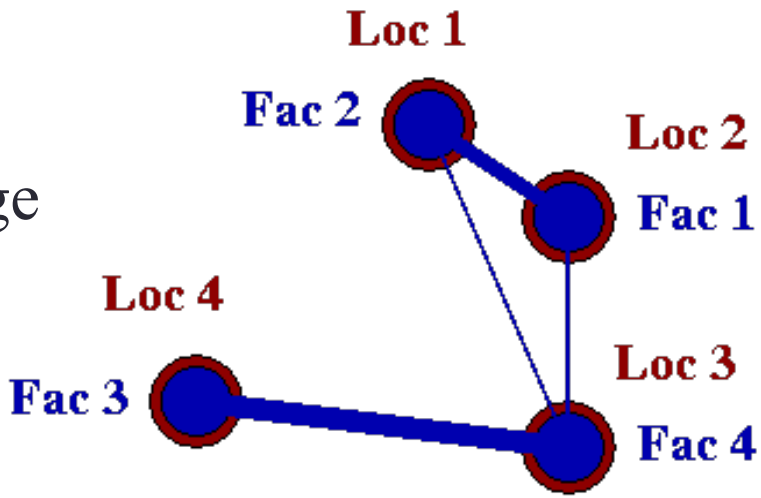
CONTROL ROOM ACCELERATOR PHYSICS

Day 3

A Primer on the XAL Solver

Outline

1. Overview
2. Solver Quick Start
3. More Advanced Solver Usage
4. Summary



XAL Solver

Overview – Solver of Optimization Problems

The XAL solver expects problems of the basic form

$$\min_{\mathbf{x} \in U} J(\mathbf{x})$$

where

$\mathbf{x}$ $= (x_1, x_2, \ldots, x_n)$ are the *parameters* or *variables* of the problem

U $= I_1 \times I_2 \ldots \times I_n$; $I_i = [x_{i,min}, x_{i,max}]$ are *constraint intervals* for x_i

$J(\mathbf{x})$ is the *objective* for the problem

- Any "problem" must be formulated in terms of
  - Parameters
  - An objective (multiple objects for advanced solver applications)
  - (Evaluations – for advanced solver applications)

XAL Solver

Quick Start

- The easiest way to use the XAL Solver is to…
  1. Creating class that implements `Scorer` interface defining the objective
     1. Represents $J(\mathbf{x})$
  2. Instantiate a `List` of `Variable` objects and their limits
     1. Represents $\mathbf{x}$
  3. Create a `Problem` object passing the `Variables` and the Scorer to a `ProblemFactory` method.
     1. Represents $\min_{\mathbf{x}} J(\mathbf{x})$
  4. Create a `Solver` object and solve problem

XAL Solver

Quick Start – Defining the Variables

- Instantiate one `Variable` for each parameter

```
from java.util import ArrayList;

from xal.tools.solver import Variable;


arrVars = ArrayList()
arrVars.add( Variable( "x", 0.0, -25.0, 25.0 ) )
arrVars.add( Variable( "y", 0.0, -25.0, 25.0 ) )
arrVars.add( Variable( "z", 0.0, -25.0, 25.0 ) )
```

XAL Solver

Quick Start – The Scorer Interface

- Scorer interface is one method: `score(Trial, List<Variable>)`
  - Trial contains all the state information
  - Second parameter represents **x**

```
package xal.tools.solver;

import java.util.List;

/** Score a trial. */
public interface Scorer {
    /**
     * Score the trial.
     * @param trial      the trial to score
     * @return           the score for the trial
     */
public double score( final Trial trial, final List<Variable> variables );
}
```

XAL Solver

Quick Start – Implementing the Scorer Interface

- Create a class that implements `Scorer`

Provides a figure of merit evaluation for a given trial set of variable values

```
from java.util import List;

from xal.tools.solver import Variable;
from xal.tools.solver import Solver;
from xal.tools.solver import Trial;
from xal.tools.solver import TrialPoint;

class TargetScorer(Scorer):

    def __init__( self, mapTargetVal):
        self._mapTargetVal = mapTargetVal;

    def score( self, trial, listVar ):
        norm2 = 0.0;
        for var in lstVar.toArray():
            diff = trial.getTrialPoint.getValue( var ) – self._mapTargetVal.get( var );
            norm2 = norm2 + diff*diff;
        return norm2;
```

mapTargetVal is of type **HashMap**

$mapTargetVal = \{(\text{var}, x_{i,tar})\}$

$\mathbf{x}_{tar} = (x_{1,tar}, \ldots, x_{n,tar})$

$\text{Score} = \| \mathbf{x} - \mathbf{x}_{tar} \|^2$

XAL Solver

Quick Start – Instantiation of a `Problem` Object

- Pick a problem type (min, max, least squares, etc.) by factory method
- Pass Variables and Scorer to ProblemFactory method

```
from java.util import HashMap;

from xal.solver import ProblemFactory;

mapTarget = HashMap();
mapTarget.put("x", 0.0);
mapTarget.put("y", 0.0);
mapTarget.put("z",0.0);

scorer = TargetScorer(mapTarget);

problem = ProblemFactory.getInverseSquareMinimizerProblem( arrVars, scorer,  0.001 )
```

Numeric tolerance parameter

XAL Solver

Quick Start – Solving the Problem

- Instantiate Solver object with passing a selected Stopper object
  - Pick a `Stopper` object from the `SolveStopperFactory`
- Solve the Problem

```
from xal.tools.solver import Solver;
from xal.tools.solver import Stopper;
from xal.tools.solver import SolveStopperFactory;

maxEvalStopper = SolveStopperFactory.maxEvaluationsStopper( 100 );
solver                 = Solver( maxMaxEvalStopper );

solver.solve( problem )

# Print out solver statistics
print solver.getScoreBoard()
```

XAL Solver

Quick Start Addendum – Note on "Constraints"

- The XAL Solver also facilitates a weak form of constrained optimization
  - Process works by implementing subclass of `Constraint` base
  - `Constraint` objects validate whether a `Trial` object is valid or not

```
/**
 * Constraint is the class which holds the users's constraint.
 */
abstract public class Constraint {
   protected String name;

   /** Creates a new instance of Constraint
    * @param aName The name of the constraint.
    */
   public Constraint(String aName) {   name = aName;   }

  /** Used to validate whether a trial is valid.
    * @param trial The trial to be validated.
    * @return A trial veto.
    */
   abstract public TrialVeto validate(Trial trial);
}
```

Advanced Use of the XAL Solver

Problems with "Multi-Objectives"

- The XAL Solver may be applied to more general optimization problems

- We consider problems with multi-objectives using satisfaction curves
  - Multi-objectives optimization problems have the form

$$\min_{\mathbf{x} \in U} J(\mathbf{x})$$

where $J(\mathbf{x}) = J_1(\mathbf{x}) + J_2(\mathbf{x}) + \ldots + J_n(\mathbf{x})$,
$J_i(\mathbf{x})$ being the *satisfaction* for *objective i*

  - Multi-objective `Problem`'s are implemented using the `Objective` superclass and the `Evaluator` interface

Advanced Use of the XAL Solver

Advanced Solver: Creating Multi-Objective Problems

- In order to define a `Problem` object…
  - Instantiate one `Variable` object for each free parameter
  - Define each objective
    - Create child class of `Objective` base, implementing the `satisfaction(double)` method (quantifying an objective)
      - The `satisfaction` method must return a `double` between 0 and 1
    - Instantiate an Objective child for each problem objective
    - Note: you can also combine all considerations in one objective
  - Create an `Evaluator` object
    - Must implement the `Evaluator` interface which computes the "score" for each objective at the current value of all the variables

Advanced Use of XAL Solver

Declaring Parameters

- Instantiate one `Variable` for each parameter
  - This process is the same as before

```
from java.util import ArrayList;

from xal.tools.solver import Variable;


arrVariables = ArrayList()
arrVariables.add( Variable( "x", 0.0, -25.0, 25.0 ) )
arrVariables.add( Variable( "y", 0.0, -25.0, 25.0 ) )
```

Advanced Use of XAL Solver

Defining Objectives

- Create child of `Objective` for each objective type
  - Must implement method `satisfaction(double): [0,1]`

```
from gov.sns.tools.math.r3 import R3;
from gov.sns.tools.solver import Objective;

class TargetObjective (Objective):

    def __init__( self, name, mapTargetVal):
        Objective.__init__( self, name )
        self._mapTargetVal = mapTargetVal

    def score( self, inputs ):
         norm2 = 0.0;
        for key in inputs.keySet().toArray():
            diff = inputs.get( key ) – self._mapTargetVal.get( key );
            norm2 = norm2 + diff*diff;
        return norm2;

    def satisfaction( self, score ):
        error = self._targetVal - score;
        return 1.0 / ( 1 + error * error )
```

mapTargetVal is of type **HashMap** represents parameter vector **x**

Score = $\| \mathbf{x} - \mathbf{x}_{tar} \|^2$

$$J_i(x_i) = \frac{1}{1 - \left\| \mathbf{x}_{tar} - \mathbf{x} \right\|^2}$$

Advanced Use of XAL Solver

Creating the Evaluator

- Create class implementing the Evaluator interface
  - Implement `evaluate(Trial)` for computing objective from parameter values

```
/**
 * Evaluator is an interface to a custom evaluator for a specific problem.
 *
*/
public interface Evaluator {

    /**
     * Score the trial.
     *
     * @param trial  The trial to evaluate.
     */
    public void evaluate( Trial trial );
}
```

Advanced Use of XAL Solver

Creating the Evaluator

- Implementing the Evaluator class
  - Must set the score for each objective: call `Trial.setScore(Objective, Double)`

```
from gov.sns.tools.solver import Evaluator;

class TestEvaluator (Evaluator):
    def __init__( self, objectives, variables ):
        self._objectives = objectives
        self._variables = variables

    def evaluate( self, trial ):
        inputs = HashMap( self._variables.size() )

        for variable in self._variables.toArray():
            value = trial.getTrialPoint().getValue( variable )
            inputs.put( variable, Double( value ) )

        for objective in self._objectives.toArray():
            score = objective.score( inputs )
            trial.setScore( objective, score )
```

Advanced Use of XAL Solver

Creating the Problem

- Instantiate a Problem object with arguments of
  - Objectives
  - Variables
  - Evaluator
- Solve the problem as before

```
mapX1 = HashMap();
mapX1.put("x", 0.0);
mapX1.put("y", 0.0);
mapX1.put("z",0.0);

mapX2 = HashMap();
mapX2.put("x", 1.0);
mapX2.put("y", 1.0);
mapX2.put("z",1.0);

J1 = TargetObject(mapX1);
J2 = TargetObject(mapX2);
```

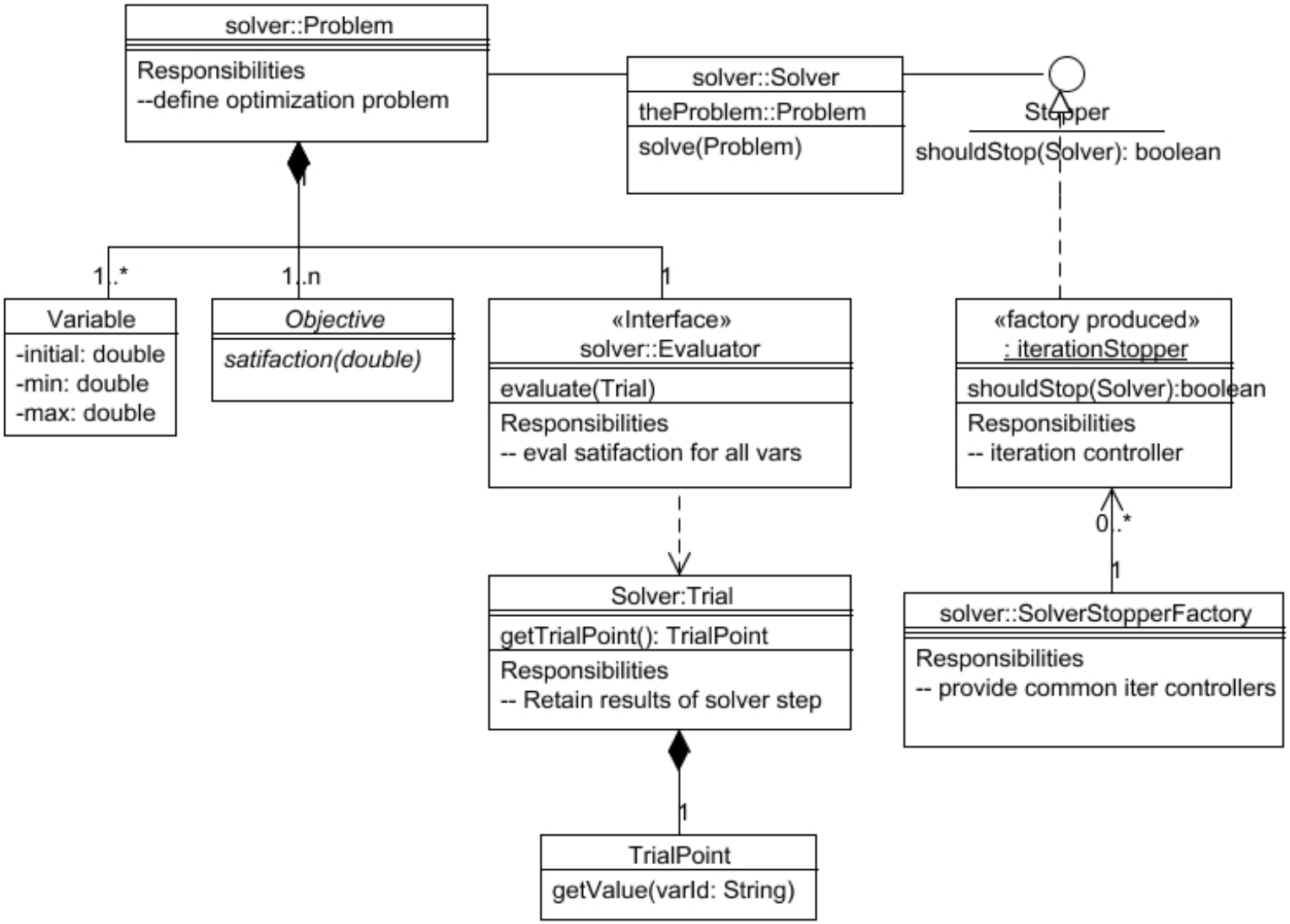
```
…

objectives = ArrayList()
objectives.add( J1);
objectives.add( J2 );

evaluator = TestEvaluator( objectives, variables )

problem = Problem( objectives, variables, evaluator )
```

XAL Solver Architecture



XAL Solver

Summary and Features

- Optimization by search
- Handles noisy data
- Callbacks for monitoring optimization progress
- Satisfaction curves
- Factory for quick configuration of simple problems
- Objectives with dynamic balancing
- Multiple algorithms dynamically adapt to problem