm type for details.

The base genetic algorithm class keeps track of evolution statistics such as number of mutations, number of crossovers, number of evaluations, best/mean/worst in each generation, and initial/current population statistics. It also defines the terminator, a member function that specifies the stopping criterion for the algorithm.

You can maximize or minimize by calling the appropriate member function. If you derive your own genetic algorithm, remember that users of your algorithm may need either type of optimization.

Statistics can be written to file each generation or periodically by specifying a flush frequency. Generational scores can be recorded each generation or less frequently by specifying a score frequency.

Parameters such as generations-to-completion, crossover probability and mutation probability can be set by member functions, command-line, or from file.

The evolve member function first calls initialize then calls the step member function until the done member function returns gaTrue. It calls the flushScores member as needed when the evolution is complete. If you evolve the genetic algorithm without using the evolve member function, be sure to call initialize before stepping through the evolution. You can use the step member function to evolve a single generation. You should call flushScores when the evolution is finished so that any buffered scores are flushed.

The names of the individual parameter member functions correspond to the #defined string names. You may set the parameters on a genetic algorithm one at a time (for example, using the nGenerations member function), using a parameter list (for example, using the parameters member function with a GAParameList), by parsing the command line (for example, using the parameters member function with argc and argv), by name-value pairs (for example, using the set member function with a parameter name and value), or by reading a stream or file (for example, using the parameters member with a filename or stream).

see also: GAParameList

see also: GAStatistics

see also: Terminators

### class hierarchy

```
class GAGeneticAlgorithm : public GAID
```

### typedefs and constants

```
GABoolean (*GAGeneticAlgorithm::Terminator)(GAGeneticAlgorithm&)
enum { MINIMIZE = -1, MAXIMIZE = 1 };
```

### member function index

```
static GAParameList& registerDefaultParameters(GAParameList&)
void * userData()
void * userData(void *)
void initialize(unsigned int seed=0)
void evolve(unsigned int seed=0) void step()
GABoolean done()
GAGeneticAlgorithm::Terminator terminator()
GAGeneticAlgorithm::Terminator terminator(GAGeneticAlgorithm::Terminator)
const GAStatistics & statistics() const
float convergence() const
```

## Programming Interface: GAGeneticAlgorithm

```
int generation() const
void flushScores()
int minimaxi() const
int minimaxi(int)
int minimize()
int maximize()
int nGenerations() const
int nGenerations(unsigned int)
int nConvergence() const
int nConvergence(unsigned int)
float pConvergence() const
float pConvergence(float)
float pMutation() const
float pMutation(float) float pCrossover() const
float pCrossover(float)
GAGenome::SexualCrossover crossover(GAGenome::SexualCrossover func)
GAGenome::SexualCrossover sexual() const
GAGenome::AsexualCrossover crossover(GAGenome::AsexualCrossover func)
GAGenome::AsexualCrossover asexual() const
const GAPopulation & population() const
const GAPopulation & population(const GAPopulation&)
int populationSize() const
int populationSize(unsigned int n)
int nBestGenomes() const
int nBestGenomes(unsigned int n)
GAScalingScheme & scaling() const
GAScalingScheme & scaling(const GAScalingScheme&)
GASelectionScheme & selector() const
GASelectionScheme & selector(const GASelectionScheme& s)
void objectiveFunction(GAGenome::Evaluator)
void objectiveData(const GAEvalData&)
int scoreFrequency() const
int scoreFrequency(unsigned int frequency)
int flushFrequency() const
int flushFrequency(unsigned int frequency)
char* scoreFilename() const
char* scoreFilename(const char *filename)
int selectScores() const
int selectScores(GAStatistics::ScoreID which)
GABoolean recordDiversity() const
GABoolean recordDiversity(GABoolean flag)
const GAParameterList & parameters()
const GAParameterList & parameters(const GAParameterList &)
const GAParameterList & parameters(int& argc, char** argv, GABoolean flag = gaFalse)
const GAParameterList & parameters(const char* filename, GABoolean flag = gaFalse)
const GAParameterList & parameters(istream&, GABoolean flag = gaFalse);
int set(const char* s, int v)
int set(const char* s, unsigned int v)
int set(const char* s, char v)
int set(const char* s, const char* v)
int set(const char* s, const void* v)
int set(const char* s, double v);
int write(const char* filename)
int write(ostream&)
int read(const char* filename)
int read(ostream&)
```

### member function descriptions

#### convergence

Returns the current convergence. The convergence is defined as the ratio of the Nth previous best-of-generation score to the current best-of-generation score.

## Programming Interface: GAGeneticAlgorithm

### **crossover**

Specify the mating method to use for evolution. This can be changed during the course of an evolution. This genetic algorithm uses only sexual crossover.

### **done**

Returns gaTrue if the termination criteria have been met, returns gaFalse otherwise. This function simply calls the completion function that was specified using the terminator member function.

### **evolve**

Initialize the genetic algorithm then evolve it until the termination criteria have been satisfied. This function first calls initialize then calls the step member function until the done member function returns gaTrue. It calls the flushScores member as needed when the evolution is complete. You may pass a seed to evolve if you want to specify your own random seed.

### **flushFrequency**

Use this member function to specify how often the scores should be flushed to disk. A value of 0 means do not write to disk. A value of 100 means to flush the scores every 100 generations.

### **flushScores**

Force the genetic algorithm to flush its generational data to disk. If you have specified a flushFrequency of 0 or specified a scoreFilename of nil then calling this function has no effect.

### **generation**

Returns the current generation.

### **initialize**

Initialize the genetic algorithm. If you specify a seed, this function calls GARandomSeed with that value. If you do not specify a seed, GAlib will choose one for you as described in the random functions section. It then initializes the population and does the first population evaluation.

### **nBestGenomes**

Specify how many 'best' genomes to record. For example, if you specify 10, the genetic algorithm will keep the 10 best genomes that it ever encounters. Beware that if you specify a large number here the algorithm will slow down because it must compare the best of each generation with its current list of best individuals. The default is 1.

### **nConvergence**

Set/Get the number of generations used for the convergence test.

### **nGenerations**

Set/Get the number of generations.

### **objectiveData**

Set the objective data member on all individuals used by the genetic algorithm. This can be changed during the course of an evolution.

### **objectiveFunction**

Set the objective function on all individuals used by the genetic algorithm. This can be changed during the course of an evolution.

## Programming Interface: GAGeneticAlgorithm

### **parameters**

Returns a reference to a parameter list containing the current values of the genetic algorithm parameters.

### **parameters(GAParameterList&)**

Set the parameters for the genetic algorithm. To use this member function you must create a parameter list (an array of name-value pairs) then pass it to the genetic algorithm.

### **parameters(int& argc, char\*\* argv, GABoolean flag = gaFalse)**

Set the parameters for the genetic algorithm. Use this member function to let the genetic algorithm parse your command line for arguments that GAlib understands. This method decrements argc and moves the pointers in argv appropriately to remove from the list the arguments that it understands. If you pass gaTrue as the third argument then the method will complain about any command-line arguments that are not recognized by this genetic algorithm.

### **parameters(char\* filename, GABoolean flag = gaFalse)** **parameters(istream&, GABoolean flag = gaFalse)**

Set the parameters for the genetic algorithm. This version of the parameters member function will parse the specified file or stream for parameters that the genetic algorithm understands. If you pass gaTrue as the second argument then the method will complain about any parameters that are not recognized by this genetic algorithm.

### **pConvergence**

Set/Get the convergence percentage. The convergence is defined as the ratio of the Nth previous best-of-generation score to the current best-of-generation score. N is defined by the nConvergence member function.

### **pCrossover**

Set/Get the crossover probability.

### **pMutation**

Set/Get the mutation probability.

### **population**

Set/Get the population. Returns a reference to the current population.

### **populationSize**

Set/Get the population size. This can be changed during the course of an evolution.

### **recordDiversity**

Convenience function for specifying whether or not to calculate diversity. Since diversity calculations require comparison of each individual with every other, recording this statistic can be expensive. The default is gaFalse (diversity is not recorded).

### **registerDefaultParameters**

Each genetic algorithm defines this member function to declare the parameters that work with it. Pass a parameter list to this function and this function will configure the list with the default parameter list and values for the genetic algorithm class from which you called it. This is a statically defined function, so invoke it using the class name of the genetic algorithm whose parameters you want to use, for example, GASimpleGA::registerDefaultParameters(list). The default parameters for the base genetic algorithm class are:

## Programming Interface: GAGeneticAlgorithm

flushFrequency	pConvergence	scoreFilename
minimaxi	pCrossover	scoreFrequency
nBestGenomes	pMutation	selectScores
nGenerations	populationSize	
nConvergence	recordDiversity	

### **scaling**

Set/Get the scaling scheme. The specified scaling scheme must be derived from the GAScalingScheme class. This can be changed during the course of an evolution.

### **scoreFilename**

Specify the name of the file to which the scores should be recorded.

### **scoreFrequency**

Specify how often the generational scores should be recorded. The default depends on the type of genetic algorithm that you are using. You can record mean, max, min, stddev, and diversity for every n generations.

### **selector**

Set/Get the selection scheme for the genetic algorithm. The selector is used to pick individuals from a population before mating and mutation occur. This can be changed during the course of an evolution.

### **selectScores**

This function is used to specify which scores should be saved to disk. The argument is the logical OR of the following values: Mean, Maximum, Minimum, Deviation, Diversity (all defined in the scope of the GAStatistics object). To record all of the scores, pass GAStatistics::AllScores. When written to file, the format is as follows:

```
generation TAB mean TAB max TAB min TAB deviation TAB diversity NEWLINE
```

### **set**

Set individual parameters for the genetic algorithm. The

first argument should be the full- or short-name of the parameter you wish to set. The second argument is the value to which you would like to set the parameter.

### **statistics**

Returns a reference to the statistics object in the genetic algorithm. The statistics object maintains information such as best, worst, mean, and standard deviation, and diversity of each generation as well as a separate population with the best individuals ever encountered by the genetic algorithm.

### **step**

Evolve the genetic algorithm for one generation.

### **terminator**

Set/Get the termination function. The genetic algorithm is complete when the completion function returns gaTrue. The function must have the proper signature.

### **userData**

Set/Get the userData member of the genetic algorithm. This member is a generic pointer to any information that needs to be stored with the genetic algorithm.

## Programming Interface: GADemeGA

### GADemeGA

(parallel populations with migration)

This genetic algorithm has multiple, independent populations. It creates the populations by cloning the genome or population that you pass when you create it.

Each population evolves using a steady-state genetic algorithm, but each generation some individuals migrate from one population to another. The migration algorithm is deterministic stepping-stone; each population migrates a fixed number of its best individuals to its neighbor. The master population is updated each generation with best individual from each population.

If you want to experiment with other migration methods, derive a new class from this one and define a new migration operator. You can change the evolution behavior by defining a new step method in a derived class.

see also: *GAGeneticAlgorithm*

#### class hierarchy

```
class GADemeGA : public GAGeneticAlgorithm
```

#### typedefs and constants

```
enum { ALL= -1 };
```

#### constructors

```
GADemeGA(const GAGenome&)
GADemeGA(const GAPopulation&)
GADemeGA(const GADemeGA&)
```

#### member function index

```
static GAParameterList& registerDefaultParameters(GAParameterList&);
void migrate()
GADemeGA & operator++()
const GAPopulation& population(unsigned int i) const
const GAPopulation& population(int i, const GAPopulation&)
int populationSize(unsigned int i) const
int populationSize(int i, unsigned int n)
int nReplacement(unsigned int i) const
int nReplacement(int i, unsigned int n)
int nMigration() const
int nMigration(unsigned int i)
int nPopulations() const
int nPopulations(unsigned int i)
const GAStatistics& statistics() const
const GAStatistics& statistics(unsigned int i) const
```

#### member function descriptions

##### **nMigration**

Specify the number of individuals to migrate each generation. Each population will migrate this many of its best individuals to the next population (the stepping-stone migration model). The individuals replace the worst individuals in the receiving population.

##### **nReplacement**

Specify a number of individuals to replace each generation. When you specify a number of individuals to replace, the pReplacement value is set to 0. The first argument specifies which population should be modified. Use GADemeGA::ALL to apply to all populations.

## Programming Interface: GADemeGA

### `operator++`

The increment operator evolves the genetic algorithm's population by one generation by calling the step member function.

### `nReplacement`

Specify a percentage of the population to replace each generation. When you specify a replacement percentage, the nReplacement value is set to 0. The first argument specifies which population should be modified. Use GADemeGA::ALL to apply to all populations.

### `registerDefaultParameters`

This function adds parameters to the specified list that are of interest to this genetic algorithm. The default parameters for the deme genetic algorithm are the parameters for the base genetic algorithm class plus the following:

```
nMigration  
nPopulations
```

## **GAIncrementalGA**

*(overlapping populations with 1 or 2 children per generation)*

This genetic algorithm is similar to those based on the GENITOR model. It uses overlapping populations, but very little overlap (only one or two individuals get replaced each generation). The default replacement scheme is WORST. A replacement function is required only if you use CUSTOM or CROWDING as the replacement scheme. You can do DeJong-style crowding by specifying a distance function with the CROWDING option. (for best DeJong-style results, derive your own genetic algorithm)

You can specify the number of children that are generated in each 'generation' by using the nOffspring member function. Since this genetic algorithm is based on a two-parent crossover model, the number of offspring must be either 1 or 2. The default is 2.

Use the replacement method to specify which type of replacement the genetic algorithm should use. The replacement strategy determines how the new children will be inserted into the population. If you want the new child to replace one of its parents, use the Parent strategy. If you want the child to replace a random population member, use the Random strategy. If you want the child to replace the worst population member, use the Worst strategy.

If you specify CUSTOM or CROWDING you must also specify a replacement function with the proper signature. This function is used to pick which genome will be replaced. The first argument passed to the replacement function is the individual that is supposed to go into the population. The second argument is the population into which the individual is supposed to go. The replacement function should return a reference to the genome that the individual should replace. If no replacement should take place, the replacement function should return a reference to the individual.

The score frequency for this genetic algorithm defaults to 100 (it records the best-of-generation every 100th generation). The default scaling is Linear, the default selection is RouletteWheel.

see also: GAGeneticAlgorithm

### **class hierarchy**

```
class GAIncrementalGA : public GAGeneticAlgorithm
```

### **typedefs and constants**

```
GAGenome& (*GAIncrementalGA::ReplacementFunction)(GAGenome &, GAPopulation &)
enum ReplacementScheme {
    RANDOM = GAPopulation::RANDOM,
    BEST = GAPopulation::BEST,
    WORST = GAPopulation::WORST,
    CUSTOM = -30,
    CROWDING = -30,
    PARENT = -10
};
```

### **constructors**

```
GAIncrementalGA(const GAGenome&)
GAIncrementalGA(const GAPopulation&)
GAIncrementalGA(const GAIncrementalGA&)
```

### **member function index**

```
static GAParameterList& registerDefaultParameters(GAParameterList&)
GASteadyStateGA & operator++()
ReplacementScheme replacement()
ReplacementScheme replacement(ReplacementScheme, ReplacementFunction f = NULL)
int nOffspring() const
```

## Programming Interface: GAIncrementalGA

```
int noffspring(unsigned int n)
```

### member function descriptions

#### nOffspring

The incremental genetic algorithm can produce either one or two individuals each generation. Use this member function to specify how many individuals you would like.

#### operator++

The increment operator evolves the genetic algorithm's population by one generation by calling the step member function.

#### registerDefaultParameters

This function adds to the specified list parameters that are of interest to this genetic algorithm. The default parameters for the incremental genetic algorithm are the parameters for the base genetic algorithm class plus the following: noOffspring

#### replacement

Specify a replacement method. The scheme can be one of:

GAIncrementalGA::RANDOM  
GAIncrementalGA::PARENT

GAIncrementalGA::BEST  
GAIncrementalGA::WORST

GAIncrementalGA::CUSTOM  
GAIncrementalGA::CROWDING

If you specify custom or crowding replacement then you must also specify a function. The replacement function takes two arguments: the individual to insert and the population into which it will be inserted. The replacement function should return a reference to the genome that should be replaced. If no replacement should take place, the replacement function should return a reference to the individual passed to it.

## GASimpleGA

(*non-overlapping populations*)

This genetic algorithm is the 'simple' genetic algorithm that Goldberg describes in his book. It uses non-overlapping populations. When you create a simple genetic algorithm, you must specify either an individual or a population of individuals. The new genetic algorithm will clone the individual(s) that you specify to make its own population. You can change most of the genetic algorithm behaviors after creation and during the course of the evolution.

The simple genetic algorithm creates an initial population by cloning the individual or population you pass when you create it. Each generation the algorithm creates an entirely new population of individuals by selecting from the previous population then mating to produce the new offspring for the new population. This process continues until the stopping criteria are met (determined by the terminator).

Elitism is optional. By default, elitism is on, meaning that the best individual from each generation is carried over to the next generation. To turn off elitism, pass `gaFalse` to the `elitist` member function.

The score frequency for this genetic algorithm defaults to 1 (it records the best-of-generation every generation). The default scaling is Linear, the default selection is RouletteWheel.

### class hierarchy

```
class GASimpleGA : public GAGeneticAlgorithm
```

### constructors

```
GASimpleGA(const GAGenome&)
GASimpleGA(const GAPopulation&)
GASimpleGA(const GASimpleGA&)
```

### member function index

```
static GAParameterList& registerDefaultParameters(GAParameterList&)
GASimpleGA & operator++()
GABoolean elitist() const
GABoolean elitist(GABoolean flag)
```

### member function descriptions

#### elitist

Set/Get the elitism flag. If you specify `gaTrue`, the genetic algorithm will copy the best individual from the previous population into the current population if no individual in the current population is any better.

#### operator++

The increment operator evolves the genetic algorithm's population by one generation by calling the step member function.

#### registerDefaultParameters

This function adds to the specified list parameters that are of interest to this genetic algorithm. The default parameters for the simple genetic algorithm are the parameters for the base genetic algorithm class plus the following: `elitism`

## **GASteadyStateGA**

*(overlapping populations)*

This genetic algorithm is similar to the algorithms described by DeJong. It uses overlapping populations with a user-specifiable amount of overlap. The algorithm creates a population of individuals by cloning the genome or population that you pass when you create it. Each generation the algorithm creates a temporary population of individuals, adds these to the previous population, then removes the worst individuals in order to return the population to its original size.

You can select the amount of overlap between generations by specifying the pReplacement parameter. This is the percentage of the population that should be replaced each generation. Newly generated offspring are added to the population, then the worst individuals are destroyed (so the new offspring may or may not make it into the population, depending on whether they are better than the worst in the population).

If you specify a replacement percentage, then that percentage of the population will be replaced each generation. Alternatively, you can specify a number of individuals (less than the number in the population) to replace each generation. You cannot specify both - in a parameter list containing both parameters, the latter is used.

The score frequency for this genetic algorithm defaults to 100 (it records the best-of-generation every 100th generation). The default scaling is Linear, the default selection is RouletteWheel.

see also: GAGeneticAlgorithm

### **class hierarchy**

```
class GASteadyStateGA : public GAGeneticAlgorithm
```

### **constructors**

```
GASteadyStateGA(const GAGenome&)
GASteadyStateGA(const GAPopulation&)
GASteadyStateGA(const GASteadyStateGA&)
```

### **member function index**

```
static GAParameterList& registerDefaultParameters(GAParameterList&)
GASteadyStateGA & operator++()
float pReplacement() const
float pReplacement(float percentage)
int nReplacement() const
int nReplacement(unsigned int)
```

### **member function descriptions**

#### **nReplacement**

Specify a number of individuals to replace each generation. When you specify a number of individuals to replace, the pReplacement value is set to 0.

#### **operator++**

The increment operator evolves the genetic algorithm's population by one generation by calling the step member function.

#### **pReplacement**

Specify a percentage of the population to replace each generation. When you specify a replacement percentage, the nReplacement value is set to 0.

## Programming Interface: GASteadyStateGA

### **registerDefaultParameters**

This function adds to the specified list parameters that are of interest to this genetic algorithm. The default parameters for the steady-state genetic algorithm are the parameters for the base genetic algorithm class plus the following:

```
pReplacement  
nReplacement
```

## **Terminators**

Completion functions are used to determine whether or not a genetic algorithm is finished. The done member function simply calls the completion function to determine whether or not the genetic algorithm should continue. The predefined completion functions use generation and convergence to determine whether or not the genetic algorithm is finished.

The completion function returns gaTrue when the genetic algorithm should finish, and gaFalse when the genetic algorithm should continue.

In this context, convergence refers to the the similarity of the objective scores, not similarity of underlying genetic structure. The built-in convergence measures use the best-of-generation scores to determine whether or not the genetic algorithm has plateaued.

```
GABoolean GAGeneticAlgorithm::TerminateUponGeneration(GAGeneticAlgorithm &)
GABoolean GAGeneticAlgorithm::TerminateUponConvergence(GAGeneticAlgorithm &)
GABoolean GAGeneticAlgorithm::TerminateUponPopConvergence(GAGeneticAlgorithm &)
```

### **TerminateUponGeneration**

This function compares the current generation to the specified number of generations. If the current generation is less than the requested number of generations, it returns gaFalse. Otherwise, it returns gaTrue.

### **TerminateUponConvergence**

This function compares the current convergence to the specified convergence value. If the current convergence is less than the requested convergence, it returns gaFalse. Otherwise, it returns gaTrue.

Convergence is a number between 0 and 1. A convergence of 1 means that the nth previous best-of-generation is equal to the current best-of-generation. When you use convergence as a stopping criterion you must specify the convergence percentage and you may specify the number of previous generations against which to compare. The genetic algorithm will always run at least this many generations.

### **TerminateUponPopConvergence**

This function compares the population average to the score of the best individual in the population. If the population average is within pConvergence of the best individual's score, it returns gaTrue. Otherwise, it returns gaFalse.

For details about how to write your own termination function, see the customizations section.

## Replacement Schemes

The replacement scheme is used by the incremental genetic algorithm to determine how a new individual should be inserted into a population. Valid replacement schemes include:

GAIncrementalGA::RANDOM  
GAIncrementalGA::BEST  
GAIncrementalGA::WORST

GAIncrementalGA::CUSTOM  
GAIncrementalGA::CROWDING  
GAIncrementalGA::PARENT

In general, replace worst produces the best results. Replace parent is useful for basic speciation, and custom replacement can be used when you want to do your own type of speciation.

If you specify CUSTOM or CROWDING replacement then you must also specify a replacement function. The replacement function takes as arguments an individual and the population into which the individual should be placed. It returns a reference to the genome that the individual should replace. If the individual should not be inserted into the population, the function should return a reference to the individual.

Any replacement function must have the following function prototype:

```
typedef GAGenome& (*GAIncrementalGA::ReplacementFunction)(GAGenome &, GAPopulation &);
```

The first argument is the genome that will be inserted into the population, the second argument is the population into which the genome should be inserted. The function should return a reference to the genome that will be replaced. If no replacement occurs, the function should return a reference to the original genome.

For details about how to write your own replacement function, see the customizations section.

## GAGenome

The genome is a virtual base class and cannot be instantiated. It defines a number of constants and function prototypes specific to the genome and its derived classes.

The dimension is used to specify which dimension is being referred to in multi-dimensional genomes. The clone method specifies whether to clone the entire genome (a new genome with contents identical to the original will be created) or just the attributes of the genome (a new genome with identical characteristics will be created). In both cases the caller is responsible for deleting the memory allocated by the clone member function. The resize constants are used when specifying a resizable genome's resize behavior.

The genetic operators for genomes are functions that take generic genomes as their arguments. This makes it possible to define new behaviors for existing genome classes without deriving a new class.

### class hierarchy

```
class GAGenome : public GAID
```

### typedefs and constants

```
enum GAGenome::Dimension { LENGTH, WIDTH, HEIGHT, DEPTH }
enum GAGenome::CloneMethod { CONTENTS, ATTRIBUTES }
enum { FIXED_SIZE = -1, ANY_SIZE = -10 }
float (*GAGenome::Evaluator)(GAGenome &)
void (*GAGenome::Initializer)(GAGenome &)
int (*GAGenome::Mutator)(GAGenome &, float)
float (*GAGenome::Comparator)(const GAGenome &, const GAGenome&)
int (*GAGenome::SexualCrossover)(const GAGenome&, const GAGenome&, GAGenome*, GAGenome* );
int (*GAGenome::AsexualCrossover)(const GAGenome&, GAGenome* );
```

### member function index

```
virtual void copy(const GAGenome & c)
virtual GAGenome * clone(CloneMethod flag = CONTENTS)
float score() const
float score(float s)
int nevals()
float evaluate(GABoolean flag = gaFalse) const
GAGenome::Evaluator evaluator() const
GAGenome::Evaluator evaluator(GAGenome::Evaluator func)
void initialize()
GAGenomeInitializer initializer() const
GAGenomeInitializer initializer(GAGenome::Initializer func)
int mutate(float pmutation)
GAGenome::Mutator mutator() const
GAGenome::Mutator mutator(GAGenome::Mutator func)
float compare(const GAGenome& g) const
GAGenome::Comparator comparator() const
GAGenome::Comparator comparator(GAGenome::Comparator c)
GAGenome::SexualCrossover crossover(GAGenome::SexualCrossover f)
GAGenome::SexualCrossover sexual()
GAGenome::AsexualCrossover crossover(GAGenome::AsexualCrossover f)
GAGenome::AsexualCrossover asexual()
GAGeneticAlgorithm * geneticAlgorithm() const
GAGeneticAlgorithm * geneticAlgorithm(GAGeneticAlgorithm &)
void * userData() const
void * userData(void * data)
GAEvalData * evalData() const
GAEvalData * evalData(void * data)
virtual int read(istream & )
virtual int write(ostream & ) const
```

## Programming Interface: GAGenome

```
virtual int equal(const GAGenome &) const  
virtual int notequal(const GAGenome &) const
```

*These operators call the corresponding virtual members so that they will work on any properly derived genome class.*

```
int operator==(const GAGenome&, const GAGenome&)  
int operator!=(const GAGenome&, const GAGenome&)  
ostream & operator<<(ostream&, const GAGenome&)  
istream & operator>>(istream&, GAGenome&)
```

### member function descriptions

#### **clone**

This method allocates space for a new genome whereas the copy method uses the space of the genome to which it belongs.

#### **compare**

Compare two genomes. The comparison can be genotype- or phenotype-based. The comparison returns a value greater than or equal to 0. 0 means the two genomes are identical (no diversity). The exact meaning of the comparison is up to you.

#### **comparator**

Set/Get the comparison method. The comparator must have the correct signature.

#### **copy**

The copy member function is called by the base class' operator= and clone members. You can use it to copy the contents of a genome into an existing genome.

#### **crossover**

Each genome class can define its preferred mating method. Use this method to assign the preferred crossover for a genome instance.

#### **equal** **notequal**

'equal' and 'notequal' are genome-specific. See the documentation for each genome class for specific details about what 'equal' means. For example, genomes that have identical contents but different allele sets may or may not be considered equal. By default, notequal just calls the equal function, but you can override this in derived classes if you need to optimize the comparison.

#### **evalData**

Set/Get the object used to store genome-specific evaluation data. Each genome owns its own evaluation data object; cloning a genome clones the evaluation data as well.

#### **evaluate**

Invoke the genome's evaluation function. If you call this member with gaTrue, the evaluation function is called no matter what (assuming one has been assigned to the genome). By default, the argument to this function is gaFalse, so the genome's evaluation function is called only if the state of the genome has not changed since the last time the evaluator was invoked.

#### **evaluator**

Set/Get the function used to evaluate the genome.

## Programming Interface: GAGenome

### **geneticAlgorithm**

The member function returns a pointer to the genetic algorithm that 'owns' the genome. If this function returns nil then the genome has no genetic algorithm owner.

### **initialize**

Calls the initialization function for the genome.

### **initializer**

Set/Get the initialization method. The initializer must have the correct signature.

### **mutate**

Calls the mutation method for the genome. The value is typically the mutation likelihood, but the exact interpretation of this value is up to the designer of the mutation method.

### **mutator**

Set/Get the mutation method. The mutator must have the correct signature.

### **nevals**

Returns the number of objective function evaluations since the genome was initialized.

### **operator==                  operator!= operator<<                  operator>>**

These methods call the associated virtual member functions. They can be used on any generic genome. If the derived class was properly defined, the appropriate derived functions will be called and the functions will operate on the derived classes rather than the base class.

### **read**

Fill the genome with the data read from the specified stream. sexual

### **asexual**

Returns a pointer to the preferred mating method for this genome. If this function returns nil, no mating method has been defined for the genome. The genetic algorithm object has ultimate control over the mating method that is actually used in the evolution.

### **score**

Returns the objective score of the genome using the objective function assigned to the genome. If no objective function has been assigned and no score has been set, a score of 0 will be returned. If the score function is called with an argument, the genome's objective score is set to that value (useful for population-based objective functions in which the population object does the evaluations).

### **userData**

Each genome contains a generic pointer to user-specifiable data. Use this member function to set/get that pointer. Notice that cloning a genome will cause the cloned genome to refer to the same user data pointer as the original; the user data is not cloned as well. So all genomes in a population refer to the same user data.

### **write**

Send the contents of the genome to the specified stream.

## Programming Interface: GA1DArrayGenome<T>

### GA1DArrayGenome<T>

The 1D array genome is a generic, resizable array of objects. It is a template class derived from the GAGenome class as well as the GAArray<> class.

Each element in the array is a gene. The values of the genes are determined by the type of the genome. For example, an array of ints may have integer values whereas an array of doubles may have floating point values.

see also: GAArray, GAGenome

#### class hierarchy

```
class GA1DArrayGenome<T> : public GAArray<T>, public GAGenome
```

#### constructors

```
GA1DArrayGenome(unsigned int length, GAGenome::Evaluator objective = NULL, void * userData  
                  = NULL)  
GA1DArrayGenome(const GA1DArrayGenome<T> &)
```

#### member function index

```
const T & gene(unsigned int x=0) const  
T & gene(unsigned int x=0)  
T & gene(unsigned int x, const T& value) const  
T & operator[](unsigned int x) const  
T & operator[](unsigned int x)  
int length() const  
int length(int l)  
int resize(int x)  
int resizeBehaviour() const  
int resizeBehaviour(unsigned int minx, unsigned int maxx)  
void copy(const GA1DArrayGenome<T>& original, unsigned int dest, unsigned int src,  
          unsigned int length)  
void swap(unsigned int x1, unsigned int x2)
```

#### member function descriptions

##### copy

Copy the specified bits from the designated genome.

##### gene

Set/Get the specified element.

##### length

Set/Get the length.

##### resize

Set the length.

##### resizeBehaviour

Set/Get the resize behavior. The min value specifies the minimum allowable length, the max value specifies the maximum allowable length. If min and max are equal, the genome is not resizable.

Use the resizeBehaviour and resize member functions to control the size of the genome. The default behavior is fixed size. Using the resizeBehaviour method you can specify minimum and maximum values for the size of the genome. If you specify minimum and maximum as the same values then fixed

## Programming Interface: GA1DArrayGenome<T>

size is assumed. If you use the resize method to specify a size that is outside the bounds set earlier using resizeBehaviour, the bounds will be 'stretched' to accommodate the value you specify with resize. Conversely, if the values you specify with resizeBehaviour conflict with the genome's current size, the genome will be resized to accommodate the new values.

When resizeBehaviour is called with no arguments, it returns the maximum size if the genome is resizable, or GAGenome::FIXED\_SIZE if the size is fixed.

### swap

Swap the specified elements.

### genetic operators for this class

```
GA1DArrayGenome<>::SwapMutator
GA1DArrayGenome<>::ElementComparator
GA1DArrayGenome<>::UniformCrossover
GA1DArrayGenome<>::EvenOddCrossover
GA1DArrayGenome<>::OnePointCrossover
GA1DArrayGenome<>::TwoPointCrossover
GA1DArrayGenome<>::PartialMatchCrossover
GA1DArrayGenome<>::OrderCrossover
GA1DArrayGenome<>::CycleCrossover
```

### default genetic operators for this class

<b>initialization:</b>	GAGenome::NoInitializer
<b>comparison:</b>	GA1DArrayGenome<>::ElementComparator
<b>mutation:</b>	GA1DArrayGenome<>::SwapMutator
<b>crossover:</b>	GA1DArrayGenome<>::OnePointCrossover

## GA1DArrayAlleleGenome<T>

The one-dimensional array allele genome is derived from the one-dimensional array genome class. It shares the same behaviors, but adds the features of allele sets. The value assumed by each element in an array allele genome depends upon the allele set specified for that element. In the simplest case, you can create a single allele set which defines the possible values for any element in the array. More complicated examples can have a different allele set for each element in the array.

If you create the genome with a single allele set, the genome will have a length that you specify and the allele set will be used for the mapping of each element. If you create the genome using an array of allele sets, the genome will have a length equal to the number of allele sets in the array and each element of the array will be mapped using the corresponding allele set.

When you define an allele set for an array genome, the genome makes its own copy. Subsequent clones of this genome will refer to the original genome's allele set (allele sets do reference counting).

see also: GAArray, GA1DArrayGenome, GAAAlleleSet, GAAAlleleSetArray

### class hierarchy

```
class GA1DArrayAlleleGenome<T> : public GAArrayGenome<T>
```

### constructors

```
GA1DArrayAlleleGenome(unsigned int length, const GAAAlleleSet<T>& alleleset,
GAGenome::Evaluator objective = NULL, void * userData = NULL)
GA1DArrayAlleleGenome(const GAAAlleleSetArray<T>& allelesets, GAGenome::Evaluator objective
= NULL, void * userData = NULL)
GA1DArrayAlleleGenome(const GA1DArrayAlleleGenome<T>&)
```

### member function index

```
const GAAAlleleSet<T>& alleleset(unsigned int i = 0) const
```

### member function descriptions

#### alleleset

Returns a reference to the allele set for the specified gene. If the genome was created using a single allele set, the allele set will be the same for every gene. If the genome was created using an allele set array, each gene may have a different allele set.

### genetic operators for this class

```
GA1DArrayAlleleGenome<>::UniformInitializer
GA1DArrayAlleleGenome<>::OrderedInitializer
GA1DArrayAlleleGenome<>::FlipMutator
```

### default genetic operators for this class

<b>initialization:</b>	GA1DArrayAlleleGenome<>::UniformInitializer
<b>comparison:</b>	GA1DArrayGenome<>::ElementComparator
<b>mutation:</b>	GA1DArrayAlleleGenome<>::FlipMutator
<b>crossover:</b>	GA1DArrayGenome<>::OnePointCrossover

## Programming Interface: GA2DArrayGenome<T>

### GA2DArrayGenome<T>

The two-dimensional array genome is a generic, resizable array of objects. It is a template class derived from the GAGenome class as well as the GAArray<> class.

Each element in the array is a gene. The values of the genes are determined by the type of the genome. For example, an array of ints may have integer values whereas an array of doubles may have floating point values.

see also: GAArray, GAGenome

#### class hierarchy

```
class GA2DArrayGenome<T> : public GAArray<T>, public GAGenome
```

#### constructors

```
GA2DArrayGenome(unsigned int width, unsigned int height, GAGenome::Evaluator objective =
    NULL, void * userData = NULL)
GA2DArrayGenome(const GA2DArrayGenome<T> &)
```

#### member function index

```
const T & gene(unsigned int x, unsigned int y) const
T & gene(unsigned int x, unsigned int y)
T & gene(unsigned int x, unsigned int y, const T& value)
int width() const
int width(int w)
int height() const
int height(int h)
int resize(int x, int y)
int resizeBehaviour(GADimension which) const
int resizeBehaviour(GADimension which, unsigned int min, unsigned int max)
int resizeBehaviour(unsigned int minx, unsigned int maxx, unsigned int miny, unsigned int
    maxy)
void copy(const GA2DArrayGenome<T>& original, unsigned int xdest, unsigned int ydest,
    unsigned int xsrc, unsigned int ysrc, unsigned int width, unsigned int height)
void swap(unsigned int x1, unsigned int y1, unsigned int x2, unsigned int y2)
```

#### member function descriptions

##### copy

Copy the specified bits from the designated genome.

##### gene

Set/Get the specified element.

##### height

Set/Get the height.

##### resize

Change the size to the specified dimensions.

##### resizeBehaviour

Set/Get the resize behavior. The min value specifies the minimum allowable length, the max value specifies the maximum allowable length. If min and max are equal, the genome is not resizable.

## Programming Interface: GA2DArrayGenome<T>

Use the `resizeBehaviour` and `resize` member functions to control the size of the genome. The default behavior is fixed size. Using the `resizeBehaviour` method you can specify minimum and maximum values for the size of the genome. If you specify minimum and maximum as the same values then fixed size is assumed. If you use the `resize` method to specify a size that is outside the bounds set earlier using `resizeBehaviour`, the bounds will be 'stretched' to accommodate the value you specify with `resize`. Conversely, if the values you specify with `resizeBehaviour` conflict with the genome's current size, the genome will be resized to accommodate the new values.

When `resizeBehaviour` is called with no arguments, it returns the maximum size if the genome is resizable, or `GAGenome::FIXED_SIZE` if the size is fixed.

The `resizeBehaviour` function works similarly to that of the 1D array genome. In this case, however, you must also specify for which dimension you are setting the resize behavior. When `resizeBehaviour` is called with no arguments, it returns the maximum size if the genome is resizable, or `gaNoResize` if the size is fixed.

**swap**

Swap the specified elements.

**width**

Set/Get the width.

### genetic operators for this class

```
GA2DArrayGenome<>::SwapMutator
GA2DArrayGenome<>::ElementComparator
GA2DArrayGenome<>::UniformCrossover
GA2DArrayGenome<>::EvenOddCrossover
GA2DArrayGenome<>::OnePointCrossover
```

### default genetic operators for this class

<b>initialization:</b>	<code>GAGenome::NoInitializer</code>
<b>comparison:</b>	<code>GA2DArrayGenome&lt;&gt;::ElementComparator</code>
<b>mutation:</b>	<code>GA2DArrayGenome&lt;&gt;::SwapMutator</code>
<b>crossover:</b>	<code>GA2DArrayGenome&lt;&gt;::OnePointCrossover</code>

## GA2DArrayAlleleGenome<T>

The two-dimensional array allele genome is derived from the two-dimensional array genome class. It shares the same behaviors, but adds the features of allele sets. The value assumed by each element in an array allele genome depends upon the allele set specified for that element. In the simplest case, you can create a single allele set which defines the possible values for any element in the array. More complicated examples can have a different allele set for each element in the array.

The genome will have width and height that you specify and the allele set will be used for the mapping of each element. When you define an allele set for an array genome, the genome makes its own copy. Subsequent clones of this genome will refer to the original genome's allele set (allele sets do reference counting).

If you create a genome using an allele set array, the array of alleles will be mapped to the two dimensions in the order width-then-height.

see also: GAArray, GA2DArrayGenome, GAAAlleleSet, GAAAlleleSetArray

### class hierarchy

```
class GA1DArrayAlleleGenome<T> : public GAArrayGenome<T>
```

### constructors

```
GA2DArrayAlleleGenome(unsigned int width, unsigned int height, GAAAlleleSet<T>& alleles,
                      GAGenome::Evaluator objective = NULL, void * userData = NULL)
GA2DArrayAlleleGenome(unsigned int width, unsigned int height, GAAAlleleSetArray<T>&
                      allelesets, GAGenome::Evaluator objective = NULL, void * userData = NULL)
GA2DArrayAlleleGenome(const GA2DArrayAlleleGenome<T> &)
```

### member function index

```
const GAAAlleleSet<T>& alleleset(unsigned int i = 0, unsigned int j = 0) const
```

### member function descriptions

#### alleleset

Returns a reference to the allele set for the specified gene. If the genome was created using a single allele set, the allele set will be the same for every gene. If the genome was created using an allele set array, each gene may have a different allele set.

### genetic operators for this class

```
GA2DArrayAlleleGenome<>::UniformInitializer
GA2DArrayAlleleGenome<>::FlipMutator
```

### default genetic operators for this class

<b>initialization:</b>	GA2DArrayAlleleGenome<>::UniformInitializer
<b>comparison:</b>	GA2DArrayGenome<>::ElementComparator
<b>mutation:</b>	GA2DArrayAlleleGenome<>::FlipMutator
<b>crossover:</b>	GA2DArrayGenome<>::OnePointCrossover

## Programming Interface: GA3DArrayGenome<T>

### GA3DArrayGenome<T>

The three-dimensional array genome is a generic, resizable array of objects. It is a template class derived from the GAGenome class as well as the GAArraY<> class.

Each element in the array is a gene. The values of the genes are determined by the type of the genome. For example, an array of ints may have integer values whereas an array of doubles may have floating point values.

see also: GAArraY, GAGenome

#### class hierarchy

```
class GA3DArrayGenome<T> : public GAArraY<T>, public GAGenome
```

#### constructors

```
GA3DArrayGenome(unsigned int width, unsigned int height, unsigned int depth,
                 GAGenome::Evaluator objective = NULL, void * userData = NULL)
GA3DArrayGenome(const GA3DArrayGenome<T>&)
```

#### member function index

```
const T & gene(unsigned int x, unsigned int y, unsigned int z) const
T & gene(unsigned int x, unsigned int y, unsigned int z)
T & gene(unsigned int x, unsigned int y, unsigned int z, const T& value)
int width() const
int width(int w)
int height() const
int height(int h)
int depth() const
int depth(int d)
int resize(int x, int y, int z)
int resizeBehaviour(GADimension which) const
int resizeBehaviour(GADimension which, unsigned int min, unsigned int max)
int resizeBehaviour(unsigned int minx, unsigned int maxx, unsigned int miny, unsigned int
                   maxy, unsigned int minz, unsigned int maxz)
void copy(const GA3DArrayGenome<T>& original, unsigned int xdest, unsigned int ydest,
          unsigned int zdest, unsigned int xsrc, unsigned int ysrc, unsigned int zsrc,
          unsigned int width, unsigned int height, unsigned int depth)
void swap(unsigned int x1, unsigned int y1, unsigned int z1, unsigned int x2, unsigned int
          y2, unsigned int z2)
```

#### member function descriptions

##### copy

Copy the specified bits from the designated genome.

##### depth

Set/Get the depth.

##### gene

Set/Get the specified element.

##### height

Set/Get the height.

##### resize

Change the size to the specified dimensions.

## Programming Interface: GA3DArrayGenome<T>

### **resizeBehaviour**

Set/Get the resize behavior. The min value specifies the minimum allowable length, the max value specifies the maximum allowable length. If min and max are equal, the genome is not resizable.

Use the resizeBehaviour and resize member functions to control the size of the genome. The default behavior is fixed size. Using the resizeBehaviour method you can specify minimum and maximum values for the size of the genome. If you specify minimum and maximum as the same values then fixed size is assumed. If you use the resize method to specify a size that is outside the bounds set earlier using resizeBehaviour, the bounds will be 'stretched' to accommodate the value you specify with resize. Conversely, if the values you specify with resizeBehaviour conflict with the genome's current size, the genome will be resized to accommodate the new values.

When resizeBehaviour is called with no arguments, it returns the maximum size if the genome is resizable, or GAGenome::FIXED\_SIZE if the size is fixed.

The resizeBehaviour function works similarly to that of the 1D array genome. In this case, however, you must also specify for which dimension you are setting the resize behavior. When resizeBehaviour is called with no arguments, it returns the maximum size if the genome is resizable, or gaNoResize if the size is fixed.

### **swap**

Swap the specified elements.

### **width**

Set/Get the width.

### **genetic operators for this class**

```
GA3DArrayGenome<>::SwapMutator
GA3DArrayGenome<>::ElementComparator
GA3DArrayGenome<>::UniformCrossover
GA3DArrayGenome<>::EvenOddCrossover
GA3DArrayGenome<>::OnePointCrossover
```

### **default genetic operators**

<b>initialization:</b>	GAGenome::NoInitializer
<b>comparison:</b>	GA3DArrayGenome<>::ElementComparator
<b>mutation:</b>	GA3DArrayGenome<>::SwapMutator
<b>crossover:</b>	GA3DArrayGenome<>::OnePointCrossover

## GA3DArrayAlleleGenome<T>

The three-dimensional array allele genome is derived from the three-dimensional array genome class. It shares the same behaviors, but adds the features of allele sets. The value assumed by each element in an array allele genome depends upon the allele set specified for that element. In the simplest case, you can create a single allele set which defines the possible values for any element in the array. More complicated examples can have a different allele set for each element in the array.

The genome will have width, height, and depth that you specify and the allele set will be used for the mapping of each element. When you define an allele set for an array genome, the genome makes its own copy. Subsequent clones of this genome will refer to the original genome's allele set (allele sets do reference counting).

If you create a genome using an allele set array, the array of alleles will be mapped to the three dimensions in the order width-then-height-then-depth.

see also: GAArray, GA3DArrayGenome, GAAleleSet, GAAleleSetArray

### class hierarchy

```
class GA1DArrayAlleleGenome<T> : public GAArrayGenome<T>
```

### constructors

```
GA3DArrayAlleleGenome(unsigned int width, unsigned int height, unsigned int depth,
                      GAAleleSet<T>& alleles, GAGenome::Evaluator objective = NULL, void * userData =
                      NULL)
GA3DArrayAlleleGenome(unsigned int width, unsigned int height, unsigned int depth,
                      GAAleleSet<T>& alleles, GAGenome::Evaluator objective = NULL, void * userData =
                      NULL)
GA3DArrayAlleleGenome(const GA3DArrayAlleleGenome<T> &)
```

### member function index

```
const GAAleleSet<T>& alleleSet(unsigned int i = 0, unsigned int j = 0, unsigned int k =
0) const
```

### member function descriptions

#### alleleSet

Returns a reference to the allele set for the specified gene. If the genome was created using a single allele set, the allele set will be the same for every gene. If the genome was created using an allele set array, each gene may have a different allele set.

### genetic operators for this class

```
GA3DArrayAlleleGenome<>::UniformInitializer
GA3DArrayAlleleGenome<>::FlipMutator
```

### default genetic operators for this class

initialization:	GA3DArrayAlleleGenome<>::UniformInitializer
comparison:	GA3DArrayGenome<>::ElementComparator
mutation:	GA3DArrayAlleleGenome<>::FlipMutator
crossover:	GA3DArrayGenome<>::OnePointCrossover

## GA1DBinaryStringGenome

The binary string genome is derived from the GABinaryString and GAGenome classes. It is a string of 1s and 0s whose length may be fixed or variable. The genes in this genomes are bits. The alleles for each bit are 0 and 1.

see also: *GABinaryString*

see also: *GAGenome*

### class hierarchy

```
class GA1DBinaryStringGenome : public GABinaryString, public GAGenome
```

### constructors

```
GA1DBinaryStringGenome(unsigned int x, GAGenome::Evaluator objective = NULL, void *  
                      userData = NULL)  
GA1DBinaryStringGenome(const GA1DBinaryStringGenome&)
```

### member function index

```
short gene(unsigned int x = 0) const  
short gene(unsigned int, short value)  
int length() const  
int length(int l)  
int resize(int x)  
int resizeBehaviour() const  
int resizeBehaviour(unsigned int minx, unsigned int maxx)  
void copy(const GA1DBinaryStringGenome &, unsigned int xdest, unsigned int xsrc, unsigned  
          int length)  
void set(unsigned int x, unsigned int length)  
void unset(unsigned int x, unsigned int length)
```

### member function descriptions

#### copy

Copy the specified bits from the designated genome.

#### gene

Set/Get the specified bit.

#### length

Set/Get the length of the bit string.

#### resize

Set the length of the bit string.

#### resizeBehaviour

Set/Get the resize behavior. The min value specifies the minimum allowable length, the max value specifies the maximum allowable length. If min and max are equal, the genome is not resizable.

Use the resizeBehaviour and resize member functions to control the size of the genome. The default behavior is fixed size. Using the resizeBehaviour method you can specify minimum and maximum values for the size of the genome. If you specify minimum and maximum as the same values then fixed size is assumed. If you use the resize method to specify a size that is outside the bounds set earlier using resizeBehaviour, the bounds will be 'stretched' to accommodate the value you specify with resize.

## Programming Interface: GA1DBinaryStringGenome

Conversely, if the values you specify with `resizeBehaviour` conflict with the genome's current size, the genome will be resized to accommodate the new values.

When `resizeBehaviour` is called with no arguments, it returns the maximum size if the genome is resizable, or `GAGenome::FIXED_SIZE` if the size is fixed.

```
set
unset
```

Set/Unset the bits in the specified range. If you specify a range that is not represented by the genome, the range that you specified will be clipped to fit the genome.

### genetic operators for this class

```
GA1DBinaryStringGenome::UniformInitializer
GA1DBinaryStringGenome::SetInitializer
GA1DBinaryStringGenome::UnsetInitializer
GA1DBinaryStringGenome::FlipMutator
GA1DBinaryStringGenome::BitComparator
GA1DBinaryStringGenome::UniformCrossover
GA1DBinaryStringGenome::EvenOddCrossover
GA1DBinaryStringGenome::OnePointCrossover
GA1DBinaryStringGenome::TwoPointCrossover
```

### default genetic operators for this class

<b>initialization:</b>	<code>GA1DBinaryStringGenome::UniformInitializer</code>
<b>comparison:</b>	<code>GA1DBinaryStringGenome::BitComparator</code>
<b>mutation:</b>	<code>GA1DBinaryStringGenome::FlipMutator</code>
<b>crossover:</b>	<code>GA1DBinaryStringGenome::OnePointCrossover</code>

## GA2DBinaryStringGenome

The binary string genome is derived from the GABinaryString and GAGenome classes. It is a matrix of 1s and 0s whose width and height may be fixed or variable. The genes in this genomes are bits. The alleles for each bit are 0 and 1.

see also: *GABinaryString*

see also: *GAGenome*

### class hierarchy

```
class GA2DBinaryStringGenome : public GABinaryString, public GAGenome
```

### constructors

```
GA2DBinaryStringGenome(unsigned int x, unsigned int y, GAGenome::Evaluator objective =
    NULL, void * userData = NULL)
GA2DBinaryStringGenome(const GA2DBinaryStringGenome &)
```

### member function index

```
short gene(unsigned int x, unsigned int y) const
short gene(unsigned int x, unsigned int y, const short value)
int width() const
int width(int w)
int height() const
int height(int h)
int resize(int x, int y)
int resizeBehaviour(GADimension which) const
int resizeBehaviour(GADimension which, unsigned int min, unsigned int max)
int resizeBehaviour(unsigned int minx, unsigned int maxx, unsigned int miny, unsigned int
    maxy)
void copy(const GA2DBinaryStringGenome &, unsigned int xdest, unsigned int ydest, unsigned
    int xsrc, unsigned int ysrc, unsigned int width, unsigned int height)
void set(unsigned int, unsigned int, unsigned int, unsigned int)
void unset(unsigned int, unsigned int, unsigned int, unsigned int)
```

### member function descriptions

#### copy

Copy the specified bits from the designated genome. If you specify a range that is not represented by the genome, the range that you specified will be clipped to fit the genome.

#### gene

Set/Get the specified bit.

#### height

Set/Get the height of the bit string.

#### resize

Set the size of the genome to the specified dimensions.

#### resizeBehaviour

Set/Get the resize behavior. The min value specifies the minimum allowable length, the max value specifies the maximum allowable length. If min and max are equal, the genome is not resizable.

Use the resizeBehaviour and resize member functions to control the size of the genome. The default behavior is fixed size. Using the resizeBehaviour method you can specify minimum and maximum

## Programming Interface: GA2DBinaryStringGenome

values for the size of the genome. If you specify minimum and maximum as the same values then fixed size is assumed. If you use the resize method to specify a size that is outside the bounds set earlier using resizeBehaviour, the bounds will be 'stretched' to accommodate the value you specify with resize. Conversely, if the values you specify with resizeBehaviour conflict with the genome's current size, the genome will be resized to accommodate the new values.

When resizeBehaviour is called with no arguments, it returns the maximum size if the genome is resizable, or GAGenome::FIXED\_SIZE if the size is fixed.

**set**  
**unset**

Set/Unset the bits in the specified range. If you specify a range that is not represented by the genome, the range that you specified will be clipped to fit the genome.

**width**

Set/Get the width of the bit string.

### genetic operators for this class

```
GA2DBinaryStringGenome::UniformInitializer  
GA2DBinaryStringGenome::SetInitializer  
GA2DBinaryStringGenome::UnsetInitializer  
GA2DBinaryStringGenome::FlipMutator  
GA2DBinaryStringGenome::BitComparator  
GA2DBinaryStringGenome::UniformCrossover  
GA2DBinaryStringGenome::EvenOddCrossover  
GA2DBinaryStringGenome::OnePointCrossover
```

### default genetic operators for this class

<b>initialization:</b>	GA2DBinaryStringGenome::UniformInitializer
<b>comparison:</b>	GA2DBinaryStringGenome::BitComparator
<b>mutation:</b>	GA2DBinaryStringGenome::FlipMutator
<b>crossover:</b>	GA2DBinaryStringGenome::OnePointCrossover

## GA3DBinaryStringGenome

The binary string genome is derived from the GABinaryString and GAGenome classes. It is a three-dimensional block of 1s and 0s whose width, height, and depth can be fixed or variable. The genes in this genomes are bits. The alleles for each bit are 0 and 1.

see also: *GABinaryString*

see also: *GAGenome*

### class hierarchy

```
class GA3DBinaryStringGenome : public GABinaryString, public GAGenome
```

### constructors

```
GA3DBinaryStringGenome(unsigned int x, unsigned int y, unsigned int z, GAGenome::Evaluator  
                      objective = NULL, void * userData = NULL)  
GA3DBinaryStringGenome(const GA3DBinaryStringGenome&)
```

### member function index

```
short gene(unsigned int x, unsigned int y, unsigned int z) const  
short gene(unsigned int x, unsigned int y, unsigned int z, short value)  
int width() const  
int width(int w)  
int height() const  
int height(int h)  
int depth() const  
int depth(int d)  
int resize(int x, int y, int z)  
int resizeBehaviour(GADimension which) const  
int resizeBehaviour(GADimension which, unsigned int min, unsigned int max)  
int resizeBehaviour(unsigned int minx, unsigned int maxx, unsigned int miny, unsigned int  
                   maxy, unsigned int minz, unsigned int maxz)  
void copy(const GA3DBinaryStringGenome &, unsigned int xdest, unsigned int ydest, unsigned  
          int zdest, unsigned int xsrc, unsigned int ysrc, unsigned int zsrc, unsigned int  
          width, unsigned int height, unsigned int depth);  
void set(unsigned int, unsigned int, unsigned int, unsigned int, unsigned int, unsigned  
        int);  
void unset(unsigned int, unsigned int, unsigned int, unsigned int, unsigned int, unsigned  
          int);
```

### member function descriptions

#### copy

Copy the specified bits from the designated genome. If you specify a range that is not represented by the genome, the range that you specified will be clipped to fit the genome.

#### depth

Set/Get the depth of the bit string.

#### gene

Set/Get the specified bit.

#### height

Set/Get the height of the bit string.

#### resize

Set the size of the genome to the specified dimensions.

## Programming Interface: GA3DBinaryStringGenome

### **resizeBehaviour**

Set/Get the resize behavior. The min value specifies the minimum allowable length, the max value specifies the maximum allowable length. If min and max are equal, the genome is not resizable.

Use the resizeBehaviour and resize member functions to control the size of the genome. The default behavior is fixed size. Using the resizeBehaviour method you can specify minimum and maximum values for the size of the genome. If you specify minimum and maximum as the same values then fixed size is assumed. If you use the resize method to specify a size that is outside the bounds set earlier using resizeBehaviour, the bounds will be 'stretched' to accommodate the value you specify with resize. Conversely, if the values you specify with resizeBehaviour conflict with the genome's current size, the genome will be resized to accommodate the new values.

When resizeBehaviour is called with no arguments, it returns the maximum size if the genome is resizable, or GAGenome::FIXED\_SIZE if the size is fixed.

### **set unset**

Set/Unset the bits in the specified range. If you specify a range that is not represented by the genome, the range that you specified will be clipped to fit the genome.

### **width**

Set/Get the width of the bit string.

### **genetic operators for this class**

```
GA3DBinaryStringGenome::UniformInitializer
GA3DBinaryStringGenome::SetInitializer
GA3DBinaryStringGenome::UnsetInitializer
GA3DBinaryStringGenome::FlipMutator
GA3DBinaryStringGenome::BitComparator
GA3DBinaryStringGenome::UniformCrossover
GA3DBinaryStringGenome::EvenOddCrossover
GA3DBinaryStringGenome::OnePointCrossover
```

### **default genetic operators for this class**

<b>initialization:</b>	GA3DBinaryStringGenome::UniformInitializer
<b>comparison:</b>	GA3DBinaryStringGenome::BitComparator
<b>mutation:</b>	GA3DBinaryStringGenome::FlipMutator
<b>crossover:</b>	GA3DBinaryStringGenome::OnePointCrossover

## GABin2DecGenome

This genome is an implementation of the traditional method for converting binary strings to decimal values. It contains a mechanism for customized encoding of the bit string; binary-to-decimal and one form of Gray coding are built in to the library. The default is binary-to-decimal mapping (counting in base 2). To use this genome, you must create a mapping of bits to decimal values by specifying how many bits will be used to represent what bounded numbers. The binary-to-decimal genome is derived from the 1DBinaryStringGenome class.

You must create a phenotype before you can instantiate this genome. The phenotype defines how bits should map into decimal values and vice versa. A single binary-to-decimal phenotype contains the number of bits used to represent the decimal value and the minimum and maximum decimal values to which the set of bits will map.

*see also:* GA1DBinaryStringGenome

*see also:* GABin2DecPhenotype

*see also:* GACrossover

### class hierarchy

```
class GABin2DecGenome : public GA1DBinaryStringGenome
```

### constructors

```
GABin2DecGenome(const GABin2DecPhenotype &, GAGenome::Evaluator objective = NULL, void *  
                  userData = NULL)  
GABin2DecGenome(const GABin2DecGenome&)
```

### member function index

```
const GABin2DecPhenotype& phenotypes(const GABin2DecPhenotype &)  
const GABin2DecPhenotype& phenotypes() const  
int nPhenotypes() const  
float phenotype(unsigned int n) const  
float phenotype(unsigned int n, float value)  
void encoder(GABinaryEncoder)  
void decoder(GABinaryDecoder)
```

### member function descriptions

**encoder**  
**decoder**

Use these member functions to set the encoder/decoder for the genome. These functions determine what method will be used for converting the binary bits to decimal numbers. The functions that you specify here must have the proper signature.

**nPhenotype**

Returns the number of phenotypes (i.e. the number of decimal values represented) in the genome.

**phenotypes**

Set/Get the mapping from binary to decimal numbers.

**phenotype**

Set/Get the specified phenotype.

## Programming Interface: GABin2DecGenome

### default genetic operators for this class

<b>initialization:</b>	GALDBinaryStringGenome::UniformInitializer
<b>comparison:</b>	GALDBinaryStringGenome::BitComparator
<b>mutation:</b>	GALDBinaryStringGenome::FlipMutator
<b>crossover:</b>	GALDBinaryStringGenome::OnePointCrossover
<b>de/encoding:</b>	GABinaryEncode/GABinaryDecode

### additional information

Conversion functions are defined for transforming strings of bits to decimal values and vice versa. The function prototypes for the encoding (decimal-to-binary) and decoding (binary-to-decimal) are defined as follows:

```
typedef int (*GABinaryEncoder)(float& value, GABit* bits, unsigned int nbits, float min,  
                               float max);  
typedef int (*GABinaryDecoder)(float& value, const GABit* bits, unsigned int nbits, float  
                               min, float max);
```

The library includes the following binary-to-decimal/decimal-to-binary converters:

**GABinaryEncode/GABinaryDecode**

Convert using a binary coding scheme.

**GAGrayEncode/GAGrayDecode**

Convert using a Gray coding scheme.

## GAListGenome<T>

The list genome is a template class. It is derived from the GAGenome class as well as the GAList<> class. It can be used for order-based representations or variable length sequences as well as traditional applications of lists.

You must define an initialization operator for this class. The default initializer is NoInitializer - if you do not assign an initialization operator then you'll get errors about no initializer defined when you try to initialize the genome.

*see also:* GAList

*see also:* GAGenome

### class hierarchy

```
class GAListGenome<T> : public GAList<T>, public GAGenome
```

### constructors

```
GAListGenome(GAGenome::Evaluator objective = NULL, void * userData = NULL)  
GAListGenome(const GAListGenome<T> &)
```

### genetic operators for this class

```
GAListGenome<>::DestructiveMutator  
GAListGenome<>::SwapMutator  
GAListGenome<>::OnePointCrossover  
GAListGenome<>::PartialMatchCrossover  
GAListGenome<>::OrderCrossover  
GAListGenome<>::CycleCrossover
```

### default genetic operators for this class

<b>initialization:</b>	GAGenome::NoInitializer
<b>comparison:</b>	GAGenome::NoComparator
<b>mutation:</b>	GAListGenome<>::SwapMutator
<b>crossover:</b>	GAListGenome<>::OnePointCrossover

## GARealGenome

The real number genome was designed to be used for applications whose representation requires an array of (possibly bounded) real number parameters. The elements of the array can assume bounded values, discretized bounded values, or enumerated values, depending on the type of allele set that is used to create the genome. You can mix the bounding within the genome by specifying an appropriate array of allele sets. The allele set defines the possible values that each element in the genome may assume.

The real number genome is a specialization of the array genome with alleles. The specialization is of type float. You must create an allele set or array of allele sets before you can instantiate this genome. If you create a real number genome using a single allele set, each element in the genome will use that allele set to determine its value. If you create a real number genome using an allele set array, the genome will have a length equal to the number of elements in the array and each element of the real number will be governed by the allele set corresponding to its location in the genome.

To use the real genome in your code, you must include the real genome header file in each of your files that uses the real genome. You must also include the real genome source file (it contains template specialization code) in one (and only one) of your source files. Including the real genome source file will force the compiler to use the real specializations. If you do not include the real genome source file you will get the generic array routines instead (and some of the allele methods will not work as expected).

see also: *GA1DArrayAlleleGenome*, *GAAlleleSet*, *GAAlleleSetArray*

### class hierarchy

typedef GAAlleleSet<float>	GARealAlleleSet
typedef GAAlleleSetCore<float>	GARealAlleleSetCore
typedef GAAlleleSetArray<float>	GARealAlleleSetArray
typedef GA1DArrayAlleleGenome<float>	GARealGenome

### constructors

```
GARealGenome(unsigned int length, const GARealAlleleSet &, GAGenome::Evaluator objective =  
             NULL, void * userData = NULL)  
GARealGenome(const GARealAlleleSetArray &, GAGenome::Evaluator objective = NULL, void *  
             userData = NULL)  
GARealGenome(const GARealGenome&)
```

### genetic operators for this class

```
GARealGenome::UniformInitializer  
GARealGenome::OrderedInitializer  
GARealGenome::FlipMutator  
GARealGenome::SwapMutator  
GARealGaussianMutator  
GARealGenome::UniformCrossover  
GARealGenome::EvenOddCrossover  
GARealGenome::OnePointCrossover  
GARealGenome::TwoPointCrossover  
GARealGenome::PartialMatchCrossover  
GARealGenome::OrderCrossover  
GARealGenome::CycleCrossover
```

### default genetic operators for this class

<b>initialization:</b>	GARealGenome::UniformInitializer
<b>comparison:</b>	GARealGenome::ElementComparator
<b>mutation:</b>	GARealGaussianMutator
<b>crossover:</b>	GARealGenome::UniformCrossover

## GAStringGenome

The string genome can be used for order-based applications, variable length string applications, or non-binary allele set alphabets. The allele set defines the possible values that each element in the string may assume.

The string genome is a specialization of the array genome with alleles. The specialization is of type char. You must create an allele set or array of allele sets before you can instantiate this genome.

If you create a string genome using a single allele set, each element in the genome will use that allele set to determine its value. If you create a string genome using an allele set array, the string will have a length equal to the number of elements in the array and each element of the string will be governed by the allele set corresponding to its location in the string.

To use the string genome in your code, you must include the string genome header file in each of your files that uses the string genome. You must also include the string genome source file (it contains template specialization code) in one (and only one) of your source files. Including the string genome source file will force the compiler to use the string specializations. If you do not include the string genome source file you will get the generic array routines instead (and some of the allele methods will not work as expected).

see also: *GA1DArrayAlleleGenome*, *GAAlleleSet*, *GAAlleleSetArray*

### class hierarchy

```
typedef GAAlleleSet<char>           GAStringAlleleSet
typedef GAAlleleSetCore<char>         GAStringAlleleSetCore
typedef GAAlleleSetArray<char>        GAStringAlleleSetArray
typedef GA1DArrayAlleleGenome<char>   GAStringGenome
```

### constructors

```
GAStringGenome(unsigned int length, const GAStringAlleleSet &, GAGenome::Evaluator
               objective = NULL, void * userData = NULL)
GAStringGenome(const GAStringAlleleSetArray &, GAGenome::Evaluator objective = NULL, void
               * userData = NULL)
GAStringGenome(const GAStringGenome&)
```

### genetic operators for this class

```
GAStringGenome::UniformInitializer
GAStringGenome::OrderedInitializer
GAStringGenome::FlipMutator
GAStringGenome::SwapMutator
GAStringGenome::UniformCrossover
GAStringGenome::EvenOddCrossover
GAStringGenome::OnePointCrossover
GAStringGenome::TwoPointCrossover
GAStringGenome::PartialMatchCrossover
GAStringGenome::OrderCrossover
GAStringGenome::CycleCrossover
```

### default genetic operators for this class

<b>initialization:</b>	GAStringGenome::UniformInitializer
<b>comparison:</b>	GAStringGenome::ElementComparator
<b>mutation:</b>	GAStringGenome::FlipMutator
<b>crossover:</b>	GAStringGenome::UniformCrossover

## Programming Interface: GATreeGenome<T>

### GATreeGenome<T>

The tree genome is a template class. It is derived from the GAGenome class as well as the GATree<> class. The tree genome can be used for direct manipulation of tree objects. It can be used to represent binary trees as well as non-binary trees.

You must define an initialization operator for this class. The default initializer is NoInitializer - if you do not assign an initialization operator then you'll get errors about no initializer defined when you try to initialize the genome.

*see also:* GATree

*see also:* GAGenome

#### class hierarchy

```
class GATreeGenome<T> : public GATree<T>, public GAGenome
```

#### constructors

```
GATreeGenome(GAGenome::Evaluator objective = NULL, void * userData = NULL)  
GATreeGenome(const GATreeGenome<T> &)
```

#### genetic operators for this class

```
GATreeGenome<>::DestructiveMutator  
GATreeGenome<>::SwapSubtreeMutator  
GATreeGenome<>::SwapNodeMutator  
GATreeGenome<>::OnePointCrossover
```

#### default genetic operators for this class

<b>initialization:</b>	GAGenome::NoInitializer
<b>comparison:</b>	GAGenome::NoComparator
<b>mutation:</b>	GATreeGenome<>::SwapSubtreeMutator
<b>crossover:</b>	GATreeGenome<>::OnePointCrossover

## GAEvalData

The evaluation data object is a generic base class for genome- and/or population-specific data. Whereas the userData member of the genome is shared by all genomes in a population, the evalData member is unique to each genome. The base class defines the copy/clone interface for the evaluation data object. Your derived classes should use this mechanism. Any derived class must define a clone and copy member function. These will be called by the base class when the evaluation data is cloned/copied by the genomes/populations.

### class hierarchy

```
class GAEvalData : public GAID
```

### constructors

```
GAEvalData()
GAEvalData(const GAEvalData&)
```

### member functions

```
GAEvalData* clone() const
void copy(const GAEvalData&)
```

## GABin2DecPhenotype

The binary-to-decimal phenotype defines the mapping from binary string to decimal values. A mapping for a single binary-to-decimal conversion consists of a range of decimal values and a number of bits. For example, a map of 8 bits and range of [0,255] would use 8 bits to represent the numbers from 0 to 255, inclusive. This object does reference counting in order to minimize the memory overhead imposed by instantiating binary-to-decimal mappings.

### constructors

```
GABin2DecPhenotype()
GABin2DecPhenotype(const GABin2DecPhenotype&)
```

### member function index

```
void add(unsigned int nbits, float min, float max)
void remove(unsigned int which)
int size() const
int nPhenotypes() const
float min(unsigned int which) const
float max(unsigned int which) const
int length(unsigned int which) const
int offset(unsigned int which) const
void link(GABin2DecPhenotype&)
void unlink()
```

### member function descriptions

#### add

Create a mapping that tells the phenotype that nbits should be used to represent a floating point number from min to max, inclusive.

#### link unlink

The phenotype object does reference counting to reduce the number of instantiated objects. Use the link member to make a phenotype object refer to another. Use the unlink member to remove the connection. When you unlink, the phenotype makes its own copy of the mapping information.

#### length

Returns the number of bits required for the specified mapping.

#### max min

Returns the maximum/minimum decimal value for the specified mapping.

#### offset

Returns the offset (in bits) for the specified mapping.

#### remove

Removes a single binary-to-decimal from the phenotype.

#### size

Returns the number of bits that the set of mappings requires for converting a decimal value to binary and back again.

## Programming Interface: GAAlleleSet<T>

### GAAlleleSet<T>

The allele set class is a container for the different values that a gene may assume. It can contain objects of any type as long as the object has the =, ==, and != operators defined.

Allele sets may be enumerated, bounded, or bounded with discretization. For example, an integer allele set may be defined as {1,3,5,2,99,-53} (an enumerated set). A bounded float set may be defined such as [2,743] (the set of numbers from 2, inclusive, to 743, exclusive). A bounded, discretized set may be defined such as [4.5,7.05](0.05) (the set of numbers from 4.5 to 7.5, inclusive, with increment of 0.05).

If you call the allele member function with no argument, the allele set picks randomly from the alleles it contains and returns one of them.

#### constructors

```
GAAlleleSet()
GAAlleleSet(unsigned int n, const T a[])
GAAlleleSet(const T& lower, const T& upper, GAAllele::BoundType
            lowerbound=GAAllele::INCLUSIVE, GAAllele::BoundType upperbound=GAAllele::INCLUSIVE)
GAAlleleSet(const T& lower, const T& upper, const T& increment, GAAllele::BoundType
            lowerbound=GAAllele::INCLUSIVE, GAAllele::BoundType upperbound=GAAllele::INCLUSIVE)
GAAlleleSet(const GAAlleleSet<T>& set)
```

#### member function index

```
GAAlleleSet<T> * clone() const
T add(const T& allele)
T remove(T& allele)
T allele() const
T allele(unsigned int i)
int size() const
T lower() const
T upper() const
T inc() const
GAAllele::BoundType lowerBoundType() const
GAAllele::BoundType upperBoundType() const
GAAllele::Type type() const
void link(GAAlleleSet<T>&) void unlink()
```

#### member function descriptions

**add**  
**remove**

Add/Remove the indicated allele from the set. This method works only for enumerated allele sets. Both functions return zero if the operation was successful, non-zero status otherwise.

**lower**  
**upper**

Returns the lower/upper bounds on the allele set. If the allele set is enumerated, lower returns the first element of the set and upper returns the last element of the set.

**inc**

Returns the increment of the allele set. If the set is not discretized, the first element or lower bounds of the set is returned.

## Programming Interface: GAAlleleSet<T>

**lowerBoundType**  
**upperBoundType**

Returns GAAllele::INCLUSIVE or GAAllele::EXCLUSIVE to indicate the type of bound on the limits of the allele set. If no bounds have been defined, these method return GAAllele::NONE.

**link**  
**unlink**

The alleleset object does reference counting to reduce the number of instantiated objects. Use the link member to make an alleleset object refer to the data in another. Use the unlink member to remove the connection. When you unlink, the alleleset makes its own copy of the set data.

**size**

Returns the number of elements in the allele set. This member is meaningful only for the enumerated allele set.

**type**

Returns GAAllele::ENUMERATED, GAAllele::BOUNDED, or GAAllele::DISCRETIZED to indicate the type of allele set that has been defined. The type of the allele set is specified by the creator used to instantiate the allele set.

## Programming Interface: GAAlleleSetArray<T>

### GAAlleleSetArray<T>

The GAAlleleSetArray is a container object with an array of allele sets.

#### constructors

```
GAAlleleSetArray()
GAAlleleSetArray(const GAAlleleSet<T>&)
GAAlleleSetArray(const GAAlleleSetArray<T>&)
```

#### member function index

```
int size() const
const GAAlleleSet<T>& set(unsigned int i) const
int add(const GAAlleleSet<T>& s)
int add(unsigned int n, const T a[])
int add(const T& lower, const T& upper, GAAllele::BoundType lb=GAAllele::INCLUSIVE,
        GAAllele::BoundType ub=GAAllele::INCLUSIVE)
int add(const T& lower, const T& upper, const T& increment, GAAllele::BoundType
        lb=GAAllele::INCLUSIVE, GAAllele::BoundType ub=GAAllele::INCLUSIVE)
int remove(unsigned int)
```

#### member function descriptions

##### add

Use the add members to append an allele set to the end of the array. Each of the overloaded add members invokes a corresponding allele set creator, so you can use the appropriate add member for your particular allele set application.

##### remove

Remove the indicated allele set from the array. Returns zero if successful, non-zero otherwise.

##### size

Returns the number of allele sets in the array.

## GAParameter and GAParameterList

The parameter list object contains information about how genetic algorithms should behave. Each parameter list contains an array of parameters. Each parameter is a name-value pair, where the name is a string (e.g. "number\_of\_generations") and the value is an int, float, double, char, string, boolean, or pointer.

Each parameter is uniquely identified by a pair of names: the full name and the short name. Associated with the names is a value. Each parameter also has a type from the enumerated list of types shown above. The GAParameter object automatically does type coercion of the pointer that is passed to it based upon the type that is passed to it upon its creation. The type cannot be changed once the parameter has been created.

### typedefs and constants

```
enum GAParameter::Type {BOOLEAN, CHAR, STRING, INT, FLOAT, DOUBLE, POINTER};
```

### constructors

```
GAParameter(const char* fn, const char* sn, Type tp, const void* v)
GAParameter(const GAParameter& orig)
```

### member function index

```
void copy(const GAParameter&)
char* fullname() const
char* shrtnname() const
const void* value() const
const void* value(const void* v) Type type() const
```

### constructors

```
GAParameterList()
GAParameterList(const GAParameterList&)
```

### member function index

```
int size() const
int get(const char*, void*) const
int set(const char*, const void*)
int set(const char* s, int v)
int set(const char* s, unsigned int v)
int set(const char* s, char v)
int set(const char* s, char* v)
int set(const char* s, double v)
int add(const char*, const char*, GAParameter::Type, const void*)
int remove();
GAParameter& operator[](unsigned int i) const
GAParameter& next()
GAParameter& prev()
GAParameter& current() const
GAParameter& first()
GAParameter& last()
GAParameter* operator()(const char* name)
int parse(int& argc, char **argv, GABoolean flag = gaFalse)
int write(const char* filename) const
int write(ostream& os) const
int read(const char* filename)
int read(istream& is)
ostream& operator<<(ostream& os, const GAParameterList& plist)
istream& operator>>(istream& is, GAParameterList& plist)
```

## Programming Interface: GAParameter and GAParameterList

### member function descriptions

#### `add`

Add a parameter with specified name, type, and default value to the parameter list. This becomes the current parameter.

#### `current`

Return a reference to the current parameter in the list.

#### `first`

Return a reference to the first parameter in the list. This becomes the current parameter.

#### `get`

Fills the contents of the space pointed to by `ptr` with the current value of the named parameter. Returns 0 if the parameter was found, non-zero otherwise.

#### `last`

Return a reference to the last parameter in the list. This becomes the current parameter.

#### `next`

Return a reference to the next parameter in the list. This becomes the current parameter.

#### `parse`

Parse an argument list (in command-line format) for recognized name-value pairs. If you pass `gaTrue` as the third argument then this method will post warnings about names that it does not recognize.

#### `prev`

Return a reference to the next parameter in the list. This becomes the current parameter.

#### `read`

Read a parameter list from the specified file or stream. `set`

Set the named parameter to the specified value. Returns 0 if the parameter was found and successfully set, non-zero otherwise. You can use either the full or short name to specify a parameter.

#### `size`

Returns the number of parameters in the parameter list.

#### `remove`

Remove the current parameter from the parameter list.

#### `write`

Write the parameter list to the specified file or stream.

## GAStatistics

The statistics object contains information about the current state of the genetic algorithm objects. Every genetic algorithm contains a statistics object.

The statistics object defines the following enumerated constants for use by the selectScores member. They can be bitwise-ORed to specify desired combinations of components. Use the class name to refer to the values, for example GAStatistics::Mean | GAStatistics::Deviation

### typedefs and constants

```
enum { NoScores, Mean, Maximum, Minimum, Deviation, Diversity, AllScores }
```

### constructors

```
GAStatistics()
GAStatistics(const GAStatistics&)
```

### member function index

```
void copy(const GAStatistics &);
float online() const
float offline() const
float initial(ScoreID w=Maximum) const
float current(ScoreID w=Maximum) const
float worstEver() const
float bestEver() const
int generation() const
float convergence() const
int selections() const
int crossovers() const
int mutations() const
int replacements() const
int nConvergence(unsigned int)
int nConvergence() const
int nBestGenomes(const GAGenome&, unsigned int)
int nBestGenomes() const
int scoreFrequency(unsigned int x)
int scoreFrequency() const
int flushFrequency(unsigned int x)
int flushFrequency() const
char* scoreFilename(const char *filename)
char* scoreFilename() const
int selectScores(int whichScores)
int selectScores() const
GABoolean recordDiversity(GABoolean flag)
GABoolean recordDiversity() const
void flushScores()
void update(const GAPopulation& pop)
void reset(const GAPopulation& pop)
const GAPopulation& bestPopulation() const
const GAGenome& bestIndividual(unsigned int n=0) const
int scores(const char* filename, ScoreID which=NoScores)
int scores(ostream& os, ScoreID which=NoScores)
int write(const char* filename) const
int write(ostream& os) const;
ostream& operator<<(ostream&, const GAStatistics&)
```

### **member function descriptions**

#### **bestEver**

Returns the score of the best individual ever encountered.

#### **bestIndividual**

This function returns a reference to the best individual encountered by the genetic algorithm.

#### **bestPopulation**

This function returns a reference to a population containing the best individuals encountered by the genetic algorithm. The size of this population is specified using the nBestGenomes member function.

#### **convergence**

Returns the current convergence. Here convergence means the ratio of the nth previous best-of-generation to the current best-of-generation.

#### **crossovers**

Returns the number of crossovers that have occurred since initialization.

#### **current**

Returns the specified score from the current population.

#### **flushFrequency**

Set/Get the frequency at which the generational scores should be flushed to disk. A score frequency of 100 means that at every 100th recorded score the scores buffer will be appended to the scores file.

#### **flushScores**

Force a flush of the scores buffer to the score file.

#### **generation**

Returns the current generation number.

#### **initial**

Returns the specified score from the initial population.

#### **mutations**

Returns the number of mutations that have occurred since initialization.

#### **nBestGenomes**

Set/Get the number of unique best genomes to keep.

#### **nConvergence**

Set/Get the number of generations to use for the convergence measure. A value of 10 means the best-of-generation from 10 generations previous will be used for the convergence test.

#### **offline**

Returns the average of the best-of-generation scores.

#### **online**

Returns the average of all scores.

## Programming Interface: GAStatistics

### **recordDiversity**

This boolean option determines whether or not the diversity of the population will be calculated each generation. By default, this option is set to false.

### **replacements**

Returns the number of replacements that have occurred since initialization.

### **reset**

Reset the contents of the statistics object using the contents of the specified population.

### **scoreFilename**

Set the name of the file to which the scores should be output. If the filename is set to nil, the scores will not be written to disk. The default filename is "generations.dat".

### **scoreFrequency**

Set/Get the frequency at which the generational scores should be recorded. A score frequency of 1 means the scores will be recorded each generation. The default depends on the type of genetic algorithm that is being used.

### **scores**

Print the generational scores to the specified stream. Output is tab-delimited with each line containing the generation number and the specified scores. You can specify which score you would like by logically ORing one of the score identifiers listed above. The order of the tab-delimited scores is as follows:

```
generation TAB mean TAB max TAB min TAB deviation TAB diversity NEWLINE
```

### **selections**

Returns the number of selections that have occurred since initialization.

### **selectScores**

This function is used to specify which scores should be saved to disk. The argument is the logical OR of the following values: Mean, Maximum, Minimum, Deviation, Diversity (all defined in the scope of the GAStatistics object). To record all of the scores, pass GAStatistics::AllScores.

### **update**

Update the contents of the statistics object to reflect the state of the specified population.

### **worstEver**

Returns the score of the worst individual ever encountered.

### GAPopulation

The population object is a container for the genomes. It also contains population statistics such as average, maximum, and minimum genome objective scores. Each population contains a scaling object that is used to determine the fitness of its genomes. The population also contains a function used for selecting individuals from the population.

Whenever possible, the population caches the statistics. This means that the first call to one of the statistics members will be slower than subsequent calls.

You can customize the initialization, evaluation, and sort methods. Use the appropriate member function. Your customized functions must have the appropriate signature.

The default scaling scheme is linear scaling. The default evaluator invokes the objective function for each genome. The default selector is roulette wheel and uses the scaled (fitness) scores for its selections.

#### typedefs and constants

```
void (*GAPopulation::Initializer)(GAPopulation &)
void (*GAPopulation::Evaluator)(GAPopulation &)
enum SortBasis { RAW, SCALED };
enum SortOrder { LOW_IS_BEST, HIGH_IS_BEST };
enum Replacement { BEST = -1, WORST = -2, RANDOM = -3 };
```

#### constructors

```
GAPopulation()
GAPopulation(const GAGenome&, unsigned int popsize = gaDefPopSize)
GAPopulation(const GAPopulation&)
```

#### member function index

```
GAPopulation * clone() const
void copy(const GAPopulation&)
int size(unsigned int popsize)
int size() const
float sum() const
float ave() const
float var() const
float dev() const
float max() const
float min() const
float div() const
float div(unsigned int i, unsigned int j) const
float fitsum() const
float fitave() const
float fitmax() const
float fitmin() const
float fitvar() const
float fitdev() const
float psum(unsigned int i) const
int nevals() const
void touch()
void statistics(GABoolean flag = gaFalse) const
void diversity(GABoolean flag = gaFalse) const
void preselect(GABoolean flag = gaFalse) const
GAGenome& select()
GASelectionScheme& selector() const
GASelectionScheme& selector(const GASelectionScheme&)
void scale(GABoolean flag = gaFalse) const
GAScalingScheme& scaling() const
GAScalingScheme& scaling(const GAScalingScheme&)
```

## Programming Interface: GAPopulation

```
void sort(GABoolean flag = gaFalse, SortBasis basis = RAW) const
SortOrder order() const
SortOrder order(SortOrder flag)
void evaluate(GABoolean flag = gaFalse) const
GAPopulation::Evaluator evaluator(GAPopulation::Evaluator func)
GAPopulation::Evaluator evaluator(GAPopulation::Evaluator func)
void initialize()
GAPopulation::Initializer initializer(GAPopulation::Initializer func)
GAPopulation::Initializer initializer(GAPopulation::Initializer func)
GAGeneticAlgorithm * geneticAlgorithm() const
GAGeneticAlgorithm * geneticAlgorithm(GA&)
void * userData() const
void * userData(void * u)
GAEvalData * evalData() const
GAEvalData * evalData(const GAEvalData&)
GAGenome& individual(unsigned int x, SortBasis basis = RAW) const
GAGenome& best(unsigned int i = 0, SortBasis basis = RAW) const
GAGenome& worst(unsigned int i = 0, SortBasis basis = RAW) const
GAGenome * add(GAGenome *)
GAGenome * add(const GAGenome&)
GAGenome * remove(unsigned int i, SortBasis basis = RAW)
GAGenome * remove(GAGenome *)
GAGenome * replace(GAGenome *, int which = gaPopReplaceRandom, SortBasis basis = RAW)
GAGenome * replace(GAGenome *, GAGenome *)
void destroy(int w = WORST, SortBasis basis = RAW)
virtual void read(istream &)
virtual void write(ostream &) const
ostream& operator<<(ostream &, const GAPopulation &)
istream& operator>>(istream &, GAPopulation &)
```

### member function descriptions

#### **add**

Add the specified individual to the population. If you call this method with a reference to a genome, the population will clone the genome. If you call this method with a pointer to a genome, the population will use the genome pointed to by the pointer. From then on the population is responsible for deleting the genome.

#### **ave**

Returns the average of the objective scores.

#### **best**

Returns a reference to the best individual in the population. Use the SortBasis flag to specify whether you want the best in terms of raw objective score or scaled (fitness) score.

#### **destroy**

Remove the specified individual from the population and free the memory used by that individual. Use the SortBasis flag to specify whether to use raw objective score or scaled (fitness) score when determining which genome to destroy.

#### **dev**

Returns the standard deviation of the objective scores.

#### **div**

Returns the diversity of the population. Diversity is a number between 0 and 1 where 0 indicates that each individual is completely different than every other individual. If you specify two indices, this

## Programming Interface: GAPopulation

member function returns the diversity of the specified individuals (it invokes the comparison function for those individuals).

### **evalData**

Set/Get the evaluation data for the population. This object is unrelated to any evaluation data objects used by the genomes in the population.

### **evaluate**

Evaluate the population using the method set by the evaluator function. The default evaluator simply calls the evaluate member of each genome in the population. If you call this function with gaTrue then the population performs the evaluation even if it has already cached the evaluation results.

### **evaluator**

Specifies which function to use to evaluate the population. The specified function must have the proper signature.

### **fitave**

Returns the average of the fitness scores.

### **fitdev**

Returns the standard deviation of the fitness scores.

### **fitmax**

Returns the maximum fitness score.

### **fitmin**

Returns the minimum fitness score.

### **fitsum**

Returns the sum of the fitness scores.

### **fitvar**

Returns the variance of the fitness scores.

### **geneticAlgorithm**

Set/Get the genetic algorithm that 'owns' this population. A return value of nil indicates that the population is owned by no genetic algorithm.

### **individual**

Returns a reference to the specified individual. Indices for individuals in the population start at 0 and go to size()-1. the 0th individual is the best individual when the population has been sorted. Use the SortBasis flag to specify whether you want the ith individual based upon the raw objective score or scaled (fitness) score.

### **initialize**

Initialize the population using the method set by initializer. The default initializer simply calls the initialize method of each genome in the population.

## Programming Interface: GAPopulation

### **initializer**

Specifies which function to use to initialize the population. The specified function must have the proper signature.

### **max**

Returns the maximum objective score in the population.

### **min**

Returns the minimum objective score in the population.

### **order**

Set/Get the sort order. A population may be sorted in two ways, highest-score-is-best or lowest-score-is-best.

### **prepselect**

The function calls the selector's update method. It is typically called by the population before it does a selection.

### **psum**

Returns the partial sum of the ith fitness score in the array of (sorted) fitness scores.

### **remove**

Remove the specified individual from the population. The genome to be replaced can be specified by either an index or by pointer. This function returns a pointer to the genome that was removed from the population. The caller is responsible for the memory used by the returned genome. Use the SortBasis flag to specify whether to use raw objective score or scaled (fitness) score when determining which genome to remove.

### **replace**

Replace the specified individual with the first argument. The genome to be replaced can be specified by either an index or by pointer. This function returns a pointer to the genome that was replaced. If no genome was replaced or the specified index or pointer is bogus, it returns nil. Use the SortBasis flag to specify whether to use raw objective score or scaled (fitness) score when determining which genome to replace.

### **scale**

Scale the raw (objective) scores in the population using the scaling method. If you call this function with gaTrue then the scaled scores are recalculated even if the population has already cached them.

### **scaling**

Set/Get the scaling method for this population.

### **select**

Returns a reference to a genome from the population using the selection scheme associated with the population.

### **selector**

Set/Get the selection method for this population.

## Programming Interface: GAPopulation

### **size**

Set/Get the number of individuals in the population. If you resize to a larger size, the new individuals will be initialized but not evaluated. If you resize to a smaller size, the best individuals will be kept.

### **sort**

Sort the individuals in the population. Individuals may be sorted based upon their raw or scaled scores.

### **statistics**

Calculate the population statistics. This method is automatically invoked whenever any of the population statistics are requested. If you call this function with gaTrue then the statistics are recalculated even if the population has already cached them.

### **sum**

Returns the sum of the objective scores.

### **touch**

The population object remembers its state so that it does not execute the evaluate or sort methods unless its state has been changed. If you want to force the population to execute any of its methods the next time they are invoked, invoke this method.

### **userData**

Set/Get the user data pointer for the population. You can use the user data member to store a pointer to any object.

### **var**

Returns the variance of the objective scores.

### **worst**

Returns a reference to the worst individual in the population. Use the SortBasis flag to specify whether you want the worst in terms of raw objective score or scaled (fitness) score.

## GAScalingScheme

The scaling object is embedded in the population object. The base scaling object is not instantiable. This object keeps track of the fitness scores (not the objective scores) of each individual in the population. The genomes that it returns are the genomes in the population to which it is linked; it does not make its own copies.

For details about how to write your own scaling scheme, see the customizations section.

### constructors

```
GAScalingScheme()
GAScalingScheme(const GAScalingScheme& s)
```

### member function index

```
virtual GAScalingScheme * clone() const
virtual void copy(const GAScalingScheme &)
virtual void evaluate(const GAPopulation & p)
```

### built-in scaling schemes

GAlib contains a number of instantiable scaling objects derived from the base class. Here are the constructors for these scaling schemes:

```
GANoScaling()
```

The fitness scores are identical to the objective scores. No scaling takes place.

```
GALinearScaling(float c = gaDefLinearScalingMultiplier)
```

The fitness scores are derived from the objective scores using the linear scaling method described in Goldberg's book. You can specify the scaling coefficient. Negative objective scores are not allowed with this method. Objective scores are converted to fitness scores using the relation

$$f = a \cdot obj + b$$

where *a* and *b* are calculated based upon the objective scores of the individuals in the population as described in Goldberg's book.

```
GASigmaTruncationScaling(float c = gaDefSigmaTruncationMultiplier)
```

Use this scaling method if your objective scores will be negative. It scales based on the variation from the population average and truncates arbitrarily at 0. The mapping from objective to fitness score for each individual is given by

$$f = obj - (obj\_ave - c \cdot obj\_dev)$$

```
GAPowerLawScaling(int k = gaDefPowerScalingFactor)
```

Power law scaling maps objective scores to fitness scores using an exponential relationship defined as

$$f = obj^k$$

```
GASHaring(GAGenome::Comparator func = 0,
      float cutoff = gaDefSharingCutoff, float alpha = 1)
```

This scaling method is used to do speciation. The fitness score is derived from its objective score by comparing the individual against the other individuals in the population. If there are other similar individuals then the fitness is derated. The distance function is used to specify how similar to each other

## Programming Interface: GAScalingScheme

two individuals are. A distance function must return a value of 0 or higher, where 0 means that the two individuals are identical (no diversity). For a given individual,

$$f = \frac{\text{obj}}{\sum_{j=0}^n s(d_j)}$$

$$s(d_j) = \begin{cases} d_j & d_j < 1 - \frac{d_j}{d_j} \\ 0 & \text{otherwise} \end{cases}$$

$d_j$  = distance between current individual and individual  $j$

$n$  = number of individuals in the population

The default sharing object uses the triangular sharing function described in Goldberg's book. You can specify the cutoff value (sigma in Goldberg's book) using the sigma member function. The curvature of the sharing function is controlled by the alpha value. When alpha is 1.0 the sharing function is a straight line (triangular sharing). If you specify a comparator, that function will be used as the distance function for all comparisons. If you do not specify a comparator, the sharing object will use the default comparator of each genome.

Notice that the sharing scaling differs depending on whether the objective is to maximized or minimized. If the goal is to maximize the objective score, the raw scores will be divided by the sharing factor. If the goal is to minimize the objective score, the raw scores will be multiplied by the sharing factor. You can explicitly tell the sharing object to do minimize- or maximize-based scaling by using the minimaxi member function. By default, it uses the min/max settings of the genetic algorithm that is using it (based on information in the population with which the sharing object is associated). If the scaling object is associated with a population that has been created independently of any genetic algorithm object, the sharing object will use the population's order to decide whether to multiply or divide to do its scaling.

## GASelectionScheme

Selection schemes are used to pick genomes from a population for mating. The GASelectionScheme object defines the basic selector behavior. It is an abstract class and cannot be instantiated. Each selector object may be linked to a population from which it will make its selections. The select member returns a reference to a single genome. A selector may operate on the scaled objective scores or the raw objective scores. Default behavior is to operate on the scaled (fitness) scores.

For details about how to write your own selection scheme, see the customizations section.

### typedefs and constants

```
enum { RAW, SCALED };
```

### constructors

```
GASelectionScheme(int which = FITNESS)
GASelectionScheme(const GASelectionScheme&)
```

### member function index

```
virtual GASelectionScheme* clone() const;
virtual void copy(const GASelectionScheme& orig)
virtual void assign(GAPopulation& pop)
virtual void update()
virtual GAGenome& select() const;
```

### built-in selection schemes

GAlib contains a number of instantiable scaling objects derived from the base class. Here are the constructors for these scaling schemes:

```
GRankSelector(int w=GASelectionScheme::SCALED)
```

The rank selector picks the best member of the population every time.

```
GRouletteWheelSelector(int w=GASelectionScheme::SCALED)
```

This selection method picks an individual based on the magnitude of the fitness score relative to the rest of the population. The higher the score, the more likely an individual will be selected. Any individual has a probability  $p$  of being chosen where  $p$  is equal to the fitness of the individual divided by the sum of the fitnesses of each individual in the population.

```
GTournamentSelector(int w=GASelectionScheme::SCALED)
```

The tournament selector uses the roulette wheel method to select two individuals then picks the one with the higher score. The tournament selector typically chooses higher valued individuals more often than the RouletteWheelSelector.

```
GADSSelector(int w=GASelectionScheme::SCALED)
```

The deterministic sampling selector (DS) uses a two-staged selection procedure. In the first stage, each individual's expected representation is calculated. A temporary population is filled using the individuals with the highest expected numbers. Any remaining positions are filled by first sorting the original individuals according to the decimal part of their expected representation, then selecting those highest in the list. The second stage of selection is uniform random selection from the temporary population.

## Programming Interface: GASelectionScheme

```
GASRSSelector(int w=GASelectionScheme::SCALED)
```

The stochastic remainder sampling selector (SRS) uses a two-staged selection procedure. In the first stage, each individual's expected representation is calculated. A temporary population is filled using the individuals with the highest expected numbers. Any fractional expected representations are used to give the individual more likelihood of filling a space. For example, an individual with e of 1.4 will have 1 position then a 40% chance of a second position. The second stage of selection is uniform random selection from the temporary population.

```
GAUniformSelector(int w=GASelectionScheme::SCALED)
```

The stochastic uniform sampling selector picks randomly from the population. Any individual in the population has a probability p of being chosen where p is equal to 1 divided by the population size.

## Programming Interface: GAArray<T>

### GAArray<T>

The GAArray<T> object is defined for your convenience so that you do not have to create your own array object. It is a template-ized container class whose elements can contain objects of any type. The 1-, 2-, and 3-dimensional arrays used in GALib are all based upon this single-dimensional array object. This object is defined in the file arraytmpl.h.



The squares are elements in the array. Arrays are 1-dimensional, but derived classes can have 2 or more dimensions. Each element contains a user-specified object.

Any object in the array must have the following methods defined and publicly available:

copy constructor	operator ==
operator =	operator !=

The elements in an array are indexed starting with 0 (the first element in the array is element number 0). The last element in array with n elements is element n-1.

#### constructors

```
GAArray(unsigned int)
GAArray(const GAArray<T>&)
```

#### member function index

```
GAArray<T> & operator=(const GAArray<T>& orig)
GAArray<T> & operator=(const T array [])
GAArray<T> * clone()
const T & operator[](unsigned int i)
const T & operator[](unsigned int i)
void copy(const GAArray<T>& orig)
void copy(const GAArray<T>& orig, unsigned int dest, unsigned int src, unsigned int length)
void move(unsigned int dest, unsigned int src, unsigned int length)
void swap(unsigned int i, unsigned int j)
int size() const
int size(unsigned int n)
int equal(const GAArray<T>& b, unsigned int dest, unsigned int src, unsigned int length)
const
int operator==(const GAArray<T>& a, const GAArray<T>& b)
int operator!=(const GAArray<T>& a, const GAArray<T>& b)
```

#### member function descriptions

##### clone

Return a pointer to an exact duplicate of the original array. The caller is responsible for the memory allocated by the call to this function.

##### copy

Duplicate the specified array or part of the specified array. If duplicating a part of the specified array, length elements starting at position src in the original are copied into position dest in the copy. If there is not enough space in the copy, the extra elements are not copied.

##### equal

Return 1 if the specified portion of the two arrays is identical, return 0 otherwise.

## Programming Interface: GAArray<T>

### **move**

Move the number of elements specified with length from position src to position dest.

### **operator[]**

Return a reference to the contents of the ith element of the array.

### **size**

Return the number of elements in the array.

### **swap**

Swap the contents of element i with the contents of element j.

## Programming Interface: GABinaryString

### GABinaryString

The binary string object is a simple implementation of a string of bits. Each bit is represented by a single word of memory (no fancy bit-munging happens here). The binary string class defines the following member functions. Binary strings are resizable.

#### constructors

```
GABinaryString(unsigned int length)
GABinaryString(const GABinaryString&)
```

#### member function index

```
void copy(const GABinaryString&)
int resize(unsigned int)
int size() const
short bit(unsigned int a) const
short bit(unsigned int a, short val)
int equal(const GABinaryString& b, unsigned int dest, unsigned int src, unsigned int
length) const
void copy(const GABinaryString& orig, unsigned int dest, unsigned int src, unsigned int
length)
void move(unsigned int dest, unsigned int src, unsigned int length)
void set(unsigned int a, unsigned int length)
void unset(unsigned int a, unsigned int length)
void randomize(unsigned int a, unsigned int length)
```

#### member function descriptions

##### copy

Makes an exact copy of the specified string. If invoked with a range of bits then copies the specified range of bits.

##### bit

Set/Get the specified bit.

##### equal

Returns 1 if the specified range of bits are equal, 0 otherwise.

##### move

Move length bits starting at src to dest.

##### set/unset

Set/Unset length bits starting at a

##### size resize

Set/Get the length of the bit string.

##### randomize

Set to random values length bits starting at a

## GAList<T> and GAListIter<T>

The GAList<T> object is defined for your convenience so that you do not have to create your own list object. It is a template-ized container class whose nodes can contain objects of any type. The GAList<T> object is circular and doubly-linked. A list iterator object is also defined to be used when moving around the list to keep track of the current, next, previous, or whichever node. Iterators do not change the state of the list.

The circles are nodes in the list. Each node contains a user-specified object; the initialization method determines the size of the list and the contents of each node. The list is circular and doubly linked.



The template-ized GAList<T> is derived from a generic list base class called GAListBASE. The template list is defined in listtmpl.h, the list base class is defined in listbase.h

Any object used in the nodes must have the following methods defined and publicly available:

copy constructor	operator ==
operator =	operator !=

Each list object contains an iterator. The list's traversal member functions (next, prev, etc) simply call the member functions on the internal iterator. You can also instantiate iterators external to the list object so that you can traverse the list without modifying its state.

The list base class defines constants for specifying where insertions should take place (these are relative to the node to which the iterator is currently pointing).

Nodes in the list are numbered from 0 to 1 less than the list size. The head node is node 0.

When you do an insertion, the list makes a copy of the specified object (allocating space for it in the process). The internal iterator is left pointing to the node which was just inserted. The insertion function uses the copy constructor member to do this, so the objects in your list must have a copy constructor defined. The new node is inserted relative to the current location of the list's internal iterator. Use the where flag to determine whether the new node will be inserted before or after the current node, or if the new node should become the head node of the list.

The remove member returns a pointer to the object that was in the specified node. You are responsible for deallocating the memory for this object! The destroy member deallocates the memory used by the object in the current node. In both cases the iterator is left pointing to the node previous to the one that was deleted.

All of the list traversal functions (prev, next, current, etc) return a pointer to the contents of the node on which they are operating. You should test the pointer to see if it is NULL before you dereference it. When you call any of the traversal functions, the list's internal iterator is left pointing to the node to which traversal function moved. You can create additional iterators (external to the list) to keep track of multiple positions in the list.

### typedefs and constants

```
GAListBASE::HEAD
GAListBASE::TAIL
GAListBASE::BEFORE
GAListBASE::AFTER
```

### constructors

```
GAListIter(const GAList<T> &)
```

## Programming Interface: GALIST<T> and GALISTIter<T>

### member function index

```
T * current()
T * head()
T * tail()
T * next()
T * prev()
T * warp(const GALIST<T>& t)
T * warp(const GALISTIter<T>& i)
T * warp(unsigned int i)
```

### constructors

```
GALIST()
GALIST(const T& t)
GALIST(const GALIST<T>& orig)
```

### member function index

```
GALIST<T> * clone()
void copy(const GALIST<T>& orig)
void destroy()
void swap(unsigned int, unsigned int)
T * remove()
void insert(GALIST<T> * t, GALISTBASE::Location where=AFTER)
void insert(const T& t, GALISTBASE::Location where=AFTER)
T * current()
T * head()
T * tail()
T * next()
T * prev()
T * warp(unsigned int i)
T * warp(const GALISTIter<T>& i)
T * operator[](unsigned int i)
int size() const
```

### member function descriptions

*These functions change the state of the list.*

#### clone

Return a pointer to an exact duplicate of the original list. The caller is responsible for the memory allocated by the call to this function.

#### copy

Duplicate the specified list.

#### destroy

Destroy the current node in the list. This function uses the location of the internal iterator to determine which node should be destroyed. If the head node is destroyed, the next node in the list becomes the head node.

#### insert

Add a node or list to the list. The insertion is made relative to the location of the internal iterator. The where flag specifies whether the insertion should be made before or after the current node.

#### remove

Returns a pointer to the contents of the current node and removes the current node from the list. The iterator moves to the previous node. The caller is responsible for the memory used by the contents.

## Programming Interface: GAList<T> and GAListIter<T>

### **swap**

Swap the positions of the two specified nodes. The internal iterator is not affected. If the iterator was pointing to one of the nodes before the swap it will still point to that node after the swap, even if that node was swapped.

*These functions do not change the contents of the list, but they change the state of the list's internal iterator (when invoked on a list object).*

### **current**

Returns a pointer to the contents of the current node.

### **head**

Returns a pointer to the contents of the first node in the list.

### **next**

Returns a pointer to the contents of the next node.

### **operator[]**

Returns a pointer to the contents of the ith node in the list (same as warp).

### **prev**

Returns a pointer to the contents of the previous node.

### **tail**

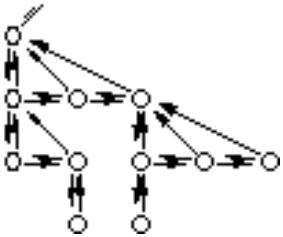
Returns a pointer to the contents of the last node in the list.

### **warp**

Returns a pointer to the contents of the ith node in the list, or a pointer to the element in the list pointed to by the specified iterator. The head node is number 0.

## GATree<T> and GATreeIter<T>

The GATree<T> object is defined for your convenience so that you do not have to create your own tree object. It is a template-sized container class whose nodes can contain objects of any type. Each level in the GATree<T> object is a circular and doubly-linked list. The eldest child of a level is the head of the linked list, each child in a level points to its parent, and the parent of those children points to the eldest child. Any tree can have only one root node. Any node can have any number of children. A tree iterator is also defined to be used when moving around the list to keep track of the current, next, parent, or whichever node. Iterators do not change the state of the tree.



The circles are nodes in the tree. Each node contains a user-specified object; the initialization method determines the tree topology and the contents of each node. Each tree contains one (and only one) root node. Each level in the tree is a circular, doubly linked list. The head of each list is called the 'eldest' child, each node in a level has a link to its parent, and each parent has a link to the eldest of its children (if it has any children).

The template-sized GATree<T> is derived from a generic tree base class called GATreeBASE. The template tree is defined in treetmpl.h, the tree base class is defined in treebase.h

Any object used in the nodes have the following methods defined and publicly available:

copy constructor	operator ==
operator =	operator !=

Each tree object contains an iterator. The tree's traversal member functions (next, prev, etc) simply call the member functions on the internal iterator. You can also instantiate iterators external to the tree object so that you can traverse the tree without modifying its contents.

The tree base class defines constants for specifying where insertions should occur.

Nodes in a tree are numbered starting at 0 then increasing in a depth-first traversal of the tree. The root node is node 0. A tree can have only one root node, but any node in the tree can have any number of children.

When you do an insertion, the tree makes a copy of the specified object (allocating space for it in the process). The internal iterator is left pointing to the node which was just inserted. The insertion function uses the copy constructor member to do this, so the objects in your tree must have a copy constructor defined. The new node is inserted relative to the current location of the tree's internal iterator. Use the where flag to determine whether the new node will be inserted before, after, or below the current node, or if the new node should become the root node of the tree.

The remove member returns a pointer to a tree. The root node of this tree is the node at which the iterator was pointing. You are responsible for deallocating the memory for this tree! The destroy member deallocates the memory used by the object in the current node and completely destroys any subtree hanging on that node. In both cases, the iterator is left pointing to the elder child or parent of the node that was removed/destroyed.

All of the tree traversal functions (prev, next, current, etc) return a pointer to the contents of the node on which they are operating. You should test the pointer to see if it is NULL before you dereference it. Also, the iterator is left pointing to the node to which you traverse with each traversal function. You can create additional iterators (external to the tree) to keep track of multiple positions in the tree.

## Programming Interface: GATree<T> and GATreeIter<T>

### typedefs and constants

```
GATreeBASE::ROOT  
GATreeBASE::BEFORE  
GATreeBASE::AFTER  
GATreeBASE::BELOW
```

### constructors

```
GATreeIter(const GATree<T>& t)
```

### member function index

```
T * current()  
T * root()  
T * next()  
T * prev()  
T * parent()  
T * child()  
T * eldest()  
T * youngest()  
T * warp(const GATree<T>& t)  
T * warp(const GATreeIter<T>& i)  
T * warp(unsigned int i)  
int size()  
int depth()  
int nchildren()  
int nsiblings()
```

### constructors

```
GATree()  
GATree(const T& t)  
GATree(const GATree<T>& orig)
```

### member function index

```
GATree<T> * clone()  
void copy(const GATree<T>& orig)  
void destroy()  
void swaptree(GATree<T> * t)  
void swaptree(unsigned int, unsigned int)  
void swap(unsigned int, unsigned int)  
GATree<T> * remove()  
void insert(GATree<T> * t, GATreeBASE::Location where=BELOW)  
void insert(const T& t, GATreeBASE::Location where=BELOW)  
T * current()  
T * root()  
T * next()  
T * prev()  
T * parent()  
T * child()  
T * eldest()  
T * youngest()  
T * warp(unsigned int i)  
T * warp(const GATreeIter<T>& i)  
int ancestral(unsigned int i, unsigned int j) const  
int size()  
int depth()  
int nchildren()  
int nsiblings()
```

### member function descriptions

*These functions change the state of the tree.*

## Programming Interface: GATree<T> and GATreeIter<T>

### **clone**

Return a pointer to an exact duplicate of the original tree. The caller is responsible for the memory allocated by the call to this function.

### **copy**

Duplicate the specified tree.

### **destroy**

Destroy the current node in the tree. If the node has children, the entire sub-tree connected to the node is destroyed as well. This function uses the location of the internal iterator to determine which node should be destroyed. If the root node is destroyed, the entire contents of the tree will be destroyed, but the tree object itself will not be deleted.

### **insert**

Add a node or tree to the tree. The insertion is made relative to the location of the internal iterator. The where flag specifies whether the insertion should be made before, after, or below the current node.

### **remove**

Returns a pointer to a new tree object whose root node is the (formerly) current node of the original tree. Any subtree connected to the node stays with the node. The iterator moves to the previous node in the current generation, or the parent node if no elder sibling exists. The caller is responsible for the memory used by the new tree.

### **swap**

Swap the contents of the two specified nodes. Sub-trees connected to either node are not affected; only the specified nodes are swapped.

### **swaptree**

Swap the contents of the two specified nodes as well as any sub-trees connected to the specified nodes.

*These functions do not change the contents of the tree, but they change the state of the tree's internal iterator (when invoked on a tree object).*

### **ancestral**

Returns 1 if one of the two specified nodes is the ancestor of the other, returns 0 otherwise.

### **child**

Returns a pointer to the contents of the eldest child of the current node. If the current node has no children, this function returns NULL.

### **current**

Returns a pointer to the contents of the current node.

### **depth**

Returns the number of generations (the depth) of the tree. When called as the member function of a tree iterator, this function returns the depth of the subtree connected to the iterator's current node.

### **eldest**

Returns a pointer to the contents of the eldest node in the current generation. The eldest node is the node pointed to by the 'child' function in the node's parent.

## Programming Interface: GATree<T> and GATreeIter<T>

### **nchildren**

Returns the number of children of the node to which the iterator is pointing.

### **next**

Returns a pointer to the contents of the next node in the current generation.

### **nsiblings**

Returns the number of nodes in the level of the tree as the node to which the iterator is pointing.

### **parent**

Returns a pointer to the contents of the parent of the current node. If the current node is the root node, this function returns NULL.

### **prev**

Returns a pointer to the contents of the previous node in the current generation.

### **root**

Returns a pointer to the contents of the root node of the tree.

### **size**

Returns the number of nodes in the tree. When called as the member function of a tree iterator, this function returns the size of the subtree connected to the iterator's current node.

### **warp**

Returns a pointer to the contents of the ith node in the tree, or a pointer to the element in the tree pointed to by the specified iterator. The head node is number 0 then the count increases as a depth-first traversal of the tree.

### **youngest**

Returns a pointer to the contents of the youngest node in the current generation.

## Customizing GAlib

---

This document describes how to extend GAlib's capabilities by defining your own genomes and genetic operators. The best way to customize the behavior of an object is to derive a new class. If you do not want to do that much work, GAlib is designed to let you replace behaviors of existing objects by defining new functions.

### Deriving your own genome class

You can create your own genome class by multiply-inheriting from the base genome class and your own data type. For example, if you have already have an object defined, say `MyObject`, then you would derive a new genome class called `MyGenome`, whose class definition looks like this:

```
// Class definition for the new genome object, including statically
// defined declarations for default evaluation, initialization,
// mutation, and comparison methods for this genome class.

class MyGenome : public MyObject, public GAGenome {
public:
    GADefineIdentity("MyGenome", 201);
    static void Init(GAGenome&);
    static int Mutate(GAGenome&, float);
    static float Compare(const GAGenome&, const GAGenome&);
    static float Evaluate(GAGenome&);
    static int Cross(const GAGenome&, const GAGenome&, GAGenome*, GAGenome*);

public:
    MyGenome() : GAGenome(Init, Mutate, Compare) {
        evaluator(Evaluate);
        crossover(Cross);
    }
    MyGenome(const MyGenome& orig) { copy(orig); }
    virtual ~MyGenome() {}
    MyGenome& operator=(const GAGenome& orig){
        if(&orig != this) copy(orig);
        return *this;
    }
    virtual GAGenome* clone(CloneMethod) const
        {return new MyGenome(*this);}
    virtual void copy(const GAGenome& orig) {
        GAGenome::copy(orig); // this copies all of the base genome parts
        // copy any parts of MyObject here
        // copy any parts of MyGenome here
    }
    // any data/member functions specific to this new class
};

void
MyGenome::Init(GAGenome&){
    // your initializer here
}

int
MyGenome::Mutate(GAGenome&, float){
    // your mutator here
}

float
MyGenome::Compare(const GAGenome&, const GAGenome&){
```

## Customizing GAlib: Deriving your own genome class

```
// your comparison here
}

float
MyGenome::Evaluate(GAGenome&){
    // your evaluation here
}

int
MyGenome::Cross(const GAGenome& mom, const GAGenome& dad, GAGenome* sis, GAGenome* bro){
    // your crossover here
}
```

By convention, one of the arguments to a derived genome constructor is the objective function. Alternatively (as illustrated in this example), you can hard code a default objective function into your genome - just call the evaluator member somewhere in your constructor and pass the function you want used as the default.

Once you have defined your genome class, you should define the initialization, mutation, comparison, and crossover operators for it. The comparison operator is optional, but if you do not define it you will not be able to use the diversity measures in the genetic algorithms and/or populations.

Note that the genetic comparator is not necessarily the same as the boolean operator== and operator!= comparators. The genetic comparator returns 0 if the two individuals are the same, -1 if the comparison fails for some reason, and a real number greater than 0 indicating the degree of difference if the individuals are not identical but can be compared. It may be based on genotype or phenotype. The boolean comparators, on the other hand, indicate only whether or not two individuals are identical. In most cases, the boolean comparator can simply call the genetic comparator, but in some cases it is more efficient to define different operators (the boolean comparators are called much more often than the genetic comparators, especially if no diversity is being measured).

To work properly with the GAlib, you must define the following:

```
MyGenome( -default-args-for-your-genome-constructor )
MyGenome(const MyGenome&)
virtual GAGenome* clone(GAGenome::CloneMethod) const
```

If your genome adds any non-trivial member data, you must define these:

```
virtual ~MyGenome()
virtual copy(const GAGenome&)
virtual int equal(const GAGenome&) const
```

To enable streams-based reading and writing of your genome, you should define these:

```
virtual int read(istream&)
virtual int write(ostream&) const
```

When you derive a genome, don't forget to use the \_evaluated flag to indicate when the state of the genome has changed and an evaluation is needed. If a member function changes the state of your genome, that member function should set the \_evaluated flag to gaFalse. GAlib uses the \_evaluated flag to control its caching of the genome scores, so setting and unsetting the flag is critical. If your member functions do not unset the flag when they modify the contents of the genome, then the genome will not be (re)evaluated.

Assign a default crossover, mutation, initialization, and comparison method so that users don't have to assign one unless they want to.

It is a good idea to define an identity for your genome (especially if you will be using it in an environment with multiple genome types running around). Use the DefineIdentity macro (defined in id.h) to do this in your class definition. The DefineIdentity macro sets a class ID number and the name

## Customizing GAlib: Genome Initialization

that will be used in error messages for the class. You can use any number above 200 for the ID, but be sure to use a different number for each of your classes.

When run-time type information (RTTI) has stabilized across compilers, GAlib will probably use that instead of the Define/Declare identity macros.

### Genome Initialization

The initializer takes a single argument: the genome to be initialized. The genome has already been allocated; the intializer only needs to populate it with appropriate contents.

Here is the implementation of an initializer for the GATreeGenome<int> class.

```
void
TreeInitializer(GAGenome & c) {
    GATreeGenome<int> &child=(GATreeGenome<int> &)c;
    // destroy any pre-existing tree
    child.root();
    child.destroy();
    // Create a new tree with depth of 'depth' and each eldest node
    // containing 'n' children (the other siblings have none).
    int depth=2, n=3, count=0;
    child.insert(count++, GATreeBASE::ROOT);
    for(int i=0; i<depth; i++){ child.eldest();
        child.insert(count++);
        for(int j=0; j<n; j++) child.insert(count++, GATreeBASE::AFTER);
    }
}
```

### Genome Mutation

The genome mutator takes two arguments: the genome that will receive the mutation(s) and a mutation probability. The exact meaning of the mutation probability is up to the designer of the mutation operator. The mutator should return the number of mutations that occurred.

Most genetic algorithms invoke the mutation method on each newly generated offspring. So your mutation operator should base its actions on the value of the mutation probability. For example, an array of floats could flip a pmut-biased coin for each element in the array. If the coin toss returns true, the element gets a Gaussian mutation. If it returns false, the element is left unchanged. Alternatively, a single biased coin toss could be used to determine whether or not the entire genome should be mutated.

Here is an implementation of the flip mutator for the GA1DBinaryString class. This mutator flips a biased coin for each bit in the string.

```
int
GA1DBinStrFlipMutator(GAGenome & c, float pmut) {
    GA1DBinaryStringGenome &child=(GA1DBinaryStringGenome &)c;
    if(pmut <= 0.0) return(0);
    int nMut=0;
    for(int i=child.length()-1; i>=0; i--){
        if(GAFlipCoin(pmut)){
            child.gene(i, ((child.gene(i) == 0) ? 1 : 0));
            nMut++;
        }
    }
    return nMut;
}
```

## Genome Crossover

The crossover method is used by the genetic algorithm to mate individuals from the population to form new offspring. Each genome should define a default crossover method for the genetic algorithms to use. The sexual and asexual member functions return a pointer to the preferred sexual and asexual mating methods, respectively. The crossover member function is used to change the preferred mating method. The genome does not have a member function to invoke the crossover; only the genetic algorithm can actually perform the crossover.

Some genetic algorithms use sexual mating, others use asexual mating. If possible, define both so that your genome will work with either kind of genetic algorithm. If your derived class does not define a cross method, an error message will be posted whenever crossover is attempted.

Sexual crossover takes four arguments: two parents and two children. If one child is nil, the operator should be able to generate a single child. The genomes have already been allocated, so the crossover operator should simply modify the contents of the child genome as appropriate. The crossover function should return the number of crossovers that occurred. Your crossover function should be able to operate on one or two children, so be sure to test the child pointers to see if the genetic algorithm is asking you to create one or two children.

Here is an implementation of the two-parent/one-or-two-child single point crossover operator for fixed-length genomes of the GA1DBinaryStringGenome class.

```
int
SinglePointCrossover(const GAGenome& p1, const GAGenome& p2, GAGenome* c1, GAGenome* c2){
    GA1DBinaryStringGenome &mom=(GA1DBinaryStringGenome &)p1;
    GA1DBinaryStringGenome &dad=(GA1DBinaryStringGenome &)p2;
    int n=0;
    unsigned int site = GARandomInt(0, mom.length());
    unsigned int len = mom.length() - site;
    if(c1){
        GA1DBinaryStringGenome &sis=(GA1DBinaryStringGenome &)*c1;
        sis.copy(mom, 0, 0, site);
        sis.copy(dad, site, site, len);
        n++;
    }
    if(c2){
        GA1DBinaryStringGenome &bro=(GA1DBinaryStringGenome &)*c2;
        bro.copy(dad, 0, 0, site);
        bro.copy(mom, site, site, len);
        n++;
    }
    return n;
}
```

## Genome Comparison

The comparison method is used for diversity calculations. It compares two genomes and returns a number that is greater than or equal to zero. A value of 0 means that the two genomes are identical (no diversity). There is no maximum value for the return value from the comparator. A value of -1 indicates that the diversity could not be calculated.

Here is the comparator for the binary string genomes. It simply counts up the number of bits that both genomes share. In this example, we return a -1 if the genomes are not the same length.

```
float
GA1DBinStrComparator(const GAGenome& a, const GAGenome& b){    GA1DBinaryStringGenome
    &sis=(GA1DBinaryStringGenome &)a;                      GA1DBinaryStringGenome
    &bro=(GA1DBinaryStringGenome &)b;
    if(sis.length() != bro.length()) return -1;
    float count = 0.0;
```

## Customizing GAlib: Genome Evaluation

```
for(int i=sis.length()-1; i>=0; i--)
    count += ((sis.gene(i) == bro.gene(i)) ? 0 : 1);
return count/sis.length();
}
```

### Genome Evaluation

The genome evaluator is the objective function for your problem. It takes a single genome as its argument. The evaluator returns a number that indicates how good or bad the genome is. You must cast the generic genome to the genome type that you are using. If your objective function works with different genome types, then use the genome object's `className` and/or `classID` member functions to determine the genome class before you do the casts.

Here is a simple evaluation function for a real number genome with a single element. The function tries to maximize a sinusoidal.

```
float
Objective(GAGenome& g){
    GARRealGenome& genome = (GARRealGenome &)g;
    return 1 + sin(genome.gene(0)*2*M_PI);
}
```

### Population Initialization

This method is invoked when the population is initialized.

Here is an implementation that invokes the initializer for each genome in the population.

```
void
PopInitializer(GAPopulation & p){
    for(int i=0; i<p.size(); i++)
        p.individual(i).initialize();
}
```

### Population Evaluation

This method is invoked when the population is evaluated. If your objective is population-based, you can use this method to set the score for each genome rather than invoking an evaluator for each genome.

Here is an implementation that invokes the evaluation method for each genome in the population.

```
void
PopEvaluator(GAPopulation & p){
    for(int i=0; i<p.size(); i++)
        p.individual(i).evaluate();
}
```

### Scaling Scheme

The scaling object does the transformation from raw (objective) scores to scaled (fitness) scores. The most important member function you will have to define for a new scaling object is the `evaluate` member function. This function calculates the fitness scores based on the objective scores in the population that is passed to it.

The `GAScalingScheme` class is a pure virtual (abstract) class and cannot be instantiated. To make your derived class non-virtual, you must define the `clone` and `evaluate` functions. You should also define the `copy` method if your derived class introduces any additional data members that require non-trivial copy.

## Customizing GAlib: Selection Scheme

The scaling class is polymorphic, so you should define the object's identity using the `GADefineIdentity` macro. This macro sets a class ID number and the name that will be used in error messages for the class. You can use any number above 200 for the ID, but be sure to use a different number for each of your objects.

Here is an implementation of sigma truncation scaling.

```
class SigmaTruncationScaling : public GAScalingScheme {
public:
    GADefineIdentity("SigmaTruncationScaling", 286);
    SigmaTruncationScaling(float m=gaDefSigmaTruncationMultiplier) :
        c(m) {}
    SigmaTruncationScaling(const SigmaTruncationScaling & arg)
        {copy(arg);}
    SigmaTruncationScaling & operator=(const GAScalingScheme & arg)
        { copy(arg); return *this; }
    virtual ~SigmaTruncationScaling() {}
    virtual GAScalingScheme * clone() const
        { return new SigmaTruncationScaling(*this); }
    virtual void evaluate(const GAPopulation & p);
    virtual void copy(const GAScalingScheme & arg){
        if(&arg != this && sameClass(arg)){
            GAScalingScheme::copy(arg);
            c=((SigmaTruncationScaling&)arg).c;
        }
    }
    float multiplier(float fm) { return c=fm; }
    float multiplier() const { return c; }

protected:
    float c;                                // std deviation multiplier
};

void
SigmaTruncationScaling::evaluate(const GAPopulation & p) {
    float f;
    for(int i=0; i<p.size(); i++){
        f = p.individual(i).score() - p.ave() + c * p.dev();
        if(f < 0) f = 0;
        p.individual(i).fitness(f);
    }
}
```

## Selection Scheme

The selection object is used to pick individuals from the population. Before a selection occurs, the update method is called. You can use this method to do any pre-selection data transformations for your selection scheme. When a selection is requested, the select method is called. The select method should return a reference to a single individual from the population.

A selector may make its selections based either on the scaled (fitness) scores or on the raw (objective) scores of the individuals in the population. Note also that a population may be sorted either low-to-high or high-to-low, depending on which sort order was chosen. Your selector should be able to handle either order (this way it will work with genetic algorithms that maximize or minimize).

The selection scheme class is polymorphic, so you should define the object's identity using the `GADefineIdentity` macro. This macro sets a class ID number and the name that will be used in error messages for the class. You can use any number above 200 for the ID, but be sure to use a different number for each of your objects.

## Customizing GAlib: Selection Scheme

Here is an implementation of a tournament selector. It is based on the roulette wheel selector and shares some of the roulette wheel selector's functionality. In particular, this tournament selector uses the roulette wheel selector's update method, so it does not define its own. The select method does two fitness-proportionate selections then returns the individual with better score.

```
class TournamentSelector : public GARouletteWheelSelector {
public:
    GADefineIdentity("TournamentSelector", 255);
    TournamentSelector(int w=GASelectionScheme::FITNESS) :
        GARouletteWheelSelector(w) {}
    TournamentSelector(const TournamentSelector& orig) { copy(orig); }
    TournamentSelector& operator=(const GASelectionScheme& orig)
    { if(&orig != this) copy(orig); return *this; }
    virtual ~TournamentSelector() {}
    virtual GASelectionScheme* clone() const
    { return new TournamentSelector; }
    virtual GAGenome& select() const;
};

GAGenome &
TournamentSelector::select() const {
    int picked=0;
    float cutoff;
    int i, upper, lower;
    cutoff = GARandomFloat();
    lower = 0; upper = pop->size()-1;
    while(upper >= lower){
        i = lower + (upper-lower)/2;
        if(psum[i] > cutoff)
            upper = i-1;
        else
            lower = i+1;
    }
    lower = Min(pop->size()-1, lower);
    lower = Max(0, lower);
    picked = lower;
    cutoff = GARandomFloat();
    lower = 0; upper = pop->size()-1;
    while(upper >= lower){
        i = lower + (upper-lower)/2;
        if(psum[i] > cutoff)
            upper = i-1;
        else
            lower = i+1;
    }
    lower = Min(pop->size()-1, lower);
    lower = Max(0, lower);
    GAPopulation::SortBasis basis =
        (which == FITNESS ? GAPopulation::SCALED : GAPopulation::RAW);
    if(pop->order() == GAPopulation::LOW_IS_BEST){
        if(pop->individual(lower,basis).score() <
           pop->individual(picked,basis).score())
            picked = lower;
    }
    else{
        if(pop->individual(lower,basis).score() >
           pop->individual(picked,basis).score())
            picked = lower;
    }
    return pop->individual(picked,basis);
}
```

## Genetic Algorithm

Here is a sample derived class that does restricted mating. In this example, one of the parents is selected as usual. The second individual is select as the first, but it is used only if it is similar to the first individual. If not, we make another selection. If enough selections fail, we take what we can get.

```
class RestrictedMatingGA : public GASteadyStateGA {
public:
    GADefineIdentity("RestrictedMatingGA", 288);
    RestrictedMatingGA(const GAGenome& g) : GASteadyStateGA(g) {}
    virtual ~RestrictedMatingGA() {}
    virtual void step();
    RestrictedMatingGA & operator++() { step(); return *this; }
};

void
RestrictedMatingGA::step() {
    int i, k;
    for(i=0; i<tmpPop->size(); i++){
        mom = &(pop->select());
        k=0;
        do {
            k++; dad = &(pop->select());
        } while(mom->compare(*dad) < THRESHOLD && k<pop->size());
        stats.numsel += 2;
        if(GAFlipCoin(pCrossover()))
            stats.numcro += (*scross)(*mom, *dad, &tmpPop->individual(i), 0);
        else
            tmpPop->individual(i).copy(*mom);
        stats.nummut += tmpPop->individual(i).mutate(pMutation());
    }
    for(i=0; i<tmpPop->size(); i++)
        pop->add(tmpPop->individual(i));
    pop->evaluate();           // get info about current pop for next
    time pop->scale();         // remind the population to do its scaling
    for(i=0; i<tmpPop->size(); i++)
        pop->destroy(GAPopulation::WORST, GAPopulation::SCALING);
    stats.update(*pop);          // update the statistics by one generation
}
```

## Termination Function

The termination function determines when the genetic algorithm should stop evolving. It takes a genetic algorithm as its argument and returns gaTrue if the genetic algorithm should stop or gaFalse if the algorithm should continue.

Here are three examples of termination functions. The first compares the current generation to the desired number of generations. If the current generation is less than the desired number of generations, it returns gaFalse to signify that the GA is not yet complete.

```
GABoolean
GATerminateUponGeneration(GAGeneticAlgorithm & ga){
    return(ga.generation() < ga.nGenerations() ? gaFalse : gaTrue);
}
```

The second example compares the average score in the current population with the score of the best individual in the current population. If the ratio of these exceeds a specified threshhold, it returns gaTrue to signify that the GA should stop. Basically this means that the entire population has converged to a 'good' score.

```
// stop when pop average is 95% of best
const float desiredRatio = 0.95;
```

## Customizing GAlib: Termination Function

```
GABoolean  
GATerminateUponScoreConvergence(GAGeneticAlgorithm & ga){  
    if(ga.statistics().current(GAStatistics::Mean) /  
       ga.statistics().current(GAStatistics::Maximum) > desiredRatio)  
        return gaTrue;  
    else  
        return gaFalse;  
}
```

The third uses the population diversity as the criterion for stopping. If the diversity drops below a specified threshold, the genetic algorithm will stop.

```
// stop when population diversity is below this  
const float thresh = 0.01;  
  
GABoolean  
StopWhenNoDiversity(GAGeneticAlgorithm & ga){  
    if(ga.statistics().current(GAStatistics::Diversity) < thresh)  
        return gaTrue;  
    else  
        return gaFalse;  
}
```

A faster method of doing a nearly equivalent termination is to use the population's standard deviation as the stopping criterion (this method does not require comparisons of each individual). Notice that this judges diversity based upon the genome scores rather than their actual genetic diversity.

```
// stop when population deviation is below this  
const float thresh = 0.01;  
  
GABoolean  
StopWhenNoDeviation(GAGeneticAlgorithm & ga){  
    if(ga.statistics().current(GAStatistics::Deviation) < thresh)  
        return gaTrue;  
    else  
        return gaFalse;  
}
```

## Descriptions of the Examples

---

Each of the examples contains comments in the source files with complete description about what is going on. Here is a short summary of what each one of the examples does:

**ex1**

Fill a 2DBinaryStringGenome with alternating 0s and 1s using a SimpleGA.

**ex2**

Generate a sequence of random numbers, then use a Bin2DecChromosome and SimpleGA to try and match the sequence. This example shows how to use the user-data member of genomes in objective functions.

**ex3**

Read a 2D pattern from a data file then try to match the pattern using a 2DBinaryStringGenome and a SimpleGA. This example also shows how to use the GAParametes object for setting genetic algorithm parameters and reading command-line arguments.

**ex4**

Fill a 3DBinaryStringChromosome with alternating 0s and 1s using a SteadyStateGA. This example uses many member functions of the genetic algorithm to control which statistics are recorded and dumped to file.

**ex5**

This example shows how to build a composite genome (a cell?) using a 2DBinaryStringGenome and a Bin2DecGenome. The composite genome uses behaviors that are defined in each of the genomes that it contains. The objective is to match a pattern and sequence of numbers.

**ex6**

Grow a GATreeGenome using a SteadyStateGA. This example illustrates the use of specialized methods to override the default initialization method and to specialize the output from a tree. It also shows how to use templated genome classes. Finally, it shows the use of the parameters object to set default values then allow these to be modified from the command line. The objective function in this example tries to grow the tree as large as possible.

**ex7**

Identical in function to example 3, this example shows how to use the increment operator (++), completion measure, and other member functions of the GA. It uses a GA with overlapping populations rather than the non-overlapping GA in example 3 and illustrates the use of many of the GA member functions. It also illustrates the use of the parameter list for reading settings from a file, and shows how to stuff a genome with data from an input stream.

**ex8**

Grow a GAListGenome using a GA with overlapping populations. This shows how to randomly initialize a list of integers, how to use the sigma truncation scaling object to handle objective scores that may be positive or negative, and the 'set' member of the genetic algorithm for controlling statistics and other genetic algorithm parameters.

## Descriptions of the Examples

### **ex9**

Find the maximum value of a continuous function in two variables. This example uses a GABin2DecGenome and simple GA. It also illustrates how to use the GASigmaTruncationScaling object (rather than the default linear scaling). Sigma truncation is particularly useful for objective functions that return negative values.

### **ex10**

Find the maximum value of a continuous, periodic function. This example illustrates the use of sharing to do speciation. It defines a sample distance function (one that does the distance measure based on the genotype, the other based on phenotype). It uses a binary- to-decimal genome to represent the function values.

### **ex11**

Generate a sequence of descending numbers using an order-based list. This example illustrates the use of a GAListGenome as an order-based chromosome. It contains a custom initializer and shows how to use this custom initializer in the List genome.

### **ex12**

Alphabetize a sequence of characters. Similar to example 11, this example illustrates the use of the GAStringGenome (rather than a list) as an order-based chromosome.

### **ex13**

This program runs a GA-within-GA. The outer level GA tries to match the pattern read in from a file. The inner GA tries to match a sequence of randomly generated numbers (the sequence is generated at the beginning of the program's execution). The inner level GA is run only when the outer GA reaches a threshhold objective score.

### **ex14**

Another illustration of how to use composite chromosomes. In this example, the composite chromosome contains a user-specifiable number of lists. Each list behaves differently and is not affected by mutations, crossovers, or initializations of the other lists.

### **ex15**

The completion function of a GA determines when it is "done". This example uses the convergence to tell when the GA has reached the optimum (the default completion measure is number-of-generations). It uses a binary-to-decimal genome and tries to match a sequence of randomly generated numbers.

### **ex16**

Tree chromosomes can contain any kind of object in the nodes. This example shows how to put a point object into the nodes of a tree to represent a 3D plant. The objective function tries to maximize the size of the plant.

### **ex17**

Array chromosomes can be used when you need tri-valued alleles. This example uses a 2D array with trinary alleles.

### **ex18**

This example compares the performance of three different genetic algorithms. The genome and objective function are those used in example 3, but this example lets you specify which type of GA you want to use to solve the problem. You can use steady state, simple, or incremental just by specifying

## Descriptions of the Examples

one of them on the command line. The example saves the generational data to file so that you can then plot the convergence data to see how the performance of each genetic algorithm compares to the others.

**ex19**

The 5 DeJong test problems.

**ex20**

Holland's royal road function. This example computes Holland's 1993 ICGA version of the Royal Road problem. Holland posed this problem as a challenge to test the performance of genetic algorithms and challenged other GA users to match or beat his performance.

**ex21**

This example illustrates various uses of the allele set in array genomes. The allele set may be an enumerated list of items or a bounded range of continuous values, or a bounded set of discrete values. This example shows how each of these may be used in combination with a real number genome.

**ex22**

This example shows how to derive a new genetic algorithm class in order to customize the replacement method. Here we derive a new type of steady-state genetic algorithm in which speciation is done more effectively by not only scaling fitness values but also by controlling the way new individuals are inserted into the population.

**ex23**

The genetic algorithm object can either maximize or minimize your objective function. This example shows how to use the minimize abilities of the genetic algorithm. It uses a real number genome with one element to find the maximum or minimum of a sinusoid.

**ex24**

This example shows how to restricted mating using a custom genetic algorithm and custom selection scheme. The restricted mating in the genetic algorithm tries to pick individuals that are similar (based upon their comparator). The selector chooses only the upper half of the population (so it cannot choose very bad individuals, unlike the roulette wheel selector, for example).

**ex25**

Multiple populations on a single CPU. This example uses the genetic algorithm class called a 'DemeGA'. The genetic algorithm controls the migration behavior for moving individuals between populations. In this example, the island model is used with a stepping-stone migration behavior in which the best individuals from each population migrate to their nearest neighboring population. You can easily modify both the migration algorithm and the population behaviors by deriving a new class from the DemeGA.

**ex26**

Travelling Salesperson Problem. Although genetic algorithms are not the best way to solve the TSP, we include an example of how it can be done. This example uses an order-based list as the genome to figure out the shortest path that connects a bunch of towns such that each town is visited exactly once. It uses the edge recombination crossover operator (you can try it with the partial match crossover as well to see how poorly PMX does on this particular problem).

**ex27**

Deterministic crowding. Although the algorithms built-in to GAlib allow you to do quite a bit of customization, sometimes you'll want to derive your own class so that you can really tweak the way the

## **Descriptions of the Examples**

algorithm works. This example shows one way of implementing the deterministic crowding method by deriving an entirely new genetic algorithm class.

### **graphic<sup>1</sup>**

You can learn a great deal by watching the genetic algorithm evolve. This example has a simple X windows interface that lets you start, stop, restart, and incrementally evolve a population of individuals. You can see the evolution in action, so it becomes very obvious if your operators are not working correctly or if the algorithm is converging prematurely.

The directory contains two different examples. In the first you can choose between 3 different genetic algorithms, 2 different genomes (real or binary-to-decimal), and 4 different functions. In the second you can watch a population of routes evolve for the travelling salesman problem. Both programs use X resources as well as command-line arguments to control their behavior. You can also use a standard GAlib settings file. These programs will compile using either the Motif or the athena widget set.

### **gnu<sup>1</sup>**

This directory contains the code for an example that uses the BitString object from the GNU class library. The example illustrates how to incorporate an existing object (in this case the BitString) into a GAlib Genome type. The gnu directory contains the source code needed for the BitString object (taken from the GNU library) plus the two files (bitstr.h and bitstr.C) needed to define the new genome type and the example file that runs the GA (gnuex.C).

### **pvmind<sup>1</sup>**

This directory contains code that illustrates how to use GAlib with PVM in a master-slave configuration wherein the master process is the genetic algorithm with a single population and each slave process is a genome evaluator. The master sends individual genomes to the slave processes to be evaluated then the slaves return the evaluations.

### **pvmppop<sup>1</sup>**

This directory contains code that illustrates a PVM implementation of parallel populations. The master process initiates a cluster of slaves each of which contains a single population. The master process harvests individuals from all of the distributed populations. With a few modifications you can also use this example with the deme GA from example 25 (it uses migration to distribute diversity between pops).

### **randtest**

Use this program to verify that the random number generator is generating suitably random numbers on your machine. This is by no means a comprehensive random number testor, but it will give you some idea of how well GAlib's random number generator is working.

---

<sup>1</sup> These examples are included only in the UNIX distribution.