



# HeuristicLab

A Paradigm-Independent and Extensible  
Environment for Heuristic Optimization

## Programming HeuristicLab

### Algorithms and Problems

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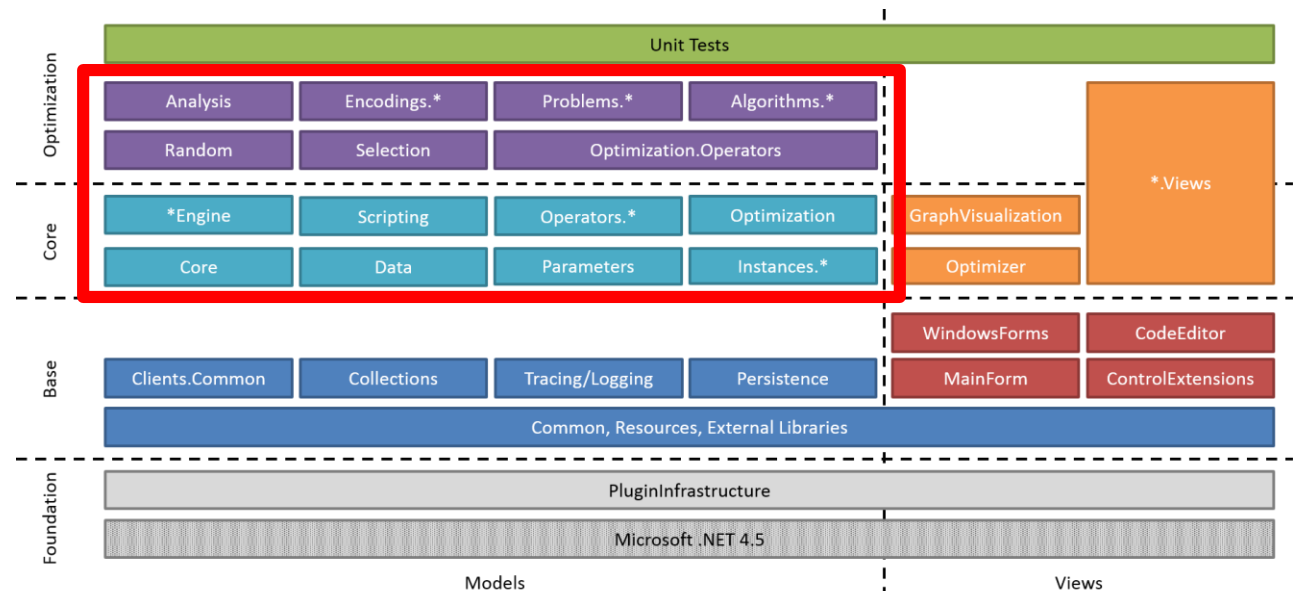
**HEAL**

Heuristic and Evolutionary  
Algorithms Laboratory

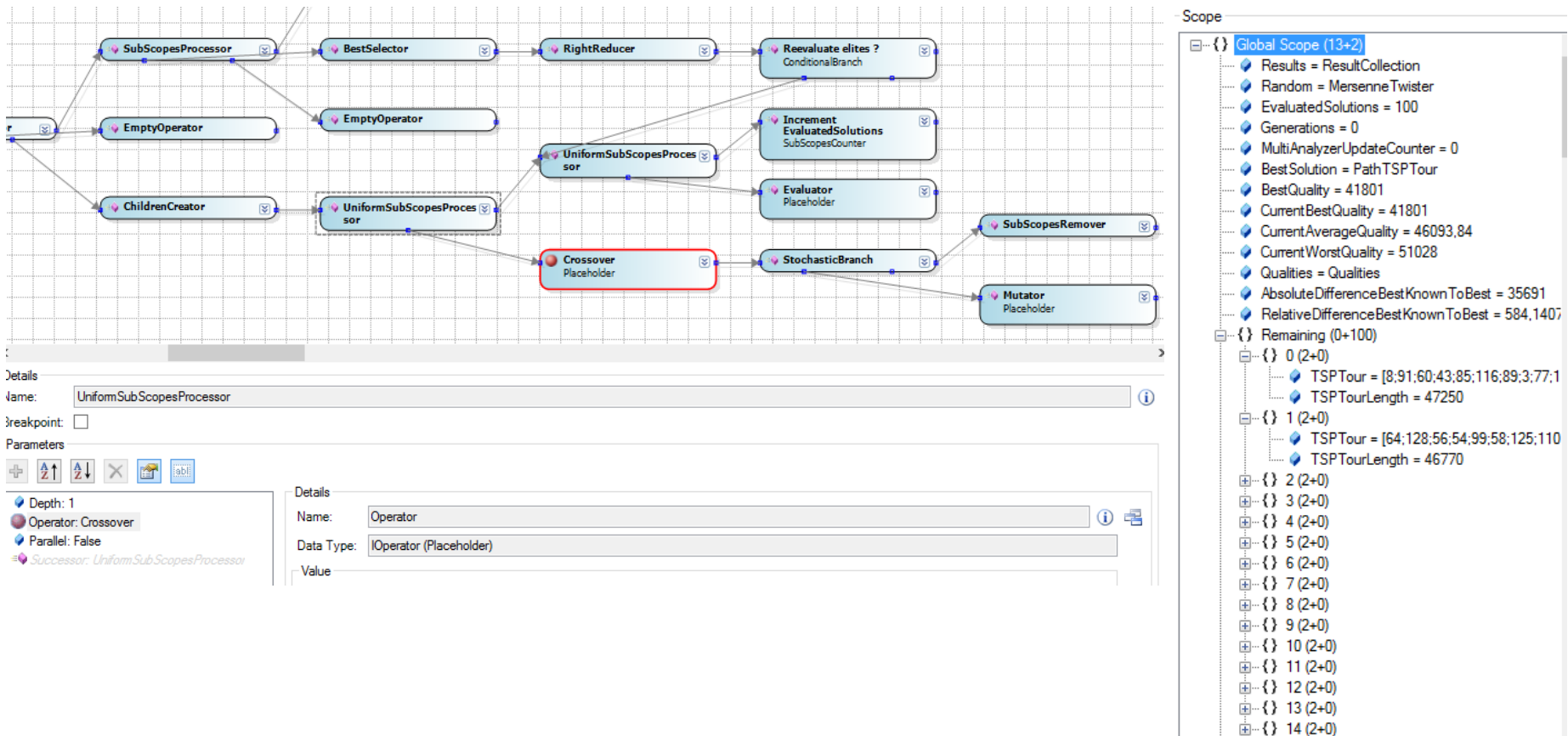


# Overview

- HL Algorithm Model
- Parameters, Operators and Scopes
- Algorithms
- Problems



# Parameters, Operators and Scopes



The screenshot displays the HeuristicLab interface. On the left, a workflow diagram shows a sequence of operators: SubScopesProcessor, BestSelector, RightReducer, and Reevaluate elites? ConditionalBranch. Below this, a details panel for the selected 'UniformSubScopesProcessor' operator is shown, with fields for Name, Breakpoint, Parameters, and Details. On the right, a 'Scope' tree is visible, showing a hierarchical structure of scopes and their associated parameters and values.

```
graph LR; Start(( )) --> EmptyOperator1[EmptyOperator]; Start --> ChildrenCreator[ChildrenCreator]; EmptyOperator1 --> SubScopesProcessor[SubScopesProcessor]; ChildrenCreator --> UniformSubScopesProcessor1[UniformSubScopesProcessor]; SubScopesProcessor --> BestSelector[BestSelector]; SubScopesProcessor --> EmptyOperator2[EmptyOperator]; BestSelector --> RightReducer[RightReducer]; EmptyOperator2 --> UniformSubScopesProcessor2[UniformSubScopesProcessor]; RightReducer --> ReevaluateElites[Reevaluate elites? ConditionalBranch]; UniformSubScopesProcessor1 --> UniformSubScopesProcessor3[UniformSubScopesProcessor]; UniformSubScopesProcessor2 --> UniformSubScopesProcessor3; UniformSubScopesProcessor3 --> CrossoverPlaceholder[Crossover Placeholder]; UniformSubScopesProcessor3 --> StochasticBranch[StochasticBranch]; ReevaluateElites --> IncrementEvaluatedSolutions[Increment EvaluatedSolutions SubScopesCounter]; ReevaluateElites --> EvaluatorPlaceholder[Evaluator Placeholder]; CrossoverPlaceholder --> MutatorPlaceholder[Mutator Placeholder]; StochasticBranch --> MutatorPlaceholder; IncrementEvaluatedSolutions --> SubScopesRemover[SubScopesRemover]; EvaluatorPlaceholder --> SubScopesRemover; MutatorPlaceholder --> SubScopesRemover;
```

**Details**  
Name: UniformSubScopesProcessor  
Breakpoint:   
Parameters  
Depth: 1  
Operator: Crossover  
Parallel: False  
Successor: UniformSubScopesProcessor

**Details**  
Name: Operator  
Data Type: Operator (Placeholder)  
Value

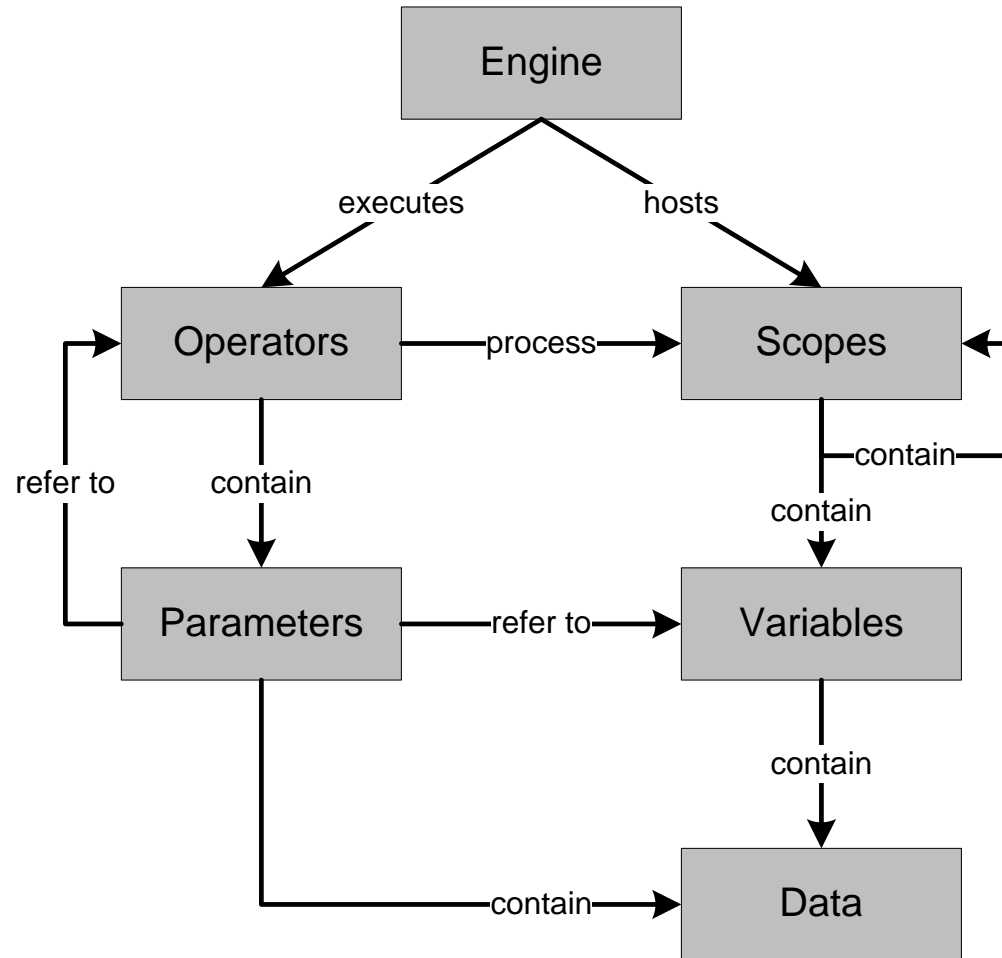
**Scope**  
Global Scope (13+2)  
Results = ResultCollection  
Random = MersenneTwister  
EvaluatedSolutions = 100  
Generations = 0  
MultiAnalyzerUpdateCounter = 0  
BestSolution = PathTSPTour  
BestQuality = 41801  
CurrentBestQuality = 41801  
CurrentAverageQuality = 46093.84  
CurrentWorstQuality = 51028  
Qualities = Qualities  
AbsoluteDifferenceBestKnownToBest = 35691  
RelativeDifferenceBestKnownToBest = 584,1407  
Remaining (0+100)  
0 (2+0)  
TSPTour = [8;91;60;43;85;116;89;3;77;1  
TSPTourLength = 47250  
1 (2+0)  
TSPTour = [64;128;56;54;99;58;125;110  
TSPTourLength = 46770  
2 (2+0)  
3 (2+0)  
4 (2+0)  
5 (2+0)  
6 (2+0)  
7 (2+0)  
8 (2+0)  
9 (2+0)  
10 (2+0)  
11 (2+0)  
12 (2+0)  
13 (2+0)  
14 (2+0)

# HL Algorithm Model



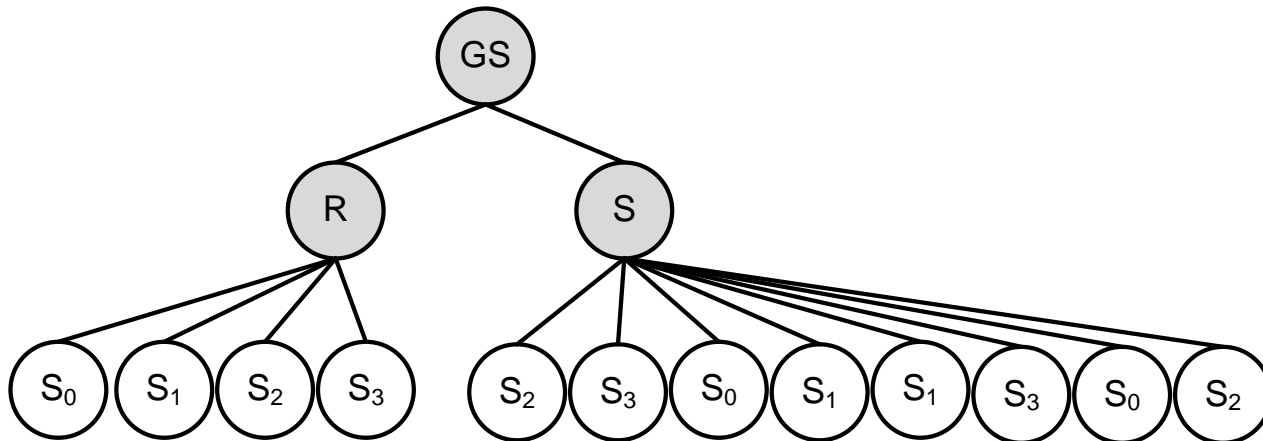
- Typically, HL algorithms are constructed by chaining together operators
- An engine executes these operators
  - Enables pausing and debugging
  - Available engines:
    - Sequential engine
    - Parallel engine
    - Debug engine
    - (Hive engine)

# HL Algorithm Model



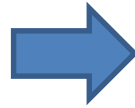
# Scopes

- A scope is a node in the scope tree
- Contains link to parent and sub-scopes
- Contains variables (e.g., solutions or their quality)
- Operators usually work on scopes (either directly or through parameters)
- Example - Selection:

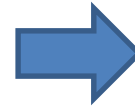


# Scopes – Debug Engine

```
Global Scope (13+100)
├── Results = ResultCollection
├── Random = Mersenne Twister
├── EvaluatedSolutions = 100
├── Generations = 0
├── MultiAnalyzerUpdateCounter = 0
├── BestSolution = PathTSPTour
├── BestQuality = 41160
├── CurrentBestQuality = 41160
├── CurrentAverageQuality = 46512.37
├── CurrentWorstQuality = 50948
├── Qualities = Qualities
├── AbsoluteDifferenceBestKnownToBest = 35050
├── RelativeDifferenceBestKnownToBest = 573.649754500818
├── Remaining (0+100)
├── Selected (0+100)
├── 0 (2+0)
│   ├── TSPTour = [75;64;92;19;80;116;53;42;126;56;121;70;2]
│   └── TSPTourLength = 49295
├── 1 (2+0)
│   ├── TSPTour = [38;37;55;122;74;87;102;56;94;58;43;95;64]
│   └── TSPTourLength = 44136
├── 2 (2+0)
├── 3 (2+0)
├── 4 (2+0)
├── 5 (2+0)
├── 6 (2+0)
├── 7 (2+0)
├── 8 (2+0)
├── 9 (2+0)
├── 10 (2+0)
├── 11 (2+0)
├── 12 (2+0)
├── 13 (2+0)
├── 14 (2+0)
├── 15 (2+0)
├── 16 (2+0)
├── 17 (2+0)
├── 18 (2+0)
├── 19 (2+0)
├── 20 (2+0)
├── 21 (2+0)
├── 22 (2+0)
├── 23 (2+0)
```



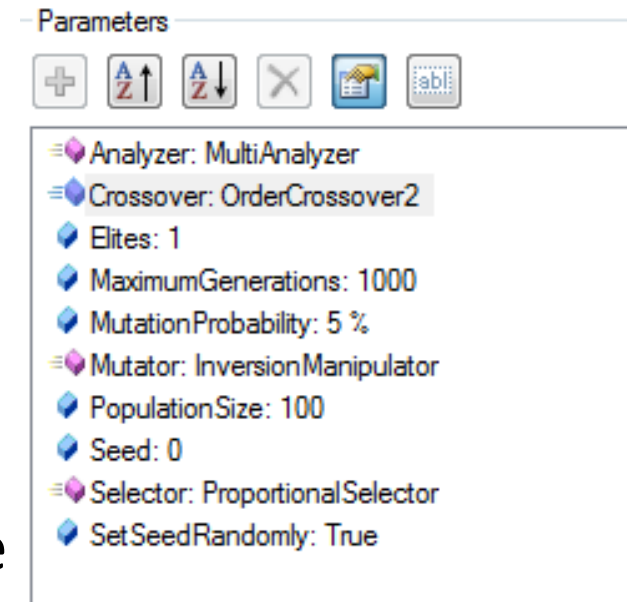
```
Global Scope (13+2)
├── Results = ResultCollection
├── Random = Mersenne Twister
├── EvaluatedSolutions = 100
├── Generations = 0
├── MultiAnalyzerUpdateCounter = 0
├── BestSolution = PathTSPTour
├── BestQuality = 41160
├── CurrentBestQuality = 41160
├── CurrentAverageQuality = 46512.37
├── CurrentWorstQuality = 50948
├── Qualities = Qualities
├── AbsoluteDifferenceBestKnownToBest = 35050
├── RelativeDifferenceBestKnownToBest = 573.649754500818
├── Remaining (0+100)
├── Selected (0+198)
├── 87 (2+0)
│   ├── TSPTour = [117;121;43;59;82;89;0;110;83;94;79;46]
│   └── TSPTourLength = 43222
├── 72 (2+0)
│   ├── TSPTour = [98;120;68;88;100;23;54;19;110;91;17;11]
│   └── TSPTourLength = 46328
├── 6 (2+0)
├── 10 (2+0)
├── 0 (2+0)
├── 64 (2+0)
├── 3 (2+0)
├── 34 (2+0)
├── 25 (2+0)
├── 73 (2+0)
├── 75 (2+0)
├── 11 (2+0)
├── 65 (2+0)
├── 43 (2+0)
├── 94 (2+0)
├── 93 (2+0)
├── 83 (2+0)
├── 60 (2+0)
├── 8 (2+0)
├── 89 (2+0)
├── 10 (2+0)
├── 49 (2+0)
```



```
Global Scope (13+2)
├── Results = ResultCollection
├── Random = Mersenne Twister
├── EvaluatedSolutions = 100
├── Generations = 0
├── MultiAnalyzerUpdateCounter = 0
├── BestSolution = PathTSPTour
├── BestQuality = 41160
├── CurrentBestQuality = 41160
├── CurrentAverageQuality = 46512.37
├── CurrentWorstQuality = 50948
├── Qualities = Qualities
├── AbsoluteDifferenceBestKnownToBest = 35050
├── RelativeDifferenceBestKnownToBest = 573.649754500818
├── Remaining (0+100)
├── Selected (0+99)
├── 0 (0+2)
│   ├── 87 (2+0)
│   │   ├── TSPTour = [117;121;43;59;82;89;0;110;83;94;79]
│   │   └── TSPTourLength = 43222
│   └── 72 (2+0)
│       ├── TSPTour = [98;120;68;88;100;23;54;19;110;91;1]
│       └── TSPTourLength = 46328
├── 1 (0+2)
│   ├── 6 (2+0)
│   └── 10 (2+0)
├── 2 (0+2)
├── 3 (0+2)
├── 4 (0+2)
├── 5 (0+2)
├── 6 (0+2)
├── 7 (0+2)
├── 8 (0+2)
├── 9 (0+2)
├── 10 (0+2)
├── 11 (0+2)
├── 12 (0+2)
├── 13 (0+2)
├── 14 (0+2)
├── 15 (0+2)
├── 16 (0+2)
├── 17 (0+2)
```

# Parameters

- Used to configure algorithms, problems and operators
- Used for accessing variables in the scope
- E.g., population size, analyzers, crossover operator
- Operators
  - Look up these parameters from the algorithm, problem or scope
  - Use them to store values (in the scope tree)





# Parameters

- `ValueParameter`:
  - Stores a value (Item) that can be looked up; e.g., mutation rate, crossover operator,...
- `LookupParameter`:
  - Looks up parameters/items (variables) from the scope/parent scopes.
- `ConstrainedValueParameter`:
  - Contains a list of selectable values.
- `ScopeTreeLookupParameter`:
  - Goes down the scope tree and looks up variables.
- `ScopeParameter`:
  - Returns the current scope.
- `ValueLookupParameter`, `OptionalConstrainedValueParameter`,  
`OperatorParameter`, `FixedValueParameter`,  
`OptionalValueParameter`,...

# Parameters

- Everything that is a `ParameterizedNamedItem` has a `parameters` collection
- Normally used in the following way:
  - Add parameter to `parameters` collection
  - Implement getter for convenience
  - Use parameter
  - Lookup parameter

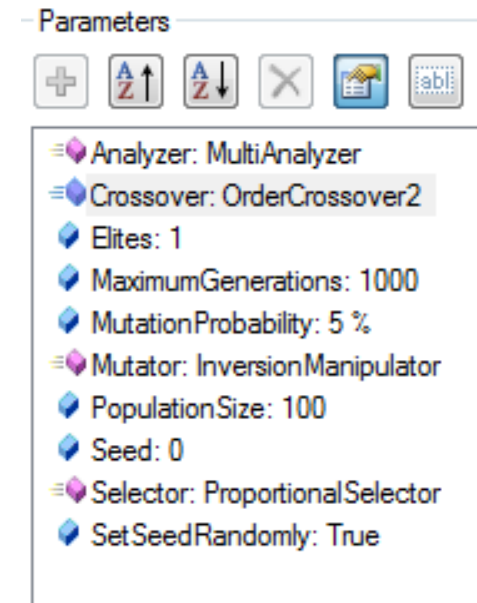
# Add parameter to parameters collection

- The Crossover parameter enables the user to select different crossover operators:

```
Parameters.Add(new ConstrainedValueParameter<ICrossover>("Crossover",  
"The operator used to cross solutions."));
```

- The PopulationSize is a freely configurable integer value:

```
Parameters.Add(new ValueParameter<IntValue>("PopulationSize",  
"The size of the population of solutions.", new IntValue(100)));
```



# Implement getter for convenience



- Getter for crossover parameter:

```
public IConstrainedValueParameter<ICrossover> CrossoverParameter {  
    get { return (IConstrainedValueParameter<ICrossover>)Parameters["Crossover"]; }  
}
```

- Getter for PopulationSize parameter:

```
private ValueParameter<IntValue> PopulationSizeParameter {  
    get { return (ValueParameter<IntValue>)Parameters["PopulationSize"]; }  
}
```

# Use parameter

- Use crossover parameter:

```
ICrossover defaultCrossover = Problem.Operators.OfType<ICrossover>().FirstOrDefault();  
foreach (ICrossover crossover in Problem.Operators.OfType<ICrossover>().OrderBy(x => x.Name))  
    CrossoverParameter.ValidValues.Add(crossover);  
CrossoverParameter.Value = defaultCrossover;
```

- Use PopulationSize parameter:

```
PopulationSizeParameter.Value.Value = 42;
```

# Lookup Parameter

- Defining lookup parameter for crossover:

```
Parameters.Add(new ValueLookupParameter<IOperator>("Crossover",  
"The operator used to cross solutions."));
```

```
public ValueLookupParameter<IntValue> PopulationSizeParameter {  
    get { return (ValueLookupParameter<IntValue>)Parameters["PopulationSize"]; }  
}
```

- Defining lookup parameter for population size:

```
Parameters.Add(new ValueLookupParameter<IntValue>("PopulationSize",  
"The size of the population."));
```

```
public ValueLookupParameter<IOperator> CrossoverParameter {  
    get { return (ValueLookupParameter<IOperator>)Parameters["Crossover"]; }  
}
```

# Use Lookup Parameter

- Set crossover parameter:

```
CrossoverParameter.Value =  
ga.CrossoverParameter.ValidValues.Single(x => x.GetType() == typeof(OrderCrossover));
```

- Set PopulationSize parameter:

```
PopulationSizeParameter.Value.Value = 42;
```

# Use Lookup Parameter

- In the genetic algorithm, a placeholder looks up the crossover that it executes:

- Create placeholder

```
Placeholder crossover = new Placeholder();
```

- Set the name of operator to lookup

```
crossover.OperatorParameter.ActualName = "Crossover";
```

- In the placeholder operator

```
OperationCollection next = new OperationCollection(base.Apply());  
IOperator op = OperatorParameter.ActualValue;  
if (op != null)  
    next.Insert(0, ExecutionContext.CreateOperation(op));  
return next;
```

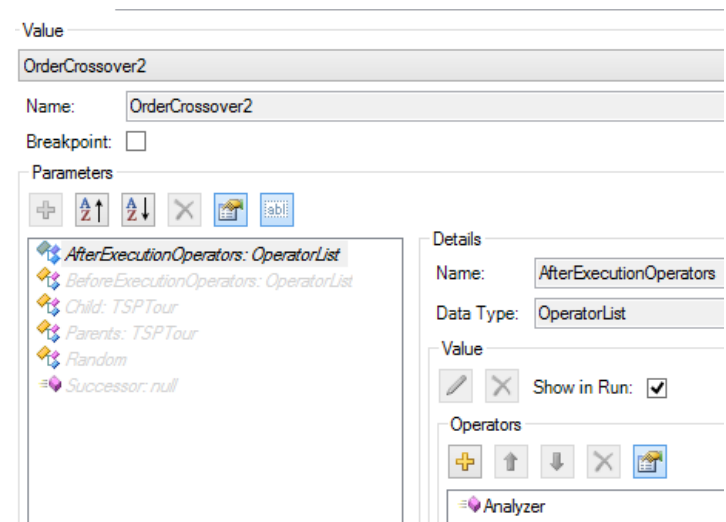


# Operators

- Inherit from `SingleSuccessorOperator`
- Override the `Apply()` method
- Must return `base.Apply()`
  - Returns successor operation
- Use `ExecutionContext` to access scopes
- Or better: Use parameters to retrieve scopes, values from scopes or manipulate them

# Instrumented Operators

- Inherit from `InstrumentedOperator`
- Override `InstrumentedApply()`
- Must return `base.InstrumentedApply()`
- Allows to configure before and after actions
- Useful for analyzers, additional functionality,... without changing the algorithm
- Think of aspect-oriented programming



# Operators

A operator that increments a value from the scope by „Increment“

For easier access to parameter values

A parameter for retrieving „Value“ (default name, can be configure with ActualValue) from scope or parent scopes

If the value is not found it can also be created in the scope

```
[Item("IntCounter", "An operator which increments an integer variable.")]
[StorableClass]
public sealed class IntCounter : SingleSuccessorOperator {
    public LookupParameter<IntValue> ValueParameter {
        get { return (LookupParameter<IntValue>)Parameters["Value"]; }
    }
    public ValueLookupParameter<IntValue> IncrementParameter {
        get { return (ValueLookupParameter<IntValue>)Parameters["Increment"]; }
    }
    public IntValue Increment {
        get { return IncrementParameter.Value; }
        set { IncrementParameter.Value = value; }
    }

    [StorableConstructor]
    private IntCounter(bool deserializing) : base(deserializing) { }
    private IntCounter(IntCounter original, Cloner cloner)
        : base(original, cloner) {
    }
    public IntCounter()
        : base() {
        Parameters.Add(new LookupParameter<IntValue>("Value", "The value which should be incremented.));
        Parameters.Add(new ValueLookupParameter<IntValue>("Increment", "The increment which is added to
the value.", new IntValue(1)));
    }

    public override IDeepCloneable Clone(Cloner cloner) {
        return new IntCounter(this, cloner);
    }

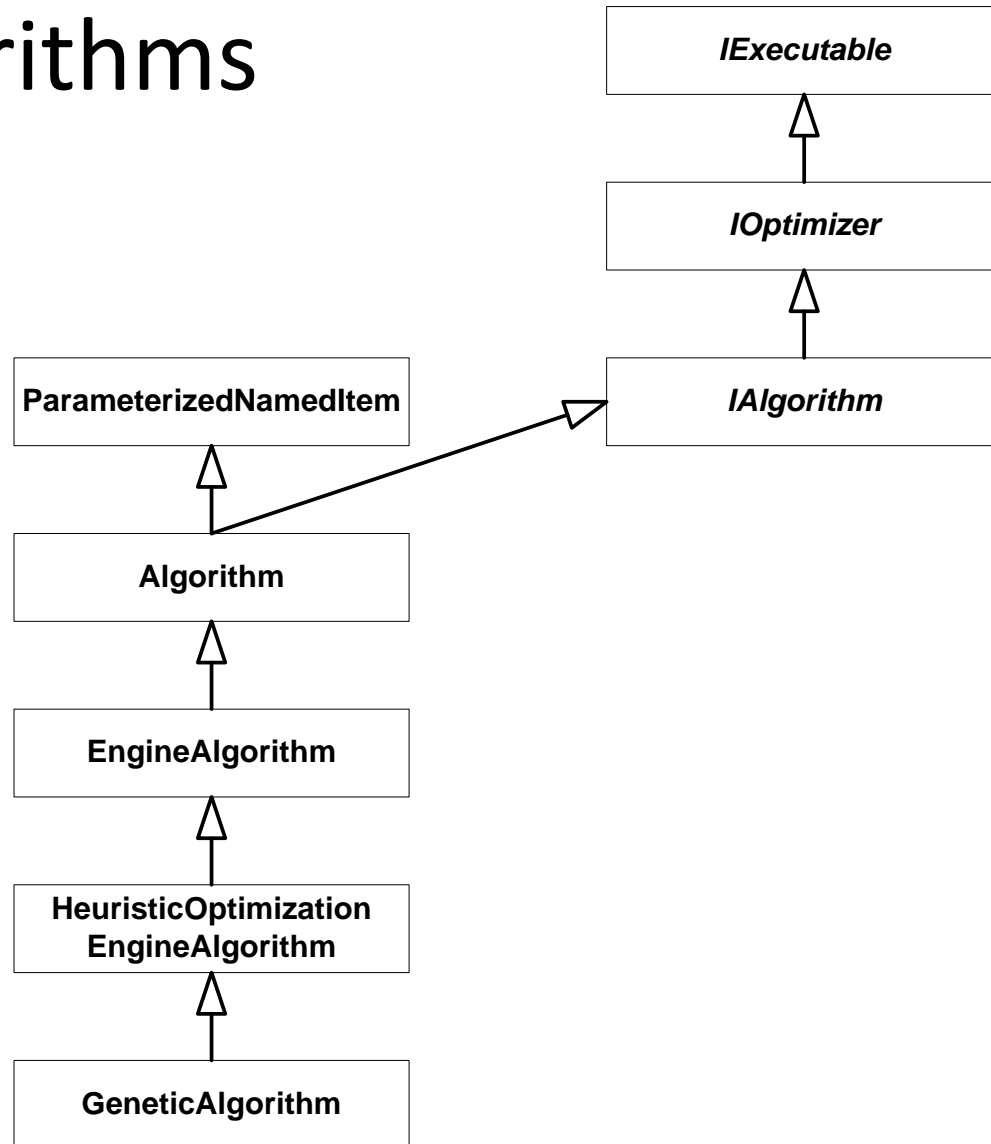
    public override IOperation Apply() {
        if (ValueParameter.ActualValue == null) ValueParameter.ActualValue = new IntValue();
        ValueParameter.ActualValue.Value += IncrementParameter.ActualValue.Value;
        return base.Apply();
    }
}
```

# Algorithms and Problems



- Different ways to implement algorithms and problems
- Algorithms
  - Flexible: Inherit from `HeuristicOptimizationEngineAlgorithm`
  - Easy: Inherit from `BasicAlgorithm`
- Problems
  - Flexible: Inherit from `SingleObjectiveHeuristicOptimizationProblem`
  - Easy: Inherit from `[Single|Multi]ObjectiveBasicProblem`

# Base classes/interfaces for algorithms



# Base classes/interfaces for algorithms



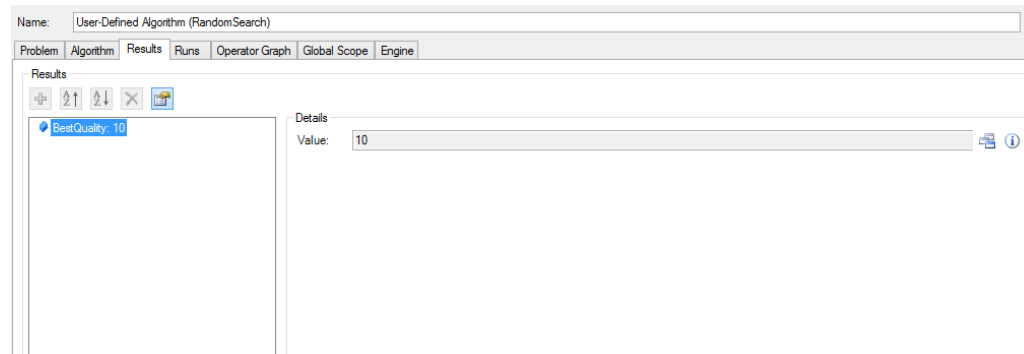
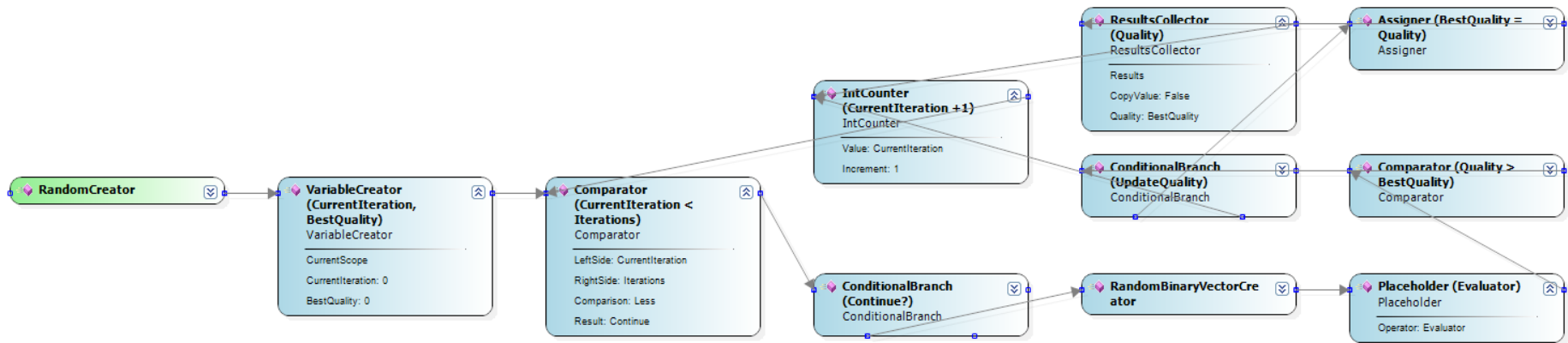
- `IExecutable (Executable)`:
  - Defines methods for starting, stopping, etc. of algorithms
- `IOptimizer`:
  - Contains a run collection
- `IAlgorithm`:
  - Contains a problem on which the algorithm is applied as well as a result
- `Algorithm`:
  - Base class, implements `IAlgorithm`
- `EngineAlgorithm`:
  - Extensions for execution with an engine (operator graph, scope, engine)
- `HeuristicOptimizationEngineAlgorithm`:
  - Specifies problem: `IHeuristicOptimizationProblem`

# What does an HL algorithm do?



- Create operator graph of algorithm by chaining together operators (the actual algorithm)
- Offer user configuration options through parameters
- Discover operators from the operators collection of the problem/encoding
- Parameterize/wire (react to changes in operators) operators where necessary

# Example – Random Search

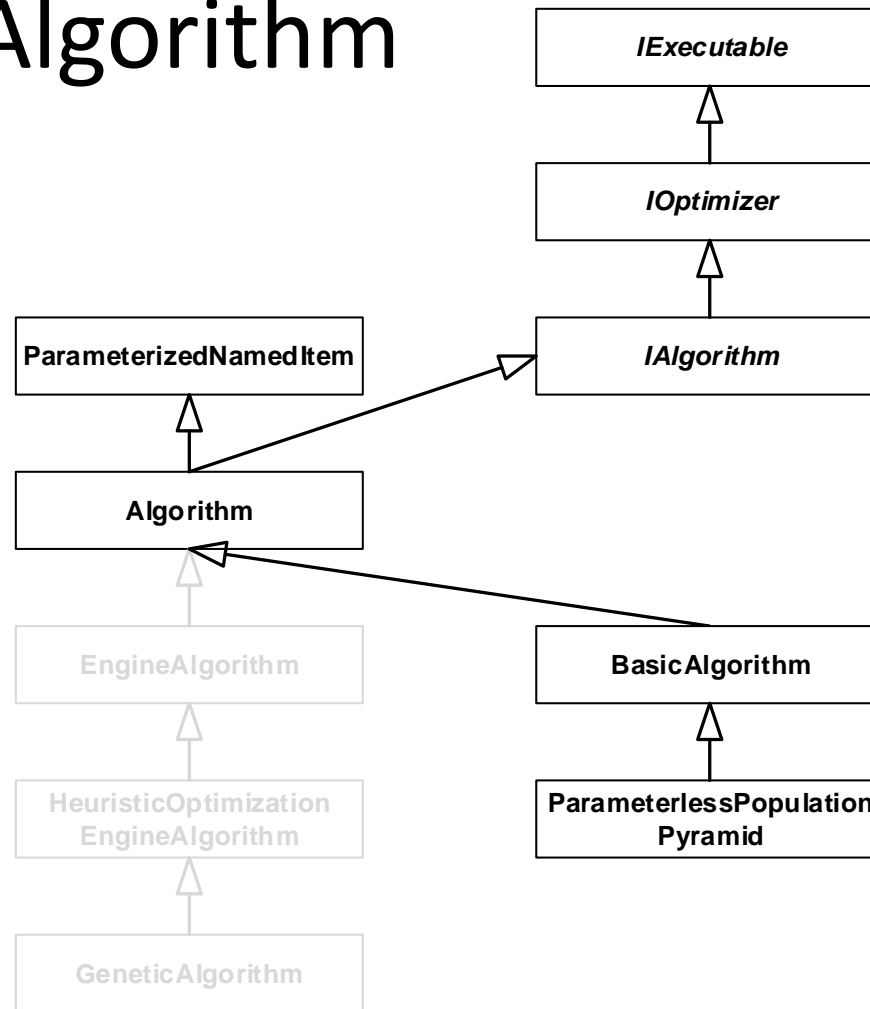




# BasicAlgorithm

- Creating an operator graph can be quite tricky
- Wiring operators is error-prone
- `BasicAlgorithms` are
  - Easy to implement
  - No boilerplate code
  - Hard-coded (no operator graph)
  - Don't support pausing
  - Support mainly single problems

# Base classes/Interfaces for BasicAlgorithm



# BasicAlgorithm - Interface

- Implement the Run method

```
protected override void Run(CancellationTokentoken cancellationToken)
```

- Optional: Fix problem type

```
public override Type ProblemType {  
    get { return typeof(BinaryProblem); }  
}  
  
public new BinaryProblem Problem {  
    get { return (BinaryProblem)base.Problem; }  
    set { base.Problem = value; }  
}
```

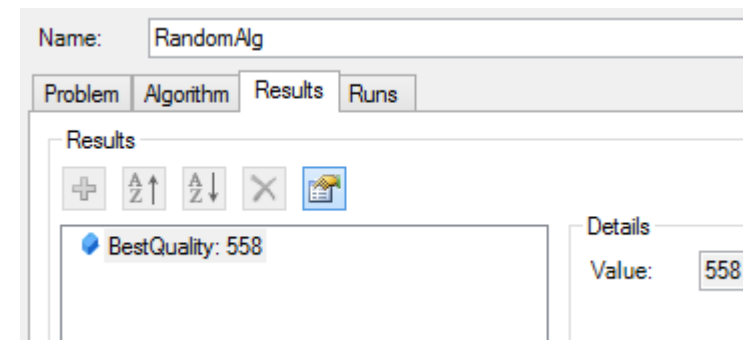
# Example – Random Search

```
protected override void Run(CancellationTok... {
    DoubleValue bestQuality = new DoubleValue(0.0);
    Results.Add(new Result("BestQuality", bestQuality));

    for(int i = 0; i < 100000; i++) {
        cancellationTok...ThrowIfCancellationRequested();

        BinaryVector b = new BinaryVector(Problem.Length, random);
        double curQuality = Problem.Evaluate(b, random);

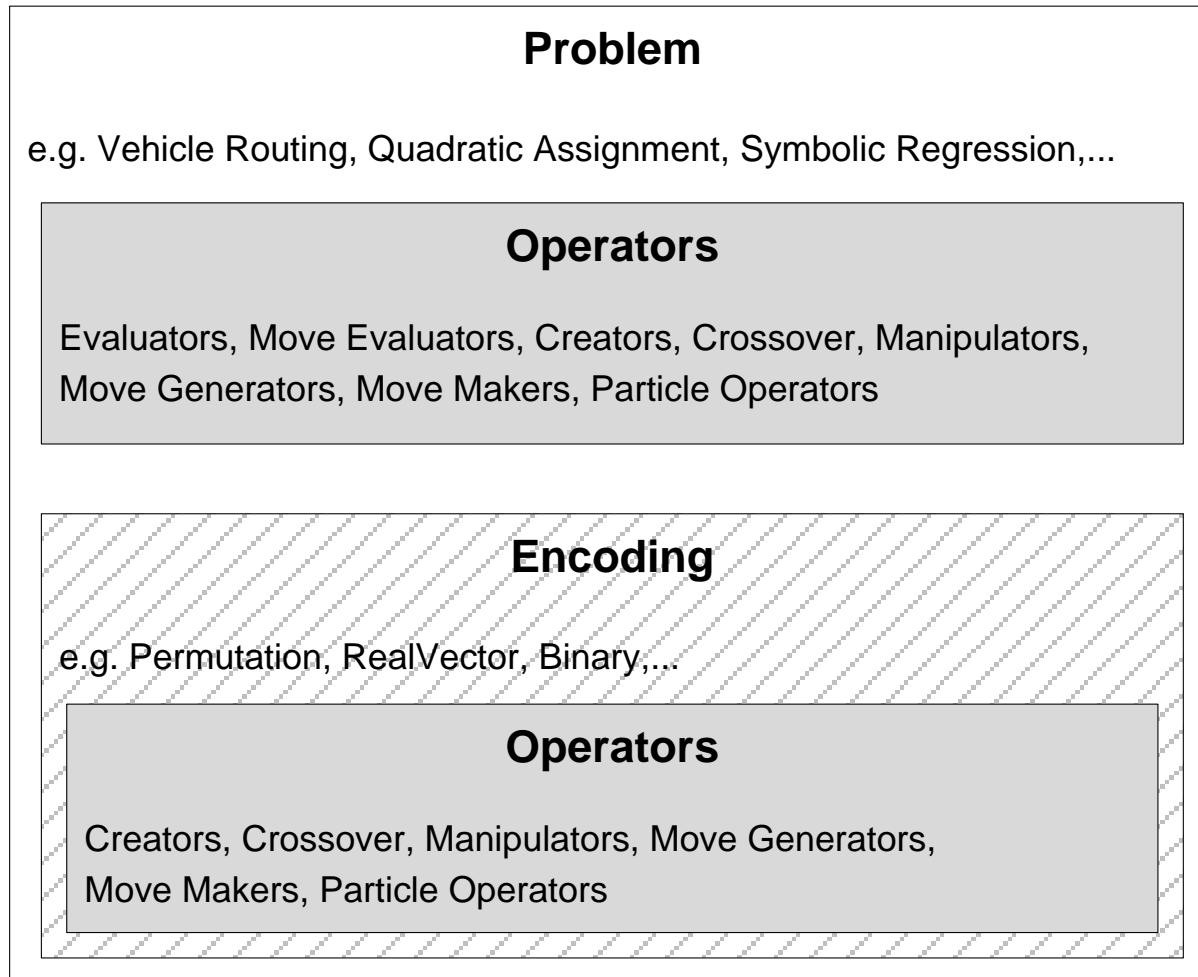
        if(Problem.Maximization && curQuality > bestQuality.Value) {
            bestQuality.Value = curQuality;
        } else if(!Problem.Maximization && curQuality < bestQuality.Value) {
            bestQuality.Value = curQuality;
        }
    }
}
```



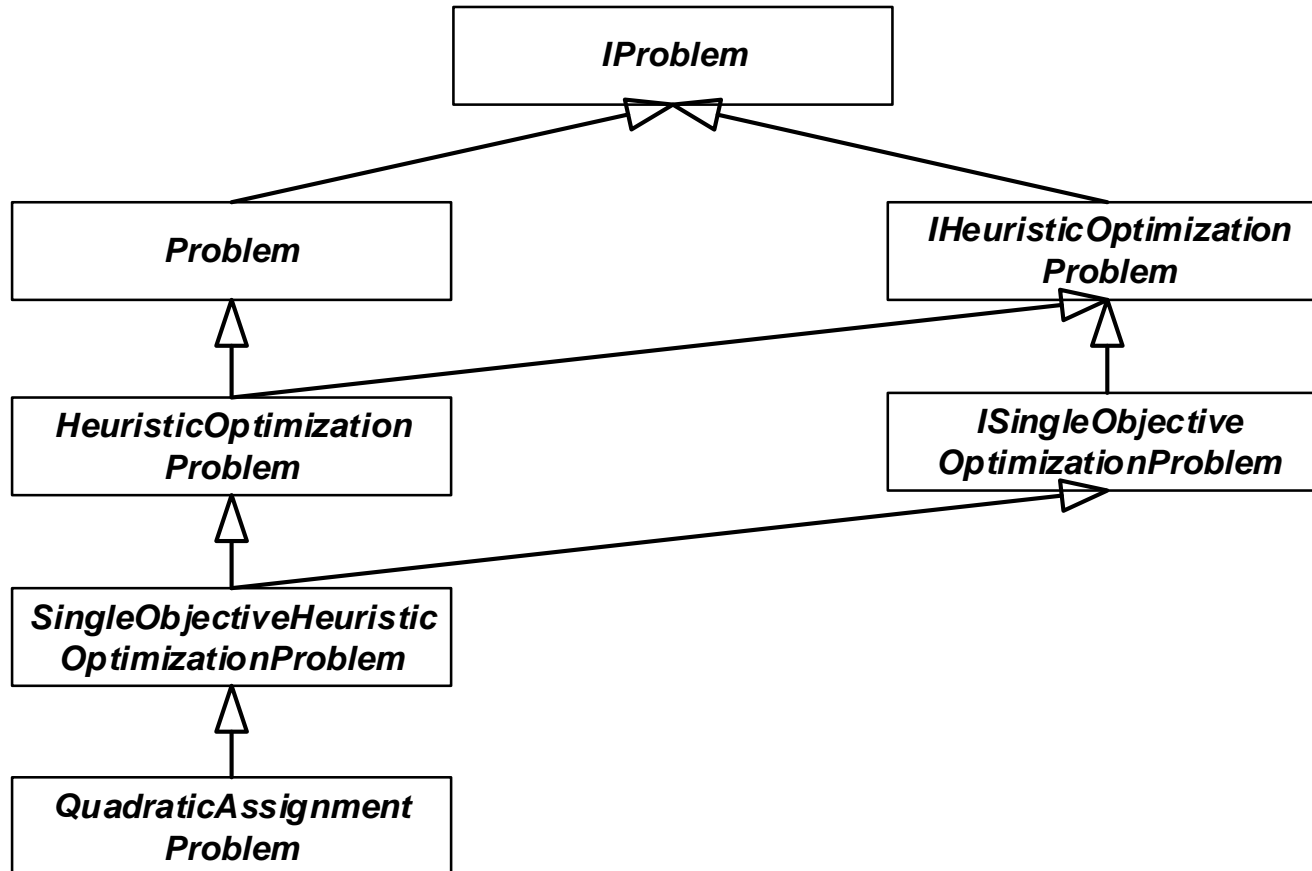
# Problems

- Use encodings for representing solutions
- Encodings consist of solution candidate definitions and corresponding operators
- Problems contain
  - the evaluator
  - the solution creator
- Define maximization or minimization
- Contain the „problem data“ (e.g., a distance matrix, a simulation, a function definition), usually supplied by a problem instance provider
- Can be single- or multi-objective
- Configured with parameters

# Problem Architecture



# Base classes/interfaces for problems



# Base classes/interfaces for problems



- `IProblem`:
  - Contains the operators collection; all operators that can be used by the problem, algorithm and user
- `IHeuristicOptimizationProblem`:
  - Defines solution creator and evaluator
- `Problem`,  
`HeuristicOptimizationProblem` **and**  
`Single/MultiObjectiveHeuristicOptimizationProblem` **provide abstract base classes**



# Recap: What does a HL problem do?

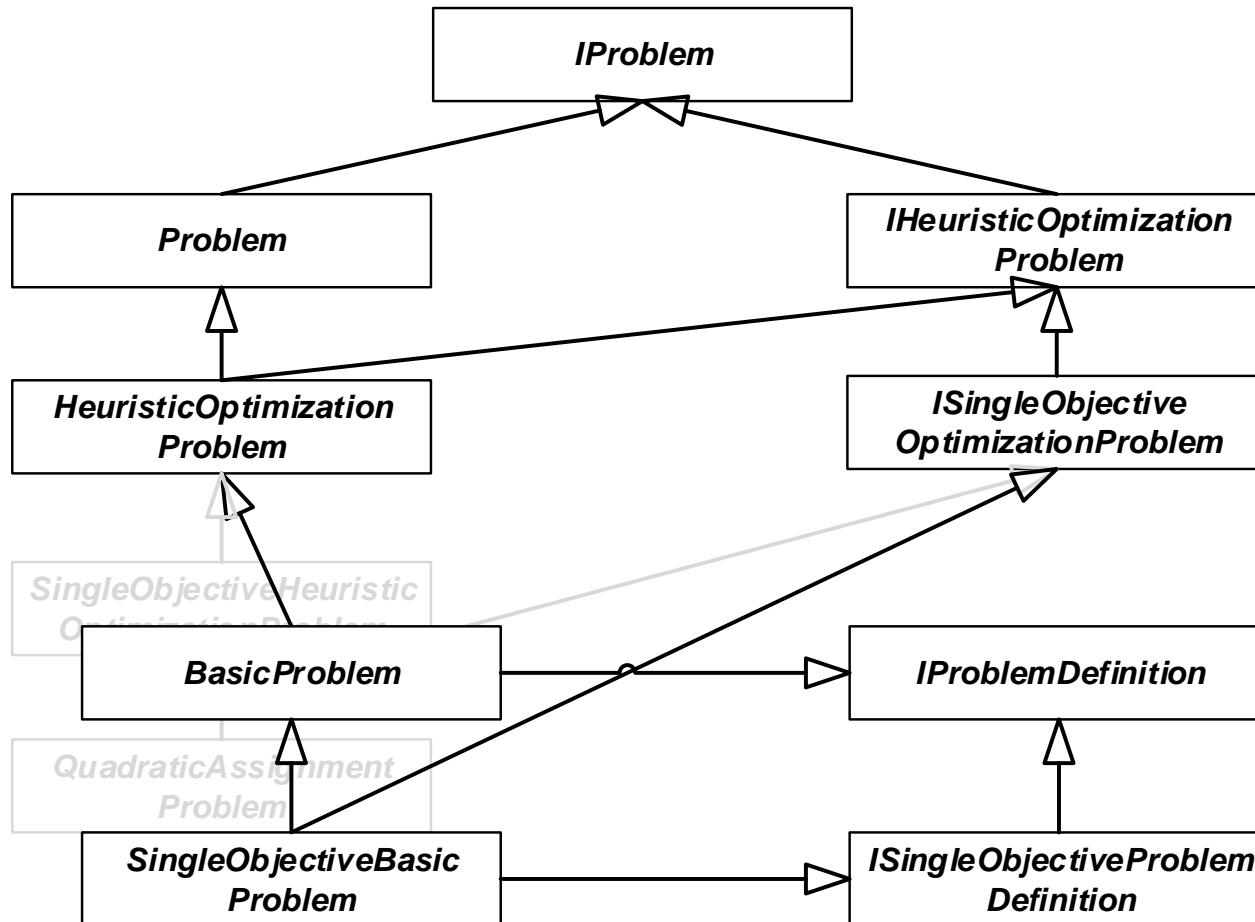


- Defines used encoding
- Defines single/multi objective
- Defines min/maximization
- Discovers correct operators
  - Are used by the algorithm
- Wires/parameterizes operators
- Wires/parameterizes parameters
- Loads problem data using a corresponding problem instance provider

# BasicProblem

- Similar concept as `BasicAlgorithm`
- Makes implementing new problems easier
- No wiring/operators necessary
- Use automatic encoding configuration
- Don't work with all algorithm types, e.g., algorithms that use very specific operators
  - Simulated Annealing
  - Scatter Search
  - Particle Swarm Optimization

# Base classes/interfaces for BasicProblem



# BasicProblem - Interface

- Define encoding

```
MyNewProblem : SingleObjectiveBasicProblem<BinaryVectorEncoding>
```

- Define maximization or minimization

```
bool Maximization { get; }
```

- Evaluate a solution and return quality

```
double Evaluate(Individual individual, IRandom random);
```

# BasicProblem - Interface

- Until now only GA variants can use the problem
- Implement neighbourhood function to also use trajectory-based metaheuristics

```
IEnumerable<Individual> GetNeighbors(Individual individual, IRandom random);
```

- Optional: Add analysis code for tracking results

```
void Analyze(Individual[] individuals, double[] qualities, ResultCollection results, IRandom random);
```

# BasicProblem – Example: OneMax



```
class OneMaxProblem : SingleObjectiveBasicProblem<BinaryVectorEncoding> {
    public OneMaxProblem() { }
    [StorableConstructor]
    protected OneMaxProblem(bool deserializing) : base(deserializing) {
}

    public OneMaxProblem(OneMaxProblem alg, Cloner cloner)
        : base(alg, cloner) { }
    public override IDeepCloneable Clone(Cloner cloner) {
        return new OneMaxProblem(this, cloner);
    }

    public override bool Maximization { get { return true; } }

    public override double Evaluate(Individual individual,
                                     IRandom random) {
        return individual.BinaryVector().Count(b => b);
    }
}
```

# Useful Links



<http://dev.heuristiclab.com/trac.fcgi/wiki/Documentation>

<http://dev.heuristiclab.com/trac.fcgi/wiki/Research>

[heuristiclab@googlegroups.com](mailto:heuristiclab@googlegroups.com)

<http://www.youtube.com/heuristiclab>