Pyomo Documentation

Release 6.1.2

Pyomo

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CONTENTS

Pyomo is a Python-based, open-source optimization modeling language with a diverse set of optimization capabilities.

CHAPTER

ONE

INSTALLATION

Pyomo currently supports the following versions of Python:

- CPython: 3.6, 3.7, 3.8, 3.9
- PyPy: 3

1.1 Using CONDA

We recommend installation with *conda*, which is included with the Anaconda distribution of Python. You can install Pyomo in your system Python installation by executing the following in a shell:

```
conda install -c conda-forge pyomo
```

Optimization solvers are not installed with Pyomo, but some open source optimization solvers can be installed with conda as well:

```
conda install -c conda-forge ipopt glpk
```

1.2 Using PIP

The standard utility for installing Python packages is *pip*. You can install Pyomo in your system Python installation by executing the following in a shell:

```
pip install pyomo
```

1.3 Conditional Dependencies

Extensions to Pyomo, and many of the contributions in *pyomo.contrib*, also have conditional dependencies on a variety of third-party Python packages including but not limited to: numpy, scipy, sympy, networkx, openpxl, pyodbc, xlrd, pandas, matplotlib, pymysql, pyro4, and pint. Pyomo extensions that require any of these packages will generate an error message for missing dependencies upon use.

Many of the conditional dependencies are already distributed with Anaconda. You can check which Python packages you already have installed using the command `conda list` or `pip list`. Additional Python packages may be installed as needed.

CHAPTER

TWO

CITING PYOMO

2.1 Pyomo

Hart, William E., Jean-Paul Watson, and David L. Woodruff. "Pyomo: modeling and solving mathematical programs in Python." Mathematical Programming Computation 3, no. 3 (2011): 219-260.

Hart, William E., Carl Laird, Jean-Paul Watson, David L. Woodruff, Gabriel A. Hackebeil, Bethany L. Nicholson, and John D. Siirola. Pyomo – Optimization Modeling in Python. Springer, 2017.

2.2 PySP

Watson, Jean-Paul, David L. Woodruff, and William E. Hart. "PySP: modeling and solving stochastic programs in Python." Mathematical Programming Computation 4, no. 2 (2012): 109-149.

CHAPTER

THREE

PYOMO OVERVIEW

3.1 Mathematical Modeling

This section provides an introduction to Pyomo: Python Optimization Modeling Objects. A more complete description is contained in the [PyomoBookII] book. Pyomo supports the formulation and analysis of mathematical models for complex optimization applications. This capability is commonly associated with commercially available algebraic modeling languages (AMLs) such as [AMPL], [AIMMS], and [GAMS]. Pyomo's modeling objects are embedded within Python, a full-featured, high-level programming language that contains a rich set of supporting libraries.

Modeling is a fundamental process in many aspects of scientific research, engineering and business. Modeling involves the formulation of a simplified representation of a system or real-world object. Thus, modeling tools like Pyomo can be used in a variety of ways:

- *Explain phenomena* that arise in a system,
- *Make predictions* about future states of a system,
- *Assess key factors* that influence phenomena in a system,
- *Identify extreme states* in a system, that might represent worst-case scenarios or minimal cost plans, and
- *Analyze trade-offs* to support human decision makers.

Mathematical models represent system knowledge with a formalized language. The following mathematical concepts are central to modern modeling activities:

3.1.1 Variables

Variables represent unknown or changing parts of a model (e.g., whether or not to make a decision, or the characteristic of a system outcome). The values taken by the variables are often referred to as a *solution* and are usually an output of the optimization process.

3.1.2 Parameters

Parameters represents the data that must be supplied to perform the optimization. In fact, in some settings the word *data* is used in place of the word *parameters*.

3.1.3 Relations

These are equations, inequalities or other mathematical relationships that define how different parts of a model are connected to each other.

3.1.4 Goals

These are functions that reflect goals and objectives for the system being modeled.

The widespread availability of computing resources has made the numerical analysis of mathematical models a commonplace activity. Without a modeling language, the process of setting up input files, executing a solver and extracting the final results from the solver output is tedious and error-prone. This difficulty is compounded in complex, large-scale real-world applications which are difficult to debug when errors occur. Additionally, there are many different formats used by optimization software packages, and few formats are recognized by many optimizers. Thus the application of multiple optimization solvers to analyze a model introduces additional complexities.

Pyomo is an AML that extends Python to include objects for mathematical modeling. [PyomoBookI], [PyomoBookII], and [PyomoJournal] compare Pyomo with other AMLs. Although many good AMLs have been developed for optimization models, the following are motivating factors for the development of Pyomo:

- *Open Source*

  Pyomo is developed within Pyomo's open source project to promote transparency of the modeling framework and encourage community development of Pyomo capabilities.

- *Customizable Capability*

  Pyomo supports a customizable capability through the extensive use of plug-ins to modularize software components.

- *Solver Integration*

  Pyomo models can be optimized with solvers that are written either in Python or in compiled, low-level languages.

- *Programming Language*

  Pyomo leverages a high-level programming language, which has several advantages over custom AMLs: a very robust language, extensive documentation, a rich set of standard libraries, support for modern programming features like classes and functions, and portability to many platforms.

3.2 Overview of Modeling Components and Processes

Pyomo supports an object-oriented design for the definition of optimization models. The basic steps of a simple modeling process are:

- Create model and declare components
- Instantiate the model
- Apply solver
- Interrogate solver results

In practice, these steps may be applied repeatedly with different data or with different constraints applied to the model. However, we focus on this simple modeling process to illustrate different strategies for modeling with Pyomo.

A Pyomo *model* consists of a collection of modeling *components* that define different aspects of the model. Pyomo includes the modeling components that are commonly supported by modern AMLs: index sets, symbolic parameters,

decision variables, objectives, and constraints. These modeling components are defined in Pyomo through the following Python classes:

3.2.1 Set

set data that is used to define a model instance

3.2.2 Param

parameter data that is used to define a model instance

3.2.3 Var

decision variables in a model

3.2.4 Objective

expressions that are minimized or maximized in a model

3.2.5 Constraint

constraint expressions that impose restrictions on variable values in a model

3.3 Abstract Versus Concrete Models

A mathematical model can be defined using symbols that represent data values. For example, the following equations represent a linear program (LP) to find optimal values for the vector x with parameters n and b, and parameter vectors a and c:

$$\begin{array}{lll} \min & \sum_{j=1}^{n} c_j x_j & \\ \text{s.t.} & \sum_{j=1}^{n} a_{ij} x_j \geq b_i & \forall i = 1 \ldots m \\ & x_j \geq 0 & \forall j = 1 \ldots n \end{array}$$

Note: As a convenience, we use the symbol $\forall$ to mean "for all" or "for each."

We call this an *abstract* or *symbolic* mathematical model since it relies on unspecified parameter values. Data values can be used to specify a *model instance*. The `AbstractModel` class provides a context for defining and initializing abstract optimization models in Pyomo when the data values will be supplied at the time a solution is to be obtained.

In many contexts, a mathematical model can and should be directly defined with the data values supplied at the time of the model definition. We call these *concrete* mathematical models. For example, the following LP model is a concrete instance of the previous abstract model:

$$\begin{array}{ll} \min & 2x_1 + 3x_2 \\ \text{s.t.} & 3x_1 + 4x_2 \geq 1 \\ & x_1, x_2 \geq 0 \end{array}$$

The `ConcreteModel` class is used to define concrete optimization models in Pyomo.

Note: Python programmers will probably prefer to write concrete models, while users of some other algebraic modeling languages may tend to prefer to write abstract models. The choice is largely a matter of taste; some applications may be a little more straightforward using one or the other.

3.4 Simple Models

3.4.1 A Simple Concrete Pyomo Model

It is possible to get the same flexible behavior from models declared to be abstract and models declared to be concrete in Pyomo; however, we will focus on a straightforward concrete example here where the data is hard-wired into the model file. Python programmers will quickly realize that the data could have come from other sources.

Given the following model from the previous section:

$$\begin{array}{ll} \min & 2x_1 + 3x_2 \\ \text{s.t.} & 3x_1 + 4x_2 \geq 1 \\ & x_1, x_2 \geq 0 \end{array}$$

This can be implemented as a concrete model as follows:

```
import pyomo.environ as pyo

model = pyo.ConcreteModel()

model.x = pyo.Var([1,2], domain=pyo.NonNegativeReals)

model.OBJ = pyo.Objective(expr = 2*model.x[1] + 3*model.x[2])

model.Constraint1 = pyo.Constraint(expr = 3*model.x[1] + 4*model.x[2] >= 1)
```

Although rule functions can also be used to specify constraints and objectives, in this example we use the `expr` option that is available only in concrete models. This option gives a direct specification of the expression.

3.4.2 A Simple Abstract Pyomo Model

We repeat the abstract model from the previous section:

$$\begin{array}{lll} \min & \sum_{j=1}^{n} c_j x_j & \\ \text{s.t.} & \sum_{j=1}^{n} a_{ij} x_j \geq b_i & \forall i = 1 \ldots m \\ & x_j \geq 0 & \forall j = 1 \ldots n \end{array}$$

One way to implement this in Pyomo is as shown as follows:

```
from __future__ import division
import pyomo.environ as pyo

model = pyo.AbstractModel()

model.m = pyo.Param(within=pyo.NonNegativeIntegers)
model.n = pyo.Param(within=pyo.NonNegativeIntegers)

model.I = pyo.RangeSet(1, model.m)
model.J = pyo.RangeSet(1, model.n)

model.a = pyo.Param(model.I, model.J)
model.b = pyo.Param(model.I)
model.c = pyo.Param(model.J)

# the next line declares a variable indexed by the set J
model.x = pyo.Var(model.J, domain=pyo.NonNegativeReals)

def obj_expression(m):
```

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```
    return pyo.summation(m.c, m.x)

model.OBJ = pyo.Objective(rule=obj_expression)

def ax_constraint_rule(m, i):
    # return the expression for the constraint for i
    return sum(m.a[i,j] * m.x[j] for j in m.J) >= m.b[i]

# the next line creates one constraint for each member of the set model.I
model.AxbConstraint = pyo.Constraint(model.I, rule=ax_constraint_rule)
```

Note: Python is interpreted one line at a time. A line continuation character, \ (backslash), is used for Python statements that need to span multiple lines. In Python, indentation has meaning and must be consistent. For example, lines inside a function definition must be indented and the end of the indentation is used by Python to signal the end of the definition.

We will now examine the lines in this example. The first import line is used to ensure that `int` or `long` division arguments are converted to floating point values before division is performed.

```
from __future__ import division
```

In Python versions before 3.0, division returns the floor of the mathematical result of division if arguments are `int` or `long`. This import line avoids unexpected behavior when developing mathematical models with integer values in Python 2.x (and is not necessary in Python 3.x).

The next import line that is required in every Pyomo model. Its purpose is to make the symbols used by Pyomo known to Python.

```
import pyomo.environ as pyo
```

The declaration of a model is also required. The use of the name `model` is not required. Almost any name could be used, but we will use the name `model` in most of our examples. In this example, we are declaring that it will be an abstract model.

```
model = pyo.AbstractModel()
```

We declare the parameters m and n using the Pyomo `Param` component. This component can take a variety of arguments; this example illustrates use of the `within` option that is used by Pyomo to validate the data value that is assigned to the parameter. If this option were not given, then Pyomo would not object to any type of data being assigned to these parameters. As it is, assignment of a value that is not a non-negative integer will result in an error.

```
model.m = pyo.Param(within=pyo.NonNegativeIntegers)
model.n = pyo.Param(within=pyo.NonNegativeIntegers)
```

Although not required, it is convenient to define index sets. In this example we use the `RangeSet` component to declare that the sets will be a sequence of integers starting at 1 and ending at a value specified by the the parameters `model.m` and `model.n`.

```
model.I = pyo.RangeSet(1, model.m)
model.J = pyo.RangeSet(1, model.n)
```

The coefficient and right-hand-side data are defined as indexed parameters. When sets are given as arguments to the `Param` component, they indicate that the set will index the parameter.

```
model.a = pyo.Param(model.I, model.J)
model.b = pyo.Param(model.I)
model.c = pyo.Param(model.J)
```

The next line that is interpreted by Python as part of the model declares the variable x. The first argument to the `Var` component is a set, so it is defined as an index set for the variable. In this case the variable has only one index set, but multiple sets could be used as was the case for the declaration of the parameter `model.a`. The second argument specifies a domain for the variable. This information is part of the model and will passed to the solver when data is provided and the model is solved. Specification of the `NonNegativeReals` domain implements the requirement that the variables be greater than or equal to zero.

```
# the next line declares a variable indexed by the set J
model.x = pyo.Var(model.J, domain=pyo.NonNegativeReals)
```

Note: In Python, and therefore in Pyomo, any text after pound sign is considered to be a comment.

In abstract models, Pyomo expressions are usually provided to objective and constraint declarations via a function defined with a Python `def` statement. The `def` statement establishes a name for a function along with its arguments. When Pyomo uses a function to get objective or constraint expressions, it always passes in the model (i.e., itself) as the the first argument so the model is always the first formal argument when declaring such functions in Pyomo. Additional arguments, if needed, follow. Since summation is an extremely common part of optimization models, Pyomo provides a flexible function to accommodate it. When given two arguments, the `summation()` function returns an expression for the sum of the product of the two arguments over their indexes. This only works, of course, if the two arguments have the same indexes. If it is given only one argument it returns an expression for the sum over all indexes of that argument. So in this example, when `summation()` is passed the arguments `m.c, m.x` it returns an internal representation of the expression $\sum_{j=1}^{n} c_j x_j$.

```
def obj_expression(m):
    return pyo.summation(m.c, m.x)
```

To declare an objective function, the Pyomo component called `Objective` is used. The `rule` argument gives the name of a function that returns the objective expression. The default *sense* is minimization. For maximization, the `sense=pyo.maximize` argument must be used. The name that is declared, which is `OBJ` in this case, appears in some reports and can be almost any name.

```
model.OBJ = pyo.Objective(rule=obj_expression)
```

Declaration of constraints is similar. A function is declared to generate the constraint expression. In this case, there can be multiple constraints of the same form because we index the constraints by i in the expression $\sum_{j=1}^{n} a_{ij} x_j \geq b_i \ \ \forall i = 1 \ldots m$, which states that we need a constraint for each value of i from one to m. In order to parametrize the expression by i we include it as a formal parameter to the function that declares the constraint expression. Technically, we could have used anything for this argument, but that might be confusing. Using an `i` for an i seems sensible in this situation.

```
def ax_constraint_rule(m, i):
    # return the expression for the constraint for i
    return sum(m.a[i,j] * m.x[j] for j in m.J) >= m.b[i]
```

Note: In Python, indexes are in square brackets and function arguments are in parentheses.

In order to declare constraints that use this expression, we use the Pyomo `Constraint` component that takes a variety

of arguments. In this case, our model specifies that we can have more than one constraint of the same form and we have created a set, `model.I`, over which these constraints can be indexed so that is the first argument to the constraint declaration. The next argument gives the rule that will be used to generate expressions for the constraints. Taken as a whole, this constraint declaration says that a list of constraints indexed by the set `model.I` will be created and for each member of `model.I`, the function `ax_constraint_rule` will be called and it will be passed the model object as well as the member of `model.I`

```
# the next line creates one constraint for each member of the set model.I
model.AxbConstraint = pyo.Constraint(model.I, rule=ax_constraint_rule)
```

In the object oriented view of all of this, we would say that `model` object is a class instance of the `AbstractModel` class, and `model.J` is a `Set` object that is contained by this model. Many modeling components in Pyomo can be optionally specified as *indexed components*: collections of components that are referenced using one or more values. In this example, the parameter `model.c` is indexed with set `model.J`.

In order to use this model, data must be given for the values of the parameters. Here is one file that provides data (in AMPL "`.dat`" format).

```
# one way to input the data in AMPL format
# for indexed parameters, the indexes are given before the value

param m := 1 ;
param n := 2 ;

param a :=
1 1 3
1 2 4
;

param c:=
1 2
2 3
;

param b := 1 1 ;
```

There are multiple formats that can be used to provide data to a Pyomo model, but the AMPL format works well for our purposes because it contains the names of the data elements together with the data. In AMPL data files, text after a pound sign is treated as a comment. Lines generally do not matter, but statements must be terminated with a semi-colon.

For this particular data file, there is one constraint, so the value of `model.m` will be one and there are two variables (i.e., the vector `model.x` is two elements long) so the value of `model.n` will be two. These two assignments are accomplished with standard assignments. Notice that in AMPL format input, the name of the model is omitted.

```
param m := 1 ;
param n := 2 ;
```

There is only one constraint, so only two values are needed for `model.a`. When assigning values to arrays and vectors in AMPL format, one way to do it is to give the index(es) and the the value. The line 1 2 4 causes `model.a[1,2]` to get the value 4. Since `model.c` has only one index, only one index value is needed so, for example, the line 1 2 causes `model.c[1]` to get the value 2. Line breaks generally do not matter in AMPL format data files, so the assignment of the value for the single index of `model.b` is given on one line since that is easy to read.

```
param a :=
 1 1 3
```

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```
1 2 4
;

param c:=
1 2
2 3
;

param b := 1 1 ;
```

3.4.3 Symbolic Index Sets

When working with Pyomo (or any other AML), it is convenient to write abstract models in a somewhat more abstract way by using index sets that contain strings rather than index sets that are implied by $1, \ldots, m$ or the summation from 1 to n. When this is done, the size of the set is implied by the input, rather than specified directly. Furthermore, the index entries may have no real order. Often, a mixture of integers and indexes and strings as indexes is needed in the same model. To start with an illustration of general indexes, consider a slightly different Pyomo implementation of the model we just presented.

```
# abstract2.py

from __future__ import division
from pyomo.environ import *

model = AbstractModel()

model.I = Set()
model.J = Set()

model.a = Param(model.I, model.J)
model.b = Param(model.I)
model.c = Param(model.J)

# the next line declares a variable indexed by the set J
model.x = Var(model.J, domain=NonNegativeReals)

def obj_expression(model):
    return summation(model.c, model.x)

model.OBJ = Objective(rule=obj_expression)

def ax_constraint_rule(model, i):
    # return the expression for the constraint for i
    return sum(model.a[i,j] * model.x[j] for j in model.J) >= model.b[i]

# the next line creates one constraint for each member of the set model.I
model.AxbConstraint = Constraint(model.I, rule=ax_constraint_rule)
```

To get the same instantiated model, the following data file can be used.

```
# abstract2a.dat AMPL format

set I := 1 ;
set J := 1 2 ;

param a :=
1 1 3
1 2 4
;

param c:=
1 2
2 3
;

param b := 1 1 ;
```

However, this model can also be fed different data for problems of the same general form using meaningful indexes.

```
# abstract2.dat AMPL data format

set I := TV Film ;
set J := Graham John Carol ;

param a :=
TV  Graham 3
TV John 4.4
TV Carol 4.9
Film Graham 1
Film John 2.4
Film Carol 1.1
;

param c := [*]
 Graham 2.2
 John 3.1416
 Carol 3
;

param b := TV 1 Film 1 ;
```

3.4.4 Solving the Simple Examples

Pyomo supports modeling and scripting but does not install a solver automatically. In order to solve a model, there must be a solver installed on the computer to be used. If there is a solver, then the `pyomo` command can be used to solve a problem instance.

Suppose that the solver named glpk (also known as glpsol) is installed on the computer. Suppose further that an abstract model is in the file named `abstract1.py` and a data file for it is in the file named `abstract1.dat`. From the command prompt, with both files in the current directory, a solution can be obtained with the command:

```
pyomo solve abstract1.py abstract1.dat --solver=glpk
```

Since glpk is the default solver, there really is no need specify it so the `--solver` option can be dropped.

Note: There are two dashes before the command line option names such as `solver`.

To continue the example, if CPLEX is installed then it can be listed as the solver. The command to solve with CPLEX is

```
pyomo solve abstract1.py abstract1.dat --solver=cplex
```

This yields the following output on the screen:

```
[    0.00] Setting up Pyomo environment
[    0.00] Applying Pyomo preprocessing actions
[    0.07] Creating model
[    0.15] Applying solver
[    0.37] Processing results
Number of solutions: 1
Solution Information
Gap: 0.0
Status: optimal
Function Value: 0.666666666667
Solver results file: results.json
[    0.39] Applying Pyomo postprocessing actions
[    0.39] Pyomo Finished
```

The numbers in square brackets indicate how much time was required for each step. Results are written to the file named `results.json`, which has a special structure that makes it useful for post-processing. To see a summary of results written to the screen, use the `--summary` option:

```
pyomo solve abstract1.py abstract1.dat --solver=cplex --summary
```

To see a list of Pyomo command line options, use:

```
pyomo solve --help
```

Note: There are two dashes before `help`.

For a concrete model, no data file is specified on the Pyomo command line.

CHAPTER

FOUR

PYOMO MODELING COMPONENTS

4.1 Sets

4.1.1 Declaration

Sets can be declared using instances of the *Set* and *RangeSet* classes or by assigning set expressions. The simplest set declaration creates a set and postpones creation of its members:

```
model.A = pyo.Set()
```

The *Set* class takes optional arguments such as:

- `dimen` = Dimension of the members of the set
- `doc` = String describing the set
- `filter` = A Boolean function used during construction to indicate if a potential new member should be assigned to the set
- `initialize` = An iterable containing the initial members of the Set, or function that returns an iterable of the initial members the set.
- `ordered` = A Boolean indicator that the set is ordered; the default is `True`
- `validate` = A Boolean function that validates new member data
- `within` = Set used for validation; it is a super-set of the set being declared.

In general, Pyomo attempts to infer the "dimensionality" of Set components (that is, the number of apparent indices) when they are constructed. However, there are situations where Pyomo either cannot detect a dimensionality (e.g., a *Set* that was not initialized with any members), or you the user may want to assert the dimensionality of the set. This can be accomplished through the `dimen` keyword. For example, to create a set whose members will be tuples with two items, one could write:

```
model.B = pyo.Set(dimen=2)
```

To create a set of all the numbers in set `model.A` doubled, one could use

```
def DoubleA_init(model):
    return (i*2 for i in model.A)
model.C = pyo.Set(initialize=DoubleA_init)
```

As an aside we note that as always in Python, there are lot of ways to accomplish the same thing. Also, note that this will generate an error if `model.A` contains elements for which multiplication times two is not defined.

The `initialize` option can accept any Python iterable, including a `set`, `list`, or `tuple`. This data may be returned from a function or specified directly as in

```
model.D = pyo.Set(initialize=['red', 'green', 'blue'])
```

The `initialize` option can also specify either a generator or a function to specify the Set members. In the case of a generator, all data yielded by the generator will become the initial set members:

```
def X_init(m):
    for i in range(10):
        yield 2*i+1
model.X = pyo.Set(initialize=X_init)
```

For initialization functions, Pyomo supports two signatures. In the first, the function returns an iterable (`set`, `list`, or `tuple`) containing the data with which to initialize the Set:

```
def Y_init(m):
    return [2*i+1 for i in range(10)]
model.Y = pyo.Set(initialize=Y_init)
```

In the second signature, the function is called for each element, passing the element number in as an extra argument. This is repeated until the function returns the special value `Set.End`:

```
def Z_init(model, i):
    if i > 10:
        return pyo.Set.End
    return 2*i+1
model.Z = pyo.Set(initialize=Z_init)
```

Note that the element number starts with 1 and not 0:

```
>>> model.X.pprint()
X : Size=1, Index=None, Ordered=Insertion
    Key  : Dimen : Domain : Size : Members
    None :     1 :    Any :   10 : {1, 3, 5, 7, 9, 11, 13, 15, 17, 19}
>>> model.Y.pprint()
Y : Size=1, Index=None, Ordered=Insertion
    Key  : Dimen : Domain : Size : Members
    None :     1 :    Any :   10 : {1, 3, 5, 7, 9, 11, 13, 15, 17, 19}
>>> model.Z.pprint()
Z : Size=1, Index=None, Ordered=Insertion
    Key  : Dimen : Domain : Size : Members
    None :     1 :    Any :   10 : {3, 5, 7, 9, 11, 13, 15, 17, 19, 21}
```

Additional information about iterators for set initialization is in the [PyomoBookII] book.

Note: For Abstract models, data specified in an input file or through the `data` argument to *`AbstractModel.create_instance()`* will override the data specified by the initialize options.

If sets are given as arguments to *`Set`* without keywords, they are interpreted as indexes for an array of sets. For example, to create an array of sets that is indexed by the members of the set `model.A`, use:

```
model.E = pyo.Set(model.A)
```

Arguments can be combined. For example, to create an array of sets, indexed by set `model.A` where each set contains three dimensional members, use:

```
model.F = pyo.Set(model.A, dimen=3)
```

The `initialize` option can be used to create a set that contains a sequence of numbers, but the *RangeSet* class provides a concise mechanism for simple sequences. This class takes as its arguments a start value, a final value, and a step size. If the *RangeSet* has only a single argument, then that value defines the final value in the sequence; the first value and step size default to one. If two values given, they are the first and last value in the sequence and the step size defaults to one. For example, the following declaration creates a set with the numbers 1.5, 5 and 8.5:

```
model.G = pyo.RangeSet(1.5, 10, 3.5)
```

4.1.2 Operations

Sets may also be created by storing the result of *set operations* using other Pyomo sets. Pyomo supports set operations including union, intersection, difference, and symmetric difference:

```
model.I = model.A | model.D # union
model.J = model.A & model.D # intersection
model.K = model.A - model.D # difference
model.L = model.A ^ model.D # exclusive-or
```

For example, the cross-product operator is the asterisk (*). To define a new set `M` that is the cross product of sets `B` and `C`, one could use

```
model.M = model.B * model.C
```

This creates a *virtual* set that holds references to the original sets, so any updates to the original sets (`B` and `C`) will be reflected in the new set (`M`). In contrast, you can also create a *concrete* set, which directly stores the values of the cross product at the time of creation and will *not* reflect subsequent changes in the original sets with:

```
model.M_concrete = pyo.Set(initialize=model.B * model.C)
```

Finally, you can indicate that the members of a set are restricted to be in the cross product of two other sets, one can use the `within` keyword:

```
model.N = pyo.Set(within=model.B * model.C)
```

4.1.3 Predefined Virtual Sets

For use in specifying domains for sets, parameters and variables, Pyomo provides the following pre-defined virtual sets:

- `Any` = all possible values
- `Reals` = floating point values
- `PositiveReals` = strictly positive floating point values
- `NonPositiveReals` = non-positive floating point values
- `NegativeReals` = strictly negative floating point values
- `NonNegativeReals` = non-negative floating point values

- `PercentFraction` = floating point values in the interval [0,1]
- `UnitInterval` = alias for PercentFraction
- `Integers` = integer values
- `PositiveIntegers` = positive integer values
- `NonPositiveIntegers` = non-positive integer values
- `NegativeIntegers` = negative integer values
- `NonNegativeIntegers` = non-negative integer values
- `Boolean` = Boolean values, which can be represented as False/True, 0/1, 'False'/'True' and 'F'/'T'
- `Binary` = the integers {0, 1}

For example, if the set `model.O` is declared to be within the virtual set `NegativeIntegers` then an attempt to add anything other than a negative integer will result in an error. Here is the declaration:

```
model.O = pyo.Set(within=pyo.NegativeIntegers)
```

4.1.4 Sparse Index Sets

Sets provide indexes for parameters, variables and other sets. Index set issues are important for modelers in part because of efficiency considerations, but primarily because the right choice of index sets can result in very natural formulations that are conducive to understanding and maintenance. Pyomo leverages Python to provide a rich collection of options for index set creation and use.

The choice of how to represent indexes often depends on the application and the nature of the instance data that are expected. To illustrate some of the options and issues, we will consider problems involving networks. In many network applications, it is useful to declare a set of nodes, such as

```
model.Nodes = pyo.Set()
```

and then a set of arcs can be created with reference to the nodes.

Consider the following simple version of minimum cost flow problem:

$$\begin{array}{lll} \text{minimize} & \sum_{a \in \mathcal{A}} c_a x_a & \\ \text{subject to:} & S_n + \sum_{(i,n) \in \mathcal{A}} x_{(i,n)} & \\ & -D_n - \sum_{(n,j) \in \mathcal{A}} x_{(n,j)} & n \in \mathcal{N} \\ & x_a \geq 0, & a \in \mathcal{A} \end{array}$$

where

- Set: Nodes $\equiv \mathcal{N}$
- Set: Arcs $\equiv \mathcal{A} \subseteq \mathcal{N} \times \mathcal{N}$
- Var: Flow on arc $(i,j) \equiv x_{i,j},\ (i,j) \in \mathcal{A}$
- Param: Flow Cost on arc $(i,j) \equiv c_{i,j},\ (i,j) \in \mathcal{A}$
- Param: Demand at node latexmath:$i \equiv D_i,\ i \in \mathcal{N}$
- Param: Supply at node latexmath:$i \equiv S_i,\ i \in \mathcal{N}$

In the simplest case, the arcs can just be the cross product of the nodes, which is accomplished by the definition

```
model.Arcs = model.Nodes*model.Nodes
```

that creates a set with two dimensional members. For applications where all nodes are always connected to all other nodes this may suffice. However, issues can arise when the network is not fully dense. For example, the burden of avoiding flow on arcs that do not exist falls on the data file where high-enough costs must be provided for those arcs. Such a scheme is not very elegant or robust.

For many network flow applications, it might be better to declare the arcs using

```
model.Arcs = pyo.Set(dimen=2)
```

or

```
model.Arcs = pyo.Set(within=model.Nodes*model.Nodes)
```

where the difference is that the first version will provide error checking as data is assigned to the set elements. This would enable specification of a sparse network in a natural way. But this results in a need to change the `FlowBalance` constraint because as it was written in the simple example, it sums over the entire set of nodes for each node. One way to remedy this is to sum only over the members of the set `model.arcs` as in

```
def FlowBalance_rule(m, node):
    return m.Supply[node] \
        + sum(m.Flow[i, node] for i in m.Nodes if (i,node) in m.Arcs) \
        - m.Demand[node] \
        - sum(m.Flow[node, j] for j in m.Nodes if (j,node) in m.Arcs) \
        == 0
```

This will be OK unless the number of nodes becomes very large for a sparse network, then the time to generate this constraint might become an issue (admittely, only for very large networks, but such networks do exist).

Another method, which comes in handy in many network applications, is to have a set for each node that contain the nodes at the other end of arcs going to the node at hand and another set giving the nodes on out-going arcs. If these sets are called `model.NodesIn` and `model.NodesOut` respectively, then the flow balance rule can be re-written as

```
def FlowBalance_rule(m, node):
    return m.Supply[node] \
        + sum(m.Flow[i, node] for i in m.NodesIn[node]) \
        - m.Demand[node] \
        - sum(m.Flow[node, j] for j in m.NodesOut[node]) \
        == 0
```

The data for `NodesIn` and `NodesOut` could be added to the input file, and this may be the most efficient option.

For all but the largest networks, rather than reading `Arcs`, `NodesIn` and `NodesOut` from a data file, it might be more elegant to read only `Arcs` from a data file and declare `model.NodesIn` with an `initialize` option specifying the creation as follows:

```
def NodesIn_init(m, node):
    for i, j in m.Arcs:
        if j == node:
            yield i
model.NodesIn = pyo.Set(model.Nodes, initialize=NodesIn_init)
```

with a similar definition for `model.NodesOut`. This code creates a list of sets for `NodesIn`, one set of nodes for each node. The full model is:

```
import pyomo.environ as pyo
```

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```
model = pyo.AbstractModel()

model.Nodes = pyo.Set()
model.Arcs = pyo.Set(dimen=2)

def NodesOut_init(m, node):
    for i, j in m.Arcs:
        if i == node:
            yield j
model.NodesOut = pyo.Set(model.Nodes, initialize=NodesOut_init)

def NodesIn_init(m, node):
    for i, j in m.Arcs:
        if j == node:
            yield i
model.NodesIn = pyo.Set(model.Nodes, initialize=NodesIn_init)

model.Flow = pyo.Var(model.Arcs, domain=pyo.NonNegativeReals)
model.FlowCost = pyo.Param(model.Arcs)

model.Demand = pyo.Param(model.Nodes)
model.Supply = pyo.Param(model.Nodes)

def Obj_rule(m):
    return pyo.summation(m.FlowCost, m.Flow)
model.Obj = pyo.Objective(rule=Obj_rule, sense=pyo.minimize)

def FlowBalance_rule(m, node):
    return m.Supply[node] \
        + sum(m.Flow[i, node] for i in m.NodesIn[node]) \
        - m.Demand[node] \
        - sum(m.Flow[node, j] for j in m.NodesOut[node]) \
        == 0
model.FlowBalance = pyo.Constraint(model.Nodes, rule=FlowBalance_rule)
```

for this model, a toy data file (in AMPL ".dat" format) would be:

```
set Nodes := CityA CityB CityC ;

set Arcs :=
CityA CityB
CityA CityC
CityC CityB
;

param : FlowCost :=
CityA CityB 1.4
CityA CityC 2.7
CityC CityB 1.6
 ;

param Demand :=
```

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```
CityA 0
CityB 1
CityC 1
;

param Supply :=
CityA 2
CityB 0
CityC 0
;
```

This can also be done somewhat more efficiently, and perhaps more clearly, using a `BuildAction` (for more information, see *BuildAction and BuildCheck*):

```
model.NodesOut = pyo.Set(model.Nodes, within=model.Nodes)
model.NodesIn = pyo.Set(model.Nodes, within=model.Nodes)

def Populate_In_and_Out(model):
    # loop over the arcs and record the end points
    for i, j in model.Arcs:
        model.NodesIn[j].add(i)
        model.NodesOut[i].add(j)

model.In_n_Out = pyo.BuildAction(rule=Populate_In_and_Out)
```

Sparse Index Sets Example

One may want to have a constraint that holds

$$\forall\, i \in I, k \in K, v \in V_k$$

There are many ways to accomplish this, but one good way is to create a set of tuples composed of all `model.k, model.V[k]` pairs. This can be done as follows:

```
def kv_init(m):
    return ((k,v) for k in m.K for v in m.V[k])
model.KV = pyo.Set(dimen=2, initialize=kv_init)
```

We can now create the constraint $x_{i,k,v} \leq a_{i,k} y_i \;\forall\, i \in I, k \in K, v \in V_k$ with:

```
model.a = pyo.Param(model.I, model.K, default=1)

model.y = pyo.Var(model.I)
model.x = pyo.Var(model.I, model.KV)

def c1_rule(m, i, k, v):
    return m.x[i,k,v] <= m.a[i,k]*m.y[i]
model.c1 = pyo.Constraint(model.I, model.KV, rule=c1_rule)
```

4.2 Parameters

The word "parameters" is used in many settings. When discussing a Pyomo model, we use the word to refer to data that must be provided in order to find an optimal (or good) assignment of values to the decision variables. Parameters are declared as instances of a *Param* class, which takes arguments that are somewhat similar to the *Set* class. For example, the following code snippet declares sets `model.A` and `model.B`, and then a parameter `model.P` that is indexed by `model.A` and `model.B`:

```
model.A = pyo.RangeSet(1,3)
model.B = pyo.Set()
model.P = pyo.Param(model.A, model.B)
```

In addition to sets that serve as indexes, *Param* takes the following options:

- `default` = The parameter value absent any other specification.
- `doc` = A string describing the parameter.
- `initialize` = A function (or Python object) that returns data used to initialize the parameter values.
- `mutable` = Boolean value indicating if the Param values are allowed to change after the Param is initialized.
- `validate` = A callback function that takes the model, proposed value, and indices of the proposed value; returning `True` if the value is valid. Returning `False` will generate an exception.
- `within` = Set used for validation; it specifies the domain of valid parameter values.

These options perform in the same way as they do for *Set*. For example, given `model.A` with values `{1, 2, 3}`, then there are many ways to create a parameter that represents a square matrix with 9, 16, 25 on the main diagonal and zeros elsewhere, here are two ways to do it. First using a Python object to initialize:

```
v={}
v[1,1] = 9
v[2,2] = 16
v[3,3] = 25
model.S1 = pyo.Param(model.A, model.A, initialize=v, default=0)
```

And now using an initialization function that is automatically called once for each index tuple (remember that we are assuming that `model.A` contains `{1, 2, 3}`)

```
def s_init(model, i, j):
    if i == j:
        return i*i
    else:
        return 0.0
model.S2 = pyo.Param(model.A, model.A, initialize=s_init)
```

In this example, the index set contained integers, but index sets need not be numeric. It is very common to use strings.

Note: Data specified in an input file will override the data specified by the `initialize` option.

Parameter values can be checked by a validation function. In the following example, the every value of the parameter `T` (indexed by `model.A`) is checked to be greater than 3.14159. If a value is provided that is less than that, the model instantation will be terminated and an error message issued. The validation function should be written so as to return `True` if the data is valid and `False` otherwise.

```
t_data = {1: 10, 2: 3, 3: 20}

def t_validate(model, v, i):
    return v > 3.14159

model.T = pyo.Param(model.A, validate=t_validate, initialize=t_data)
```

This example will prodice the following error, indicating that the value provided for `T[2]` failed validation:

```
Traceback (most recent call last):
  ...
ValueError: Invalid parameter value: T[2] = '3', value type=<class 'int'>.
    Value failed parameter validation rule
```

4.3 Variables

Variables are intended to ultimately be given values by an optimization package. They are declared and optionally bounded, given initial values, and documented using the Pyomo `Var` function. If index sets are given as arguments to this function they are used to index the variable. Other optional directives include:

- bounds = A function (or Python object) that gives a (lower,upper) bound pair for the variable
- domain = A set that is a super-set of the values the variable can take on.
- initialize = A function (or Python object) that gives a starting value for the variable; this is particularly important for non-linear models
- within = (synonym for `domain`)

The following code snippet illustrates some aspects of these options by declaring a *singleton* (i.e. unindexed) variable named `model.LumberJack` that will take on real values between zero and 6 and it initialized to be 1.5:

```
model.LumberJack = Var(within=NonNegativeReals, bounds=(0,6), initialize=1.5)
```

Instead of the `initialize` option, initialization is sometimes done with a Python assignment statement as in

```
model.LumberJack = 1.5
```

For indexed variables, bounds and initial values are often specified by a rule (a Python function) that itself may make reference to parameters or other data. The formal arguments to these rules begins with the model followed by the indexes. This is illustrated in the following code snippet that makes use of Python dictionaries declared as lb and ub that are used by a function to provide bounds:

```
model.A = Set(initialize=['Scones', 'Tea'])
lb = {'Scones':2, 'Tea':4}
ub = {'Scones':5, 'Tea':7}
def fb(model, i):
   return (lb[i], ub[i])
model.PriceToCharge = Var(model.A, domain=PositiveIntegers, bounds=fb)
```

Note: Many of the pre-defined virtual sets that are used as domains imply bounds. A strong example is the set `Boolean` that implies bounds of zero and one.

4.4 Objectives

An objective is a function of variables that returns a value that an optimization package attempts to maximize or minimize. The `Objective` function in Pyomo declares an objective. Although other mechanisms are possible, this function is typically passed the name of another function that gives the expression. Here is a very simple version of such a function that assumes `model.x` has previously been declared as a `Var`:

```
>>> def ObjRule(model):
...     return 2*model.x[1] + 3*model.x[2]
>>> model.obj1 = pyo.Objective(rule=ObjRule)
```

It is more common for an objective function to refer to parameters as in this example that assumes that `model.p` has been declared as a `Param` and that `model.x` has been declared with the same index set, while `model.y` has been declared as a singleton:

```
>>> def ObjRule(model):
...     return pyo.summation(model.p, model.x) + model.y
>>> model.obj2 = pyo.Objective(rule=ObjRule, sense=pyo.maximize)
```

This example uses the `sense` option to specify maximization. The default sense is `minimize`.

4.5 Constraints

Most constraints are specified using equality or inequality expressions that are created using a rule, which is a Python function. For example, if the variable `model.x` has the indexes 'butter' and 'scones', then this constraint limits the sum over these indexes to be exactly three:

```
def teaOKrule(model):
    return(model.x['butter'] + model.x['scones'] == 3)
model.TeaConst = Constraint(rule=teaOKrule)
```

Instead of expressions involving equality (==) or inequalities (<= or >=), constraints can also be expressed using a 3-tuple if the form (lb, expr, ub) where lb and ub can be `None`, which is interpreted as lb <= expr <= ub. Variables can appear only in the middle expr. For example, the following two constraint declarations have the same meaning:

```
model.x = Var()

def aRule(model):
   return model.x >= 2
model.Boundx = Constraint(rule=aRule)

def bRule(model):
   return (2, model.x, None)
model.boundx = Constraint(rule=bRule)
```

For this simple example, it would also be possible to declare `model.x` with a `bounds` option to accomplish the same thing.

Constraints (and objectives) can be indexed by lists or sets. When the declaration contains lists or sets as arguments, the elements are iteratively passed to the rule function. If there is more than one, then the cross product is sent. For example the following constraint could be interpreted as placing a budget of i on the i^{th} item to buy where the cost per item is given by the parameter `model.a`:

```
model.A = RangeSet(1,10)
model.a = Param(model.A, within=PositiveReals)
model.ToBuy = Var(model.A)
def bud_rule(model, i):
    return model.a[i]*model.ToBuy[i] <= i
aBudget = Constraint(model.A, rule=bud_rule)
```

Note: Python and Pyomo are case sensitive so `model.a` is not the same as `model.A`.

4.6 Expressions

In this section, we use the word "expression" in two ways: first in the general sense of the word and second to desribe a class of Pyomo objects that have the name `Expression` as described in the subsection on expression objects.

4.6.1 Rules to Generate Expressions

Both objectives and constraints make use of rules to generate expressions. These are Python functions that return the appropriate expression. These are first-class functions that can access global data as well as data passed in, including the model object.

Operations on model elements results in expressions, which seems natural in expressions like the constraints we have seen so far. It is also possible to build up expressions. The following example illustrates this, along with a reference to global Python data in the form of a Python variable called `switch`:

```
switch = 3

model.A = RangeSet(1, 10)
model.c = Param(model.A)
model.d = Param()
model.x = Var(model.A, domain=Boolean)

def pi_rule(model):
    accexpr = summation(model.c, model.x)
    if switch >= 2:
        accexpr = accexpr - model.d
    return accexpr >= 0.5
PieSlice = Constraint(rule=pi_rule)
```

In this example, the constraint that is generated depends on the value of the Python variable called `switch`. If the value is 2 or greater, then the constraint is `summation(model.c, model.x) - model.d >= 0.5`; otherwise, the `model.d` term is not present.

Warning: Because model elements result in expressions, not values, the following does not work as expected in an abstract model!

```
model.A = RangeSet(1, 10)
model.c = Param(model.A)
model.d = Param()
model.x = Var(model.A, domain=Boolean)
```

```
def pi_rule(model):
    accexpr = summation(model.c, model.x)
    if model.d >= 2:  # NOT in an abstract model!!
        accexpr = accexpr - model.d
    return accexpr >= 0.5
PieSlice = Constraint(rule=pi_rule)
```

The trouble is that `model.d >= 2` results in an expression, not its evaluated value. Instead use `if value(model.d) >= 2`

Note: Pyomo supports non-linear expressions and can call non-linear solvers such as Ipopt.

4.6.2 Piecewise Linear Expressions

Pyomo has facilities to add piecewise constraints of the form y=f(x) for a variety of forms of the function f.

The piecewise types other than SOS2, BIGM_SOS1, BIGM_BIN are implement as described in the paper [Vielma_et_al].

There are two basic forms for the declaration of the constraint:

```
#model.pwconst = Piecewise(indexes, yvar, xvar, **Keywords)
#model.pwconst = Piecewise(yvar,xvar,**Keywords)
```

where `pwconst` can be replaced by a name appropriate for the application. The choice depends on whether the x and y variables are indexed. If so, they must have the same index sets and these sets are give as the first arguments.

Keywords:

- **pw_pts={ },[ ],( )**

  A dictionary of lists (where keys are the index set) or a single list (for the non-indexed case or when an identical set of breakpoints is used across all indices) defining the set of domain breakpoints for the piecewise linear function.

  Note: pw_pts is always required. These give the breakpoints for the piecewise function and are expected to fully span the bounds for the independent variable(s).

- **pw_repn=<Option>**

  Indicates the type of piecewise representation to use. This can have a major impact on solver performance. Options: (Default "SOS2")

  - "SOS2" - Standard representation using sos2 constraints.
  - "BIGM_BIN" - BigM constraints with binary variables. The theoretically tightest M values are automatically determined.
  - "BIGM_SOS1" - BigM constraints with sos1 variables. The theoretically tightest M values are automatically determined.

  - "DCC" - Disaggregated convex combination model.
  - "DLOG" - Logarithmic disaggregated convex combination model.
  - "CC" - Convex combination model.
  - "LOG" - Logarithmic branching convex combination.
  - "MC" - Multiple choice model.
  - "INC" - Incremental (delta) method.

Note: Step functions are supported for all but the two BIGM options. Refer to the 'force_pw' option.

- **pw_constr_type= <Option>**

  Indicates the bound type of the piecewise function. Options:

  - "UB" - y variable is bounded above by piecewise function.
  - "LB" - y variable is bounded below by piecewise function.
  - "EQ" - y variable is equal to the piecewise function.

- **f_rule=f(model,i,j,...,x), { }, [ ], ( )**

  An object that returns a numeric value that is the range value corresponding to each piecewise domain point. For functions, the first argument must be a Pyomo model. The last argument is the domain value at which the function evaluates (Not a Pyomo `Var`). Intermediate arguments are the corresponding indices of the Piecewise component (if any). Otherwise, the object can be a dictionary of lists/tuples (with keys the same as the indexing set) or a singe list/tuple (when no indexing set is used or when all indices use an identical piecewise function). Examples:

```
# A function that changes with index
def f(model,j,x):
   if (j == 2):
      return x**2 + 1.0
   else:
      return x**2 + 5.0

# A nonlinear function
f = lambda model,x : exp(x) + value(model.p)

# A step function
f = [0,0,1,1,2,2]
```

- **force_pw=True/False**

  Using the given function rule and pw_pts, a check for convexity/concavity is implemented. If (1) the function is convex and the piecewise constraints are lower bounds or if (2) the function is concave and the piecewise constraints are upper bounds then the piecewise constraints will be substituted for linear constraints. Setting 'force_pw=True' will force the use of the original piecewise constraints even when one of these two cases applies.

- **warning_tol=<float>**

  To aid in debugging, a warning is printed when consecutive slopes of piecewise segments are within <warning_tol> of each other. Default=1e-8

- **warn_domain_coverage=True/False**

Print a warning when the feasible region of the domain variable is not completely covered by the piecewise breakpoints. Default=True

- **unbounded_domain_var=True/False**

  Allow an unbounded or partially bounded Pyomo Var to be used as the domain variable. Default=False

---

Note: This does not imply unbounded piecewise segments will be constructed. The outermost piecewise breakpoints will bound the domain variable at each index. However, the Var attributes .lb and .ub will not be modified.

Here is an example of an assignment to a Python dictionary variable that has keywords for a picewise constraint:

```
kwds = {'pw_constr_type':'EQ','pw_repn':'SOS2','sense':maximize,'force_pw':True}
```

Here is a simple example based on the example given earlier in *Symbolic Index Sets*. In this new example, the objective function is the sum of c times x to the fourth. In this example, the keywords are passed directly to the `Piecewise` function without being assigned to a dictionary variable. The upper bound on the x variables was chosen whimsically just to make the example. The important thing to note is that variables that are going to appear as the independent variable in a piecewise constraint must have bounds.

```
# abstract2piece.py
# Similar to abstract2.py, but the objective is now c times x to the fourth power

from pyomo.environ import *

model = AbstractModel()

model.I = Set()
model.J = Set()

Topx = 6.1 # range of x variables

model.a = Param(model.I, model.J)
model.b = Param(model.I)
model.c = Param(model.J)

# the next line declares a variable indexed by the set J
model.x = Var(model.J, domain=NonNegativeReals, bounds=(0, Topx))
model.y = Var(model.J, domain=NonNegativeReals)

# to avoid warnings, we set breakpoints at or beyond the bounds
PieceCnt = 100
bpts = []
for i in range(PieceCnt+2):
    bpts.append(float((i*Topx)/PieceCnt))

def f4(model, j, xp):
    # we not need j, but it is passed as the index for the constraint
    return xp**4

model.ComputeObj = Piecewise(model.J, model.y, model.x, pw_pts=bpts, pw_constr_type='EQ',
↪ f_rule=f4)

def obj_expression(model):
```

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```
    return summation(model.c, model.y)

model.OBJ = Objective(rule=obj_expression)

def ax_constraint_rule(model, i):
    # return the expression for the constraint for i
    return sum(model.a[i,j] * model.x[j] for j in model.J) >= model.b[i]

# the next line creates one constraint for each member of the set model.I
model.AxbConstraint = Constraint(model.I, rule=ax_constraint_rule)
```

A more advanced example is provided in abstract2piecebuild.py in *BuildAction and BuildCheck*.

4.6.3 Expression Objects

Pyomo `Expression` objects are very similar to the `Param` component (with `mutable=True`) except that the underlying values can be numeric constants or Pyomo expressions. Here's an illustration of expression objects in an AbstractModel. An expression object with an index set that is the numbers 1, 2, 3 is created and initialized to be the model variable x times the index. Later in the model file, just to illustrate how to do it, the expression is changed but just for the first index to be x squared.

```
model = ConcreteModel()
model.x = Var(initialize=1.0)
def _e(m,i):
    return m.x*i
model.e = Expression([1,2,3], rule=_e)

instance = model.create_instance()

print (value(instance.e[1])) # -> 1.0
print (instance.e[1]())           # -> 1.0
print (instance.e[1].value)  # -> a pyomo expression object

# Change the underlying expression
instance.e[1].value = instance.x**2

#... solve
#... load results

# print the value of the expression given the loaded optimal solution
print (value(instance.e[1]))
```

An alternative is to create Python functions that, potentially, manipulate model objects. E.g., if you define a function

```
def f(x, p):
    return x + p
```

You can call this function with or without Pyomo modeling components as the arguments. E.g., f(2,3) will return a number, whereas f(model.x, 3) will return a Pyomo expression due to operator overloading.

If you take this approach you should note that anywhere a Pyomo expression is used to generate another expression (e.g., f(model.x, 3) + 5), the initial expression is always cloned so that the new generated expression is independent of the old. For example:

```
model = ConcreteModel()
model.x = Var()

# create a Pyomo expression
e1 = model.x + 5

# create another Pyomo expression
# e1 is copied when generating e2
e2 = e1 + model.x
```

If you want to create an expression that is shared between other expressions, you can use the `Expression` component.

4.7 Suffixes

Suffixes provide a mechanism for declaring extraneous model data, which can be used in a number of contexts. Most commonly, suffixes are used by solver plugins to store extra information about the solution of a model. This and other suffix functionality is made available to the modeler through the use of the Suffix component class. Uses of Suffix include:

- Importing extra information from a solver about the solution of a mathematical program (e.g., constraint duals, variable reduced costs, basis information).
- Exporting information to a solver or algorithm to aid in solving a mathematical program (e.g., warm-starting information, variable branching priorities).
- Tagging modeling components with local data for later use in advanced scripting algorithms.

4.7.1 Suffix Notation and the Pyomo NL File Interface

The Suffix component used in Pyomo has been adapted from the suffix notation used in the modeling language AMPL [AMPL]. Therefore, it follows naturally that AMPL style suffix functionality is fully available using Pyomo's NL file interface. For information on AMPL style suffixes the reader is referred to the AMPL website:

http://www.ampl.com

A number of scripting examples that highlight the use AMPL style suffix functionality are available in the `examples/pyomo/suffixes` directory distributed with Pyomo.

4.7.2 Declaration

The effects of declaring a Suffix component on a Pyomo model are determined by the following traits:

- direction: This trait defines the direction of information flow for the suffix. A suffix direction can be assigned one of four possible values:
  - `LOCAL` - suffix data stays local to the modeling framework and will not be imported or exported by a solver plugin (default)
  - `IMPORT` - suffix data will be imported from the solver by its respective solver plugin
  - `EXPORT` - suffix data will be exported to a solver by its respective solver plugin
  - `IMPORT_EXPORT` - suffix data flows in both directions between the model and the solver or algorithm
- datatype: This trait advertises the type of data held on the suffix for those interfaces where it matters (e.g., the NL file interface). A suffix datatype can be assigned one of three possible values:

- `FLOAT` - the suffix stores floating point data (default)
- `INT` - the suffix stores integer data
- `None` - the suffix stores any type of data

Note: Exporting suffix data through Pyomo's NL file interface requires all active export suffixes have a strict datatype (i.e., `datatype=None` is not allowed).

The following code snippet shows examples of declaring a Suffix component on a Pyomo model:

```
import pyomo.environ as pyo

model = pyo.ConcreteModel()

# Export integer data
model.priority = pyo.Suffix(
    direction=pyo.Suffix.EXPORT, datatype=pyo.Suffix.INT)

# Export and import floating point data
model.dual = pyo.Suffix(direction=pyo.Suffix.IMPORT_EXPORT)

# Store floating point data
model.junk = pyo.Suffix()
```

Declaring a Suffix with a non-local direction on a model is not guaranteed to be compatible with all solver plugins in Pyomo. Whether a given Suffix is acceptable or not depends on both the solver and solver interface being used. In some cases, a solver plugin will raise an exception if it encounters a Suffix type that it does not handle, but this is not true in every situation. For instance, the NL file interface is generic to all AMPL-compatible solvers, so there is no way to validate that a Suffix of a given name, direction, and datatype is appropriate for a solver. One should be careful in verifying that Suffix declarations are being handled as expected when switching to a different solver or solver interface.

4.7.3 Operations

The Suffix component class provides a dictionary interface for mapping Pyomo modeling components to arbitrary data. This mapping functionality is captured within the ComponentMap base class, which is also available within Pyomo's modeling environment. The ComponentMap can be used as a more lightweight replacement for Suffix in cases where a simple mapping from Pyomo modeling components to arbitrary data values is required.

Note: ComponentMap and Suffix use the built-in `id()` function for hashing entry keys. This design decision arises from the fact that most of the modeling components found in Pyomo are either not hashable or use a hash based on a mutable numeric value, making them unacceptable for use as keys with the built-in `dict` class.

Warning: The use of the built-in `id()` function for hashing entry keys in ComponentMap and Suffix makes them inappropriate for use in situations where built-in object types must be used as keys. It is strongly recommended that only Pyomo modeling components be used as keys in these mapping containers (`Var`, `Constraint`, etc.).

Warning: Do not attempt to pickle or deepcopy instances of ComponentMap or Suffix unless doing so along with the components for which they hold mapping entries. As an example, placing one of these objects on a model and then cloning or pickling that model is an acceptable scenario.

In addition to the dictionary interface provided through the ComponentMap base class, the Suffix component class also provides a number of methods whose default semantics are more convenient for working with indexed modeling components. The easiest way to highlight this functionality is through the use of an example.

```
model = pyo.ConcreteModel()
model.x = pyo.Var()
model.y = pyo.Var([1,2,3])
model.foo = pyo.Suffix()
```

In this example we have a concrete Pyomo model with two different types of variable components (indexed and non-indexed) as well as a Suffix declaration (foo). The next code snippet shows examples of adding entries to the suffix foo.

```
# Assign a suffix value of 1.0 to model.x
model.foo.set_value(model.x, 1.0)

# Same as above with dict interface
model.foo[model.x] = 1.0

# Assign a suffix value of 0.0 to all indices of model.y
# By default this expands so that entries are created for
# every index (y[1], y[2], y[3]) and not model.y itself
model.foo.set_value(model.y, 0.0)

# The same operation using the dict interface results in an entry only
# for the parent component model.y
model.foo[model.y] = 50.0

# Assign a suffix value of -1.0 to model.y[1]
model.foo.set_value(model.y[1], -1.0)

# Same as above with the dict interface
model.foo[model.y[1]] = -1.0
```

In this example we highlight the fact that the `__setitem__` and `setValue` entry methods can be used interchangeably except in the case where indexed components are used (model.y). In the indexed case, the `__setitem__` approach creates a single entry for the parent indexed component itself, whereas the `setValue` approach by default creates an entry for each index of the component. This behavior can be controlled using the optional keyword 'expand', where assigning it a value of `False` results in the same behavior as `__setitem__`.

Other operations like accessing or removing entries in our mapping can performed as if the built-in `dict` class is in use.

```
>>> print(model.foo.get(model.x))
1.0
>>> print(model.foo[model.x])
1.0

>>> print(model.foo.get(model.y[1]))
```

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```
-1.0
>>> print(model.foo[model.y[1]])
-1.0

>>> print(model.foo.get(model.y[2]))
0.0
>>> print(model.foo[model.y[2]])
0.0

>>> print(model.foo.get(model.y))
50.0
>>> print(model.foo[model.y])
50.0

>>> del model.foo[model.y]
>>> print(model.foo.get(model.y))
None

>>> print(model.foo[model.y])
Traceback (most recent call last):
  ...
KeyError: "Component with id '...': y"
```

The non-dict method `clear_value` can be used in place of `__delitem__` to remove entries, where it inherits the same default behavior as `setValue` for indexed components and does not raise a KeyError when the argument does not exist as a key in the mapping.

```
>>> model.foo.clear_value(model.y)

>>> print(model.foo[model.y[1]])
Traceback (most recent call last):
  ...
KeyError: "Component with id '...': y[1]"

>>> del model.foo[model.y[1]]
Traceback (most recent call last):
  ...
KeyError: "Component with id '...': y[1]"

>>> model.foo.clear_value(model.y[1])
```

A summary non-dict Suffix methods is provided here:

clearAllValues()
: Clears all suffix data.

clear_value(component, expand=True)
: Clears suffix information for a component.

setAllValues(value)
: Sets the value of this suffix on all components.

setValue(component, value, expand=True)
: Sets the value of this suffix on the specified component.

updateValues(data_buffer, expand=True)
: Updates the suffix data given a list of component,value tuples. Provides an improvement in efficiency over calling setValue on every component.

getDatatype()
: Return the suffix datatype.

setDatatype(datatype)
: Set the suffix datatype.

getDirection()
: Return the suffix direction.

setDirection(direction)
: Set the suffix direction.

importEnabled()
: Returns True when this suffix is enabled for import from solutions.

exportEnabled()
: Returns True when this suffix is enabled for export to solvers.

4.7.4 Importing Suffix Data

Importing suffix information from a solver solution is achieved by declaring a Suffix component with the appropriate name and direction. Suffix names available for import may be specific to third-party solvers as well as individual solver interfaces within Pyomo. The most common of these, available with most solvers and solver interfaces, is constraint dual multipliers. Requesting that duals be imported into suffix data can be accomplished by declaring a Suffix component on the model.

```
model = pyo.ConcreteModel()
model.dual = pyo.Suffix(direction=pyo.Suffix.IMPORT)
model.x = pyo.Var()
model.obj = pyo.Objective(expr=model.x)
model.con = pyo.Constraint(expr=model.x >= 1.0)
```

The existence of an active suffix with the name dual that has an import style suffix direction will cause constraint dual information to be collected into the solver results (assuming the solver supplies dual information). In addition to this, after loading solver results into a problem instance (using a python script or Pyomo callback functions in conjunction with the `pyomo` command), one can access the dual values associated with constraints using the dual Suffix component.

```
>>> results = pyo.SolverFactory('glpk').solve(model)
>>> pyo.assert_optimal_termination(results)
>>> print(model.dual[model.con])
1.0
```

Alternatively, the `pyomo` option `--solver-suffixes` can be used to request suffix information from a solver. In the

event that suffix names are provided via this command-line option, the `pyomo` script will automatically declare these Suffix components on the constructed instance making these suffixes available for import.

4.7.5 Exporting Suffix Data

Exporting suffix data is accomplished in a similar manner as to that of importing suffix data. One simply needs to declare a Suffix component on the model with an export style suffix direction and associate modeling component values with it. The following example shows how one can declare a special ordered set of type 1 using AMPL-style suffix notation in conjunction with Pyomo's NL file interface.

```
model = pyo.ConcreteModel()
model.y = pyo.Var([1,2,3], within=pyo.NonNegativeReals)

model.sosno = pyo.Suffix(direction=pyo.Suffix.EXPORT)
model.ref = pyo.Suffix(direction=pyo.Suffix.EXPORT)

# Add entry for each index of model.y
model.sosno.set_value(model.y, 1)
model.ref[model.y[1]] = 0
model.ref[model.y[2]] = 1
model.ref[model.y[3]] = 2
```

Most AMPL-compatible solvers will recognize the suffix names `sosno` and `ref` as declaring a special ordered set, where a positive value for `sosno` indicates a special ordered set of type 1 and a negative value indicates a special ordered set of type 2.

Note: Pyomo provides the `SOSConstraint` component for declaring special ordered sets, which is recognized by all solver interfaces, including the NL file interface.

Pyomo's NL file interface will recognize an EXPORT style Suffix component with the name 'dual' as supplying initializations for constraint multipliers. As such it will be treated separately than all other EXPORT style suffixes encountered in the NL writer, which are treated as AMPL-style suffixes. The following example script shows how one can warmstart the interior-point solver Ipopt by supplying both primal (variable values) and dual (suffixes) solution information. This dual suffix information can be both imported and exported using a single Suffix component with an IMPORT_EXPORT direction.

```
model = pyo.ConcreteModel()
model.x1 = pyo.Var(bounds=(1,5),initialize=1.0)
model.x2 = pyo.Var(bounds=(1,5),initialize=5.0)
model.x3 = pyo.Var(bounds=(1,5),initialize=5.0)
model.x4 = pyo.Var(bounds=(1,5),initialize=1.0)
model.obj = pyo.Objective(
    expr=model.x1*model.x4*(model.x1 + model.x2 + model.x3) + model.x3)
model.inequality = pyo.Constraint(
    expr=model.x1*model.x2*model.x3*model.x4 >= 25.0)
model.equality = pyo.Constraint(
    expr=model.x1**2 + model.x2**2 + model.x3**2 + model.x4**2 == 40.0)

### Declare all suffixes
# Ipopt bound multipliers (obtained from solution)
model.ipopt_zL_out = pyo.Suffix(direction=pyo.Suffix.IMPORT)
model.ipopt_zU_out = pyo.Suffix(direction=pyo.Suffix.IMPORT)
```

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```
# Ipopt bound multipliers (sent to solver)
model.ipopt_zL_in = pyo.Suffix(direction=pyo.Suffix.EXPORT)
model.ipopt_zU_in = pyo.Suffix(direction=pyo.Suffix.EXPORT)
# Obtain dual solutions from first solve and send to warm start
model.dual = pyo.Suffix(direction=pyo.Suffix.IMPORT_EXPORT)

ipopt = pyo.SolverFactory('ipopt')
```

The difference in performance can be seen by examining Ipopt's iteration log with and without warm starting:

- Without Warmstart:

```
ipopt.solve(model, tee=True)
```

```
...
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du alpha_pr  ls
   0  1.6109693e+01 1.12e+01 5.28e-01  -1.0 0.00e+00    -  0.00e+00 0.00e+00   0
   1  1.6982239e+01 7.30e-01 1.02e+01  -1.0 6.11e-01    -  7.19e-02 1.00e+00f  1
   2  1.7318411e+01 3.60e-02 5.05e-01  -1.0 1.61e-01    -  1.00e+00 1.00e+00h  1
   3  1.6849424e+01 2.78e-01 6.68e-02  -1.7 2.85e-01    -  7.94e-01 1.00e+00h  1
   4  1.7051199e+01 4.71e-03 2.78e-03  -1.7 6.06e-02    -  1.00e+00 1.00e+00h  1
   5  1.7011979e+01 7.19e-03 8.50e-03  -3.8 3.66e-02    -  9.45e-01 9.98e-01h  1
   6  1.7014271e+01 1.74e-05 9.78e-06  -3.8 3.33e-03    -  1.00e+00 1.00e+00h  1
   7  1.7014021e+01 1.23e-07 1.82e-07  -5.7 2.69e-04    -  1.00e+00 1.00e+00h  1
   8  1.7014017e+01 1.77e-11 2.52e-11  -8.6 3.32e-06    -  1.00e+00 1.00e+00h  1

Number of Iterations....: 8
...
```

- With Warmstart:

```
### Set Ipopt options for warm-start
# The current values on the ipopt_zU_out and ipopt_zL_out suffixes will
# be used as initial conditions for the bound multipliers to solve the
# new problem
model.ipopt_zL_in.update(model.ipopt_zL_out)
model.ipopt_zU_in.update(model.ipopt_zU_out)
ipopt.options['warm_start_init_point'] = 'yes'
ipopt.options['warm_start_bound_push'] = 1e-6
ipopt.options['warm_start_mult_bound_push'] = 1e-6
ipopt.options['mu_init'] = 1e-6

ipopt.solve(model, tee=True)
```

```
...
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du alpha_pr  ls
   0  1.7014032e+01 2.00e-06 4.07e-06  -6.0 0.00e+00    -  0.00e+00 0.00e+00   0
   1  1.7014019e+01 3.65e-12 1.00e-11  -6.0 2.50e-01    -  1.00e+00 1.00e+00h  1
   2  1.7014017e+01 4.48e-12 6.42e-12  -9.0 1.92e-06    -  1.00e+00 1.00e+00h  1

Number of Iterations....: 2
...
```

4.7.6 Using Suffixes With an AbstractModel

In order to allow the declaration of suffix data within the framework of an AbstractModel, the Suffix component can be initialized with an optional construction rule. As with constraint rules, this function will be executed at the time of model construction. The following simple example highlights the use of the `rule` keyword in suffix initialization. Suffix rules are expected to return an iterable of (component, value) tuples, where the `expand=True` semantics are applied for indexed components.

```
model = pyo.AbstractModel()
model.x = pyo.Var()
model.c = pyo.Constraint(expr=model.x >= 1)

def foo_rule(m):
   return ((m.x, 2.0), (m.c, 3.0))
model.foo = pyo.Suffix(rule=foo_rule)
```

```
>>> # Instantiate the model
>>> inst = model.create_instance()

>>> print(inst.foo[inst.x])
2.0
>>> print(inst.foo[inst.c])
3.0

>>> # Note that model.x and inst.x are not the same object
>>> print(inst.foo[model.x])
Traceback (most recent call last):
  ...
KeyError: "Component with id '...': x"
```

The next example shows an abstract model where suffixes are attached only to the variables:

```
model = pyo.AbstractModel()
model.I = pyo.RangeSet(1,4)
model.x = pyo.Var(model.I)
def c_rule(m, i):
    return m.x[i] >= i
model.c = pyo.Constraint(model.I, rule=c_rule)

def foo_rule(m):
    return ((m.x[i], 3.0*i) for i in m.I)
model.foo = pyo.Suffix(rule=foo_rule)
```

```
>>> # instantiate the model
>>> inst = model.create_instance()
>>> for i in inst.I:
...     print((i, inst.foo[inst.x[i]]))
(1, 3.0)
(2, 6.0)
(3, 9.0)
(4, 12.0)
```

CHAPTER

FIVE

SOLVING PYOMO MODELS

5.1 Solving ConcreteModels

If you have a ConcreteModel, add these lines at the bottom of your Python script to solve it

```
>>> opt = pyo.SolverFactory('glpk')
>>> opt.solve(model)
```

5.2 Solving AbstractModels

If you have an AbstractModel, you must create a concrete instance of your model before solving it using the same lines as above:

```
>>> instance = model.create_instance()
>>> opt = pyo.SolverFactory('glpk')
>>> opt.solve(instance)
```

5.3 `pyomo solve` Command

To solve a ConcreteModel contained in the file `my_model.py` using the `pyomo` command and the solver GLPK, use the following line in a terminal window:

```
pyomo solve my_model.py --solver='glpk'
```

To solve an AbstractModel contained in the file `my_model.py` with data in the file `my_data.dat` using the `pyomo` command and the solver GLPK, use the following line in a terminal window:

```
pyomo solve my_model.py my_data.dat --solver='glpk'
```

5.4 Supported Solvers

Pyomo supports a wide variety of solvers. Pyomo has specialized interfaces to some solvers (for example, BARON, CBC, CPLEX, and Gurobi). It also has generic interfaces that support calling any solver that can read AMPL ".nl" and write ".sol" files and the ability to generate GAMS-format models and retrieve the results. You can get the current list of supported solvers using the pyomo command:

```
pyomo help --solvers
```

CHAPTER

SIX

WORKING WITH PYOMO MODELS

This section gives an overview of commonly used scripting commands when working with Pyomo models. These commands must be applied to a concrete model instance or in other words an instantiated model.

6.1 Repeated Solves

```
>>> import pyomo.environ as pyo
>>> from pyomo.opt import SolverFactory
>>> model = pyo.ConcreteModel()
>>> model.nVars = pyo.Param(initialize=4)
>>> model.N = pyo.RangeSet(model.nVars)
>>> model.x = pyo.Var(model.N, within=pyo.Binary)
>>> model.obj = pyo.Objective(expr=pyo.summation(model.x))
>>> model.cuts = pyo.ConstraintList()
>>> opt = SolverFactory('glpk')
>>> opt.solve(model)

>>> # Iterate, adding a cut to exclude the previously found solution
>>> for i in range(5):
...     expr = 0
...     for j in model.x:
...         if pyo.value(model.x[j]) < 0.5:
...             expr += model.x[j]
...         else:
...             expr += (1 - model.x[j])
...     model.cuts.add( expr >= 1 )
...     results = opt.solve(model)
...     print ("\n===== iteration",i)
...     model.display()
```

To illustrate Python scripts for Pyomo we consider an example that is in the file `iterative1.py` and is executed using the command

```
python iterative1.py
```

Note: This is a Python script that contains elements of Pyomo, so it is executed using the `python` command. The `pyomo` command can be used, but then there will be some strange messages at the end when Pyomo finishes the script and attempts to send the results to a solver, which is what the `pyomo` command does.

This script creates a model, solves it, and then adds a constraint to preclude the solution just found. This process is repeated, so the script finds and prints multiple solutions. The particular model it creates is just the sum of four binary variables. One does not need a computer to solve the problem or even to iterate over solutions. This example is provided just to illustrate some elementary aspects of scripting.

```
# iterative1.py
import pyomo.environ as pyo
from pyomo.opt import SolverFactory

# Create a solver
opt = pyo.SolverFactory('glpk')

#
# A simple model with binary variables and
# an empty constraint list.
#
model = pyo.AbstractModel()
model.n = pyo.Param(default=4)
model.x = pyo.Var(pyo.RangeSet(model.n), within=pyo.Binary)
def o_rule(model):
    return pyo.summation(model.x)
model.o = pyo.Objective(rule=o_rule)
model.c = pyo.ConstraintList()

# Create a model instance and optimize
instance = model.create_instance()
results = opt.solve(instance)
instance.display()

# Iterate to eliminate the previously found solution
for i in range(5):
    expr = 0
    for j in instance.x:
        if pyo.value(instance.x[j]) == 0:
            expr += instance.x[j]
        else:
            expr += (1-instance.x[j])
    instance.c.add( expr >= 1 )
    results = opt.solve(instance)
    print ("\n===== iteration",i)
    instance.display()
```

Let us now analyze this script. The first line is a comment that happens to give the name of the file. This is followed by two lines that import symbols for Pyomo. The pyomo namespace is imported as `pyo`. Therefore, `pyo.` must precede each use of a Pyomo name.

```
# iterative1.py
import pyomo.environ as pyo
from pyomo.opt import SolverFactory
```

An object to perform optimization is created by calling `SolverFactory` with an argument giving the name of the solver. The argument would be `'gurobi'` if, e.g., Gurobi was desired instead of glpk:

```
# Create a solver
opt = pyo.SolverFactory('glpk')
```

The next lines after a comment create a model. For our discussion here, we will refer to this as the base model because it will be extended by adding constraints later. (The words "base model" are not reserved words, they are just being introduced for the discussion of this example). There are no constraints in the base model, but that is just to keep it simple. Constraints could be present in the base model. Even though it is an abstract model, the base model is fully specified by these commands because it requires no external data:

```
model = pyo.AbstractModel()
model.n = pyo.Param(default=4)
model.x = pyo.Var(pyo.RangeSet(model.n), within=pyo.Binary)
def o_rule(model):
    return pyo.summation(model.x)
model.o = pyo.Objective(rule=o_rule)
```

The next line is not part of the base model specification. It creates an empty constraint list that the script will use to add constraints.

```
model.c = pyo.ConstraintList()
```

The next non-comment line creates the instantiated model and refers to the instance object with a Python variable `instance`. Models run using the `pyomo` script do not typically contain this line because model instantiation is done by the `pyomo` script. In this example, the `create` function is called without arguments because none are needed; however, the name of a file with data commands is given as an argument in many scripts.

```
instance = model.create_instance()
```

The next line invokes the solver and refers to the object contain results with the Python variable `results`.

```
results = opt.solve(instance)
```

The solve function loads the results into the instance, so the next line writes out the updated values.

```
instance.display()
```

The next non-comment line is a Python iteration command that will successively assign the integers from 0 to 4 to the Python variable `i`, although that variable is not used in script. This loop is what causes the script to generate five more solutions:

```
for i in range(5):
```

An expression is built up in the Python variable named `expr`. The Python variable `j` will be iteratively assigned all of the indexes of the variable `x`. For each index, the value of the variable (which was loaded by the `load` method just described) is tested to see if it is zero and the expression in `expr` is augmented accordingly. Although `expr` is initialized to 0 (an integer), its type will change to be a Pyomo expression when it is assigned expressions involving Pyomo variable objects:

```
    expr = 0
    for j in instance.x:
        if pyo.value(instance.x[j]) == 0:
            expr += instance.x[j]
        else:
            expr += (1-instance.x[j])
```

During the first iteration (when `i` is 0), we know that all values of `x` will be 0, so we can anticipate what the expression will look like. We know that `x` is indexed by the integers from 1 to 4 so we know that `j` will take on the values from 1 to 4 and we also know that all value of `x` will be zero for all indexes so we know that the value of `expr` will be something like

```
0 + instance.x[1] + instance.x[2] + instance.x[3] + instance.x[4]
```

The value of `j` will be evaluated because it is a Python variable; however, because it is a Pyomo variable, the value of `instance.x[j]` not be used, instead the variable object will appear in the expression. That is exactly what we want in this case. When we wanted to use the current value in the `if` statement, we used the `value` function to get it.

The next line adds to the constaint list called `c` the requirement that the expression be greater than or equal to one:

```
    instance.c.add( expr >= 1 )
```

The proof that this precludes the last solution is left as an exerise for the reader.

The final lines in the outer for loop find a solution and display it:

```
    results = opt.solve(instance)
    print ("\n===== iteration",i)
    instance.display()
```

Note: The assignment of the solve output to a results object is somewhat anachronistic. Many scripts just use

```
>>> opt.solve(instance)
```

since the results are moved to the instance by default, leaving the results object with little of interest. If, for some reason, you want the results to stay in the results object and *not* be moved to the instance, you would use

```
>>> results = opt.solve(instance, load_solutions=False)
```

This approach can be usefull if there is a concern that the solver did not terminate with an optimal solution. For example,

```
>>> results = opt.solve(instance, load_solutions=False)
>>> if results.solver.termination_condition == TerminationCondition.optimal:
...     instance.solutions.load_from(results)
```

6.2 Changing the Model or Data and Re-solving

The `iterative1.py` example above illustrates how a model can be changed and then re-solved. In that example, the model is changed by adding a constraint, but the model could also be changed by altering the values of parameters. Note, however, that in these examples, we make the changes to the concrete model instances. This is particularly important for `AbstractModel` users, as this implies working with the `instance` object rather than the `model` object, which allows us to avoid creating a new `model` object for each solve. Here is the basic idea for users of an `AbstractModel`:

1. Create an `AbstractModel` (suppose it is called `model`)
2. Call `model.create_instance()` to create an instance (suppose it is called `instance`)
3. Solve `instance`
4. Change someting in `instance`
5. Solve `instance` again

Note: Users of `ConcreteModel` typically name their models `model`, which can cause confusion to novice readers of documentation. Examples based on an `AbstractModel` will refer to `instance` where users of a `ConcreteModel` would typically use the name `model`.

If `instance` has a parameter whose name is `Theta` that was declared to be `mutable` (i.e., `mutable=True`) with an index that contains `idx`, then the value in `NewVal` can be assigned to it using

```
>>> instance.Theta[idx] = NewVal
```

For a singleton parameter named `sigma` (i.e., if it is not indexed), the assignment can be made using

```
>>> instance.sigma = NewVal
```

Note: If the `Param` is not declared to be mutable, an error will occur if an assignment to it is attempted.

For more information about access to Pyomo parameters, see the section in this document on `Param` access *Accessing Parameter Values*. Note that for concrete models, the model is the instance.

6.3 Fixing Variables and Re-solving

Instead of changing model data, scripts are often used to fix variable values. The following example illustrates this.

```
# iterative2.py

import pyomo.environ as pyo
from pyomo.opt import SolverFactory

# Create a solver
opt = pyo.SolverFactory('cplex')

#
# A simple model with binary variables and
# an empty constraint list.
#
model = pyo.AbstractModel()
model.n = pyo.Param(default=4)
model.x = pyo.Var(pyo.RangeSet(model.n), within=pyo.Binary)
def o_rule(model):
    return summation(model.x)
model.o = pyo.Objective(rule=o_rule)
model.c = pyo.ConstraintList()

# Create a model instance and optimize
instance = model.create_instance()
results = opt.solve(instance)
instance.display()

# "flip" the value of x[2] (it is binary)
# then solve again
```

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```
if pyo.value(instance.x[2]) == 0:
    instance.x[2].fix(1)
else:
    instance.x[2].fix(0)

results = opt.solve(instance)
instance.display()
```

In this example, the variables are binary. The model is solved and then the value of `model.x[2]` is flipped to the opposite value before solving the model again. The main lines of interest are:

```
if pyo.value(instance.x[2]) == 0:
    instance.x[2].fix(1)
else:
    instance.x[2].fix(0)

results = opt.solve(instance)
```

This could also have been accomplished by setting the upper and lower bounds:

```
>>> if instance.x[2].value == 0:
...     instance.x[2].setlb(1)
...     instance.x[2].setub(1)
... else:
...     instance.x[2].setlb(0)
...     instance.x[2].setub(0)
```

Notice that when using the bounds, we do not set `fixed` to `True` because that would fix the variable at whatever value it presently has and then the bounds would be ignored by the solver.

For more information about access to Pyomo variables, see the section in this document on `Var` access *Accessing Variable Values*.

Note that

```
>>> instance.x.fix(2)
```

is equivalent to

```
>>> instance.x.value = 2
>>> instance.x.fixed = True
```

and

```
>>> instance.x.fix()
```

is equivalent to

```
>>> instance.x.fixed = True
```

6.4 Extending the Objective Function

One can add terms to an objective function of a `ConcreteModel` (or and instantiated `AbstractModel`) using the `expr` attribute of the objective function object. Here is a simple example:

```
>>> import pyomo.environ as pyo
>>> from pyomo.opt import SolverFactory

>>> model = pyo.ConcreteModel()

>>> model.x = pyo.Var(within=pyo.PositiveReals)
>>> model.y = pyo.Var(within=pyo.PositiveReals)

>>> model.sillybound = pyo.Constraint(expr = model.x + model.y <= 2)

>>> model.obj = pyo.Objective(expr = 20 * model.x)

>>> opt = SolverFactory('glpk')
>>> opt.solve(model)

>>> model.pprint()

>>> print ("-------------- extend obj --------------")
>>> model.obj.expr += 10 * model.y

>>> opt = SolverFactory('cplex')
>>> opt.solve(model)
>>> model.pprint()
```

6.5 Activating and Deactivating Objectives

Multiple objectives can be declared, but only one can be active at a time (at present, Pyomo does not support any solvers that can be given more than one objective). If both `model.obj1` and `model.obj2` have been declared using `Objective`, then one can ensure that `model.obj2` is passed to the solver as shown in this simple example:

```
>>> model = pyo.ConcreteModel()
>>> model.obj1 = pyo.Objective(expr = 0)
>>> model.obj2 = pyo.Objective(expr = 0)

>>> model.obj1.deactivate()
>>> model.obj2.activate()
```

For abstract models this would be done prior to instantiation or else the `activate` and `deactivate` calls would be on the instance rather than the model.

6.6 Activating and Deactivating Constraints

Constraints can be temporarily disabled using the `deactivate()` method. When the model is sent to a solver inactive constraints are not included. Disabled constraints can be re-enabled using the `activate()` method.

```
>>> model = pyo.ConcreteModel()
>>> model.v = pyo.Var()
>>> model.con = pyo.Constraint(expr=model.v**2 + model.v >= 3)
>>> model.con.deactivate()
>>> model.con.activate()
```

Indexed constraints can be deactivated/activated as a whole or by individual index:

```
>>> model = pyo.ConcreteModel()
>>> model.s = pyo.Set(initialize=[1,2,3])
>>> model.v = pyo.Var(model.s)
>>> def _con(m, s):
...     return m.v[s]**2 + m.v[s] >= 3
>>> model.con = pyo.Constraint(model.s, rule=_con)
>>> model.con.deactivate()    # Deactivate all indices
>>> model.con[1].activate()  # Activate single index
```

6.7 Accessing Variable Values

6.7.1 Primal Variable Values

Often, the point of optimization is to get optimal values of variables. Some users may want to process the values in a script. We will describe how to access a particular variable from a Python script as well as how to access all variables from a Python script and from a callback. This should enable the reader to understand how to get the access that they desire. The Iterative example given above also illustrates access to variable values.

6.7.2 One Variable from a Python Script

Assuming the model has been instantiated and solved and the results have been loded back into the instance object, then we can make use of the fact that the variable is a member of the instance object and its value can be accessed using its `value` member. For example, suppose the model contains a variable named `quant` that is a singleton (has no indexes) and suppose further that the name of the instance object is `instance`. Then the value of this variable can be accessed using `pyo.value(instance.quant)`. Variables with indexes can be referenced by supplying the index.

Consider the following very simple example, which is similar to the iterative example. This is a concrete model. In this example, the value of `x[2]` is accessed.

```
# noiteration1.py

import pyomo.environ as pyo
from pyomo.opt import SolverFactory

# Create a solver
opt = SolverFactory('glpk')
```

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```
#
# A simple model with binary variables and
# an empty constraint list.
#
model = pyo.ConcreteModel()
model.n = pyo.Param(default=4)
model.x = pyo.Var(pyo.RangeSet(model.n), within=pyo.Binary)
def o_rule(model):
    return summation(model.x)
model.o = pyo.Objective(rule=o_rule)
model.c = pyo.ConstraintList()

results = opt.solve(model)

if pyo.value(model.x[2]) == 0:
    print("The second index has a zero")
else:
    print("x[2]=",pyo.value(model.x[2]))
```

Note: If this script is run without modification, Pyomo is likely to issue a warning because there are no constraints. The warning is because some solvers may fail if given a problem instance that does not have any constraints.

6.7.3 All Variables from a Python Script

As with one variable, we assume that the model has been instantiated and solved. Assuming the instance object has the name `instance`, the following code snippet displays all variables and their values:

```
>>> for v in instance.component_objects(pyo.Var, active=True):
...     print("Variable",v)
...     for index in v:
...         print ("   ",index, pyo.value(v[index]))
```

Alternatively,

```
>>> for v in instance.component_data_objects(pyo.Var, active=True):
...     print(v, pyo.value(v))
```

This code could be improved by checking to see if the variable is not indexed (i.e., the only index value is `None`), then the code could print the value without the word `None` next to it.

Assuming again that the model has been instantiated and solved and the results have been loded back into the instance object. Here is a code snippet for fixing all integers at their current value:

```
>>> for var in instance.component_data_objects(pyo.Var, active=True):
...     if not var.is_continuous():
...         print ("fixing "+str(v))
...         var.fixed = True # fix the current value
```

Another way to access all of the variables (particularly if there are blocks) is as follows (this particular snippet assumes that instead of *import pyomo.environ as pyo from pyo.environ import* * was used):

```
for v in model.component_objects(Var, descend_into=True):
    print("FOUND VAR:" + v.name)
    v.pprint()

for v_data in model.component_data_objects(Var, descend_into=True):
    print("Found: "+v_data.name+", value = "+str(value(v_data)))
```

6.8 Accessing Parameter Values

Accessing parameter values is completely analogous to accessing variable values. For example, here is a code snippet to print the name and value of every Parameter in a model:

```
>>> for parmobject in instance.component_objects(pyo.Param, active=True):
...     nametoprint = str(str(parmobject.name))
...     print ("Parameter ", nametoprint)
...     for index in parmobject:
...         vtoprint = pyo.value(parmobject[index])
...         print ("   ",index, vtoprint)
```

6.9 Accessing Duals

Access to dual values in scripts is similar to accessing primal variable values, except that dual values are not captured by default so additional directives are needed before optimization to signal that duals are desired.

To get duals without a script, use the `pyomo` option `--solver-suffixes='dual'` which will cause dual values to be included in output. Note: In addition to duals (`dual`) , reduced costs (`rc`) and slack values (`slack`) can be requested. All suffixes can be requested using the `pyomo` option `--solver-suffixes='.*'`

> **Warning:** Some of the duals may have the value `None`, rather than `0`.

6.9.1 Access Duals in a Python Script

To signal that duals are desired, declare a Suffix component with the name "dual" on the model or instance with an IMPORT or IMPORT_EXPORT direction.

```
# Create a 'dual' suffix component on the instance
# so the solver plugin will know which suffixes to collect
instance.dual = pyo.Suffix(direction=pyo.Suffix.IMPORT)
```

See the section on Suffixes *Suffixes* for more information on Pyomo's Suffix component. After the results are obtained and loaded into an instance, duals can be accessed in the following fashion.

```
# display all duals
print ("Duals")
for c in instance.component_objects(pyo.Constraint, active=True):
    print ("   Constraint",c)
    for index in c:
        print ("      ", index, instance.dual[c[index]])
```

The following snippet will only work, of course, if there is a constraint with the name `AxbConstraint` that has and index, which is the string `Film`.

```
# access one dual
print ("Dual for Film=", instance.dual[instance.AxbConstraint['Film']])
```

Here is a complete example that relies on the file `abstract2.py` to provide the model and the file `abstract2.dat` to provide the data. Note that the model in `abstract2.py` does contain a constraint named `AxbConstraint` and `abstract2.dat` does specify an index for it named `Film`.

```
# driveabs2.py
from __future__ import division
import pyomo.environ as pyo
from pyomo.opt import SolverFactory

# Create a solver
opt = SolverFactory('cplex')

# get the model from another file
from abstract2 import model

# Create a model instance and optimize
instance = model.create_instance('abstract2.dat')

# Create a 'dual' suffix component on the instance
# so the solver plugin will know which suffixes to collect
instance.dual = pyo.Suffix(direction=pyo.Suffix.IMPORT)

results = opt.solve(instance)
# also puts the results back into the instance for easy access

# display all duals
print ("Duals")
for c in instance.component_objects(pyo.Constraint, active=True):
    print ("   Constraint",c)
    for index in c:
        print ("      ", index, instance.dual[c[index]])

# access one dual
print ("Dual for Film=", instance.dual[instance.AxbConstraint['Film']])
```

Concrete models are slightly different because the model is the instance. Here is a complete example that relies on the file `concrete1.py` to provide the model and instantiate it.

```
# driveconc1.py
from __future__ import division
import pyomo.environ as pyo
from pyomo.opt import SolverFactory

# Create a solver
opt = SolverFactory('cplex')

# get the model from another file
from concrete1 import model
```

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```
# Create a 'dual' suffix component on the instance
# so the solver plugin will know which suffixes to collect
model.dual = pyo.Suffix(direction=pyo.Suffix.IMPORT)

results = opt.solve(model) # also load results to model

# display all duals
print ("Duals")
for c in model.component_objects(pyo.Constraint, active=True):
    print ("   Constraint",c)
    for index in c:
        print ("      ", index, model.dual[c[index]])
```

6.10 Accessing Slacks

The functions `lslack()` and `uslack()` return the upper and lower slacks, respectively, for a constraint.

6.11 Accessing Solver Status

After a solve, the results object has a member `Solution.Status` that contains the solver status. The following snippet shows an example of access via a `print` statement:

```
results = opt.solve(instance)
#print ("The solver returned a status of:"+str(results.solver.status))
```

The use of the Python `str` function to cast the value to a be string makes it easy to test it. In particular, the value 'optimal' indicates that the solver succeeded. It is also possible to access Pyomo data that can be compared with the solver status as in the following code snippet:

```
from pyomo.opt import SolverStatus, TerminationCondition

#...

if (results.solver.status == SolverStatus.ok) and (results.solver.termination_condition␣
↪== TerminationCondition.optimal):
    print ("this is feasible and optimal")
elif results.solver.termination_condition == TerminationCondition.infeasible:
    print ("do something about it? or exit?")
else:
    # something else is wrong
    print (str(results.solver))
```

Alternatively,

```
from pyomo.opt import TerminationCondition

...

results = opt.solve(model, load_solutions=False)
if results.solver.termination_condition == TerminationCondition.optimal:
    model.solutions.load_from(results)
else:
    print ("Solution is not optimal")
    # now do something about it? or exit? ...
```

6.12 Display of Solver Output

To see the output of the solver, use the option `tee=True` as in

```
results = opt.solve(instance, tee=True)
```

This can be useful for troubleshooting solver difficulties.

6.13 Sending Options to the Solver

Most solvers accept options and Pyomo can pass options through to a solver. In scripts or callbacks, the options can be attached to the solver object by adding to its options dictionary as illustrated by this snippet:

```
optimizer = pyo.SolverFactory['cbc']
optimizer.options["threads"] = 4
```

If multiple options are needed, then multiple dictionary entries should be added.

Sometimes it is desirable to pass options as part of the call to the solve function as in this snippet:

```
results = optimizer.solve(instance, options="threads=4", tee=True)
```

The quoted string is passed directly to the solver. If multiple options need to be passed to the solver in this way, they should be separated by a space within the quoted string. Notice that `tee` is a Pyomo option and is solver-independent, while the string argument to `options` is passed to the solver without very little processing by Pyomo. If the solver does not have a "threads" option, it will probably complain, but Pyomo will not.

There are no default values for options on a `SolverFactory` object. If you directly modify its options dictionary, as was done above, those options will persist across every call to `optimizer.solve(...)` unless you delete them from the options dictionary. You can also pass a dictionary of options into the `opt.solve(...)` method using the `options` keyword. Those options will only persist within that solve and temporarily override any matching options in the options dictionary on the solver object.

6.14 Specifying the Path to a Solver

Often, the executables for solvers are in the path; however, for situations where they are not, the SolverFactory function accepts the keyword `executable`, which you can use to set an absolute or relative path to a solver executable. E.g.,

```
opt = pyo.SolverFactory("ipopt", executable="../ipopt")
```

6.15 Warm Starts

Some solvers support a warm start based on current values of variables. To use this feature, set the values of variables in the instance and pass `warmstart=True` to the `solve()` method. E.g.,

```
instance = model.create()
instance.y[0] = 1
instance.y[1] = 0

opt = pyo.SolverFactory("cplex")

results = opt.solve(instance, warmstart=True)
```

Note: The Cplex and Gurobi LP file (and Python) interfaces will generate an MST file with the variable data and hand this off to the solver in addition to the LP file.

Warning: Solvers using the NL file interface (e.g., "gurobi_ampl", "cplexamp") do not accept warmstart as a keyword to the solve() method as the NL file format, by default, includes variable initialization data (drawn from the current value of all variables).

6.16 Solving Multiple Instances in Parallel

Building and solving Pyomo models in parallel is a common requirement for many applications. We recommend using MPI for Python (mpi4py) for this purpose. For more information on mpi4py, see the mpi4py documentation (https://mpi4py.readthedocs.io/en/stable/). The example below demonstrates how to use mpi4py to solve two pyomo models in parallel. The example can be run with the following command:

```
mpirun -np 2 python -m mpi4py parallel.py
```

```
# parallel.py
# run with mpirun -np 2 python -m mpi4py parallel.py
import pyomo.environ as pyo
from mpi4py import MPI

rank = MPI.COMM_WORLD.Get_rank()
size = MPI.COMM_WORLD.Get_size()
assert size == 2, 'This example only works with 2 processes; please us mpirun -np 2␣
↪python -m mpi4py parallel.py'
```

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```
# Create a solver
opt = pyo.SolverFactory('cplex_direct')

#
# A simple model with binary variables
#
model = pyo.ConcreteModel()
model.n = pyo.Param(initialize=4)
model.x = pyo.Var(pyo.RangeSet(model.n), within=pyo.Binary)
model.obj = pyo.Objective(expr=sum(model.x.values()))

if rank == 1:
    model.x[1].fix(1)

results = opt.solve(model)
print('rank: ', rank, '    objective: ', pyo.value(model.obj.expr))
```

6.17 Changing the temporary directory

A "temporary" directory is used for many intermediate files. Normally, the name of the directory for temporary files is provided by the operating system, but the user can specify their own directory name. The pyomo command-line `--tempdir` option propagates through to the TempFileManager service. One can accomplish the same through the following few lines of code in a script:

```
from pyomo.common.tempfiles import TempfileManager
TempfileManager.tempdir = YourDirectoryNameGoesHere
```

CHAPTER

SEVEN

WORKING WITH ABSTRACT MODELS

7.1 Instantiating Models

If you start with a *ConcreteModel*, each component you add to the model will be fully constructed and initialized at the time it attached to the model. However, if you are starting with an *AbstractModel*, construction occurs in two phases. When you first declare and attach components to the model, those components are empty containers and *not* fully constructed, even if you explicitly provide data.

```
>>> import pyomo.environ as pyo
>>> model = pyo.AbstractModel()
>>> model.is_constructed()
False

>>> model.p = pyo.Param(initialize=5)
>>> model.p.is_constructed()
False

>>> model.I = pyo.Set(initialize=[1,2,3])
>>> model.x = pyo.Var(model.I)
>>> model.x.is_constructed()
False
```

If you look at the `model` at this point, you will see that everything is "empty":

```
>>> model.pprint()
1 Set Declarations
    I : Size=0, Index=None, Ordered=Insertion
        Not constructed

1 Param Declarations
    p : Size=0, Index=None, Domain=Any, Default=None, Mutable=False
        Not constructed

1 Var Declarations
    x : Size=0, Index=I
        Not constructed

3 Declarations: p I x
```

Before you can manipulate modeling components or solve the model, you must first create a concrete *instance* by applying data to your abstract model. This can be done using the *create_instance()* method, which takes the

abstract model and optional data and returns a new *concrete* instance by constructing each of the model components in the order in which they were declared (attached to the model). Note that the instance creation is performed "out of place"; that is, the original abstract `model` is left untouched.

```
>>> instance = model.create_instance()
>>> model.is_constructed()
False
>>> type(instance)
<class 'pyomo.core.base.PyomoModel.ConcreteModel'>
>>> instance.is_constructed()
True
>>> instance.pprint()
1 Set Declarations
    I : Size=1, Index=None, Ordered=Insertion
        Key  : Dimen : Domain : Size : Members
        None :     1 :    Any :    3 : {1, 2, 3}

1 Param Declarations
    p : Size=1, Index=None, Domain=Any, Default=None, Mutable=False
        Key  : Value
        None :     5

1 Var Declarations
    x : Size=3, Index=I
        Key : Lower : Value : Upper : Fixed : Stale : Domain
          1 :  None :  None :  None : False :  True :  Reals
          2 :  None :  None :  None : False :  True :  Reals
          3 :  None :  None :  None : False :  True :  Reals

3 Declarations: p I x
```

Note: AbstractModel users should note that in some examples, your concrete model instance is called "*instance*" and not "*model*". This is the case here, where we are explicitly calling `instance = model.create_instance()`.

The *create_instance()* method can also take a reference to external data, which overrides any data specified in the original component declarations. The data can be provided from several sources, including using a *dict*, *DataPortal*, or *DAT file*. For example:

```
>>> instance2 = model.create_instance({None: {'I': {None: [4,5]}}})
>>> instance2.pprint()
1 Set Declarations
    I : Size=1, Index=None, Ordered=Insertion
        Key  : Dimen : Domain : Size : Members
        None :     1 :    Any :    2 : {4, 5}

1 Param Declarations
    p : Size=1, Index=None, Domain=Any, Default=None, Mutable=False
        Key  : Value
        None :     5

1 Var Declarations
    x : Size=2, Index=I
```

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```
        Key : Lower : Value : Upper : Fixed : Stale : Domain
          4 :  None :  None :  None : False :  True :  Reals
          5 :  None :  None :  None : False :  True :  Reals

3 Declarations: p I x
```

7.2 Managing Data in AbstractModels

There are roughly three ways of using data to construct a Pyomo model:

1. use standard Python objects,
2. initialize a model with data loaded with a `DataPortal` object, and
3. load model data from a Pyomo data command file.

Standard Python data objects include native Python data types (e.g. lists, sets, and dictionaries) as well as standard data formats like numpy arrays and Pandas data frames. Standard Python data objects can be used to define constant values in a Pyomo model, and they can be used to initialize *Set* and *Param* components. However, initializing *Set* and *Param* components in this manner provides few advantages over direct use of standard Python data objects. (An import exception is that components indexed by *Set* objects use less memory than components indexed by native Python data.)

The `DataPortal` class provides a generic facility for loading data from disparate sources. A `DataPortal` object can load data in a consistent manner, and this data can be used to simply initialize all *Set* and *Param* components in a model. `DataPortal` objects can be used to initialize both concrete and abstract models in a uniform manner, which is important in some scripting applications. But in practice, this capability is only necessary for abstract models, whose data components are initialized after being constructed. (In fact, all abstract data components in an abstract model are loaded from `DataPortal` objects.)

Finally, Pyomo data command files provide a convenient mechanism for initializing *Set* and *Param* components with a high-level data specification. Data command files can be used with both concrete and abstract models, though in a different manner. Data command files are parsed using a `DataPortal` object, which must be done explicitly for a concrete model. However, abstract models can load data from a data command file directly, after the model is constructed. Again, this capability is only necessary for abstract models, whose data components are initialized after being constructed.

The following sections provide more detail about how data can be used to initialize Pyomo models.

7.2.1 Using Standard Data Types

Defining Constant Values

In many cases, Pyomo models can be constructed without *Set* and *Param* data components. Native Python data types class can be simply used to define constant values in Pyomo expressions. Consequently, Python sets, lists and dictionaries can be used to construct Pyomo models, as well as a wide range of other Python classes.

TODO

More examples here: set, list, dict, numpy, pandas.

Initializing Set and Parameter Components

The *Set* and *Param* components used in a Pyomo model can also be initialized with standard Python data types. This enables some modeling efficiencies when manipulating sets (e.g. when re-using sets for indices), and it supports validation of set and parameter data values. The *Set* and *Param* components are initialized with Python data using the `initialize` option.

Set Components

In general, *Set* components can be initialized with iterable data. For example, simple sets can be initialized with:

- list, set and tuple data:

```
model.A = Set(initialize=[2,3,5])
model.B = Set(initialize=set([2,3,5]))
model.C = Set(initialize=(2,3,5))
```

- generators:

```
model.D = Set(initialize=range(9))
model.E = Set(initialize=(i for i in model.B if i%2 == 0))
```

- numpy arrays:

```
f = numpy.array([2, 3, 5])
model.F = Set(initialize=f)
```

Sets can also be indirectly initialized with functions that return native Python data:

```
def g(model):
    return [2,3,5]
model.G = Set(initialize=g)
```

Indexed sets can be initialized with dictionary data where the dictionary values are iterable data:

```
H_init = {}
H_init[2] = [1,3,5]
H_init[3] = [2,4,6]
H_init[4] = [3,5,7]
model.H = Set([2,3,4],initialize=H_init)
```

Parameter Components

When a parameter is a single value, then a *Param* component can be simply initialized with a value:

```
model.a = Param(initialize=1.1)
```

More generally, *Param* components can be initialized with dictionary data where the dictionary values are single values:

```
model.b = Param([1,2,3], initialize={1:1, 2:2, 3:3})
```

Parameters can also be indirectly initialized with functions that return native Python data:

```
def c(model):
    return {1:1, 2:2, 3:3}
model.c = Param([1,2,3], initialize=c)
```

7.2.2 Using a Python Dictionary

Data can be passed to the model *create_instance()* method through a series of nested native Python dictionaries. The structure begins with a dictionary of *namespaces*, with the only required entry being the `None` namespace. Each namespace contains a dictionary that maps component names to dictionaries of component values. For scalar components, the required data dictionary maps the implicit index `None` to the desired value:

```
>>> from pyomo.environ import *
>>> m = AbstractModel()
>>> m.I = Set()
>>> m.p = Param()
>>> m.q = Param(m.I)
>>> m.r = Param(m.I, m.I, default=0)
>>> data = {None: {
...     'I': {None: [1,2,3]},
...     'p': {None: 100},
...     'q': {1: 10, 2:20, 3:30},
...     'r': {(1,1): 110, (1,2): 120, (2,3): 230},
... }}
>>> i = m.create_instance(data)
>>> i.pprint()
2 Set Declarations
    I : Size=1, Index=None, Ordered=Insertion
        Key  : Dimen : Domain : Size : Members
        None :     1 :    Any :    3 : {1, 2, 3}
    r_index : Size=1, Index=None, Ordered=True
        Key  : Dimen : Domain : Size : Members
        None :     2 :    I*I :    9 : {(1, 1), (1, 2), (1, 3), (2, 1), (2, 2),
↪ (2, 3), (3, 1), (3, 2), (3, 3)}

3 Param Declarations
    p : Size=1, Index=None, Domain=Any, Default=None, Mutable=False
        Key  : Value
        None :   100
    q : Size=3, Index=I, Domain=Any, Default=None, Mutable=False
        Key : Value
          1 :    10
          2 :    20
          3 :    30
    r : Size=9, Index=r_index, Domain=Any, Default=0, Mutable=False
        Key    : Value
        (1, 1) :   110
        (1, 2) :   120
        (2, 3) :   230

5 Declarations: I p q r_index r
```

7.2.3 Data Command Files

Note: The discussion and presentation below are adapted from Chapter 6 of the "Pyomo Book" [PyomoBookII]. The discussion of the `DataPortal` class uses these same examples to illustrate how data can be loaded into Pyomo models within Python scripts (see the *Data Portals* section).

Model Data

Pyomo's *data command files* employ a domain-specific language whose syntax closely resembles the syntax of AMPL's data commands [AMPL]. A data command file consists of a sequence of commands that either (a) specify set and parameter data for a model, or (b) specify where such data is to be obtained from external sources (e.g. table files, CSV files, spreadsheets and databases).

The following commands are used to declare data:

- The `set` command declares set data.
- The `param` command declares a table of parameter data, which can also include the declaration of the set data used to index the parameter data.
- The `table` command declares a two-dimensional table of parameter data.
- The `load` command defines how set and parameter data is loaded from external data sources, including ASCII table files, CSV files, XML files, YAML files, JSON files, ranges in spreadsheets, and database tables.

The following commands are also used in data command files:

- The `include` command specifies a data command file that is processed immediately.
- The `data` and `end` commands do not perform any actions, but they provide compatibility with AMPL scripts that define data commands.
- The `namespace` keyword allows data commands to be organized into named groups that can be enabled or disabled during model construction.

The following data types can be represented in a data command file:

- **Numeric value**: Any Python numeric value (e.g. integer, float, scientific notation, or boolean).
- **Simple string**: A sequence of alpha-numeric characters.
- **Quoted string**: A simple string that is included in a pair of single or double quotes. A quoted string can include quotes within the quoted string.

Numeric values are automatically converted to Python integer or floating point values when a data command file is parsed. Additionally, if a quoted string can be intepreted as a numeric value, then it will be converted to Python numeric types when the data is parsed. For example, the string "100" is converted to a numeric value automatically.

Warning: Pyomo data commands do *not* exactly correspond to AMPL data commands. The `set` and `param` commands are designed to closely match AMPL's syntax and semantics, though these commands only support a subset of the corresponding declarations in AMPL. However, other Pyomo data commands are not generally designed to match the semantics of AMPL.

Note: Pyomo data commands are terminated with a semicolon, and the syntax of data commands does not depend on whitespace. Thus, data commands can be broken across multiple lines – newlines and tab characters are ignored – and

data commands can be formatted with whitespace with few restrictions.

The `set` Command

Simple Sets

The `set` data command explicitly specifies the members of either a single set or an array of sets, i.e., an indexed set. A single set is specified with a list of data values that are included in this set. The formal syntax for the set data command is:

```
set <setname> := [<value>] ... ;
```

A set may be empty, and it may contain any combination of numeric and non-numeric string values. For example, the following are valid `set` commands:

```
# An empty set
set A := ;

# A set of numbers
set A := 1 2 3;

# A set of strings
set B := north south east west;

# A set of mixed types
set C :=
0
-1.0e+10
'foo bar'
infinity
"100"
;
```

Sets of Tuple Data

The `set` data command can also specify tuple data with the standard notation for tuples. For example, suppose that set `A` contains 3-tuples:

```
model.A = Set(dimen=3)
```

The following `set` data command then specifies that `A` is the set containing the tuples `(1,2,3)` and `(4,5,6)`:

```
set A := (1,2,3) (4,5,6) ;
```

Alternatively, set data can simply be listed in the order that the tuple is represented:

```
set A := 1 2 3 4 5 6 ;
```

Obviously, the number of data elements specified using this syntax should be a multiple of the set dimension.

Sets with 2-tuple data can also be specified in a matrix denoting set membership. For example, the following `set` data command declares 2-tuples in `A` using plus (+) to denote valid tuples and minus (-) to denote invalid tuples:

```
set A : A1 A2 A3 A4 :=
    1   +  -  -  +
    2   +  -  +  -
    3   -  +  -  - ;
```

This data command declares the following five 2-tuples: `('A1',1)`, `('A1',2)`, `('A2',3)`, `('A3',2)`, and `('A4',1)`.

Finally, a set of tuple data can be concisely represented with tuple *templates* that represent a *slice* of tuple data. For example, suppose that the set `A` contains 4-tuples:

```
model.A = Set(dimen=4)
```

The following `set` data command declares groups of tuples that are defined by a template and data to complete this template:

```
set A :=
    (1,2,*,4) A B
    (*,2,*,4) A B C D ;
```

A tuple template consists of a tuple that contains one or more asterisk (*) symbols instead of a value. These represent indices where the tuple value is replaced by the values from the list of values that follows the tuple template. In this example, the following tuples are in set `A`:

```
(1, 2, 'A', 4)
(1, 2, 'B', 4)
('A', 2, 'B', 4)
('C', 2, 'D', 4)
```

Set Arrays

The `set` data command can also be used to declare data for a set array. Each set in a set array must be declared with a separate `set` data command with the following syntax:

```
set <set-name>[<index>] := [<value>] ... ;
```

Because set arrays can be indexed by an arbitrary set, the index value may be a numeric value, a non-numeric string value, or a comma-separated list of string values.

Suppose that a set `A` is used to index a set `B` as follows:

```
model.A = Set()
model.B = Set(model.A)
```

Then set `B` is indexed using the values declared for set `A`:

```
set A := 1 aaa 'a b';

set B[1] := 0 1 2;
set B[aaa] := aa bb cc;
set B['a b'] := 'aa bb cc';
```

The `param` Command

Simple or non-indexed parameters are declared in an obvious way, as shown by these examples:

```
param A := 1.4;
param B := 1;
param C := abc;
param D := true;
param E := 1.0e+04;
```

Parameters can be defined with numeric data, simple strings and quoted strings. Note that parameters cannot be defined without data, so there is no analog to the specification of an empty set.

One-dimensional Parameter Data

Most parameter data is indexed over one or more sets, and there are a number of ways the `param` data command can be used to specify indexed parameter data. One-dimensional parameter data is indexed over a single set. Suppose that the parameter `B` is a parameter indexed by the set `A`:

```
model.A = Set()
model.B = Param(model.A)
```

A `param` data command can specify values for `B` with a list of index-value pairs:

```
set A := a c e;

param B := a 10 c 30 e 50;
```

Because whitespace is ignored, this example data command file can be reorganized to specify the same data in a tabular format:

```
set A := a c e;

param B :=
a 10
c 30
e 50
;
```

Multiple parameters can be defined using a single `param` data command. For example, suppose that parameters `B`, `C`, and `D` are one-dimensional parameters all indexed by the set `A`:

```
model.A = Set()
model.B = Param(model.A)
model.C = Param(model.A)
model.D = Param(model.A)
```

Values for these parameters can be specified using a single `param` data command that declares these parameter names followed by a list of index and parameter values:

```
set A := a c e;

param : B C D :=
```

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```
a 10 -1 1.1
c 30 -3 3.3
e 50 -5 5.5
;
```

The values in the `param` data command are interpreted as a list of sublists, where each sublist consists of an index followed by the corresponding numeric value.

Note that parameter values do not need to be defined for all indices. For example, the following data command file is valid:

```
set A := a c e g;

param : B C D :=
a 10 -1 1.1
c 30 -3 3.3
e 50 -5 5.5
;
```

The index `g` is omitted from the `param` command, and consequently this index is not valid for the model instance that uses this data. More complex patterns of missing data can be specified using the period (`.`) symbol to indicate a missing value. This syntax is useful when specifying multiple parameters that do not necessarily have the same index values:

```
set A := a c e;

param : B C D :=
a  . -1 1.1
c 30  . 3.3
e 50 -5   .
;
```

This example provides a concise representation of parameters that share a common index set while using different index values.

Note that this data file specifies the data for set `A` twice: (1) when `A` is defined and (2) implicitly when the parameters are defined. An alternate syntax for `param` allows the user to concisely specify the definition of an index set along with associated parameters:

```
param : A : B C D :=
a 10 -1 1.1
c 30 -3 3.3
e 50 -5 5.5
;
```

Finally, we note that default values for missing data can also be specified using the `default` keyword:

```
set A := a c e;

param B default 0.0 :=
c 30
e 50
;
```

Note that default values can only be specified in `param` commands that define values for a single parameter.

Multi-Dimensional Parameter Data

Multi-dimensional parameter data is indexed over either multiple sets or a single multi-dimensional set. Suppose that parameter `B` is a parameter indexed by set `A` that has dimension 2:

```
model.A = Set(dimen=2)
model.B = Param(model.A)
```

The syntax of the `param` data command remains essentially the same when specifying values for `B` with a list of index and parameter values:

```
set A := a 1 c 2 e 3;

param B :=
a 1 10
c 2 30
e 3 50;
```

Missing and default values are also handled in the same way with multi-dimensional index sets:

```
set A := a 1 c 2 e 3;

param B default 0 :=
a 1 10
c 2 .
e 3 50;
```

Similarly, multiple parameters can defined with a single `param` data command. Suppose that parameters `B`, `C`, and `D` are parameters indexed over set `A` that has dimension 2:

```
model.A = Set(dimen=2)
model.B = Param(model.A)
model.C = Param(model.A)
model.D = Param(model.A)
```

These parameters can be defined with a single `param` command that declares the parameter names followed by a list of index and parameter values:

```
set A := a 1 c 2 e 3;

param : B C D :=
a 1 10 -1 1.1
c 2 30 -3 3.3
e 3 50 -5 5.5
;
```

Similarly, the following `param` data command defines the index set along with the parameters:

```
param : A : B C D :=
a 1 10 -1 1.1
c 2 30 -3 3.3
e 3 50 -5 5.5
;
```

The param command also supports a matrix syntax for specifying the values in a parameter that has a 2-dimensional index. Suppose parameter B is indexed over set A that has dimension 2:

```
model.A = Set(dimen=2)
model.B = Param(model.A)
```

The following param command defines a matrix of parameter values:

```
set A := 1 a 1 c 1 e 2 a 2 c 2 e 3 a 3 c 3 e;

param B : a c e :=
1 1 2 3
2 4 5 6
3 7 8 9
;
```

Additionally, the following syntax can be used to specify a transposed matrix of parameter values:

```
set A := 1 a 1 c 1 e 2 a 2 c 2 e 3 a 3 c 3 e;

param B (tr) : 1 2 3 :=
a 1 4 7
c 2 5 8
e 3 6 9
;
```

This functionality facilitates the presentation of parameter data in a natural format. In particular, the transpose syntax may allow the specification of tables for which the rows comfortably fit within a single line. However, a matrix may be divided column-wise into shorter rows since the line breaks are not significant in Pyomo data commands.

For parameters with three or more indices, the parameter data values may be specified as a series of slices. Each slice is defined by a template followed by a list of index and parameter values. Suppose that parameter B is indexed over set A that has dimension 4:

```
model.A = Set(dimen=4)
model.B = Param(model.A)
```

The following param command defines a matrix of parameter values with multiple templates:

```
set A := (a,1,a,1) (a,2,a,2) (b,1,b,1) (b,2,b,2);

param B :=

  [*,1,*,1] a a 10 b b 20
  [*,2,*,2] a a 30 b b 40
;
```

The B parameter consists of four values: B[a,1,a,1]=10, B[b,1,b,1]=20, B[a,2,a,2]=30, and B[b,2,b,2]=40.

The `table` Command

The `table` data command explicitly specifies a two-dimensional array of parameter data. This command provides a more flexible and complete data declaration than is possible with a `param` declaration. The following example illustrates a simple `table` command that declares data for a single parameter:

```
table M(A) :
A  B  M   N :=
A1 B1 4.3 5.3
A2 B2 4.4 5.4
A3 B3 4.5 5.5
;
```

The parameter `M` is indexed by column `A`, which must be pre-defined unless declared separately (see below). The column labels are provided after the colon and before the colon-equal (`:=`). Subsequently, the table data is provided. The syntax is not sensitive to whitespace, so the following is an equivalent `table` command:

```
table M(A) :
A  B  M   N :=
A1 B1 4.3 5.3 A2 B2 4.4 5.4 A3 B3 4.5 5.5 ;
```

Multiple parameters can be declared by simply including additional parameter names. For example:

```
table M(A) N(A,B) :
A  B  M   N :=
A1 B1 4.3 5.3
A2 B2 4.4 5.4
A3 B3 4.5 5.5
;
```

This example declares data for the `M` and `N` parameters, which have different indexing columns. The indexing columns represent set data, which is specified separately. For example:

```
table A={A} Z={A,B} M(A) N(A,B) :
A  B  M   N :=
A1 B1 4.3 5.3
A2 B2 4.4 5.4
A3 B3 4.5 5.5
;
```

This example declares data for the `M` and `N` parameters, along with the `A` and `Z` indexing sets. The correspondence between the index set `Z` and the indices of parameter `N` can be made more explicit by indexing `N` by `Z`:

```
table A={A} Z={A,B} M(A) N(Z) :
A  B  M   N :=
A1 B1 4.3 5.3
A2 B2 4.4 5.4
A3 B3 4.5 5.5
;
```

Set data can also be specified independent of parameter data:

```
table Z={A,B} Y={M,N} :
A  B  M   N :=
```

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```
A1 B1 4.3 5.3
A2 B2 4.4 5.4
A3 B3 4.5 5.5
;
```

Warning: If a `table` command does not explicitly indicate the indexing sets, then these are assumed to be initialized separately. A `table` command can separately initialize sets and parameters in a Pyomo model, and there is no presumed association between the data that is initialized. For example, the `table` command initializes a set `Z` and a parameter `M` that are not related:

```
table Z={A,B} M(A):
A  B  M   N :=
A1 B1 4.3 5.3
A2 B2 4.4 5.4
A3 B3 4.5 5.5
;
```

Finally, simple parameter values can also be specified with a `table` command:

```
table pi := 3.1416 ;
```

The previous examples considered examples of the `table` command where column labels are provided. The `table` command can also be used without column labels. For example, the first example can be revised to omit column labels as follows:

```
table columns=4 M(1)={3} :=
A1 B1 4.3 5.3
A2 B2 4.4 5.4
A3 B3 4.5 5.5
;
```

The `columns=4` is a keyword-value pair that defines the number of columns in this table; this must be explicitly specified in tables without column labels. The default column labels are integers starting from `1`; the labels are columns `1`, `2`, `3`, and `4` in this example. The `M` parameter is indexed by column `1`. The braces syntax declares the column where the `M` data is provided.

Similarly, set data can be declared referencing the integer column labels:

```
table columns=4 A={1} Z={1,2} M(1)={3} N(1,2)={4} :=
A1 B1 4.3 5.3
A2 B2 4.4 5.4
A3 B3 4.5 5.5
;
```

Declared set names can also be used to index parameters:

```
table columns=4 A={1} Z={1,2} M(A)={3} N(Z)={4} :=
A1 B1 4.3 5.3
A2 B2 4.4 5.4
A3 B3 4.5 5.5
;
```

Finally, we compare and contrast the `table` and `param` commands. Both commands can be used to declare parameter and set data, and both commands can be used to declare a simple parameter. However, there are some important differences between these data commands:

- The `param` command can declare a single set that is used to index one or more parameters. The `table` command can declare data for any number of sets, independent of whether they are used to index parameter data.
- The `param` command can declare data for multiple parameters only if they share the same index set. The `table` command can declare data for any number of parameters that are may be indexed separately.
- The `table` syntax unambiguously describes the dimensionality of indexing sets. The `param` command must be interpreted with a model that provides the dimension of the indexing set.

This last point provides a key motivation for the `table` command. Specifically, the `table` command can be used to reliably initialize concrete models using Pyomo's `DataPortal` class. By contrast, the `param` command can only be used to initialize concrete models with parameters that are indexed by a single column (i.e., a simple set).

The `load` Command

The `load` command provides a mechanism for loading data from a variety of external tabular data sources. This command loads a table of data that represents set and parameter data in a Pyomo model. The table consists of rows and columns for which all rows have the same length, all columns have the same length, and the first row represents labels for the column data.

The `load` command can load data from a variety of different external data sources:

- **TAB File**: A text file format that uses whitespace to separate columns of values in each row of a table.
- **CSV File**: A text file format that uses comma or other delimiters to separate columns of values in each row of a table.
- **XML File**: An extensible markup language for documents and data structures. XML files can represent tabular data.
- **Excel File**: A spreadsheet data format that is primarily used by the Microsoft Excel application.
- **Database**: A relational database.

This command uses a *data manager* that coordinates how data is extracted from a specified *data source*. In this way, the `load` command provides a generic mechanism that enables Pyomo models to interact with standard data repositories that are maintained in an application-specific manner.

Simple Load Examples

The simplest illustration of the `load` command is specifying data for an indexed parameter. Consider the file `Y.tab`:

```
A  Y
A1 3.3
A2 3.4
A3 3.5
```

This file specifies the values of parameter `Y` which is indexed by set `A`. The following `load` command loads the parameter data:

```
load Y.tab : [A] Y;
```

The first argument is the filename. The options after the colon indicate how the table data is mapped to model data. Option `[A]` indicates that set `A` is used as the index, and option `Y` indicates the parameter that is initialized.

Similarly, the following load command loads both the parameter data as well as the index set A:

```
load Y.tab : A=[A] Y;
```

The difference is the specification of the index set, A=[A], which indicates that set A is initialized with the index loaded from the ASCII table file.

Set data can also be loaded from a ASCII table file that contains a single column of data:

```
A
A1
A2
A3
```

The format option must be specified to denote the fact that the relational data is being interpreted as a set:

```
load A.tab format=set : A;
```

Note that this allows for specifying set data that contains tuples. Consider file C.tab:

```
A  B
A1 1
A1 2
A1 3
A2 1
A2 2
A2 3
A3 1
A3 2
A3 3
```

A similar load syntax will load this data into set C:

```
load C.tab format=set : C;
```

Note that this example requires that C be declared with dimension two.

Load Syntax Options

The syntax of the load command is broken into two parts. The first part ends with the colon, and it begins with a filename, database URL, or DSN (data source name). Additionally, this first part can contain option value pairs. The following options are recognized:

format	A string that denotes how the relational table is interpreted
password	The password that is used to access a database
query	The query that is used to request data from a database
range	The subset of a spreadsheet that is requestedindex{spreadsheet}
user	The user name that is used to access the data source
using	The data manager that is used to process the data source
table	The database table that is requested

The format option is the only option that is required for all data managers. This option specifies how a relational table is interpreted to represent set and parameter data. If the using option is omitted, then the filename suffix is used to select the data manager. The remaining options are specific to spreadsheets and relational databases (see below).

The second part of the `load` command consists of the specification of column names for indices and data. The remainder of this section describes different specifications and how they define how data is loaded into a model. Suppose file `ABCD.tab` defines the following relational table:

```
A  B  C D
A1 B1 1 10
A2 B2 2 20
A3 B3 3 30
```

There are many ways to interpret this relational table. It could specify a set of 4-tuples, a parameter indexed by 3-tuples, two parameters indexed by 2-tuples, and so on. Additionally, we may wish to select a subset of this table to initialize data in a model. Consequently, the `load` command provides a variety of syntax options for specifying how a table is interpreted.

A simple specification is to interpret the relational table as a set:

```
load ABCD.tab format=set : Z ;
```

Note that `Z` is a set in the model that the data is being loaded into. If this set does not exist, an error will occur while loading data from this table.

Another simple specification is to interpret the relational table as a parameter with indexed by 3-tuples:

```
load ABCD.tab : [A,B,C] D ;
```

Again, this requires that `D` be a parameter in the model that the data is being loaded into. Additionally, the index set for `D` must contain the indices that are specified in the table. The `load` command also allows for the specification of the index set:

```
load ABCD.tab : Z=[A,B,C] D ;
```

This specifies that the index set is loaded into the `Z` set in the model. Similarly, data can be loaded into another parameter than what is specified in the relational table:

```
load ABCD.tab : Z=[A,B,C] Y=D ;
```

This specifies that the index set is loaded into the `Z` set and that the data in the `D` column in the table is loaded into the `Y` parameter.

This syntax allows the `load` command to provide an arbitrary specification of data mappings from columns in a relational table into index sets and parameters. For example, suppose that a model is defined with set `Z` and parameters `Y` and `W`:

```
model.Z = Set()
model.Y = Param(model.Z)
model.W = Param(model.Z)
```

Then the following command defines how these data items are loaded using columns `B`, `C` and `D`:

```
load ABCD.tab : Z=[B] Y=D W=C;
```

When the `using` option is omitted the data manager is inferred from the filename suffix. However, the filename suffix does not always reflect the format of the data it contains. For example, consider the relational table in the file `ABCD.txt`:

```
A,B,C,D
A1,B1,1,10
```

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```
A2,B2,2,20
A3,B3,3,30
```

We can specify the `using` option to load from this file into parameter `D` and set `Z`:

```
load ABCD.txt using=csv : Z=[A,B,C] D ;
```

Note: The data managers supported by Pyomo can be listed with the `pyomo help` subcommand

```
pyomo help --data-managers
```

The following data managers are supported in Pyomo 5.1:

```
Pyomo Data Managers
-------------------
  csv
      CSV file interface
  dat
      Pyomo data command file interface
  json
      JSON file interface
  pymysql
      pymysql database interface
  pyodbc
      pyodbc database interface
  pypyodbc
      pypyodbc database interface
  sqlite3
      sqlite3 database interface
  tab
      TAB file interface
  xls
      Excel XLS file interface
  xlsb
      Excel XLSB file interface
  xlsm
      Excel XLSM file interface
  xlsx
      Excel XLSX file interface
  xml
      XML file interface
  yaml
      YAML file interface
```

Interpreting Tabular Data

By default, a table is interpreted as columns of one or more parameters with associated index columns. The `format` option can be used to specify other interpretations of a table:

`array`	The table is a matrix representation of a two dimensional parameter.
`param`	The data is a simple parameter value.
`set`	Each row is a set element.
`set_array`	The table is a matrix representation of a set of 2-tuples.
`transposed_array`	The table is a transposed matrix representation of a two dimensional parameter.

We have previously illustrated the use of the `set` format value to interpret a relational table as a set of values or tuples. The following examples illustrate the other format values.

A table with a single value can be interpreted as a simple parameter using the `param` format value. Suppose that `Z.tab` contains the following table:

```
1.1
```

The following load command then loads this value into parameter `p`:

```
load Z.tab format=param: p;
```

Sets with 2-tuple data can be represented with a matrix format that denotes set membership. The `set_array` format value interprets a relational table as a matrix that defines a set of 2-tuples where + denotes a valid tuple and - denotes an invalid tuple. Suppose that `D.tab` contains the following relational table:

```
B  A1  A2  A3
1  +   -   -
2  -   +   -
3  -   -   +
```

Then the following load command loads data into set `B`:

```
load D.tab format=set_array: B;
```

This command declares the following 2-tuples: `('A1',1)`, `('A2',2)`, and `('A3',3)`.

Parameters with 2-tuple indices can be interpreted with a matrix format that where rows and columns are different indices. Suppose that `U.tab` contains the following table:

```
I  A1  A2  A3
I1 1.3 2.3 3.3
I2 1.4 2.4 3.4
I3 1.5 2.5 3.5
I4 1.6 2.6 3.6
```

Then the following load command loads this value into parameter `U` with a 2-dimensional index using the `array` format value.:

```
load U.tab format=array: A=[X] U;
```

The `transpose_array` format value also interprets the table as a matrix, but it loads the data in a transposed format:

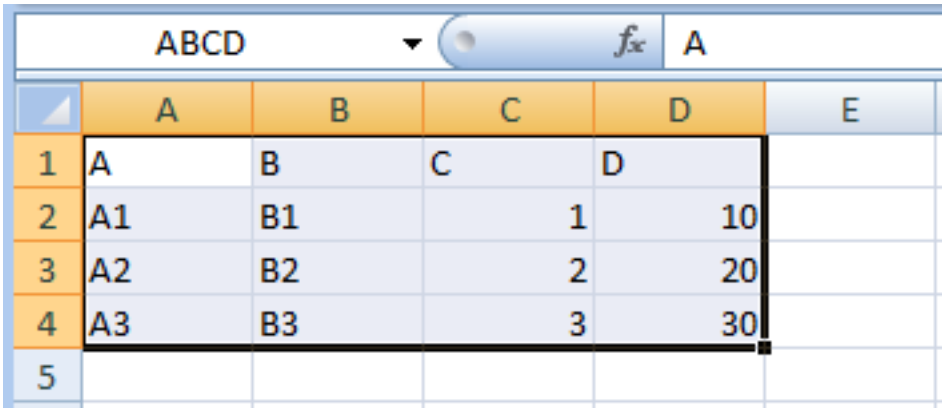
```
load U.tab format=transposed_array: A=[X] U;
```

Note that these format values do not support the initialization of the index data.

Loading from Spreadsheets and Relational Databases

Many of the options for the `load` command are specific to spreadsheets and relational databases. The `range` option is used to specify the range of cells that are loaded from a spreadsheet. The range of cells represents a table in which the first row of cells defines the column names for the table.

Suppose that file `ABCD.xls` contains the range `ABCD` that is shown in the following figure:



The following command loads this data to initialize parameter `D` and index `Z`:

```
load ABCD.xls range=ABCD : Z=[A,B,C] Y=D ;
```

Thus, the syntax for loading data from spreadsheets only differs from CSV and ASCII text files by the use of the `range` option.

When loading from a relational database, the data source specification is a filename or data connection string. Access to a database may be restricted, and thus the specification of `username` and `password` options may be required. Alternatively, these options can be specified within a data connection string.

A variety of database interface packages are available within Python. The `using` option is used to specify the database interface package that will be used to access a database. For example, the `pyodbc` interface can be used to connect to Excel spreadsheets. The following command loads data from the Excel spreadsheet `ABCD.xls` using the `pyodbc` interface. The command loads this data to initialize parameter `D` and index `Z`:

```
load ABCD.xls using=pyodbc table=ABCD : Z=[A,B,C] Y=D ;
```

The `using` option specifies that the `pyodbc` package will be used to connect with the Excel spreadsheet. The `table` option specifies that the table `ABCD` is loaded from this spreadsheet. Similarly, the following command specifies a data connection string to specify the ODBC driver explicitly:

```
load "Driver={Microsoft Excel Driver (*.xls)}; Dbq=ABCD.xls;"
    using=pyodbc
    table=ABCD : Z=[A,B,C] Y=D ;
```

ODBC drivers are generally tailored to the type of data source that they work with; this syntax illustrates how the `load` command can be tailored to the details of the database that a user is working with.

The previous examples specified the `table` option, which declares the name of a relational table in a database. Many databases support the Structured Query Language (SQL), which can be used to dynamically compose a relational table from other tables in a database. The classic diet problem will be used to illustrate the use of SQL queries to initialize a Pyomo model. In this problem, a customer is faced with the task of minimizing the cost for a meal at a fast food restaurant – they must purchase a sandwich, side, and a drink for the lowest cost. The following is a Pyomo model for this problem:

```
# diet1.py
from pyomo.environ import *

infinity = float('inf')
MAX_FOOD_SUPPLY = 20.0 # There is a finite food supply

model = AbstractModel()

# ------------------------------------------------------

model.FOOD = Set()
model.cost = Param(model.FOOD, within=PositiveReals)
model.f_min = Param(model.FOOD, within=NonNegativeReals, default=0.0)
def f_max_validate (model, value, j):
    return model.f_max[j] > model.f_min[j]
model.f_max = Param(model.FOOD, validate=f_max_validate, default=MAX_FOOD_SUPPLY)

model.NUTR = Set()
model.n_min = Param(model.NUTR, within=NonNegativeReals, default=0.0)
model.n_max = Param(model.NUTR, default=infinity)
model.amt = Param(model.NUTR, model.FOOD, within=NonNegativeReals)

# ------------------------------------------------------

def Buy_bounds(model, i):
    return (model.f_min[i], model.f_max[i])
model.Buy = Var(model.FOOD, bounds=Buy_bounds, within=NonNegativeIntegers)

# ------------------------------------------------------

def Total_Cost_rule(model):
    return sum(model.cost[j] * model.Buy[j] for j in model.FOOD)
model.Total_Cost = Objective(rule=Total_Cost_rule, sense=minimize)

# ------------------------------------------------------

def Entree_rule(model):
    entrees = ['Cheeseburger', 'Ham Sandwich', 'Hamburger', 'Fish Sandwich', 'Chicken␣
↪Sandwich']
    return sum(model.Buy[e] for e in entrees) >= 1
model.Entree = Constraint(rule=Entree_rule)

def Side_rule(model):
    sides = ['Fries', 'Sausage Biscuit']
    return sum(model.Buy[s] for s in sides) >= 1
model.Side = Constraint(rule=Side_rule)
```

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```
def Drink_rule(model):
    drinks = ['Lowfat Milk', 'Orange Juice']
    return sum(model.Buy[d] for d in drinks) >= 1
model.Drink = Constraint(rule=Drink_rule)
```

Suppose that the file `diet1.sqlite` be a SQLite database file that contains the following data in the `Food` table:

FOOD	cost
Cheeseburger	1.84
Ham Sandwich	2.19
Hamburger	1.84
Fish Sandwich	1.44
Chicken Sandwich	2.29
Fries	0.77
Sausage Biscuit	1.29
Lowfat Milk	0.60
Orange Juice	0.72

In addition, the `Food` table has two additional columns, `f_min` and `f_max`, with no data for any row. These columns exist to match the structure for the parameters used in the model.

We can solve the `diet1` model using the Python definition in `diet1.py` and the data from this database. The file `diet.sqlite.dat` specifies a `load` command that uses that `sqlite3` data manager and embeds a SQL query to retrieve the data:

```
# File diet.sqlite.dat

load "diet.sqlite"
     using=sqlite3
     query="SELECT FOOD,cost,f_min,f_max FROM Food"
     : FOOD=[FOOD] cost f_min f_max ;
```

The PyODBC driver module will pass the SQL query through an Access ODBC connector, extract the data from the `diet1.mdb` file, and return it to Pyomo. The Pyomo ODBC handler can then convert the data received into the proper format for solving the model internally. More complex SQL queries are possible, depending on the underlying database and ODBC driver in use. However, the name and ordering of the columns queried are specified in the Pyomo data file; using SQL wildcards (e.g., `SELECT *`) or column aliasing (e.g., `SELECT f AS FOOD`) may cause errors in Pyomo's mapping of relational data to parameters.

The `include` Command

The `include` command allows a data command file to execute data commands from another file. For example, the following command file executes data commands from `ex1.dat` and then `ex2.dat`:

```
include ex1.dat;
include ex2.dat;
```

Pyomo is sensitive to the order of execution of data commands, since data commands can redefine set and parameter values. The `include` command respects this data ordering; all data commands in the included file are executed before the remaining data commands in the current file are executed.

The namespace Keyword

The namespace keyword is not a data command, but instead it is used to structure the specification of Pyomo's data commands. Specifically, a namespace declaration is used to group data commands and to provide a group label. Consider the following data command file:

```
set C := 1 2 3 ;

namespace ns1
{
    set C := 4 5 6 ;
}

namespace ns2
{
    set C := 7 8 9 ;
}
```

This data file defines two namespaces: ns1 and ns2 that initialize a set C. By default, data commands contained within a namespace are ignored during model construction; when no namespaces are specified, the set C has values 1,2,3. When namespace ns1 is specified, then the set C values are overridden with the set 4,5,6.

7.2.4 Data Portals

Pyomo's DataPortal class standardizes the process of constructing model instances by managing the process of loading data from different data sources in a uniform manner. A DataPortal object can load data from the following data sources:

- **TAB File**: A text file format that uses whitespace to separate columns of values in each row of a table.
- **CSV File**: A text file format that uses comma or other delimiters to separate columns of values in each row of a table.
- **JSON File**: A popular lightweight data-interchange format that is easily parsed.
- **YAML File**: A human friendly data serialization standard.
- **XML File**: An extensible markup language for documents and data structures. XML files can represent tabular data.
- **Excel File**: A spreadsheet data format that is primarily used by the Microsoft Excel application.
- **Database**: A relational database.
- **DAT File**: A Pyomo data command file.

Note that most of these data formats can express tabular data.

Warning: The DataPortal class requires the installation of Python packages to support some of these data formats:

- **YAML File**: pyyaml
- **Excel File**: win32com, openpyxl or xlrd

  These packages support different data Excel data formats: the win32com package supports .xls, .xlsm and .xlsx, the openpyxl package supports .xlsx and the xlrd package supports .xls.

- **Database**: `pyodbc`, `pypyodbc`, `sqlite3` or `pymysql`

  These packages support different database interface APIs: the `pyodbc` and `pypyodbc` packages support the ODBC database API, the `sqlite3` package uses the SQLite C library to directly interface with databases using the DB-API 2.0 specification, and `pymysql` is a pure-Python MySQL client.

`DataPortal` objects can be used to initialize both concrete and abstract Pyomo models. Consider the file `A.tab`, which defines a simple set with a tabular format:

```
A
A1
A2
A3
```

The `load` method is used to load data into a `DataPortal` object. Components in a concrete model can be explicitly initialized with data loaded by a `DataPortal` object:

```
data = DataPortal()
data.load(filename='A.tab', set="A", format="set")

model = ConcreteModel()
model.A = Set(initialize=data['A'])
```

All data needed to initialize an abstract model *must* be provided by a `DataPortal` object, and the use of the `DataPortal` object to initialize components is automated for the user:

```
model = AbstractModel()
model.A = Set()
data = DataPortal()
data.load(filename='A.tab', set=model.A)
instance = model.create_instance(data)
```

Note the difference in the execution of the `load` method in these two examples: for concrete models data is loaded by name and the format must be specified, and for abstract models the data is loaded by component, from which the data format can often be inferred.

The `load` method opens the data file, processes it, and loads the data in a format that can be used to construct a model instance. The `load` method can be called multiple times to load data for different sets or parameters, or to override data processed earlier. The `load` method takes a variety of arguments that define how data is loaded:

- `filename`: This option specifies the source data file.
- `format`: This option specifies the how to interpret data within a table. Valid formats are: `set`, `set_array`, `param`, `table`, `array`, and `transposed_array`.
- `set`: This option is either a string or model compent that defines a set that will be initialized with this data.
- `param`: This option is either a string or model compent that defines a parameter that will be initialized with this data. A list or tuple of strings or model components can be used to define multiple parameters that are initialized.
- `index`: This option is either a string or model compent that defines an index set that will be initialized with this data.
- `using`: This option specifies the Python package used to load this data source. This option is used when loading data from databases.

- `select`: This option defines the columns that are selected from the data source. The column order may be changed from the data source, which allows the `DataPortal` object to define
- `namespace`: This option defines the data namespace that will contain this data.

The use of these options is illustrated below.

The `DataPortal` class also provides a simple API for accessing set and parameter data that are loaded from different data sources. The `[]` operator is used to access set and parameter values. Consider the following example, which loads data and prints the value of the `[]` operator:

```
data = DataPortal()
data.load(filename='A.tab', set="A", format="set")
print(data['A'])    #['A1', 'A2', 'A3']

data.load(filename='Z.tab', param="z", format="param")
print(data['z'])    #1.1

data.load(filename='Y.tab', param="y", format="table")
for key in sorted(data['y']):
    print("%s %s" % (key, data['y'][key]))
```

The `DataPortal` class also has several methods for iterating over the data that has been loaded:

- `keys()`: Returns an iterator of the data keys.
- `values()`: Returns an iterator of the data values.
- `items()`: Returns an iterator of (name, value) tuples from the data.

Finally, the `data()` method provides a generic mechanism for accessing the underlying data representation used by `DataPortal` objects.

Loading Structured Data

JSON and YAML files are structured data formats that are well-suited for data serialization. These data formats do not represent data in tabular format, but instead they directly represent set and parameter values with lists and dictionaries:

- **Simple Set**: a list of string or numeric value
- **Indexed Set**: a dictionary that maps an index to a list of string or numeric value
- **Simple Parameter**: a string or numeric value
- **Indexed Parameter**: a dictionary that maps an index to a numeric value

For example, consider the following JSON file:

```
{   "A": ["A1", "A2", "A3"],
    "B": [[1, "B1"], [2, "B2"], [3, "B3"]],
    "C": {"A1": [1, 2, 3], "A3": [10, 20, 30]},
    "p": 0.1,
    "q": {"A1": 3.3, "A2": 3.4, "A3": 3.5},
    "r": [   {"index": [1, "B1"], "value": 3.3},
             {"index": [2, "B2"], "value": 3.4},
             {"index": [3, "B3"], "value": 3.5}]}
```

The data in this file can be used to load the following model:

```
model = AbstractModel()
data = DataPortal()
model.A = Set()
model.B = Set(dimen=2)
model.C = Set(model.A)
model.p = Param()
model.q = Param(model.A)
model.r = Param(model.B)
data.load(filename='T.json')
```

Note that no `set` or `param` option needs to be specified when loading a `JSON` or `YAML` file. All of the set and parameter data in the file are loaded by the `DataPortal`> object, and only the data needed for model construction is used.

The following YAML file has a similar structure:

```
A: [A1, A2, A3]
B:
- [1, B1]
- [2, B2]
- [3, B3]
C:
  'A1': [1, 2, 3]
  'A3': [10, 20, 30]
p: 0.1
q: {A1: 3.3, A2: 3.4, A3: 3.5}
r:
- index: [1, B1]
  value: 3.3
- index: [2, B2]
  value: 3.4
- index: [3, B3]
  value: 3.5
```

The data in this file can be used to load a Pyomo model with the same syntax as a JSON file:

```
model = AbstractModel()
data = DataPortal()
model.A = Set()
model.B = Set(dimen=2)
model.C = Set(model.A)
model.p = Param()
model.q = Param(model.A)
model.r = Param(model.B)
data.load(filename='T.yaml')
```

Loading Tabular Data

Many data sources supported by Pyomo are tabular data formats. Tabular data is numerical or textual data that is organized into one or more simple tables, where data is arranged in a matrix. Each table consists of a matrix of numeric string values, simple strings, and quoted strings. All rows have the same length, all columns have the same length, and the first row typically represents labels for the column data.

The following section describes the tabular data sources supported by Pyomo, and the subsequent sections illustrate ways that data can be loaded from tabular data using TAB files. Subsequent sections describe options for loading data from Excel spreadsheets and relational databases.

Tabular Data

TAB files represent tabular data in an ascii file using whitespace as a delimiter. A TAB file consists of rows of values, where each row has the same length. For example, the file `PP.tab` has the format:

```
A  B  PP
A1 B1 4.3
A2 B2 4.4
A3 B3 4.5
```

CSV files represent tabular data in a format that is very similar to TAB files. Pyomo assumes that a CSV file consists of rows of values, where each row has the same length. For example, the file `PP.csv` has the format:

```
A,B,PP
A1,B1,4.3
A2,B2,4.4
A3,B3,4.5
```

Excel spreadsheets can express complex data relationships. A *range* is a contiguous, rectangular block of cells in an Excel spreadsheet. Thus, a range in a spreadsheet has the same tabular structure as is a TAB file or a CSV file. For example, consider the file `excel.xls` that has the range `PPtable`:

PPtable		
A	B	PP
A1	B1	4.3
A2	B2	4.4
A3	B3	4.5

A relational database is an application that organizes data into one or more tables (or *relations*) with a unique key in each row. Tables both reflect the data in a database as well as the result of queries within a database.

XML files represent tabular using `table` and `row` elements. Each sub-element of a `row` element represents a different column, where each row has the same length. For example, the file `PP.xml` has the format:

```
<table>
  <row>
    <A value="A1"/><B value="B1"/><PP value="4.3"/>
  </row>
  <row>
    <A value="A2"/><B value="B2"/><PP value="4.4"/>
  </row>
  <row>
    <A value="A3"/><B value="B3"/><PP value="4.5"/>
```

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```
  </row>
</table>
```

Loading Set Data

The `set` option is used specify a `Set` component that is loaded with data.

Loading a Simple Set

Consider the file `A.tab`, which defines a simple set:

```
A
A1
A2
A3
```

In the following example, a `DataPortal` object loads data for a simple set `A`:

```
model = AbstractModel()
model.A = Set()
data = DataPortal()
data.load(filename='A.tab', set=model.A)
instance = model.create_instance(data)
```

Loading a Set of Tuples

Consider the file `C.tab`:

```
A  B
A1 1
A1 2
A1 3
A2 1
A2 2
A2 3
A3 1
A3 2
A3 3
```

In the following example, a `DataPortal` object loads data for a two-dimensional set `C`:

```
model = AbstractModel()
model.C = Set(dimen=2)
data = DataPortal()
data.load(filename='C.tab', set=model.C)
instance = model.create_instance(data)
```

In this example, the column titles do not directly impact the process of loading data. Column titles can be used to select a subset of columns from a table that is loaded (see below).

Loading a Set Array

Consider the file `D.tab`, which defines an array representation of a two-dimensional set:

```
B  A1  A2  A3
1  +   -   -
2  -   +   -
3  -   -   +
```

In the following example, a `DataPortal` object loads data for a two-dimensional set `D`:

```
model = AbstractModel()
model.D = Set(dimen=2)
data = DataPortal()
data.load(filename='D.tab', set=model.D, format='set_array')
instance = model.create_instance(data)
```

The `format` option indicates that the set data is declared in a array format.

Loading Parameter Data

The `param` option is used specify a `Param` component that is loaded with data.

Loading a Simple Parameter

The simplest parameter is simply a singleton value. Consider the file `Z.tab`:

```
1.1
```

In the following example, a `DataPortal` object loads data for a simple parameter `z`:

```
model = AbstractModel()
data = DataPortal()
model.z = Param()
data.load(filename='Z.tab', param=model.z)
instance = model.create_instance(data)
```

Loading an Indexed Parameter

An indexed parameter can be defined by a single column in a table. For example, consider the file `Y.tab`:

```
A  Y
A1 3.3
A2 3.4
A3 3.5
```

In the following example, a `DataPortal` object loads data for an indexed parameter `y`:

```
model = AbstractModel()
data = DataPortal()
```

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```
model.A = Set(initialize=['A1','A2','A3'])
model.y = Param(model.A)
data.load(filename='Y.tab', param=model.y)
instance = model.create_instance(data)
```

When column names are not used to specify the index and parameter data, then the `DataPortal` object assumes that the rightmost column defines parameter values. In this file, the `A` column contains the index values, and the `Y` column contains the parameter values.

Loading Set and Parameter Values

Note that the data for set `A` is predefined in the previous example. The index set can be loaded with the parameter data using the `index` option. In the following example, a `DataPortal` object loads data for set `A` and the indexed parameter `y`

```
model = AbstractModel()
data = DataPortal()
model.A = Set()
model.y = Param(model.A)
data.load(filename='Y.tab', param=model.y, index=model.A)
instance = model.create_instance(data)
```

An index set with multiple dimensions can also be loaded with an indexed parameter. Consider the file `PP.tab`:

```
A  B  PP
A1 B1 4.3
A2 B2 4.4
A3 B3 4.5
```

In the following example, a `DataPortal` object loads data for a tuple set and an indexed parameter:

```
model = AbstractModel()
data = DataPortal()
model.A = Set(dimen=2)
model.p = Param(model.A)
data.load(filename='PP.tab', param=model.p, index=model.A)
instance = model.create_instance(data)
```

Loading a Parameter with Missing Values

Missing parameter data can be expressed in two ways. First, parameter data can be defined with indices that are a subset of valid indices in the model. The following example loads the indexed parameter `y`:

```
model = AbstractModel()
data = DataPortal()
model.A = Set(initialize=['A1','A2','A3','A4'])
model.y = Param(model.A)
data.load(filename='Y.tab', param=model.y)
instance = model.create_instance(data)
```

The model defines an index set with four values, but only three parameter values are declared in the data file `Y.tab`.

Parameter data can also be declared with missing values using the period (.) symbol. For example, consider the file S.tab:

```
A  B  PP
A1 B1 4.3
A2 B2 4.4
A3 B3 4.5
```

In the following example, a DataPortal object loads data for the index set A and indexed parameter y:

```
model = AbstractModel()
data = DataPortal()
model.A = Set()
model.s = Param(model.A)
data.load(filename='S.tab', param=model.s, index=model.A)
instance = model.create_instance(data)
```

The period (.) symbol indicates a missing parameter value, but the index set A contains the index value for the missing parameter.

Loading Multiple Parameters

Multiple parameters can be initialized at once by specifying a list (or tuple) of component parameters. Consider the file XW.tab:

```
A  X   W
A1 3.3 4.3
A2 3.4 4.4
A3 3.5 4.5
```

In the following example, a DataPortal object loads data for parameters x and w:

```
model = AbstractModel()
data = DataPortal()
model.A = Set(initialize=['A1','A2','A3'])
model.x = Param(model.A)
model.w = Param(model.A)
data.load(filename='XW.tab', param=(model.x,model.w))
instance = model.create_instance(data)
```

Selecting Parameter Columns

We have previously noted that the column names do not need to be specified to load set and parameter data. However, the select option can be to identify the columns in the table that are used to load parameter data. This option specifies a list (or tuple) of column names that are used, in that order, to form the table that defines the component data.

For example, consider the following load declaration:

```
model = AbstractModel()
data = DataPortal()
model.A = Set()
model.w = Param(model.A)
```

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```
data.load(filename='XW.tab', select=('A','W'),
                param=model.w, index=model.A)
instance = model.create_instance(data)
```

The columns `A` and `W` are selected from the file `XW.tab`, and a single parameter is defined.

Loading a Parameter Array

Consider the file `U.tab`, which defines an array representation of a multiply-indexed parameter:

```
I  A1  A2  A3
I1 1.3 2.3 3.3
I2 1.4 2.4 3.4
I3 1.5 2.5 3.5
I4 1.6 2.6 3.6
```

In the following example, a `DataPortal` object loads data for a two-dimensional parameter `u`:

```
model = AbstractModel()
data = DataPortal()
model.A = Set(initialize=['A1','A2','A3'])
model.I = Set(initialize=['I1','I2','I3','I4'])
model.u = Param(model.I, model.A)
data.load(filename='U.tab', param=model.u,
                                    format='array')
instance = model.create_instance(data)
```

The `format` option indicates that the parameter data is declared in a array format. The `format` option can also indicate that the parameter data should be transposed.

```
model = AbstractModel()
data = DataPortal()
model.A = Set(initialize=['A1','A2','A3'])
model.I = Set(initialize=['I1','I2','I3','I4'])
model.t = Param(model.A, model.I)
data.load(filename='U.tab', param=model.t,
                                    format='transposed_array')
instance = model.create_instance(data)
```

Note that the transposed parameter data changes the index set for the parameter.

Loading from Spreadsheets and Databases

Tabular data can be loaded from spreadsheets and databases using auxilliary Python packages that provide an interface to these data formats. Data can be loaded from Excel spreadsheets using the `win32com`, `xlrd` and `openpyxl` packages. For example, consider the following range of cells, which is named `PPtable`:

PPtable		
A	B	PP
A1	B1	4.3
A2	B2	4.4
A3	B3	4.5

In the following example, a `DataPortal` object loads the named range `PPtable` from the file `excel.xls`:

```
model = AbstractModel()
data = DataPortal()
model.A = Set(dimen=2)
model.p = Param(model.A)
data.load(filename='excel.xls', range='PPtable',
                    param=model.p, index=model.A)
instance = model.create_instance(data)
```

Note that the `range` option is required to specify the table of cell data that is loaded from the spreadsheet.

There are a variety of ways that data can be loaded from a relational database. In the simplest case, a table can be specified within a database:

```
model = AbstractModel()
data = DataPortal()
model.A = Set(dimen=2)
model.p = Param(model.A)
data.load(filename='PP.sqlite', using='sqlite3',
                    table='PPtable',
                    param=model.p, index=model.A)
instance = model.create_instance(data)
```

In this example, the interface `sqlite3` is used to load data from an SQLite database in the file `PP.sqlite`. More generally, an SQL query can be specified to dynamicly generate a table. For example:

```
model = AbstractModel()
data = DataPortal()
model.A = Set()
model.p = Param(model.A)
data.load(filename='PP.sqlite', using='sqlite3',
                    query="SELECT A,PP FROM PPtable",
                    param=model.p, index=model.A)
instance = model.create_instance(data)
```

Data Namespaces

The `DataPortal` class supports the concept of a *namespace* to organize data into named groups that can be enabled or disabled during model construction. Various `DataPortal` methods have an optional `namespace` argument that defaults to `None`:

- `data(name=None, namespace=None)`: Returns the data associated with data in the specified namespace
- `[]`: For a `DataPortal` object `data`, the function `data['A']` returns data corresponding to `A` in the default namespace, and `data['ns1','A']` returns data corresponding to `A` in namespace `ns1`.
- `namespaces()`: Returns an iteratore for the data namespaces.

- `keys(namespace=None)`: Returns an iterator of the data keys in the specified namespace.
- `values(namespace=None)`: Returns and iterator of the data values in the specified namespace.
- `items(namespace=None)`: Returns an iterator of (name, value) tuples in the specified namespace.

By default, data within a namespace are ignored during model construction. However, concrete models can be initialized with data from a specific namespace. Further, abstract models can be initialized with a list of namespaces that define the data used to initialized model components. For example, the following script generates two model instances from an abstract model using data loaded into different namespaces:

```
model = AbstractModel()
model.C = Set(dimen=2)
data = DataPortal()
data.load(filename='C.tab', set=model.C, namespace='ns1')
data.load(filename='D.tab', set=model.C, namespace='ns2',
                            format='set_array')
instance1 = model.create_instance(data, namespaces=['ns1'])
instance2 = model.create_instance(data, namespaces=['ns2'])
```

7.2.5 Storing Data from Pyomo Models

Currently, Pyomo has rather limited capabilities for storing model data into standard Python data types and serialized data formats. However, this capability is under active development.

Storing Model Data in Excel

TODO

More here.

7.3 The `pyomo` Command

The `pyomo` command is issued to the DOS prompt or a Unix shell. To see a list of Pyomo command line options, use:

```
pyomo solve --help
```

Note: There are two dashes before `help`.

In this section we will detail some of the options.

7.3.1 Passing Options to a Solver

To pass arguments to a solver when using the `pyomo solve` command, appned the Pyomo command line with the argument `--solver-options=` followed by an argument that is a string to be sent to the solver (perhaps with dashes added by Pyomo). So for most MIP solvers, the mip gap can be set using

```
--solver-options= "mipgap=0.01 "
```

Multiple options are separated by a space. Options that do not take an argument should be specified with the equals sign followed by either a space or the end of the string.

For example, to specify that the solver is GLPK, then to specify a mipgap of two percent and the GLPK cuts option, use

```
solver=glpk --solver-options="mipgap=0.02 cuts="
```

If there are multiple "levels" to the keyword, as is the case for some Gurobi and CPLEX options, the tokens are separated by underscore. For example, `mip cuts all` would be specified as `mip_cuts_all`. For another example, to set the solver to be CPLEX, then to set a mip gap of one percent and to specify 'y' for the sub-option `numerical` to the option `emphasis` use

```
--solver=cplex --solver-options="mipgap=0.001 emphasis_numerical=y"
```

See *Sending Options to the Solver* for a discussion of passing options in a script.

7.3.2 Troubleshooting

Many of things that can go wrong are covered by error messages, but sometimes they can be confusing or do not provide enough information. Depending on what the troubles are, there might be ways to get a little additional information.

If there are syntax errors in the model file, for example, it can occasionally be helpful to get error messages directly from the Python interpreter rather than through Pyomo. Suppose the name of the model file is scuc.py, then

```
python scuc.py
```

can sometimes give useful information for fixing syntax errors.

When there are no syntax errors, but there troubles reading the data or generating the information to pass to a solver, then the `--verbose` option provides a trace of the execution of Pyomo. The user should be aware that for some models this option can generate a lot of output.

If there are troubles with solver (i.e., after Pyomo has output "Applying Solver"), it is often helpful to use the option `--stream-solver` that causes the solver output to be displayed rather than trapped. (See <<TeeTrue>> for information about getting this output in a script). Advanced users may wish to examine the files that are generated to be passed to a solver. The type of file generated is controlled by the `--solver-io` option and the `--keepfiles` option instructs pyomo to keep the files and output their names. However, the `--symbolic-solver-labels` option should usually also be specified so that meaningful names are used in these files.

When there seem to be troubles expressing the model, it is often useful to embed print commands in the model in places that will yield helpful information. Consider the following snippet:

```
def ax_constraint_rule(model, i):
    # return the expression for the constraint for i
    print ("ax_constraint_rule was called for i=",str(i))
    return sum(model.a[i,j] * model.x[j] for j in model.J) >= model.b[i]
```

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```
# the next line creates one constraint for each member of the set model.I
model.AxbConstraint = Constraint(model.I, rule=ax_constraint_rule)
```

The effect will be to output every member of the set `model.I` at the time the constraint named `model.AxbConstraint` is constructed.

7.3.3 Direct Interfaces to Solvers

In many applications, the default solver interface works well. However, in some cases it is useful to specify the interface using the `solver-io` option. For example, if the solver supports a direct Python interface, then the option would be specified on the command line as

```
--solver-io=python
```

Here are some of the choices:

- lp: generate a standard linear programming format file with filename extension `lp`
- nlp: generate a file with a standard format that supports linear and nonlinear optimization with filename extension `nl`
- os: generate an OSiL format XML file.
- python: use the direct Python interface.

Note: Not all solvers support all interfaces.

7.4 `BuildAction` and `BuildCheck`

This is a somewhat advanced topic. In some cases, it is desirable to trigger actions to be done as part of the model building process. The `BuildAction` function provides this capability in a Pyomo model. It takes as arguments optional index sets and a function to peform the action. For example,

```
model.BuildBpts = BuildAction(model.J, rule=bpts_build)
```

calls the function `bpts_build` for each member of `model.J`. The function `bpts_build` should have the model and a variable for the members of `model.J` as formal arguments. In this example, the following would be a valid declaration for the function:

```
def bpts_build(model, j):
```

A full example, which extends the *Symbolic Index Sets* and *Piecewise Linear Expressions* examples, is

```
# abstract2piecebuild.py
# Similar to abstract2piece.py, but the breakpoints are created using a build action

from pyomo.environ import *

model = AbstractModel()

model.I = Set()
```

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```
model.J = Set()

model.a = Param(model.I, model.J)
model.b = Param(model.I)
model.c = Param(model.J)

model.Topx = Param(default=6.1) # range of x variables
model.PieceCnt = Param(default=100)

# the next line declares a variable indexed by the set J
model.x = Var(model.J, domain=NonNegativeReals, bounds=(0,model.Topx))
model.y = Var(model.J, domain=NonNegativeReals)

# to avoid warnings, we set breakpoints beyond the bounds
# we are using a dictionary so that we can have different
# breakpoints for each index. But we won't.
model.bpts = {}
def bpts_build(model, j):
    model.bpts[j] = []
    for i in range(model.PieceCnt+2):
        model.bpts[j].append(float((i*model.Topx)/model.PieceCnt))
# The object model.BuildBpts is not refered to again;
# the only goal is to trigger the action at build time
model.BuildBpts = BuildAction(model.J, rule=bpts_build)

def f4(model, j, xp):
    # we not need j in this example, but it is passed as the index for the constraint
    return xp**4

model.ComputePieces = Piecewise(model.J, model.y, model.x, pw_pts=model.bpts, pw_constr_
↪type='EQ', f_rule=f4)

def obj_expression(model):
    return summation(model.c, model.y)

model.OBJ = Objective(rule=obj_expression)

def ax_constraint_rule(model, i):
    # return the expression for the constraint for i
    return sum(model.a[i,j] * model.x[j] for j in model.J) >= model.b[i]

# the next line creates one constraint for each member of the set model.I
model.AxbConstraint = Constraint(model.I, rule=ax_constraint_rule)
```

This example uses the build action to create a model component with breakpoints for a *Piecewise Linear Expressions* function. The `BuildAction` is triggered by the assignment to `model.BuildBpts`. This object is not referenced again, the only goal is to cause the execution of `bpts_build`, which places data in the `model.bpts` dictionary. Note that if `model.bpts` had been a `Set`, then it could have been created with an `initialize` argument to the `Set` declaration. Since it is a special-purpose dictionary to support the *Piecewise Linear Expressions* functionality in Pyomo, we use a `BuildAction`.

Another application of `BuildAction` can be intialization of Pyomo model data from Python data structures, or efficient initialization of Pyomo model data from other Pyomo model data. Consider the *Sparse Index Sets* example. Rather

than using an initialization for each list of sets `NodesIn` and `NodesOut` separately using `initialize`, it is a little more efficient and probably a little clearer, to use a build action.

The full model is:

```
# Isinglebuild.py
# NodesIn and NodesOut are created by a build action using the Arcs
from pyomo.environ import *

model = AbstractModel()

model.Nodes = Set()
model.Arcs = Set(dimen=2)

model.NodesOut = Set(model.Nodes, within=model.Nodes, initialize=[])
model.NodesIn = Set(model.Nodes, within=model.Nodes, initialize=[])

def Populate_In_and_Out(model):
    # loop over the arcs and put the end points in the appropriate places
    for (i,j) in model.Arcs:
        model.NodesIn[j].add(i)
        model.NodesOut[i].add(j)

model.In_n_Out = BuildAction(rule = Populate_In_and_Out)

model.Flow = Var(model.Arcs, domain=NonNegativeReals)
model.FlowCost = Param(model.Arcs)

model.Demand = Param(model.Nodes)
model.Supply = Param(model.Nodes)

def Obj_rule(model):
    return summation(model.FlowCost, model.Flow)
model.Obj = Objective(rule=Obj_rule, sense=minimize)

def FlowBalance_rule(model, node):
    return model.Supply[node] \
     + sum(model.Flow[i, node] for i in model.NodesIn[node]) \
     - model.Demand[node] \
     - sum(model.Flow[node, j] for j in model.NodesOut[node]) \
     == 0
model.FlowBalance = Constraint(model.Nodes, rule=FlowBalance_rule)
```

for this model, the same data file can be used as for Isinglecomm.py in *Sparse Index Sets* such as the toy data file:

```
set Nodes := CityA CityB CityC ;

set Arcs :=
CityA CityB
CityA CityC
CityC CityB
;

param : FlowCost :=
```

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```
CityA CityB 1.4
CityA CityC 2.7
CityC CityB 1.6
 ;

param Demand :=
CityA 0
CityB 1
CityC 1
;

param Supply :=
CityA 2
CityB 0
CityC 0
;
```

Build actions can also be a way to implement data validation, particularly when multiple Sets or Parameters must be analyzed. However, the the `BuildCheck` component is prefered for this purpose. It executes its rule just like a `BuildAction` but will terminate the construction of the model instance if the rule returns `False`.

CHAPTER

EIGHT

MODELING EXTENSIONS

8.1 Bilevel Programming

`pyomo.bilevel` provides extensions supporting modeling of multi-level optimization problems.

8.2 Dynamic Optimization with pyomo.DAE

The pyomo.DAE modeling extension [PyomoDAE] allows users to incorporate systems of differential algebraic equations (DAE)s in a Pyomo model. The modeling components in this extension are able to represent ordinary or partial differential equations. The differential equations do not have to be written in a particular format and the components are flexible enough to represent higher-order derivatives or mixed partial derivatives. Pyomo.DAE also includes model transformations which use simultaneous discretization approaches to transform a DAE model into an algebraic model. Finally, pyomo.DAE includes utilities for simulating DAE models and initializing dynamic optimization problems.

8.2.1 Modeling Components

Pyomo.DAE introduces three new modeling components to Pyomo:

pyomo.dae.ContinuousSet	Represents a bounded continuous domain
pyomo.dae.DerivativeVar	Represents derivatives in a model and defines how a *Var* is differentiated
pyomo.dae.Integral	Represents an integral over a continuous domain

As will be shown later, differential equations can be declared using using these new modeling components along with the standard Pyomo *Var* and *Constraint* components.

ContinuousSet

This component is used to define continuous bounded domains (for example 'spatial' or 'time' domains). It is similar to a Pyomo *Set* component and can be used to index things like variables and constraints. Any number of *ContinuousSets* can be used to index a component and components can be indexed by both *Sets* and *ContinuousSets* in arbitrary order.

In the current implementation, models with *ContinuousSet* components may not be solved until every *ContinuousSet* has been discretized. Minimally, a *ContinuousSet* must be initialized with two numeric values representing the upper and lower bounds of the continuous domain. A user may also specify additional points in the domain to be used as finite element points in the discretization.

class pyomo.dae.**ContinuousSet**(**args*, ***kwds*)

Represents a bounded continuous domain

Minimally, this set must contain two numeric values defining the bounds of a continuous range. Discrete points of interest may be added to the continuous set. A continuous set is one dimensional and may only contain numerical values.

Parameters

- **initialize** (*list*) – Default discretization points to be included
- **bounds** (*tuple*) – The bounding points for the continuous domain. The bounds will be included as discrete points in the *ContinuousSet* and will be used to bound the points added to the *ContinuousSet* through the 'initialize' argument, a data file, or the add() method

_changed

This keeps track of whether or not the ContinuousSet was changed during discretization. If the user specifies all of the needed discretization points before the discretization then there is no need to go back through the model and reconstruct things indexed by the *ContinuousSet*

Type *boolean*

_fe

This is a sorted list of the finite element points in the *ContinuousSet*. i.e. this list contains all the discrete points in the *ContinuousSet* that are not collocation points. Points that are both finite element points and collocation points will be included in this list.

Type *list*

_discretization_info

This is a dictionary which contains information on the discretization transformation which has been applied to the *ContinuousSet*.

Type *dict*

construct(*values=None*)

Constructs a *ContinuousSet* component

find_nearest_index(*target*, *tolerance=None*)

Returns the index of the nearest point in the *ContinuousSet*.

If a tolerance is specified, the index will only be returned if the distance between the target and the closest point is less than or equal to that tolerance. If there is a tie for closest point, the index on the left is returned.

Parameters

- **target** (*float*) –
- **tolerance** (*float* or *None*) –

Returns

Return type *float* or *None*

get_changed()
Returns flag indicating if the *ContinuousSet* was changed during discretization

Returns "True" if additional points were added to the *ContinuousSet* while applying a discretization scheme

Returns

Return type *boolean*

get_discretization_info()
Returns a *dict* with information on the discretization scheme that has been applied to the *ContinuousSet*.

Returns

Return type *dict*

get_finite_elements()
Returns the finite element points

If the *ContinuousSet* has been discretizaed using a collocation scheme, this method will return a list of the finite element discretization points but not the collocation points within each finite element. If the *ContinuousSet* has not been discretized or a finite difference discretization was used, this method returns a list of all the discretization points in the *ContinuousSet*.

Returns

Return type *list* of *floats*

get_lower_element_boundary(*point*)
Returns the first finite element point that is less than or equal to 'point'

Parameters **point** (*float*) –

Returns

Return type float

get_upper_element_boundary(*point*)
Returns the first finite element point that is greater or equal to 'point'

Parameters **point** (*float*) –

Returns

Return type float

set_changed(*newvalue*)
Sets the _changed flag to 'newvalue'

Parameters **newvalue** (*boolean*) –

The following code snippet shows examples of declaring a *ContinuousSet* component on a concrete Pyomo model:

```
Required imports
>>> from pyomo.environ import *
>>> from pyomo.dae import *

>>> model = ConcreteModel()

Declaration by providing bounds
>>> model.t = ContinuousSet(bounds=(0,5))
```

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```
Declaration by initializing with desired discretization points
>>> model.x = ContinuousSet(initialize=[0,1,2,5])
```

Note: A *ContinuousSet* may not be constructed unless at least two numeric points are provided to bound the continuous domain.

The following code snippet shows an example of declaring a *ContinuousSet* component on an abstract Pyomo model using the example data file.

```
set t := 0 0.5 2.25 3.75 5;
```

```
Required imports
>>> from pyomo.environ import *
>>> from pyomo.dae import *

>>> model = AbstractModel()

The ContinuousSet below will be initialized using the points
in the data file when a model instance is created.
>>> model.t = ContinuousSet()
```

Note: If a separate data file is used to initialize a *ContinuousSet*, it is done using the 'set' command and not 'continuousset'

Note: Most valid ways to declare and initialize a *Set* can be used to declare and initialize a *ContinuousSet*. See the documentation for *Set* for additional options.

Warning: Be careful using a *ContinuousSet* as an implicit index in an expression, i.e. `sum(m.v[i] for i in m.myContinuousSet)`. The expression will be generated using the discretization points contained in the *ContinuousSet* at the time the expression was constructed and will not be updated if additional points are added to the set during discretization.

Note: *ContinuousSet* components are always ordered (sorted) therefore the `first()` and `last()` *Set* methods can be used to access the lower and upper boundaries of the *ContinuousSet* respectively

DerivativeVar

class pyomo.dae.**DerivativeVar**(**args*, ***kwds*)

Represents derivatives in a model and defines how a *Var* is differentiated

The *DerivativeVar* component is used to declare a derivative of a *Var*. The constructor accepts a single positional argument which is the *Var* that's being differentiated. A *Var* may only be differentiated with respect to a *ContinuousSet* that it is indexed by. The indexing sets of a *DerivativeVar* are identical to those of the *Var* it is differentiating.

Parameters

- **sVar** (pyomo.environ.Var) – The variable being differentiated
- **wrt** (pyomo.dae.ContinuousSet or tuple) – Equivalent to *withrespectto* keyword argument. The *ContinuousSet* that the derivative is being taken with respect to. Higher order derivatives are represented by including the *ContinuousSet* multiple times in the tuple sent to this keyword. i.e. `wrt=(m.t, m.t)` would be the second order derivative with respect to `m.t`

get_continuousset_list()

Return the a list of *ContinuousSet* components the derivative is being taken with respect to.

Returns

Return type *list*

get_derivative_expression()

Returns the current discretization expression for this derivative or creates an access function to its `Var` the first time this method is called. The expression gets built up as the discretization transformations are sequentially applied to each *ContinuousSet* in the model.

get_state_var()

Return the `Var` that is being differentiated.

Returns

Return type *Var*

is_fully_discretized()

Check to see if all the *ContinuousSets* this derivative is taken with respect to have been discretized.

Returns

Return type *boolean*

set_derivative_expression(*expr*)

Sets``_expr``, an expression representing the discretization equations linking the *DerivativeVar* to its state `Var`

The code snippet below shows examples of declaring *DerivativeVar* components on a Pyomo model. In each case, the variable being differentiated is supplied as the only positional argument and the type of derivative is specified using the 'wrt' (or the more verbose 'withrespectto') keyword argument. Any keyword argument that is valid for a Pyomo *Var* component may also be specified.

```
Required imports
>>> from pyomo.environ import *
>>> from pyomo.dae import *

>>> model = ConcreteModel()
>>> model.s = Set(initialize=['a','b'])
```

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```
>>> model.t = ContinuousSet(bounds=(0,5))
>>> model.l = ContinuousSet(bounds=(-10,10))

>>> model.x = Var(model.t)
>>> model.y = Var(model.s,model.t)
>>> model.z = Var(model.t,model.l)

Declare the first derivative of model.x with respect to model.t
>>> model.dxdt = DerivativeVar(model.x, withrespectto=model.t)

Declare the second derivative of model.y with respect to model.t
Note that this DerivativeVar will be indexed by both model.s and model.t
>>> model.dydt2 = DerivativeVar(model.y, wrt=(model.t,model.t))

Declare the partial derivative of model.z with respect to model.l
Note that this DerivativeVar will be indexed by both model.t and model.l
>>> model.dzdl = DerivativeVar(model.z, wrt=(model.l), initialize=0)

Declare the mixed second order partial derivative of model.z with respect
to model.t and model.l and set bounds
>>> model.dz2 = DerivativeVar(model.z, wrt=(model.t, model.l), bounds=(-10, 10))
```

Note: The 'initialize' keyword argument will initialize the value of a derivative and is **not** the same as specifying an initial condition. Initial or boundary conditions should be specified using a *Constraint* or ConstraintList or by fixing the value of a *Var* at a boundary point.

8.2.2 Declaring Differential Equations

A differential equations is declared as a standard Pyomo *Constraint* and is not required to have any particular form. The following code snippet shows how one might declare an ordinary or partial differential equation.

```
Required imports
>>> from pyomo.environ import *
>>> from pyomo.dae import *

>>> model = ConcreteModel()
>>> model.s = Set(initialize=['a', 'b'])
>>> model.t = ContinuousSet(bounds=(0, 5))
>>> model.l = ContinuousSet(bounds=(-10, 10))

>>> model.x = Var(model.s, model.t)
>>> model.y = Var(model.t, model.l)
>>> model.dxdt = DerivativeVar(model.x, wrt=model.t)
>>> model.dydt = DerivativeVar(model.y, wrt=model.t)
>>> model.dydl2 = DerivativeVar(model.y, wrt=(model.l, model.l))

An ordinary differential equation
>>> def _ode_rule(m, s, t):
...     if t == 0:
```

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```
...         return Constraint.Skip
...     return m.dxdt[s, t] == m.x[s, t]**2
>>> model.ode = Constraint(model.s, model.t, rule=_ode_rule)

A partial differential equation
>>> def _pde_rule(m, t, l):
...     if t == 0 or l == m.l.first() or l == m.l.last():
...         return Constraint.Skip
...     return m.dydt[t, l] == m.dydl2[t, l]
>>> model.pde = Constraint(model.t, model.l, rule=_pde_rule)
```

By default, a *Constraint* declared over a *ContinuousSet* will be applied at every discretization point contained in the set. Often a modeler does not want to enforce a differential equation at one or both boundaries of a continuous domain. This may be addressed explicitly in the *Constraint* declaration using `Constraint.Skip` as shown above. Alternatively, the desired constraints can be deactivated just before the model is sent to a solver as shown below.

```
>>> def _ode_rule(m, s, t):
...     return m.dxdt[s, t] == m.x[s, t]**2
>>> model.ode = Constraint(model.s, model.t, rule=_ode_rule)

>>> def _pde_rule(m, t, l):
...     return m.dydt[t, l] == m.dydl2[t, l]
>>> model.pde = Constraint(model.t, model.l, rule=_pde_rule)

Declare other model components and apply a discretization transformation
...

Deactivate the differential equations at certain boundary points
>>> for con in model.ode[:, model.t.first()]:
...     con.deactivate()

>>> for con in model.pde[0, :]:
...     con.deactivate()

>>> for con in model.pde[:, model.l.first()]:
...     con.deactivate()

>>> for con in model.pde[:, model.l.last()]:
...   con.deactivate()

Solve the model
...
```

Note: If you intend to use the pyomo.DAE *Simulator* on your model then you **must** use **constraint deactivation** instead of **constraint skipping** in the differential equation rule.

8.2.3 Declaring Integrals

Warning: The *Integral* component is still under development and considered a prototype. It currently includes only basic functionality for simple integrals. We welcome feedback on the interface and functionality but **we do not recommend using it** on general models. Instead, integrals should be reformulated as differential equations.

class pyomo.dae.**Integral**(**args*, ***kwds*)

Represents an integral over a continuous domain

The *Integral* component can be used to represent an integral taken over the entire domain of a *ContinuousSet*. Once every *ContinuousSet* in a model has been discretized, any integrals in the model will be converted to algebraic equations using the trapezoid rule. Future development will include more sophisticated numerical integration methods.

Parameters

- ***args** – Every indexing set needed to evaluate the integral expression
- **wrt** (*ContinuousSet*) – The continuous domain over which the integral is being taken
- **rule** (*function*) – Function returning the expression being integrated

get_continuousset()

Return the *ContinuousSet* the integral is being taken over

Declaring an *Integral* component is similar to declaring an `Expression` component. A simple example is shown below:

```
>>> model = ConcreteModel()
>>> model.time = ContinuousSet(bounds=(0,10))
>>> model.X = Var(model.time)
>>> model.scale = Param(initialize=1E-3)

>>> def _intX(m,t):
...     return m.X[t]
>>> model.intX = Integral(model.time,wrt=model.time,rule=_intX)

>>> def _obj(m):
...     return m.scale*m.intX
>>> model.obj = Objective(rule=_obj)
```

Notice that the positional arguments supplied to the *Integral* declaration must include all indices needed to evaluate the integral expression. The integral expression is defined in a function and supplied to the 'rule' keyword argument. Finally, a user must specify a *ContinuousSet* that the integral is being evaluated over. This is done using the 'wrt' keyword argument.

Note: The *ContinuousSet* specified using the 'wrt' keyword argument must be explicitly specified as one of the indexing sets (meaning it must be supplied as a positional argument). This is to ensure consistency in the ordering and dimension of the indexing sets

---

After an *Integral* has been declared, it can be used just like a Pyomo `Expression` component and can be included in constraints or the objective function as shown above.

If an *Integral* is specified with multiple positional arguments, i.e. multiple indexing sets, the final component will be indexed by all of those sets except for the *ContinuousSet* that the integral was taken over. In other words, the

ContinuousSet specified with the 'wrt' keyword argument is removed from the indexing sets of the *Integral* even though it must be specified as a positional argument. This should become more clear with the following example showing a double integral over the *ContinuousSet* components `model.t1` and `model.t2`. In addition, the expression is also indexed by the *Set* `model.s`. The mathematical representation and implementation in Pyomo are shown below:

$$\sum_{s} \int_{t_2} \int_{t_1} X(t_1, t_2, s)\, dt_1\, dt_2$$

```
>>> model = ConcreteModel()
>>> model.t1 = ContinuousSet(bounds=(0, 10))
>>> model.t2 = ContinuousSet(bounds=(-1, 1))
>>> model.s = Set(initialize=['A', 'B', 'C'])

>>> model.X = Var(model.t1, model.t2, model.s)

>>> def _intX1(m, t1, t2, s):
...     return m.X[t1, t2, s]
>>> model.intX1 = Integral(model.t1, model.t2, model.s, wrt=model.t1,
...                        rule=_intX1)

>>> def _intX2(m, t2, s):
...     return m.intX1[t2, s]
>>> model.intX2 = Integral(model.t2, model.s, wrt=model.t2, rule=_intX2)

>>> def _obj(m):
...     return sum(m.intX2[k] for k in m.s)
>>> model.obj = Objective(rule=_obj)
```

8.2.4 Discretization Transformations

Before a Pyomo model with *DerivativeVar* or *Integral* components can be sent to a solver it must first be sent through a discretization transformation. These transformations approximate any derivatives or integrals in the model by using a numerical method. The numerical methods currently included in pyomo.DAE discretize the continuous domains in the problem and introduce equality constraints which approximate the derivatives and integrals at the discretization points. Two families of discretization schemes have been implemented in pyomo.DAE, Finite Difference and Collocation. These schemes are described in more detail below.

Note: The schemes described here are for derivatives only. All integrals will be transformed using the trapezoid rule.

The user must write a Python script in order to use these discretizations, they have not been tested on the pyomo command line. Example scripts are shown below for each of the discretization schemes. The transformations are applied to Pyomo model objects which can be further manipulated before being sent to a solver. Examples of this are also shown below.

Finite Difference Transformation

This transformation includes implementations of several finite difference methods. For example, the Backward Difference method (also called Implicit or Backward Euler) has been implemented. The discretization equations for this method are shown below:

$$
\begin{aligned}
&\text{Given :}\\
&\tfrac{dx}{dt} = f(t,x), \quad x(t_0) = x_0\\
&\text{discretize } t \text{ and } x \text{ such that}\\
&x(t_0 + kh) = x_k\\
&x_{k+1} = x_k + h * f(t_{k+1}, x_{k+1})\\
&t_{k+1} = t_k + h
\end{aligned}
$$

where h is the step size between discretization points or the size of each finite element. These equations are generated automatically as *Constraints* when the backward difference method is applied to a Pyomo model.

There are several discretization options available to a `dae.finite_difference` transformation which can be specified as keyword arguments to the `.apply_to()` function of the transformation object. These keywords are summarized below:

Keyword arguments for applying a finite difference transformation:

'nfe' The desired number of finite element points to be included in the discretization. The default value is 10.

'wrt' Indicates which *ContinuousSet* the transformation should be applied to. If this keyword argument is not specified then the same scheme will be applied to every *ContinuousSet* .

'scheme' Indicates which finite difference method to apply. Options are 'BACKWARD', 'CENTRAL', or 'FORWARD'. The default scheme is the backward difference method.

If the existing number of finite element points in a *ContinuousSet* is less than the desired number, new discretization points will be added to the set. If a user specifies a number of finite element points which is less than the number of points already included in the *ContinuousSet* then the transformation will ignore the specified number and proceed with the larger set of points. Discretization points will never be removed from a *ContinousSet* during the discretization.

The following code is a Python script applying the backward difference method. The code also shows how to add a constraint to a discretized model.

```
Discretize model using Backward Difference method
>>> discretizer = TransformationFactory('dae.finite_difference')
>>> discretizer.apply_to(model,nfe=20,wrt=model.time,scheme='BACKWARD')

Add another constraint to discretized model
>>> def _sum_limit(m):
...     return sum(m.x1[i] for i in m.time) <= 50
>>> model.con_sum_limit = Constraint(rule=_sum_limit)

Solve discretized model
>>> solver = SolverFactory('ipopt')
>>> results = solver.solve(model)
```

Collocation Transformation

This transformation uses orthogonal collocation to discretize the differential equations in the model. Currently, two types of collocation have been implemented. They both use Lagrange polynomials with either Gauss-Radau roots or Gauss-Legendre roots. For more information on orthogonal collocation and the discretization equations associated with this method please see chapter 10 of the book "Nonlinear Programming: Concepts, Algorithms, and Applications to Chemical Processes" by L.T. Biegler.

The discretization options available to a `dae.collocation` transformation are the same as those described above for the finite difference transformation with different available schemes and the addition of the 'ncp' option.

Additional keyword arguments for collocation discretizations:

'scheme' The desired collocation scheme, either 'LAGRANGE-RADAU' or 'LAGRANGE-LEGENDRE'. The default is 'LAGRANGE-RADAU'.

'ncp' The number of collocation points within each finite element. The default value is 3.

Note: If the user's version of Python has access to the package Numpy then any number of collocation points may be specified, otherwise the maximum number is 10.

Note: Any points that exist in a *ContinuousSet* before discretization will be used as finite element boundaries and not as collocation points. The locations of the collocation points cannot be specified by the user, they must be generated by the transformation.

The following code is a Python script applying collocation with Lagrange polynomials and Radau roots. The code also shows how to add an objective function to a discretized model.

```
Discretize model using Radau Collocation
>>> discretizer = TransformationFactory('dae.collocation')
>>> discretizer.apply_to(model,nfe=20,ncp=6,scheme='LAGRANGE-RADAU')

Add objective function after model has been discretized
>>> def obj_rule(m):
...     return sum((m.x[i]-m.x_ref)**2 for i in m.time)
>>> model.obj = Objective(rule=obj_rule)

Solve discretized model
>>> solver = SolverFactory('ipopt')
>>> results = solver.solve(model)
```

Restricting Optimal Control Profiles

When solving an optimal control problem a user may want to restrict the number of degrees of freedom for the control input by forcing, for example, a piecewise constant profile. Pyomo.DAE provides the `reduce_collocation_points` function to address this use-case. This function is used in conjunction with the `dae.collocation` discretization transformation to reduce the number of free collocation points within a finite element for a particular variable.

class pyomo.dae.plugins.colloc.**Collocation_Discretization_Transformation**

reduce_collocation_points(*instance*, *var=None*, *ncp=None*, *contset=None*)

This method will add additional constraints to a model to reduce the number of free collocation points (degrees of freedom) for a particular variable.

Parameters

- **instance** (*Pyomo model*) – The discretized Pyomo model to add constraints to
- **var** (pyomo.environ.Var) – The Pyomo variable for which the degrees of freedom will be reduced
- **ncp** (*int*) – The new number of free collocation points for *var*. Must be less that the number of collocation points used in discretizing the model.
- **contset** (pyomo.dae.ContinuousSet) – The *ContinuousSet* that was discretized and for which the *var* will have a reduced number of degrees of freedom

An example of using this function is shown below:

```
>>> discretizer = TransformationFactory('dae.collocation')
>>> discretizer.apply_to(model, nfe=10, ncp=6)
>>> model = discretizer.reduce_collocation_points(model,
...                                               var=model.u,
...                                               ncp=1,
...                                               contset=model.time)
```

In the above example, the `reduce_collocation_points` function restricts the variable `model.u` to have only **1** free collocation point per finite element, thereby enforcing a piecewise constant profile. Fig. 8.1 shows the solution profile before and after appling the `reduce_collocation_points` function.

Applying Multiple Discretization Transformations

Discretizations can be applied independently to each *ContinuousSet* in a model. This allows the user great flexibility in discretizing their model. For example the same numerical method can be applied with different resolutions:

```
>>> discretizer = TransformationFactory('dae.finite_difference')
>>> discretizer.apply_to(model,wrt=model.t1,nfe=10)
>>> discretizer.apply_to(model,wrt=model.t2,nfe=100)
```

This also allows the user to combine different methods. For example, applying the forward difference method to one *ContinuousSet* and the central finite difference method to another *ContinuousSet*:

```
>>> discretizer = TransformationFactory('dae.finite_difference')
>>> discretizer.apply_to(model,wrt=model.t1,scheme='FORWARD')
>>> discretizer.apply_to(model,wrt=model.t2,scheme='CENTRAL')
```

In addition, the user may combine finite difference and collocation discretizations. For example:

```
>>> disc_fe = TransformationFactory('dae.finite_difference')
>>> disc_fe.apply_to(model,wrt=model.t1,nfe=10)
>>> disc_col = TransformationFactory('dae.collocation')
>>> disc_col.apply_to(model,wrt=model.t2,nfe=10,ncp=5)
```

If the user would like to apply the same discretization to all *ContinuousSet* components in a model, just specify the discretization once without the 'wrt' keyword argument. This will apply that scheme to all *ContinuousSet* components in the model that haven't already been discretized.

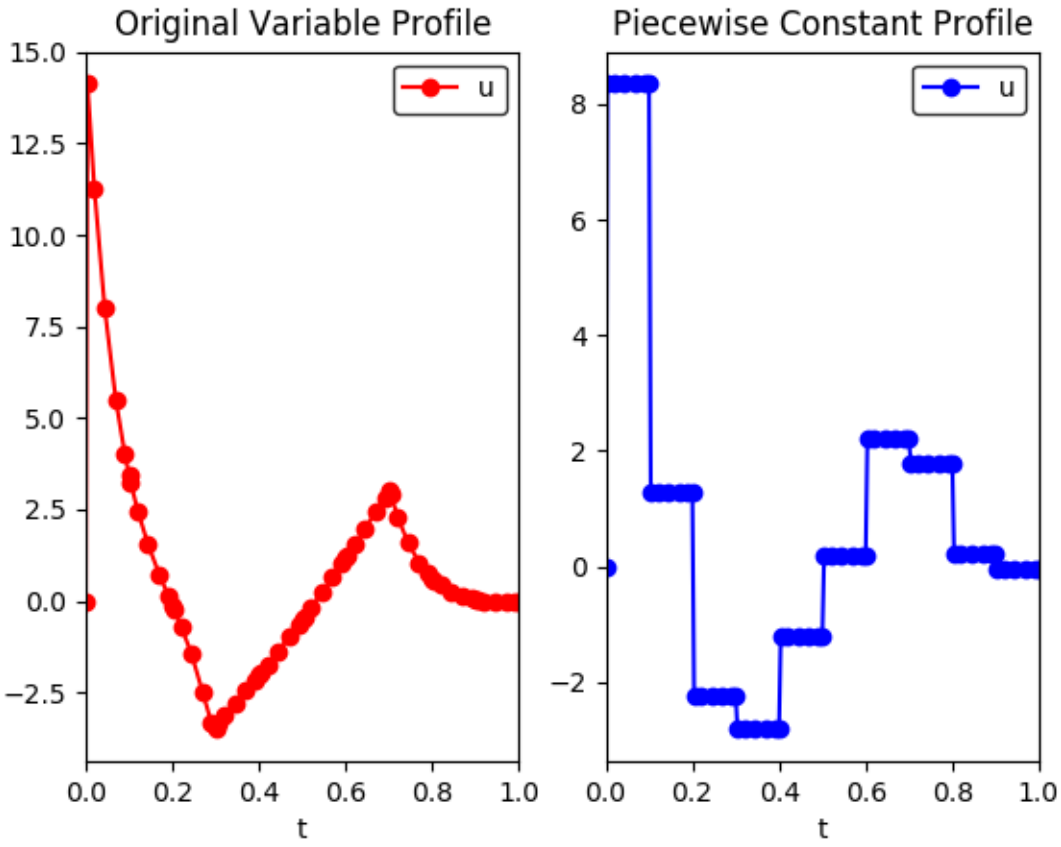

Fig. 8.1: (left) Profile before applying the `reduce_collocation_points` function (right) Profile after applying the function, restricting `model.u` to have a piecewise constant profile.

Custom Discretization Schemes

A transformation framework along with certain utility functions has been created so that advanced users may easily implement custom discretization schemes other than those listed above. The transformation framework consists of the following steps:

1. Specify Discretization Options
2. Discretize the ContinuousSet(s)
3. Update Model Components
4. Add Discretization Equations
5. Return Discretized Model

If a user would like to create a custom finite difference scheme then they only have to worry about step (4) in the framework. The discretization equations for a particular scheme have been isolated from of the rest of the code for implementing the transformation. The function containing these discretization equations can be found at the top of the source code file for the transformation. For example, below is the function for the forward difference method:

```
def _forward_transform(v,s):
"""
Applies the Forward Difference formula of order O(h) for first derivatives
"""
    def _fwd_fun(i):
        tmp = sorted(s)
        idx = tmp.index(i)
        return 1/(tmp[idx+1]-tmp[idx])*(v(tmp[idx+1])-v(tmp[idx]))
    return _fwd_fun
```

In this function, 'v' represents the continuous variable or function that the method is being applied to. 's' represents the set of discrete points in the continuous domain. In order to implement a custom finite difference method, a user would have to copy the above function and just replace the equation next to the first return statement with their method.

After implementing a custom finite difference method using the above function template, the only other change that must be made is to add the custom method to the 'all_schemes' dictionary in the `dae.finite_difference` class.

In the case of a custom collocation method, changes will have to be made in steps (2) and (4) of the transformation framework. In addition to implementing the discretization equations, the user would also have to ensure that the desired collocation points are added to the ContinuousSet being discretized.

8.2.5 Dynamic Model Simulation

The pyomo.dae Simulator class can be used to simulate systems of ODEs and DAEs. It provides an interface to integrators available in other Python packages.

Note: The pyomo.dae Simulator does not include integrators directly. The user must have at least one of the supported Python packages installed in order to use this class.

---

class pyomo.dae.**Simulator**(*m*, *package='scipy'*)

Simulator objects allow a user to simulate a dynamic model formulated using pyomo.dae.

Parameters

- **m** (*Pyomo Model*) – The Pyomo model to be simulated should be passed as the first argument

- **package** (*string*) – The Python simulator package to use. Currently 'scipy' and 'casadi' are the only supported packages

get_variable_order(*vartype=None*)

This function returns the ordered list of differential variable names. The order corresponds to the order being sent to the integrator function. Knowing the order allows users to provide initial conditions for the differential equations using a list or map the profiles returned by the simulate function to the Pyomo variables.

Parameters **vartype** (*string* or None) – Optional argument for specifying the type of variables to return the order for. The default behavior is to return the order of the differential variables. 'time-varying' will return the order of all the time-dependent algebraic variables identified in the model. 'algebraic' will return the order of algebraic variables used in the most recent call to the simulate function. 'input' will return the order of the time-dependent algebraic variables that were treated as inputs in the most recent call to the simulate function.

Returns

Return type *list*

initialize_model()

This function will initialize the model using the profile obtained from simulating the dynamic model.

simulate(*numpoints=None*, *tstep=None*, *integrator=None*, *varying_inputs=None*, *initcon=None*, *integrator_options=None*)

Simulate the model. Integrator-specific options may be specified as keyword arguments and will be passed on to the integrator.

Parameters

- **numpoints** (*int*) – The number of points for the profiles returned by the simulator. Default is 100
- **tstep** (*int or float*) – The time step to use in the profiles returned by the simulator. This is not the time step used internally by the integrators. This is an optional parameter that may be specified in place of 'numpoints'.
- **integrator** (*string*) – The string name of the integrator to use for simulation. The default is 'lsoda' when using Scipy and 'idas' when using CasADi
- **varying_inputs** (pyomo.environ.Suffix) – A Suffix object containing the piecewise constant profiles to be used for certain time-varying algebraic variables.
- **initcon** (*list of floats*) – The initial conditions for the the differential variables. This is an optional argument. If not specified then the simulator will use the current value of the differential variables at the lower bound of the ContinuousSet for the initial condition.
- **integrator_options** (*dict*) – Dictionary containing options that should be passed to the integrator. See the documentation for a specific integrator for a list of valid options.

Returns The first return value is a 1D array of time points corresponding to the second return value which is a 2D array of the profiles for the simulated differential and algebraic variables.

Return type numpy array, numpy array

Note: Any keyword options supported by the integrator may be specified as keyword options to the simulate function and will be passed to the integrator.

Supported Simulator Packages

The Simulator currently includes interfaces to SciPy and CasADi. ODE simulation is supported in both packages however, DAE simulation is only supported by CasADi. A list of available integrators for each package is given below. Please refer to the SciPy and CasADi documentation directly for the most up-to-date information about these packages and for more information about the various integrators and options.

SciPy Integrators:

- **'vode'** : Real-valued Variable-coefficient ODE solver, options for non-stiff and stiff systems
- **'zvode'** : Complex-values Variable-coefficient ODE solver, options for non-stiff and stiff systems
- **'lsoda'** : Real-values Variable-coefficient ODE solver, automatic switching of algorithms for non-stiff or stiff systems
- **'dopri5'** : Explicit runge-kutta method of order (4)5 ODE solver
- **'dop853'** : Explicit runge-kutta method of order 8(5,3) ODE solver

CasADi Integrators:

- **'cvodes'** : CVodes from the Sundials suite, solver for stiff or non-stiff ODE systems
- **'idas'** : IDAS from the Sundials suite, DAE solver
- **'collocation'** : Fixed-step implicit runge-kutta method, ODE/DAE solver
- **'rk'** : Fixed-step explicit runge-kutta method, ODE solver

Using the Simulator

We now show how to use the Simulator to simulate the following system of ODEs:

$$\begin{aligned} \frac{d\theta}{dt} &= \omega \\ \frac{d\omega}{dt} &= -b * \omega - c * sin(\theta) \end{aligned}$$

We begin by formulating the model using pyomo.DAE

```
>>> m = ConcreteModel()

>>> m.t = ContinuousSet(bounds=(0.0, 10.0))

>>> m.b = Param(initialize=0.25)
>>> m.c = Param(initialize=5.0)

>>> m.omega = Var(m.t)
>>> m.theta = Var(m.t)

>>> m.domegadt = DerivativeVar(m.omega, wrt=m.t)
>>> m.dthetadt = DerivativeVar(m.theta, wrt=m.t)

Setting the initial conditions
>>> m.omega[0].fix(0.0)
>>> m.theta[0].fix(3.14 - 0.1)

>>> def _diffeq1(m, t):
...     return m.domegadt[t] == -m.b * m.omega[t] - m.c * sin(m.theta[t])
>>> m.diffeq1 = Constraint(m.t, rule=_diffeq1)
```

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```
>>> def _diffeq2(m, t):
...     return m.dthetadt[t] == m.omega[t]
>>> m.diffeq2 = Constraint(m.t, rule=_diffeq2)
```

Notice that the initial conditions are set by *fixing* the values of `m.omega` and `m.theta` at t=0 instead of being specified as extra equality constraints. Also notice that the differential equations are specified without using `Constraint.Skip` to skip enforcement at t=0. The Simulator cannot simulate any constraints that contain if-statements in their construction rules.

To simulate the model you must first create a Simulator object. Building this object prepares the Pyomo model for simulation with a particular Python package and performs several checks on the model to ensure compatibility with the Simulator. Be sure to read through the list of limitations at the end of this section to understand the types of models supported by the Simulator.

```
>>> sim = Simulator(m, package='scipy')
```

After creating a Simulator object, the model can be simulated by calling the simulate function. Please see the API documentation for the *Simulator* for more information about the valid keyword arguments for this function.

```
>>> tsim, profiles = sim.simulate(numpoints=100, integrator='vode')
```

The `simulate` function returns numpy arrays containing time points and the corresponding values for the dynamic variable profiles.

***Simulator Limitations*:**

- Differential equations must be first-order and separable
- Model can only contain a single ContinuousSet
- Can't simulate constraints with if-statements in the construction rules
- Need to provide initial conditions for dynamic states by setting the value or using fix()

Specifying Time-Varing Inputs

The *Simulator* supports simulation of a system of ODE's or DAE's with time-varying parameters or control inputs. Time-varying inputs can be specified using a Pyomo `Suffix`. We currently only support piecewise constant profiles. For more complex inputs defined by a continuous function of time we recommend adding an algebraic variable and constraint to your model.

The profile for a time-varying input should be specified using a Python dictionary where the keys correspond to the switching times and the values correspond to the value of the input at a time point. A `Suffix` is then used to associate this dictionary with the appropriate `Var` or `Param` and pass the information to the *Simulator*. The code snippet below shows an example.

```
>>> m = ConcreteModel()

>>> m.t = ContinuousSet(bounds=(0.0, 20.0))

Time-varying inputs
>>> m.b = Var(m.t)
>>> m.c = Param(m.t, default=5.0)
```

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```
>>> m.omega = Var(m.t)
>>> m.theta = Var(m.t)

>>> m.domegadt = DerivativeVar(m.omega, wrt=m.t)
>>> m.dthetadt = DerivativeVar(m.theta, wrt=m.t)

Setting the initial conditions
>>> m.omega[0] = 0.0
>>> m.theta[0] = 3.14 - 0.1

>>> def _diffeq1(m, t):
...     return m.domegadt[t] == -m.b[t] * m.omega[t] - \
...                             m.c[t] * sin(m.theta[t])
>>> m.diffeq1 = Constraint(m.t, rule=_diffeq1)

>>> def _diffeq2(m, t):
...     return m.dthetadt[t] == m.omega[t]
>>> m.diffeq2 = Constraint(m.t, rule=_diffeq2)

Specifying the piecewise constant inputs
>>> b_profile = {0: 0.25, 15: 0.025}
>>> c_profile = {0: 5.0, 7: 50}

Declaring a Pyomo Suffix to pass the time-varying inputs to the Simulator
>>> m.var_input = Suffix(direction=Suffix.LOCAL)
>>> m.var_input[m.b] = b_profile
>>> m.var_input[m.c] = c_profile

Simulate the model using scipy
>>> sim = Simulator(m, package='scipy')
>>> tsim, profiles = sim.simulate(numpoints=100,
...                               integrator='vode',
...                               varying_inputs=m.var_input)
```

Note: The Simulator does not support multi-indexed inputs (i.e. if `m.b` in the above example was indexed by another set besides `m.t`)

8.2.6 Dynamic Model Initialization

Providing a good initial guess is an important factor in solving dynamic optimization problems. There are several model initialization tools under development in pyomo.DAE to help users initialize their models. These tools will be documented here as they become available.

From Simulation

The *Simulator* includes a function for initializing discretized dynamic optimization models using the profiles returned from the simulator. An example using this function is shown below

```
Simulate the model using scipy
>>> sim = Simulator(m, package='scipy')
>>> tsim, profiles = sim.simulate(numpoints=100, integrator='vode',
...                               varying_inputs=m.var_input)

Discretize the model using Orthogonal Collocation
>>> discretizer = TransformationFactory('dae.collocation')
>>> discretizer.apply_to(m, nfe=10, ncp=3)

Initialize the discretized model using the simulator profiles
>>> sim.initialize_model()
```

Note: A model must be simulated before it can be initialized using this function

8.3 Generalized Disjunctive Programming

The Pyomo.GDP modeling extension provides support for Generalized Disjunctive Programming (GDP)[1], an extension of Disjunctive Programming[2] from the operations research community to include nonlinear relationships. The classic form for a GDP is given by:

$$
\begin{aligned}
\min\ & obj = f(x,z) \\
\text{s.t.}\quad & Ax + Bz \leq d \\
& g(x,z) \leq 0 \\
& \bigvee_{i \in D_k} \begin{bmatrix} Y_{ik} \\ M_{ik}x + N_{ik}z \leq e_{ik} \\ r_{ik}(x,z) \leq 0 \end{bmatrix} \quad k \in K \\
& \Omega(Y) = True \\
& x \in X \subseteq \mathbb{R}^n \\
& Y \in \{True, False\}^p \\
& z \in Z \subseteq \mathbb{Z}^m
\end{aligned}
$$

Here, we have the minimization of an objective obj subject to global linear constraints $Ax + Bz \leq d$ and nonlinear constraints $g(x,z) \leq 0$, with conditional linear constraints $M_{ik}x + N_{ik}z \leq e_{ik}$ and nonlinear constraints $r_{ik}(x,z) \leq 0$. These conditional constraints are collected into disjuncts D_k, organized into disjunctions K. Finally, there are logical propositions $\Omega(Y) = True$. Decision/state variables can be continuous x, Boolean Y, and/or integer z.

[1] Raman, R., & Grossmann, I. E. (1994). Modelling and computational techniques for logic based integer programming. *Computers & Chemical Engineering*, 18(7), 563–578. https://doi.org/10.1016/0098-1354(93)E0010-7

[2] Balas, E. (1985). Disjunctive Programming and a Hierarchy of Relaxations for Discrete Optimization Problems. *SIAM Journal on Algebraic Discrete Methods*, 6(3), 466–486. https://doi.org/10.1137/0606047

GDP is useful to model discrete decisions that have implications on the system behavior[3]. For example, in process design, a disjunction may model the choice between processes A and B. If A is selected, then its associated equations and inequalities will apply; otherwise, if B is selected, then its respective constraints should be enforced.

Modelers often ask to model if-then-else relationships. These can be expressed as a disjunction as follows:

$$\begin{bmatrix} Y_1 \\ \text{constraints} \\ \text{for } \textit{then} \end{bmatrix} \veebar \begin{bmatrix} Y_2 \\ \text{constraints} \\ \text{for } \textit{else} \end{bmatrix}$$
$$Y_1 \veebar Y_2$$

Here, if the Boolean Y_1 is `True`, then the constraints in the first disjunct are enforced; otherwise, the constraints in the second disjunct are enforced. The following sections describe the key concepts, modeling, and solution approaches available for Generalized Disjunctive Programming.

8.3.1 Key Concepts

Generalized Disjunctive Programming (GDP) provides a way to bridge high-level propositional logic and algebraic constraints. The GDP standard form from the *index page* is repeated below.

$$\begin{aligned} \min \ & obj = f(x,z) \\ \text{s.t.} \quad & Ax + Bz \leq d \\ & g(x,z) \leq 0 \\ & \bigvee_{i \in D_k} \begin{bmatrix} Y_{ik} \\ M_{ik}x + N_{ik}z \leq e_{ik} \\ r_{ik}(x,z) \leq 0 \end{bmatrix} \quad k \in K \\ & \Omega(Y) = True \\ & x \in X \subseteq \mathbb{R}^n \\ & Y \in \{True, False\}^p \\ & z \in Z \subseteq \mathbb{Z}^m \end{aligned}$$

Original support in Pyomo.GDP focused on the disjuncts and disjunctions, allowing the modelers to group relational expressions in disjuncts, with disjunctions describing logical-OR relationships between the groupings. As a result, we implemented the `Disjunct` and `Disjunction` objects before `BooleanVar` and the rest of the logical expression system. Accordingly, we also describe the disjuncts and disjunctions first below.

Disjuncts

Disjuncts represent groupings of relational expressions (e.g. algebraic constraints) summarized by a Boolean indicator variable Y through implication:

$$\begin{aligned} Y_{ik} \Rightarrow \quad & M_{ik}x + N_{ik}z \leq e_{ik} \\ Y_{ik} \Rightarrow \quad & r_{ik}(x,z) \leq 0 \end{aligned} \qquad \forall i \in D_k, \forall k \in K$$

Logically, this means that if $Y_{ik} = True$, then the constraints $M_{ik}x + N_{ik}z \leq e_{ik}$ and $r_{ik}(x,z) \leq 0$ must be satisfied. However, if $Y_{ik} = False$, then the corresponding constraints are ignored. Note that $Y_{ik} = False$ does **not** imply that the corresponding constraints are *violated*.

[3] Grossmann, I. E., & Trespalacios, F. (2013). Systematic modeling of discrete-continuous optimization models through generalized disjunctive programming. *AIChE Journal*, 59(9), 3276–3295. https://doi.org/10.1002/aic.14088

Disjunctions

Disjunctions describe a logical *OR* relationship between two or more Disjuncts. The simplest and most common case is a 2-term disjunction:

$$\begin{bmatrix} Y_1 \\ \exp(x_2) - 1 = x_1 \\ x_3 = x_4 = 0 \end{bmatrix} \bigvee \begin{bmatrix} Y_2 \\ \exp\left(\frac{x_4}{1.2}\right) - 1 = x_3 \\ x_1 = x_2 = 0 \end{bmatrix}$$

The disjunction above describes the selection between two units in a process network. Y_1 and Y_2 are the Boolean variables corresponding to the selection of process units 1 and 2, respectively. The continuous variables x_1, x_2, x_3, x_4 describe flow in and out of the first and second units, respectively. If a unit is selected, the nonlinear equality in the corresponding disjunct enforces the input/output relationship in the selected unit. The final equality in each disjunct forces flows for the absent unit to zero.

Boolean Variables

Boolean variables are decision variables that may take a value of `True` or `False`. These are most often encountered as the indicator variables of disjuncts. However, they can also be independently defined to represent other problem decisions.

Note: Boolean variables are not intended to participate in algebraic expressions. That is, $3 \times$ True does not make sense; hence, $x = 3Y_1$ does not make sense. Instead, you may have the disjunction

$$\begin{bmatrix} Y_1 \\ x = 3 \end{bmatrix} \bigvee \begin{bmatrix} \neg Y_1 \\ x = 0 \end{bmatrix}$$

Logical Propositions

Logical propositions are constraints describing relationships between the Boolean variables in the model.

These logical propositions can include:

Operator	Example	Y_1	Y_2	Result
Negation	$\neg Y_1$	True		False
		False		True
Equivalence	$Y_1 \Leftrightarrow Y_2$	True	True	True
		True	False	False
		False	True	False
		False	False	True
Conjunction	$Y_1 \wedge Y_2$	True	True	True
		True	False	False
		False	True	False
		False	False	False
Disjunction	$Y_1 \vee Y_2$	True	True	True
		True	False	True
		False	True	True
		False	False	False
Exclusive OR	$Y_1 \veebar Y_2$	True	True	False
		True	False	True
		False	True	True
		False	False	False
Implication	$Y_1 \Rightarrow Y_2$	True	True	True
		True	False	False
		False	True	True
		False	False	True

8.3.2 Modeling in Pyomo.GDP

Disjunctions

To demonstrate modeling with disjunctions in Pyomo.GDP, we revisit the small example from *the previous page*.

$$\begin{bmatrix} Y_1 \\ \exp(x_2) - 1 = x_1 \\ x_3 = x_4 = 0 \end{bmatrix} \bigvee \begin{bmatrix} Y_2 \\ \exp\left(\frac{x_4}{1.2}\right) - 1 = x_3 \\ x_1 = x_2 = 0 \end{bmatrix}$$

Explicit syntax: more descriptive

Pyomo.GDP explicit syntax (see below) provides more clarity in the declaration of each modeling object, and gives the user explicit control over the `Disjunct` names. Assuming the `ConcreteModel` object `m` and variables have been defined, lines 1 and 5 declare the `Disjunct` objects corresponding to selection of unit 1 and 2, respectively. Lines 2 and 6 define the input-output relations for each unit, and lines 3-4 and 7-8 enforce zero flow through the unit that is not selected. Finally, line 9 declares the logical disjunction between the two disjunctive terms.

```
1 m.unit1 = Disjunct()
2 m.unit1.inout = Constraint(expr=exp(m.x[2]) - 1 == m.x[1])
3 m.unit1.no_unit2_flow1 = Constraint(expr=m.x[3] == 0)
4 m.unit1.no_unit2_flow2 = Constraint(expr=m.x[4] == 0)
5 m.unit2 = Disjunct()
6 m.unit2.inout = Constraint(expr=exp(m.x[4] / 1.2) - 1 == m.x[3])
7 m.unit2.no_unit1_flow1 = Constraint(expr=m.x[1] == 0)
8 m.unit2.no_unit1_flow2 = Constraint(expr=m.x[2] == 0)
9 m.use_unit1or2 = Disjunction(expr=[m.unit1, m.unit2])
```

The indicator variables for each disjunct Y_1 and Y_2 are automatically generated by Pyomo.GDP, accessible via `m.unit1.indicator_var` and `m.unit2.indicator_var`.

Compact syntax: more concise

For more advanced users, a compact syntax is also available below, taking advantage of the ability to declare disjuncts and constraints implicitly. When the `Disjunction` object constructor is passed a list of lists, the outer list defines the disjuncts and the inner list defines the constraint expressions associated with the respective disjunct.

```
m.use1or2 = Disjunction(expr=[
    # First disjunct
    [exp(m.x[2])-1 == m.x[1],
     m.x[3] == 0, m.x[4] == 0],
    # Second disjunct
    [exp(m.x[4]/1.2)-1 == m.x[3],
     m.x[1] == 0, m.x[2] == 0]])
```

Note: By default, Pyomo.GDP `Disjunction` objects enforce an implicit "exactly one" relationship among the selection of the disjuncts (generalization of exclusive-OR). That is, exactly one of the `Disjunct` indicator variables should take a `True` value. This can be seen as an implicit logical proposition, in our example, $Y_1 \veebar Y_2$.

Logical Propositions

Pyomo.GDP also supports the use of logical propositions through the use of the `BooleanVar` and `LogicalConstraint` objects. The `BooleanVar` object in Pyomo represents Boolean variables, analogous to `Var` for numeric variables. `BooleanVar` can be indexed over a Pyomo `Set`, as below:

```
>>> m = ConcreteModel()
>>> m.my_set = RangeSet(4)
>>> m.Y = BooleanVar(m.my_set)
>>> m.Y.display()
Y : Size=4, Index=my_set
    Key : Value : Fixed : Stale
      1 :  None : False :  True
      2 :  None : False :  True
      3 :  None : False :  True
      4 :  None : False :  True
```

Using these Boolean variables, we can define `LogicalConstraint` objects, analogous to algebraic `Constraint` objects.

```
>>> m.p = LogicalConstraint(expr=m.Y[1].implies(land(m.Y[2], m.Y[3])).lor(m.Y[4]))
>>> m.p.pprint()
p : Size=1, Index=None, Active=True
    Key  : Body                          : Active
    None : (Y[1] --> Y[2]  Y[3])  Y[4] :   True
```

Supported Logical Operators

Pyomo.GDP logical expression system supported operators and their usage are listed in the table below.

Operator	Operator	Method	Function
Conjunction		`Y[1].land(Y[2])`	`land(Y[1],Y[2])`
Disjunction		`Y[1].lor(Y[2])`	`lor(Y[1],Y[2])`
Negation	`~Y[1]`		`lnot(Y[1])`
Exclusive OR		`Y[1].xor(Y[2])`	`xor(Y[1], Y[2])`
Implication		`Y[1].implies(Y[2])`	`implies(Y[1], Y[2])`
Equivalence		`Y[1].equivalent_to(Y[2])`	`equivalent(Y[1], Y[2])`

In addition, the following constraint-programming-inspired operators are provided: `exactly`, `atmost`, and `atleast`. These predicates enforce, respectively, that exactly, at most, or at least N of their `BooleanVar` arguments are `True`.

Usage:

- `atleast(3, Y[1], Y[2], Y[3])`
- `atmost(3, Y)`
- `exactly(3, Y)`

Note: We omit support for most infix operators, e.g. `Y[1] >> Y[2]`, due to concerns about non-intuitive Python operator precedence. That is `Y[1] | Y[2] >> Y[3]` would translate to $Y_1 \vee (Y_2 \Rightarrow Y_3)$ rather than $(Y_1 \vee Y_2) \Rightarrow Y_3$

```
>>> m = ConcreteModel()
>>> m.my_set = RangeSet(4)
>>> m.Y = BooleanVar(m.my_set)
>>> m.p = LogicalConstraint(expr=atleast(3, m.Y))
>>> TransformationFactory('core.logical_to_linear').apply_to(m)
>>> m.logic_to_linear.transformed_constraints.pprint()  # constraint auto-generated by␣
↪transformation
transformed_constraints : Size=1, Index=logic_to_linear.transformed_constraints_index,␣
↪Active=True
    Key : Lower : Body                                                          : Upper␣
↪: Active
      1 :   3.0 : Y_asbinary[1] + Y_asbinary[2] + Y_asbinary[3] + Y_asbinary[4] :  +Inf␣
↪:   True
>>> m.p.pprint()
p : Size=1, Index=None, Active=False
    Key  : Body                                 : Active
    None : atleast(3: [Y[1], Y[2], Y[3], Y[4]]) :  False
```

Indexed logical constraints

Like `Constraint` objects for algebraic expressions, `LogicalConstraint` objects can be indexed. An example of this usage may be found below for the expression:

$$Y_{i+1} \Rightarrow Y_i, \quad i \in \{1, 2, \ldots, n-1\}$$

```
>>> m = ConcreteModel()
>>> n = 5
>>> m.I = RangeSet(n)
>>> m.Y = BooleanVar(m.I)

>>> @m.LogicalConstraint(m.I)
... def p(m, i):
...     return m.Y[i+1].implies(m.Y[i]) if i < n else Constraint.Skip

>>> m.p.pprint()
p : Size=4, Index=I, Active=True
    Key : Body          : Active
      1 : Y[2] --> Y[1] :   True
      2 : Y[3] --> Y[2] :   True
      3 : Y[4] --> Y[3] :   True
      4 : Y[5] --> Y[4] :   True
```

Integration with Disjunctions

Note: Historically, the `indicator_var` on `Disjunct` objects was implemented as a binary `Var`. Beginning in Pyomo 6.0, that has been changed to the more mathematically correct `BooleanVar`, with the associated binary variable available as `binary_indicator_var`.

The logical expression system is designed to augment the previously introduced `Disjunct` and `Disjunction` components. Mathematically, the disjunct indicator variable is Boolean, and can be used directly in logical propositions.

Here, we demonstrate this capability with a toy example:

$$
\begin{aligned}
&\min x \\
&\text{s.t.} \begin{bmatrix} Y_1 \\ x \geq 2 \end{bmatrix} \vee \begin{bmatrix} Y_2 \\ x \geq 3 \end{bmatrix} \\
&\quad \begin{bmatrix} Y_3 \\ x \leq 8 \end{bmatrix} \vee \begin{bmatrix} Y_4 \\ x = 2.5 \end{bmatrix} \\
&\quad Y_1 \veebar Y_2 \\
&\quad Y_3 \veebar Y_4 \\
&\quad Y_1 \Rightarrow Y_4
\end{aligned}
$$

```
>>> m = ConcreteModel()
>>> m.s = RangeSet(4)
>>> m.ds = RangeSet(2)
>>> m.d = Disjunct(m.s)
>>> m.djn = Disjunction(m.ds)
>>> m.djn[1] = [m.d[1], m.d[2]]
>>> m.djn[2] = [m.d[3], m.d[4]]
>>> m.x = Var(bounds=(-2, 10))
>>> m.d[1].c = Constraint(expr=m.x >= 2)
>>> m.d[2].c = Constraint(expr=m.x >= 3)
>>> m.d[3].c = Constraint(expr=m.x <= 8)
>>> m.d[4].c = Constraint(expr=m.x == 2.5)
>>> m.o = Objective(expr=m.x)

>>> # Add the logical proposition
>>> m.p = LogicalConstraint(
...     expr=m.d[1].indicator_var.implies(m.d[4].indicator_var))
>>> # Note: the implicit XOR enforced by m.djn[1] and m.djn[2] still apply

>>> # Convert logical propositions to linear algebraic constraints
>>> # and apply the Big-M reformulation.
>>> TransformationFactory('core.logical_to_linear').apply_to(m)
>>> TransformationFactory('gdp.bigm').apply_to(m)

>>> # Before solve, Boolean vars have no value
>>> Reference(m.d[:].indicator_var).display()
IndexedBooleanVar : Size=4, Index=s
    Key : Value : Fixed : Stale
      1 :  None : False :  True
```

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```
      2 :  None : False :  True
      3 :  None : False :  True
      4 :  None : False :  True

>>> # Solve the reformulated model and update the Boolean variables
>>> # based on the algebraic model results
>>> run_data = SolverFactory('glpk').solve(m)
>>> Reference(m.d[:].indicator_var).display()
IndexedBooleanVar : Size=4, Index=s
    Key : Value : Fixed : Stale
      1 :  True : False : False
      2 : False : False : False
      3 : False : False : False
      4 :  True : False : False
```

We elaborate on the `logical_to_linear` transformation *on the next page*.

Advanced LogicalConstraint Examples

Support for complex nested expressions is a key benefit of the logical expression system. Below are examples of expressions that we support, and with some, an explanation of their implementation.

Composition of standard operators

$$Y_1 \vee Y_2 \implies Y_3 \wedge \neg Y_4 \wedge (Y_5 \vee Y_6)$$

```
m.p = LogicalConstraint(expr=lor(m.Y[1], m.Y[2]).implies(
    land(m.Y[3], ~m.Y[4], m.Y[5].lor(m.Y[6])))
)
```

Expressions within CP-type operators

$$\text{atleast}(3, Y_1, Y_2 \vee Y_3, Y_4 \Rightarrow Y_5, Y_6)$$

Here, augmented variables may be automatically added to the model as follows:

$$\begin{aligned} \text{atleast}(3, & Y_1, Y_A, Y_B, Y_6) \\ & Y_A \Leftrightarrow Y_2 \vee Y_3 \\ & Y_B \Leftrightarrow (Y_4 \Rightarrow Y_5) \end{aligned}$$

```
m.p = LogicalConstraint(
    expr=atleast(3, m.Y[1], Or(m.Y[2], m.Y[3]), m.Y[4].implies(m.Y[5]), m.Y[6]))
```

Nested CP-style operators

$$\text{atleast}(2, Y_1, \text{exactly}(2, Y_2, Y_3, Y_4), Y_5, Y_6)$$

Here, we again need to add augmented variables:

$$\begin{gathered}\text{atleast}(2, Y_1, Y_A, Y_5, Y_6) \\ Y_A \Leftrightarrow \text{exactly}(2, Y_2, Y_3, Y_4)\end{gathered}$$

However, we also need to further interpret the second statement as a disjunction:

$$\begin{gathered}\text{atleast}(2, Y_1, Y_A, Y_5, Y_6) \\ \begin{bmatrix} Y_A \\ \text{exactly}(2, Y_2, Y_3, Y_4) \end{bmatrix} \vee \left[\begin{gathered}\neg Y_A \\ \begin{bmatrix} Y_B \\ \text{atleast}(3, Y_2, Y_3, Y_4) \end{bmatrix} \vee \begin{bmatrix} Y_C \\ \text{atmost}(1, Y_2, Y_3, Y_4) \end{bmatrix}\end{gathered}\right]\end{gathered}$$

or equivalently,

$$\begin{gathered}\text{atleast}(2, Y_1, Y_A, Y_5, Y_6) \\ \text{exactly}(1, Y_A, Y_B, Y_C) \\ \begin{bmatrix} Y_A \\ \text{exactly}(2, Y_2, Y_3, Y_4) \end{bmatrix} \vee \begin{bmatrix} Y_B \\ \text{atleast}(3, Y_2, Y_3, Y_4) \end{bmatrix} \vee \begin{bmatrix} Y_C \\ \text{atmost}(1, Y_2, Y_3, Y_4) \end{bmatrix}\end{gathered}$$

```
m.p = LogicalConstraint(
    expr=atleast(2, m.Y[1], exactly(2, m.Y[2], m.Y[3], m.Y[4]), m.Y[5], m.Y[6]))
```

In the `logical_to_linear` transformation, we automatically convert these special disjunctions to linear form using a Big M reformulation.

Additional Examples

The following models all work and are equivalent for $[x = 0] \veebar [y = 0]$:

```
Option 1: Rule-based construction

>>> from pyomo.environ import *
>>> from pyomo.gdp import *
>>> model = ConcreteModel()

>>> model.x = Var()
>>> model.y = Var()

>>> # Two conditions
>>> def _d(disjunct, flag):
...     model = disjunct.model()
...     if flag:
...         # x == 0
...         disjunct.c = Constraint(expr=model.x == 0)
...     else:
```

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```
...         # y == 0
...         disjunct.c = Constraint(expr=model.y == 0)
>>> model.d = Disjunct([0,1], rule=_d)

>>> # Define the disjunction
>>> def _c(model):
...     return [model.d[0], model.d[1]]
>>> model.c = Disjunction(rule=_c)

Option 2: Explicit disjuncts

>>> from pyomo.environ import *
>>> from pyomo.gdp import *
>>> model = ConcreteModel()

>>> model.x = Var()
>>> model.y = Var()

>>> model.fix_x = Disjunct()
>>> model.fix_x.c = Constraint(expr=model.x == 0)

>>> model.fix_y = Disjunct()
>>> model.fix_y.c = Constraint(expr=model.y == 0)

>>> model.c = Disjunction(expr=[model.fix_x, model.fix_y])

Option 3: Implicit disjuncts (disjunction rule returns a list of
expressions or a list of lists of expressions)

>>> from pyomo.environ import *
>>> from pyomo.gdp import *
>>> model = ConcreteModel()

>>> model.x = Var()
>>> model.y = Var()

>>> model.c = Disjunction(expr=[model.x == 0, model.y == 0])
```

8.3.3 Solving Logic-based Models with Pyomo.GDP

Flexible Solution Suite

Once a model is formulated as a GDP model, a range of solution strategies are available to manipulate and solve it.

The traditional approach is reformulation to a MI(N)LP, but various other techniques are possible, including direct solution via the *GDPopt solver*. Below, we describe some of these capabilities.

Reformulations

Logical constraints

At present, logical propositions must be converted to algebraic form prior to use of the MI(N)LP reformulations or the GDPopt solver. This may be accomplished via transformation:

```
TransformationFactory('core.logical_to_linear').apply_to(model)
```

The transformation creates a constraint list with a unique name starting with `logic_to_linear`, within which the algebraic equivalents of the logical constraints are placed. If not already associated with a binary variable, each `BooleanVar` object will receive a generated binary counterpart. These associated binary variables may be accessed via the `get_associated_binary()` method.

```
m.Y[1].get_associated_binary()
```

Additional augmented variables and their corresponding constraints may also be created, as described in *Advanced LogicalConstraint Examples*.

Following solution of the GDP model, values of the Boolean variables may be updated from their algebraic binary counterparts using the `update_boolean_vars_from_binary()` function.

pyomo.core.plugins.transform.logical_to_linear.**update_boolean_vars_from_binary**(*model*, *integer_tolerance=1e-05*)

Updates all Boolean variables based on the value of their linked binary variables.

Reformulation to MI(N)LP

To use standard commercial solvers, you must convert the disjunctive model to a standard MILP/MINLP model. The two classical strategies for doing so are the (included) Big-M and Hull reformulations.

Big-M (BM) Reformulation

The Big-M reformulation[4] results in a smaller transformed model, avoiding the need to add extra variables; however, it yields a looser continuous relaxation. By default, the BM transformation will estimate reasonably tight M values for you if variables are bounded. For nonlinear models where finite expression bounds may be inferred from variable bounds, the BM transformation may also be able to automatically compute M values for you. For all other models, you will need to provide the M values through a "BigM" Suffix, or through the *bigM* argument to the transformation. We will raise a `GDP_Error` for missing M values. We implement the multiple-parameter Big-M (MBM) approach described in literature[3].

To apply the BM reformulation within a python script, use:

```
TransformationFactory('gdp.bigm').apply_to(model)
```

From the Pyomo command line, include the `--transform pyomo.gdp.bigm` option.

[4] Nemhauser, G. L., & Wolsey, L. A. (1988). *Integer and combinatorial optimization*. New York: Wiley.

[3] Trespalacios, F., & Grossmann, I. E. (2015). Improved Big-M reformulation for generalized disjunctive programs. *Computers and Chemical Engineering*, 76, 98–103. https://doi.org/10.1016/j.compchemeng.2015.02.013

Hull Reformulation (HR)

The Hull Reformulation requires a lifting into a higher-dimensional space and consequently introduces disaggregated variables and their corresponding constraints.

Note:

- All variables that appear in disjuncts need upper and lower bounds.
- The hull reformulation is an exact reformulation at the solution points even for nonconvex GDP models, but the resulting MINLP will also be nonconvex.

To apply the Hull reformulation within a python script, use:

```
TransformationFactory('gdp.hull').apply_to(model)
```

From the Pyomo command line, include the `--transform pyomo.gdp.hull` option.

Hybrid BM/HR Reformulation

An experimental (for now) implementation of the cutting plane approach described in literature[5] is provided for linear GDP models. The transformation augments the BM reformulation by a set of cutting planes generated from the HR model by solving separation problems. This gives a model that is not as large as the HR, but with a stronger continuous relaxation than the BM.

This transformation is accessible via:

```
TransformationFactory('gdp.cuttingplane').apply_to(model)
```

Direct GDP solvers

Pyomo includes the contributed GDPopt solver, which can directly solve GDP models. Its usage is described within the *contributed packages documentation*.

References

8.3.4 Literature References

8.4 MPEC

`pyomo.mpec` supports modeling complementarity conditions and optimization problems with equilibrium constraints.

[5] Sawaya, N. W., & Grossmann, I. E. (2003). A cutting plane method for solving linear generalized disjunctive programming problems. *Computer Aided Chemical Engineering*, 15(C), 1032–1037. https://doi.org/10.1016/S1570-7946(03)80444-3

8.5 Stochastic Programming in Pyomo

There are two extensions for modeling and solving Stochastic Programs in Pyomo. Both are currently distributed as independent Python packages. PySP was the original extension (and up through Pyomo 5.7.3 was distributed as part of Pyomo). You can find the documentation here:

https://pysp.readthedocs.io

In 2020, the PySP developers released the mpi-sppy package, which reimplemented much of the functionality from PySP in a new scalable framework built on top of MPI and the mpi4py package. Future development of stochastic programming capabilities is occurring in mpi-sppy. The documentation is available here:

https://mpi-sppy.readthedocs.io

8.6 Pyomo Network

Pyomo Network is a package that allows users to easily represent their model as a connected network of units. Units are blocks that contain ports, which contain variables, that are connected to other ports via arcs. The connection of two ports to each other via an arc typically represents a set of constraints equating each member of each port to each other, however there exist other connection rules as well, in addition to support for custom rules. Pyomo Network also includes a model transformation that will automatically expand the arcs and generate the appropriate constraints to produce an algebraic model that a solver can handle. Furthermore, the package also introduces a generic sequential decomposition tool that can leverage the modeling components to decompose a model and compute each unit in the model in a logically ordered sequence.

8.6.1 Modeling Components

Pyomo Network introduces two new modeling components to Pyomo:

pyomo.network.Port	A collection of variables, which may be connected to other ports
pyomo.network.Arc	Component used for connecting the members of two Port objects

Port

class pyomo.network.**Port**(**args*, ***kwds*)

A collection of variables, which may be connected to other ports

The idea behind Ports is to create a bundle of variables that can be manipulated together by connecting them to other ports via Arcs. A preprocess transformation will look for Arcs and expand them into a series of constraints that involve the original variables contained within the Port. The way these constraints are built can be specified for each Port member when adding members to the port, but by default the Port members will be equated to each other. Additionally, other objects such as expressions can be added to Ports as long as they, or their indexed members, can be manipulated within constraint expressions.

Parameters

- **rule** (*function*) – A function that returns a dict of (name: var) pairs to be initially added to the Port. Instead of var it could also be a tuples of (var, rule). Or it could return an iterable of either vars or tuples of (var, rule) for implied names.

- **initialize** – Follows same specifications as rule's return value, gets initially added to the Port
- **implicit** – An iterable of names to be initially added to the Port as implicit vars
- **extends** (*Port*) – A Port whose vars will be added to this Port upon construction

static Equality(*port*, *name*, *index_set*)
Arc Expansion procedure to generate simple equality constraints

static Extensive(*port*, *name*, *index_set*, *include_splitfrac=None*, *write_var_sum=True*)
Arc Expansion procedure for extensive variable properties

This procedure is the rule to use when variable quantities should be conserved; that is, split for outlets and combined for inlets.

This will first go through every destination of the port (i.e., arcs whose source is this Port) and create a new variable on the arc's expanded block of the same index as the current variable being processed to store the amount of the variable that flows over the arc. For ports that have multiple outgoing arcs, this procedure will create a single splitfrac variable on the arc's expanded block as well. Then it will generate constraints for the new variable that relate it to the port member variable using the split fraction, ensuring that all extensive variables in the Port are split using the same ratio. The generation of the split fraction variable and constraint can be suppressed by setting the *include_splitfrac* argument to *False*.

Once all arc-specific variables are created, this procedure will create the "balancing constraint" that ensures that the sum of all the new variables equals the original port member variable. This constraint can be suppressed by setting the *write_var_sum* argument to *False*; in which case, a single constraint will be written that states the sum of the split fractions equals 1.

Finally, this procedure will go through every source for this port and create a new arc variable (unless it already exists), before generating the balancing constraint that ensures the sum of all the incoming new arc variables equals the original port variable.

Model simplifications:

If the port has a 1-to-1 connection on either side, it will not create the new variables and instead write a simple equality constraint for that side.

If the outlet side is not 1-to-1 but there is only one outlet, it will not create a splitfrac variable or write the split constraint, but it will still write the outsum constraint which will be a simple equality.

If the port only contains a single Extensive variable, the splitfrac variables and the splitting constraints will be skipped since they will be unnecessary. However, they can be still be included by passing *include_splitfrac=True*.

Note: If split fractions are skipped, the *write_var_sum=False* option is not allowed.

---

class pyomo.network.port.**_PortData**(*component=None*)
This class defines the data for a single Port

vars
A dictionary mapping added names to variables

Type *dict*

__getattr__(*name*)
Returns *self.vars[name]* if it exists

add(*var*, *name=None*, *rule=None*, ***kwds*)
Add *var* to this Port, casting it to a Pyomo numeric if necessary

Parameters

- **var** – A variable or some *NumericValue* like an expression
- **name** (*str*) – Name to associate with this member of the Port
- **rule** (*function*) – Function implementing the desired expansion procedure for this member. *Port.Equality* by default, other options include *Port.Extensive*. Customs are allowed.
- **kwds** – Keyword arguments that will be passed to rule

arcs(*active=None*)
A list of Arcs in which this Port is a member

dests(*active=None*)
A list of Arcs in which this Port is a source

fix()
Fix all variables in the port at their current values. For expressions, fix every variable in the expression.

free()
Unfix all variables in the port. For expressions, unfix every variable in the expression.

get_split_fraction(*arc*)
Returns a tuple (val, fix) for the split fraction of this arc that was set via *set_split_fraction* if it exists, and otherwise None.

is_binary()
Return True if all variables in the Port are binary

is_continuous()
Return True if all variables in the Port are continuous

is_equality(*name*)
Return True if the rule for this port member is Port.Equality

is_extensive(*name*)
Return True if the rule for this port member is Port.Extensive

is_fixed()
Return True if all vars/expressions in the Port are fixed

is_integer()
Return True if all variables in the Port are integer

is_potentially_variable()
Return True as ports may (should!) contain variables

iter_vars(*expr_vars=False*, *fixed=None*, *names=False*)
Iterate through every member of the port, going through the indices of indexed members.

Parameters

- **expr_vars** (*bool*) – If True, call *identify_variables* on expression type members
- **fixed** (*bool*) – Only include variables/expressions with this type of fixed
- **names** (*bool*) – If True, yield (name, index, var/expr) tuples

polynomial_degree()
Returns the maximum polynomial degree of all port members

remove(*name*)
Remove this member from the port

rule_for(*name*)
Return the rule associated with the given port member

set_split_fraction(*arc*, *val*, *fix=True*)
Set the split fraction value to be used for an arc during arc expansion when using *Port.Extensive*.

sources(*active=None*)
A list of Arcs in which this Port is a destination

unfix()
Unfix all variables in the port. For expressions, unfix every variable in the expression.

The following code snippet shows examples of declaring and using a `Port` component on a concrete Pyomo model:

```
>>> from pyomo.environ import *
>>> from pyomo.network import *
>>> m = ConcreteModel()
>>> m.x = Var()
>>> m.y = Var(['a', 'b']) # can be indexed
>>> m.z = Var()
>>> m.e = 5 * m.z # you can add Pyomo expressions too
>>> m.w = Var()

>>> m.p = Port()
>>> m.p.add(m.x) # implicitly name the port member "x"
>>> m.p.add(m.y, "foo") # name the member "foo"
>>> m.p.add(m.e, rule=Port.Extensive) # specify a rule
>>> m.p.add(m.w, rule=Port.Extensive, write_var_sum=False) # keyword arg
```

Arc

class pyomo.network.**Arc**(**args*, ***kwds*)
Component used for connecting the members of two Port objects

Parameters

- **source** (*Port*) – A single Port for a directed arc. Aliases to src.
- **destination** (*Port*) – A single`Port for a directed arc. Aliases to dest.
- **ports** – A two-member list or tuple of single Ports for an undirected arc
- **directed** (*bool*) – Set True for directed. Use along with *rule* to be able to return an implied (source, destination) tuple.
- **rule** (*function*) – A function that returns either a dictionary of the arc arguments or a two-member iterable of ports

class pyomo.network.arc.**_ArcData**(*component=None*, ***kwds*)
This class defines the data for a single Arc

source
The source Port when directed, else None. Aliases to src.

Type *Port*

destination
The destination Port when directed, else None. Aliases to dest.

Type *Port*

ports
A tuple containing both ports. If directed, this is in the order (source, destination).

Type *tuple*

directed
True if directed, False if not

Type *bool*

expanded_block
A reference to the block on which expanded constraints for this arc were placed

Type *Block*

__getattr__(*name*)
Returns *self.expanded_block.name* if it exists

set_value(*vals*)
Set the port attributes on this arc

The following code snippet shows examples of declaring and using an *Arc* component on a concrete Pyomo model:

```
>>> from pyomo.environ import *
>>> from pyomo.network import *
>>> m = ConcreteModel()
>>> m.x = Var()
>>> m.y = Var(['a', 'b'])
>>> m.u = Var()
>>> m.v = Var(['a', 'b'])
>>> m.w = Var()
>>> m.z = Var(['a', 'b']) # indexes need to match

>>> m.p = Port(initialize=[m.x, m.y])
>>> m.q = Port(initialize={"x": m.u, "y": m.v})
>>> m.r = Port(initialize={"x": m.w, "y": m.z}) # names need to match
>>> m.a = Arc(source=m.p, destination=m.q) # directed
>>> m.b = Arc(ports=(m.p, m.q)) # undirected
>>> m.c = Arc(ports=(m.p, m.q), directed=True) # directed
>>> m.d = Arc(src=m.p, dest=m.q) # aliases work
>>> m.e = Arc(source=m.r, dest=m.p) # ports can have both in and out
```

8.6.2 Arc Expansion Transformation

The examples above show how to declare and instantiate a *Port* and an *Arc*. These two components form the basis of the higher level representation of a connected network with sets of related variable quantities. Once a network model has been constructed, Pyomo Network implements a transformation that will expand all (active) arcs on the model and automatically generate the appropriate constraints. The constraints created for each port member will be indexed by the same indexing set as the port member itself.

During transformation, a new block is created on the model for each arc (located on the arc's parent block), which serves to contain all of the auto generated constraints for that arc. At the end of the transformation, a reference is created on the arc that points to this new block, available via the arc property *arc.expanded_block*.

The constraints produced by this transformation depend on the rule assigned for each port member and can be different between members on the same port. For example, you can have two different members on a port where one member's rule is *Port.Equality* and the other member's rule is *Port.Extensive*.

Port.Equality is the default rule for port members. This rule simply generates equality constraints on the expanded block between the source port's member and the destination port's member. Another implemented expansion method is *Port.Extensive*, which essentially represents implied splitting and mixing of certain variable quantities. Users can refer to the documentation of the static method itself for more details on how this implicit splitting and mixing is implemented. Additionally, should users desire, the expansion API supports custom rules that can be implemented to generate whatever is needed for special cases.

The following code demonstrates how to call the transformation to expand the arcs on a model:

```
>>> from pyomo.environ import *
>>> from pyomo.network import *
>>> m = ConcreteModel()
>>> m.x = Var()
>>> m.y = Var(['a', 'b'])
>>> m.u = Var()
>>> m.v = Var(['a', 'b'])

>>> m.p = Port(initialize=[m.x, (m.y, Port.Extensive)]) # rules must match
>>> m.q = Port(initialize={"x": m.u, "y": (m.v, Port.Extensive)})
>>> m.a = Arc(source=m.p, destination=m.q)

>>> TransformationFactory("network.expand_arcs").apply_to(m)
```

8.6.3 Sequential Decomposition

Pyomo Network implements a generic *SequentialDecomposition* tool that can be used to compute each unit in a network model in a logically ordered sequence.

The sequential decomposition procedure is commenced via the *run* method.

Creating a Graph

To begin this procedure, the Pyomo Network model is first utilized to create a networkx *MultiDiGraph* by adding edges to the graph for every arc on the model, where the nodes of the graph are the parent blocks of the source and destination ports. This is done via the *create_graph* method, which requires all arcs on the model to be both directed and already expanded. The *MultiDiGraph* class of networkx supports both direccted edges as well as having multiple edges between the same two nodes, so users can feel free to connect as many ports as desired between the same two units.

Computation Order

The order of computation is then determined by treating the resulting graph as a tree, starting at the roots of the tree, and making sure by the time each node is reached, all of its predecessors have already been computed. This is implemented through the *calculation_order* and *tree_order* methods. Before this, however, the procedure will first select a set of tear edges, if necessary, such that every loop in the graph is torn, while minimizing both the number of times any single loop is torn as well as the total number of tears.

Tear Selection

A set of tear edges can be selected in one of two ways. By default, a Pyomo MIP model is created and optimized resulting in an optimal set of tear edges. The implementation of this MIP model is based on a set of binary "torn" variables for every edge in the graph, and constraints on every loop in the graph that dictate that there must be at least one tear on the loop. Then there are two objectives (represented by a doubly weighted objective). The primary objective is to minimize the number of times any single loop is torn, and then secondary to that is to minimize the total number of tears. This process is implemented in the *select_tear_mip* method, which uses the model returned from the *select_tear_mip_model* method.

Alternatively, there is the *select_tear_heuristic* method. This uses a heuristic procedure that walks back and forth on the graph to find every optimal tear set, and returns each equally optimal tear set it finds. This method is much slower than the MIP method on larger models, but it maintains some use in the fact that it returns every possible optimal tear set.

A custom tear set can be assigned before calling the *run* method. This is useful so users can know what their tear set will be and thus what arcs will require guesses for uninitialized values. See the *set_tear_set* method for details.

Running the Sequential Decomposition Procedure

After all of this computational order preparation, the sequential decomposition procedure will then run through the graph in the order it has determined. Thus, the *function* that was passed to the *run* method will be called on every unit in sequence. This function can perform any arbitrary operations the user desires. The only thing that *SequentialDecomposition* expects from the function is that after returning from it, every variable on every outgoing port of the unit will be specified (i.e. it will have a set current value). Furthermore, the procedure guarantees to the user that for every unit, before the function is called, every variable on every incoming port of the unit will be fixed.

In between computing each of these units, port member values are passed across existing arcs involving the unit currently being computed. This means that after computing a unit, the expanded constraints from each arc coming out of this unit will be satisfied, and the values on the respective destination ports will be fixed at these new values. While running the computational order, values are not passed across tear edges, as tear edges represent locations in loops to stop computations (during iterations). This process continues until all units in the network have been computed. This concludes the "first pass run" of the network.

Guesses and Fixing Variables

When passing values across arcs while running the computational order, values at the destinations of each of these arcs will be fixed at the appropriate values. This is important to the fact that the procedure guarantees every inlet variable will be fixed before calling the function. However, since values are not passed across torn arcs, there is a need for user-supplied guesses for those values. See the *set_guesses_for* method for details on how to supply these values.

In addition to passing dictionaries of guesses for certain ports, users can also assign current values to the variables themselves and the procedure will pick these up and fix the variables in place. Alternatively, users can utilize the *default_guess* option to specify a value to use as a default guess for all free variables if they have no guess or current value. If a free variable has no guess or current value and there is no default guess option, then an error will be raised.

Similarly, if the procedure attempts to pass a value to a destination port member but that port member is already fixed and its fixed value is different from what is trying to be passed to it (by a tolerance specified by the *almost_equal_tol* option), then an error will be raised. Lastly, if there is more than one free variable in a constraint while trying to pass values across an arc, an error will be raised asking the user to fix more variables by the time values are passed across said arc.

Tear Convergence

After completing the first pass run of the network, the sequential decomposition procedure will proceed to converge all tear edges in the network (unless the user specifies not to, or if there are no tears). This process occurs separately for every strongly connected component (SCC) in the graph, and the SCCs are computed in a logical order such that each SCC is computed before other SCCs downstream of it (much like *tree_order*).

There are two implemented methods for converging tear edges: direct substitution and Wegstein acceleration. Both of these will iteratively run the computation order until every value in every tear arc has converged to within the specified tolerance. See the *SequentialDecomposition* parameter documentation for details on what can be controlled about this procedure.

The following code demonstrates basic usage of the *SequentialDecomposition* class:

```
>>> from pyomo.environ import *
>>> from pyomo.network import *
>>> m = ConcreteModel()
>>> m.unit1 = Block()
>>> m.unit1.x = Var()
>>> m.unit1.y = Var(['a', 'b'])
>>> m.unit2 = Block()
>>> m.unit2.x = Var()
>>> m.unit2.y = Var(['a', 'b'])
>>> m.unit1.port = Port(initialize=[m.unit1.x, (m.unit1.y, Port.Extensive)])
>>> m.unit2.port = Port(initialize=[m.unit2.x, (m.unit2.y, Port.Extensive)])
>>> m.a = Arc(source=m.unit1.port, destination=m.unit2.port)
>>> TransformationFactory("network.expand_arcs").apply_to(m)

>>> m.unit1.x.fix(10)
>>> m.unit1.y['a'].fix(15)
>>> m.unit1.y['b'].fix(20)

>>> seq = SequentialDecomposition(tol=1.0E-3) # options can go to init
>>> seq.options.select_tear_method = "heuristic" # or set them like so
>>> # seq.set_tear_set([...]) # assign a custom tear set
>>> # seq.set_guesses_for(m.unit.inlet, {...}) # choose guesses
>>> def initialize(b):
...     # b.initialize()
...     pass
...
>>> seq.run(m, initialize)
```

class pyomo.network.**SequentialDecomposition**(***kwds*)

A sequential decomposition tool for Pyomo Network models

The following parameters can be set upon construction of this class or via the *options* attribute.

Parameters

- **graph** (*MultiDiGraph*) – A networkx graph representing the model to be solved.

  default=None (will compute it)

- **tear_set** (*list*) – A list of indexes representing edges to be torn. Can be set with a list of edge tuples via set_tear_set.

  default=None (will compute it)

- **select_tear_method** (*str*) – Which method to use to select a tear set, either "mip" or "heuristic".

  default="mip"

- **run_first_pass** (*bool*) – Boolean indicating whether or not to run through network before running the tear stream convergence procedure.

  default=True

- **solve_tears** (*bool*) – Boolean indicating whether or not to run iterations to converge tear streams.

  default=True

- **guesses** (*ComponentMap*) – ComponentMap of guesses to use for first pass (see set_guesses_for method).

  default=ComponentMap()

- **default_guess** (*float*) – Value to use if a free variable has no guess.

  default=None

- **almost_equal_tol** (*float*) – Difference below which numbers are considered equal when checking port value agreement.

  default=1.0E-8

- **log_info** (*bool*) – Set logger level to INFO during run.

  default=False

- **tear_method** (*str*) – Method to use for converging tear streams, either "Direct" or "Wegstein".

  default="Direct"

- **iterLim** (*int*) – Limit on the number of tear iterations.

  default=40

- **tol** (*float*) – Tolerance at which to stop tear iterations.

  default=1.0E-5

- **tol_type** (*str*) – Type of tolerance value, either "abs" (absolute) or "rel" (relative to current value).

  default="abs"

- **report_diffs** (*bool*) – Report the matrix of differences across tear streams for every iteration.

  default=False

- **accel_min** (*float*) – Min value for Wegstein acceleration factor.

  default=-5

- **accel_max** (*float*) – Max value for Wegstein acceleration factor.

  default=0

- **tear_solver** (*str*) – Name of solver to use for select_tear_mip.

  default="cplex"

- **tear_solver_io** (*str*) – Solver IO keyword for the above solver.

  default=None

- **tear_solver_options** (*dict*) – Keyword options to pass to solve method.

  default={}

calculation_order(*G*, *roots=None*, *nodes=None*)
Rely on tree_order to return a calculation order of nodes

Parameters

- **roots** – List of nodes to consider as tree roots, if None then the actual roots are used
- **nodes** – Subset of nodes to consider in the tree, if None then all nodes are used

create_graph(*model*)
Returns a networkx MultiDiGraph of a Pyomo network model

The nodes are units and the edges follow Pyomo Arc objects. Nodes that get added to the graph are determined by the parent blocks of the source and destination Ports of every Arc in the model. Edges are added for each Arc using the direction specified by source and destination. All Arcs in the model will be used whether or not they are active (since this needs to be done after expansion), and they all need to be directed.

indexes_to_arcs(*G*, *lst*)
Converts a list of edge indexes to the corresponding Arcs

Parameters

- **G** – A networkx graph corresponding to lst
- **lst** – A list of edge indexes to convert to tuples

Returns A list of arcs

run(*model*, *function*)
Compute a Pyomo Network model using sequential decomposition

Parameters

- **model** – A Pyomo model
- **function** – A function to be called on each block/node in the network

select_tear_heuristic(*G*)
This finds optimal sets of tear edges based on two criteria. The primary objective is to minimize the maximum number of times any cycle is broken. The seconday criteria is to minimize the number of tears.

This function uses a branch and bound type approach.

Returns

- *tsets* – List of lists of tear sets. All the tear sets returned are equally good. There are often a very large number of equally good tear sets.
- *upperbound_loop* – The max number of times any single loop is torn
- *upperbound_total* – The total number of loops

Improvemnts for the future

I think I can imporve the efficency of this, but it is good enough for now. Here are some ideas for improvement:

1. Reduce the number of redundant solutions. It is possible to find tears sets [1,2] and [2,1]. I eliminate redundent solutions from the results, but they can occur and it reduces efficency.

2. Look at strongly connected components instead of whole graph. This would cut back on the size of graph we are looking at. The flowsheets are rarely one strongly conneted component.

3. When you add an edge to a tear set you could reduce the size of the problem in the branch by only looking at strongly connected components with that edge removed.

4. This returns all equally good optimal tear sets. That may not really be necessary. For very large flowsheets, there could be an extremely large number of optimial tear edge sets.

`select_tear_mip`(*G*, *solver*, *solver_io=None*, *solver_options={}*)

This finds optimal sets of tear edges based on two criteria. The primary objective is to minimize the maximum number of times any cycle is broken. The seconday criteria is to minimize the number of tears.

This function creates a MIP problem in Pyomo with a doubly weighted objective and solves it with the solver arguments.

`select_tear_mip_model`(*G*)

Generate a model for selecting tears from the given graph

Returns

- *model*
- *bin_list* – A list of the binary variables representing each edge, indexed by the edge index of the graph

`set_guesses_for`(*port*, *guesses*)

Set the guesses for the given port

These guesses will be checked for all free variables that are encountered during the first pass run. If a free variable has no guess, its current value will be used. If its current value is None, the default_guess option will be used. If that is None, an error will be raised.

All port variables that are downstream of a non-tear edge will already be fixed. If there is a guess for a fixed variable, it will be silently ignored.

The guesses should be a dict that maps the following:

Port Member Name -> Value

Or, for indexed members, multiple dicts that map:

Port Member Name -> Index -> Value

For extensive members, "Value" must be a list of tuples of the form (arc, value) to guess a value for the expanded variable of the specified arc. However, if the arc connecting this port is a 1-to-1 arc with its peer, then there will be no expanded variable for the single arc, so a regular "Value" should be provided.

This dict cannot be used to pass guesses for variables within expression type members. Guesses for those variables must be assigned to the variable's current value before calling run.

While this method makes things more convenient, all it does is:

self.options["guesses"][port] = guesses

`set_tear_set`(*tset*)

Set a custom tear set to be used when running the decomposition

The procedure will use this custom tear set instead of finding its own, thus it can save some time. Additionally, this will be useful for knowing which edges will need guesses.

Parameters `tset` – A list of Arcs representing edges to tear

While this method makes things more convenient, all it does is:

self.options["tear_set"] = tset

tear_set_arcs(*G*, *method='mip'*, ***kwds*)
Call the specified tear selection method and return a list of arcs representing the selected tear edges.

The kwds will be passed to the method.

tree_order(*adj*, *adjR*, *roots=None*)
This function determines the ordering of nodes in a directed tree. This is a generic function that can operate on any given tree represented by the adjaceny and reverse adjacency lists. If the adjacency list does not represent a tree the results are not valid.

In the returned order, it is sometimes possible for more than one node to be caclulated at once. So a list of lists is returned by this function. These represent a bredth first search order of the tree. Following the order, all nodes that lead to a particular node will be visited before it.

Parameters

- **adj** – An adjeceny list for a directed tree. This uses generic integer node indexes, not node names from the graph itself. This allows this to be used on sub-graphs and graps of components more easily.
- **adjR** – The reverse adjacency list coresponing to adj
- **roots** – List of node indexes to start from. These do not need to be the root nodes of the tree, in some cases like when a node changes the changes may only affect nodes reachable in the tree from the changed node, in the case that roots are supplied not all the nodes in the tree may appear in the ordering. If no roots are supplied, the roots of the tree are used.

CHAPTER

NINE

PYOMO TUTORIAL EXAMPLES

Additional Pyomo tutorials and examples can be found at the following links:

Prof. Jeffrey Kantor's Pyomo Cookbook

Pyomo Gallery

CHAPTER

TEN

DEBUGGING PYOMO MODELS

10.1 Interrogating Pyomo Models

Show solver output by adding the *tee=True* option when calling the *solve* function

```
>>> SolverFactory('glpk').solve(model, tee=True)
```

You can use the *pprint* function to display the model or individual model components

```
>>> model.pprint()
>>> model.x.pprint()
```

10.2 FAQ

1. Solver not found

Solvers are **not** distributed with Pyomo and must be installed separately by the user. In general, the solver executable must be accessible using a terminal command. For example, ipopt can only be used as a solver if the command

```
$ ipopt
```

invokes the solver. For example

```
$ ipopt -?
usage: ipopt [options] stub [-AMPL] [<assignment> ...]

Options:
     --  {end of options}
     -=  {show name= possibilities}
     -?  {show usage}
     -bf {read boundsfile f}
     -e  {suppress echoing of assignments}
     -of {write .sol file to file f}
     -s  {write .sol file (without -AMPL)}
     -v  {just show version}
```

10.3 Getting Help

See the Pyomo Forum for online discussions of Pyomo or to ask a question:

- http://groups.google.com/group/pyomo-forum/

Ask a question on StackOverflow using the *#pyomo* tag:

- https://stackoverflow.com/questions/ask?tags=pyomo

CHAPTER

ELEVEN

ADVANCED TOPICS

11.1 Persistent Solvers

The purpose of the persistent solver interfaces is to efficiently notify the solver of incremental changes to a Pyomo model. The persistent solver interfaces create and store model instances from the Python API for the corresponding solver. For example, the *GurobiPersistent* class maintaints a pointer to a gurobipy Model object. Thus, we can make small changes to the model and notify the solver rather than recreating the entire model using the solver Python API (or rewriting an entire model file - e.g., an lp file) every time the model is solved.

Warning: Users are responsible for notifying persistent solver interfaces when changes to a model are made!

11.1.1 Using Persistent Solvers

The first step in using a persistent solver is to create a Pyomo model as usual.

```
>>> import pyomo.environ as pe
>>> m = pe.ConcreteModel()
>>> m.x = pe.Var()
>>> m.y = pe.Var()
>>> m.obj = pe.Objective(expr=m.x**2 + m.y**2)
>>> m.c = pe.Constraint(expr=m.y >= -2*m.x + 5)
```

You can create an instance of a persistent solver through the SolverFactory.

```
>>> opt = pe.SolverFactory('gurobi_persistent')
```

This returns an instance of `GurobiPersistent`. Now we need to tell the solver about our model.

```
>>> opt.set_instance(m)
```

This will create a gurobipy Model object and include the appropriate variables and constraints. We can now solve the model.

```
>>> results = opt.solve()
```

We can also add or remove variables, constraints, blocks, and objectives. For example,

```
>>> m.c2 = pe.Constraint(expr=m.y >= m.x)
>>> opt.add_constraint(m.c2)
```

This tells the solver to add one new constraint but otherwise leave the model unchanged. We can now resolve the model.

```
>>> results = opt.solve()
```

To remove a component, simply call the corresponding remove method.

```
>>> opt.remove_constraint(m.c2)
>>> del m.c2
>>> results = opt.solve()
```

If a pyomo component is replaced with another component with the same name, the first component must be removed from the solver. Otherwise, the solver will have multiple components. For example, the following code will run without error, but the solver will have an extra constraint. The solver will have both y >= -2*x + 5 and y <= x, which is not what was intended!

```
>>> m = pe.ConcreteModel()
>>> m.x = pe.Var()
>>> m.y = pe.Var()
>>> m.c = pe.Constraint(expr=m.y >= -2*m.x + 5)
>>> opt = pe.SolverFactory('gurobi_persistent')
>>> opt.set_instance(m)
>>> # WRONG:
>>> del m.c
>>> m.c = pe.Constraint(expr=m.y <= m.x)
>>> opt.add_constraint(m.c)
```

The correct way to do this is:

```
>>> m = pe.ConcreteModel()
>>> m.x = pe.Var()
>>> m.y = pe.Var()
>>> m.c = pe.Constraint(expr=m.y >= -2*m.x + 5)
>>> opt = pe.SolverFactory('gurobi_persistent')
>>> opt.set_instance(m)
>>> # Correct:
>>> opt.remove_constraint(m.c)
>>> del m.c
>>> m.c = pe.Constraint(expr=m.y <= m.x)
>>> opt.add_constraint(m.c)
```

Warning: Components removed from a pyomo model must be removed from the solver instance by the user.

Additionally, unexpected behavior may result if a component is modified before being removed.

```
>>> m = pe.ConcreteModel()
>>> m.b = pe.Block()
>>> m.b.x = pe.Var()
>>> m.b.y = pe.Var()
>>> m.b.c = pe.Constraint(expr=m.b.y >= -2*m.b.x + 5)
>>> opt = pe.SolverFactory('gurobi_persistent')
>>> opt.set_instance(m)
>>> m.b.c2 = pe.Constraint(expr=m.b.y <= m.b.x)
```

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```
>>> # ERROR: The constraint referenced by m.b.c2 does not
>>> # exist in the solver model.
>>> opt.remove_block(m.b)
```

In most cases, the only way to modify a component is to remove it from the solver instance, modify it with Pyomo, and then add it back to the solver instance. The only exception is with variables. Variables may be modified and then updated with with solver:

```
>>> m = pe.ConcreteModel()
>>> m.x = pe.Var()
>>> m.y = pe.Var()
>>> m.obj = pe.Objective(expr=m.x**2 + m.y**2)
>>> m.c = pe.Constraint(expr=m.y >= -2*m.x + 5)
>>> opt = pe.SolverFactory('gurobi_persistent')
>>> opt.set_instance(m)
>>> m.x.setlb(1.0)
>>> opt.update_var(m.x)
```

11.1.2 Working with Indexed Variables and Constraints

The examples above all used simple variables and constraints; in order to use indexed variables and/or constraints, the code must be slightly adapted:

```
>>> for v in indexed_var.values():
...     opt.add_var(v)
>>> for v in indexed_con.values():
...     opt.add_constraint(v)
```

This must be done when removing variables/constraints, too. Not doing this would result in AttributeError exceptions, for example:

```
>>> opt.add_var(indexed_var)
>>> # ERROR: AttributeError: 'IndexedVar' object has no attribute 'is_binary'
>>> opt.add_constraint(indexed_con)
>>> # ERROR: AttributeError: 'IndexedConstraint' object has no attribute 'body'
```

The method “is_indexed” can be used to automate the process, for example:

```
>>> def add_variable(opt, variable):
...     if variable.is_indexed():
...         for v in variable.values():
...             opt.add_var(v)
...     else:
...         opt.add_var(v)
```

11.1.3 Persistent Solver Performance

In order to get the best performance out of the persistent solvers, use the "save_results" flag:

```
>>> import pyomo.environ as pe
>>> m = pe.ConcreteModel()
>>> m.x = pe.Var()
>>> m.y = pe.Var()
>>> m.obj = pe.Objective(expr=m.x**2 + m.y**2)
>>> m.c = pe.Constraint(expr=m.y >= -2*m.x + 5)
>>> opt = pe.SolverFactory('gurobi_persistent')
>>> opt.set_instance(m)
>>> results = opt.solve(save_results=False)
```

Note that if the "save_results" flag is set to False, then the following is not supported.

```
>>> results = opt.solve(save_results=False, load_solutions=False)
>>> if results.solver.termination_condition == TerminationCondition.optimal:
...     m.solutions.load_from(results)
```

However, the following will work:

```
>>> results = opt.solve(save_results=False, load_solutions=False)
>>> if results.solver.termination_condition == TerminationCondition.optimal:
...     opt.load_vars()
```

Additionally, a subset of variable values may be loaded back into the model:

```
>>> results = opt.solve(save_results=False, load_solutions=False)
>>> if results.solver.termination_condition == TerminationCondition.optimal:
...     opt.load_vars(m.x)
```

11.2 Units Handling in Pyomo

Pyomo Units Container Module

This module provides support for including units within Pyomo expressions. This module can be used to define units on a model, and to check the consistency of units within the underlying constraints and expressions in the model. The module also supports conversion of units within expressions using the *convert* method to support construction of constraints that contain embedded unit conversions.

To use this package within your Pyomo model, you first need an instance of a PyomoUnitsContainer. You can use the module level instance already defined as 'units'. This object 'contains' the units - that is, you can access units on this module using common notation.

```
>>> from pyomo.environ import units as u
>>> print(3.0*u.kg)
3.0*kg
```

Units can be assigned to Var, Param, and ExternalFunction components, and can be used directly in expressions (e.g., defining constraints). You can also verify that the units are consistent on a model, or on individual components like the objective function, constraint, or expression using *assert_units_consistent* (from pyomo.util.check_units). There are other methods there that may be helpful for verifying correct units on a model.

```
>>> from pyomo.environ import ConcreteModel, Var, Objective
>>> from pyomo.environ import units as u
>>> from pyomo.util.check_units import assert_units_consistent, assert_units_
↪equivalent, check_units_equivalent
>>> model = ConcreteModel()
>>> model.acc = Var(initialize=5.0, units=u.m/u.s**2)
>>> model.obj = Objective(expr=(model.acc - 9.81*u.m/u.s**2)**2)
>>> assert_units_consistent(model.obj) # raise exc if units invalid on obj
>>> assert_units_consistent(model) # raise exc if units invalid anywhere on␣
↪the model
>>> assert_units_equivalent(model.obj.expr, u.m**2/u.s**4) # raise exc if␣
↪units not equivalent
>>> print(u.get_units(model.obj.expr)) # print the units on the objective
m**2/s**4
>>> print(check_units_equivalent(model.acc, u.m/u.s**2))
True
```

The implementation is currently based on the pint package and supports all the units that are supported by pint. The list of units that are supported by pint can be found at the following url: https://github.com/hgrecco/pint/blob/master/pint/default_en.txt.

If you need a unit that is not in the standard set of defined units, you can create your own units by adding to the unit definitions within pint. See *PyomoUnitsContainer.load_definitions_from_file()* or *PyomoUnitsContainer.load_definitions_from_strings()* for more information.

Note: In this implementation of units, "offset" units for temperature are not supported within expressions (i.e. the non-absolute temperature units including degrees C and degrees F). This is because there are many non-obvious combinations that are not allowable. This concern becomes clear if you first convert the non-absolute temperature units to absolute and then perform the operation. For example, if you write 30 degC + 30 degC == 60 degC, but convert each entry to Kelvin, the expression is not true (i.e., 303.15 K + 303.15 K is not equal to 333.15 K). Therefore, there are several operations that are not allowable with non-absolute units, including addition, multiplication, and division.

This module does support conversion of offset units to absolute units numerically, using convert_value_K_to_C, convert_value_C_to_K, convert_value_R_to_F, convert_value_F_to_R. These are useful for converting input data to absolute units, and for converting data to convenient units for reporting.

Please see the pint documentation here for more discussion. While pint implements "delta" units (e.g., delta_degC) to support correct unit conversions, it can be difficult to identify and guarantee valid operations in a general algebraic modeling environment. While future work may support units with relative scale, the current implementation requires use of absolute temperature units (i.e. K and R) within expressions and a direct conversion of numeric values using specific functions for converting input data and reporting.

---

class pyomo.core.base.units_container.**PyomoUnitsContainer**

Bases: `object`

Class that is used to create and contain units in Pyomo.

This is the class that is used to create, contain, and interact with units in Pyomo. The module (*pyomo.core.base.units_container*) also contains a module level units container `units` that is an instance of a PyomoUnitsContainer. This module instance should typically be used instead of creating your own instance of a *PyomoUnitsContainer*. For an overview of the usage of this class, see the module documentation (*pyomo.core.base.units_container*)

This class is based on the "pint" module. Documentation for available units can be found at the following url: https://github.com/hgrecco/pint/blob/master/pint/default_en.txt

Note: Pre-defined units can be accessed through attributes on the PyomoUnitsContainer class; however, these attributes are created dynamically through the __getattr__ method, and are not present on the class until they are requested.

convert(*src*, *to_units=None*)
This method returns an expression that contains the explicit conversion from one unit to another.

Parameters

- **src** (*Pyomo expression*) – The source value that will be converted. This could be a Pyomo Var, Pyomo Param, or a more complex expression.
- **to_units** (*Pyomo units expression*) – The desired target units for the new expression

Returns ret

Return type Pyomo expression

convert_temp_C_to_K(*value_in_C*)
Convert a value in degrees Celcius to Kelvin Note that this method converts a numerical value only. If you need temperature conversions in expressions, please work in absolute temperatures only.

convert_temp_F_to_R(*value_in_F*)
Convert a value in degrees Fahrenheit to Rankine. Note that this method converts a numerical value only. If you need temperature conversions in expressions, please work in absolute temperatures only.

convert_temp_K_to_C(*value_in_K*)
Convert a value in Kelvin to degrees Celcius. Note that this method converts a numerical value only. If you need temperature conversions in expressions, please work in absolute temperatures only.

convert_temp_R_to_F(*value_in_R*)
Convert a value in Rankine to degrees Fahrenheit. Note that this method converts a numerical value only. If you need temperature conversions in expressions, please work in absolute temperatures only.

convert_value(*num_value*, *from_units=None*, *to_units=None*)
This method performs explicit conversion of a numerical value from one unit to another, and returns the new value.

The argument "num_value" must be a native numeric type (e.g. float). Note that this method returns a numerical value only, and not an expression with units.

Parameters

- **num_value** (*float or other native numeric type*) – The value that will be converted
- **from_units** (*Pyomo units expression*) – The units to convert from
- **to_units** (*Pyomo units expression*) – The units to convert to

Returns float

Return type The converted value

get_units(*expr*)
Return the Pyomo units corresponding to this expression (also performs validation and will raise an exception if units are not consistent).

Parameters **expr** (*Pyomo expression*) – The expression containing the desired units

Returns Returns the units corresponding to the expression

Return type Pyomo unit (*expression*)

Raises *pyomo.core.base.units_container.UnitsError* –

load_definitions_from_file(*definition_file*)
Load new units definitions from a file

This method loads additional units definitions from a user specified definition file. An example of a definitions file can be found at: https://github.com/hgrecco/pint/blob/master/pint/default_en.txt

If we have a file called `my_additional_units.txt` with the following lines:

```
USD = [currency]
```

Then we can add this to the container with:

```
>>> u.load_definitions_from_file('my_additional_units.txt')
>>> print(u.USD)
USD
```

load_definitions_from_strings(*definition_string_list*)
Load new units definitions from a string

This method loads additional units definitions from a list of strings (one for each line). An example of the definitions strings can be found at: https://github.com/hgrecco/pint/blob/master/pint/default_en.txt

For example, to add the currency dimension and US dollars as a unit, use

```
>>> u.load_definitions_from_strings(['USD = [currency]'])
>>> print(u.USD)
USD
```

class pyomo.core.base.units_container.**UnitsError**(*msg*)
An exception class for all general errors/warnings associated with units

class pyomo.core.base.units_container.**InconsistentUnitsError**(*exp1*, *exp2*, *msg*)
An exception indicating that inconsistent units are present on an expression.

E.g., x == y, where x is in units of kg and y is in units of meter

11.3 LinearExpression

Significant speed improvements can be obtained using the `LinearExpression` object when there are long, dense, linear expressions. The arguments are

```
constant, linear_coeffs, linear_vars
```

where the second and third arguments are lists that must be of the same length. Here is a simple example that illustrates the syntax. This example creates two constraints that are the same:

```
>>> import pyomo.environ as pyo
>>> from pyomo.core.expr.numeric_expr import LinearExpression
>>> model = pyo.ConcreteModel()
>>> model.nVars = pyo.Param(initialize=4)
>>> model.N = pyo.RangeSet(model.nVars)
>>> model.x = pyo.Var(model.N, within=pyo.Binary)
>>>
>>> model.coefs = [1, 1, 3, 4]
```

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```
>>>
>>> model.linexp = LinearExpression(constant=0,
...                                 linear_coefs=model.coefs,
...                                 linear_vars=[model.x[i] for i in model.N])
>>> def caprule(m):
...     return m.linexp <= 6
>>> model.capme = pyo.Constraint(rule=caprule)
>>>
>>> def caprule2(m):
...     return sum(model.coefs[i-1]*model.x[i] for i in model.N) <= 6
>>> model.capme2 = pyo.Constraint(rule=caprule2)
```

Warning: The lists that are passed to `LinearModel` are not copied, so caution must be excercised if they are modified after the component is constructed.

CHAPTER

TWELVE

DEVELOPER REFERENCE

This section provides documentation about fundamental capabilities in Pyomo. This documentation serves as a reference for both (1) Pyomo developers and (2) advanced users who are developing Python scripts using Pyomo.

12.1 The Pyomo Configuration System

The Pyomo config system provides a set of three classes (*ConfigDict*, *ConfigList*, and *ConfigValue*) for managing and documenting structured configuration information and user input. The system is based around the ConfigValue class, which provides storage for a single configuration entry. ConfigValue objects can be grouped using two containers (ConfigDict and ConfigList), which provide functionality analogous to Python's dict and list classes, respectively.

At its simplest, the Config system allows for developers to specify a dictionary of documented configuration entries, allow users to provide values for those entries, and retrieve the current values:

```
>>> from pyomo.common.config import (
...     ConfigDict, ConfigList, ConfigValue, In,
... )
>>> config = ConfigDict()
>>> config.declare('filename', ConfigValue(
...     default=None,
...     domain=str,
...     description="Input file name",
... ))
<pyomo.common.config.ConfigValue object at ...>
>>> config.declare("bound tolerance", ConfigValue(
...     default=1E-5,
...     domain=float,
...     description="Bound tolerance",
...     doc="Relative tolerance for bound feasibility checks"
... ))
<pyomo.common.config.ConfigValue object at ...>
>>> config.declare("iteration limit", ConfigValue(
...     default=30,
...     domain=int,
...     description="Iteration limit",
...     doc="Number of maximum iterations in the decomposition methods"
... ))
<pyomo.common.config.ConfigValue object at ...>
>>> config['filename'] = 'tmp.txt'
>>> print(config['filename'])
```

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```
tmp.txt
>>> print(config['iteration limit'])
30
```

For convenience, ConfigDict objects support read/write access via attributes (with spaces in the declaration names replaced by underscores):

```
>>> print(config.filename)
tmp.txt
>>> print(config.iteration_limit)
30
>>> config.iteration_limit = 20
>>> print(config.iteration_limit)
20
```

12.1.1 Domain validation

All Config objects support a `domain` keyword that accepts a callable object (type, function, or callable instance). The domain callable should take data and map it onto the desired domain, optionally performing domain validation (see *ConfigValue*, *ConfigDict*, and *ConfigList* for more information). This allows client code to accept a very flexible set of inputs without "cluttering" the code with input validation:

```
>>> config.iteration_limit = 35.5
>>> print(config.iteration_limit)
35
>>> print(type(config.iteration_limit).__name__)
int
```

In addition to common types (like `int`, `float`, `bool`, and `str`), the config system profides a number of custom domain validators for common use cases:

PositiveInt(val)	Domain validation function admitting strictly positive integers
NegativeInt(val)	Domain validation function admitting strictly negative integers
NonNegativeInt(val)	Domain validation function admitting integers >= 0
NonPositiveInt(val)	Domain validation function admitting integers <= 0
PositiveFloat(val)	Domain validation function admitting strictly positive numbers
NegativeFloat(val)	Domain validation function admitting strictly negative numbers
NonPositiveFloat(val)	Domain validation function admitting numbers less than or equal to 0
NonNegativeFloat(val)	Domain validation function admitting numbers greater than or equal to 0
In(domain[, cast])	Domain validation class admitting a Container of possible values
InEnum(domain)	Domain validation class admitting an enum value/name.
Path([basePath, expandPath])	Domain validator for path-like options.
PathList([basePath, expandPath])	Domain validator for a list of path-like objects.

12.1.2 Configuring class hierarchies

A feature of the Config system is that the core classes all implement `__call__`, and can themselves be used as `domain` values. Beyond providing domain verification for complex hierarchical structures, this feature allows ConfigDicts to cleanly support the configuration of derived objects. Consider the following example:

```
>>> class Base(object):
...     CONFIG = ConfigDict()
...     CONFIG.declare('filename', ConfigValue(
...         default='input.txt',
...         domain=str,
...     ))
...     def __init__(self, **kwds):
...         c = self.CONFIG(kwds)
...         c.display()
...
>>> class Derived(Base):
...     CONFIG = Base.CONFIG()
...     CONFIG.declare('pattern', ConfigValue(
...         default=None,
...         domain=str,
...     ))
...
>>> tmp = Base(filename='foo.txt')
filename: foo.txt
>>> tmp = Derived(pattern='.*warning')
filename: input.txt
pattern: .*warning
```

Here, the base class `Base` declares a class-level attribute CONFIG as a ConfigDict containing a single entry (`filename`). The derived class (`Derived`) then starts by making a copy of the base class' `CONFIG`, and then defines an additional entry (*pattern*). Instances of the base class will still create `c` instances that only have the single `filename` entry, whereas instances of the derived class will have `c` instances with two entries: the `pattern` entry declared by the derived class, and the `filename` entry "inherited" from the base class.

An extension of this design pattern provides a clean approach for handling "ephemeral" instance options. Consider an interface to an external "solver". Our class implements a `solve()` method that takes a problem and sends it to the solver along with some solver configuration options. We would like to be able to set those options "persistently" on instances of the interface class, but still override them "temporarily" for individual calls to `solve()`. We implement this by creating copies of the class's configuration for both specific instances and for use by each `solve()` call:

```
>>> class Solver(object):
...     CONFIG = ConfigDict()
...     CONFIG.declare('iterlim', ConfigValue(
...         default=10,
...         domain=int,
...     ))
...     def __init__(self, **kwds):
...         self.config = self.CONFIG(kwds)
...     def solve(self, model, **options):
...         config = self.config(options)
...         # Solve the model with the specified iterlim
...         config.display()
...
```

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```
>>> solver = Solver()
>>> solver.solve(None)
iterlim: 10
>>> solver.config.iterlim = 20
>>> solver.solve(None)
iterlim: 20
>>> solver.solve(None, iterlim=50)
iterlim: 50
>>> solver.solve(None)
iterlim: 20
```

12.1.3 Interacting with argparse

In addition to basic storage and retrieval, the Config system provides hooks to the argparse command-line argument parsing system. Individual Config entries can be declared as argparse arguments using the *declare_as_argument()* method. To make declaration simpler, the `declare()` method returns the declared Config object so that the argument declaration can be done inline:

```
>>> import argparse
>>> config = ConfigDict()
>>> config.declare('iterlim', ConfigValue(
...     domain=int,
...     default=100,
...     description="iteration limit",
... )).declare_as_argument()
<pyomo.common.config.ConfigValue object at ...>
>>> config.declare('lbfgs', ConfigValue(
...     domain=bool,
...     description="use limited memory BFGS update",
... )).declare_as_argument()
<pyomo.common.config.ConfigValue object at ...>
>>> config.declare('linesearch', ConfigValue(
...     domain=bool,
...     default=True,
...     description="use line search",
... )).declare_as_argument()
<pyomo.common.config.ConfigValue object at ...>
>>> config.declare('relative tolerance', ConfigValue(
...     domain=float,
...     description="relative convergence tolerance",
... )).declare_as_argument('--reltol', '-r', group='Tolerances')
<pyomo.common.config.ConfigValue object at ...>
>>> config.declare('absolute tolerance', ConfigValue(
...     domain=float,
...     description="absolute convergence tolerance",
... )).declare_as_argument('--abstol', '-a', group='Tolerances')
<pyomo.common.config.ConfigValue object at ...>
```

The ConfigDict can then be used to initialize (or augment) an argparse ArgumentParser object:

```
>>> parser = argparse.ArgumentParser("tester")
>>> config.initialize_argparse(parser)
```

Key information from the ConfigDict is automatically transferred over to the ArgumentParser object:

```
>>> print(parser.format_help())
usage: tester [-h] [--iterlim INT] [--lbfgs] [--disable-linesearch]
              [--reltol FLOAT] [--abstol FLOAT]

optional arguments:
  -h, --help            show this help message and exit
  --iterlim INT         iteration limit
  --lbfgs               use limited memory BFGS update
  --disable-linesearch  [DON'T] use line search

Tolerances:
  --reltol FLOAT, -r FLOAT
                        relative convergence tolerance
  --abstol FLOAT, -a FLOAT
                        absolute convergence tolerance
```

Parsed arguments can then be imported back into the ConfigDict:

```
>>> args=parser.parse_args(['--lbfgs', '--reltol', '0.1', '-a', '0.2'])
>>> args = config.import_argparse(args)
>>> config.display()
iterlim: 100
lbfgs: true
linesearch: true
relative tolerance: 0.1
absolute tolerance: 0.2
```

12.1.4 Accessing user-specified values

It is frequently useful to know which values a user explicitly set, and which values a user explicitly set but have never been retrieved. The configuration system provides two generator methods to return the items that a user explicitly set (`user_values()`) and the items that were set but never retrieved (`unused_user_values()`):

```
>>> print([val.name() for val in config.user_values()])
['lbfgs', 'relative tolerance', 'absolute tolerance']
>>> print(config.relative_tolerance)
0.1
>>> print([val.name() for val in config.unused_user_values()])
['lbfgs', 'absolute tolerance']
```

12.1.5 Generating output & documentation

Configuration objects support three methods for generating output and documentation: `display()`, `generate_yaml_template()`, and `generate_documentation()`. The simplest is `display()`, which prints out the current values of the configuration object (and if it is a container type, all of it's children). `generate_yaml_template()` is simular to `display()`, but also includes the description fields as formatted comments.

```
>>> solver_config = config
>>> config = ConfigDict()
>>> config.declare('output', ConfigValue(
...     default='results.yml',
...     domain=str,
...     description='output results filename'
... ))
<pyomo.common.config.ConfigValue object at ...>
>>> config.declare('verbose', ConfigValue(
...     default=0,
...     domain=int,
...     description='output verbosity',
...     doc='This sets the system verbosity.  The default (0) only logs '
...     'warnings and errors.  Larger integer values will produce '
...     'additional log messages.',
... ))
<pyomo.common.config.ConfigValue object at ...>
>>> config.declare('solvers', ConfigList(
...     domain=solver_config,
...     description='list of solvers to apply',
... ))
<pyomo.common.config.ConfigList object at ...>
>>> config.display()
output: results.yml
verbose: 0
solvers: []
>>> print(config.generate_yaml_template())
output: results.yml  # output results filename
verbose: 0           # output verbosity
solvers: []          # list of solvers to apply
```

It is important to note that both methods document the current state of the configuration object. So, in the example above, since the *solvers* list is empty, you will not get any information on the elements in the list. Of course, if you add a value to the list, then the data will be output:

```
>>> tmp = config()
>>> tmp.solvers.append({})
>>> tmp.display()
output: results.yml
verbose: 0
solvers:
  -
    iterlim: 100
    lbfgs: true
    linesearch: true
    relative tolerance: 0.1
```

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```
    absolute tolerance: 0.2
>>> print(tmp.generate_yaml_template())
output: results.yml          # output results filename
verbose: 0                   # output verbosity
solvers:                     # list of solvers to apply
  -
    iterlim: 100             # iteration limit
    lbfgs: true              # use limited memory BFGS update
    linesearch: true         # use line search
    relative tolerance: 0.1  # relative convergence tolerance
    absolute tolerance: 0.2  # absolute convergence tolerance
```

The third method (`generate_documentation()`) behaves differently. This method is designed to generate reference documentation. For each configuration item, the *doc* field is output. If the item has no *doc*, then the *description* field is used.

List containers have their *domain* documented and not their current values. The documentation can be configured through optional arguments. The defaults generate LaTeX documentation:

```
>>> print(config.generate_documentation())
\begin{description}[topsep=0pt,parsep=0.5em,itemsep=-0.4em]
  \item[{output}]\hfill
    \\output results filename
  \item[{verbose}]\hfill
    \\This sets the system verbosity.  The default (0) only logs warnings and
    errors.  Larger integer values will produce additional log messages.
  \item[{solvers}]\hfill
    \\list of solvers to apply
  \begin{description}[topsep=0pt,parsep=0.5em,itemsep=-0.4em]
    \item[{iterlim}]\hfill
      \\iteration limit
    \item[{lbfgs}]\hfill
      \\use limited memory BFGS update
    \item[{linesearch}]\hfill
      \\use line search
    \item[{relative tolerance}]\hfill
      \\relative convergence tolerance
    \item[{absolute tolerance}]\hfill
      \\absolute convergence tolerance
  \end{description}
\end{description}
```

12.2 Pyomo Expressions

Warning: This documentation does not explicitly reference objects in pyomo.core.kernel. While the Pyomo5 expression system works with pyomo.core.kernel objects, the documentation of these documents was not sufficient to appropriately descibe the use of kernel objects in expressions.

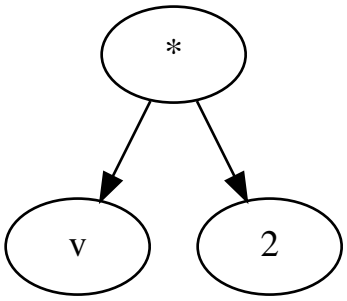
Pyomo supports the declaration of symbolic expressions that represent objectives, constraints and other optimization modeling components. Pyomo expressions are represented in an expression tree, where the leaves are operands, such as

constants or variables, and the internal nodes contain operators. Pyomo relies on so-called magic methods to automate the construction of symbolic expressions. For example, consider an expression `e` declared as follows:

```
M = ConcreteModel()
M.v = Var()

e = M.v*2
```

Python determines that the magic method `__mul__` is called on the `M.v` object, with the argument `2`. This method returns a Pyomo expression object `ProductExpression` that has arguments `M.v` and `2`. This represents the following symbolic expression tree:



Note: End-users will not likely need to know details related to how symbolic expressions are generated and managed in Pyomo. Thus, most of the following documentation of expressions in Pyomo is most useful for Pyomo developers. However, the discussion of runtime performance in the first section will help end-users write large-scale models.

12.2.1 Building Expressions Faster

Expression Generation

Pyomo expressions can be constructed using native binary operators in Python. For example, a sum can be created in a simple loop:

```
M = ConcreteModel()
M.x = Var(range(5))

s = 0
for i in range(5):
    s = s + M.x[i]
```

Additionally, Pyomo expressions can be constructed using functions that iteratively apply Python binary operators. For example, the Python `sum()` function can be used to replace the previous loop:

```
s = sum(M.x[i] for i in range(5))
```

The `sum()` function is both more compact and more efficient. Using `sum()` avoids the creation of temporary variables, and the summation logic is executed in the Python interpreter while the loop is interpreted.

Linear, Quadratic and General Nonlinear Expressions

Pyomo can express a very wide range of algebraic expressions, and there are three general classes of expressions that are recognized by Pyomo:

- **linear polynomials**
- **quadratic polynomials**
- **nonlinear expressions**, including higher-order polynomials and expressions with intrinsic functions

These classes of expressions are leveraged to efficiently generate compact representations of expressions, and to transform expression trees into standard forms used to interface with solvers. Note that There not all quadratic polynomials are recognized by Pyomo; in other words, some quadratic expressions are treated as nonlinear expressions.

For example, consider the following quadratic polynomial:

```
s = sum(M.x[i] for i in range(5))**2
```

This quadratic polynomial is treated as a nonlinear expression unless the expression is explicilty processed to identify quadratic terms. This *lazy* identification of of quadratic terms allows Pyomo to tailor the search for quadratic terms only when they are explicitly needed.

Pyomo Utility Functions

Pyomo includes several similar functions that can be used to create expressions:

prod A function to compute a product of Pyomo expressions.

quicksum A function to efficiently compute a sum of Pyomo expressions.

sum_product A function that computes a generalized dot product.

prod

The *prod* function is analogous to the builtin `sum()` function. Its main argument is a variable length argument list, `args`, which represents expressions that are multiplied together. For example:

```
M = ConcreteModel()
M.x = Var(range(5))
M.z = Var()

# The product M.x[0] * M.x[1] * ... * M.x[4]
e1 = prod(M.x[i] for i in M.x)

# The product M.x[0]*M.z
e2 = prod([M.x[0], M.z])

# The product M.z*(M.x[0] + ... + M.x[4])
e3 = prod([sum(M.x[i] for i in M.x), M.z])
```

quicksum

The behavior of the *quicksum* function is similar to the builtin `sum()` function, but this function often generates a more compact Pyomo expression. Its main argument is a variable length argument list, `args`, which represents expressions that are summed together. For example:

```
M = ConcreteModel()
M.x = Var(range(5))

# Summation using the Python sum() function
e1 = sum(M.x[i]**2 for i in M.x)

# Summation using the Pyomo quicksum function
e2 = quicksum(M.x[i]**2 for i in M.x)
```

The summation is customized based on the `start` and `linear` arguments. The `start` defines the initial value for summation, which defaults to zero. If `start` is a numeric value, then the `linear` argument determines how the sum is processed:

- If `linear` is `False`, then the terms in `args` are assumed to be nonlinear.
- If `linear` is `True`, then the terms in `args` are assumed to be linear.
- If `linear` is `None`, the first term in `args` is analyze to determine whether the terms are linear or nonlinear.

This argument allows the *quicksum* function to customize the expression representation used, and specifically a more compact representation is used for linear polynomials. The *quicksum* function can be slower than the builtin `sum()` function, but this compact representation can generate problem representations more quickly.

Consider the following example:

```
M = ConcreteModel()
M.A = RangeSet(100000)
M.p = Param(M.A, mutable=True, initialize=1)
M.x = Var(M.A)

start = time.time()
e = sum( (M.x[i] - 1)**M.p[i] for i in M.A)
print("sum:      %f" % (time.time() - start))

start = time.time()
generate_standard_repn(e)
print("repn:     %f" % (time.time() - start))

start = time.time()
e = quicksum( (M.x[i] - 1)**M.p[i] for i in M.A)
print("quicksum: %f" % (time.time() - start))

start = time.time()
generate_standard_repn(e)
print("repn:     %f" % (time.time() - start))
```

The sum consists of linear terms because the exponents are one. The following output illustrates that quicksum can identify this linear structure to generate expressions more quickly:

```
sum:      1.447861
repn:     0.870225
quicksum: 1.388344
repn:     0.864316
```

If `start` is not a numeric value, then the *quicksum* sets the initial value to `start` and executes a simple loop to sum the terms. This allows the sum to be stored in an object that is passed into the function (e.g. the linear context manager *linear_expression*).

Warning: By default, `linear` is `None`. While this allows for efficient expression generation in normal cases, there are circumstances where the inspection of the first term in `args` is misleading. Consider the following example:

```
M = ConcreteModel()
M.x = Var(range(5))

e = quicksum(M.x[i]**2 if i > 0 else M.x[i] for i in range(5))
```

The first term created by the generator is linear, but the subsequent terms are nonlinear. Pyomo gracefully transitions to a nonlinear sum, but in this case *quicksum* is doing additional work that is not useful.

sum_product

The *sum_product* function supports a generalized dot product. The `args` argument contains one or more components that are used to create terms in the summation. If the `args` argument contains a single components, then its sequence of terms are summed together; the sum is equivalent to calling *quicksum*. If two or more components are provided, then the result is the summation of their terms multiplied together. For example:

```
M = ConcreteModel()
M.z = RangeSet(5)
M.x = Var(range(10))
M.y = Var(range(10))

# Sum the elements of x
e1 = sum_product(M.x)

# Sum the product of elements in x and y
e2 = sum_product(M.x, M.y)

# Sum the product of elements in x and y, over the index set z
e3 = sum_product(M.x, M.y, index=M.z)
```

The `denom` argument specifies components whose terms are in the denominator. For example:

```
# Sum the product of x_i/y_i
e1 = sum_product(M.x, denom=M.y)

# Sum the product of 1/(x_i*y_i)
e2 = sum_product(denom=(M.x, M.y))
```

The terms summed by this function are explicitly specified, so *sum_product* can identify whether the resulting expression is linear, quadratic or nonlinear. Consequently, this function is typically faster than simple loops, and it generates compact representations of expressions..

Finally, note that the *dot_product* function is an alias for *sum_product*.

12.2.2 Design Overview

Historical Comparison

This document describes the "Pyomo5" expressions, which were introduced in Pyomo 5.6. The main differences between "Pyomo5" expressions and the previous expression system, called "Coopr3", are:

- Pyomo5 supports both CPython and PyPy implementations of Python, while Coopr3 only supports CPython.

  The key difference in these implementations is that Coopr3 relies on CPython reference counting, which is not part of the Python language standard. Hence, this implementation is not guaranteed to run on other implementations of Python.

  Pyomo5 does not rely on reference counting, and it has been tested with PyPy. In the future, this should allow Pyomo to support other Python implementations (e.g. Jython).

- Pyomo5 expression objects are immutable, while Coopr3 expression objects are mutable.

  This difference relates to how expression objects are managed in Pyomo. Once created, Pyomo5 expression objects cannot be changed. Further, the user is guaranteed that no "side effects" occur when expressions change at a later point in time. By contrast, Coopr3 allows expressions to change in-place, and thus "side effects" make occur when expressions are changed at a later point in time. (See discussion of entanglement below.)

- Pyomo5 provides more consistent runtime performance than Coopr3.

  While this documentation does not provide a detailed comparison of runtime performance between Coopr3 and Pyomo5, the following performance considerations also motivated the creation of Pyomo5:

  - There were surprising performance inconsistencies in Coopr3. For example, the following two loops had dramatically different runtime:

    ```
    M = ConcreteModel()
    M.x = Var(range(100))

    # This loop is fast.
    e = 0
    for i in range(100):
        e = e + M.x[i]

    # This loop is slow.
    e = 0
    for i in range(100):
        e = M.x[i] + e
    ```

  - Coopr3 eliminates side effects by automatically cloning sub-expressions. Unfortunately, this can easily lead to unexpected cloning in models, which can dramatically slow down Pyomo model generation. For example:

    ```
    M = ConcreteModel()
    M.p = Param(initialize=3)
    M.q = 1/M.p
    ```

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```
M.x = Var(range(100))

# The value M.q is cloned every time it is used.
e = 0
for i in range(100):
    e = e + M.x[i]*M.q
```

– Coopr3 leverages recursion in many operations, including expression cloning. Even simple non-linear expressions can result in deep expression trees where these recursive operations fail because Python runs out of stack space.

– The immutable representation used in Pyomo5 requires more memory allocations than Coopr3 in simple loops. Hence, a pure-Python execution of Pyomo5 can be 10% slower than Coopr3 for model construction. But when Cython is used to optimize the execution of Pyomo5 expression generation, the runtimes for Pyomo5 and Coopr3 are about the same. (In principle, Cython would improve the runtime of Coopr3 as well, but the limitations noted above motivated a new expression system in any case.)

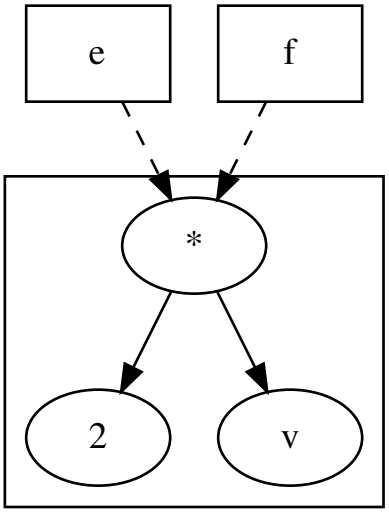
Expression Entanglement and Mutability

Pyomo fundamentally relies on the use of magic methods in Python to generate expression trees, which means that Pyomo has very limited control for how expressions are managed in Python. For example:

- Python variables can point to the same expression tree

```
M = ConcreteModel()
M.v = Var()

e = f = 2*M.v
```

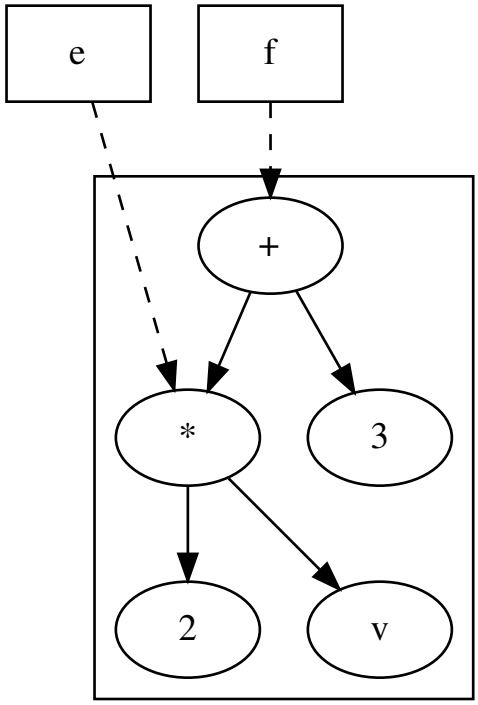
This is illustrated as follows:



- A variable can point to a sub-tree that another variable points to

```
M = ConcreteModel()
M.v = Var()

e = 2*M.v
f = e + 3
```

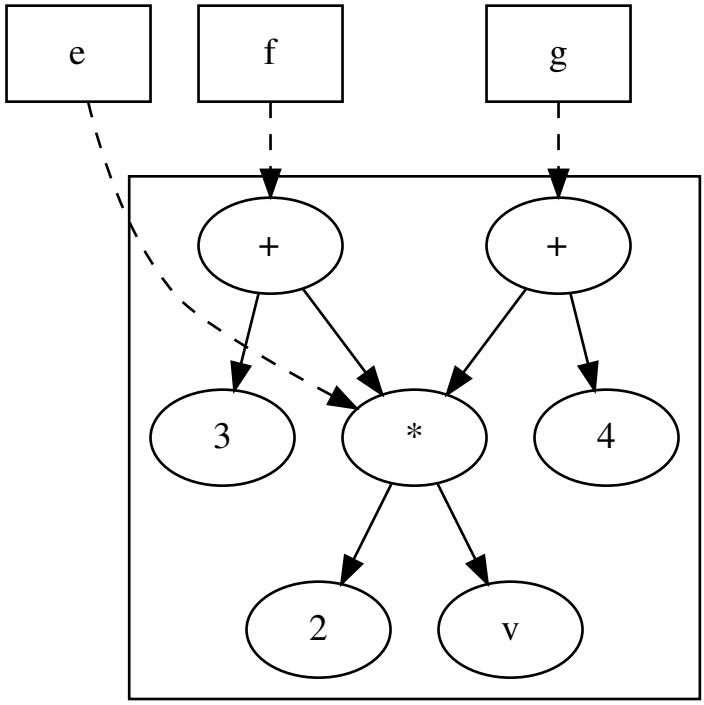
This is illustrated as follows:



- Two expression trees can point to the same sub-tree

```
M = ConcreteModel()
M.v = Var()

e = 2*M.v
f = e + 3
g = e + 4
```

This is illustrated as follows:



In each of these examples, it is almost impossible for a Pyomo user or developer to detect whether expressions are being shared. In CPython, the reference counting logic can support this to a limited degree. But no equivalent mechanisms are available in PyPy and other Python implementations.

Entangled Sub-Expressions

We say that expressions are *entangled* if they share one or more sub-expressions. The first example above does not represent entanglement, but rather the fact that multiple Python variables can point to the same expression tree. In the second and third examples, the expressions are entangled because the subtree represented by `e` is shared. However, if a leave node like `M.v` is shared between expressions, we do not consider those expressions entangled.

Expression entanglement is problematic because shared expressions complicate the expected behavior when sub-expressions are changed. Consider the following example:

```
M = ConcreteModel()
M.v = Var()
M.w = Var()

e = 2*M.v
f = e + 3

e += M.w
```

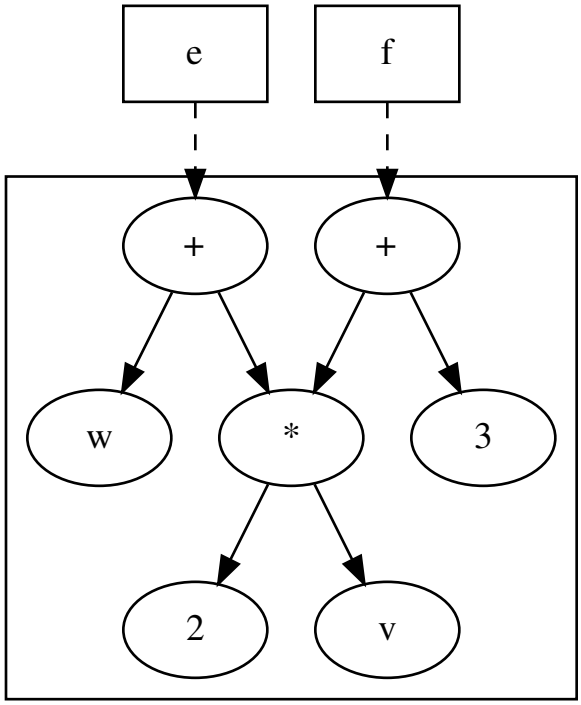
What is the value of `e` after `M.w` is added to it? What is the value of `f`? The answers to these questions are not

immediately obvious, and the fact that Coopr3 uses mutable expression objects makes them even less clear. However, Pyomo5 and Coopr3 enforce the following semantics:

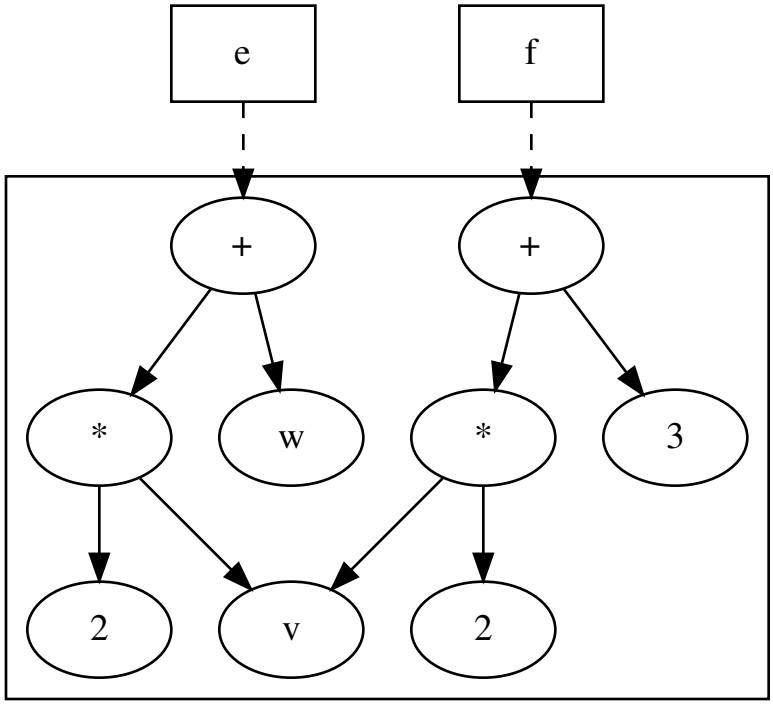
> A change to an expression *e* that is a sub-expression of *f* does not change the expression tree for *f*.

This property ensures a change to an expression does not create side effects that change the values of other, previously defined expressions.

For instance, the previous example results in the following (in Pyomo5):



With Pyomo5 expressions, each sub-expression is immutable. Thus, the summation operation generates a new expression `e` without changing existing expression objects referenced in the expression tree for `f`. By contrast, Coopr3 imposes the same property by cloning the expression `e` before added `M.w`, resulting in the following:



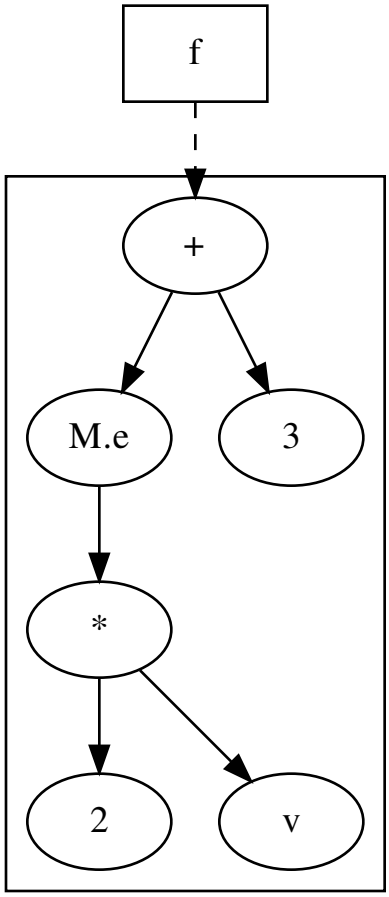
This example also illustrates that leaves may be shared between expressions.

Mutable Expression Components

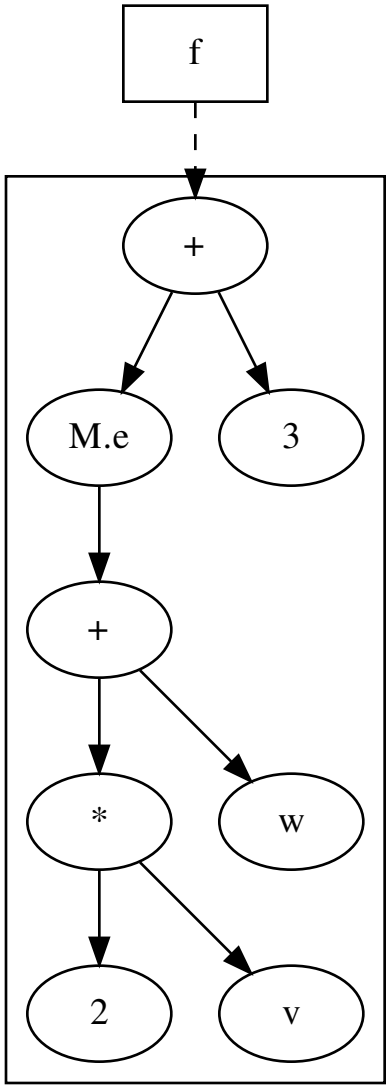
There is one important exception to the entanglement property described above. The `Expression` component is treated as a mutable expression when shared between expressions. For example:

```
M = ConcreteModel()
M.v = Var()
M.w = Var()

M.e = Expression(expr=2*M.v)
f = M.e + 3

M.e += M.w
```

Here, the expression `M.e` is a so-called *named expression* that the user has declared. Named expressions are explicitly intended for re-use within models, and they provide a convenient mechanism for changing sub-expressions in complex applications. In this example, the expression tree is as follows before `M.w` is added:



And the expression tree is as follows after `M.w` is added.



When considering named expressions, Pyomo5 and Coopr3 enforce the following semantics:

> A change to a named expression *e* that is a sub-expression of *f* changes the expression tree for *f*, because *f* continues to point to *e* after it is changed.

12.2.3 Design Details

Warning: Pyomo expression trees are not composed of Python objects from a single class hierarchy. Consequently, Pyomo relies on duck typing to ensure that valid expression trees are created.

Most Pyomo expression trees have the following form

1. Interior nodes are objects that inherit from the *ExpressionBase* class. These objects typically have one or more child nodes. Linear expression nodes do not have child nodes, but they are treated as interior nodes in the expression tree because they references other leaf nodes.
2. Leaf nodes are numeric values, parameter components and variable components, which represent the *inputs* to the expresion.

Expression Classes

Expression classes typically represent unary and binary operations. The following table describes the standard operators in Python and their associated Pyomo expression class:

Operation	Python Syntax	Pyomo Class
sum	`x + y`	*SumExpression*
product	`x * y`	*ProductExpression*
negation	`- x`	*NegationExpression*
reciprocal	`1 / x`	*ReciprocalExpression*
power	`x ** y`	PowExpression
inequality	`x <= y`	*InequalityExpression*
equality	`x == y`	*EqualityExpression*

Additionally, there are a variety of other Pyomo expression classes that capture more general logical relationships, which are summarized in the following table:

Operation	Example	Pyomo Class
exernal function	`myfunc(x,y,z)`	*ExternalFunctionExpression*
logical if-then-else	`Expr_if(IF=x, THEN=y, ELSE=z)`	*Expr_ifExpression*
intrinsic function	`sin(x)`	*UnaryFunctionExpression*
absolute function	`abs(x)`	*AbsExpression*

Expression objects are immutable. Specifically, the list of arguments to an expression object (a.k.a. the list of child nodes in the tree) cannot be changed after an expression class is constructed. To enforce this property, expression objects have a standard API for accessing expression arguments:

- `args` - a class property that returns a generator that yields the expression arguments
- `arg(i)` - a function that returns the `i`-th argument
- `nargs()` - a function that returns the number of expression arguments

Warning: Developers should never use the `_args_` property directly! The semantics for the use of this data has changed since earlier versions of Pyomo. For example, in some expression classes the the value `nargs()` may not equal `len(_args_)`!

Expression trees can be categorized in four different ways:

- constant expressions - expressions that do not contain numeric constants and immutable parameters.
- mutable expressions - expressions that contain mutable parameters but no variables.
- potentially variable expressions - expressions that contain variables, which may be fixed.
- fixed expressions - expressions that contain variables, all of which are fixed.

These three categories are illustrated with the following example:

```
m = ConcreteModel()
m.p = Param(default=10, mutable=False)
m.q = Param(default=10, mutable=True)
m.x = Var()
m.y = Var(initialize=1)
m.y.fixed = True
```

The following table describes four different simple expressions that consist of a single model component, and it shows how they are categorized:

Category	m.p	m.q	m.x	m.y
constant	True	False	False	False
not potentially variable	True	True	False	False
potentially_variable	False	False	True	True
fixed	True	True	False	True

Expressions classes contain methods to test whether an expression tree is in each of these categories. Additionally, Pyomo includes custom expression classes for expression trees that are *not potentially variable*. These custom classes will not normally be used by developers, but they provide an optimization of the checks for potentially variability.

Special Expression Classes

The following classes are *exceptions* to the design principles describe above.

Named Expressions

Named expressions allow for changes to an expression after it has been constructed. For example, consider the expression `f` defined with the `Expression` component:

```
M = ConcreteModel()
M.v = Var()
M.w = Var()

M.e = Expression(expr=2*M.v)
f = M.e + 3                    # f == 2*v + 3
M.e += M.w                     # f == 2*v + 3 + w
```

Although `f` is an immutable expression, whose definition is fixed, a sub-expressions is the named expression `M.e`. Named expressions have a mutable value. In other words, the expression that they point to can change. Thus, a change to the value of `M.e` changes the expression tree for any expression that includes the named expression.

Note: The named expression classes are not implemented as sub-classes of *ExpressionBase*. This reflects design constraints related to the fact that these are modeling components that belong to class hierarchies other than the expression class hierarchy, and Pyomo's design prohibits the use of multiple inheritance for these classes.

Linear Expressions

Pyomo includes a special expression class for linear expressions. The class `LinearExpression` provides a compact description of linear polynomials. Specifically, it includes a constant value `constant` and two lists for coefficients and variables: `linear_coefs` and `linear_vars`.

This expression object does not have arguments, and thus it is treated as a leaf node by Pyomo visitor classes. Further, the expression API functions described above do not work with this class. Thus, developers need to treat this class differently when walking an expression tree (e.g. when developing a problem transformation).

Sum Expressions

Pyomo does not have a binary sum expression class. Instead, it has an `n`-ary summation class, *SumExpression*. This expression class treats sums as `n`-ary sums for efficiency reasons; many large optimization models contain large sums. But note tht this class maintains the immutability property described above. This class shares an underlying list of arguments with other *SumExpression* objects. A particular object owns the first `n` arguments in the shared list, but different objects may have different values of `n`.

This class acts like a normal immutable expression class, and the API described above works normally. But direct access to the shared list could have unexpected results.

Mutable Expressions

Finally, Pyomo includes several **mutable** expression classes that are private. These are not intended to be used by users, but they might be useful for developers in contexts where the developer can appropriately control how the classes are used. Specifically, immutability eliminates side-effects where changes to a sub-expression unexpectedly create changes to the expression tree. But within the context of model transformations, developers may be able to limit the use of expressions to avoid these side-effects. The following mutable private classes are available in Pyomo:

`_MutableSumExpression` This class is used in the *nonlinear_expression* context manager to efficiently combine sums of nonlinear terms.

`_MutableLinearExpression` This class is used in the *linear_expression* context manager to efficiently combine sums of linear terms.

Expression Semantics

Pyomo clear semantics regarding what is considered a valid leaf and interior node.

The following classes are valid interior nodes:

- Subclasses of *ExpressionBase*
- Classes that that are *duck typed* to match the API of the *ExpressionBase* class. For example, the named expression class `Expression`.

The following classes are valid leaf nodes:

- Members of *nonpyomo_leaf_types*, which includes standard numeric data types like `int`, `float` and `long`, as well as numeric data types defined by *numpy* and other commonly used packages. This set also includes `NonNumericValue`, which is used to wrap non-numeric arguments to the `ExternalFunctionExpression` class.
- Parameter component classes like `ScalarParam` and `_ParamData`, which arise in expression trees when the parameters are declared as mutable. (Immutable parameters are identified when generating expressions, and they are replaced with their associated numeric value.)
- Variable component classes like `ScalarVar` and `_GeneralVarData`, which often arise in expression trees. <pyomo.core.expr.current.pyomo5_variable_types>`.

Note: In some contexts the `LinearExpression` class can be treated as an interior node, and sometimes it can be treated as a leaf. This expression object does not have any child arguments, so `nargs()` is zero. But this expression references variables and parameters in a linear expression, so in that sense it does not represent a leaf node in the tree.

Context Managers

Pyomo defines several context managers that can be used to declare the form of expressions, and to define a mutable expression object that efficiently manages sums.

The *linear_expression* object is a context manager that can be used to declare a linear sum. For example, consider the following two loops:

```
M = ConcreteModel()
M.x = Var(range(5))

s = 0
for i in range(5):
    s += M.x[i]

with linear_expression() as e:
    for i in range(5):
        e += M.x[i]
```

The first apparent difference in these loops is that the value of `s` is explicitly initialized while `e` is initialized when the context manager is entered. However, a more fundamental difference is that the expression representation for `s` differs from `e`. Each term added to `s` results in a new, immutable expression. By contrast, the context manager creates a mutable expression representation for `e`. This difference allows for both (a) a more efficient processing of each sum, and (b) a more compact representation for the expression.

The difference between *linear_expression* and *nonlinear_expression* is the underlying representation that each supports. Note that both of these are instances of context manager classes. In singled-threaded applications, these objects can be safely used to construct different expressions with different context declarations.

Finally, note that these context managers can be passed into the `start` method for the *quicksum* function. For example:

```
M = ConcreteModel()
M.x = Var(range(5))
M.y = Var(range(5))

with linear_expression() as e:
    quicksum((M.x[i] for i in M.x), start=e)
    quicksum((M.y[i] for i in M.y), start=e)
```

This sum contains terms for `M.x[i]` and `M.y[i]`. The syntax in this example is not intuitive because the sum is being stored in `e`.

Note: We do not generally expect users or developers to use these context managers. They are used by the *quicksum* and *sum_product* functions to accelerate expression generation, and there are few cases where the direct use of these context managers would provide additional utility to users and developers.

12.2.4 Managing Expressions

Creating a String Representation of an Expression

There are several ways that string representations can be created from an expression, but the *expression_to_string* function provides the most flexible mechanism for generating a string representation. The options to this function control distinct aspects of the string representation.

Algebraic vs. Nested Functional Form

The default string representation is an algebraic form, which closely mimics the Python operations used to construct an expression. The `verbose` flag can be set to `True` to generate a string representation that is a nested functional form. For example:

```
from pyomo.core.expr import current as EXPR

M = ConcreteModel()
M.x = Var()

e = sin(M.x) + 2*M.x

# sin(x) + 2*x
print(EXPR.expression_to_string(e))

# sum(sin(x), prod(2, x))
print(EXPR.expression_to_string(e, verbose=True))
```

Labeler and Symbol Map

The string representation used for variables in expression can be customized to define different label formats. If the `labeler` option is specified, then this function (or class functor) is used to generate a string label used to represent the variable. Pyomo defines a variety of labelers in the *pyomo.core.base.label* module. For example, the `NumericLabeler` defines a functor that can be used to sequentially generate simple labels with a prefix followed by the variable count:

```
from pyomo.core.expr import current as EXPR

M = ConcreteModel()
M.x = Var()
M.y = Var()

e = sin(M.x) + 2*M.y
```

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```
# sin(x1) + 2*x2
print(EXPR.expression_to_string(e, labeler=NumericLabeler('x')))
```

The `smap` option is used to specify a symbol map object (*SymbolMap*), which caches the variable label data. This option is normally specified in contexts where the string representations for many expressions are being generated. In that context, a symbol map ensures that variables in different expressions have a consistent label in their associated string representations.

Standardized String Representations

The `standardize` option can be used to re-order the string representation to print polynomial terms before nonlinear terms. By default, `standardize` is `False`, and the string representation reflects the order in which terms were combined to form the expression. Pyomo does not guarantee that the string representation exactly matches the Python expression order, since some simplification and re-ordering of terms is done automatically to improve the efficiency of expression generation. But in most cases the string representation will closely correspond to the Python expression order.

If `standardize` is `True`, then the pyomo expression is processed to identify polynomial terms, and the string representation consists of the constant and linear terms followed by an expression that contains other nonlinear terms. For example:

```
from pyomo.core.expr import current as EXPR

M = ConcreteModel()
M.x = Var()
M.y = Var()

e = sin(M.x) + 2*M.y + M.x*M.y - 3

# -3 + 2*y + sin(x) + x*y
print(EXPR.expression_to_string(e, standardize=True))
```

Other Ways to Generate String Representations

There are two other standard ways to generate string representations:

- Call the `__str__()` magic method (e.g. using the Python `str()` function. This calls *expression_to_string* with the option `standardize` equal to `True` (see below).
- Call the `to_string()` method on the *ExpressionBase* class. This defaults to calling *expression_to_string* with the option `standardize` equal to `False` (see below).

In practice, we expect at the `__str__()` magic method will be used by most users, and the standardization of the output provides a consistent ordering of terms that should make it easier to interpret expressions.

Cloning Expressions

Expressions are automatically cloned only during certain expression transformations. Since this can be an expensive operation, the *clone_counter* context manager object is provided to track the number of times the *clone_expression* function is executed.

For example:

```
from pyomo.core.expr import current as EXPR

M = ConcreteModel()
M.x = Var()

with EXPR.clone_counter() as counter:
    start = counter.count
    e1 = sin(M.x)
    e2 = e1.clone()
    total = counter.count - start
    assert(total == 1)
```

Evaluating Expressions

Expressions can be evaluated when all variables and parameters in the expression have a value. The `value` function can be used to walk the expression tree and compute the value of an expression. For example:

```
M = ConcreteModel()
M.x = Var()
M.x.value = math.pi/2.0
val = value(M.x)
assert(isclose(val, math.pi/2.0))
```

Additionally, expressions define the `__call__()` method, so the following is another way to compute the value of an expression:

```
val = M.x()
assert(isclose(val, math.pi/2.0))
```

If a parameter or variable is undefined, then the `value` function and `__call__()` method will raise an exception. This exception can be suppressed using the `exception` option. For example:

```
M = ConcreteModel()
M.x = Var()
val = value(M.x, exception=False)
assert(val is None)
```

This option is useful in contexts where adding a try block is inconvenient in your modeling script.

Note: Both the `value` function and `__call__()` method call the *evaluate_expression* function. In practice, this function will be slightly faster, but the difference is only meaningful when expressions are evaluated many times.

Identifying Components and Variables

Expression transformations sometimes need to find all nodes in an expression tree that are of a given type. Pyomo contains two utility functions that support this functionality. First, the *identify_components* function is a generator function that walks the expression tree and yields all nodes whose type is in a specified set of node types. For example:

```
from pyomo.core.expr import current as EXPR

M = ConcreteModel()
M.x = Var()
M.p = Param(mutable=True)

e = M.p+M.x
s = set([type(M.p)])
assert(list(EXPR.identify_components(e, s)) == [M.p])
```

The *identify_variables* function is a generator function that yields all nodes that are variables. Pyomo uses several different classes to represent variables, but this set of variable types does not need to be specified by the user. However, the `include_fixed` flag can be specified to omit fixed variables. For example:

```
from pyomo.core.expr import current as EXPR

M = ConcreteModel()
M.x = Var()
M.y = Var()

e = M.x+M.y
M.y.value = 1
M.y.fixed = True

assert(set(id(v) for v in EXPR.identify_variables(e)) == set([id(M.x), id(M.y)]))
assert(set(id(v) for v in EXPR.identify_variables(e, include_fixed=False)) == set([id(M.
↪x)]))
```

Walking an Expression Tree with a Visitor Class

Many of the utility functions defined above are implemented by walking an expression tree and performing an operation at nodes in the tree. For example, evaluating an expression is performed using a post-order depth-first search process where the value of a node is computed using the values of its children.

Walking an expression tree can be tricky, and the code requires intimate knowledge of the design of the expression system. Pyomo includes several classes that define so-called visitor patterns for walking expression tree:

SimpleExpressionVisitor A `visitor()` method is called for each node in the tree, and the visitor class collects information about the tree.

ExpressionValueVisitor When the `visitor()` method is called on each node in the tree, the *values* of its children have been computed. The *value* of the node is returned from `visitor()`.

ExpressionReplacementVisitor When the `visitor()` method is called on each node in the tree, it may clone or otherwise replace the node using objects for its children (which themselves may be clones or replacements from the original child objects). The new node object is returned from `visitor()`.

These classes define a variety of suitable tree search methods:

- *SimpleExpressionVisitor*

  - **xbfs**: breadth-first search where leaf nodes are immediately visited
  - **xbfs_yield_leaves**: breadth-first search where leaf nodes are immediately visited, and the visit method yields a value
- *ExpressionValueVisitor*
  - **dfs_postorder_stack**: postorder depth-first search using a stack
- *ExpressionReplacementVisitor*
  - **dfs_postorder_stack**: postorder depth-first search using a stack

---

Note: The PyUtilib visitor classes define several other search methods that could be used with Pyomo expressions. But these are the only search methods currently used within Pyomo.

To implement a visitor object, a user creates a subclass of one of these classes. Only one of a few methods will need to be defined to implement the visitor:

visitor() Defines the operation that is performed when a node is visited. In the *ExpressionValueVisitor* and *ExpressionReplacementVisitor* visitor classes, this method returns a value that is used by its parent node.

visiting_potential_leaf() Checks if the search should terminate with this node. If no, then this method returns the tuple `(False, None)`. If yes, then this method returns `(False, value)`, where *value* is computed by this method. This method is not used in the *SimpleExpressionVisitor* visitor class.

finalize() This method defines the final value that is returned from the visitor. This is not normally redefined.

Detailed documentation of the APIs for these methods is provided with the class documentation for these visitors.

SimpleExpressionVisitor Example

In this example, we describe an visitor class that counts the number of nodes in an expression (including leaf nodes). Consider the following class:

```
from pyomo.core.expr import current as EXPR

class SizeofVisitor(EXPR.SimpleExpressionVisitor):

    def __init__(self):
        self.counter = 0

    def visit(self, node):
        self.counter += 1

    def finalize(self):
        return self.counter
```

The class constructor creates a counter, and the `visit()` method increments this counter for every node that is visited. The `finalize()` method returns the value of this counter after the tree has been walked. The following function illustrates this use of this visitor class:

```
def sizeof_expression(expr):
    #
    # Create the visitor object
    #
```

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```
    visitor = SizeofVisitor()
    #
    # Compute the value using the :func:`xbfs` search method.
    #
    return visitor.xbfs(expr)
```

ExpressionValueVisitor Example

In this example, we describe an visitor class that clones the expression tree (including leaf nodes). Consider the following class:

```
from pyomo.core.expr import current as EXPR

class CloneVisitor(EXPR.ExpressionValueVisitor):

    def __init__(self):
        self.memo = {'__block_scope__': { id(None): False }}

    def visit(self, node, values):
        #
        # Clone the interior node
        #
        return node.construct_clone(tuple(values), self.memo)

    def visiting_potential_leaf(self, node):
        #
        # Clone leaf nodes in the expression tree
        #
        if node.__class__ in native_numeric_types or\
           node.__class__ not in pyomo5_expression_types:\
            return True, copy.deepcopy(node, self.memo)

        return False, None
```

The `visit()` method creates a new expression node with children specified by `values`. The `visiting_potential_leaf()` method performs a `deepcopy()` on leaf nodes, which are native Python types or non-expression objects.

```
def clone_expression(expr):
    #
    # Create the visitor object
    #
    visitor = CloneVisitor()
    #
    # Clone the expression using the :func:`dfs_postorder_stack`
    # search method.
    #
    return visitor.dfs_postorder_stack(expr)
```

ExpressionReplacementVisitor Example

In this example, we describe an visitor class that replaces variables with scaled variables, using a mutable parameter that can be modified later. the following class:

```
from pyomo.core.expr import current as EXPR

class ScalingVisitor(EXPR.ExpressionReplacementVisitor):

    def __init__(self, scale):
        super(ScalingVisitor, self).__init__()
        self.scale = scale

    def visiting_potential_leaf(self, node):
        #
        # Clone leaf nodes in the expression tree
        #
        if node.__class__ in native_numeric_types:
            return True, node

        if node.is_variable_type():
            return True, self.scale[id(node)]*node

        if isinstance(node, EXPR.LinearExpression):
            node_ = copy.deepcopy(node)
            node_.constant = node.constant
            node_.linear_vars = copy.copy(node.linear_vars)
            node_.linear_coefs = []
            for i,v in enumerate(node.linear_vars):
                node_.linear_coefs.append( node.linear_coefs[i]*self.scale[id(v)] )
            return True, node_

        return False, None
```

No `visit()` method needs to be defined. The `visiting_potential_leaf()` function identifies variable nodes and returns a product expression that contains a mutable parameter. The `_LinearExpression` class has a different representation that embeds variables. Hence, this class must be handled in a separate condition that explicitly transforms this sub-expression.

```
def scale_expression(expr, scale):
    #
    # Create the visitor object
    #
    visitor = ScalingVisitor(scale)
    #
    # Scale the expression using the :func:`dfs_postorder_stack`
    # search method.
    #
    return visitor.dfs_postorder_stack(expr)
```

The `scale_expression()` function is called with an expression and a dictionary, `scale`, that maps variable ID to model parameter. For example:

```
M = ConcreteModel()
M.x = Var(range(5))
M.p = Param(range(5), mutable=True)

scale={}
for i in M.x:
  scale[id(M.x[i])] = M.p[i]

e = quicksum(M.x[i] for i in M.x)
f = scale_expression(e,scale)

# p[0]*x[0] + p[1]*x[1] + p[2]*x[2] + p[3]*x[3] + p[4]*x[4]
print(f)
```

CHAPTER

THIRTEEN

LIBRARY REFERENCE

Pyomo is being increasingly used as a library to support Python scripts. This section describes library APIs for key elements of Pyomo's core library. This documentation serves as a reference for both (1) Pyomo developers and (2) advanced users who are developing Python scripts using Pyomo.

13.1 Common Utilities

Pyomo provides a set of general-purpose utilites through `pyomo.common`. These utilities are self-contained and do not import or rely on any other parts of Pyomo.

13.1.1 pyomo.common.config

Core classes

ConfigDict([description, doc, implicit, ...])	Store and manipulate a dictionary of configuration values.
ConfigList(*args, **kwds)	Store and manipulate a list of configuration values.
ConfigValue(*args, **kwds)	Store and manipulate a single configuration value.

Domain validators

PositiveInt(val)	Domain validation function admitting strictly positive integers
NegativeInt(val)	Domain validation function admitting strictly negative integers
NonNegativeInt(val)	Domain validation function admitting integers >= 0
NonPositiveInt(val)	Domain validation function admitting integers <= 0
PositiveFloat(val)	Domain validation function admitting strictly positive numbers
NegativeFloat(val)	Domain validation function admitting strictly negative numbers
NonPositiveFloat(val)	Domain validation function admitting numbers less than or equal to 0
NonNegativeFloat(val)	Domain validation function admitting numbers greater than or equal to 0

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Table 13.2 – continued from previous page

In(domain[, cast])	Domain validation class admitting a Container of possible values
InEnum(domain)	Domain validation class admitting an enum value/name.
Path([basePath, expandPath])	Domain validator for path-like options.
PathList([basePath, expandPath])	Domain validator for a list of path-like objects.
DynamicImplicitDomain(callback)	Implicit domain that can return a custom domain based on the key.

class pyomo.common.config.**ConfigBase**(*default=None*, *domain=None*, *description=None*, *doc=None*, *visibility=0*)

class **NoArgument**

declare_as_argument(**args*, ***kwds*)
Map this Config item to an argparse argument.

Valid arguments include all valid arguments to argparse's ArgumentParser.add_argument() with the exception of 'default'. In addition, you may provide a group keyword argument to either pass in a pre-defined option group or subparser, or else pass in the string name of a group, subparser, or (subparser, group).

display(*content_filter=None*, *indent_spacing=2*, *ostream=None*, *visibility=None*)

generate_documentation(*block_start=None*, *block_end=None*, *item_start=None*, *item_body=None*, *item_end=None*, *indent_spacing=2*, *width=78*, *visibility=0*, *format='latex'*)

generate_yaml_template(*indent_spacing=2*, *width=78*, *visibility=0*)

import_argparse(*parsed_args*)

initialize_argparse(*parser*)

name(*fully_qualified=False*)

reset()

set_default_value(*default*)

set_domain(*domain*)

unused_user_values()

user_values()

class pyomo.common.config.**ConfigDict**(*description=None*, *doc=None*, *implicit=False*, *implicit_domain=None*, *visibility=0*)

Bases: pyomo.common.config.

Store and manipulate a dictionary of configuration values.

Parameters

- **description** (*str, optional*) – The short description of this list
- **doc** (*str, optional*) – The long documentation string for this list
- **implicit** (*bool, optional*) – If True, the ConfigDict will allow "implicitly" declared keys, that is, keys can be stored into the ConfigDict that were not prevously declared using *declare()* or *declare_from()*.
- **implicit_domain** (*callable, optional*) – The domain that will be used for any implicitly-declared keys. Follows the same rules as *ConfigValue()*'s *domain*.

- **visibility** (*int, optional*) – The visibility of this ConfigDict when generating templates and documentation. Visibility supports specification of "advanced" or "developer" options. ConfigDicts with visibility=0 (the default) will always be printed / included. ConfigDicts with higher visibility values will only be included when the generation method specifies a visibility greater than or equal to the visibility of this object.

add(*name*, *config*)

content_filters = {'all', 'userdata', None}

declare(*name*, *config*)

declare_from(*other*, *skip=None*)

get(*key*, *default=NOTSET*)

items()

iteritems()
DEPRECATED.

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.keys().

iterkeys()
DEPRECATED.

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()
DEPRECATED.

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.keys().

keys()

reset()

set_value(*value*, *skip_implicit=False*)

setdefault(*key*, *default=NOTSET*)

value(*accessValue=True*)

values()

class pyomo.common.config.**ConfigList**(**args*, ***kwds*)
Bases: pyomo.common.config.

Store and manipulate a list of configuration values.

Parameters

- **default** (*optional*) – The default value that this ConfigList will take if no value is provided. If default is a list or ConfigList, then each member is cast to the ConfigList's domain to build the default value, otherwise the default is cast to the domain and forms a default list with a single element.
- **domain** (*callable, optional*) – The domain can be any callable that accepts a candidate value and returns the value converted to the desired type, optionally performing any data validation. The result will be stored / added to the ConfigList. Examples include type constructors like *int* or *float*. More complex domain examples include callable objects; for example, the *In* class that ensures that the value falls into an acceptable set or even a complete *ConfigDict* instance.
- **description** (*str, optional*) – The short description of this list

- **doc** (*str, optional*) – The long documentation string for this list
- **visibility** (*int, optional*) – The visibility of this ConfigList when generating templates and documentation. Visibility supports specification of "advanced" or "developer" options. ConfigLists with visibility=0 (the default) will always be printed / included. ConfigLists with higher visibility values will only be included when the generation method specifies a visibility greater than or equal to the visibility of this object.

add(*value=NOTSET*)
DEPRECATED.

Append the specified value to the list, casting as necessary.

Deprecated since version 5.7.2: ConfigList.add() has been deprecated. Use append()

append(*value=NOTSET*)

get(*key*, *default=NOTSET*)

reset()

set_value(*value*)

value(*accessValue=True*)

class pyomo.common.config.**ConfigValue**(**args*, ***kwds*)
Bases: pyomo.common.config.

Store and manipulate a single configuration value.

Parameters

- **default** (*optional*) – The default value that this ConfigValue will take if no value is provided.
- **domain** (*callable, optional*) – The domain can be any callable that accepts a candidate value and returns the value converted to the desired type, optionally performing any data validation. The result will be stored into the ConfigValue. Examples include type constructors like *int* or *float*. More complex domain examples include callable objects; for example, the *In* class that ensures that the value falls into an acceptable set or even a complete *ConfigDict* instance.
- **description** (*str, optional*) – The short description of this value
- **doc** (*str, optional*) – The long documentation string for this value
- **visibility** (*int, optional*) – The visibility of this ConfigValue when generating templates and documentation. Visibility supports specification of "advanced" or "developer" options. ConfigValues with visibility=0 (the default) will always be printed / included. ConfigValues with higher visibility values will only be included when the generation method specifies a visibility greater than or equal to the visibility of this object.

set_value(*value*)

value(*accessValue=True*)

class pyomo.common.config.**DynamicImplicitDomain**(*callback*)
Implicit domain that can return a custom domain based on the key.

This provides a mechanism for managing plugin-like systems, where the key specifies a source for additional configuration information. For example, given the plugin module, pyomo/common/tests/config_plugin.py:

```
from pyomo.common.config import ConfigDict, ConfigValue

def get_configuration(config):
    ans = ConfigDict()
    ans.declare('key1', ConfigValue(default=0, domain=int))
    ans.declare('key2', ConfigValue(default=5, domain=str))
    return ans(config)
```

```
>>> def _pluginImporter(name, config):
...     mod = importlib.import_module(name)
...     return mod.get_configuration(config)
>>> config = ConfigDict()
>>> config.declare('plugins', ConfigDict(
...     implicit=True,
...     implicit_domain=DynamicImplicitDomain(_pluginImporter)))
<pyomo.common.config.ConfigDict object at ...>
>>> config.plugins['pyomo.common.tests.config_plugin'] = {'key1': 5}
>>> config.display()
plugins:
  pyomo.common.tests.config_plugin:
    key1: 5
    key2: '5'
```

Note: This initializer is only useful for the *ConfigDict* `implicit_domain` argument (and not for "regular" `domain` arguments)

Parameters **callback** (*Callable[[str, object], ConfigBase]*) – A callable (function) that is passed the ConfigDict key and value, and is expected to return the appropriate Config object (ConfigValue, ConfigList, or ConfigDict)

pyomo.common.config.**PositiveInt**(*val*)
Domain validation function admitting strictly positive integers

This domain will admit positive integers (n > 0), as well as any types that are convertible to positive integers.

pyomo.common.config.**NegativeInt**(*val*)
Domain validation function admitting strictly negative integers

This domain will admit negative integers (n < 0), as well as any types that are convertible to negative integers.

pyomo.common.config.**NonNegativeInt**(*val*)
Domain validation function admitting integers >= 0

This domain will admit non-negative integers (n >= 0), as well as any types that are convertible to non-negative integers.

pyomo.common.config.**NonPositiveInt**(*val*)
Domain validation function admitting integers <= 0

This domain will admit non-positive integers (n <= 0), as well as any types that are convertible to non-positive integers.

pyomo.common.config.**PositiveFloat**(*val*)
Domain validation function admitting strictly positive numbers

This domain will admit positive floating point numbers (n > 0), as well as any types that are convertible to positive floating point numbers.

pyomo.common.config.**NegativeFloat**(*val*)
Domain validation function admitting strictly negative numbers

This domain will admit negative floating point numbers (n < 0), as well as any types that are convertible to negative floating point numbers.

pyomo.common.config.**NonPositiveFloat**(*val*)
Domain validation function admitting numbers less than or equal to 0

This domain will admit non-positive floating point numbers (n <= 0), as well as any types that are convertible to non-positive floating point numbers.

pyomo.common.config.**NonNegativeFloat**(*val*)
Domain validation function admitting numbers greater than or equal to 0

This domain will admit non-negative floating point numbers (n >= 0), as well as any types that are convertible to non-negative floating point numbers.

class pyomo.common.config.**In**(*domain*, *cast=None*)
Domain validation class admitting a Container of possible values

This will admit any value that is in the *domain* Container (i.e., Container.__contains__() returns True). Most common domains are list, set, and dict objects. If specified, incoming values are first passed to *cast()* to convert them to the appropriate type before looking them up in *domain*.

Parameters

- **domain** (*Container*) – The container that specifies the allowable values. Incoming values are passed to `domain.__contains__()`, and if `True` is returned, the value is accepted and returned.
- **cast** (*callable, optional*) – A callable object. If specified, incoming values are first passed to *cast*, and the resulting object is checked for membership in *domain*

Note: For backwards compatibility, *In* accepts *enum.Enum* classes as *domain* Containers. If the domain is an Enum, then the constructor returns an instance of *InEnum*.

---

class pyomo.common.config.**InEnum**(*domain*)
Domain validation class admitting an enum value/name.

This will admit any value that is in the specified Enum, including Enum members, values, and string names. The incoming value will be automatically cast to an Enum member.

Parameters **domain** (*enum.Enum*) – The enum that incoming values should be mapped to

class pyomo.common.config.**Path**(*basePath=None*, *expandPath=None*)
Domain validator for path-like options.

This will admit any object and convert it to a string. It will then expand any environment variables and leading usernames (e.g., "~myuser" or "~/") appearing in either the value or the base path before concatenating the base path and value, expanding the path to an absolute path, and normalizing the path.

Parameters

- **basePath** (*None, str,* ConfigValue) – The base path that will be prepended to any non-absolute path values provided. If None, defaults to `Path.BasePath`.

- **expandPath** (*bool*) – If True, then the value will be expanded and normalized. If False, the string representation of the value will be returned unchanged. If None, expandPath will defer to the (negated) value of `Path.SuppressPathExpansion`

class pyomo.common.config.**PathList**(*basePath=None*, *expandPath=None*)
Domain validator for a list of path-like objects.

This will admit any iterable or object convertable to a string. Iterable objects (other than strings) will have each member normalized using *Path*. Other types will be passed to *Path*, returning a list with the single resulting path.

Parameters

- **basePath** (*Union[None, str, ConfigValue]*) – The base path that will be prepended to any non-absolute path values provided. If None, defaults to `Path.BasePath`.
- **expandPath** (*bool*) – If True, then the value will be expanded and normalized. If False, the string representation of the value will be returned unchanged. If None, expandPath will defer to the (negated) value of `Path.SuppressPathExpansion`

13.1.2 pyomo.common.dependencies

exception pyomo.common.dependencies.**DeferredImportError**

class pyomo.common.dependencies.**ModuleUnavailable**(*name*, *message*, *version_error*, *import_error*)
Mock object that raises a DeferredImportError upon attribute access

This object is returned by *attempt_import()* in lieu of the module in the case that the module import fails. Any attempts to access attributes on this object will raise a DeferredImportError exception.

Parameters

- **name** (*str*) – The module name that was being imported
- **message** (*str*) – The string message to return in the raised exception
- **version_error** (*str*) – A string to add to the message if the module failed to import because it did not match the required version
- **import_error** (*str*) – A string to add to the message documenting the Exception raised when the module failed to import.

log_import_warning(*logger='pyomo'*, *msg=None*)
Log the import error message to the specified logger

This will log the the import error message to the specified logger. If `msg=` is specified, it will override the default message passed to this instance of *ModuleUnavailable*.

generate_import_warning(*logger='pyomo.common'*)
DEPRECATED.

Deprecated since version 6.0: use *log_import_warning()*

class pyomo.common.dependencies.**DeferredImportModule**(*indicator*, *deferred_submodules*, *submodule_name*)
Mock module object to support the deferred import of a module.

This object is returned by *attempt_import()* in lieu of the module when *attempt_import()* is called with `defer_check=True`. Any attempts to access attributes on this object will trigger the actual module import and return either the appropriate module attribute or else if the module import fails, raise a DeferredImportError exception.

class pyomo.common.dependencies.**DeferredImportIndicator**(*name*, *error_message*, *catch_exceptions*, *minimum_version*, *original_globals*, *callback*, *importer*, *deferred_submodules*)

Placeholder indicating if an import was successful.

This object serves as a placeholder for the Boolean indicator if a deferred module import was successful. Casting this instance to bool will cause the import to be attempted. The actual import logic is here and not in the DeferredImportModule to reduce the number of attributes on the DeferredImportModule.

`DeferredImportIndicator` supports limited logical expressions using the & (and) and | (or) binary operators. Creating these expressions does not trigger the import of the corresponding *DeferredImportModule* instances, although casting the resulting expression to `bool()` will trigger any relevant imports.

pyomo.common.dependencies.**attempt_import**(*name*, *error_message=None*, *only_catch_importerror=None*, *minimum_version=None*, *alt_names=None*, *callback=None*, *importer=None*, *defer_check=True*, *deferred_submodules=None*, *catch_exceptions=None*)

Attempt to import the specified module.

This will attempt to import the specified module, returning a `(module, available)` tuple. If the import was successful, `module` will be the imported module and `available` will be True. If the import results in an exception, then `module` will be an instance of *ModuleUnavailable* and `available` will be False

The following

```
>>> from pyomo.common.dependencies import attempt_import
>>> numpy, numpy_available = attempt_import('numpy')
```

Is roughly equivalent to

```
>>> from pyomo.common.dependencies import ModuleUnavailable
>>> try:
...     import numpy
...     numpy_available = True
... except ImportError as e:
...     numpy = ModuleUnavailable('numpy', 'Numpy is not available',
...                               '', str(e))
...     numpy_available = False
```

The import can be "deferred" until the first time the code either attempts to access the module or checks the Boolean value of the available flag. This allows optional dependencies to be declared at the module scope but not imported until they are actually used by the module (thereby speeding up the initial package import). Deferred imports are handled by two helper classes (*DeferredImportModule* and *DeferredImportIndicator*). Upon actual import, `DeferredImportIndicator.resolve()` attempts to replace those objects (in both the local and original global namespaces) with the imported module and Boolean flag so that subsequent uses of the module do not incur any overhead due to the delayed import.

Parameters

- **name** (*str*) – The name of the module to import
- **error_message** (*str, optional*) – The message for the exception raised by *ModuleUnavailable*
- **only_catch_importerror** (*bool, optional*) – DEPRECATED: use catch_exceptions instead or only_catch_importerror. If True (the default), exceptions other than `ImportError` raised during module import will be reraised. If False, any exception will result in returning a *ModuleUnavailable* object. (deprecated in version 5.7.3)

- **minimum_version** (*str, optional*) – The minimum acceptable module version (retrieved from `module.__version__`)
- **alt_names** (*list, optional*) – DEPRECATED: alt_names no longer needs to be specified and is ignored. A list of common alternate names by which to look for this module in the `globals()` namespaces. For example, the alt_names for NumPy would be `['np']`. (deprecated in version 6.0)
- **callback** (*function, optional*) – A function with the signature "`fcn(module, available)`" that will be called after the import is first attempted.
- **importer** (*function, optional*) – A function that will perform the import and return the imported module (or raise an `ImportError`). This is useful for cases where there are several equivalent modules and you want to import/return the first one that is available.
- **defer_check** (*bool, optional*) – If True (the default), then the attempted import is deferred until the first use of either the module or the availability flag. The method will return instances of DeferredImportModule and DeferredImportIndicator.
- **deferred_submodules** (*Iterable[str], optional*) – If provided, an iterable of submodule names within this module that can be accessed without triggering a deferred import of this module. For example, this module uses `deferred_submodules=['pyplot', 'pylab']` for `matplotlib`.
- **catch_exceptions** (*Iterable[Exception], optional*) – If provide, this is the list of exceptions that will be caught when importing the target module, resulting in `attempt_import` returning a *ModuleUnavailable* instance. The default is to only catch `ImportError`. This is useful when a module can regularly return additional exceptions during import.

Returns

- *module* – the imported module, or an instance of *ModuleUnavailable*, or an instance of *DeferredImportModule*
- *bool* – Boolean indicating if the module import succeeded or an instance of *DeferredImportIndicator*

pyomo.common.dependencies.**declare_deferred_modules_as_importable**(*globals_dict*)

Make all DeferredImportModules in `globals_dict` importable

This function will go throught the specified `globals_dict` dictionary and add any instances of *DeferredImportModule* that it finds (and any of their deferred submodules) to `sys.modules` so that the modules can be imported through the `globals_dict` namespace.

For example, `pyomo/common/dependencies.py` declares:

```
>>> scipy, scipy_available = attempt_import(
...     'scipy', callback=_finalize_scipy,
...     deferred_submodules=['stats', 'sparse', 'spatial', 'integrate'])
>>> declare_deferred_modules_as_importable(globals())
```

Which enables users to use:

```
>>> import pyomo.common.dependencies.scipy.sparse as spa
```

If the deferred import has not yet been triggered, then the *DeferredImportModule* is returned and named `spa`. However, if the import has already been triggered, then `spa` will either be the `scipy.sparse` module, or a *ModuleUnavailable* instance.

13.1.3 pyomo.common.timing

pyomo.common.timing.**report_timing**(*stream=True*)
Set reporting of Pyomo timing information.

Parameters **stream** (*bool, TextIOBase*) – The destination stream to emit timing information. If `True`, defaults to `sys.stdout`. If `False` or `None`, disables reporting of timing information.

class pyomo.common.timing.**TicTocTimer**(*ostream=NOTSET*, *logger=None*)
A class to calculate and report elapsed time.

Examples

```
>>> from pyomo.common.timing import TicTocTimer
>>> timer = TicTocTimer()
>>> timer.tic('starting timer') # starts the elapsed time timer (from 0)
[    0.00] starting timer
>>> # ... do task 1
>>> dT = timer.toc('task 1')
[+   0.00] task 1
>>> print("elapsed time: %0.1f" % dT)
elapsed time: 0.0
```

If no ostream or logger is provided, then output is printed to sys.stdout

Parameters

- **ostream** (*FILE*) – an optional output stream to print the timing information
- **logger** (*Logger*) – an optional output stream using the python logging package. Note: the timing logged using `logger.info()`

tic(*msg=NOTSET*, *ostream=NOTSET*, *logger=NOTSET*)
Reset the tic/toc delta timer.

This resets the reference time from which the next delta time is calculated to the current time.

Parameters

- **msg** (*str*) – The message to print out. If not specified, then prints out "Resetting the tic/toc delta timer"; if msg is None, then no message is printed.
- **ostream** (*FILE*) – an optional output stream (overrides the ostream provided when the class was constructed).
- **logger** (*Logger*) – an optional output stream using the python logging package (overrides the ostream provided when the class was constructed). Note: timing logged using logger.info

toc(*msg=NOTSET*, *delta=True*, *ostream=NOTSET*, *logger=NOTSET*)
Print out the elapsed time.

This resets the reference time from which the next delta time is calculated to the current time.

Parameters

- **msg** (*str*) – The message to print out. If not specified, then print out the file name, line number, and function that called this method; if msg is None, then no message is printed.
- **delta** (*bool*) – print out the elapsed wall clock time since the last call to *tic()* or *toc()* (`True` (default)) or since the module was first loaded (`False`).

- **ostream** (*FILE*) – an optional output stream (overrides the ostream provided when the class was constructed).
- **logger** (*Logger*) – an optional output stream using the python logging package (overrides the ostream provided when the class was constructed). Note: timing logged using logger.info

pyomo.common.timing.**tic**(*msg=NOTSET*, *ostream=NOTSET*, *logger=NOTSET*)
Reset the global *TicTocTimer* instance.

See *TicTocTimer.tic()*.

pyomo.common.timing.**toc**(*msg=NOTSET*, *delta=True*, *ostream=NOTSET*, *logger=NOTSET*)
Print the elapsed time from the global *TicTocTimer* instance.

See *TicTocTimer.toc()*.

class pyomo.common.timing.**HierarchicalTimer**
A class for hierarchical timing.

Examples

```
>>> import time
>>> from pyomo.common.timing import HierarchicalTimer
>>> timer = HierarchicalTimer()
>>> timer.start('all')
>>> time.sleep(0.2)
>>> for i in range(10):
...     timer.start('a')
...     time.sleep(0.1)
...     for i in range(5):
...         timer.start('aa')
...         time.sleep(0.01)
...         timer.stop('aa')
...     timer.start('ab')
...     timer.stop('ab')
...     timer.stop('a')
...
>>> for i in range(10):
...     timer.start('b')
...     time.sleep(0.02)
...     timer.stop('b')
...
>>> timer.stop('all')
>>> print(timer)
Identifier        ncalls   cumtime   percall      %
-----------------------------------------------------
all                    1     2.248     2.248  100.0
     ----------------------------------------------
     a                10     1.787     0.179   79.5
          -----------------------------------------
          aa          50     0.733     0.015   41.0
          ab          10     0.000     0.000    0.0
          other      n/a     1.055       n/a   59.0
          =========================================
```

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```
    b                10     0.248     0.025   11.0
    other           n/a     0.213       n/a    9.5
    ============================================
================================================
```

The columns are:

ncalls The number of times the timer was started and stopped

cumtime The cumulative time (in seconds) the timer was active (started but not stopped)

percall cumtime (in seconds) / ncalls

"%" This is cumtime of the timer divided by cumtime of the parent timer times 100

```
>>> print('a total time: %f' % timer.get_total_time('all.a'))
a total time: 1.902037
>>> print('ab num calls: %d' % timer.get_num_calls('all.a.ab'))
ab num calls: 10
>>> print('aa %% time: %f' % timer.get_relative_percent_time('all.a.aa'))
aa % time: 44.144148
>>> print('aa %% total: %f' % timer.get_total_percent_time('all.a.aa'))
aa % total: 35.976058
```

Notes

The *HierarchicalTimer* use a stack to track which timers are active at any point in time. Additionally, each timer has a dictionary of timers for its children timers. Consider

```
>>> timer = HierarchicalTimer()
>>> timer.start('all')
>>> timer.start('a')
>>> timer.start('aa')
```

After the above code is run, `timer.stack` will be `['all', 'a', 'aa']` and `timer.timers` will have one key, `'all'` and one value which will be a `_HierarchicalHelper`. The `_HierarchicalHelper` has its own timers dictionary:

```
{'a':  _HierarchicalHelper}
```

and so on. This way, we can easily access any timer with something that looks like the stack. The logic is recursive (although the code is not).

start(*identifier*)
Start incrementing the timer identified with identifier

Parameters **identifier** (*str*) – The name of the timer

stop(*identifier*)
Stop incrementing the timer identified with identifier

Parameters **identifier** (*str*) – The name of the timer

reset()
Completely reset the timer.

get_total_time(*identifier*)

Parameters **identifier** (*str*) – The full name of the timer including parent timers separated with dots.

Returns **total_time** – The total time spent with the specified timer active.

Return type float

get_num_calls(*identifier*)

Parameters **identifier** (*str*) – The full name of the timer including parent timers separated with dots.

Returns **num_calss** – The number of times start was called for the specified timer.

Return type int

get_relative_percent_time(*identifier*)

Parameters **identifier** (*str*) – The full name of the timer including parent timers separated with dots.

Returns **percent_time** – The percent of time spent in the specified timer relative to the timer's immediate parent.

Return type float

get_total_percent_time(*identifier*)

Parameters **identifier** (*str*) – The full name of the timer including parent timers separated with dots.

Returns **percent_time** – The percent of time spent in the specified timer relative to the total time in all timers.

Return type float

get_timers()

Returns **identifiers** – Returns a list of all timer identifiers

Return type list of str

13.2 AML Library Reference

The following modeling components make up the core of the Pyomo Algebraic Modeling Language (AML). These classes are all available through the *pyomo.environ* namespace.

ConcreteModel(*args, **kwds)	A concrete optimization model that does not defer construction of components.
AbstractModel(*args, **kwds)	An abstract optimization model that defers construction of components.
Block(*args, **kwds)	Blocks are indexed components that contain other components (including blocks).
Set(*args, **kwds)	A component used to index other Pyomo components.
RangeSet(*args, **kwds)	A set object that represents a set of numeric values

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Table 13.3 – continued from previous page

Param(*args, **kwds)	A parameter value, which may be defined over an index.
Var(*args, **kwds)	A numeric variable, which may be defined over an index.
Objective(*args, **kwds)	This modeling component defines an objective expression.
Constraint(*args, **kwds)	This modeling component defines a constraint expression using a rule function.
Reference(reference[, ctype])	Creates a component that references other components

13.2.1 AML Component Documentation

class pyomo.environ.**ConcreteModel**(**args*, ***kwds*)

Bases: pyomo.core.base.PyomoModel.Model

A concrete optimization model that does not defer construction of components.

activate()

Set the active attribute to True

property active

Return the active attribute

active_blocks(**args*, ***kwargs*)

DEPRECATED.

Deprecated since version 4.1.10486: The active_blocks method is deprecated. Use the Block.block_data_objects() method.

active_component_data(**args*, ***kwargs*)

DEPRECATED.

Deprecated since version 4.1.10486: The active_component_data method is deprecated. Use the Block.component_data_objects() method.

active_components(**args*, ***kwargs*)

DEPRECATED.

Deprecated since version 4.1.10486: The active_components method is deprecated. Use the Block.component_objects() method.

add_component(*name*, *val*)

Add a component 'name' to the block.

This method assumes that the attribute is not in the model.

all_blocks(**args*, ***kwargs*)

DEPRECATED.

Deprecated since version 4.1.10486: The all_blocks method is deprecated. Use the Block.block_data_objects() method.

all_component_data(**args*, ***kwargs*)

DEPRECATED.

Deprecated since version 4.1.10486: The all_component_data method is deprecated. Use the Block.component_data_objects() method.

all_components(**args*, ***kwargs*)

DEPRECATED.

Deprecated since version 4.1.10486: The all_components method is deprecated. Use the Block.component_objects() method.

block_data_objects(*active=None*, *sort=False*, *descend_into=True*, *descent_order=None*)
This method returns a generator that iterates through the current block and recursively all sub-blocks. This is semantically equivalent to

component_data_objects(Block, ...)

clear_suffix_value(*suffix_or_name*, *expand=True*)
Set the suffix value for this component data

clone()
TODO

cname(**args*, ***kwds*)
DEPRECATED.

Deprecated since version 5.0: The cname() method has been renamed to getname(). The preferred method of obtaining a component name is to use the .name property, which returns the fully qualified component name. The .local_name property will return the component name only within the context of the immediate parent container.

collect_ctypes(*active=None*, *descend_into=True*)
Count all component types stored on or under this block.

Parameters

- **active** (*True/None*) – Set to True to indicate that only active components should be counted. The default value of None indicates that all components (including those that have been deactivated) should be counted.
- **descend_into** (*bool*) – Indicates whether or not component types should be counted on sub-blocks. Default is True.

Returns: A set of component types.

component(*name_or_object*)
Return a child component of this block.

If passed a string, this will return the child component registered by that name. If passed a component, this will return that component IFF the component is a child of this block. Returns None on lookup failure.

component_data_iterindex(*ctype=None*, *active=None*, *sort=False*, *descend_into=True*, *descent_order=None*)
Return a generator that returns a tuple for each component data object in a block. By default, this generator recursively descends into sub-blocks. The tuple is

((component name, index value), _ComponentData)

component_data_objects(*ctype=None*, *active=None*, *sort=False*, *descend_into=True*, *descent_order=None*)
Return a generator that iterates through the component data objects for all components in a block. By default, this generator recursively descends into sub-blocks.

component_map(*ctype=None*, *active=None*, *sort=False*)
Returns a PseudoMap of the components in this block.

Parameters

- **ctype** (*None or type or iterable*) – Specifies the component types (*ctypes*) to include in the resulting PseudoMap

None	All components
type	A single component type
iterable	All component types in the iterable

- **active** (*None or bool*) – Filter components by the active flag

None	Return all components
True	Return only active components
False	Return only inactive components

- **sort** (*bool*) – Iterate over the components in a sorted otder

True	Iterate using Block.alphabetizeComponentAndIndex
False	Iterate using Block.declarationOrder

component_objects(*ctype=None*, *active=None*, *sort=False*, *descend_into=True*, *descent_order=None*)
Return a generator that iterates through the component objects in a block. By default, the generator recursively descends into sub-blocks.

compute_statistics(*active=True*)
Compute model statistics

construct(*data=None*)
Initialize the block

contains_component(*ctype*)
Return True if the component type is in _ctypes and ... TODO.

create(*filename=None*, ***kwargs*)
DEPRECATED.

Create a concrete instance of this Model, possibly using data read in from a file.

Deprecated since version 4.3.11323: The Model.create() method is deprecated. Call Model.create_instance() to create a concrete instance from an abstract model. You do not need to call Model.create() for a concrete model.

create_instance(*filename=None*, *data=None*, *name=None*, *namespace=None*, *namespaces=None*, *profile_memory=0*, *report_timing=False*, ***kwds*)
Create a concrete instance of an abstract model, possibly using data read in from a file.

Parameters

- **filename** (*str*, optional) – The name of a Pyomo Data File that will be used to load data into the model.
- **data** (*dict*, optional) – A dictionary containing initialization data for the model to be used if there is no filename
- **name** (*str*, optional) – The name given to the model.
- **namespace** (*str*, optional) – A namespace used to select data.
- **namespaces** (*list*, optional) – A list of namespaces used to select data.
- **profile_memory** (*int*, optional) – A number that indicates the profiling level.
- **report_timing** (*bool*, optional) – Report timing statistics during construction.

property ctype
Return the class type for this component

deactivate()
Set the active attribute to False

del_component(*name_or_object*)
Delete a component from this block.

dim()
Return the dimension of the index

display(*filename=None*, *ostream=None*, *prefix=''*)
Display values in the block

find_component(*label_or_component*)
Return a block component given a name.

get_suffix_value(*suffix_or_name*, *default=None*)
Get the suffix value for this component data

getname(*fully_qualified=False*, *name_buffer=None*, *relative_to=None*)
Return a string with the component name and index

id_index_map()
Return an dictionary id->index for all ComponentData instances.

index()
Returns the index of this ComponentData instance relative to the parent component index set. None is returned if this instance does not have a parent component, or if - for some unknown reason - this instance does not belong to the parent component's index set. This method is not intended to be a fast method; it should be used rarely, primarily in cases of label formulation.

index_set()
Return the index set

is_component_type()
Return True if this class is a Pyomo component

is_constructed()
A boolean indicating whether or not all *active* components of the input model have been properly constructed.

is_expression_type()
Return True if this numeric value is an expression

is_indexed()
Return true if this component is indexed

is_logical_type()
Return True if this class is a Pyomo Boolean value, variable, or expression.

is_named_expression_type()
Return True if this numeric value is a named expression

is_numeric_type()
Return True if this class is a Pyomo numeric object

is_parameter_type()
Return False unless this class is a parameter object

is_reference()
Return True if this component is a reference, where "reference" is interpreted as any component that does not own its own data.

is_variable_type()
Return False unless this class is a variable object

items()
Return an iterator of (index,data) tuples from the dictionary

iteritems()
DEPRECATED.

Return a list (index,data) tuples from the dictionary

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.items().

iterkeys()
DEPRECATED.

Return a list of keys in the dictionary

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()
DEPRECATED.

Return a list of the component data objects in the dictionary

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.values().

keys()
Iterate over the keys in the dictionary

load(*arg*, *namespaces=[None]*, *profile_memory=0*, *report_timing=None*)
Load the model with data from a file, dictionary or DataPortal object.

property local_name
Get the component name only within the context of the immediate parent container.

model()
Return the model of the component that owns this data.

property name
Get the fully qualifed component name.

parent_block()
Return the parent of the component that owns this data.

parent_component()
Returns the component associated with this object.

pprint(*ostream=None*, *verbose=False*, *prefix=''*)
Print component information

preprocess(*preprocessor=None*)
DEPRECATED.

Deprecated since version 6.0: The Model.preprocess() method is deprecated and no longer performs any actions

reclassify_component_type(*name_or_object*, *new_ctype*, *preserve_declaration_order=True*)
TODO

reconstruct(*data=None*)
REMOVED: reconstruct() was removed in Pyomo 6.0.

Re-constructing model components was fragile and did not correctly update instances of the component used in other components or contexts (this was particularly problemmatic for Var, Param, and Set). Users who wish to reproduce the old behavior of reconstruct(), are comfortable manipulating non-public interfaces, and who take the time to verify that the correct thing happens to their model can approximate the old behavior of reconstruct with:

component.clear() component._constructed = False component.construct()

root_block()
Return self.model()

set_suffix_value(*suffix_or_name*, *value*, *expand=True*)
Set the suffix value for this component data

to_dense_data()
TODO

to_string(*verbose=None*, *labeler=None*, *smap=None*, *compute_values=False*)
Return a string representation of this component, applying the labeler if passed one.

transfer_attributes_from(*src*)
Transfer user-defined attributes from src to this block

This transfers all components and user-defined attributes from the block or dictionary *src* and places them on this Block. Components are transferred in declaration order.

If a Component on *src* is also declared on this block as either a Component or attribute, the local Component or attribute is replaced by the incoming component. If an attribute name on *src* matches a Component declared on this block, then the incoming attribute is passed to the local Component's *set_value()* method. Attribute names appearing in this block's *_Block_reserved_words* set will not be transferred (although Components will be).

Parameters **src** (*_BlockData or dict*) – The Block or mapping that contains the new attributes to assign to this block.

transform(*name=None*, ***kwds*)
DEPRECATED.

Deprecated since version 4.3.11323: Model.transform() is deprecated.

type()
DEPRECATED.

Return the class type for this component

Deprecated since version 5.7: Component.type() method has been replaced by the .ctype property.

valid_model_component()
Return True if this can be used as a model component.

valid_problem_types()
This method allows the pyomo.opt convert function to work with a Model object.

values()
Return an iterator of the component data objects in the dictionary

write(*filename=None*, *format=None*, *solver_capability=None*, *io_options={}*)
Write the model to a file, with a given format.

class pyomo.environ.**AbstractModel**(**args*, ***kwds*)
Bases: pyomo.core.base.PyomoModel.Model

An abstract optimization model that defers construction of components.

activate()
Set the active attribute to True

property active
Return the active attribute

active_blocks(**args*, ***kwargs*)
DEPRECATED.

Deprecated since version 4.1.10486: The active_blocks method is deprecated. Use the Block.block_data_objects() method.

active_component_data(**args*, ***kwargs*)
DEPRECATED.

Deprecated since version 4.1.10486: The active_component_data method is deprecated. Use the Block.component_data_objects() method.

active_components(**args*, ***kwargs*)
DEPRECATED.

Deprecated since version 4.1.10486: The active_components method is deprecated. Use the Block.component_objects() method.

add_component(*name*, *val*)
Add a component 'name' to the block.

This method assumes that the attribute is not in the model.

all_blocks(**args*, ***kwargs*)
DEPRECATED.

Deprecated since version 4.1.10486: The all_blocks method is deprecated. Use the Block.block_data_objects() method.

all_component_data(**args*, ***kwargs*)
DEPRECATED.

Deprecated since version 4.1.10486: The all_component_data method is deprecated. Use the Block.component_data_objects() method.

all_components(**args*, ***kwargs*)
DEPRECATED.

Deprecated since version 4.1.10486: The all_components method is deprecated. Use the Block.component_objects() method.

block_data_objects(*active=None*, *sort=False*, *descend_into=True*, *descent_order=None*)
This method returns a generator that iterates through the current block and recursively all sub-blocks. This is semantically equivalent to

component_data_objects(Block, ...)

clear_suffix_value(*suffix_or_name*, *expand=True*)
Set the suffix value for this component data

clone()
TODO

cname(**args*, ***kwds*)
DEPRECATED.

Deprecated since version 5.0: The cname() method has been renamed to getname(). The preferred method of obtaining a component name is to use the .name property, which returns the fully qualified component name. The .local_name property will return the component name only within the context of the immediate parent container.

collect_ctypes(*active=None*, *descend_into=True*)
Count all component types stored on or under this block.

Parameters

- **active** (*True/None*) – Set to True to indicate that only active components should be counted. The default value of None indicates that all components (including those that have been deactivated) should be counted.
- **descend_into** (*bool*) – Indicates whether or not component types should be counted on sub-blocks. Default is True.

Returns: A set of component types.

component(*name_or_object*)
Return a child component of this block.

If passed a string, this will return the child component registered by that name. If passed a component, this will return that component IFF the component is a child of this block. Returns None on lookup failure.

component_data_iterindex(*ctype=None*, *active=None*, *sort=False*, *descend_into=True*, *descent_order=None*)
Return a generator that returns a tuple for each component data object in a block. By default, this generator recursively descends into sub-blocks. The tuple is

((component name, index value), _ComponentData)

component_data_objects(*ctype=None*, *active=None*, *sort=False*, *descend_into=True*, *descent_order=None*)
Return a generator that iterates through the component data objects for all components in a block. By default, this generator recursively descends into sub-blocks.

component_map(*ctype=None*, *active=None*, *sort=False*)
Returns a PseudoMap of the components in this block.

Parameters

- **ctype** (*None or type or iterable*) – Specifies the component types (*ctypes*) to include in the resulting PseudoMap

None	All components
type	A single component type
iterable	All component types in the iterable

- **active** (*None or bool*) – Filter components by the active flag

None	Return all components
True	Return only active components
False	Return only inactive components

- **sort** (*bool*) – Iterate over the components in a sorted otder

True	Iterate using Block.alphabetizeComponentAndIndex
False	Iterate using Block.declarationOrder

component_objects(*ctype=None*, *active=None*, *sort=False*, *descend_into=True*, *descent_order=None*)
Return a generator that iterates through the component objects in a block. By default, the generator recursively descends into sub-blocks.

compute_statistics(*active=True*)
Compute model statistics

construct(*data=None*)
Initialize the block

contains_component(*ctype*)
Return True if the component type is in _ctypes and ... TODO.

create(*filename=None*, ***kwargs*)
DEPRECATED.

Create a concrete instance of this Model, possibly using data read in from a file.

Deprecated since version 4.3.11323: The Model.create() method is deprecated. Call Model.create_instance() to create a concrete instance from an abstract model. You do not need to call Model.create() for a concrete model.

create_instance(*filename=None*, *data=None*, *name=None*, *namespace=None*, *namespaces=None*, *profile_memory=0*, *report_timing=False*, ***kwds*)
Create a concrete instance of an abstract model, possibly using data read in from a file.

Parameters

- **filename** (*str*, optional) – The name of a Pyomo Data File that will be used to load data into the model.
- **data** (*dict*, optional) – A dictionary containing initialization data for the model to be used if there is no filename
- **name** (*str*, optional) – The name given to the model.
- **namespace** (*str*, optional) – A namespace used to select data.
- **namespaces** (*list*, optional) – A list of namespaces used to select data.
- **profile_memory** (*int*, optional) – A number that indicates the profiling level.
- **report_timing** (*bool*, optional) – Report timing statistics during construction.

property ctype
Return the class type for this component

deactivate()
Set the active attribute to False

del_component(*name_or_object*)
Delete a component from this block.

dim()
Return the dimension of the index

display(*filename=None*, *ostream=None*, *prefix=''*)
Display values in the block

find_component(*label_or_component*)
Return a block component given a name.

get_suffix_value(*suffix_or_name*, *default=None*)
Get the suffix value for this component data

getname(*fully_qualified=False*, *name_buffer=None*, *relative_to=None*)
Return a string with the component name and index

id_index_map()
Return an dictionary id->index for all ComponentData instances.

index()
Returns the index of this ComponentData instance relative to the parent component index set. None is returned if this instance does not have a parent component, or if - for some unknown reason - this instance does not belong to the parent component's index set. This method is not intended to be a fast method; it should be used rarely, primarily in cases of label formulation.

index_set()
Return the index set

is_component_type()
Return True if this class is a Pyomo component

is_constructed()
A boolean indicating whether or not all *active* components of the input model have been properly constructed.

is_expression_type()
Return True if this numeric value is an expression

is_indexed()
Return true if this component is indexed

is_logical_type()
Return True if this class is a Pyomo Boolean value, variable, or expression.

is_named_expression_type()
Return True if this numeric value is a named expression

is_numeric_type()
Return True if this class is a Pyomo numeric object

is_parameter_type()
Return False unless this class is a parameter object

is_reference()
Return True if this component is a reference, where "reference" is interpreted as any component that does not own its own data.

is_variable_type()
Return False unless this class is a variable object

items()
Return an iterator of (index,data) tuples from the dictionary

iteritems()
DEPRECATED.

Return a list (index,data) tuples from the dictionary

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.items().

iterkeys()
DEPRECATED.

Return a list of keys in the dictionary

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()
DEPRECATED.

Return a list of the component data objects in the dictionary

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.values().

keys()
Iterate over the keys in the dictionary

load(*arg*, *namespaces=[None]*, *profile_memory=0*, *report_timing=None*)
Load the model with data from a file, dictionary or DataPortal object.

property local_name
Get the component name only within the context of the immediate parent container.

model()
Return the model of the component that owns this data.

property name
Get the fully qualifed component name.

parent_block()
Return the parent of the component that owns this data.

parent_component()
Returns the component associated with this object.

pprint(*ostream=None*, *verbose=False*, *prefix=''*)
Print component information

preprocess(*preprocessor=None*)
DEPRECATED.

Deprecated since version 6.0: The Model.preprocess() method is deprecated and no longer performs any actions

reclassify_component_type(*name_or_object*, *new_ctype*, *preserve_declaration_order=True*)
TODO

reconstruct(*data=None*)
REMOVED: reconstruct() was removed in Pyomo 6.0.

Re-constructing model components was fragile and did not correctly update instances of the component used in other components or contexts (this was particularly problemmatic for Var, Param, and Set). Users who wish to reproduce the old behavior of reconstruct(), are comfortable manipulating non-public interfaces, and who take the time to verify that the correct thing happens to their model can approximate the old behavior of reconstruct with:

component.clear() component._constructed = False component.construct()

root_block()
Return self.model()

set_suffix_value(*suffix_or_name*, *value*, *expand=True*)
Set the suffix value for this component data

to_dense_data()
TODO

to_string(*verbose=None*, *labeler=None*, *smap=None*, *compute_values=False*)
Return a string representation of this component, applying the labeler if passed one.

transfer_attributes_from(*src*)
Transfer user-defined attributes from src to this block

This transfers all components and user-defined attributes from the block or dictionary *src* and places them on this Block. Components are transferred in declaration order.

If a Component on *src* is also declared on this block as either a Component or attribute, the local Component or attribute is replaced by the incoming component. If an attribute name on *src* matches a Component declared on this block, then the incoming attribute is passed to the local Component's *set_value()* method. Attribute names appearing in this block's *_Block_reserved_words* set will not be transferred (although Components will be).

Parameters **src** (*_BlockData or dict*) – The Block or mapping that contains the new attributes to assign to this block.

transform(*name=None*, ***kwds*)
DEPRECATED.

Deprecated since version 4.3.11323: Model.transform() is deprecated.

type()
DEPRECATED.

Return the class type for this component

Deprecated since version 5.7: Component.type() method has been replaced by the .ctype property.

valid_model_component()
Return True if this can be used as a model component.

valid_problem_types()
This method allows the pyomo.opt convert function to work with a Model object.

values()
Return an iterator of the component data objects in the dictionary

write(*filename=None*, *format=None*, *solver_capability=None*, *io_options={}*)
Write the model to a file, with a given format.

class pyomo.environ.**Block**(**args*, ***kwds*)
Bases: pyomo.core.base.indexed_component.ActiveIndexedComponent

Blocks are indexed components that contain other components (including blocks). Blocks have a global attribute that defines whether construction is deferred. This applies to all components that they contain except blocks. Blocks contained by other blocks use their local attribute to determine whether construction is deferred.

activate()
Set the active attribute to True

property active
Return the active attribute

clear()
Clear the data in this component

clear_suffix_value(*suffix_or_name*, *expand=True*)
Clear the suffix value for this component data

cname(**args*, ***kwds*)
DEPRECATED.

Deprecated since version 5.0: The cname() method has been renamed to getname(). The preferred method of obtaining a component name is to use the .name property, which returns the fully qualified component

name. The .local_name property will return the component name only within the context of the immediate parent container.

construct(*data=None*)
Initialize the block

property ctype
Return the class type for this component

deactivate()
Set the active attribute to False

dim()
Return the dimension of the index

display(*filename=None*, *ostream=None*, *prefix=''*)
Display values in the block

get_suffix_value(*suffix_or_name*, *default=None*)
Get the suffix value for this component data

getname(*fully_qualified=False*, *name_buffer=None*, *relative_to=None*)
Returns the component name associated with this object.

Parameters

- **fully_qualified** (*bool*) – Generate full name from nested block names
- **name_buffer** (*dict*) – A dictionary that caches encountered names and indices. Providing a `name_buffer` can significantly speed up iterative name generation
- **relative_to** (Block) – Generate fully_qualified names reletive to the specified block.

id_index_map()
Return an dictionary id->index for all ComponentData instances.

index_set()
Return the index set

is_component_type()
Return True if this class is a Pyomo component

is_constructed()
Return True if this class has been constructed

is_expression_type()
Return True if this numeric value is an expression

is_indexed()
Return true if this component is indexed

is_logical_type()
Return True if this class is a Pyomo Boolean value, variable, or expression.

is_named_expression_type()
Return True if this numeric value is a named expression

is_numeric_type()
Return True if this class is a Pyomo numeric object

is_parameter_type()
Return False unless this class is a parameter object

is_reference()
Return True if this component is a reference, where "reference" is interpreted as any component that does not own its own data.

is_variable_type()
Return False unless this class is a variable object

items()
Return an iterator of (index,data) tuples from the dictionary

iteritems()
DEPRECATED.

Return a list (index,data) tuples from the dictionary

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.items().

iterkeys()
DEPRECATED.

Return a list of keys in the dictionary

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()
DEPRECATED.

Return a list of the component data objects in the dictionary

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.values().

keys()
Iterate over the keys in the dictionary

property local_name
Get the component name only within the context of the immediate parent container.

model()
Returns the model associated with this object.

property name
Get the fully qualifed component name.

parent_block()
Returns the parent of this object.

parent_component()
Returns the component associated with this object.

pprint(*ostream=None*, *verbose=False*, *prefix=''*)
Print component information

reconstruct(*data=None*)
REMOVED: reconstruct() was removed in Pyomo 6.0.

Re-constructing model components was fragile and did not correctly update instances of the component used in other components or contexts (this was particularly problemmatic for Var, Param, and Set). Users who wish to reproduce the old behavior of reconstruct(), are comfortable manipulating non-public interfaces, and who take the time to verify that the correct thing happens to their model can approximate the old behavior of reconstruct with:

component.clear() component._constructed = False component.construct()

root_block()
Return self.model()

set_suffix_value(*suffix_or_name*, *value*, *expand=True*)
Set the suffix value for this component data

set_value(*value*)
Set the value of a scalar component.

to_dense_data()
TODO

to_string(*verbose=None*, *labeler=None*, *smap=None*, *compute_values=False*)
Return the component name

type()
DEPRECATED.

Return the class type for this component

Deprecated since version 5.7: Component.type() method has been replaced by the .ctype property.

valid_model_component()
Return True if this can be used as a model component.

values()
Return an iterator of the component data objects in the dictionary

class pyomo.environ.**Constraint**(**args*, ***kwds*)
Bases: pyomo.core.base.indexed_component.ActiveIndexedComponent

This modeling component defines a constraint expression using a rule function.

Constructor arguments:

expr A Pyomo expression for this constraint

rule A function that is used to construct constraint expressions

doc A text string describing this component

name A name for this component

Public class attributes:

doc A text string describing this component

name A name for this component

active A boolean that is true if this component will be used to construct a model instance

rule The rule used to initialize the constraint(s)

Private class attributes:

_constructed A boolean that is true if this component has been constructed

_data A dictionary from the index set to component data objects

_index The set of valid indices

_implicit_subsets A tuple of set objects that represents the index set

_model A weakref to the model that owns this component

_parent A weakref to the parent block that owns this component

_type The class type for the derived subclass

activate()
Set the active attribute to True

property active
Return the active attribute

clear()
Clear the data in this component

clear_suffix_value(*suffix_or_name*, *expand=True*)
Clear the suffix value for this component data

cname(**args*, ***kwds*)
DEPRECATED.

Deprecated since version 5.0: The cname() method has been renamed to getname(). The preferred method of obtaining a component name is to use the .name property, which returns the fully qualified component name. The .local_name property will return the component name only within the context of the immediate parent container.

construct(*data=None*)
Construct the expression(s) for this constraint.

property ctype
Return the class type for this component

deactivate()
Set the active attribute to False

dim()
Return the dimension of the index

display(*prefix=''*, *ostream=None*)
Print component state information

This duplicates logic in Component.pprint()

get_suffix_value(*suffix_or_name*, *default=None*)
Get the suffix value for this component data

getname(*fully_qualified=False*, *name_buffer=None*, *relative_to=None*)
Returns the component name associated with this object.

Parameters

- **fully_qualified** (*bool*) – Generate full name from nested block names
- **name_buffer** (*dict*) – A dictionary that caches encountered names and indices. Providing a `name_buffer` can significantly speed up iterative name generation
- **relative_to** (Block) – Generate fully_qualified names reletive to the specified block.

id_index_map()
Return an dictionary id->index for all ComponentData instances.

index_set()
Return the index set

is_component_type()
Return True if this class is a Pyomo component

is_constructed()
Return True if this class has been constructed

is_expression_type()
Return True if this numeric value is an expression

is_indexed()
Return true if this component is indexed

is_logical_type()
Return True if this class is a Pyomo Boolean value, variable, or expression.

is_named_expression_type()
Return True if this numeric value is a named expression

is_numeric_type()
Return True if this class is a Pyomo numeric object

is_parameter_type()
Return False unless this class is a parameter object

is_reference()
Return True if this component is a reference, where "reference" is interpreted as any component that does not own its own data.

is_variable_type()
Return False unless this class is a variable object

items()
Return an iterator of (index,data) tuples from the dictionary

iteritems()
DEPRECATED.

Return a list (index,data) tuples from the dictionary

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.items().

iterkeys()
DEPRECATED.

Return a list of keys in the dictionary

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()
DEPRECATED.

Return a list of the component data objects in the dictionary

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.values().

keys()
Iterate over the keys in the dictionary

property local_name
Get the component name only within the context of the immediate parent container.

model()
Returns the model associated with this object.

property name
Get the fully qualifed component name.

parent_block()
Returns the parent of this object.

parent_component()
Returns the component associated with this object.

pprint(*ostream=None*, *verbose=False*, *prefix=''*)
Print component information

reconstruct(*data=None*)
REMOVED: reconstruct() was removed in Pyomo 6.0.

Re-constructing model components was fragile and did not correctly update instances of the component used in other components or contexts (this was particularly problemmatic for Var, Param, and Set). Users who wish to reproduce the old behavior of reconstruct(), are comfortable manipulating non-public interfaces, and who take the time to verify that the correct thing happens to their model can approximate the old behavior of reconstruct with:

component.clear() component._constructed = False component.construct()

root_block()
Return self.model()

set_suffix_value(*suffix_or_name*, *value*, *expand=True*)
Set the suffix value for this component data

set_value(*value*)
Set the value of a scalar component.

to_dense_data()
TODO

to_string(*verbose=None*, *labeler=None*, *smap=None*, *compute_values=False*)
Return the component name

type()
DEPRECATED.

Return the class type for this component

Deprecated since version 5.7: Component.type() method has been replaced by the .ctype property.

valid_model_component()
Return True if this can be used as a model component.

values()
Return an iterator of the component data objects in the dictionary

class pyomo.environ.**Objective**(**args*, ***kwds*)
Bases: pyomo.core.base.indexed_component.ActiveIndexedComponent

This modeling component defines an objective expression.

Note that this is a subclass of NumericValue to allow objectives to be used as part of expressions.

Constructor arguments:

expr A Pyomo expression for this objective

rule A function that is used to construct objective expressions

sense Indicate whether minimizing (the default) or maximizing

doc A text string describing this component

name A name for this component

Public class attributes:

doc A text string describing this component

name A name for this component

active A boolean that is true if this component will be used to construct a model instance

rule The rule used to initialize the objective(s)

sense The objective sense

Private class attributes:

_constructed A boolean that is true if this component has been constructed

_data A dictionary from the index set to component data objects

_index The set of valid indices

_implicit_subsets A tuple of set objects that represents the index set

_model A weakref to the model that owns this component

_parent A weakref to the parent block that owns this component

_type The class type for the derived subclass

`activate()`
Set the active attribute to True

`property active`
Return the active attribute

`clear()`
Clear the data in this component

`clear_suffix_value(suffix_or_name, expand=True)`
Clear the suffix value for this component data

`cname(*args, **kwds)`
DEPRECATED.

Deprecated since version 5.0: The cname() method has been renamed to getname(). The preferred method of obtaining a component name is to use the .name property, which returns the fully qualified component name. The .local_name property will return the component name only within the context of the immediate parent container.

`construct(data=None)`
Construct the expression(s) for this objective.

`property ctype`
Return the class type for this component

`deactivate()`
Set the active attribute to False

`dim()`
Return the dimension of the index

`display(prefix='', ostream=None)`
Provide a verbose display of this object

`get_suffix_value(suffix_or_name, default=None)`
Get the suffix value for this component data

`getname(fully_qualified=False, name_buffer=None, relative_to=None)`
Returns the component name associated with this object.

Parameters

- **fully_qualified** (*bool*) – Generate full name from nested block names

- **name_buffer** (*dict*) – A dictionary that caches encountered names and indices. Providing a `name_buffer` can significantly speed up iterative name generation
- **relative_to** (`Block`) – Generate fully_qualified names reletive to the specified block.

id_index_map()
Return an dictionary id->index for all ComponentData instances.

index_set()
Return the index set

is_component_type()
Return True if this class is a Pyomo component

is_constructed()
Return True if this class has been constructed

is_expression_type()
Return True if this numeric value is an expression

is_indexed()
Return true if this component is indexed

is_logical_type()
Return True if this class is a Pyomo Boolean value, variable, or expression.

is_named_expression_type()
Return True if this numeric value is a named expression

is_numeric_type()
Return True if this class is a Pyomo numeric object

is_parameter_type()
Return False unless this class is a parameter object

is_reference()
Return True if this component is a reference, where "reference" is interpreted as any component that does not own its own data.

is_variable_type()
Return False unless this class is a variable object

items()
Return an iterator of (index,data) tuples from the dictionary

iteritems()
DEPRECATED.

Return a list (index,data) tuples from the dictionary

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.items().

iterkeys()
DEPRECATED.

Return a list of keys in the dictionary

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()
DEPRECATED.

Return a list of the component data objects in the dictionary

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.values().

keys()
Iterate over the keys in the dictionary

property local_name
Get the component name only within the context of the immediate parent container.

model()
Returns the model associated with this object.

property name
Get the fully qualifed component name.

parent_block()
Returns the parent of this object.

parent_component()
Returns the component associated with this object.

pprint(*ostream=None*, *verbose=False*, *prefix=''*)
Print component information

reconstruct(*data=None*)
REMOVED: reconstruct() was removed in Pyomo 6.0.

Re-constructing model components was fragile and did not correctly update instances of the component used in other components or contexts (this was particularly problemmatic for Var, Param, and Set). Users who wish to reproduce the old behavior of reconstruct(), are comfortable manipulating non-public interfaces, and who take the time to verify that the correct thing happens to their model can approximate the old behavior of reconstruct with:

component.clear() component._constructed = False component.construct()

root_block()
Return self.model()

set_suffix_value(*suffix_or_name*, *value*, *expand=True*)
Set the suffix value for this component data

set_value(*value*)
Set the value of a scalar component.

to_dense_data()
TODO

to_string(*verbose=None*, *labeler=None*, *smap=None*, *compute_values=False*)
Return the component name

type()
DEPRECATED.

Return the class type for this component

Deprecated since version 5.7: Component.type() method has been replaced by the .ctype property.

valid_model_component()
Return True if this can be used as a model component.

values()
Return an iterator of the component data objects in the dictionary

class pyomo.environ.**Param**(**args*, ***kwds*)
Bases: pyomo.core.base.indexed_component.IndexedComponent, pyomo.core.base.indexed_component.IndexedComponent_NDArrayMixin

A parameter value, which may be defined over an index.

Constructor Arguments:

name The name of this parameter

index The index set that defines the distinct parameters. By default, this is None, indicating that there is a single parameter.

domain A set that defines the type of values that each parameter must be.

within A set that defines the type of values that each parameter must be.

validate A rule for validating this parameter w.r.t. data that exists in the model

default A scalar, rule, or dictionary that defines default values for this parameter

initialize A dictionary or rule for setting up this parameter with existing model data

unit: pyomo unit expression An expression containing the units for the parameter

mutable: *boolean* Flag indicating if the value of the parameter may change between calls to a solver. Defaults to *False*

`class NoValue`
Bases: `object`

A dummy type that is pickle-safe that we can use as the default value for Params to indicate that no valid value is present.

`property active`
Return the active attribute

`clear()`
Clear the data in this component

`clear_suffix_value(suffix_or_name, expand=True)`
Clear the suffix value for this component data

`cname(*args, **kwds)`
DEPRECATED.

Deprecated since version 5.0: The cname() method has been renamed to getname(). The preferred method of obtaining a component name is to use the .name property, which returns the fully qualified component name. The .local_name property will return the component name only within the context of the immediate parent container.

`construct(data=None)`
Initialize this component.

A parameter is constructed using the initial data or the data loaded from an external source. We first set all the values based on self._rule, and then allow the data dictionary to overwrite anything.

Note that we allow an undefined Param value to be constructed. We throw an exception if a user tries to use an uninitialized Param.

`property ctype`
Return the class type for this component

`default()`
Return the value of the parameter default.

Possible values:

Param.NoValue No default value is provided.

Numeric A constant value that is the default value for all undefined parameters.

Function f(model, i) returns the value for the default value for parameter i

dim()
Return the dimension of the index

extract_values()
A utility to extract all index-value pairs defined for this parameter, returned as a dictionary.

This method is useful in contexts where key iteration and repeated __getitem__ calls are too expensive to extract the contents of a parameter.

extract_values_sparse()
A utility to extract all index-value pairs defined with non-default values, returned as a dictionary.

This method is useful in contexts where key iteration and repeated __getitem__ calls are too expensive to extract the contents of a parameter.

get_suffix_value(*suffix_or_name*, *default=None*)
Get the suffix value for this component data

get_units()
Return the units for this ParamData

getname(*fully_qualified=False*, *name_buffer=None*, *relative_to=None*)
Returns the component name associated with this object.

Parameters

- **fully_qualified** (*bool*) – Generate full name from nested block names
- **name_buffer** (*dict*) – A dictionary that caches encountered names and indices. Providing a name_buffer can significantly speed up iterative name generation
- **relative_to** (Block) – Generate fully_qualified names reletive to the specified block.

id_index_map()
Return an dictionary id->index for all ComponentData instances.

index_set()
Return the index set

is_component_type()
Return True if this class is a Pyomo component

is_constructed()
Return True if this class has been constructed

is_expression_type()
Return True if this numeric value is an expression

is_indexed()
Return true if this component is indexed

is_logical_type()
Return True if this class is a Pyomo Boolean value, variable, or expression.

is_named_expression_type()
Return True if this numeric value is a named expression

is_numeric_type()
Return True if this class is a Pyomo numeric object

is_parameter_type()
Return False unless this class is a parameter object

is_reference()
Return True if this component is a reference, where "reference" is interpreted as any component that does not own its own data.

is_variable_type()
Return False unless this class is a variable object

items()
Return an iterator of (index,data) tuples from the dictionary

iteritems()
DEPRECATED.

Return a list (index,data) tuples from the dictionary

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.items().

iterkeys()
DEPRECATED.

Return a list of keys in the dictionary

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()
DEPRECATED.

Return a list of the component data objects in the dictionary

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.values().

keys()
Iterate over the keys in the dictionary. If the default value is specified, then iterate over all keys in the component index.

property local_name
Get the component name only within the context of the immediate parent container.

model()
Returns the model associated with this object.

property name
Get the fully qualifed component name.

parent_block()
Returns the parent of this object.

parent_component()
Returns the component associated with this object.

pprint(*ostream=None*, *verbose=False*, *prefix=''*)
Print component information

reconstruct(*data=None*)
REMOVED: reconstruct() was removed in Pyomo 6.0.

Re-constructing model components was fragile and did not correctly update instances of the component used in other components or contexts (this was particularly problemmatic for Var, Param, and Set). Users who wish to reproduce the old behavior of reconstruct(), are comfortable manipulating non-public interfaces, and who take the time to verify that the correct thing happens to their model can approximate the old behavior of reconstruct with:

component.clear() component._constructed = False component.construct()

root_block()
Return self.model()

set_default(*val*)
Perform error checks and then set the default value for this parameter.

NOTE: this test will not validate the value of function return values.

set_suffix_value(*suffix_or_name*, *value*, *expand=True*)
Set the suffix value for this component data

set_value(*value*)
Set the value of a scalar component.

sparse_items()
Return a list (index,data) tuples for defined parameters

sparse_iteritems()
Return an iterator of (index,data) tuples for defined parameters

sparse_iterkeys()
Return an iterator for the keys in the defined parameters

sparse_itervalues()
Return an iterator for the defined param data objects

sparse_keys()
Return a list of keys in the defined parameters

sparse_values()
Return a list of the defined param data objects

store_values(*new_values*, *check=True*)
A utility to update a Param with a dictionary or scalar.

If check=True, then both the index and value are checked through the __getitem__ method. Using check=False should only be used by developers!

to_dense_data()
TODO

to_string(*verbose=None*, *labeler=None*, *smap=None*, *compute_values=False*)
Return the component name

type()
DEPRECATED.

Return the class type for this component

Deprecated since version 5.7: Component.type() method has been replaced by the .ctype property.

valid_model_component()
Return True if this can be used as a model component.

values()
Return an iterator of the component data objects in the dictionary

class pyomo.environ.**RangeSet**(**args*, ***kwds*)
Bases: pyomo.core.base.component.Component

A set object that represents a set of numeric values

RangeSet objects are based around *NumericRange* objects, which include support for non-finite ranges (both continuous and unbounded). Similarly, boutique ranges (like semi-continuous domains) can be represented, e.g.:

```
>>> from pyomo.core.base.range import NumericRange
>>> from pyomo.environ import RangeSet
>>> print(RangeSet(ranges=(NumericRange(0,0,0), NumericRange(1,100,0))))
([0] | [1..100])
```

The *RangeSet* object continues to support the notation for specifying discrete ranges using "[first=1], last, [step=1]" values:

```
>>> r = RangeSet(3)
>>> print(r)
[1:3]
>>> print(list(r))
[1, 2, 3]

>>> r = RangeSet(2, 5)
>>> print(r)
[2:5]
>>> print(list(r))
[2, 3, 4, 5]

>>> r = RangeSet(2, 5, 2)
>>> print(r)
[2:4:2]
>>> print(list(r))
[2, 4]

>>> r = RangeSet(2.5, 4, 0.5)
>>> print(r)
([2.5] | [3.0] | [3.5] | [4.0])
>>> print(list(r))
[2.5, 3.0, 3.5, 4.0]
```

By implementing RangeSet using NumericRanges, the global Sets (like *Reals*, *Integers*, *PositiveReals*, etc.) are trivial instances of a RangeSet and support all Set operations.

Parameters

- ***args** (*int | float | None*) – The range defined by ([start=1], end, [step=1]). If only a single positional parameter, *end* is supplied, then the RangeSet will be the integers starting at 1 up through and including end. Providing two positional arguments, *x* and *y*, will result in a range starting at x up to and including y, incrementing by 1. Providing a 3-tuple enables the specification of a step other than 1.
- **finite** (*bool, optional*) – This sets if this range is finite (discrete and bounded) or infinite
- **ranges** (*iterable, optional*) – The list of range objects that compose this RangeSet
- **bounds** (*tuple, optional*) – The lower and upper bounds of values that are admissible in this RangeSet
- **filter** (*function, optional*) – Function (rule) that returns True if the specified value is in the RangeSet or False if it is not.

- **validate** (*function, optional*) – Data validation function (rule). The function will be called for every data member of the set, and if it returns False, a ValueError will be raised.

property active
Return the active attribute

clear_suffix_value(*suffix_or_name*, *expand=True*)
Clear the suffix value for this component data

cname(**args*, ***kwds*)
DEPRECATED.

Deprecated since version 5.0: The cname() method has been renamed to getname(). The preferred method of obtaining a component name is to use the .name property, which returns the fully qualified component name. The .local_name property will return the component name only within the context of the immediate parent container.

construct(*data=None*)
API definition for constructing components

property ctype
Return the class type for this component

get_suffix_value(*suffix_or_name*, *default=None*)
Get the suffix value for this component data

getname(*fully_qualified=False*, *name_buffer=None*, *relative_to=None*)
Returns the component name associated with this object.

Parameters

- **fully_qualified** (*bool*) – Generate full name from nested block names
- **name_buffer** (*dict*) – A dictionary that caches encountered names and indices. Providing a `name_buffer` can significantly speed up iterative name generation
- **relative_to** (`Block`) – Generate fully_qualified names reletive to the specified block.

is_component_type()
Return True if this class is a Pyomo component

is_constructed()
Return True if this class has been constructed

is_expression_type()
Return True if this numeric value is an expression

is_indexed()
Return true if this component is indexed

is_logical_type()
Return True if this class is a Pyomo Boolean value, variable, or expression.

is_named_expression_type()
Return True if this numeric value is a named expression

is_numeric_type()
Return True if this class is a Pyomo numeric object

is_parameter_type()
Return False unless this class is a parameter object

is_reference()
Return True if this object is a reference.

is_variable_type()
Return False unless this class is a variable object

property local_name
Get the component name only within the context of the immediate parent container.

model()
Returns the model associated with this object.

property name
Get the fully qualifed component name.

parent_block()
Returns the parent of this object.

parent_component()
Returns the component associated with this object.

pprint(*ostream=None*, *verbose=False*, *prefix=''*)
Print component information

reconstruct(*data=None*)
REMOVED: reconstruct() was removed in Pyomo 6.0.

Re-constructing model components was fragile and did not correctly update instances of the component used in other components or contexts (this was particularly problemmatic for Var, Param, and Set). Users who wish to reproduce the old behavior of reconstruct(), are comfortable manipulating non-public interfaces, and who take the time to verify that the correct thing happens to their model can approximate the old behavior of reconstruct with:

component.clear() component._constructed = False component.construct()

root_block()
Return self.model()

set_suffix_value(*suffix_or_name*, *value*, *expand=True*)
Set the suffix value for this component data

to_string(*verbose=None*, *labeler=None*, *smap=None*, *compute_values=False*)
Return the component name

type()
DEPRECATED.

Return the class type for this component

Deprecated since version 5.7: Component.type() method has been replaced by the .ctype property.

valid_model_component()
Return True if this can be used as a model component.

pyomo.environ.**Reference**(*reference*, *ctype=<object object>*)
Creates a component that references other components

`Reference` generates a *reference component*; that is, an indexed component that does not contain data, but instead references data stored in other components as defined by a component slice. The ctype parameter sets the `Component.type()` of the resulting indexed component. If the ctype parameter is not set and all data identified by the slice (at construction time) share a common `Component.type()`, then that type is assumed. If either the ctype parameter is `None` or the data has more than one ctype, the resulting indexed component will have a ctype of `IndexedComponent`.

If the indices associated with wildcards in the component slice all refer to the same *Set* objects for all data identifed by the slice, then the resulting indexed component will be indexed by the product of those sets. However,

if all data do not share common set objects, or only a subset of indices in a multidimentional set appear as wildcards, then the resulting indexed component will be indexed by a `SetOf` containing a `_ReferenceSet` for the slice.

Parameters

- **reference** (`IndexedComponent_slice`) – component slice that defines the data to include in the Reference component
- **ctype** (`type` [optional]) – the type used to create the resulting indexed component. If not specified, the data's ctype will be used (if all data share a common ctype). If multiple data ctypes are found or type is `None`, then `IndexedComponent` will be used.

Examples

```
>>> from pyomo.environ import *
>>> m = ConcreteModel()
>>> @m.Block([1,2],[3,4])
... def b(b,i,j):
...     b.x = Var(bounds=(i,j))
...
>>> m.r1 = Reference(m.b[:,:].x)
>>> m.r1.pprint()
r1 : Size=4, Index=r1_index
    Key    : Lower : Value : Upper : Fixed : Stale : Domain
    (1, 3) :     1 :  None :     3 : False :  True :  Reals
    (1, 4) :     1 :  None :     4 : False :  True :  Reals
    (2, 3) :     2 :  None :     3 : False :  True :  Reals
    (2, 4) :     2 :  None :     4 : False :  True :  Reals
```

Reference components may also refer to subsets of the original data:

```
>>> m.r2 = Reference(m.b[:,3].x)
>>> m.r2.pprint()
r2 : Size=2, Index=b_index_0
    Key : Lower : Value : Upper : Fixed : Stale : Domain
      1 :     1 :  None :     3 : False :  True :  Reals
      2 :     2 :  None :     3 : False :  True :  Reals
```

Reference components may have wildcards at multiple levels of the model hierarchy:

```
>>> from pyomo.environ import *
>>> m = ConcreteModel()
>>> @m.Block([1,2])
... def b(b,i):
...     b.x = Var([3,4], bounds=(i,None))
...
>>> m.r3 = Reference(m.b[:].x[:])
>>> m.r3.pprint()
r3 : Size=4, Index=r3_index
    Key    : Lower : Value : Upper : Fixed : Stale : Domain
    (1, 3) :     1 :  None :  None : False :  True :  Reals
    (1, 4) :     1 :  None :  None : False :  True :  Reals
```

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```
    (2, 3) :     2 :  None :  None : False :  True :  Reals
    (2, 4) :     2 :  None :  None : False :  True :  Reals
```

The resulting reference component may be used just like any other component. Changes to the stored data will be reflected in the original objects:

```
>>> m.r3[1,4] = 10
>>> m.b[1].x.pprint()
x : Size=2, Index=b[1].x_index
    Key : Lower : Value : Upper : Fixed : Stale : Domain
      3 :     1 :  None :  None : False :  True :  Reals
      4 :     1 :    10 :  None : False : False :  Reals
```

class pyomo.environ.**Set**(**args*, ***kwds*)

Bases: pyomo.core.base.indexed_component.IndexedComponent

A component used to index other Pyomo components.

This class provides a Pyomo component that is API-compatible with Python *set* objects, with additional features, including:

1. Member validation and filtering. The user can declare domains and provide callback functions to validate set members and to filter (ignore) potential members.
2. Set expressions. Operations on Set objects (&,|,*,-,^) produce Set expressions taht preserve their references to the original Set objects so that updating the argument Sets implicitly updates the Set operator instance.
3. Support for set operations with RangeSet instances (both finite and non-finite ranges).

Parameters

- **name** (*str, optional*) – The name of the set
- **doc** (*str, optional*) – A text string describing this component
- **initialize** (*initializer(iterable), optional*) – The initial values to store in the Set when it is constructed. Values passed to `initialize` may be overridden by `data` passed to the *construct()* method.
- **dimen** (*initializer(int), optional*) – Specify the Set's arity (the required tuple length for all members of the Set), or None if no arity is enforced
- **ordered** (*bool or Set.InsertionOrder or Set.SortedOrder or function*) – Specifies whether the set is ordered. Possible values are:

`False`	Unordered
`True`	Ordered by insertion order
`Set.InsertionOrder`	Ordered by insertion order [default]
`Set.SortedOrder`	Ordered by sort order
`<function>`	Ordered with this comparison function

- **within** (*initialiser(set), optional*) – A set that defines the valid values that can be contained in this set
- **domain** (*initializer(set), optional*) – A set that defines the valid values that can be contained in this set

- **bounds** (*initializer(tuple), optional*) – A tuple that specifies the bounds for valid Set values (accepts 1-, 2-, or 3-tuple RangeSet arguments)
- **filter** (*initializer(rule), optional*) – A rule for determining membership in this set. This has the functional form:

  ```
  f:  Block, *data -> bool
  ```

  and returns True if the data belongs in the set. Set will quietly ignore any values where *filter* returns False.
- **validate** (*initializer(rule), optional*) – A rule for validating membership in this set. This has the functional form:

  ```
  f:  Block, *data -> bool
  ```

  and returns True if the data belongs in the set. Set will raise a `ValueError` for any values where *validate* returns False.

Notes

Note: `domain=`, `within=`, and `bounds=` all provide restrictions on the valid set values. If more than one is specified, Set values will be restricted to the intersection of `domain`, `within`, and `bounds`.

---

property active
Return the active attribute

check_values()
DEPRECATED.

Verify that the values in this set are valid.

Deprecated since version 5.7: check_values() is deprecated: Sets only contain valid members

clear()
Clear the data in this component

clear_suffix_value(*suffix_or_name*, *expand=True*)
Clear the suffix value for this component data

cname(**args*, ***kwds*)
DEPRECATED.

Deprecated since version 5.0: The cname() method has been renamed to getname(). The preferred method of obtaining a component name is to use the .name property, which returns the fully qualified component name. The .local_name property will return the component name only within the context of the immediate parent container.

construct(*data=None*)
API definition for constructing components

property ctype
Return the class type for this component

dim()
Return the dimension of the index

get_suffix_value(*suffix_or_name*, *default=None*)
Get the suffix value for this component data

getname(*fully_qualified=False*, *name_buffer=None*, *relative_to=None*)
Returns the component name associated with this object.

Parameters

- **fully_qualified** (*bool*) – Generate full name from nested block names
- **name_buffer** (*dict*) – A dictionary that caches encountered names and indices. Providing a `name_buffer` can significantly speed up iterative name generation
- **relative_to** (`Block`) – Generate fully_qualified names reletive to the specified block.

id_index_map()
Return an dictionary id->index for all ComponentData instances.

index_set()
Return the index set

is_component_type()
Return True if this class is a Pyomo component

is_constructed()
Return True if this class has been constructed

is_expression_type()
Return True if this numeric value is an expression

is_indexed()
Return true if this component is indexed

is_logical_type()
Return True if this class is a Pyomo Boolean value, variable, or expression.

is_named_expression_type()
Return True if this numeric value is a named expression

is_numeric_type()
Return True if this class is a Pyomo numeric object

is_parameter_type()
Return False unless this class is a parameter object

is_reference()
Return True if this component is a reference, where "reference" is interpreted as any component that does not own its own data.

is_variable_type()
Return False unless this class is a variable object

items()
Return an iterator of (index,data) tuples from the dictionary

iteritems()
DEPRECATED.

Return a list (index,data) tuples from the dictionary

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.items().

iterkeys()
DEPRECATED.

Return a list of keys in the dictionary

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()
DEPRECATED.

Return a list of the component data objects in the dictionary

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.values().

keys()
Iterate over the keys in the dictionary

property local_name
Get the component name only within the context of the immediate parent container.

model()
Returns the model associated with this object.

property name
Get the fully qualifed component name.

parent_block()
Returns the parent of this object.

parent_component()
Returns the component associated with this object.

pprint(*ostream=None*, *verbose=False*, *prefix=''*)
Print component information

reconstruct(*data=None*)
REMOVED: reconstruct() was removed in Pyomo 6.0.

Re-constructing model components was fragile and did not correctly update instances of the component used in other components or contexts (this was particularly problemmatic for Var, Param, and Set). Users who wish to reproduce the old behavior of reconstruct(), are comfortable manipulating non-public interfaces, and who take the time to verify that the correct thing happens to their model can approximate the old behavior of reconstruct with:

component.clear() component._constructed = False component.construct()

root_block()
Return self.model()

set_suffix_value(*suffix_or_name*, *value*, *expand=True*)
Set the suffix value for this component data

set_value(*value*)
Set the value of a scalar component.

to_dense_data()
TODO

to_string(*verbose=None*, *labeler=None*, *smap=None*, *compute_values=False*)
Return the component name

type()
DEPRECATED.

Return the class type for this component

Deprecated since version 5.7: Component.type() method has been replaced by the .ctype property.

valid_model_component()
Return True if this can be used as a model component.

values()
Return an iterator of the component data objects in the dictionary

class pyomo.environ.**Var**(**args*, ***kwds*)
Bases: pyomo.core.base.indexed_component.IndexedComponent, pyomo.core.base.indexed_component.IndexedComponent_NDArrayMixin

A numeric variable, which may be defined over an index.

Parameters

- **domain** (*Set or function, optional*) – A Set that defines valid values for the variable (e.g., *Reals*, *NonNegativeReals*, *Binary*), or a rule that returns Sets. Defaults to *Reals*.
- **within** (*Set or function, optional*) – An alias for *domain*.
- **bounds** (*tuple or function, optional*) – A tuple of (lower, upper) bounds for the variable, or a rule that returns tuples. Defaults to (None, None).
- **initialize** (*float or function, optional*) – The initial value for the variable, or a rule that returns initial values.
- **rule** (*float or function, optional*) – An alias for *initialize*.
- **dense** (*bool, optional*) – Instantiate all elements from *index_set()* when constructing the Var (True) or just the variables returned by *initialize/rule* (False). Defaults to True.
- **units** (*pyomo units expression, optional*) – Set the units corresponding to the entries in this variable.

property active
Return the active attribute

add(*index*)
Add a variable with a particular index.

clear()
Clear the data in this component

clear_suffix_value(*suffix_or_name*, *expand=True*)
Clear the suffix value for this component data

cname(**args*, ***kwds*)
DEPRECATED.

Deprecated since version 5.0: The cname() method has been renamed to getname(). The preferred method of obtaining a component name is to use the .name property, which returns the fully qualified component name. The .local_name property will return the component name only within the context of the immediate parent container.

construct(*data=None*)
Construct this component.

property ctype
Return the class type for this component

dim()
Return the dimension of the index

extract_values(*include_fixed_values=True*)
Return a dictionary of index-value pairs.

flag_as_stale()
Set the 'stale' attribute of every variable data object to True.

get_suffix_value(*suffix_or_name*, *default=None*)
Get the suffix value for this component data

get_units()
Return the units expression for this Var.

get_values(*include_fixed_values=True*)
Return a dictionary of index-value pairs.

getname(*fully_qualified=False*, *name_buffer=None*, *relative_to=None*)
Returns the component name associated with this object.

Parameters

- **fully_qualified** (*bool*) – Generate full name from nested block names
- **name_buffer** (*dict*) – A dictionary that caches encountered names and indices. Providing a `name_buffer` can significantly speed up iterative name generation
- **relative_to** (`Block`) – Generate fully_qualified names reletive to the specified block.

id_index_map()
Return an dictionary id->index for all ComponentData instances.

index_set()
Return the index set

is_component_type()
Return True if this class is a Pyomo component

is_constructed()
Return True if this class has been constructed

is_expression_type()
Return True if this numeric value is an expression

is_indexed()
Return true if this component is indexed

is_logical_type()
Return True if this class is a Pyomo Boolean value, variable, or expression.

is_named_expression_type()
Return True if this numeric value is a named expression

is_numeric_type()
Return True if this class is a Pyomo numeric object

is_parameter_type()
Return False unless this class is a parameter object

is_reference()
Return True if this component is a reference, where "reference" is interpreted as any component that does not own its own data.

is_variable_type()
Return False unless this class is a variable object

items()
Return an iterator of (index,data) tuples from the dictionary

iteritems()
DEPRECATED.

Return a list (index,data) tuples from the dictionary

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.items().

iterkeys()
DEPRECATED.

Return a list of keys in the dictionary

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()
DEPRECATED.

Return a list of the component data objects in the dictionary

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.values().

keys()
Iterate over the keys in the dictionary

property local_name
Get the component name only within the context of the immediate parent container.

model()
Returns the model associated with this object.

property name
Get the fully qualifed component name.

parent_block()
Returns the parent of this object.

parent_component()
Returns the component associated with this object.

pprint(*ostream=None*, *verbose=False*, *prefix=''*)
Print component information

reconstruct(*data=None*)
REMOVED: reconstruct() was removed in Pyomo 6.0.

Re-constructing model components was fragile and did not correctly update instances of the component used in other components or contexts (this was particularly problemmatic for Var, Param, and Set). Users who wish to reproduce the old behavior of reconstruct(), are comfortable manipulating non-public interfaces, and who take the time to verify that the correct thing happens to their model can approximate the old behavior of reconstruct with:

component.clear() component._constructed = False component.construct()

root_block()
Return self.model()

set_suffix_value(*suffix_or_name*, *value*, *expand=True*)
Set the suffix value for this component data

set_value(*value*)
Set the value of a scalar component.

set_values(*new_values*, *valid=False*)
Set the values of a dictionary.

The default behavior is to validate the values in the dictionary.

to_dense_data()
TODO

to_string(*verbose=None*, *labeler=None*, *smap=None*, *compute_values=False*)
Return the component name

type()
DEPRECATED.

Return the class type for this component

Deprecated since version 5.7: Component.type() method has been replaced by the .ctype property.

valid_model_component()
Return True if this can be used as a model component.

values()
Return an iterator of the component data objects in the dictionary

13.3 Expression Reference

13.3.1 Utilities to Build Expressions

pyomo.core.util.**prod**(*terms*)
A utility function to compute the product of a list of terms.

Parameters **terms** (*list*) – A list of terms that are multiplied together.

Returns The value of the product, which may be a Pyomo expression object.

pyomo.core.util.**quicksum**(*args*, *start=0*, *linear=None*)
A utility function to compute a sum of Pyomo expressions.

The behavior of *quicksum()* is similar to the builtin `sum()` function, but this function generates a more compact Pyomo expression.

Parameters

- **args** – A generator for terms in the sum.
- **start** – A value that is initializes the sum. If this value is not a numeric constant, then the += operator is used to add terms to this object. Defaults to zero.
- **linear** – If `start` is not a numeric constant, then this option is ignored. Otherwise, this value indicates whether the terms in the sum are linear. If the value is `False`, then the terms are treated as nonlinear, and if `True`, then the terms are treated as linear. Default is `None`, which indicates that the first term in the `args` is used to determine this value.

Returns The value of the sum, which may be a Pyomo expression object.

pyomo.core.util.**sum_product**(**args*, ***kwds*)
A utility function to compute a generalized dot product.

This function accepts one or more components that provide terms that are multiplied together. These products are added together to form a sum.

Parameters

- ***args** – Variable length argument list of generators that create terms in the summation.
- ****kwds** – Arbitrary keyword arguments.

Keyword Arguments

- **index** – A set that is used to index the components used to create the terms

- **denom** – A component or tuple of components that are used to create the denominator of the terms
- **start** – The initial value used in the sum

Returns The value of the sum.

pyomo.core.util.**summation = <function sum_product>**
An alias for sum_product

pyomo.core.util.**dot_product = <function sum_product>**
An alias for sum_product

13.3.2 Utilities to Manage and Analyze Expressions

Functions

pyomo.core.expr.current.**expression_to_string**(*expr*, *verbose=None*, *labeler=None*, *smap=None*, *compute_values=False*)

Return a string representation of an expression.

Parameters

- **expr** – The root node of an expression tree.
- **verbose** (*bool*) – If `True`, then the output is a nested functional form. Otherwise, the output is an algebraic expression. Default is `False`.
- **labeler** – If specified, this labeler is used to label variables in the expression.
- **smap** – If specified, this *SymbolMap* is used to cache labels.
- **compute_values** (*bool*) – If `True`, then parameters and fixed variables are evaluated before the expression string is generated. Default is `False`.

Returns A string representation for the expression.

pyomo.core.expr.current.**decompose_term**(*expr*)
A function that returns a tuple consisting of (1) a flag indicated whether the expression is linear, and (2) a list of tuples that represents the terms in the linear expression.

Parameters **expr** (expression) – The root node of an expression tree

Returns A tuple with the form `(flag, list)`. If `flag` is `False`, then a nonlinear term has been found, and `list` is `None`. Otherwise, `list` is a list of tuples: `(coef, value)`. If `value` is `None`, then this represents a constant term with value `coef`. Otherwise, `value` is a variable object, and `coef` is the numeric coefficient.

pyomo.core.expr.current.**clone_expression**(*expr*, *substitute=None*)
A function that is used to clone an expression.

Cloning is equivalent to calling `copy.deepcopy` with no Block scope. That is, the expression tree is duplicated, but no Pyomo components (leaf nodes *or* named Expressions) are duplicated.

Parameters

- **expr** – The expression that will be cloned.
- **substitute** (*dict*) – A dictionary mapping object ids to objects. This dictionary has the same semantics as the memo object used with `copy.deepcopy`. Defaults to None, which indicates that no user-defined dictionary is used.

Returns The cloned expression.

pyomo.core.expr.current.**evaluate_expression**(*exp*, *exception=True*, *constant=False*)
Evaluate the value of the expression.

Parameters

- **expr** – The root node of an expression tree.
- **exception** (*bool*) – A flag that indicates whether exceptions are raised. If this flag is `False`, then an exception that occurs while evaluating the expression is caught and the return value is `None`. Default is `True`.
- **constant** (*bool*) – If True, constant expressions are evaluated and returned but nonconstant expressions raise either FixedExpressionError or NonconstantExpressionError (default=False).

Returns A floating point value if the expression evaluates normally, or `None` if an exception occurs and is caught.

pyomo.core.expr.current.**identify_components**(*expr*, *component_types*)
A generator that yields a sequence of nodes in an expression tree that belong to a specified set.

Parameters

- **expr** – The root node of an expression tree.
- **component_types** (*set or list*) – A set of class types that will be matched during the search.

Yields Each node that is found.

pyomo.core.expr.current.**identify_variables**(*expr*, *include_fixed=True*)
A generator that yields a sequence of variables in an expression tree.

Parameters

- **expr** – The root node of an expression tree.
- **include_fixed** (*bool*) – If `True`, then this generator will yield variables whose value is fixed. Defaults to `True`.

Yields Each variable that is found.

pyomo.core.expr.**differentiate**(*expr*, *wrt=None*, *wrt_list=None*, *mode=Modes.reverse_numeric*)
Return derivative of expression.

This function returns the derivative of expr with respect to one or more variables. The type of the return value depends on the arguments wrt, wrt_list, and mode. See below for details.

Parameters

- **expr** (pyomo.core.expr.numeric_expr.ExpressionBase) – The expression to differentiate
- **wrt** (*pyomo.core.base.var._GeneralVarData*) – If specified, this function will return the derivative with respect to wrt. wrt is normally a _GeneralVarData, but could also be a _ParamData. wrt and wrt_list cannot both be specified.
- **wrt_list** (*list of pyomo.core.base.var._GeneralVarData*) – If specified, this function will return the derivative with respect to each element in wrt_list. A list will be returned where the values are the derivatives with respect to the corresponding entry in wrt_list.
- **mode** (*pyomo.core.expr.calculus.derivatives.Modes*) – Specifies the method to use for differentiation. Should be one of the members of the Modes enum:

Modes.sympy: The pyomo expression will be converted to a sympy expression. Differentiation will then be done with sympy, and the result will be converted back to a pyomo expression. The sympy mode only does symbolic differentiation. The sympy mode requires exactly one of wrt and wrt_list to be specified.

Modes.reverse_symbolic: Symbolic differentiation will be performed directly with the pyomo expression in reverse mode. If neither wrt nor wrt_list are specified, then a ComponentMap is returned where there will be a key for each node in the expression tree, and the values will be the symbolic derivatives.

Modes.reverse_numeric: Numeric differentiation will be performed directly with the pyomo expression in reverse mode. If neither wrt nor wrt_list are specified, then a ComponentMap is returned where there will be a key for each node in the expression tree, and the values will be the floating point values of the derivatives at the current values of the variables.

Returns **res** – The value or expression of the derivative(s)

Return type float, `ExpressionBase`, `ComponentMap`, or list

Classes

`class` pyomo.core.expr.symbol_map.**SymbolMap**(*labeler=None*)

A class for tracking assigned labels for modeling components.

Symbol maps are used, for example, when writing problem files for input to an optimizer.

Warning: A symbol map should never be pickled. This class is typically constructed by solvers and writers, and it may be owned by models.

Note: We should change the API to not use camelcase.

`byObject`

maps (object id) to (string label)

Type dict

`bySymbol`

maps (string label) to (object weakref)

Type dict

`alias`

maps (string label) to (object weakref)

Type dict

`default_labeler`

used to compute a string label from an object

13.3.3 Context Managers

class pyomo.core.expr.current.**nonlinear_expression**
Context manager for mutable sums.

This context manager is used to compute a sum while treating the summation as a mutable object.

class pyomo.core.expr.current.**linear_expression**
Context manager for mutable linear sums.

This context manager is used to compute a linear sum while treating the summation as a mutable object.

class pyomo.core.expr.current.**clone_counter**
Context manager for counting cloning events.

This context manager counts the number of times that the *clone_expression* function is executed.

property count
A property that returns the clone count value.

13.3.4 Core Classes

The following are the two core classes documented here:

- *NumericValue*
- *ExpressionBase*

The remaining classes are the public classes for expressions, which developers may need to know about. The methods for these classes are not documented because they are described in the *ExpressionBase* class.

Sets with Expression Types

The following sets can be used to develop visitor patterns for Pyomo expressions.

pyomo.core.expr.numvalue.**native_numeric_types = {<class 'numpy.uint64'>, <class 'numpy.int64'>, <class 'numpy.ndarray'>, <class 'bool'>, <class 'numpy.float16'>, <class 'float'>, <class 'numpy.uint8'>, <class 'numpy.int8'>, <class 'numpy.float32'>, <class 'numpy.uint16'>, <class 'numpy.int16'>, <class 'int'>, <class 'numpy.uint32'>, <class 'numpy.int32'>, <class 'numpy.float64'>}**
set() -> new empty set object set(iterable) -> new set object

Build an unordered collection of unique elements.

pyomo.core.expr.numvalue.**native_types = {<class 'numpy.uint64'>, <class 'numpy.int64'>, <class 'numpy.float64'>, <class 'numpy.uint32'>, <class 'numpy.int32'>, <class 'slice'>, <class 'bool'>, <class 'numpy.float32'>, <class 'numpy.uint16'>, <class 'numpy.int16'>, <class 'numpy.bool_'>, <class 'NoneType'>, <class 'str'>, <class 'numpy.float16'>, <class 'numpy.uint8'>, <class 'numpy.int8'>, <class 'bytes'>, <class 'numpy.ndarray'>, <class 'float'>, <class 'int'>}**
set() -> new empty set object set(iterable) -> new set object

Build an unordered collection of unique elements.

pyomo.core.expr.numvalue.**nonpyomo_leaf_types = {<class 'numpy.uint64'>, <class 'numpy.int64'>, <class 'numpy.float16'>, <class 'numpy.uint8'>, <class 'numpy.int8'>, <class 'numpy.float64'>, <class 'numpy.uint32'>, <class 'numpy.int32'>, <class 'bytes'>, <class 'slice'>, <class 'numpy.ndarray'>, <class 'bool'>, <class 'pyomo.core.expr.numvalue.NonNumericValue'>, <class 'int'>, <class 'float'>, <class 'numpy.float32'>, <class 'numpy.uint16'>, <class 'numpy.int16'>, <class 'numpy.bool_'>, <class 'NoneType'>, <class 'str'>}**

set() -> new empty set object set(iterable) -> new set object

Build an unordered collection of unique elements.

NumericValue and ExpressionBase

class pyomo.core.expr.numvalue.**NumericValue**

This is the base class for numeric values used in Pyomo.

__abs__()

Absolute value

This method is called when Python processes the statement:

```
abs(self)
```

__add__(*other*)

Binary addition

This method is called when Python processes the statement:

```
self + other
```

__div__(*other*)

Binary division

This method is called when Python processes the statement:

```
self / other
```

__eq__(*other*)

Equal to operator

This method is called when Python processes the statement:

```
self == other
```

__float__()

Coerce the value to a floating point

Raises **TypeError** –

__ge__(*other*)

Greater than or equal operator

This method is called when Python processes statements of the form:

```
self >= other
other <= self
```

__getstate__()
Prepare a picklable state of this instance for pickling.

Nominally, __getstate__() should execute the following:

```
state = super(Class, self).__getstate__()
for i in Class.__slots__:
    state[i] = getattr(self,i)
return state
```

However, in this case, the (nominal) parent class is 'object', and object does not implement __getstate__. So, we will check to make sure that there is a base __getstate__() to call. You might think that there is nothing to check, but multiple inheritance could mean that another class got stuck between this class and "object" in the MRO.

Further, since there are actually no slots defined here, the real question is to either return an empty dict or the parent's dict.

__gt__(*other*)
Greater than operator

This method is called when Python processes statements of the form:

```
self > other
other < self
```

__iadd__(*other*)
Binary addition

This method is called when Python processes the statement:

```
self += other
```

__idiv__(*other*)
Binary division

This method is called when Python processes the statement:

```
self /= other
```

__imul__(*other*)
Binary multiplication

This method is called when Python processes the statement:

```
self *= other
```

__int__()
Coerce the value to an integer

Raises **TypeError** –

__ipow__(*other*)
Binary power

This method is called when Python processes the statement:

```
self **= other
```

__isub__(*other*)
Binary subtraction

This method is called when Python processes the statement:

```
self -= other
```

__itruediv__(*other*)
Binary division (when __future__.division is in effect)

This method is called when Python processes the statement:

```
self /= other
```

__le__(*other*)
Less than or equal operator

This method is called when Python processes statements of the form:

```
self <= other
other >= self
```

__lt__(*other*)
Less than operator

This method is called when Python processes statements of the form:

```
self < other
other > self
```

__mul__(*other*)
Binary multiplication

This method is called when Python processes the statement:

```
self * other
```

__neg__()
Negation

This method is called when Python processes the statement:

```
- self
```

__pos__()
Positive expression

This method is called when Python processes the statement:

```
+ self
```

__pow__(*other*)
Binary power

This method is called when Python processes the statement:

```
self ** other
```

__radd__(*other*)
Binary addition

This method is called when Python processes the statement:

```
other + self
```

__rdiv__(*other*)
Binary division

This method is called when Python processes the statement:

```
other / self
```

__rmul__(*other*)
Binary multiplication

This method is called when Python processes the statement:

```
other * self
```

when other is not a *NumericValue* object.

__rpow__(*other*)
Binary power

This method is called when Python processes the statement:

```
other ** self
```

__rsub__(*other*)
Binary subtraction

This method is called when Python processes the statement:

```
other - self
```

__rtruediv__(*other*)
Binary division (when __future__.division is in effect)

This method is called when Python processes the statement:

```
other / self
```

__setstate__(*state*)
Restore a pickled state into this instance

Our model for setstate is for derived classes to modify the state dictionary as control passes up the inheritance hierarchy (using super() calls). All assignment of state -> object attributes is handled at the last class before 'object', which may – or may not (thanks to MRO) – be here.

__sub__(*other*)
Binary subtraction

This method is called when Python processes the statement:

```
self - other
```

__truediv__(*other*)
Binary division (when __future__.division is in effect)

This method is called when Python processes the statement:

```
self / other
```

_compute_polynomial_degree(*values*)
Compute the polynomial degree of this expression given the degree values of its children.

Parameters **values** (*list*) – A list of values that indicate the degree of the children expression.

Returns None

cname(**args*, ***kwds*)
DEPRECATED.

Deprecated since version 5.0: The cname() method has been renamed to getname().

getname(*fully_qualified=False*, *name_buffer=None*)
If this is a component, return the component's name on the owning block; otherwise return the value converted to a string

is_constant()
Return True if this numeric value is a constant value

is_fixed()
Return True if this is a non-constant value that has been fixed

is_indexed()
Return True if this numeric value is an indexed object

is_numeric_type()
Return True if this class is a Pyomo numeric object

is_potentially_variable()
Return True if variables can appear in this expression

is_relational()
Return True if this numeric value represents a relational expression.

polynomial_degree()
Return the polynomial degree of the expression.

Returns None

to_string(*verbose=None*, *labeler=None*, *smap=None*, *compute_values=False*)
Return a string representation of the expression tree.

Parameters

- **verbose** (*bool*) – If True, then the the string representation consists of nested functions. Otherwise, the string representation is an algebraic equation. Defaults to False.
- **labeler** – An object that generates string labels for variables in the expression tree. Defaults to None.

Returns A string representation for the expression tree.

class pyomo.core.expr.current.**ExpressionBase**(*args*)
Bases: *pyomo.core.expr.numvalue.NumericValue*

The base class for Pyomo expressions.

This class is used to define nodes in an expression tree.

Parameters **args** (*list or tuple*) – Children of this node.

__bool__()
Compute the value of the expression and convert it to a boolean.

Returns A boolean value.

__call__(*exception=True*)
Evaluate the value of the expression tree.

Parameters **exception** (*bool*) – If `False`, then an exception raised while evaluating is captured, and the value returned is `None`. Default is `True`.

Returns The value of the expression or `None`.

__getstate__()
Pickle the expression object

Returns The pickled state.

__init__(*args*)

__nonzero__()
Compute the value of the expression and convert it to a boolean.

Returns A boolean value.

__str__()
Returns a string description of the expression.

Note: The value of `pyomo.core.expr.expr_common.TO_STRING_VERBOSE` is used to configure the execution of this method. If this value is `True`, then the string representation is a nested function description of the expression. The default is `False`, which is an algebraic description of the expression.

Returns A string.

_apply_operation(*result*)
Compute the values of this node given the values of its children.

This method is called by the `_EvaluationVisitor` class. It must be over-written by expression classes to customize this logic.

Note: This method applies the logical operation of the operator to the arguments. It does *not* evaluate the arguments in the process, but assumes that they have been previously evaluated. But noted that if this class contains auxilliary data (e.g. like the numeric coefficients in the `LinearExpression` class, then those values *must* be evaluated as part of this function call. An uninitialized parameter value encountered during the execution of this method is considered an error.

Parameters **values** (*list*) – A list of values that indicate the value of the children expressions.

Returns A floating point value for this expression.

_associativity()
Return the associativity of this operator.

Returns 1 if this operator is left-to-right associative or -1 if it is right-to-left associative. Any other return value will be interpreted as "not associative" (implying any arguments that are at this operator's _precedence() will be enclosed in parens).

_compute_polynomial_degree(*values*)
Compute the polynomial degree of this expression given the degree values of its children.

This method is called by the `_PolynomialDegreeVisitor` class. It can be over-written by expression classes to customize this logic.

Parameters **values** (*list*) – A list of values that indicate the degree of the children expression.

Returns A nonnegative integer that is the polynomial degree of the expression, or `None`. Default is `None`.

_is_fixed(*values*)
Compute whether this expression is fixed given the fixed values of its children.

This method is called by the `_IsFixedVisitor` class. It can be over-written by expression classes to customize this logic.

Parameters **values** (*list*) – A list of boolean values that indicate whether the children of this expression are fixed

Returns A boolean that is `True` if the fixed values of the children are all `True`.

_to_string(*values*, *verbose*, *smap*, *compute_values*)
Construct a string representation for this node, using the string representations of its children.

This method is called by the `_ToStringVisitor` class. It must must be defined in subclasses.

Parameters

- **values** (*list*) – The string representations of the children of this node.
- **verbose** (*bool*) – If `True`, then the the string representation consists of nested functions. Otherwise, the string representation is an algebraic equation.
- **smap** – If specified, this *SymbolMap* is used to cache labels for variables.
- **compute_values** (*bool*) – If `True`, then parameters and fixed variables are evaluated before the expression string is generated.

Returns A string representation for this node.

arg(*i*)
Return the i-th child node.

Parameters **i** (*int*) – Nonnegative index of the child that is returned.

Returns The i-th child node.

property args
Return the child nodes

Returns: Either a list or tuple (depending on the node storage model) containing only the child nodes of this node

clone(*substitute=None*)
Return a clone of the expression tree.

Note: This method does not clone the leaves of the tree, which are numeric constants and variables. It only clones the interior nodes, and expression leaf nodes like `_MutableLinearExpression`. However, named expressions are treated like leaves, and they are not cloned.

Parameters **substitute** (*dict*) – a dictionary that maps object ids to clone objects generated earlier during the cloning process.

Returns A new expression tree.

create_node_with_local_data(*args*)
Construct a node using given arguments.

This method provides a consistent interface for constructing a node, which is used in tree visitor scripts. In the simplest case, this simply returns:

```
self.__class__(args)
```

But in general this creates an expression object using local data as well as arguments that represent the child nodes.

Parameters

- **args** (*list*) – A list of child nodes for the new expression object
- **memo** (*dict*) – A dictionary that maps object ids to clone objects generated earlier during a cloning process. This argument is needed to clone objects that are owned by a model, and it can be safely ignored for most expression classes.

Returns A new expression object with the same type as the current class.

create_potentially_variable_object()
Create a potentially variable version of this object.

This method returns an object that is a potentially variable version of the current object. In the simplest case, this simply sets the value of *__class__*:

self.__class__ = self.__class__.__mro__[1]

Note that this method is allowed to modify the current object and return it. But in some cases it may create a new potentially variable object.

Returns An object that is potentially variable.

getname(**args*, ***kwds*)
Return the text name of a function associated with this expression object.

In general, no arguments are passed to this function.

Parameters

- ***arg** – a variable length list of arguments
- ****kwds** – keyword arguments

Returns A string name for the function.

is_constant()
Return True if this expression is an atomic constant

This method contrasts with the is_fixed() method. This method returns True if the expression is an atomic constant, that is it is composed exclusively of constants and immutable parameters. NumericValue objects returning is_constant() == True may be simplified to their numeric value at any point without warning.

Note: This defaults to False, but gets redefined in sub-classes.

is_expression_type()
Return `True` if this object is an expression.

This method obviously returns `True` for this class, but it is included in other classes within Pyomo that are not expressions, which allows for a check for expressions without evaluating the class type.

Returns A boolean.

is_fixed()
Return True if this expression contains no free variables.

Returns A boolean.

is_named_expression_type()
Return True if this object is a named expression.

This method returns False for this class, and it is included in other classes within Pyomo that are not named expressions, which allows for a check for named expressions without evaluating the class type.

Returns A boolean.

is_potentially_variable()
Return True if this expression might represent a variable expression.

This method returns True when (a) the expression tree contains one or more variables, or (b) the expression tree contains a named expression. In both cases, the expression cannot be treated as constant since (a) the variables may not be fixed, or (b) the named expressions may be changed at a later time to include non-fixed variables.

Returns A boolean. Defaults to True for expressions.

nargs()
Returns the number of child nodes.

By default, Pyomo expressions represent binary operations with two arguments.

Note: This function does not simply compute the length of _args_ because some expression classes use a subset of the _args_ array. Thus, it is imperative that developers use this method!

Returns A nonnegative integer that is the number of child nodes.

polynomial_degree()
Return the polynomial degree of the expression.

Returns A non-negative integer that is the polynomial degree if the expression is polynomial, or None otherwise.

size()
Return the number of nodes in the expression tree.

Returns A nonnegative integer that is the number of interior and leaf nodes in the expression tree.

to_string(*verbose=None*, *labeler=None*, *smap=None*, *compute_values=False*)
Return a string representation of the expression tree.

Parameters

- **verbose** (*bool*) – If True, then the the string representation consists of nested functions. Otherwise, the string representation is an algebraic equation. Defaults to False.
- **labeler** – An object that generates string labels for variables in the expression tree. Defaults to None.
- **smap** – If specified, this *SymbolMap* is used to cache labels for variables.
- **compute_values** (*bool*) – If True, then parameters and fixed variables are evaluated before the expression string is generated. Default is False.

Returns A string representation for the expression tree.

Other Public Classes

class pyomo.core.expr.current.**NegationExpression**(*args*)
Bases: *pyomo.core.expr.numeric_expr.ExpressionBase*

Negation expressions:

```
- x
```

PRECEDENCE = 4

_apply_operation(*result*)
Compute the values of this node given the values of its children.

This method is called by the `_EvaluationVisitor` class. It must be over-written by expression classes to customize this logic.

Note: This method applies the logical operation of the operator to the arguments. It does *not* evaluate the arguments in the process, but assumes that they have been previously evaluated. But noted that if this class contains auxilliary data (e.g. like the numeric coefficients in the `LinearExpression` class, then those values *must* be evaluated as part of this function call. An uninitialized parameter value encountered during the execution of this method is considered an error.

Parameters **values** (*list*) – A list of values that indicate the value of the children expressions.

Returns A floating point value for this expression.

_compute_polynomial_degree(*result*)
Compute the polynomial degree of this expression given the degree values of its children.

This method is called by the `_PolynomialDegreeVisitor` class. It can be over-written by expression classes to customize this logic.

Parameters **values** (*list*) – A list of values that indicate the degree of the children expression.

Returns A nonnegative integer that is the polynomial degree of the expression, or `None`. Default is `None`.

_precedence()

_to_string(*values*, *verbose*, *smap*, *compute_values*)
Construct a string representation for this node, using the string representations of its children.

This method is called by the `_ToStringVisitor` class. It must must be defined in subclasses.

Parameters

- **values** (*list*) – The string representations of the children of this node.
- **verbose** (*bool*) – If `True`, then the the string representation consists of nested functions. Otherwise, the string representation is an algebraic equation.
- **smap** – If specified, this *SymbolMap* is used to cache labels for variables.
- **compute_values** (*bool*) – If `True`, then parameters and fixed variables are evaluated before the expression string is generated.

Returns A string representation for this node.

getname(**args*, ***kwds*)
Return the text name of a function associated with this expression object.

In general, no arguments are passed to this function.

Parameters

- ***arg** – a variable length list of arguments
- ****kwds** – keyword arguments

Returns A string name for the function.

nargs()
Returns the number of child nodes.

By default, Pyomo expressions represent binary operations with two arguments.

Note: This function does not simply compute the length of `_args_` because some expression classes use a subset of the `_args_` array. Thus, it is imperative that developers use this method!

Returns A nonnegative integer that is the number of child nodes.

class pyomo.core.expr.current.**ExternalFunctionExpression**(*args*, *fcn=None*)
Bases: *pyomo.core.expr.numeric_expr.ExpressionBase*

External function expressions

Example:

```
model = ConcreteModel()
model.a = Var()
model.f = ExternalFunction(library='foo.so', function='bar')
expr = model.f(model.a)
```

Parameters

- **args** (*tuple*) – children of this node
- **fcn** – a class that defines this external function

_apply_operation(*result*)
Compute the values of this node given the values of its children.

This method is called by the `_EvaluationVisitor` class. It must be over-written by expression classes to customize this logic.

Note: This method applies the logical operation of the operator to the arguments. It does *not* evaluate the arguments in the process, but assumes that they have been previously evaluated. But noted that if this class contains auxilliary data (e.g. like the numeric coefficients in the `LinearExpression` class, then those values *must* be evaluated as part of this function call. An uninitialized parameter value encountered during the execution of this method is considered an error.

Parameters **values** (*list*) – A list of values that indicate the value of the children expressions.

Returns A floating point value for this expression.

_compute_polynomial_degree(*result*)
Compute the polynomial degree of this expression given the degree values of its children.

This method is called by the `_PolynomialDegreeVisitor` class. It can be over-written by expression classes to customize this logic.

Parameters **values** (*list*) – A list of values that indicate the degree of the children expression.

Returns A nonnegative integer that is the polynomial degree of the expression, or `None`. Default is `None`.

_fcn

_to_string(*values*, *verbose*, *smap*, *compute_values*)
Construct a string representation for this node, using the string representations of its children.

This method is called by the `_ToStringVisitor` class. It must must be defined in subclasses.

Parameters

- **values** (*list*) – The string representations of the children of this node.
- **verbose** (*bool*) – If `True`, then the the string representation consists of nested functions. Otherwise, the string representation is an algebraic equation.
- **smap** – If specified, this *SymbolMap* is used to cache labels for variables.
- **compute_values** (*bool*) – If `True`, then parameters and fixed variables are evaluated before the expression string is generated.

Returns A string representation for this node.

create_node_with_local_data(*args*)
Construct a node using given arguments.

This method provides a consistent interface for constructing a node, which is used in tree visitor scripts. In the simplest case, this simply returns:

```
self.__class__(args)
```

But in general this creates an expression object using local data as well as arguments that represent the child nodes.

Parameters

- **args** (*list*) – A list of child nodes for the new expression object
- **memo** (*dict*) – A dictionary that maps object ids to clone objects generated earlier during a cloning process. This argument is needed to clone objects that are owned by a model, and it can be safely ignored for most expression classes.

Returns A new expression object with the same type as the current class.

get_arg_units()
Return the units for this external functions arguments

get_units()
Get the units of the return value for this external function

getname(**args*, ***kwds*)
Return the text name of a function associated with this expression object.

In general, no arguments are passed to this function.

Parameters

- ***arg** – a variable length list of arguments
- ****kwds** – keyword arguments

Returns A string name for the function.

nargs()
Returns the number of child nodes.

By default, Pyomo expressions represent binary operations with two arguments.

Note: This function does not simply compute the length of _args_ because some expression classes use a subset of the _args_ array. Thus, it is imperative that developers use this method!

Returns A nonnegative integer that is the number of child nodes.

class pyomo.core.expr.current.**ProductExpression**(*args*)
Bases: *pyomo.core.expr.numeric_expr.ExpressionBase*

Product expressions:

```
x*y
```

PRECEDENCE = 4

_apply_operation(*result*)
Compute the values of this node given the values of its children.

This method is called by the _EvaluationVisitor class. It must be over-written by expression classes to customize this logic.

Note: This method applies the logical operation of the operator to the arguments. It does *not* evaluate the arguments in the process, but assumes that they have been previously evaluated. But noted that if this class contains auxilliary data (e.g. like the numeric coefficients in the LinearExpression class, then those values *must* be evaluated as part of this function call. An uninitialized parameter value encountered during the execution of this method is considered an error.

Parameters **values** (*list*) – A list of values that indicate the value of the children expressions.

Returns A floating point value for this expression.

_compute_polynomial_degree(*result*)
Compute the polynomial degree of this expression given the degree values of its children.

This method is called by the _PolynomialDegreeVisitor class. It can be over-written by expression classes to customize this logic.

Parameters **values** (*list*) – A list of values that indicate the degree of the children expression.

Returns A nonnegative integer that is the polynomial degree of the expression, or None. Default is None.

_is_fixed(*args*)
Compute whether this expression is fixed given the fixed values of its children.

This method is called by the _IsFixedVisitor class. It can be over-written by expression classes to customize this logic.

Parameters **values** (*list*) – A list of boolean values that indicate whether the children of this expression are fixed

Returns A boolean that is `True` if the fixed values of the children are all `True`.

_precedence()

_to_string(*values*, *verbose*, *smap*, *compute_values*)

Construct a string representation for this node, using the string representations of its children.

This method is called by the `_ToStringVisitor` class. It must must be defined in subclasses.

Parameters

- **values** (*list*) – The string representations of the children of this node.
- **verbose** (*bool*) – If `True`, then the the string representation consists of nested functions. Otherwise, the string representation is an algebraic equation.
- **smap** – If specified, this *SymbolMap* is used to cache labels for variables.
- **compute_values** (*bool*) – If `True`, then parameters and fixed variables are evaluated before the expression string is generated.

Returns A string representation for this node.

getname(**args*, ***kwds*)

Return the text name of a function associated with this expression object.

In general, no arguments are passed to this function.

Parameters

- ***arg** – a variable length list of arguments
- ****kwds** – keyword arguments

Returns A string name for the function.

class pyomo.core.expr.current.**ReciprocalExpression**(*args*)

Bases: *pyomo.core.expr.numeric_expr.ExpressionBase*

DEPRECATED.

Reciprocal expressions:

```
1/x
```

Deprecated since version 5.6.7: Use DivisionExpression

PRECEDENCE = 4

_apply_operation(*result*)

Compute the values of this node given the values of its children.

This method is called by the `_EvaluationVisitor` class. It must be over-written by expression classes to customize this logic.

Note: This method applies the logical operation of the operator to the arguments. It does *not* evaluate the arguments in the process, but assumes that they have been previously evaluated. But noted that if this class contains auxilliary data (e.g. like the numeric coefficients in the `LinearExpression` class, then those values *must* be evaluated as part of this function call. An uninitialized parameter value encountered during the execution of this method is considered an error.

Parameters **values** (*list*) – A list of values that indicate the value of the children expressions.

Returns A floating point value for this expression.

_associativity()
Return the associativity of this operator.

Returns 1 if this operator is left-to-right associative or -1 if it is right-to-left associative. Any other return value will be interpreted as "not associative" (implying any arguments that are at this operator's _precedence() will be enclosed in parens).

_compute_polynomial_degree(*result*)
Compute the polynomial degree of this expression given the degree values of its children.

This method is called by the `_PolynomialDegreeVisitor` class. It can be over-written by expression classes to customize this logic.

Parameters **values** (*list*) – A list of values that indicate the degree of the children expression.

Returns A nonnegative integer that is the polynomial degree of the expression, or `None`. Default is `None`.

_precedence()

_to_string(*values*, *verbose*, *smap*, *compute_values*)
Construct a string representation for this node, using the string representations of its children.

This method is called by the `_ToStringVisitor` class. It must must be defined in subclasses.

Parameters

- **values** (*list*) – The string representations of the children of this node.
- **verbose** (*bool*) – If `True`, then the the string representation consists of nested functions. Otherwise, the string representation is an algebraic equation.
- **smap** – If specified, this *SymbolMap* is used to cache labels for variables.
- **compute_values** (*bool*) – If `True`, then parameters and fixed variables are evaluated before the expression string is generated.

Returns A string representation for this node.

getname(**args*, ***kwds*)
Return the text name of a function associated with this expression object.

In general, no arguments are passed to this function.

Parameters

- ***arg** – a variable length list of arguments
- ****kwds** – keyword arguments

Returns A string name for the function.

nargs()
Returns the number of child nodes.

By default, Pyomo expressions represent binary operations with two arguments.

Note: This function does not simply compute the length of `_args_` because some expression classes use a subset of the `_args_` array. Thus, it is imperative that developers use this method!

Returns A nonnegative integer that is the number of child nodes.

class pyomo.core.expr.current.**InequalityExpression**(*args*, *strict*)
Bases: pyomo.core.expr.numeric_expr._LinearOperatorExpression

Inequality expressions, which define less-than or less-than-or-equal relations:

```
x < y
x <= y
```

Parameters

- **args** (*tuple*) – child nodes
- **strict** (*bool*) – a flag that indicates whether the inequality is strict

PRECEDENCE = 9

_apply_operation(*result*)
Compute the values of this node given the values of its children.

This method is called by the _EvaluationVisitor class. It must be over-written by expression classes to customize this logic.

Note: This method applies the logical operation of the operator to the arguments. It does *not* evaluate the arguments in the process, but assumes that they have been previously evaluated. But noted that if this class contains auxilliary data (e.g. like the numeric coefficients in the LinearExpression class, then those values *must* be evaluated as part of this function call. An uninitialized parameter value encountered during the execution of this method is considered an error.

Parameters **values** (*list*) – A list of values that indicate the value of the children expressions.

Returns A floating point value for this expression.

_precedence()

_strict

_to_string(*values*, *verbose*, *smap*, *compute_values*)
Construct a string representation for this node, using the string representations of its children.

This method is called by the _ToStringVisitor class. It must must be defined in subclasses.

Parameters

- **values** (*list*) – The string representations of the children of this node.
- **verbose** (*bool*) – If True, then the the string representation consists of nested functions. Otherwise, the string representation is an algebraic equation.
- **smap** – If specified, this *SymbolMap* is used to cache labels for variables.
- **compute_values** (*bool*) – If True, then parameters and fixed variables are evaluated before the expression string is generated.

Returns A string representation for this node.

create_node_with_local_data(*args*)
Construct a node using given arguments.

This method provides a consistent interface for constructing a node, which is used in tree visitor scripts. In the simplest case, this simply returns:

```
self.__class__(args)
```

But in general this creates an expression object using local data as well as arguments that represent the child nodes.

Parameters

- **args** (*list*) – A list of child nodes for the new expression object
- **memo** (*dict*) – A dictionary that maps object ids to clone objects generated earlier during a cloning process. This argument is needed to clone objects that are owned by a model, and it can be safely ignored for most expression classes.

Returns A new expression object with the same type as the current class.

is_constant()
Return True if this expression is an atomic constant

This method contrasts with the is_fixed() method. This method returns True if the expression is an atomic constant, that is it is composed exclusively of constants and immutable parameters. NumericValue objects returning is_constant() == True may be simplified to their numeric value at any point without warning.

Note: This defaults to False, but gets redefined in sub-classes.

is_potentially_variable()
Return `True` if this expression might represent a variable expression.

This method returns `True` when (a) the expression tree contains one or more variables, or (b) the expression tree contains a named expression. In both cases, the expression cannot be treated as constant since (a) the variables may not be fixed, or (b) the named expressions may be changed at a later time to include non-fixed variables.

Returns A boolean. Defaults to `True` for expressions.

is_relational()
Return True if this numeric value represents a relational expression.

nargs()
Returns the number of child nodes.

By default, Pyomo expressions represent binary operations with two arguments.

Note: This function does not simply compute the length of `_args_` because some expression classes use a subset of the `_args_` array. Thus, it is imperative that developers use this method!

Returns A nonnegative integer that is the number of child nodes.

property strict

class pyomo.core.expr.current.**EqualityExpression**(*args*)
Bases: pyomo.core.expr.numeric_expr._LinearOperatorExpression

Equality expression:

```
x == y
```

PRECEDENCE = 9

_apply_operation(*result*)
Compute the values of this node given the values of its children.

This method is called by the _EvaluationVisitor class. It must be over-written by expression classes to customize this logic.

Note: This method applies the logical operation of the operator to the arguments. It does *not* evaluate the arguments in the process, but assumes that they have been previously evaluated. But noted that if this class contains auxilliary data (e.g. like the numeric coefficients in the LinearExpression class, then those values *must* be evaluated as part of this function call. An uninitialized parameter value encountered during the execution of this method is considered an error.

Parameters **values** (*list*) – A list of values that indicate the value of the children expressions.

Returns A floating point value for this expression.

_precedence()

_to_string(*values*, *verbose*, *smap*, *compute_values*)
Construct a string representation for this node, using the string representations of its children.

This method is called by the _ToStringVisitor class. It must must be defined in subclasses.

Parameters

- **values** (*list*) – The string representations of the children of this node.
- **verbose** (*bool*) – If True, then the the string representation consists of nested functions. Otherwise, the string representation is an algebraic equation.
- **smap** – If specified, this *SymbolMap* is used to cache labels for variables.
- **compute_values** (*bool*) – If True, then parameters and fixed variables are evaluated before the expression string is generated.

Returns A string representation for this node.

is_constant()
Return True if this expression is an atomic constant

This method contrasts with the is_fixed() method. This method returns True if the expression is an atomic constant, that is it is composed exclusively of constants and immutable parameters. NumericValue objects returning is_constant() == True may be simplified to their numeric value at any point without warning.

Note: This defaults to False, but gets redefined in sub-classes.

is_potentially_variable()
Return True if this expression might represent a variable expression.

This method returns True when (a) the expression tree contains one or more variables, or (b) the expression tree contains a named expression. In both cases, the expression cannot be treated as constant since (a) the variables may not be fixed, or (b) the named expressions may be changed at a later time to include non-fixed variables.

Returns A boolean. Defaults to True for expressions.

is_relational()
Return True if this numeric value represents a relational expression.

nargs()
Returns the number of child nodes.

By default, Pyomo expressions represent binary operations with two arguments.

Note: This function does not simply compute the length of `_args_` because some expression classes use a subset of the `_args_` array. Thus, it is imperative that developers use this method!

Returns A nonnegative integer that is the number of child nodes.

class pyomo.core.expr.current.**SumExpression**(*args*)

Bases: pyomo.core.expr.numeric_expr.SumExpressionBase

Sum expression:

```
x + y
```

Parameters **args** (*list*) – Children nodes

PRECEDENCE = 6

_apply_operation(*result*)

Compute the values of this node given the values of its children.

This method is called by the `_EvaluationVisitor` class. It must be over-written by expression classes to customize this logic.

Note: This method applies the logical operation of the operator to the arguments. It does *not* evaluate the arguments in the process, but assumes that they have been previously evaluated. But noted that if this class contains auxilliary data (e.g. like the numeric coefficients in the `LinearExpression` class, then those values *must* be evaluated as part of this function call. An uninitialized parameter value encountered during the execution of this method is considered an error.

Parameters **values** (*list*) – A list of values that indicate the value of the children expressions.

Returns A floating point value for this expression.

_nargs

_precedence()

_shared_args

_to_string(*values*, *verbose*, *smap*, *compute_values*)

Construct a string representation for this node, using the string representations of its children.

This method is called by the `_ToStringVisitor` class. It must must be defined in subclasses.

Parameters

- **values** (*list*) – The string representations of the children of this node.
- **verbose** (*bool*) – If `True`, then the the string representation consists of nested functions. Otherwise, the string representation is an algebraic equation.
- **smap** – If specified, this *SymbolMap* is used to cache labels for variables.
- **compute_values** (*bool*) – If `True`, then parameters and fixed variables are evaluated before the expression string is generated.

Returns A string representation for this node.

add(*new_arg*)

create_node_with_local_data(*args*)

Construct a node using given arguments.

This method provides a consistent interface for constructing a node, which is used in tree visitor scripts. In the simplest case, this simply returns:

```
self.__class__(args)
```

But in general this creates an expression object using local data as well as arguments that represent the child nodes.

Parameters

- **args** (*list*) – A list of child nodes for the new expression object
- **memo** (*dict*) – A dictionary that maps object ids to clone objects generated earlier during a cloning process. This argument is needed to clone objects that are owned by a model, and it can be safely ignored for most expression classes.

Returns A new expression object with the same type as the current class.

is_constant()

Return True if this expression is an atomic constant

This method contrasts with the is_fixed() method. This method returns True if the expression is an atomic constant, that is it is composed exclusively of constants and immutable parameters. NumericValue objects returning is_constant() == True may be simplified to their numeric value at any point without warning.

Note: This defaults to False, but gets redefined in sub-classes.

is_potentially_variable()

Return `True` if this expression might represent a variable expression.

This method returns `True` when (a) the expression tree contains one or more variables, or (b) the expression tree contains a named expression. In both cases, the expression cannot be treated as constant since (a) the variables may not be fixed, or (b) the named expressions may be changed at a later time to include non-fixed variables.

Returns A boolean. Defaults to `True` for expressions.

nargs()

Returns the number of child nodes.

By default, Pyomo expressions represent binary operations with two arguments.

Note: This function does not simply compute the length of `_args_` because some expression classes use a subset of the `_args_` array. Thus, it is imperative that developers use this method!

Returns A nonnegative integer that is the number of child nodes.

class pyomo.core.expr.current.**GetItemExpression**(*args*)

Bases: *pyomo.core.expr.numeric_expr.ExpressionBase*

Expression to call `__getitem__()` on the base object.

PRECEDENCE = 1

_apply_operation(*result*)
Compute the values of this node given the values of its children.

This method is called by the `_EvaluationVisitor` class. It must be over-written by expression classes to customize this logic.

Note: This method applies the logical operation of the operator to the arguments. It does *not* evaluate the arguments in the process, but assumes that they have been previously evaluated. But noted that if this class contains auxilliary data (e.g. like the numeric coefficients in the `LinearExpression` class, then those values *must* be evaluated as part of this function call. An uninitialized parameter value encountered during the execution of this method is considered an error.

Parameters **values** (*list*) – A list of values that indicate the value of the children expressions.

Returns A floating point value for this expression.

args

_compute_polynomial_degree(*result*)
Compute the polynomial degree of this expression given the degree values of its children.

This method is called by the `_PolynomialDegreeVisitor` class. It can be over-written by expression classes to customize this logic.

Parameters **values** (*list*) – A list of values that indicate the degree of the children expression.

Returns A nonnegative integer that is the polynomial degree of the expression, or `None`. Default is `None`.

_is_fixed(*values*)
Compute whether this expression is fixed given the fixed values of its children.

This method is called by the `_IsFixedVisitor` class. It can be over-written by expression classes to customize this logic.

Parameters **values** (*list*) – A list of boolean values that indicate whether the children of this expression are fixed

Returns A boolean that is `True` if the fixed values of the children are all `True`.

_precedence()

_resolve_template(*args*)

_to_string(*values*, *verbose*, *smap*, *compute_values*)
Construct a string representation for this node, using the string representations of its children.

This method is called by the `_ToStringVisitor` class. It must must be defined in subclasses.

Parameters

- **values** (*list*) – The string representations of the children of this node.
- **verbose** (*bool*) – If `True`, then the the string representation consists of nested functions. Otherwise, the string representation is an algebraic equation.
- **smap** – If specified, this *SymbolMap* is used to cache labels for variables.
- **compute_values** (*bool*) – If `True`, then parameters and fixed variables are evaluated before the expression string is generated.

Returns A string representation for this node.

getname(**args*, ***kwds*)
Return the text name of a function associated with this expression object.

In general, no arguments are passed to this function.

Parameters

- ***arg** – a variable length list of arguments
- ****kwds** – keyword arguments

Returns A string name for the function.

is_potentially_variable()
Return `True` if this expression might represent a variable expression.

This method returns `True` when (a) the expression tree contains one or more variables, or (b) the expression tree contains a named expression. In both cases, the expression cannot be treated as constant since (a) the variables may not be fixed, or (b) the named expressions may be changed at a later time to include non-fixed variables.

Returns A boolean. Defaults to `True` for expressions.

nargs()
Returns the number of child nodes.

By default, Pyomo expressions represent binary operations with two arguments.

Note: This function does not simply compute the length of *_args_* because some expression classes use a subset of the *_args_* array. Thus, it is imperative that developers use this method!

Returns A nonnegative integer that is the number of child nodes.

class pyomo.core.expr.current.**Expr_ifExpression**(*IF_=None*, *THEN_=None*, *ELSE_=None*)
Bases: *pyomo.core.expr.numeric_expr.ExpressionBase*

A logical if-then-else expression:

```
Expr_if(IF_=x, THEN_=y, ELSE_=z)
```

Parameters

- **IF** (*expression*) – A relational expression
- **THEN** (*expression*) – An expression that is used if `IF_` is true.
- **ELSE** (*expression*) – An expression that is used if `IF_` is false.

_apply_operation(*result*)
Compute the values of this node given the values of its children.

This method is called by the `_EvaluationVisitor` class. It must be over-written by expression classes to customize this logic.

Note: This method applies the logical operation of the operator to the arguments. It does *not* evaluate the arguments in the process, but assumes that they have been previously evaluated. But noted that if this class contains auxilliary data (e.g. like the numeric coefficients in the `LinearExpression` class, then those

values *must* be evaluated as part of this function call. An uninitialized parameter value encountered during the execution of this method is considered an error.

Parameters **values** (*list*) – A list of values that indicate the value of the children expressions.

Returns A floating point value for this expression.

_compute_polynomial_degree(*result*)

Compute the polynomial degree of this expression given the degree values of its children.

This method is called by the `_PolynomialDegreeVisitor` class. It can be over-written by expression classes to customize this logic.

Parameters **values** (*list*) – A list of values that indicate the degree of the children expression.

Returns A nonnegative integer that is the polynomial degree of the expression, or `None`. Default is `None`.

_else

_if

_is_fixed(*args*)

Compute whether this expression is fixed given the fixed values of its children.

This method is called by the `_IsFixedVisitor` class. It can be over-written by expression classes to customize this logic.

Parameters **values** (*list*) – A list of boolean values that indicate whether the children of this expression are fixed

Returns A boolean that is `True` if the fixed values of the children are all `True`.

_then

_to_string(*values*, *verbose*, *smap*, *compute_values*)

Construct a string representation for this node, using the string representations of its children.

This method is called by the `_ToStringVisitor` class. It must must be defined in subclasses.

Parameters

- **values** (*list*) – The string representations of the children of this node.
- **verbose** (*bool*) – If `True`, then the the string representation consists of nested functions. Otherwise, the string representation is an algebraic equation.
- **smap** – If specified, this *SymbolMap* is used to cache labels for variables.
- **compute_values** (*bool*) – If `True`, then parameters and fixed variables are evaluated before the expression string is generated.

Returns A string representation for this node.

getname(**args*, ***kwds*)

Return the text name of a function associated with this expression object.

In general, no arguments are passed to this function.

Parameters

- ***arg** – a variable length list of arguments
- ****kwds** – keyword arguments

Returns A string name for the function.

`is_constant()`
Return True if this expression is an atomic constant

This method contrasts with the is_fixed() method. This method returns True if the expression is an atomic constant, that is it is composed exclusively of constants and immutable parameters. NumericValue objects returning is_constant() == True may be simplified to their numeric value at any point without warning.

Note: This defaults to False, but gets redefined in sub-classes.

`is_potentially_variable()`
Return `True` if this expression might represent a variable expression.

This method returns `True` when (a) the expression tree contains one or more variables, or (b) the expression tree contains a named expression. In both cases, the expression cannot be treated as constant since (a) the variables may not be fixed, or (b) the named expressions may be changed at a later time to include non-fixed variables.

Returns A boolean. Defaults to `True` for expressions.

`nargs()`
Returns the number of child nodes.

By default, Pyomo expressions represent binary operations with two arguments.

Note: This function does not simply compute the length of `_args_` because some expression classes use a subset of the `_args_` array. Thus, it is imperative that developers use this method!

Returns A nonnegative integer that is the number of child nodes.

`class pyomo.core.expr.current.UnaryFunctionExpression(args, name=None, fcn=None)`
Bases: *pyomo.core.expr.numeric_expr.ExpressionBase*

An expression object used to define intrinsic functions (e.g. sin, cos, tan).

Parameters

- **args** (*tuple*) – Children nodes
- **name** (*string*) – The function name
- **fcn** – The function that is used to evaluate this expression

`_apply_operation(result)`
Compute the values of this node given the values of its children.

This method is called by the `_EvaluationVisitor` class. It must be over-written by expression classes to customize this logic.

Note: This method applies the logical operation of the operator to the arguments. It does *not* evaluate the arguments in the process, but assumes that they have been previously evaluated. But noted that if this class contains auxilliary data (e.g. like the numeric coefficients in the `LinearExpression` class, then those values *must* be evaluated as part of this function call. An uninitialized parameter value encountered during the execution of this method is considered an error.

Parameters **values** (*list*) – A list of values that indicate the value of the children expressions.

Returns A floating point value for this expression.

_compute_polynomial_degree(*result*)
Compute the polynomial degree of this expression given the degree values of its children.

This method is called by the `_PolynomialDegreeVisitor` class. It can be over-written by expression classes to customize this logic.

Parameters **values** (*list*) – A list of values that indicate the degree of the children expression.

Returns A nonnegative integer that is the polynomial degree of the expression, or `None`. Default is `None`.

_fcn

_name

_to_string(*values*, *verbose*, *smap*, *compute_values*)
Construct a string representation for this node, using the string representations of its children.

This method is called by the `_ToStringVisitor` class. It must must be defined in subclasses.

Parameters

- **values** (*list*) – The string representations of the children of this node.
- **verbose** (*bool*) – If `True`, then the the string representation consists of nested functions. Otherwise, the string representation is an algebraic equation.
- **smap** – If specified, this *SymbolMap* is used to cache labels for variables.
- **compute_values** (*bool*) – If `True`, then parameters and fixed variables are evaluated before the expression string is generated.

Returns A string representation for this node.

create_node_with_local_data(*args*)
Construct a node using given arguments.

This method provides a consistent interface for constructing a node, which is used in tree visitor scripts. In the simplest case, this simply returns:

```
self.__class__(args)
```

But in general this creates an expression object using local data as well as arguments that represent the child nodes.

Parameters

- **args** (*list*) – A list of child nodes for the new expression object
- **memo** (*dict*) – A dictionary that maps object ids to clone objects generated earlier during a cloning process. This argument is needed to clone objects that are owned by a model, and it can be safely ignored for most expression classes.

Returns A new expression object with the same type as the current class.

getname(**args*, ***kwds*)
Return the text name of a function associated with this expression object.

In general, no arguments are passed to this function.

Parameters

- ***arg** – a variable length list of arguments
- ****kwds** – keyword arguments

Returns A string name for the function.

nargs()
Returns the number of child nodes.

By default, Pyomo expressions represent binary operations with two arguments.

Note: This function does not simply compute the length of _args_ because some expression classes use a subset of the _args_ array. Thus, it is imperative that developers use this method!

Returns A nonnegative integer that is the number of child nodes.

class pyomo.core.expr.current.**AbsExpression**(*arg*)
Bases: pyomo.core.expr.numeric_expr.

An expression object for the abs() function.

Parameters **args** (*tuple*) – Children nodes

create_node_with_local_data(*args*)
Construct a node using given arguments.

This method provides a consistent interface for constructing a node, which is used in tree visitor scripts. In the simplest case, this simply returns:

```
self.__class__(args)
```

But in general this creates an expression object using local data as well as arguments that represent the child nodes.

Parameters

- **args** (*list*) – A list of child nodes for the new expression object
- **memo** (*dict*) – A dictionary that maps object ids to clone objects generated earlier during a cloning process. This argument is needed to clone objects that are owned by a model, and it can be safely ignored for most expression classes.

Returns A new expression object with the same type as the current class.

13.3.5 Visitor Classes

class pyomo.core.expr.current.**SimpleExpressionVisitor**

Note: This class is a customization of the PyUtilib SimpleVisitor class that is tailored to efficiently walk Pyomo expression trees. However, this class is not a subclass of the PyUtilib SimpleVisitor class because all key methods are reimplemented.

---

finalize()
Return the "final value" of the search.

The default implementation returns None, because the traditional visitor pattern does not return a value.

Returns The final value after the search. Default is None.

visit(*node*)
Visit a node in an expression tree and perform some operation on it.

This method should be over-written by a user that is creating a sub-class.

Parameters **node** – a node in an expression tree

Returns nothing

xbfs(*node*)

Breadth-first search of an expression tree, except that leaf nodes are immediately visited.

Note: This method has the same functionality as the PyUtilib `SimpleVisitor.xbfs` method. The difference is that this method is tailored to efficiently walk Pyomo expression trees.

Parameters **node** – The root node of the expression tree that is searched.

Returns The return value is determined by the *finalize()* function, which may be defined by the user. Defaults to `None`.

xbfs_yield_leaves(*node*)

Breadth-first search of an expression tree, except that leaf nodes are immediately visited.

Note: This method has the same functionality as the PyUtilib `SimpleVisitor.xbfs_yield_leaves` method. The difference is that this method is tailored to efficiently walk Pyomo expression trees.

Parameters **node** – The root node of the expression tree that is searched.

Returns The return value is determined by the *finalize()* function, which may be defined by the user. Defaults to `None`.

class pyomo.core.expr.current.**ExpressionValueVisitor**

Note: This class is a customization of the PyUtilib `ValueVisitor` class that is tailored to efficiently walk Pyomo expression trees. However, this class is not a subclass of the PyUtilib `ValueVisitor` class because all key methods are reimplemented.

---

dfs_postorder_stack(*node*)

Perform a depth-first search in postorder using a stack implementation.

Note: This method has the same functionality as the PyUtilib `ValueVisitor.dfs_postorder_stack` method. The difference is that this method is tailored to efficiently walk Pyomo expression trees.

Parameters **node** – The root node of the expression tree that is searched.

Returns The return value is determined by the *finalize()* function, which may be defined by the user.

finalize(*ans*)

This method defines the return value for the search methods in this class.

The default implementation returns the value of the initial node (aka the root node), because this visitor pattern computes and returns value for each node to enable the computation of this value.

Parameters **ans** – The final value computed by the search method.

Returns The final value after the search. Defaults to simply returning `ans`.

visit(*node*, *values*)
Visit a node in a tree and compute its value using the values of its children.

This method should be over-written by a user that is creating a sub-class.

Parameters

- **node** – a node in a tree
- **values** – a list of values of this node's children

Returns The *value* for this node, which is computed using `values`

visiting_potential_leaf(*node*)
Visit a node and return its value if it is a leaf.

Note: This method needs to be over-written for a specific visitor application.

Parameters **node** – a node in a tree

Returns `(flag, value)`. If `flag` is False, then the node is not a leaf and `value` is `None`. Otherwise, `value` is the computed value for this node.

Return type A tuple

class pyomo.core.expr.current.**ExpressionReplacementVisitor**(*substitute=None*, *descend_into_named_expressions=True*, *remove_named_expressions=False*)

Note: This class is a customization of the PyUtilib `ValueVisitor` class that is tailored to support replacement of sub-trees in a Pyomo expression tree. However, this class is not a subclass of the PyUtilib `ValueVisitor` class because all key methods are reimplemented.

---

construct_node(*node*, *values*)
Call the expression create_node_with_local_data() method.

dfs_postorder_stack(*node*)
Perform a depth-first search in postorder using a stack implementation.

This method replaces subtrees. This method detects if the *visit()* method returns a different object. If so, then the node has been replaced and search process is adapted to replace all subsequent parent nodes in the tree.

Note: This method has the same functionality as the PyUtilib `ValueVisitor.dfs_postorder_stack` method that is tailored to support the replacement of sub-trees in a Pyomo expression tree.

Parameters **node** – The root node of the expression tree that is searched.

Returns The return value is determined by the *finalize()* function, which may be defined by the user.

finalize(*ans*)
This method defines the return value for the search methods in this class.

The default implementation returns the value of the initial node (aka the root node), because this visitor pattern computes and returns value for each node to enable the computation of this value.

Parameters **ans** – The final value computed by the search method.

Returns The final value after the search. Defaults to simply returning `ans`.

visit(*node*, *values*)
Visit and clone nodes that have been expanded.

Note: This method normally does not need to be re-defined by a user.

Parameters

- **node** – The node that will be cloned.
- **values** (*list*) – The list of child nodes that have been cloned. These values are used to define the cloned node.

Returns The cloned node. Default is to simply return the node.

visiting_potential_leaf(*node*)
Visit a node and return a cloned node if it is a leaf.

Note: This method needs to be over-written for a specific visitor application.

Parameters **node** – a node in a tree

Returns `(flag, value)`. If `flag` is False, then the node is not a leaf and `value` is `None`. Otherwise, `value` is a cloned node.

Return type A tuple

13.4 Solver Interfaces

13.4.1 GAMS

GAMSShell Solver

GAMSShell.available([exception_flag])	True if the solver is available.
GAMSShell.executable()	Returns the executable used by this solver.
GAMSShell.solve(*args, **kwds)	Solve a model via the GAMS executable.
GAMSShell.version()	Returns a 4-tuple describing the solver executable version.
GAMSShell.warm_start_capable()	True is the solver can accept a warm-start solution.

class pyomo.solvers.plugins.solvers.GAMS.**GAMSShell**(***kwds*)
A generic shell interface to GAMS solvers.

available(*exception_flag=True*)
True if the solver is available.

executable()
Returns the executable used by this solver.

solve(**args*, ***kwds*)
Solve a model via the GAMS executable.

Keyword Arguments

- **tee=False** (*bool*) – Output GAMS log to stdout.
- **logfile=None** (*str*) – Filename to output GAMS log to a file.
- **load_solutions=True** (*bool*) – Load solution into model. If False, the results object will contain the solution data.
- **keepfiles=False** (*bool*) – Keep temporary files.
- **tmpdir=None** (*str*) – Specify directory path for storing temporary files. A directory will be created if one of this name doesn't exist. By default uses the system default temporary path.
- **report_timing=False** (*bool*) – Print timing reports for presolve, solver, postsolve, etc.
- **io_options** (*dict*) – Options that get passed to the writer. See writer in pyomo.repn.plugins.gams_writer for details. Updated with any other keywords passed to solve method. Note: put_results is not available for modification on GAMSShell solver.

GAMSDirect Solver

GAMSDirect.available([exception_flag])	True if the solver is available.
GAMSDirect.solve(*args, **kwds)	Solve a model via the GAMS Python API.
GAMSDirect.version()	Returns a 4-tuple describing the solver executable version.
GAMSDirect.warm_start_capable()	True is the solver can accept a warm-start solution.

class pyomo.solvers.plugins.solvers.GAMS.**GAMSDirect**(***kwds*)
A generic python interface to GAMS solvers.

Visit Python API page on gams.com for installation help.

available(*exception_flag=True*)
True if the solver is available.

solve(**args*, ***kwds*)
Solve a model via the GAMS Python API.

Keyword Arguments

- **tee=False** (*bool*) – Output GAMS log to stdout.
- **logfile=None** (*str*) – Filename to output GAMS log to a file.
- **load_solutions=True** (*bool*) – Load solution into model. If False, the results object will contain the solution data.
- **keepfiles=False** (*bool*) – Keep temporary files. Equivalent of DebugLevel.KeepFiles. Summary of temp files can be found in _gams_py_gjo0.pf

- **tmpdir=None** (*str*) – Specify directory path for storing temporary files. A directory will be created if one of this name doesn't exist. By default uses the system default temporary path.
- **report_timing=False** (*bool*) – Print timing reports for presolve, solver, postsolve, etc.
- **io_options** (*dict*) – Options that get passed to the writer. See writer in pyomo.repn.plugins.gams_writer for details. Updated with any other keywords passed to solve method.

GAMS Writer

This class is most commonly accessed and called upon via model.write("filename.gms", ...), but is also utilized by the GAMS solver interfaces.

class pyomo.repn.plugins.gams_writer.**ProblemWriter_gams**

__call__(*model*, *output_filename*, *solver_capability*, *io_options*)
Write a model in the GAMS modeling language format.

Keyword Arguments

- **output_filename** (*str*) – Name of file to write GAMS model to. Optionally pass a file-like stream and the model will be written to that instead.
- **io_options** (*dict*) –
  - **warmstart=True** Warmstart by initializing model's variables to their values.
  - **symbolic_solver_labels=False** Use full Pyomo component names rather than shortened symbols (slower, but useful for debugging).
  - **labeler=None** Custom labeler. Incompatible with symbolic_solver_labels.
  - **solver=None** If None, GAMS will use default solver for model type.
  - **mtype=None** Model type. If None, will chose from lp, nlp, mip, and minlp.
  - **add_options=None** List of additional lines to write directly into model file before the solve statement. For model attributes, <model name> is GAMS_MODEL.
  - **skip_trivial_constraints=False** Skip writing constraints whose body section is fixed.
  - **file_determinism=1**

    How much effort do we want to put into ensuring the
    GAMS file is written deterministically for a Pyomo model:
    0 : None
    1 : sort keys of indexed components (default)
    2 : sort keys AND sort names (over declaration order)
  - **put_results=None** Filename for optionally writing solution values and marginals. If put_results_format is 'gdx', then GAMS will write solution values and marginals to GAMS_MODEL_p.gdx and solver statuses to {put_results}_s.gdx. If put_results_format is 'dat', then solution values and marginals are written to (put_results).dat, and solver statuses to (put_results + 'stat').dat.
  - **put_results_format='gdx'** Format used for put_results, one of 'gdx', 'dat'.

13.4.2 CPLEXPersistent

class pyomo.solvers.plugins.solvers.cplex_persistent.**CPLEXPersistent**(***kwds*)

Bases: pyomo.solvers.plugins.solvers.persistent_solver.PersistentSolver, pyomo.solvers.plugins.solvers.cplex_direct.CPLEXDirect

A class that provides a persistent interface to Cplex. Direct solver interfaces do not use any file io. Rather, they interface directly with the python bindings for the specific solver. Persistent solver interfaces are similar except that they "remember" their model. Thus, persistent solver interfaces allow incremental changes to the solver model (e.g., the gurobi python model or the cplex python model). Note that users are responsible for notifying the persistent solver interfaces when changes are made to the corresponding pyomo model.

Keyword Arguments

- **model** (ConcreteModel) – Passing a model to the constructor is equivalent to calling the set_instance mehtod.
- **type** (*str*) – String indicating the class type of the solver instance.
- **name** (*str*) – String representing either the class type of the solver instance or an assigned name.
- **doc** (*str*) – Documentation for the solver
- **options** (*dict*) – Dictionary of solver options

add_block(*block*)

Add a single Pyomo Block to the solver's model.

This will keep any existing model components intact.

Parameters **block** (Block *(scalar Block or single _BlockData)*) –

add_column(*model*, *var*, *obj_coef*, *constraints*, *coefficients*)

Add a column to the solver's and Pyomo model

This will add the Pyomo variable var to the solver's model, and put the coefficients on the associated constraints in the solver model. If the obj_coef is not zero, it will add obj_coef*var to the objective of both the Pyomo and solver's model.

Parameters

- **model** (*pyomo ConcreteModel to which the column will be added*) –
- **var** (Var *(scalar Var or single _VarData)*) –
- **obj_coef** (*float, pyo.Param*) –
- **constraints** (*list of scalar Constraints of single _ConstraintDatas*) –
- **coefficients** (*list of the coefficient to put on var in the associated constraint*) –

add_constraint(*con*)

Add a single constraint to the solver's model.

This will keep any existing model components intact.

Parameters **con** (Constraint *(scalar Constraint or single _ConstraintData)*) –

add_sos_constraint(*con*)

Add a single SOS constraint to the solver's model (if supported).

This will keep any existing model components intact.

Parameters **con** (*SOSConstraint*) –

add_var(*var*)
Add a single variable to the solver's model.

This will keep any existing model components intact.
Parameters **var** (Var) –

available(*exception_flag=True*)
True if the solver is available.

has_capability(*cap*)
Returns a boolean value representing whether a solver supports a specific feature. Defaults to 'False' if the solver is unaware of an option. Expects a string.

Example: # prints True if solver supports sos1 constraints, and False otherwise print(solver.has_capability('sos1')

prints True is solver supports 'feature', and False otherwise print(solver.has_capability('feature')
Parameters **cap** (*str*) – The feature

Returns **val** – Whether or not the solver has the specified capability.

Return type bool

has_instance()
True if set_instance has been called and this solver interface has a pyomo model and a solver model.
Returns **tmp**

Return type bool

license_is_valid()
True if the solver is present and has a valid license (if applicable)

load_duals(*cons_to_load=None*)
Load the duals into the 'dual' suffix. The 'dual' suffix must live on the parent model.
Parameters **cons_to_load** (*list of Constraint*) –

load_rc(*vars_to_load*)
Load the reduced costs into the 'rc' suffix. The 'rc' suffix must live on the parent model.
Parameters **vars_to_load** (*list of Var*) –

load_slacks(*cons_to_load=None*)
Load the values of the slack variables into the 'slack' suffix. The 'slack' suffix must live on the parent model.
Parameters **cons_to_load** (*list of Constraint*) –

load_vars(*vars_to_load=None*)
Load the values from the solver's variables into the corresponding pyomo variables.
Parameters **vars_to_load** (*list of Var*) –

problem_format()
Returns the current problem format.

remove_block(*block*)
Remove a single block from the solver's model.

This will keep any other model components intact.

WARNING: Users must call remove_block BEFORE modifying the block.
Parameters **block** (Block *(scalar Block or a single _BlockData)*) –

remove_constraint(*con*)
Remove a single constraint from the solver's model.

This will keep any other model components intact.

Parameters **con** (Constraint *(scalar Constraint or single _ConstraintData)*) –

remove_sos_constraint(*con*)
Remove a single SOS constraint from the solver's model.

This will keep any other model components intact.
Parameters **con** (*SOSConstraint*) –

remove_var(*var*)
Remove a single variable from the solver's model.

This will keep any other model components intact.
Parameters **var** (Var *(scalar Var or single _VarData)*) –

reset()
Reset the state of the solver

results
A results object return from the solve method.

results_format()
Returns the current results format.

set_callback(*name*, *callback_fn=None*)
Set the callback function for a named callback.

A call-back function has the form:
def fn(solver, model): pass
where 'solver' is the native solver interface object and 'model' is a Pyomo model instance object.

set_instance(*model*, ***kwds*)
This method is used to translate the Pyomo model provided to an instance of the solver's Python model. This discards any existing model and starts from scratch.
Parameters **model** (ConcreteModel) – The pyomo model to be used with the solver.

Keyword Arguments

- **symbolic_solver_labels** (*bool*) – If True, the solver's components (e.g., variables, constraints) will be given names that correspond to the Pyomo component names.
- **skip_trivial_constraints** (*bool*) – If True, then any constraints with a constant body will not be added to the solver model. Be careful with this. If a trivial constraint is skipped then that constraint cannot be removed from a persistent solver (an error will be raised if a user tries to remove a non-existent constraint).
- **output_fixed_variable_bounds** (*bool*) – If False then an error will be raised if a fixed variable is used in one of the solver constraints. This is useful for catching bugs. Ordinarily a fixed variable should appear as a constant value in the solver constraints. If True, then the error will not be raised.

set_objective(*obj*)
Set the solver's objective. Note that, at least for now, any existing objective will be discarded. Other than that, any existing model components will remain intact.
Parameters **obj** (Objective) –

set_problem_format(*format*)
Set the current problem format (if it's valid) and update the results format to something valid for this problem format.

set_results_format(*format*)
Set the current results format (if it's valid for the current problem format).

solve(**args*, ***kwds*)
Solve the model.

Keyword Arguments

- **suffixes** (*list of str*) – The strings should represnt suffixes support by the solver. Examples include 'dual', 'slack', and 'rc'.
- **options** (*dict*) – Dictionary of solver options. See the solver documentation for possible solver options.
- **warmstart** (*bool*) – If True, the solver will be warmstarted.
- **keepfiles** (*bool*) – If True, the solver log file will be saved.
- **logfile** (*str*) – Name to use for the solver log file.
- **load_solutions** (*bool*) – If True and a solution exists, the solution will be loaded into the Pyomo model.
- **report_timing** (*bool*) – If True, then timing information will be printed.
- **tee** (*bool*) – If True, then the solver log will be printed.

update_var(*var*)
Update a single variable in the solver's model.

This will update bounds, fix/unfix the variable as needed, and update the variable type.

Parameters **var** (Var *(scalar Var or single _VarData)*) –

version()
Returns a 4-tuple describing the solver executable version.

warm_start_capable()
True is the solver can accept a warm-start solution

write(*filename*, *filetype=''*)
Write the model to a file (e.g., and lp file).

Parameters

- **filename** (*str*) – Name of the file to which the model should be written.
- **filetype** (*str*) – The file type (e.g., lp).

13.4.3 GurobiPersistent

Methods

GurobiPersistent.add_block(block)	Add a single Pyomo Block to the solver's model.
GurobiPersistent.add_constraint(con)	Add a single constraint to the solver's model.
GurobiPersistent.set_objective(obj)	Set the solver's objective.
GurobiPersistent.add_sos_constraint(con)	Add a single SOS constraint to the solver's model (if supported).
GurobiPersistent.add_var(var)	Add a single variable to the solver's model.
GurobiPersistent.available([exception_flag])	True if the solver is available.
GurobiPersistent.has_capability(cap)	Returns a boolean value representing whether a solver supports a specific feature.

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Table 13.6 – continued from previous page

GurobiPersistent.has_instance()	True if set_instance has been called and this solver interface has a pyomo model and a solver model.
GurobiPersistent.load_vars([vars_to_load])	Load the values from the solver's variables into the corresponding pyomo variables.
GurobiPersistent.problem_format()	Returns the current problem format.
GurobiPersistent.remove_block(block)	Remove a single block from the solver's model.
GurobiPersistent.remove_constraint(con)	Remove a single constraint from the solver's model.
GurobiPersistent.remove_sos_constraint(con)	Remove a single SOS constraint from the solver's model.
GurobiPersistent.remove_var(var)	Remove a single variable from the solver's model.
GurobiPersistent.reset()	Reset the state of the solver
GurobiPersistent.results_format()	Returns the current results format.
GurobiPersistent.set_callback([func])	Specify a callback for gurobi to use.
GurobiPersistent.set_instance(model, **kwds)	This method is used to translate the Pyomo model provided to an instance of the solver's Python model.
GurobiPersistent.set_problem_format(format)	Set the current problem format (if it's valid) and update the results format to something valid for this problem format.
GurobiPersistent.set_results_format(format)	Set the current results format (if it's valid for the current problem format).
GurobiPersistent.solve(*args, **kwds)	Solve the model.
GurobiPersistent.update_var(var)	Update a single variable in the solver's model.
GurobiPersistent.version()	Returns a 4-tuple describing the solver executable version.
GurobiPersistent.write(filename)	Write the model to a file (e.g., and lp file).

class pyomo.solvers.plugins.solvers.gurobi_persistent.**GurobiPersistent**(***kwds*)

Bases: pyomo.solvers.plugins.solvers.persistent_solver.PersistentSolver, pyomo.solvers.plugins.solvers.gurobi_direct.None

A class that provides a persistent interface to Gurobi. Direct solver interfaces do not use any file io. Rather, they interface directly with the python bindings for the specific solver. Persistent solver interfaces are similar except that they "remember" their model. Thus, persistent solver interfaces allow incremental changes to the solver model (e.g., the gurobi python model or the cplex python model). Note that users are responsible for notifying the persistent solver interfaces when changes are made to the corresponding pyomo model.

Keyword Arguments

- **model** (ConcreteModel) – Passing a model to the constructor is equivalent to calling the set_instance mehtod.
- **type** (*str*) – String indicating the class type of the solver instance.
- **name** (*str*) – String representing either the class type of the solver instance or an assigned name.
- **doc** (*str*) – Documentation for the solver
- **options** (*dict*) – Dictionary of solver options

add_block(*block*)

Add a single Pyomo Block to the solver's model.

This will keep any existing model components intact.

Parameters **block** (Block *(scalar Block or single _BlockData)*) –

add_column(*model*, *var*, *obj_coef*, *constraints*, *coefficients*)

Add a column to the solver's and Pyomo model

This will add the Pyomo variable var to the solver's model, and put the coefficients on the associated constraints in the solver model. If the obj_coef is not zero, it will add obj_coef*var to the objective of both the Pyomo and solver's model.

Parameters

- **model** (*pyomo ConcreteModel to which the column will be added*) –
- **var** (*Var (scalar Var or single _VarData)*) –
- **obj_coef** (*float, pyo.Param*) –
- **constraints** (*list of scalar Constraints of single _ConstraintDatas*) –
- **coefficients** (*list of the coefficient to put on var in the associated constraint*) –

add_constraint(*con*)

Add a single constraint to the solver's model.

This will keep any existing model components intact.

Parameters **con** (*Constraint (scalar Constraint or single _ConstraintData)*) –

add_sos_constraint(*con*)

Add a single SOS constraint to the solver's model (if supported).

This will keep any existing model components intact.

Parameters **con** (*SOSConstraint*) –

add_var(*var*)

Add a single variable to the solver's model.

This will keep any existing model components intact.

Parameters **var** (*Var*) –

available(*exception_flag=True*)

True if the solver is available.

cbCut(*con*)

Add a cut within a callback.

Parameters **con** (*pyomo.core.base.constraint._GeneralConstraintData*) – The cut to add

cbGetNodeRel(*vars*)

Parameters **vars** (*Var or iterable of Var*) –

cbGetSolution(*vars*)

Parameters **vars** (*iterable of vars*) –

cbLazy(*con*)

Parameters **con** (*pyomo.core.base.constraint._GeneralConstraintData*) – The lazy constraint to add

get_gurobi_param_info(*param*)

Get information about a gurobi parameter.

Parameters **param** (*str*) – The gurobi parameter to get info for. See Gurobi documenation for possible options.

Returns

Return type six-tuple containing the parameter name, type, value, minimum value, maximum value, and default value.

`get_linear_constraint_attr`(*con*, *attr*)

Get the value of an attribute on a gurobi linear constraint.

Parameters

- **con** (*pyomo.core.base.constraint._GeneralConstraintData*) – The pyomo constraint for which the corresponding gurobi constraint attribute should be retrieved.
- **attr** (*str*) – The attribute to get. Options are:

  Sense RHS ConstrName Pi Slack CBasis DStart Lazy IISConstr SARHSLow SARHSUp FarkasDual

`get_model_attr`(*attr*)

Get the value of an attribute on the Gurobi model.

Parameters **attr** (*str*) – The attribute to get. See Gurobi documentation for descriptions of the attributes.

Options are:

NumVars NumConstrs NumSOS NumQConstrs NumgGenConstrs NumNZs DNumNZs NumQNZs NumQCNZs NumIntVars NumBinVars NumPWLObjVars ModelName ModelSense ObjCon ObjVal ObjBound ObjBoundC PoolObjBound PoolObjVal MIPGap Runtime Status SolCount IterCount BarIterCount NodeCount IsMIP IsQP IsQCP IsMultiObj IISMinimal MaxCoeff MinCoeff MaxBound MinBound MaxObjCoeff MinObjCoeff MaxRHS MinRHS MaxQCCoeff MinQCCoeff MaxQCLCoeff MinQCLCoeff MaxQCRHS MinQCRHS MaxQObjCoeff MinQObjCoeff Kappa KappaExact FarkasProof TuneResultCount LicenseExpiration BoundVio BoundSVio BoundVioIndex BoundSVioIndex BoundVioSum BoundSVioSum ConstrVio ConstrSVio ConstrVioIndex ConstrSVioIndex ConstrVioSum ConstrSVioSum ConstrResidual ConstrSResidual ConstrResidualIndex ConstrSResidualIndex ConstrResidualSum ConstrSResidualSum DualVio DualSVio DualVioIndex DualSVioIndex DualVioSum DualSVioSum DualResidual DualSResidual DualResidualIndex DualSResidualIndex DualResidualSum DualSResidualSum ComplVio ComplVioIndex ComplVioSum IntVio IntVioIndex IntVioSum

`get_quadratic_constraint_attr`(*con*, *attr*)

Get the value of an attribute on a gurobi quadratic constraint.

Parameters

- **con** (*pyomo.core.base.constraint._GeneralConstraintData*) – The pyomo constraint for which the corresponding gurobi constraint attribute should be retrieved.
- **attr** (*str*) – The attribute to get. Options are:

  QCSense QCRHS QCName QCPi QCSlack IISQConstr

`get_sos_attr`(*con*, *attr*)

Get the value of an attribute on a gurobi sos constraint.

Parameters

- **con** (*pyomo.core.base.sos._SOSConstraintData*) – The pyomo SOS constraint for which the corresponding gurobi SOS constraint attribute should be retrieved.

- **attr** (*str*) – The attribute to get. Options are:

  IISSOS

get_var_attr(*var*, *attr*)

Get the value of an attribute on a gurobi var.

Parameters

- **var** (*pyomo.core.base.var._GeneralVarData*) – The pyomo var for which the corresponding gurobi var attribute should be retrieved.
- **attr** (*str*) – The attribute to get. Options are:

  LB UB Obj VType VarName X Xn RC BarX Start VarHintVal VarHintPri BranchPriority VBasis PStart IISLB IISUB PWLObjCvx SAObjLow SAObjUp SALBLow SALBUp SAUBLow SAUBUp UnbdRay

has_capability(*cap*)

Returns a boolean value representing whether a solver supports a specific feature. Defaults to 'False' if the solver is unaware of an option. Expects a string.

Example: # prints True if solver supports sos1 constraints, and False otherwise print(solver.has_capability('sos1')

prints True is solver supports 'feature', and False otherwise print(solver.has_capability('feature')

Parameters **cap** (*str*) – The feature

Returns **val** – Whether or not the solver has the specified capability.

Return type bool

has_instance()

True if set_instance has been called and this solver interface has a pyomo model and a solver model.

Returns **tmp**

Return type bool

license_is_valid()

True if the solver is present and has a valid license (if applicable)

load_duals(*cons_to_load=None*)

Load the duals into the 'dual' suffix. The 'dual' suffix must live on the parent model.

Parameters **cons_to_load** (*list of Constraint*) –

load_rc(*vars_to_load*)

Load the reduced costs into the 'rc' suffix. The 'rc' suffix must live on the parent model.

Parameters **vars_to_load** (*list of Var*) –

load_slacks(*cons_to_load=None*)

Load the values of the slack variables into the 'slack' suffix. The 'slack' suffix must live on the parent model.

Parameters **cons_to_load** (*list of Constraint*) –

load_vars(*vars_to_load=None*)

Load the values from the solver's variables into the corresponding pyomo variables.

Parameters **vars_to_load** (*list of Var*) –

problem_format()

Returns the current problem format.

remove_block(*block*)

Remove a single block from the solver's model.

This will keep any other model components intact.

WARNING: Users must call remove_block BEFORE modifying the block.

Parameters **block** (*Block (scalar Block or a single _BlockData)*) –

remove_constraint(*con*)

Remove a single constraint from the solver's model.

This will keep any other model components intact.

Parameters **con** (*Constraint (scalar Constraint or single _ConstraintData)*) –

remove_sos_constraint(*con*)

Remove a single SOS constraint from the solver's model.

This will keep any other model components intact.

Parameters **con** (*SOSConstraint*) –

remove_var(*var*)

Remove a single variable from the solver's model.

This will keep any other model components intact.

Parameters **var** (*Var (scalar Var or single _VarData)*) –

reset()

Reset the state of the solver

results

A results object return from the solve method.

results_format()

Returns the current results format.

set_callback(*func=None*)

Specify a callback for gurobi to use.

Parameters **func** (*function*) – The function to call. The function should have three arguments. The first will be the pyomo model being solved. The second will be the GurobiPersistent instance. The third will be an enum member of gurobipy.GRB.Callback. This will indicate where in the branch and bound algorithm gurobi is at. For example, suppose we want to solve $\begin{aligned} \min \quad & 2x + y \\ \text{s.t.} \quad & y \geq (x-2)^2 \\ & 0 \leq x \leq 4 \\ & y \geq 0 \\ & y \in \mathbb{Z} \end{aligned}$ as an MILP using exteneded cutting planes in callbacks.

```
from gurobipy import GRB
import pyomo.environ as pe
from pyomo.core.expr.taylor_series import taylor_series_expansion

m = pe.ConcreteModel()
m.x = pe.Var(bounds=(0, 4))
m.y = pe.Var(within=pe.Integers, bounds=(0, None))
m.obj = pe.Objective(expr=2*m.x + m.y)
m.cons = pe.ConstraintList()  # for the cutting planes

def _add_cut(xval):
    # a function to generate the cut
    m.x.value = xval
    return m.cons.add(m.y >= taylor_series_expansion((m.x -␣
↪2)**2))
```

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```
_add_cut(0)  # start with 2 cuts at the bounds of x
_add_cut(4)  # this is an arbitrary choice

opt = pe.SolverFactory('gurobi_persistent')
opt.set_instance(m)
opt.set_gurobi_param('PreCrush', 1)
opt.set_gurobi_param('LazyConstraints', 1)

def my_callback(cb_m, cb_opt, cb_where):
    if cb_where == GRB.Callback.MIPSOL:
        cb_opt.cbGetSolution(vars=[m.x, m.y])
        if m.y.value < (m.x.value - 2)**2 - 1e-6:
            cb_opt.cbLazy(_add_cut(m.x.value))

opt.set_callback(my_callback)
opt.solve()
```

```
>>> assert abs(m.x.value - 1) <= 1e-6
>>> assert abs(m.y.value - 1) <= 1e-6
```

set_gurobi_param(*param*, *val*)

Set a gurobi parameter.

Parameters

- **param** (*str*) – The gurobi parameter to set. Options include any gurobi parameter. Please see the Gurobi documentation for options.
- **val** (*any*) – The value to set the parameter to. See Gurobi documentation for possible values.

set_instance(*model*, ***kwds*)

This method is used to translate the Pyomo model provided to an instance of the solver's Python model. This discards any existing model and starts from scratch.

Parameters **model** (ConcreteModel) – The pyomo model to be used with the solver.

Keyword Arguments

- **symbolic_solver_labels** (*bool*) – If True, the solver's components (e.g., variables, constraints) will be given names that correspond to the Pyomo component names.
- **skip_trivial_constraints** (*bool*) – If True, then any constraints with a constant body will not be added to the solver model. Be careful with this. If a trivial constraint is skipped then that constraint cannot be removed from a persistent solver (an error will be raised if a user tries to remove a non-existent constraint).
- **output_fixed_variable_bounds** (*bool*) – If False then an error will be raised if a fixed variable is used in one of the solver constraints. This is useful for catching bugs. Ordinarily a fixed variable should appear as a constant value in the solver constraints. If True, then the error will not be raised.

set_linear_constraint_attr(*con*, *attr*, *val*)

Set the value of an attribute on a gurobi linear constraint.

Parameters

- **con** (*pyomo.core.base.constraint._GeneralConstraintData*) – The pyomo constraint for which the corresponding gurobi constraint attribute should be modified.
- **attr** (*str*) – The attribute to be modified. Options are:

  CBasis DStart Lazy
- **val** (*any*) – See gurobi documentation for acceptable values.

set_objective(*obj*)
Set the solver's objective. Note that, at least for now, any existing objective will be discarded. Other than that, any existing model components will remain intact.

Parameters **obj** (Objective) –

set_problem_format(*format*)
Set the current problem format (if it's valid) and update the results format to something valid for this problem format.

set_results_format(*format*)
Set the current results format (if it's valid for the current problem format).

set_var_attr(*var*, *attr*, *val*)
Set the value of an attribute on a gurobi variable.

Parameters

- **con** (*pyomo.core.base.var._GeneralVarData*) – The pyomo var for which the corresponding gurobi var attribute should be modified.
- **attr** (*str*) – The attribute to be modified. Options are:

  Start VarHintVal VarHintPri BranchPriority VBasis PStart
- **val** (*any*) – See gurobi documentation for acceptable values.

solve(**args*, ***kwds*)
Solve the model.

Keyword Arguments

- **suffixes** (*list of str*) – The strings should represnt suffixes support by the solver. Examples include 'dual', 'slack', and 'rc'.
- **options** (*dict*) – Dictionary of solver options. See the solver documentation for possible solver options.
- **warmstart** (*bool*) – If True, the solver will be warmstarted.
- **keepfiles** (*bool*) – If True, the solver log file will be saved.
- **logfile** (*str*) – Name to use for the solver log file.
- **load_solutions** (*bool*) – If True and a solution exists, the solution will be loaded into the Pyomo model.
- **report_timing** (*bool*) – If True, then timing information will be printed.
- **tee** (*bool*) – If True, then the solver log will be printed.

update_var(*var*)
Update a single variable in the solver's model.

This will update bounds, fix/unfix the variable as needed, and update the variable type.

Parameters **var** (Var *(scalar Var or single _VarData)*) –

version()
Returns a 4-tuple describing the solver executable version.

warm_start_capable()
True is the solver can accept a warm-start solution

write(*filename*)
Write the model to a file (e.g., and lp file).
Parameters **filename** (*str*) – Name of the file to which the model should be written.

13.5 Model Data Management

class pyomo.dataportal.DataPortal.**DataPortal**(**args*, ***kwds*)
An object that manages loading and storing data from external data sources. This object interfaces to plugins that manipulate the data in a manner that is dependent on the data format.

Internally, the data in a DataPortal object is organized as follows:

```
data[namespace][symbol][index] -> value
```

All data is associated with a symbol name, which may be indexed, and which may belong to a namespace. The default namespace is None.
Parameters

- **model** – The model for which this data is associated. This is used for error checking (e.g. object names must exist in the model, set dimensions must match, etc.). Default is None.
- **filename** (*str*) – A file from which data is loaded. Default is None.
- **data_dict** (*dict*) – A dictionary used to initialize the data in this object. Default is None.

__getitem__(**args*)
Return the specified data value.

If a single argument is given, then this is the symbol name:

```
dp = DataPortal()
dp[name]
```

If a two arguments are given, then the first is the namespace and the second is the symbol name:

```
dp = DataPortal()
dp[namespace, name]
```

Parameters ***args** (*str*) – A tuple of arguents.

Returns If a single argument is given, then the data associated with that symbol in the namespace None is returned. If two arguments are given, then the data associated with symbol in the given namespace is returned.

__init__(**args*, ***kwds*)
Constructor

__setitem__(*name*, *value*)
Set the value of name with the given value.
Parameters

- **name** (*str*) – The name of the symbol that is set.
- **value** – The value of the symbol.

__weakref__
list of weak references to the object (if defined)

connect(***kwds*)
Construct a data manager object that is associated with the input source. This data manager is used to process future data imports and exports.

Parameters

- **filename** (*str*) – A filename that specifies the data source. Default is None.
- **server** (*str*) – The name of the remote server that hosts the data. Default is None.
- **using** (*str*) – The name of the resource used to load the data. Default is None.

Other keyword arguments are passed to the data manager object.

data(*name=None*, *namespace=None*)

Return the data associated with a symbol and namespace

Parameters

- **name** (*str*) – The name of the symbol that is returned. Default is None, which indicates that the entire data in the namespace is returned.
- **namespace** (*str*) – The name of the namespace that is accessed. Default is None.

Returns If name is None, then the dictionary for the namespace is returned. Otherwise, the data associated with name in given namespace is returned. The return value is a constant if None if there is a single value in the symbol dictionary, and otherwise the symbol dictionary is returned.

disconnect()
Close the data manager object that is associated with the input source.

items(*namespace=None*)
Return an iterator of (name, value) tuples from the data in the specified namespace.

Yields The next (name, value) tuple in the namespace. If the symbol has a simple data value, then that is included in the tuple. Otherwise, the tuple includes a dictionary mapping symbol indices to values.

keys(*namespace=None*)
Return an iterator of the data keys in the specified namespace.

Yields A string name for the next symbol in the specified namespace.

load(***kwds*)
Import data from an external data source.

Parameters **model** – The model object for which this data is associated. Default is None.

Other keyword arguments are passed to the *connect()* method.

namespaces()
Return an iterator for the namespaces in the data portal.

Yields A string name for the next namespace.

store(***kwds*)
Export data to an external data source.

Parameters **model** – The model object for which this data is associated. Default is None.

Other keyword arguments are passed to the *connect()* method.

values(*namespace=None*)
Return an iterator of the data values in the specified namespace.

Yields The data value for the next symbol in the specified namespace. This may be a simple value, or a dictionary of values.

class pyomo.dataportal.TableData.**TableData**
A class used to read/write data from/to a table in an external data source.

__init__()
Constructor

__weakref__
list of weak references to the object (if defined)

add_options(***kwds*)
Add the keyword options to the `Options` object in this object.

available()

Returns Return `True` if the data manager is available.

clear()
Clear the data that was extracted from this table

close()
Close the data manager.

initialize(***kwds*)
Initialize the data manager with keyword arguments.

The *filename* argument is recognized here, and other arguments are passed to the *add_options()* method.

open()
Open the data manager.

process(*model*, *data*, *default*)
Process the data that was extracted from this data manager and return it.

read()
Read data from the data manager.

write(*data*)
Write data to the data manager.

13.6 APPSI

Auto-Persistent Pyomo Solver Interfaces

13.6.1 APPSI Base Classes

class pyomo.contrib.appsi.base.**TerminationCondition**(*value*)
Bases: `enum.Enum`

An enumeration for checking the termination condition of solvers

error = 11
The solver exited due to an error

infeasible = 9
The solver exited because the problem is infeasible

infeasibleOrUnbounded = 10
The solver exited because the problem is either infeasible or unbounded

interrupted = 12
The solver exited because it was interrupted

licensingProblems = 13
The solver exited due to licensing problems

maxIterations = 2
The solver exited due to an iteration limit

maxTimeLimit = 1
The solver exited due to a time limit

minStepLength = 4
The solver exited due to a minimum step length

objectiveLimit = 3
The solver exited due to an objective limit

optimal = 5
The solver exited with the optimal solution

unbounded = 8
The solver exited because the problem is unbounded

unknown = 0
unknown serves as both a default value, and it is used when no other enum member makes sense

class pyomo.contrib.appsi.base.**Results**
Bases: object

termination_condition
The reason the solver exited. This is a member of the TerminationCondition enum.
Type *TerminationCondition*

best_feasible_objective
If a feasible solution was found, this is the objective value of the best solution found. If no feasible solution was found, this is None.
Type float

best_objective_bound
The best objective bound found. For minimization problems, this is the lower bound. For maximization problems, this is the upper bound. For solvers that do not provide an objective bound, this should be -inf (minimization) or inf (maximization)
Type float

Here is an example workflow

```
>>> import pyomo.environ as pe
>>> from pyomo.contrib import appsi
>>> m = pe.ConcreteModel()
>>> m.x = pe.Var()
>>> m.obj = pe.Objective(expr=m.x**2)
>>> opt = appsi.solvers.Ipopt()
>>> opt.config.load_solution = False
```

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```
>>> results = opt.solve(m)
>>> if results.termination_condition == appsi.base.TerminationCondition.
↪optimal:
...     print('optimal solution found: ', results.best_feasible_objective)
...     results.solution_loader.load_vars()
...     print('the optimal value of x is ', m.x.value)
... elif results.best_feasible_objective is not None:
...     print('sub-optimal but feasible solution found: ', results.best_
↪feasible_objective)
...     results.solution_loader.load_vars(vars_to_load=[m.x])
...     print('The value of x in the feasible solution is ', m.x.value)
... elif results.termination_condition in {appsi.base.TerminationCondition.
↪maxIterations, appsi.base.TerminationCondition.maxTimeLimit}:
...     print('No feasible solution was found. The best lower bound found was
↪', results.best_objective_bound)
... else:
...     print('The following termination condition was encountered: ', results.
↪termination_condition)
```

class pyomo.contrib.appsi.base.**Solver**

Bases: abc.ABC

class Availability(*value*)

Bases: enum.IntEnum

An enumeration.

BadLicense = -2

BadVersion = -1

FullLicense = 1

LimitedLicense = 2

NotFound = 0

abstract available()

Test if the solver is available on this system.

Nominally, this will return True if the solver interface is valid and can be used to solve problems and False if it cannot.

Note that for licensed solvers there are a number of "levels" of available: depending on the license, the solver may be available with limitations on problem size or runtime (e.g., 'demo' vs. 'community' vs. 'full'). In these cases, the solver may return a subclass of enum.IntEnum, with members that resolve to True if the solver is available (possibly with limitations). The Enum may also have multiple members that all resolve to False indicating the reason why the interface is not available (not found, bad license, unsupported version, etc).

Returns **available** – An enum that indicates "how available" the solver is. Note that the enum can be cast to bool, which will be True if the solver is runable at all and False otherwise.

Return type *Solver.Availability*

abstract property config

An object for configuring solve options.

Returns An object for configuring pyomo solve options such as the time limit. These options are mostly independent of the solver.

Return type *SolverConfig*

is_persistent()

Returns **is_persistent** – True if the solver is a persistent solver.

Return type bool

abstract solve(*model: pyomo.core.base.block._BlockData*, *timer: Optional[pyomo.common.timing.HierarchicalTimer] = None*) → *pyomo.contrib.appsi.base.Results*

Solve a Pyomo model.

Parameters

- **model** (*_BlockData*) – The Pyomo model to be solved
- **timer** (HierarchicalTimer) – An option timer for reporting timing

Returns **results** – A results object

Return type *Results*

abstract property symbol_map

abstract version() → Tuple

Returns **version** – A tuple representing the version

Return type tuple

class pyomo.contrib.appsi.base.**PersistentSolver**

Bases: *pyomo.contrib.appsi.base.Solver*

class Availability(*value*)

Bases: enum.IntEnum

An enumeration.

BadLicense = -2

BadVersion = -1

FullLicense = 1

LimitedLicense = 2

NotFound = 0

abstract add_block(*block: pyomo.core.base.block._BlockData*)

abstract add_constraints(*cons: List[pyomo.core.base.constraint._GeneralConstraintData]*)

abstract add_params(*params: List[pyomo.core.base.param._ParamData]*)

abstract add_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

abstract available()

Test if the solver is available on this system.

Nominally, this will return True if the solver interface is valid and can be used to solve problems and False if it cannot.

Note that for licensed solvers there are a number of "levels" of available: depending on the license, the solver may be available with limitations on problem size or runtime (e.g., 'demo' vs. 'community' vs. 'full'). In these cases, the solver may return a subclass of enum.IntEnum, with members that resolve to True if the solver is available (possibly with limitations). The Enum may also have multiple members

that all resolve to False indicating the reason why the interface is not available (not found, bad license, unsupported version, etc).

Returns **available** – An enum that indicates "how available" the solver is. Note that the enum can be cast to bool, which will be True if the solver is runable at all and False otherwise.

Return type *Solver.Availability*

abstract property config

An object for configuring solve options.

Returns An object for configuring pyomo solve options such as the time limit. These options are mostly independent of the solver.

Return type *SolverConfig*

get_duals(*cons_to_load: Optional[Sequence[pyomo.core.base.constraint._GeneralConstraintData]] = None*) → Dict[pyomo.core.base.constraint._GeneralConstraintData, float]

Declare sign convention in docstring here.

Parameters **cons_to_load** (*list*) – A list of the constraints whose duals should be loaded. If cons_to_load is None, then the duals for all constraints will be loaded.

Returns **duals** – Maps constraints to dual values

Return type dict

abstract get_primals(*vars_to_load: Optional[Sequence[pyomo.core.base.var._GeneralVarData]] = None*) → Mapping[pyomo.core.base.var._GeneralVarData, float]

get_reduced_costs(*vars_to_load: Optional[Sequence[pyomo.core.base.var._GeneralVarData]] = None*) → Mapping[pyomo.core.base.var._GeneralVarData, float]

Parameters **vars_to_load** (*list*) – A list of the variables whose reduced cost should be loaded. If vars_to_load is None, then all reduced costs will be loaded.

Returns **reduced_costs** – Maps variable to reduced cost

Return type ComponentMap

get_slacks(*cons_to_load: Optional[Sequence[pyomo.core.base.constraint._GeneralConstraintData]] = None*) → Dict[pyomo.core.base.constraint._GeneralConstraintData, float]

Parameters **cons_to_load** (*list*) – A list of the constraints whose slacks should be loaded. If cons_to_load is None, then the slacks for all constraints will be loaded.

Returns **slacks** – Maps constraints to slack values

Return type dict

is_persistent()

Returns **is_persistent** – True if the solver is a persistent solver.

Return type bool

load_vars(*vars_to_load: Optional[Sequence[pyomo.core.base.var._GeneralVarData]] = None*) → NoReturn

Load the solution of the primal variables into the value attribut of the variables.

Parameters **vars_to_load** (*list*) – A list of the variables whose solution should be loaded. If vars_to_load is None, then the solution to all primal variables will be loaded.

abstract remove_block(*block: pyomo.core.base.block._BlockData*)

abstract remove_constraints(*cons: List[pyomo.core.base.constraint._GeneralConstraintData]*)

abstract remove_params(*params: List[pyomo.core.base.param._ParamData]*)

abstract remove_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

abstract set_instance(*model*)

abstract set_objective(*obj: pyomo.core.base.objective._GeneralObjectiveData*)

abstract solve(*model: pyomo.core.base.block._BlockData*, *timer: Optional[pyomo.common.timing.HierarchicalTimer] = None*) → *pyomo.contrib.appsi.base.Results*

Solve a Pyomo model.

Parameters

- **model** (*_BlockData*) – The Pyomo model to be solved
- **timer** (HierarchicalTimer) – An option timer for reporting timing

Returns **results** – A results object

Return type *Results*

abstract property symbol_map

abstract property update_config: pyomo.contrib.appsi.base.UpdateConfig

abstract update_params()

abstract update_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

abstract version() → Tuple

Returns **version** – A tuple representing the version

Return type tuple

class pyomo.contrib.appsi.base.**SolverConfig**(*description=None*, *doc=None*, *implicit=False*, *implicit_domain=None*, *visibility=0*)

Bases: pyomo.common.config.

time_limit

Time limit for the solver

Type float

stream_solver

If True, then the solver log goes to stdout

Type bool

load_solution

If False, then the values of the primal variables will not be loaded into the model

Type bool

symbolic_solver_labels

If True, the names given to the solver will reflect the names of the pyomo components. Cannot be changed after set_instance is called.

Type bool

report_timing

If True, then some timing information will be printed at the end of the solve.

Type bool

class NoArgument

Bases: object

add(*name*, *config*)

content_filters = {'all', 'userdata', None}

declare(*name*, *config*)

declare_as_argument(**args*, ***kwds*)
Map this Config item to an argparse argument.

Valid arguments include all valid arguments to argparse's ArgumentParser.add_argument() with the exception of 'default'. In addition, you may provide a group keyword argument to either pass in a pre-defined option group or subparser, or else pass in the string name of a group, subparser, or (subparser, group).

declare_from(*other*, *skip=None*)

display(*content_filter=None*, *indent_spacing=2*, *ostream=None*, *visibility=None*)

generate_documentation(*block_start=None*, *block_end=None*, *item_start=None*, *item_body=None*, *item_end=None*, *indent_spacing=2*, *width=78*, *visibility=0*, *format='latex'*)

generate_yaml_template(*indent_spacing=2*, *width=78*, *visibility=0*)

get(*key*, *default=NOTSET*)

import_argparse(*parsed_args*)

initialize_argparse(*parser*)

items()

iteritems()
DEPRECATED.

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.keys().

iterkeys()
DEPRECATED.

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()
DEPRECATED.

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.keys().

keys()

name(*fully_qualified=False*)

reset()

set_default_value(*default*)

set_domain(*domain*)

set_value(*value*, *skip_implicit=False*)

setdefault(*key*, *default=NOTSET*)

unused_user_values()

user_values()

value(*accessValue=True*)

values()

class pyomo.contrib.appsi.base.**MIPSolverConfig**(*description=None*, *doc=None*, *implicit=False*, *implicit_domain=None*, *visibility=0*)

Bases: pyomo.contrib.appsi.base.

mip_gap
Solver will terminate if the mip gap is less than mip_gap
Type float

relax_integrality
If True, all integer variables will be relaxed to continuous variables before solving
Type bool

class NoArgument
Bases: `object`

add(*name*, *config*)

content_filters = {'all', 'userdata', None}

declare(*name*, *config*)

declare_as_argument(**args*, ***kwds*)
Map this Config item to an argparse argument.

Valid arguments include all valid arguments to argparse's ArgumentParser.add_argument() with the exception of 'default'. In addition, you may provide a group keyword argument to either pass in a pre-defined option group or subparser, or else pass in the string name of a group, subparser, or (subparser, group).

declare_from(*other*, *skip=None*)

display(*content_filter=None*, *indent_spacing=2*, *ostream=None*, *visibility=None*)

generate_documentation(*block_start=None*, *block_end=None*, *item_start=None*, *item_body=None*, *item_end=None*, *indent_spacing=2*, *width=78*, *visibility=0*, *format='latex'*)

generate_yaml_template(*indent_spacing=2*, *width=78*, *visibility=0*)

get(*key*, *default=NOTSET*)

import_argparse(*parsed_args*)

initialize_argparse(*parser*)

items()

iteritems()
DEPRECATED.

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.keys().

iterkeys()
DEPRECATED.

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()
DEPRECATED.

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.keys().

keys()

load_solution: bool

name(*fully_qualified=False*)

report_timing: bool

reset()

set_default_value(*default*)

set_domain(*domain*)

set_value(*value*, *skip_implicit=False*)

setdefault(*key*, *default=NOTSET*)

stream_solver: bool

symbolic_solver_labels: bool

time_limit: Optional[float]

unused_user_values()

user_values()

value(*accessValue=True*)

values()

class pyomo.contrib.appsi.base.**UpdateConfig**

Bases: pyomo.common.config.

check_for_new_or_removed_constraints
Type bool

check_for_new_or_removed_vars
Type bool

check_for_new_or_removed_params
Type bool

update_constraints
Type bool

update_vars
Type bool

update_params
Type bool

update_named_expressions
Type bool

class NoArgument

Bases: object

add(*name*, *config*)

content_filters = {'all', 'userdata', None}

declare(*name*, *config*)

declare_as_argument(**args*, ***kwds*)

Map this Config item to an argparse argument.

Valid arguments include all valid arguments to argparse's ArgumentParser.add_argument() with the exception of 'default'. In addition, you may provide a group keyword argument to either pass in a pre-defined option group or subparser, or else pass in the string name of a group, subparser, or (subparser, group).

declare_from(*other*, *skip=None*)

display(*content_filter=None*, *indent_spacing=2*, *ostream=None*, *visibility=None*)

generate_documentation(*block_start=None*, *block_end=None*, *item_start=None*, *item_body=None*, *item_end=None*, *indent_spacing=2*, *width=78*, *visibility=0*, *format='latex'*)

generate_yaml_template(*indent_spacing=2*, *width=78*, *visibility=0*)

get(*key*, *default=NOTSET*)

import_argparse(*parsed_args*)

initialize_argparse(*parser*)

items()

iteritems()
DEPRECATED.

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.keys().

iterkeys()
DEPRECATED.

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()
DEPRECATED.

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.keys().

keys()

name(*fully_qualified=False*)

reset()

set_default_value(*default*)

set_domain(*domain*)

set_value(*value*, *skip_implicit=False*)

setdefault(*key*, *default=NOTSET*)

unused_user_values()

user_values()

value(*accessValue=True*)

values()

13.6.2 Solvers

Gurobi

class pyomo.contrib.appsi.solvers.gurobi.**GurobiResults**(*solver*)
Bases: *pyomo.contrib.appsi.base.Results*

class pyomo.contrib.appsi.solvers.gurobi.**Gurobi**
Bases: pyomo.contrib.appsi.base.PersistentBase, *pyomo.contrib.appsi.base.PersistentSolver*

Interface to Gurobi

class Availability(*value*)
Bases: enum.IntEnum

An enumeration.

BadLicense = -2

BadVersion = -1

FullLicense = 1

LimitedLicense = 2

NotFound = 0

add_block(*block*)

add_constraints(*cons: List[pyomo.core.base.constraint._GeneralConstraintData]*)

add_params(*params: List[pyomo.core.base.param._ParamData]*)

add_sos_constraints(*cons: List[pyomo.core.base.sos._SOSConstraintData]*)

add_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

available()

Test if the solver is available on this system.

Nominally, this will return True if the solver interface is valid and can be used to solve problems and False if it cannot.

Note that for licensed solvers there are a number of "levels" of available: depending on the license, the solver may be available with limitations on problem size or runtime (e.g., 'demo' vs. 'community' vs. 'full'). In these cases, the solver may return a subclass of enum.IntEnum, with members that resolve to True if the solver is available (possibly with limitations). The Enum may also have multiple members that all resolve to False indicating the reason why the interface is not available (not found, bad license, unsupported version, etc).

Returns **available** – An enum that indicates "how available" the solver is. Note that the enum can be cast to bool, which will be True if the solver is runable at all and False otherwise.

Return type *Solver.Availability*

cbCut(*con*)

Add a cut within a callback.

Parameters **con** (*pyomo.core.base.constraint._GeneralConstraintData*) – The cut to add

cbGet(*what*)

cbGetNodeRel(*vars*)

Parameters **vars** (*Var or iterable of Var*) –

cbGetSolution(*vars*)

Parameters **vars** (*iterable of vars*) –

cbLazy(*con*)

Parameters **con** (*pyomo.core.base.constraint._GeneralConstraintData*) – The lazy constraint to add

cbSetSolution(*vars*, *solution*)

cbUseSolution()

property config: pyomo.contrib.appsi.solvers.gurobi.GurobiConfig

An object for configuring solve options.

Returns An object for configuring pyomo solve options such as the time limit. These options are mostly independent of the solver.

Return type *SolverConfig*

get_duals(*cons_to_load=None*)

Declare sign convention in docstring here.

Parameters **cons_to_load** (*list*) – A list of the constraints whose duals should be loaded. If cons_to_load is None, then the duals for all constraints will be loaded.

Returns **duals** – Maps constraints to dual values

Return type dict

get_gurobi_param_info(*param*)

Get information about a gurobi parameter.

Parameters **param** (*str*) – The gurobi parameter to get info for. See Gurobi documenation for possible options.

Returns

Return type six-tuple containing the parameter name, type, value, minimum value, maximum value, and default value.

get_linear_constraint_attr(*con*, *attr*)

Get the value of an attribute on a gurobi linear constraint.

Parameters

- **con** (*pyomo.core.base.constraint._GeneralConstraintData*) – The pyomo constraint for which the corresponding gurobi constraint attribute should be retrieved.
- **attr** (*str*) – The attribute to get. See the Gurobi documentation

get_model_attr(*attr*)

Get the value of an attribute on the Gurobi model.

Parameters **attr** (*str*) – The attribute to get. See Gurobi documentation for descriptions of the attributes.

get_primals(*vars_to_load=None*, *solution_number=0*)

get_quadratic_constraint_attr(*con*, *attr*)

Get the value of an attribute on a gurobi quadratic constraint.

Parameters

- **con** (*pyomo.core.base.constraint._GeneralConstraintData*) – The pyomo constraint for which the corresponding gurobi constraint attribute should be retrieved.
- **attr** (*str*) – The attribute to get. See the Gurobi documentation

get_reduced_costs(*vars_to_load=None*)

Parameters **vars_to_load** (*list*) – A list of the variables whose reduced cost should be loaded. If vars_to_load is None, then all reduced costs will be loaded.

Returns **reduced_costs** – Maps variable to reduced cost

Return type ComponentMap

get_slacks(*cons_to_load=None*)

Parameters **cons_to_load** (*list*) – A list of the constraints whose slacks should be loaded. If cons_to_load is None, then the slacks for all constraints will be loaded.

Returns **slacks** – Maps constraints to slack values

Return type dict

get_sos_attr(*con*, *attr*)

Get the value of an attribute on a gurobi sos constraint.

Parameters

- **con** (*pyomo.core.base.sos._SOSConstraintData*) – The pyomo SOS constraint for which the corresponding gurobi SOS constraint attribute should be retrieved.
- **attr** (*str*) – The attribute to get. See the Gurobi documentation

get_var_attr(*var*, *attr*)

Get the value of an attribute on a gurobi var.

Parameters

- **var** (*pyomo.core.base.var._GeneralVarData*) – The pyomo var for which the corresponding gurobi var attribute should be retrieved.
- **attr** (*str*) – The attribute to get. See gurobi documentation

property gurobi_options

returns: gurobi_options – A dictionary mapping solver options to values for those options. These are solver specific.

Return type dict

is_persistent()

Returns is_persistent – True if the solver is a persistent solver.

Return type bool

load_vars(*vars_to_load=None*, *solution_number=0*)

Load the solution of the primal variables into the value attribut of the variables.

Parameters vars_to_load (*list*) – A list of the variables whose solution should be loaded. If vars_to_load is None, then the solution to all primal variables will be loaded.

remove_block(*block*)

remove_constraints(*cons: List[pyomo.core.base.constraint._GeneralConstraintData]*)

remove_params(*params: List[pyomo.core.base.param._ParamData]*)

remove_sos_constraints(*cons: List[pyomo.core.base.sos._SOSConstraintData]*)

remove_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

reset()

set_callback(*func=None*)

Specify a callback for gurobi to use.

Parameters func (*function*) – The function to call. The function should have three arguments. The first will be the pyomo model being solved. The second will be the GurobiPersistent instance. The third will be an enum member of gurobipy.GRB.Callback. This will indicate where in the branch and bound algorithm gurobi is at. For example, suppose we want to solve

min 2*x + y s.t.

y >= (x-2)**2 0 <= x <= 4 y >= 0 y integer

as an MILP using exteneded cutting planes in callbacks.

```
>>> from gurobipy import GRB
>>> import pyomo.environ as pe
>>> from pyomo.core.expr.taylor_series import taylor_series_
↪expansion
>>> from pyomo.contrib import appsi
>>>
>>> m = pe.ConcreteModel()
>>> m.x = pe.Var(bounds=(0, 4))
>>> m.y = pe.Var(within=pe.Integers, bounds=(0, None))
>>> m.obj = pe.Objective(expr=2*m.x + m.y)
>>> m.cons = pe.ConstraintList()  # for the cutting planes
>>>
>>> def _add_cut(xval):
...     # a function to generate the cut
...     m.x.value = xval
...     return m.cons.add(m.y >= taylor_series_expansion((m.x -␣
↪2)**2))
>>>
>>> _c = _add_cut(0)  # start with 2 cuts at the bounds of x
>>> _c = _add_cut(4)  # this is an arbitrary choice
>>>
>>> opt = appsi.solvers.Gurobi()
>>> opt.config.stream_solver = True
>>> opt.set_instance(m)
>>> opt.gurobi_options['PreCrush'] = 1
>>> opt.gurobi_options['LazyConstraints'] = 1
>>>
>>> def my_callback(cb_m, cb_opt, cb_where):
...     if cb_where == GRB.Callback.MIPSOL:
...         cb_opt.cbGetSolution(vars=[m.x, m.y])
...         if m.y.value < (m.x.value - 2)**2 - 1e-6:
...             cb_opt.cbLazy(_add_cut(m.x.value))
>>>
>>> opt.set_callback(my_callback)
>>> res = opt.solve(m)
```

set_gurobi_param(*param*, *val*)
Set a gurobi parameter.

Parameters

- **param** (*str*) – The gurobi parameter to set. Options include any gurobi parameter. Please see the Gurobi documentation for options.
- **val** (*any*) – The value to set the parameter to. See Gurobi documentation for possible values.

set_instance(*model*)

set_linear_constraint_attr(*con*, *attr*, *val*)
Set the value of an attribute on a gurobi linear constraint.

Parameters

- **con** (*pyomo.core.base.constraint._GeneralConstraintData*) – The pyomo constraint for which the corresponding gurobi constraint attribute should be modified.

- **attr** (*str*) –

  The attribute to be modified. Options are: CBasis DStart Lazy

- **val** (*any*) – See gurobi documentation for acceptable values.

set_objective(*obj: pyomo.core.base.objective._GeneralObjectiveData*)

set_var_attr(*var*, *attr*, *val*)

Set the value of an attribute on a gurobi variable.

Parameters

- **var** (*pyomo.core.base.var._GeneralVarData*) – The pyomo var for which the corresponding gurobi var attribute should be modified.
- **attr** (*str*) –

  The attribute to be modified. Options are: Start VarHintVal VarHintPri BranchPriority VBasis PStart

- **val** (*any*) – See gurobi documentation for acceptable values.

solve(*model*, *timer: Optional[*pyomo.common.timing.HierarchicalTimer*] = None*) → *pyomo.contrib.appsi.base.Results*

Solve a Pyomo model.

Parameters

- **model** (*_BlockData*) – The Pyomo model to be solved
- **timer** (HierarchicalTimer) – An option timer for reporting timing

Returns **results** – A results object

Return type *Results*

solve_sub_block(*block*)

property symbol_map

update(*timer: Optional[*pyomo.common.timing.HierarchicalTimer*] = None*)

property update_config

update_params()

update_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

version()

Returns **version** – A tuple representing the version

Return type tuple

write(*filename*)

Write the model to a file (e.g., and lp file).

Parameters **filename** (*str*) – Name of the file to which the model should be written.

Ipopt

class pyomo.contrib.appsi.solvers.ipopt.**IpoptConfig**(*description=None*, *doc=None*, *implicit=False*, *implicit_domain=None*, *visibility=0*)

Bases: pyomo.contrib.appsi.base.

class NoArgument

Bases: object

add(*name*, *config*)

content_filters = {'all', 'userdata', None}

declare(*name*, *config*)

declare_as_argument(**args*, ***kwds*)

Map this Config item to an argparse argument.

Valid arguments include all valid arguments to argparse's ArgumentParser.add_argument() with the exception of 'default'. In addition, you may provide a group keyword argument to either pass in a pre-defined option group or subparser, or else pass in the string name of a group, subparser, or (subparser, group).

declare_from(*other*, *skip=None*)

display(*content_filter=None*, *indent_spacing=2*, *ostream=None*, *visibility=None*)

generate_documentation(*block_start=None*, *block_end=None*, *item_start=None*, *item_body=None*, *item_end=None*, *indent_spacing=2*, *width=78*, *visibility=0*, *format='latex'*)

generate_yaml_template(*indent_spacing=2*, *width=78*, *visibility=0*)

get(*key*, *default=NOTSET*)

import_argparse(*parsed_args*)

initialize_argparse(*parser*)

items()

iteritems()

DEPRECATED.

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.keys().

iterkeys()

DEPRECATED.

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()

DEPRECATED.

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.keys().

keys()

load_solution: bool

name(*fully_qualified=False*)

report_timing: bool

reset()

set_default_value(*default*)

set_domain(*domain*)

set_value(*value*, *skip_implicit=False*)

setdefault(*key*, *default=NOTSET*)

stream_solver: bool

symbolic_solver_labels: bool

time_limit: Optional[float]

unused_user_values()

user_values()

value(*accessValue=True*)

values()

class pyomo.contrib.appsi.solvers.ipopt.**Ipopt**

Bases: *pyomo.contrib.appsi.base.PersistentSolver*

class Availability(*value*)

Bases: enum.IntEnum

An enumeration.

BadLicense = -2

BadVersion = -1

FullLicense = 1

LimitedLicense = 2

NotFound = 0

add_block(*block: pyomo.core.base.block._BlockData*)

add_constraints(*cons: List[pyomo.core.base.constraint._GeneralConstraintData]*)

add_params(*params: List[pyomo.core.base.param._ParamData]*)

add_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

available()

Test if the solver is available on this system.

Nominally, this will return True if the solver interface is valid and can be used to solve problems and False if it cannot.

Note that for licensed solvers there are a number of "levels" of available: depending on the license, the solver may be available with limitations on problem size or runtime (e.g., 'demo' vs. 'community' vs. 'full'). In these cases, the solver may return a subclass of enum.IntEnum, with members that resolve to True if the solver is available (possibly with limitations). The Enum may also have multiple members that all resolve to False indicating the reason why the interface is not available (not found, bad license, unsupported version, etc).

Returns **available** – An enum that indicates "how available" the solver is. Note that the enum can be cast to bool, which will be True if the solver is runable at all and False otherwise.

Return type *Solver.Availability*

property config

An object for configuring solve options.

Returns An object for configuring pyomo solve options such as the time limit. These options are mostly independent of the solver.

Return type *SolverConfig*

get_duals(*cons_to_load=None*)
Declare sign convention in docstring here.

Parameters **cons_to_load** (*list*) – A list of the constraints whose duals should be loaded. If cons_to_load is None, then the duals for all constraints will be loaded.

Returns **duals** – Maps constraints to dual values

Return type dict

get_primals(*vars_to_load: Optional[Sequence[pyomo.core.base.var._GeneralVarData]] = None*) → Mapping[pyomo.core.base.var._GeneralVarData, float]

get_reduced_costs(*vars_to_load: Optional[Sequence[pyomo.core.base.var._GeneralVarData]] = None*) → Mapping[pyomo.core.base.var._GeneralVarData, float]

Parameters **vars_to_load** (*list*) – A list of the variables whose reduced cost should be loaded. If vars_to_load is None, then all reduced costs will be loaded.

Returns **reduced_costs** – Maps variable to reduced cost

Return type ComponentMap

get_slacks(*cons_to_load: Optional[Sequence[pyomo.core.base.constraint._GeneralConstraintData]] = None*) → Dict[pyomo.core.base.constraint._GeneralConstraintData, float]

Parameters **cons_to_load** (*list*) – A list of the constraints whose slacks should be loaded. If cons_to_load is None, then the slacks for all constraints will be loaded.

Returns **slacks** – Maps constraints to slack values

Return type dict

property ipopt_options
returns: ipopt_options – A dictionary mapping solver options to values for those options. These are solver specific.

Return type dict

is_persistent()

Returns **is_persistent** – True if the solver is a persistent solver.

Return type bool

load_vars(*vars_to_load: Optional[Sequence[pyomo.core.base.var._GeneralVarData]] = None*) → NoReturn
Load the solution of the primal variables into the value attribut of the variables.

Parameters **vars_to_load** (*list*) – A list of the variables whose solution should be loaded. If vars_to_load is None, then the solution to all primal variables will be loaded.

nl_filename()

options_filename()

remove_block(*block: pyomo.core.base.block._BlockData*)

remove_constraints(*cons: List[pyomo.core.base.constraint._GeneralConstraintData]*)

remove_params(*params: List[pyomo.core.base.param._ParamData]*)

remove_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

set_instance(*model*)

set_objective(*obj: pyomo.core.base.objective._GeneralObjectiveData*)

sol_filename()

solve(*model*, *timer: Optional[*pyomo.common.timing.HierarchicalTimer*] = None*)

Solve a Pyomo model.

Parameters

- **model** (*_BlockData*) – The Pyomo model to be solved
- **timer** (HierarchicalTimer) – An option timer for reporting timing

Returns **results** – A results object

Return type *Results*

property symbol_map

property update_config

update_params()

update_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

version()

Returns **version** – A tuple representing the version

Return type tuple

property writer

Cplex

class pyomo.contrib.appsi.solvers.cplex.**CplexConfig**(*description=None*, *doc=None*, *implicit=False*, *implicit_domain=None*, *visibility=0*)

Bases: pyomo.contrib.appsi.base.

class NoArgument

Bases: object

add(*name*, *config*)

content_filters = {'all', 'userdata', None}

declare(*name*, *config*)

declare_as_argument(**args*, ***kwds*)

Map this Config item to an argparse argument.

Valid arguments include all valid arguments to argparse's ArgumentParser.add_argument() with the exception of 'default'. In addition, you may provide a group keyword argument to either pass in a pre-defined option group or subparser, or else pass in the string name of a group, subparser, or (subparser, group).

declare_from(*other*, *skip=None*)

display(*content_filter=None*, *indent_spacing=2*, *ostream=None*, *visibility=None*)

generate_documentation(*block_start=None*, *block_end=None*, *item_start=None*, *item_body=None*, *item_end=None*, *indent_spacing=2*, *width=78*, *visibility=0*, *format='latex'*)

generate_yaml_template(*indent_spacing=2*, *width=78*, *visibility=0*)

get(*key*, *default=NOTSET*)

import_argparse(*parsed_args*)

initialize_argparse(*parser*)

items()

iteritems()
DEPRECATED.

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.keys().

iterkeys()
DEPRECATED.

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()
DEPRECATED.

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.keys().

keys()

load_solution: bool

mip_gap: Optional[float]

name(*fully_qualified=False*)

relax_integrality: bool

report_timing: bool

reset()

set_default_value(*default*)

set_domain(*domain*)

set_value(*value*, *skip_implicit=False*)

setdefault(*key*, *default=NOTSET*)

stream_solver: bool

symbolic_solver_labels: bool

time_limit: Optional[float]

unused_user_values()

user_values()

value(*accessValue=True*)

values()

class pyomo.contrib.appsi.solvers.cplex.**CplexResults**(*solver*)
Bases: *pyomo.contrib.appsi.base.Results*

class pyomo.contrib.appsi.solvers.cplex.**Cplex**
Bases: *pyomo.contrib.appsi.base.PersistentSolver*

class Availability(*value*)
Bases: enum.IntEnum

An enumeration.

BadLicense = -2

BadVersion = -1

FullLicense = 1

LimitedLicense = 2

NotFound = 0

add_block(*block: pyomo.core.base.block._BlockData*)

add_constraints(*cons: List[pyomo.core.base.constraint._GeneralConstraintData]*)

add_params(*params: List[pyomo.core.base.param._ParamData]*)

add_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

available()

Test if the solver is available on this system.

Nominally, this will return True if the solver interface is valid and can be used to solve problems and False if it cannot.

Note that for licensed solvers there are a number of "levels" of available: depending on the license, the solver may be available with limitations on problem size or runtime (e.g., 'demo' vs. 'community' vs. 'full'). In these cases, the solver may return a subclass of enum.IntEnum, with members that resolve to True if the solver is available (possibly with limitations). The Enum may also have multiple members that all resolve to False indicating the reason why the interface is not available (not found, bad license, unsupported version, etc).

Returns **available** – An enum that indicates "how available" the solver is. Note that the enum can be cast to bool, which will be True if the solver is runable at all and False otherwise.

Return type *Solver.Availability*

property config

An object for configuring solve options.

Returns An object for configuring pyomo solve options such as the time limit. These options are mostly independent of the solver.

Return type *SolverConfig*

property cplex_options

returns: cplex_options – A dictionary mapping solver options to values for those options. These are solver specific.

Return type dict

get_duals(*cons_to_load: Optional[Sequence[pyomo.core.base.constraint._GeneralConstraintData]] = None*) → Dict[pyomo.core.base.constraint._GeneralConstraintData, float]

Declare sign convention in docstring here.

Parameters **cons_to_load** (*list*) – A list of the constraints whose duals should be loaded. If cons_to_load is None, then the duals for all constraints will be loaded.

Returns **duals** – Maps constraints to dual values

Return type dict

get_primals(*vars_to_load: Optional[Sequence[pyomo.core.base.var._GeneralVarData]] = None*) → Mapping[pyomo.core.base.var._GeneralVarData, float]

get_reduced_costs(*vars_to_load: Optional[Sequence[pyomo.core.base.var._GeneralVarData]] = None*) → Mapping[pyomo.core.base.var._GeneralVarData, float]

Parameters **vars_to_load** (*list*) – A list of the variables whose reduced cost should be loaded. If vars_to_load is None, then all reduced costs will be loaded.

Returns **reduced_costs** – Maps variable to reduced cost

Return type ComponentMap

get_slacks(*cons_to_load: Optional[Sequence[pyomo.core.base.constraint._GeneralConstraintData]] = None*) → Dict[pyomo.core.base.constraint._GeneralConstraintData, float]

Parameters **cons_to_load** (*list*) – A list of the constraints whose slacks should be loaded. If cons_to_load is None, then the slacks for all constraints will be loaded.

Returns **slacks** – Maps constraints to slack values

Return type dict

is_persistent()

Returns **is_persistent** – True if the solver is a persistent solver.

Return type bool

load_vars(*vars_to_load: Optional[Sequence[pyomo.core.base.var._GeneralVarData]] = None*) → NoReturn

Load the solution of the primal variables into the value attribut of the variables.

Parameters **vars_to_load** (*list*) – A list of the variables whose solution should be loaded. If vars_to_load is None, then the solution to all primal variables will be loaded.

log_filename()

lp_filename()

remove_block(*block: pyomo.core.base.block._BlockData*)

remove_constraints(*cons: List[pyomo.core.base.constraint._GeneralConstraintData]*)

remove_params(*params: List[pyomo.core.base.param._ParamData]*)

remove_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

set_instance(*model*)

set_objective(*obj: pyomo.core.base.objective._GeneralObjectiveData*)

solve(*model*, *timer: Optional[pyomo.common.timing.HierarchicalTimer] = None*)

Solve a Pyomo model.

Parameters

- **model** (*_BlockData*) – The Pyomo model to be solved
- **timer** (HierarchicalTimer) – An option timer for reporting timing

Returns **results** – A results object

Return type *Results*

property symbol_map

property update_config

update_params()

update_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

version()

Returns **version** – A tuple representing the version

Return type tuple

property writer

Cbc

class pyomo.contrib.appsi.solvers.cbc.**CbcConfig**(*description=None*, *doc=None*, *implicit=False*, *implicit_domain=None*, *visibility=0*)

Bases: pyomo.contrib.appsi.base.

class NoArgument

Bases: object

add(*name*, *config*)

content_filters = {'all', 'userdata', None}

declare(*name*, *config*)

declare_as_argument(**args*, ***kwds*)

Map this Config item to an argparse argument.

Valid arguments include all valid arguments to argparse's ArgumentParser.add_argument() with the exception of 'default'. In addition, you may provide a group keyword argument to either pass in a pre-defined option group or subparser, or else pass in the string name of a group, subparser, or (subparser, group).

declare_from(*other*, *skip=None*)

display(*content_filter=None*, *indent_spacing=2*, *ostream=None*, *visibility=None*)

generate_documentation(*block_start=None*, *block_end=None*, *item_start=None*, *item_body=None*, *item_end=None*, *indent_spacing=2*, *width=78*, *visibility=0*, *format='latex'*)

generate_yaml_template(*indent_spacing=2*, *width=78*, *visibility=0*)

get(*key*, *default=NOTSET*)

import_argparse(*parsed_args*)

initialize_argparse(*parser*)

items()

iteritems()

DEPRECATED.

Deprecated since version 6.0: The iteritems method is deprecated. Use dict.keys().

iterkeys()

DEPRECATED.

Deprecated since version 6.0: The iterkeys method is deprecated. Use dict.keys().

itervalues()

DEPRECATED.

Deprecated since version 6.0: The itervalues method is deprecated. Use dict.keys().

keys()

load_solution: bool

name(*fully_qualified=False*)

report_timing: bool

reset()

set_default_value(*default*)

set_domain(*domain*)

set_value(*value*, *skip_implicit=False*)

setdefault(*key*, *default=NOTSET*)

stream_solver: bool

symbolic_solver_labels: bool

time_limit: Optional[float]

unused_user_values()

user_values()

value(*accessValue=True*)

values()

class pyomo.contrib.appsi.solvers.cbc.**Cbc**

Bases: *pyomo.contrib.appsi.base.PersistentSolver*

class Availability(*value*)

Bases: enum.IntEnum

An enumeration.

BadLicense = -2

BadVersion = -1

FullLicense = 1

LimitedLicense = 2

NotFound = 0

add_block(*block: pyomo.core.base.block._BlockData*)

add_constraints(*cons: List[pyomo.core.base.constraint._GeneralConstraintData]*)

add_params(*params: List[pyomo.core.base.param._ParamData]*)

add_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

available()

Test if the solver is available on this system.

Nominally, this will return True if the solver interface is valid and can be used to solve problems and False if it cannot.

Note that for licensed solvers there are a number of "levels" of available: depending on the license, the solver may be available with limitations on problem size or runtime (e.g., 'demo' vs. 'community' vs. 'full'). In these cases, the solver may return a subclass of enum.IntEnum, with members that resolve to True if the solver is available (possibly with limitations). The Enum may also have multiple members that all resolve to False indicating the reason why the interface is not available (not found, bad license, unsupported version, etc).

Returns available – An enum that indicates "how available" the solver is. Note that the enum can be cast to bool, which will be True if the solver is runable at all and False otherwise.

Return type *Solver.Availability*

property cbc_options

returns: cbc_options – A dictionary mapping solver options to values for those options. These are solver specific.

Return type dict

property config

An object for configuring solve options.

Returns An object for configuring pyomo solve options such as the time limit. These options are mostly independent of the solver.

Return type *SolverConfig*

get_duals(*cons_to_load=None*)

Declare sign convention in docstring here.

Parameters **cons_to_load** (*list*) – A list of the constraints whose duals should be loaded. If cons_to_load is None, then the duals for all constraints will be loaded.

Returns **duals** – Maps constraints to dual values

Return type dict

get_primals(*vars_to_load: Optional[Sequence[pyomo.core.base.var._GeneralVarData]] = None*) → Mapping[pyomo.core.base.var._GeneralVarData, float]

get_reduced_costs(*vars_to_load: Optional[Sequence[pyomo.core.base.var._GeneralVarData]] = None*) → Mapping[pyomo.core.base.var._GeneralVarData, float]

Parameters **vars_to_load** (*list*) – A list of the variables whose reduced cost should be loaded. If vars_to_load is None, then all reduced costs will be loaded.

Returns **reduced_costs** – Maps variable to reduced cost

Return type ComponentMap

get_slacks(*cons_to_load: Optional[Sequence[pyomo.core.base.constraint._GeneralConstraintData]] = None*) → Dict[pyomo.core.base.constraint._GeneralConstraintData, float]

Parameters **cons_to_load** (*list*) – A list of the constraints whose slacks should be loaded. If cons_to_load is None, then the slacks for all constraints will be loaded.

Returns **slacks** – Maps constraints to slack values

Return type dict

is_persistent()

Returns **is_persistent** – True if the solver is a persistent solver.

Return type bool

load_vars(*vars_to_load: Optional[Sequence[pyomo.core.base.var._GeneralVarData]] = None*) → NoReturn

Load the solution of the primal variables into the value attribut of the variables.

Parameters **vars_to_load** (*list*) – A list of the variables whose solution should be loaded. If vars_to_load is None, then the solution to all primal variables will be loaded.

log_filename()

lp_filename()

remove_block(*block: pyomo.core.base.block._BlockData*)

remove_constraints(*cons: List[pyomo.core.base.constraint._GeneralConstraintData]*)

remove_params(*params: List[pyomo.core.base.param._ParamData]*)

remove_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

set_instance(*model*)

set_objective(*obj: pyomo.core.base.objective._GeneralObjectiveData*)

soln_filename()

solve(*model*, *timer: Optional[pyomo.common.timing.HierarchicalTimer] = None*)
Solve a Pyomo model.

Parameters

- **model** (*_BlockData*) – The Pyomo model to be solved
- **timer** (HierarchicalTimer) – An option timer for reporting timing

Returns **results** – A results object

Return type *Results*

property symbol_map

property update_config

update_params()

update_variables(*variables: List[pyomo.core.base.var._GeneralVarData]*)

version()

Returns **version** – A tuple representing the version

Return type tuple

property writer

APPSI solver interfaces are designed to work very similarly to most Pyomo solver interfaces but are very efficient for resolving the same model with small changes. This is very beneficial for applications such as Benders' Decomposition, Optimization-Based Bounds Tightening, Progressive Hedging, Outer-Approximation, and many others. Here is an example of using an APPSI solver interface.

```
>>> import pyomo.environ as pe
>>> from pyomo.contrib import appsi
>>> import numpy as np
>>> from pyomo.common.timing import HierarchicalTimer
>>> m = pe.ConcreteModel()
>>> m.x = pe.Var()
>>> m.y = pe.Var()
>>> m.p = pe.Param(mutable=True)
>>> m.obj = pe.Objective(expr=m.x**2 + m.y**2)
>>> m.c1 = pe.Constraint(expr=m.y >= pe.exp(m.x))
>>> m.c2 = pe.Constraint(expr=m.y >= (m.x - m.p)**2)
>>> opt = appsi.solvers.Ipopt()
>>> timer = HierarchicalTimer()
>>> for p_val in np.linspace(1, 10, 100):
>>>     m.p.value = float(p_val)
>>>     res = opt.solve(m, timer=timer)
>>>     assert res.termination_condition == appsi.base.TerminationCondition.optimal
>>>     print(res.best_feasible_objective)
>>> print(timer)
```

Extra performance improvements can be made if you know exactly what changes will be made in your model. In the example above, only parameter values are changed, so we can setup the *UpdateConfig* so that the solver does not check for changes in variables or constraints.

```
>>> timer = HierarchicalTimer()
>>> opt.update_config.check_for_new_or_removed_constraints = False
>>> opt.update_config.check_for_new_or_removed_vars = False
>>> opt.update_config.update_constraints = False
>>> opt.update_config.update_vars = False
>>> for p_val in np.linspace(1, 10, 100):
>>>     m.p.value = float(p_val)
>>>     res = opt.solve(m, timer=timer)
>>>     assert res.termination_condition == appsi.base.TerminationCondition.optimal
>>>     print(res.best_feasible_objective)
>>> print(timer)
```

Solver independent options can be specified with the *SolverConfig* or derived classes. For example:

```
>>> opt.config.stream_solver = True
```

Solver specific options can be specified with the `solver_options()` attribute. For example:

```
>>> opt.solver_options['max_iter'] = 20
```

13.6.3 Installation

```
cd pyomo/contrib/appsi/
python build.py
```

Pyomo is under active ongoing development. The following API documentation describes *Beta* functionality.

Warning: The `pyomo.kernel` API is still in the beta phase of development. It is fully tested and functional; however, the interface may change as it becomes further integrated with the rest of Pyomo.

Warning: Models built with `pyomo.kernel` components are not yet compatible with pyomo extension modules (e.g., `PySP`, `pyomo.dae`, `pyomo.gdp`).

13.7 The Kernel Library

The `pyomo.kernel` library is an experimental modeling interface designed to provide a better experience for users doing concrete modeling and advanced application development with Pyomo. It includes the basic set of *modeling components* necessary to build algebraic models, which have been redesigned from the ground up to make it easier for users to customize and extend. For a side-by-side comparison of `pyomo.kernel` and `pyomo.environ` syntax, visit the link below.

13.7.1 Syntax Comparison Table (pyomo.kernel vs pyomo.environ)

	pyomo.kernel	pyomo.environ
Import	`import pyomo.kernel as pmo`	`import pyomo.environ as aml`

Model[1]	`def create(data):`
	`  instance = pmo.block()`
	`  # ... define instance ...`
	`  return instance`
	`instance = create(data)`
	
	`m = pmo.block()`
	`m.b = pmo.block()`
		`m = aml.AbstractModel()`
		`# ... define model ...`
		`instance = \`
		`  m.create_instance(datafile)`
		
		`m = aml.ConcreteModel()`
		`m.b = aml.Block()`

Set[2]	`m.s = [1,2]`
	
	`# [0,1,2]`
	`m.q = range(3)`
		`m.s = aml.Set(initialize=[1,2],`
		`  ordered=True)`
		
		`# [1,2,3]`
		`m.q = aml.RangeSet(1,3)`

Parameter[3]	`m.p = pmo.parameter(0)`
	
	`# pd[1] = 0, pd[2] = 1`
	`m.pd = pmo.parameter_dict()`
	`for k,i in enumerate(m.s):`
	`  m.pd[i] = pmo.parameter(k)`
	
	`# uses 0-based indexing`
	`# pl[0] = 0, pl[0] = 1, ...`
	`m.pl = pmo.parameter_list()`
	`for j in m.q:`
	`  m.pl.append(`
	`  pmo.parameter(j))`
		`m.p = aml.Param(mutable=True,`
		`  initialize=0)`
		
		`# pd[1] = 0, pd[2] = 1`
		`def pd_(m, i):`
		`  return m.s.ord(i) - 1`
		`m.pd = aml.Param(m.s,`
		`  mutable=True,`
		`  rule=pd_)`
		
		`#`
		`# No ParamList exists`
		`#`

Variable	`m.v = pmo.variable(value=1,`
	`  lb=1,`
	`  ub=4)`
	
	`m.vd = pmo.variable_dict()`
	`for i in m.s:`
	`  m.vd[i] = pmo.variable(ub=9)`
		`m.v = aml.Var(initialize=1.0,`
		`  bounds=(1,4))`
		
		`m.vd = aml.Var(m.s,`
		`  bounds=(None,9))`

Variable	`# used 0-based indexing`
	`m.vl = pmo.variable_list()`
	`for j in m.q:`
	`  m.vl.append(`
		`# used 1-based indexing`
		`def vl_(m, i):`
		`  return (i, None)`

Models built from pyomo.kernel components are fully compatible with the standard solver interfaces included with Pyomo. A minimal example script that defines and solves a model is shown below.

```
import pyomo.kernel as pmo

model = pmo.block()
model.x = pmo.variable()
model.c = pmo.constraint(model.x >= 1)
model.o = pmo.objective(model.x)

opt = pmo.SolverFactory("ipopt")

result = opt.solve(model)
assert str(result.solver.termination_condition) == "optimal"
```

13.7.2 Notable Improvements

More Control of Model Structure

Containers in pyomo.kernel are analogous to indexed components in pyomo.environ. However, pyomo.kernel containers allow for additional layers of structure as they can be nested within each other as long as they have compatible categories. The following example shows this using pyomo.kernel.variable containers.

```
vlist = pyomo.kernel.variable_list()
vlist.append(pyomo.kernel.variable_dict())
vlist[0]['x'] = pyomo.kernel.variable()
```

As the next section will show, the standard modeling component containers are also compatible with user-defined classes that derive from the existing modeling components.

Sub-Classing

The existing components and containers in pyomo.kernel are designed to make sub-classing easy. User-defined classes that derive from the standard modeling components and containers in pyomo.kernel are compatible with existing containers of the same component category. As an example, in the following code we see that the pyomo.kernel.block_list container can store both pyomo.kernel.block objects as well as a user-defined Widget object that derives from pyomo.kernel.block. The Widget object can also be placed on another block object as an attribute and treated itself as a block.

```
class Widget(pyomo.kernel.block):
    ...

model = pyomo.kernel.block()
model.blist = pyomo.kernel.block_list()
model.blist.append(Widget())
```

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[1] pyomo.kernel does not include an alternative to the AbstractModel component from pyomo.environ. All data necessary to build a model must be imported by the user.

[2] pyomo.kernel does not include an alternative to the Pyomo Set component from pyomo.environ.

[3] pyomo.kernel.parameter objects are always mutable.

[4] Special Ordered Sets

[5] Both pyomo.kernel.piecewise and pyomo.kernel.piecewise_nd create objects that are sub-classes of pyomo.kernel.block. Thus, these objects can be stored in containers such as pyomo.kernel.block_dict and pyomo.kernel.block_list.

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```
model.blist.append(pyomo.kernel.block())
model.w = Widget()
model.w.x = pyomo.kernel.variable()
```

The next series of examples goes into more detail on how to implement derived components or containers.

The following code block shows a class definition for a non-negative variable, starting from `pyomo.kernel.variable` as a base class.

```
class NonNegativeVariable(pyomo.kernel.variable):
    """A non-negative variable."""
    __slots__ = ()

    def __init__(self, **kwds):
        if 'lb' not in kwds:
            kwds['lb'] = 0
        if kwds['lb'] < 0:
            raise ValueError("lower bound must be non-negative")
        super(NonNegativeVariable, self).__init__(**kwds)

    #
    # restrict assignments to x.lb to non-negative numbers
    #
    @property
    def lb(self):
        # calls the base class property getter
        return pyomo.kernel.variable.lb.fget(self)
    @lb.setter
    def lb(self, lb):
        if lb < 0:
            raise ValueError("lower bound must be non-negative")
        # calls the base class property setter
        pyomo.kernel.variable.lb.fset(self, lb)
```

The `NonNegativeVariable` class prevents negative values from being stored into its lower bound during initialization or later on through assignment statements (e.g, `x.lb = -1` fails). Note that the `__slots__ == ()` line at the beginning of the class definition is optional, but it is recommended if no additional data members are necessary as it reduces the memory requirement of the new variable type.

The next code block defines a custom variable container called `Point` that represents a 3-dimensional point in Cartesian space. The new type derives from the `pyomo.kernel.variable_tuple` container and uses the `NonNegativeVariable` type we defined previously in the z coordinate.

```
class Point(pyomo.kernel.variable_tuple):
    """A 3-dimensional point in Cartesian space with the
    z coordinate restricted to non-negative values."""
    __slots__ = ()

    def __init__(self):
        super(Point, self).__init__(
            (pyomo.kernel.variable(),
             pyomo.kernel.variable(),
             NonNegativeVariable()))
```

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```
    @property
    def x(self):
        return self[0]
    @property
    def y(self):
        return self[1]
    @property
    def z(self):
        return self[2]
```

The `Point` class can be treated like a tuple storing three variables, and it can be placed inside of other variable containers or added as attributes to blocks. The property methods included in the class definition provide an additional syntax for accessing the three variables it stores, as the next code example will show.

The following code defines a class for building a convex second-order cone constraint from a `Point` object. It derives from the `pyomo.kernel.constraint` class, overriding the constructor to build the constraint expression and utilizing the property methods on the point class to increase readability.

```
class SOC(pyomo.kernel.constraint):
    """A convex second-order cone constraint"""
    __slots__ = ()

    def __init__(self, point):
        assert isinstance(point.z, NonNegativeVariable)
        super(SOC, self).__init__(
            point.x**2 + point.y**2 <= point.z**2)
```

Reduced Memory Usage

The `pyomo.kernel` library offers significant opportunities to reduce memory requirements for highly structured models. The situation where this is most apparent is when expressing a model in terms of many small blocks consisting of singleton components. As an example, consider expressing a model consisting of a large number of voltage transformers. One option for doing so might be to define a *Transformer* component as a subclass of `pyomo.kernel.block`. The example below defines such a component, including some helper methods for connecting input and output voltage variables and updating the transformer ratio.

```
class Transformer(pyomo.kernel.block):
    def __init__(self):
        super(Transformer,self).__init__()
        self._a = pyomo.kernel.parameter()
        self._v_in = pyomo.kernel.expression()
        self._v_out = pyomo.kernel.expression()
        self._c = pyomo.kernel.constraint(
            self._a * self._v_out == self._v_in)
    def set_ratio(self, a):
        assert a > 0
        self._a.value = a
    def connect_v_in(self, v_in):
        self._v_in.expr = v_in
    def connect_v_out(self, v_out):
        self._v_out.expr = v_out
```

A simplified version of this using `pyomo.environ` components might look like what is below.

```
def Transformer():
    b = pyomo.environ.Block(concrete=True)
    b._a = pyomo.environ.Param(mutable=True)
    b._v_in = pyomo.environ.Expression()
    b._v_out = pyomo.environ.Expression()
    b._c = pyomo.environ.Constraint(expr=\
        b._a * b._v_out == b._v_in)
    return b
```

The transformer expressed using `pyomo.kernel` components requires roughly 2 KB of memory, whereas the `pyomo.environ` version requires roughly 8.4 KB of memory (an increase of more than 4x). Additionally, the `pyomo.kernel` transformer is fully compatible with all existing `pyomo.kernel` block containers.

Direct Support For Conic Constraints with Mosek

Pyomo 5.6.3 introduced support into `pyomo.kernel` for six conic constraint forms that are directly recognized by the new Mosek solver interface. These are

- `conic.quadratic`:

  $$\sum_i x_i^2 \leq r^2, \;\; r \geq 0$$

- `conic.rotated_quadratic`:

  $$\sum_i x_i^2 \leq 2 r_1 r_2, \;\; r_1, r_2 \geq 0$$

- `conic.primal_exponential`:

  $$x_1 \exp(x_2/x_1) \leq r, \;\; x_1, r \geq 0$$

- `conic.primal_power` (α is a constant):

  $$||x||_2 \leq r_1^{\alpha} r_2^{1-\alpha}, \;\; r_1, r_2 \geq 0, \; 0 < \alpha < 1$$

- `conic.dual_exponential`:

  $$-x_2 \exp((x_1/x_2) - 1) \leq r, \;\; x_2 \leq 0, \; r \geq 0$$

- `conic.dual_power` (α is a constant):

  $$||x||_2 \leq (r_1/\alpha)^{\alpha} (r_2/(1-\alpha))^{1-\alpha}, \;\; r_1, r_2 \geq 0, \; 0 < \alpha < 1$$

Other solver interfaces will treat these objects as general nonlinear or quadratic constraints, and may or may not have the ability to identify their convexity. For instance, Gurobi will recognize the expressions produced by the `quadratic` and `rotated_quadratic` objects as representing convex domains as long as the variables involved satisfy the convexity conditions. However, other solvers may not include this functionality.

Each of these conic constraint classes are of the same category type as standard `pyomo.kernel.constraint` object, and, thus, are directly supported by the standard constraint containers (`constraint_tuple`, `constraint_list`, `constraint_dict`).

Each conic constraint class supports two methods of instantiation. The first method is to directly instantiate a conic constraint object, providing all necessary input variables:

```
import pyomo.kernel as pmo
m = pmo.block()
m.x1 = pmo.variable(lb=0)
m.x2 = pmo.variable()
m.r = pmo.variable(lb=0)
m.q = pmo.conic.primal_exponential(
```

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```
    x1=m.x1,
    x2=m.x2,
    r=m.r)
```

This method may be limiting if utilizing the Mosek solver as the user must ensure that additional conic constraints do not use variables that are directly involved in any existing conic constraints (this is a limitation the Mosek solver itself).

To overcome this limitation, and to provide a more general way of defining conic domains, each conic constraint class provides the `as_domain` class method. This alternate constructor has the same argument signature as the class, but in place of each variable, one can optionally provide a constant, a linear expression, or `None`. The `as_domain` class method returns a `block` object that includes the core conic constraint, auxiliary variables used to express the conic constraint, as well as auxiliary constraints that link the inputs (that are not `None`) to the auxiliary variables. Example:

```
import pyomo.kernel as pmo
import math
m = pmo.block()
m.x = pmo.variable(lb=0)
m.y = pmo.variable(lb=0)
m.b = pmo.conic.primal_exponential.as_domain(
    x1=math.sqrt(2)*m.x,
    x2=2.0,
    r=2*(m.x + m.y))
```

13.7.3 Reference

Modeling Components:

Blocks

Summary

pyomo.core.kernel.block.block()	A generalized container for defining hierarchical models by adding modeling components as attributes.
pyomo.core.kernel.block.block_tuple(*args, ...)	A tuple-style container for objects with category type IBlock
pyomo.core.kernel.block.block_list(*args, **kwds)	A list-style container for objects with category type IBlock
pyomo.core.kernel.block.block_dict(*args, **kwds)	A dict-style container for objects with category type IBlock

Member Documentation

class pyomo.core.kernel.block.**block**
Bases: pyomo.core.kernel.block.IBlock

A generalized container for defining hierarchical models by adding modeling components as attributes.

Examples

```
>>> import pyomo.kernel as pmo
>>> model = pmo.block()
>>> model.x = pmo.variable()
>>> model.c = pmo.constraint(model.x >= 1)
>>> model.o = pmo.objective(model.x)
```

child_ctypes()
Returns the set of child object category types stored in this container.

children(*ctype=<class 'pyomo.core.kernel.base._no_ctype'>*)
Iterate over the children of this block.

Parameters **ctype** – Indicates the category of children to include. The default value indicates that all categories should be included.

Returns iterator of child objects

load_solution(*solution*, *allow_consistent_values_for_fixed_vars=False*, *comparison_tolerance_for_fixed_vars=1e-05*)
Load a solution.

Parameters

- **solution** – A pyomo.opt.Solution object with a symbol map. Optionally, the solution can be tagged with a default variable value (e.g., 0) that will be applied to those variables in the symbol map that do not have a value in the solution.
- **allow_consistent_values_for_fixed_vars** – Indicates whether a solution can specify consistent values for variables that are fixed.
- **comparison_tolerance_for_fixed_vars** – The tolerance used to define whether or not a value in the solution is consistent with the value of a fixed variable.

write(*filename*, *format=None*, *_solver_capability=None*, *_called_by_solver=False*, ***kwds*)
Write the model to a file, with a given format.

Parameters

- **filename** (*str*) – The name of the file to write.
- **format** – The file format to use. If this is not specified, the file format will be inferred from the filename suffix.
- ****kwds** – Additional keyword options passed to the model writer.

Returns a SymbolMap

class pyomo.core.kernel.block.**block_tuple**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.tuple_container.TupleContainer*

A tuple-style container for objects with category type IBlock

class pyomo.core.kernel.block.**block_list**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.list_container.ListContainer*

A list-style container for objects with category type IBlock

class pyomo.core.kernel.block.**block_dict**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.dict_container.DictContainer*

A dict-style container for objects with category type IBlock

Variables

Summary

pyomo.core.kernel.variable.variable([...])	A decision variable
pyomo.core.kernel.variable.variable_tuple(...)	A tuple-style container for objects with category type IVariable
pyomo.core.kernel.variable.variable_list(...)	A list-style container for objects with category type IVariable
pyomo.core.kernel.variable.variable_dict(...)	A dict-style container for objects with category type IVariable

Member Documentation

class pyomo.core.kernel.variable.**variable**(*domain_type=None*, *domain=None*, *lb=None*, *ub=None*, *value=None*, *fixed=False*)
Bases: pyomo.core.kernel.variable.IVariable

A decision variable

Decision variables are used in objectives and constraints to define an optimization problem.

Parameters

- **domain_type** – Sets the domain type of the variable. Must be one of RealSet or IntegerSet. Can be updated later by assigning to the *domain_type* property. The default value of None is equivalent to RealSet, unless the *domain* keyword is used.
- **domain** – Sets the domain of the variable. This updates the *domain_type*, *lb*, and *ub* properties of the variable. The default value of None implies that this keyword is ignored. This keyword can not be used in combination with the *domain_type* keyword.
- **lb** – Sets the lower bound of the variable. Can be updated later by assigning to the *lb* property on the variable. Default is None, which is equivalent to -inf.
- **ub** – Sets the upper bound of the variable. Can be updated later by assigning to the *ub* property on the variable. Default is None, which is equivalent to +inf.
- **value** – Sets the value of the variable. Can be updated later by assigning to the *value* property on the variable. Default is None.
- **fixed** (*bool*) – Sets the fixed status of the variable. Can be updated later by assigning to the *fixed* property or by calling the fix() method. Default is False.

Examples

```
>>> import pyomo.kernel as pmo
>>> # A continuous variable with infinite bounds
>>> x = pmo.variable()
>>> # A binary variable
>>> x = pmo.variable(domain=pmo.Binary)
>>> # Also a binary variable
>>> x = pmo.variable(domain_type=pmo.IntegerSet, lb=0, ub=1)
```

property domain
Set the domain of the variable. This method updates the *domain_type* property and overwrites the *lb* and *ub* properties with the domain bounds.

property domain_type
The domain type of the variable (`RealSet` or `IntegerSet`)

property fixed
The fixed status of the variable

property lb
The lower bound of the variable

property stale
The stale status of the variable

property ub
The upper bound of the variable

property value
The value of the variable

class pyomo.core.kernel.variable.**variable_tuple**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.tuple_container.TupleContainer*

A tuple-style container for objects with category type IVariable

class pyomo.core.kernel.variable.**variable_list**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.list_container.ListContainer*

A list-style container for objects with category type IVariable

class pyomo.core.kernel.variable.**variable_dict**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.dict_container.DictContainer*

A dict-style container for objects with category type IVariable

Constraints

Summary

pyomo.core.kernel.constraint.constraint([...])	A general algebraic constraint
pyomo.core.kernel.constraint.linear_constraint([...])	A linear constraint

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pyomo.core.kernel.constraint.constraint_tuple(...)	A tuple-style container for objects with category type IConstraint
pyomo.core.kernel.constraint.constraint_list(...)	A list-style container for objects with category type IConstraint
pyomo.core.kernel.constraint.constraint_dict(...)	A dict-style container for objects with category type IConstraint
pyomo.core.kernel.matrix_constraint.matrix_constraint(A)	A container for constraints of the form lb <= Ax <= ub.

Member Documentation

class pyomo.core.kernel.constraint.**constraint**(*expr=None*, *body=None*, *lb=None*, *ub=None*, *rhs=None*)

Bases: pyomo.core.kernel.constraint._MutableBoundsConstraintMixin, pyomo.core.kernel.constraint.IConstraint

A general algebraic constraint

Algebraic constraints store relational expressions composed of linear or nonlinear functions involving decision variables.

Parameters

- **expr** – Sets the relational expression for the constraint. Can be updated later by assigning to the *expr* property on the constraint. When this keyword is used, values for the *body*, lb, ub, and rhs attributes are automatically determined based on the relational expression type. Default value is None.
- **body** – Sets the body of the constraint. Can be updated later by assigning to the *body* property on the constraint. Default is None. This keyword should not be used in combination with the *expr* keyword.
- **lb** – Sets the lower bound of the constraint. Can be updated later by assigning to the lb property on the constraint. Default is None, which is equivalent to -inf. This keyword should not be used in combination with the *expr* keyword.
- **ub** – Sets the upper bound of the constraint. Can be updated later by assigning to the ub property on the constraint. Default is None, which is equivalent to +inf. This keyword should not be used in combination with the *expr* keyword.
- **rhs** – Sets the right-hand side of the constraint. Can be updated later by assigning to the rhs property on the constraint. The default value of None implies that this keyword is ignored. Otherwise, use of this keyword implies that the equality property is set to True. This keyword should not be used in combination with the *expr* keyword.

Examples

```
>>> import pyomo.kernel as pmo
>>> # A decision variable used to define constraints
>>> x = pmo.variable()
>>> # An upper bound constraint
>>> c = pmo.constraint(0.5*x <= 1)
>>> # (equivalent form)
>>> c = pmo.constraint(body=0.5*x, ub=1)
```

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```
>>> # A range constraint
>>> c = pmo.constraint(lb=-1, body=0.5*x, ub=1)
>>> # An nonlinear equality constraint
>>> c = pmo.constraint(x**2 == 1)
>>> # (equivalent form)
>>> c = pmo.constraint(body=x**2, rhs=1)
```

property body
The body of the constraint

property expr
Get or set the expression on this constraint.

class pyomo.core.kernel.constraint.**linear_constraint**(*variables=None*, *coefficients=None*, *terms=None*, *lb=None*, *ub=None*, *rhs=None*)

Bases: pyomo.core.kernel.constraint._MutableBoundsConstraintMixin, pyomo.core.kernel.constraint.IConstraint

A linear constraint

A linear constraint stores a linear relational expression defined by a list of variables and coefficients. This class can be used to reduce build time and memory for an optimization model. It also increases the speed at which the model can be output to a solver.

Parameters

- **variables** (*list*) – Sets the list of variables in the linear expression defining the body of the constraint. Can be updated later by assigning to the `variables` property on the constraint.
- **coefficients** (*list*) – Sets the list of coefficients for the variables in the linear expression defining the body of the constraint. Can be updated later by assigning to the `coefficients` property on the constraint.
- **terms** (*list*) – An alternative way of initializing the `variables` and `coefficients` lists using an iterable of (variable, coefficient) tuples. Can be updated later by assigning to the *terms* property on the constraint. This keyword should not be used in combination with the `variables` or `coefficients` keywords.
- **lb** – Sets the lower bound of the constraint. Can be updated later by assigning to the `lb` property on the constraint. Default is `None`, which is equivalent to `-inf`.
- **ub** – Sets the upper bound of the constraint. Can be updated later by assigning to the `ub` property on the constraint. Default is `None`, which is equivalent to `+inf`.
- **rhs** – Sets the right-hand side of the constraint. Can be updated later by assigning to the `rhs` property on the constraint. The default value of `None` implies that this keyword is ignored. Otherwise, use of this keyword implies that the `equality` property is set to `True`.

Examples

```
>>> import pyomo.kernel as pmo
>>> # Decision variables used to define constraints
>>> x = pmo.variable()
>>> y = pmo.variable()
>>> # An upper bound constraint
>>> c = pmo.linear_constraint(variables=[x,y], coefficients=[1,2], ub=1)
>>> # (equivalent form)
>>> c = pmo.linear_constraint(terms=[(x,1), (y,2)], ub=1)
>>> # (equivalent form using a general constraint)
>>> c = pmo.constraint(x + 2*y <= 1)
```

property body
The body of the constraint

canonical_form(*compute_values=True*)
Build a canonical representation of the body of this constraints

property terms
An iterator over the terms in the body of this constraint as (variable, coefficient) tuples

class pyomo.core.kernel.constraint.**constraint_tuple**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.tuple_container.TupleContainer*

A tuple-style container for objects with category type IConstraint

class pyomo.core.kernel.constraint.**constraint_list**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.list_container.ListContainer*

A list-style container for objects with category type IConstraint

class pyomo.core.kernel.constraint.**constraint_dict**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.dict_container.DictContainer*

A dict-style container for objects with category type IConstraint

class pyomo.core.kernel.matrix_constraint.**matrix_constraint**(*A*, *lb=None*, *ub=None*, *rhs=None*, *x=None*, *sparse=True*)
Bases: *pyomo.core.kernel.constraint.constraint_tuple*

A container for constraints of the form lb <= Ax <= ub.

Parameters

- **A** – A scipy sparse matrix or 2D numpy array (always copied)
- **lb** – A scalar or array with the same number of rows as A that defines the lower bound of the constraints
- **ub** – A scalar or array with the same number of rows as A that defines the upper bound of the constraints
- **rhs** – A scalar or array with the same number of rows as A that defines the right-hand side of the constraints (implies equality constraints)
- **x** – A list with the same number of columns as A that stores the variable associated with each column
- **sparse** – Indicates whether or not sparse storage (CSR format) should be used to store A. Default is True.

property A
A read-only view of the constraint matrix

property equality
The array of boolean entries indicating the indices that are equality constraints

property lb
The array of constraint lower bounds

property lslack
Lower slack (body - lb)

property rhs
The array of constraint right-hand sides. Can be set to a scalar or a numpy array of the same dimension. This property can only be read when the equality property is `True` on every index. Assigning to this property implicitly sets the equality property to `True` on every index.

property slack
min(lslack, uslack)

property sparse
Boolean indicating whether or not the underlying matrix uses sparse storage

property ub
The array of constraint upper bounds

property uslack
Upper slack (ub - body)

property x
The list of variables associated with the columns of the constraint matrix

Parameters

Summary

pyomo.core.kernel.parameter.parameter([value])	A object for storing a mutable, numeric value that can be used to build a symbolic expression.
pyomo.core.kernel.parameter.functional_value([fn])	An object for storing a numeric function that can be used in a symbolic expression.
pyomo.core.kernel.parameter.parameter_tuple(...)	A tuple-style container for objects with category type IParameter
pyomo.core.kernel.parameter.parameter_list(...)	A list-style container for objects with category type IParameter
pyomo.core.kernel.parameter.parameter_dict(...)	A dict-style container for objects with category type IParameter

Member Documentation

class pyomo.core.kernel.parameter.**parameter**(*value=None*)
Bases: pyomo.core.kernel.parameter.IParameter

A object for storing a mutable, numeric value that can be used to build a symbolic expression.

property value
The value of the paramater

class pyomo.core.kernel.parameter.**functional_value**(*fn=None*)
Bases: pyomo.core.kernel.parameter.IParameter

An object for storing a numeric function that can be used in a symbolic expression.

Note that models making use of this object may require the dill module for serialization.

property fn
The function stored with this object

class pyomo.core.kernel.parameter.**parameter_tuple**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.tuple_container.TupleContainer*

A tuple-style container for objects with category type IParameter

class pyomo.core.kernel.parameter.**parameter_list**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.list_container.ListContainer*

A list-style container for objects with category type IParameter

class pyomo.core.kernel.parameter.**parameter_dict**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.dict_container.DictContainer*

A dict-style container for objects with category type IParameter

Objectives

Summary

pyomo.core.kernel.objective.objective([...])	An optimization objective.
pyomo.core.kernel.objective.objective_tuple(...)	A tuple-style container for objects with category type IObjective
pyomo.core.kernel.objective.objective_list(...)	A list-style container for objects with category type IObjective
pyomo.core.kernel.objective.objective_dict(...)	A dict-style container for objects with category type IObjective

Member Documentation

class pyomo.core.kernel.objective.**objective**(*expr=None*, *sense=1*)
Bases: pyomo.core.kernel.objective.IObjective

An optimization objective.

property expr
The stored expression

property sense
The optimization direction for the objective (minimize or maximize)

class pyomo.core.kernel.objective.**objective_tuple**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.tuple_container.TupleContainer*

A tuple-style container for objects with category type IObjective

class pyomo.core.kernel.objective.**objective_list**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.list_container.ListContainer*

A list-style container for objects with category type IObjective

class pyomo.core.kernel.objective.**objective_dict**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.dict_container.DictContainer*

A dict-style container for objects with category type IObjective

Expressions

Summary

pyomo.core.kernel.expression.expression([expr])	A named, mutable expression.
pyomo.core.kernel.expression.expression_tuple(...)	A tuple-style container for objects with category type IExpression
pyomo.core.kernel.expression.expression_list(...)	A list-style container for objects with category type IExpression
pyomo.core.kernel.expression.expression_dict(...)	A dict-style container for objects with category type IExpression

Member Documentation

class pyomo.core.kernel.expression.**expression**(*expr=None*)
Bases: pyomo.core.kernel.expression.IExpression

A named, mutable expression.

property expr
The stored expression

class pyomo.core.kernel.expression.**expression_tuple**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.tuple_container.TupleContainer*

A tuple-style container for objects with category type IExpression

class pyomo.core.kernel.expression.**expression_list**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.list_container.ListContainer*

A list-style container for objects with category type IExpression

class pyomo.core.kernel.expression.**expression_dict**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.dict_container.DictContainer*

A dict-style container for objects with category type IExpression

Special Ordered Sets

Summary

pyomo.core.kernel.sos.sos(variables[, ...])	A Special Ordered Set of type n.
pyomo.core.kernel.sos.sos1(variables[, weights])	A Special Ordered Set of type 1.
pyomo.core.kernel.sos.sos2(variables[, weights])	A Special Ordered Set of type 2.
pyomo.core.kernel.sos.sos_tuple(*args, **kwds)	A tuple-style container for objects with category type ISOS

continues on next page

Table 13.13 – continued from previous page

pyomo.core.kernel.sos.sos_list(*args, **kwds)	A list-style container for objects with category type ISOS
pyomo.core.kernel.sos.sos_dict(*args, **kwds)	A dict-style container for objects with category type ISOS

Member Documentation

class pyomo.core.kernel.sos.**sos**(*variables*, *weights=None*, *level=1*)
Bases: pyomo.core.kernel.sos.ISOS

A Special Ordered Set of type n.

property level
The sos level (e.g., 1,2,...)

property variables
The sos variables

property weights
The sos variables

pyomo.core.kernel.sos.**sos1**(*variables*, *weights=None*)
A Special Ordered Set of type 1.

This is an alias for sos(..., level=1)

pyomo.core.kernel.sos.**sos2**(*variables*, *weights=None*)
A Special Ordered Set of type 2.

This is an alias for sos(..., level=2).

class pyomo.core.kernel.sos.**sos_tuple**(**args*, ***kwds*)
Bases: pyomo.core.kernel.tuple_container.TupleContainer

A tuple-style container for objects with category type ISOS

class pyomo.core.kernel.sos.**sos_list**(**args*, ***kwds*)
Bases: pyomo.core.kernel.list_container.ListContainer

A list-style container for objects with category type ISOS

class pyomo.core.kernel.sos.**sos_dict**(**args*, ***kwds*)
Bases: pyomo.core.kernel.dict_container.DictContainer

A dict-style container for objects with category type ISOS

Suffixes

class pyomo.core.kernel.suffix.**ISuffix**(**args*, ***kwds*)
Bases: pyomo.common.collections.component_map.ComponentMap, pyomo.core.kernel.base.ICategorizedObject

The interface for suffixes.

property datatype
The suffix datatype

property direction
The suffix direction

pyomo.core.kernel.suffix.**export_suffix_generator**(*blk*, *datatype=<object object>*, *active=True*, *descend_into=True*)

Generates an efficient traversal of all suffixes that have been declared for exporting data.

Parameters

- **blk** – A block object.
- **datatype** – Restricts the suffixes included in the returned generator to those matching the provided suffix datatype.
- **active** (True/None) – Controls whether or not to filter the iteration to include only the active part of the storage tree. The default is True. Setting this keyword to None causes the active status of objects to be ignored.
- **descend_into** (*bool, function*) – Indicates whether or not to descend into a heterogeneous container. Default is True, which is equivalent to *lambda x: True*, meaning all heterogeneous containers will be descended into.

Returns iterator of suffixes

pyomo.core.kernel.suffix.**import_suffix_generator**(*blk*, *datatype=<object object>*, *active=True*, *descend_into=True*)

Generates an efficient traversal of all suffixes that have been declared for importing data.

Parameters

- **blk** – A block object.
- **datatype** – Restricts the suffixes included in the returned generator to those matching the provided suffix datatype.
- **active** (True/None) – Controls whether or not to filter the iteration to include only the active part of the storage tree. The default is True. Setting this keyword to None causes the active status of objects to be ignored.
- **descend_into** (*bool, function*) – Indicates whether or not to descend into a heterogeneous container. Default is True, which is equivalent to *lambda x: True*, meaning all heterogeneous containers will be descended into.

Returns iterator of suffixes

pyomo.core.kernel.suffix.**local_suffix_generator**(*blk*, *datatype=<object object>*, *active=True*, *descend_into=True*)

Generates an efficient traversal of all suffixes that have been declared local data storage.

Parameters

- **blk** – A block object.
- **datatype** – Restricts the suffixes included in the returned generator to those matching the provided suffix datatype.
- **active** (True/None) – Controls whether or not to filter the iteration to include only the active part of the storage tree. The default is True. Setting this keyword to None causes the active status of objects to be ignored.
- **descend_into** (*bool, function*) – Indicates whether or not to descend into a heterogeneous container. Default is True, which is equivalent to *lambda x: True*, meaning all heterogeneous containers will be descended into.

Returns iterator of suffixes

class pyomo.core.kernel.suffix.**suffix**(**args*, ***kwds*)

Bases: *pyomo.core.kernel.suffix.ISuffix*

A container for storing extraneous model data that can be imported to or exported from a solver.

clear_all_values()
DEPRECATED.

Deprecated since version 5.3: suffix.clear_all_values is replaced with suffix.clear

clear_value(*component*)
DEPRECATED.

Deprecated since version 5.3: suffix.clear_value will be removed in the future. Use 'del suffix[key]' instead.

property datatype
Return the suffix datatype.

property direction
Return the suffix direction.

property export_enabled
Returns `True` when this suffix is enabled for export to solvers.

get_datatype()
DEPRECATED.

Deprecated since version 5.3: suffix.get_datatype is replaced with the property suffix.datatype

get_direction()
DEPRECATED.

Deprecated since version 5.3: suffix.get_direction is replaced with the property suffix.direction

property import_enabled
Returns `True` when this suffix is enabled for import from solutions.

set_all_values(*value*)
DEPRECATED.

Deprecated since version 5.3: suffix.set_all_values will be removed in the future.

set_datatype(*datatype*)
DEPRECATED.

Deprecated since version 5.3: suffix.set_datatype is replaced with the property setter suffix.datatype

set_direction(*direction*)
DEPRECATED.

Deprecated since version 5.3: suffix.set_direction is replaced with the property setter suffix.direction

class pyomo.core.kernel.suffix.**suffix_dict**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.dict_container.DictContainer*

A dict-style container for objects with category type ISuffix

pyomo.core.kernel.suffix.**suffix_generator**(*blk*, *datatype=<object object>*, *active=True*, *descend_into=True*)
Generates an efficient traversal of all suffixes that have been declared.

Parameters

- **blk** – A block object.
- **datatype** – Restricts the suffixes included in the returned generator to those matching the provided suffix datatype.

- **active** (True/None) – Controls whether or not to filter the iteration to include only the active part of the storage tree. The default is True. Setting this keyword to None causes the active status of objects to be ignored.
- **descend_into** (*bool, function*) – Indicates whether or not to descend into a heterogeneous container. Default is True, which is equivalent to *lambda x: True*, meaning all heterogeneous containers will be descended into.

Returns iterator of suffixes

Piecewise Function Library

Modules

Single-variate Piecewise Functions

Summary

pyomo.core.kernel.piecewise_library.transforms.piecewise(...)	Models a single-variate piecewise linear function.
pyomo.core.kernel.piecewise_library.transforms.PiecewiseLinearFunction(...)	A piecewise linear function
pyomo.core.kernel.piecewise_library.transforms.TransformedPiecewiseLinearFunction(f)	Base class for transformed piecewise linear functions
pyomo.core.kernel.piecewise_library.transforms.piecewise_convex(...)	Simple convex piecewise representation
pyomo.core.kernel.piecewise_library.transforms.piecewise_sos2(...)	Discrete SOS2 piecewise representation
pyomo.core.kernel.piecewise_library.transforms.piecewise_dcc(...)	Discrete DCC piecewise representation
pyomo.core.kernel.piecewise_library.transforms.piecewise_cc(...)	Discrete CC piecewise representation
pyomo.core.kernel.piecewise_library.transforms.piecewise_mc(...)	Discrete MC piecewise representation
pyomo.core.kernel.piecewise_library.transforms.piecewise_inc(...)	Discrete INC piecewise representation
pyomo.core.kernel.piecewise_library.transforms.piecewise_dlog(...)	Discrete DLOG piecewise representation
pyomo.core.kernel.piecewise_library.transforms.piecewise_log(...)	Discrete LOG piecewise representation

Member Documentation

pyomo.core.kernel.piecewise_library.transforms.**piecewise**(*breakpoints*, *values*, *input=None*, *output=None*, *bound='eq'*, *repn='sos2'*, *validate=True*, *simplify=True*, *equal_slopes_tolerance=1e-06*, *require_bounded_input_variable=True*, *require_variable_domain_coverage=True*)

Models a single-variate piecewise linear function.

This function takes a list breakpoints and function values describing a piecewise linear function and transforms this input data into a block of variables and constraints that enforce a piecewise linear relationship between an input variable and an output variable. In the general case, this transformation requires the use of discrete decision variables.

Parameters

- **breakpoints** (*list*) – The list of breakpoints of the piecewise linear function. This can be a list of numbers or a list of objects that store mutable data (e.g., mutable parameters). If mutable data is used validation might need to be disabled by setting the `validate` keyword to `False`. The list of breakpoints must be in non-decreasing order.
- **values** (*list*) – The values of the piecewise linear function corresponding to the breakpoints.
- **input** – The variable constrained to be the input of the piecewise linear function.
- **output** – The variable constrained to be the output of the piecewise linear function.
- **bound** (*str*) – The type of bound to impose on the output expression. Can be one of:
  - 'lb': y <= f(x)
  - 'eq': y = f(x)
  - 'ub': y >= f(x)
- **repn** (*str*) – The type of piecewise representation to use. Choices are shown below (+ means step functions are supported)
  - 'sos2': standard representation using sos2 constraints (+)
  - 'dcc': disaggregated convex combination (+)
  - 'dlog': logarithmic disaggregated convex combination (+)
  - 'cc': convex combination (+)
  - 'log': logarithmic branching convex combination (+)
  - 'mc': multiple choice
  - 'inc': incremental method (+)
- **validate** (*bool*) – Indicates whether or not to perform validation of the input data. The default is `True`. Validation can be performed manually after the piecewise object is created by calling the `validate()` method. Validation should be performed any time the inputs are changed (e.g., when using mutable parameters in the breakpoints list or when the input variable changes).
- **simplify** (*bool*) – Indicates whether or not to attempt to simplify the piecewise representation to avoid using discrete variables. This can be done when the feasible region for the output variable, with respect to the piecewise function and the bound type, is a

convex set. Default is `True`. Validation is required to perform simplification, so this keyword is ignored when the `validate` keyword is `False`.

- **equal_slopes_tolerance** (*float*) – Tolerance used check if consecutive slopes are nearly equal. If any are found, validation will fail. Default is 1e-6. This keyword is ignored when the `validate` keyword is `False`.
- **require_bounded_input_variable** (*bool*) – Indicates if the input variable is required to have finite upper and lower bounds. Default is `True`. Setting this keyword to `False` can be used to allow general expressions to be used as the input in place of a variable. This keyword is ignored when the `validate` keyword is `False`.
- **require_variable_domain_coverage** (*bool*) – Indicates if the function domain (defined by the endpoints of the breakpoints list) needs to cover the entire domain of the input variable. Default is `True`. Ignored for any bounds of variables that are not finite, or when the input is not assigned a variable. This keyword is ignored when the `validate` keyword is `False`.

Returns a block that stores any new variables, constraints, and other modeling objects used by the piecewise representation

Return type *TransformedPiecewiseLinearFunction*

class pyomo.core.kernel.piecewise_library.transforms.**PiecewiseLinearFunction**(*breakpoints*, *values*, *validate=True*, ***kwds*)

Bases: `object`

A piecewise linear function

Piecewise linear functions are defined by a list of breakpoints and a list function values corresponding to each breakpoint. The function value between breakpoints is implied through linear interpolation.

Parameters

- **breakpoints** (*list*) – The list of function breakpoints.
- **values** (*list*) – The list of function values (one for each breakpoint).
- **validate** (*bool*) – Indicates whether or not to perform validation of the input data. The default is `True`. Validation can be performed manually after the piecewise object is created by calling the *validate()* method. Validation should be performed any time the inputs are changed (e.g., when using mutable parameters in the breakpoints list).
- ****kwds** – Additional keywords are passed to the *validate()* method when the *validate* keyword is `True`; otherwise, they are ignored.

__call__(*x*)

Evaluates the piecewise linear function at the given point using interpolation. Note that step functions are assumed lower-semicontinuous.

property breakpoints

The set of breakpoints used to defined this function

validate(*equal_slopes_tolerance=1e-06*)

Validate this piecewise linear function by verifying various properties of the breakpoints and values lists (e.g., that the list of breakpoints is nondecreasing).

Parameters **equal_slopes_tolerance** (*float*) – Tolerance used check if consecutive slopes are nearly equal. If any are found, validation will fail. Default is 1e-6.

Returns a function characterization code (see `util.characterize_function()`)

Return type int

Raises *PiecewiseValidationError* – if validation fails

property values
The set of values used to defined this function

class pyomo.core.kernel.piecewise_library.transforms.**TransformedPiecewiseLinearFunction**(*f*, *input=None*, *output=None*, *bound='eq'*, *validate=True*, ***kwds*)

Bases: *pyomo.core.kernel.block.block*

Base class for transformed piecewise linear functions

A transformed piecewise linear functions is a block of variables and constraints that enforce a piecewise linear relationship between an input variable and an output variable.

Parameters

- **f** (*PiecewiseLinearFunction*) – The piecewise linear function to transform.
- **input** – The variable constrained to be the input of the piecewise linear function.
- **output** – The variable constrained to be the output of the piecewise linear function.
- **bound** (*str*) – The type of bound to impose on the output expression. Can be one of:
  - 'lb': y <= f(x)
  - 'eq': y = f(x)
  - 'ub': y >= f(x)
- **validate** (*bool*) – Indicates whether or not to perform validation of the input data. The default is `True`. Validation can be performed manually after the piecewise object is created by calling the *validate()* method. Validation should be performed any time the inputs are changed (e.g., when using mutable parameters in the breakpoints list or when the input variable changes).
- ****kwds** – Additional keywords are passed to the *validate()* method when the *validate* keyword is `True`; otherwise, they are ignored.

__call__(*x*)
Evaluates the piecewise linear function at the given point using interpolation

property bound
The bound type assigned to the piecewise relationship ('lb','ub','eq').

property breakpoints
The set of breakpoints used to defined this function

property input
The expression that stores the input to the piecewise function. The returned object can be updated by assigning to its `expr` attribute.

property output
The expression that stores the output of the piecewise function. The returned object can be updated by assigning to its `expr` attribute.

validate(*equal_slopes_tolerance=1e-06*, *require_bounded_input_variable=True*, *require_variable_domain_coverage=True*)

Validate this piecewise linear function by verifying various properties of the breakpoints, values, and input variable (e.g., that the list of breakpoints is nondecreasing).

Parameters

- **equal_slopes_tolerance** (*float*) – Tolerance used check if consecutive slopes are nearly equal. If any are found, validation will fail. Default is 1e-6.
- **require_bounded_input_variable** (*bool*) – Indicates if the input variable is required to have finite upper and lower bounds. Default is `True`. Setting this keyword to `False` can be used to allow general expressions to be used as the input in place of a variable.
- **require_variable_domain_coverage** (*bool*) – Indicates if the function domain (defined by the endpoints of the breakpoints list) needs to cover the entire domain of the input variable. Default is `True`. Ignored for any bounds of variables that are not finite, or when the input is not assigned a variable.

Returns a function characterization code (see `util.characterize_function()`)

Return type int

Raises *PiecewiseValidationError* – if validation fails

property values

The set of values used to defined this function

class pyomo.core.kernel.piecewise_library.transforms.**piecewise_convex**(**args*, ***kwds*)

Bases: *pyomo.core.kernel.piecewise_library.transforms.TransformedPiecewiseLinearFunction*

Simple convex piecewise representation

Expresses a piecewise linear function with a convex feasible region for the output variable using a simple collection of linear constraints.

validate(***kwds*)

Validate this piecewise linear function by verifying various properties of the breakpoints, values, and input variable (e.g., that the list of breakpoints is nondecreasing).

See base class documentation for keyword descriptions.

class pyomo.core.kernel.piecewise_library.transforms.**piecewise_sos2**(**args*, ***kwds*)

Bases: *pyomo.core.kernel.piecewise_library.transforms.TransformedPiecewiseLinearFunction*

Discrete SOS2 piecewise representation

Expresses a piecewise linear function using the SOS2 formulation.

validate(***kwds*)

Validate this piecewise linear function by verifying various properties of the breakpoints, values, and input variable (e.g., that the list of breakpoints is nondecreasing).

See base class documentation for keyword descriptions.

class pyomo.core.kernel.piecewise_library.transforms.**piecewise_dcc**(**args*, ***kwds*)

Bases: *pyomo.core.kernel.piecewise_library.transforms.TransformedPiecewiseLinearFunction*

Discrete DCC piecewise representation

Expresses a piecewise linear function using the DCC formulation.

validate(***kwds*)
Validate this piecewise linear function by verifying various properties of the breakpoints, values, and input variable (e.g., that the list of breakpoints is nondecreasing).

See base class documentation for keyword descriptions.

class pyomo.core.kernel.piecewise_library.transforms.**piecewise_cc**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.piecewise_library.transforms.TransformedPiecewiseLinearFunction*

Discrete CC piecewise representation

Expresses a piecewise linear function using the CC formulation.

validate(***kwds*)
Validate this piecewise linear function by verifying various properties of the breakpoints, values, and input variable (e.g., that the list of breakpoints is nondecreasing).

See base class documentation for keyword descriptions.

class pyomo.core.kernel.piecewise_library.transforms.**piecewise_mc**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.piecewise_library.transforms.TransformedPiecewiseLinearFunction*

Discrete MC piecewise representation

Expresses a piecewise linear function using the MC formulation.

validate(***kwds*)
Validate this piecewise linear function by verifying various properties of the breakpoints, values, and input variable (e.g., that the list of breakpoints is nondecreasing).

See base class documentation for keyword descriptions.

class pyomo.core.kernel.piecewise_library.transforms.**piecewise_inc**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.piecewise_library.transforms.TransformedPiecewiseLinearFunction*

Discrete INC piecewise representation

Expresses a piecewise linear function using the INC formulation.

validate(***kwds*)
Validate this piecewise linear function by verifying various properties of the breakpoints, values, and input variable (e.g., that the list of breakpoints is nondecreasing).

See base class documentation for keyword descriptions.

class pyomo.core.kernel.piecewise_library.transforms.**piecewise_dlog**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.piecewise_library.transforms.TransformedPiecewiseLinearFunction*

Discrete DLOG piecewise representation

Expresses a piecewise linear function using the DLOG formulation. This formulation uses logarithmic number of discrete variables in terms of number of breakpoints.

validate(***kwds*)
Validate this piecewise linear function by verifying various properties of the breakpoints, values, and input variable (e.g., that the list of breakpoints is nondecreasing).

See base class documentation for keyword descriptions.

class pyomo.core.kernel.piecewise_library.transforms.**piecewise_log**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.piecewise_library.transforms.TransformedPiecewiseLinearFunction*

Discrete LOG piecewise representation

Expresses a piecewise linear function using the LOG formulation. This formulation uses logarithmic number of discrete variables in terms of number of breakpoints.

validate(***kwds*)
Validate this piecewise linear function by verifying various properties of the breakpoints, values, and input variable (e.g., that the list of breakpoints is nondecreasing).

See base class documentation for keyword descriptions.

Multi-variate Piecewise Functions

Summary

pyomo.core.kernel.piecewise_library.transforms_nd.piecewise_nd(...)	Models a multi-variate piecewise linear function.
pyomo.core.kernel.piecewise_library.transforms_nd.PiecewiseLinearFunctionND(...)	A multi-variate piecewise linear function
pyomo.core.kernel.piecewise_library.transforms_nd.TransformedPiecewiseLinearFunctionND(f)	Base class for transformed multi-variate piecewise linear functions
pyomo.core.kernel.piecewise_library.transforms_nd.piecewise_nd_cc(...)	Discrete CC multi-variate piecewise representation

Member Documentation

pyomo.core.kernel.piecewise_library.transforms_nd.**piecewise_nd**(*tri*, *values*, *input=None*, *output=None*, *bound='eq'*, *repn='cc'*)
Models a multi-variate piecewise linear function.

This function takes a D-dimensional triangulation and a list of function values associated with the points of the triangulation and transforms this input data into a block of variables and constraints that enforce a piecewise linear relationship between an D-dimensional vector of input variable and a single output variable. In the general case, this transformation requires the use of discrete decision variables.

Parameters

- **tri** (*scipy.spatial.Delaunay*) – A triangulation over the discretized variable domain. Can be generated using a list of variables using the utility function `util.generate_delaunay()`. Required attributes:
  - points: An (npoints, D) shaped array listing the D-dimensional coordinates of the discretization points.
  - simplices: An (nsimplices, D+1) shaped array of integers specifying the D+1 indices of the points vector that define each simplex of the triangulation.
- **values** (*numpy.array*) – An (npoints,) shaped array of the values of the piecewise function at each of coordinates in the triangulation points array.
- **input** – A D-length list of variables or expressions bound as the inputs of the piecewise function.
- **output** – The variable constrained to be the output of the piecewise linear function.
- **bound** (*str*) – The type of bound to impose on the output expression. Can be one of:
  - 'lb': y <= f(x)

- 'eq': y = f(x)
- 'ub': y >= f(x)

- **repn** (*str*) – The type of piecewise representation to use. Can be one of:
  - 'cc': convex combination

Returns a block containing any new variables, constraints, and other components used by the piecewise representation

Return type *TransformedPiecewiseLinearFunctionND*

class pyomo.core.kernel.piecewise_library.transforms_nd.**PiecewiseLinearFunctionND**(*tri*, *values*, *validate=True*, ***kwds*)

Bases: `object`

A multi-variate piecewise linear function

Multi-varite piecewise linear functions are defined by a triangulation over a finite domain and a list of function values associated with the points of the triangulation. The function value between points in the triangulation is implied through linear interpolation.

Parameters

- **tri** (*scipy.spatial.Delaunay*) – A triangulation over the discretized variable domain. Can be generated using a list of variables using the utility function `util.generate_delaunay()`. Required attributes:
  - points: An (npoints, D) shaped array listing the D-dimensional coordinates of the discretization points.
  - simplices: An (nsimplices, D+1) shaped array of integers specifying the D+1 indices of the points vector that define each simplex of the triangulation.
- **values** (*numpy.array*) – An (npoints,) shaped array of the values of the piecewise function at each of coordinates in the triangulation points array.

__call__(*x*)

Evaluates the piecewise linear function using interpolation. This method supports vectorized function calls as the interpolation process can be expensive for high dimensional data.

For the case when a single point is provided, the argument x should be a (D,) shaped numpy array or list, where D is the dimension of points in the triangulation.

For the vectorized case, the argument x should be a (n,D)-shaped numpy array.

property triangulation

The triangulation over the domain of this function

property values

The set of values used to defined this function

class pyomo.core.kernel.piecewise_library.transforms_nd.**TransformedPiecewiseLinearFunctionND**(*f*, *input=None*, *output=None*, *bound='eq'*)

Bases: *pyomo.core.kernel.block.block*

Base class for transformed multi-variate piecewise linear functions

A transformed multi-variate piecewise linear functions is a block of variables and constraints that enforce a piecewise linear relationship between an vector input variables and a single output variable.

Parameters

- **f** (*PiecewiseLinearFunctionND*) – The multi-variate piecewise linear function to transform.
- **input** – The variable constrained to be the input of the piecewise linear function.
- **output** – The variable constrained to be the output of the piecewise linear function.
- **bound** (*str*) – The type of bound to impose on the output expression. Can be one of:
  - 'lb': y <= f(x)
  - 'eq': y = f(x)
  - 'ub': y >= f(x)

__call__(*x*)

Evaluates the piecewise linear function using interpolation. This method supports vectorized function calls as the interpolation process can be expensive for high dimensional data.

For the case when a single point is provided, the argument x should be a (D,) shaped numpy array or list, where D is the dimension of points in the triangulation.

For the vectorized case, the argument x should be a (n,D)-shaped numpy array.

property bound

The bound type assigned to the piecewise relationship ('lb','ub','eq').

property input

The tuple of expressions that store the inputs to the piecewise function. The returned objects can be updated by assigning to their `expr` attribute.

property output

The expression that stores the output of the piecewise function. The returned object can be updated by assigning to its `expr` attribute.

property triangulation

The triangulation over the domain of this function

property values

The set of values used to defined this function

class pyomo.core.kernel.piecewise_library.transforms_nd.**piecewise_nd_cc**(**args*, ***kwds*)

Bases: *pyomo.core.kernel.piecewise_library.transforms_nd.TransformedPiecewiseLinearFunctionND*

Discrete CC multi-variate piecewise representation

Expresses a multi-variate piecewise linear function using the CC formulation.

Utilities for Piecewise Functions

exception pyomo.core.kernel.piecewise_library.util.**PiecewiseValidationError**

Bases: `Exception`

An exception raised when validation of piecewise linear functions fail.

pyomo.core.kernel.piecewise_library.util.**characterize_function**(*breakpoints*, *values*)

Characterizes a piecewise linear function described by a list of breakpoints and function values.

Parameters

- **breakpoints** (*list*) – The list of breakpoints of the piecewise linear function. It is assumed that the list of breakpoints is in non-decreasing order.
- **values** (*list*) – The values of the piecewise linear function corresponding to the breakpoints.

Returns a function characterization code and the list of slopes.
Return type (int, list)

Note: The function characterization codes are
- 1: affine
- 2: convex
- 3: concave
- 4: step
- 5: other

If the function has step points, some of the slopes may be `None`.

---

pyomo.core.kernel.piecewise_library.util.**generate_delaunay**(*variables*, *num=10*, ***kwds*)
Generate a Delaunay triangulation of the D-dimensional bounded variable domain given a list of D variables.

Requires numpy and scipy.
Parameters
- **variables** – A list of variables, each having a finite upper and lower bound.
- **num** (*int*) – The number of grid points to generate for each variable (default=10).
- ****kwds** – All additional keywords are passed to the scipy.spatial.Delaunay constructor.

Returns A scipy.spatial.Delaunay object.

pyomo.core.kernel.piecewise_library.util.**generate_gray_code**(*nbits*)
Generates a Gray code of nbits as list of lists

pyomo.core.kernel.piecewise_library.util.**is_constant**(*vals*)
Checks if a list of points is constant

pyomo.core.kernel.piecewise_library.util.**is_nondecreasing**(*vals*)
Checks if a list of points is nondecreasing

pyomo.core.kernel.piecewise_library.util.**is_nonincreasing**(*vals*)
Checks if a list of points is nonincreasing

pyomo.core.kernel.piecewise_library.util.**is_positive_power_of_two**(*x*)
Checks if a number is a nonzero and positive power of 2

pyomo.core.kernel.piecewise_library.util.**log2floor**(*n*)
Computes the exact value of floor(log2(n)) without using floating point calculations. Input argument must be a positive integer.

Conic Constraints

A collection of classes that provide an easy and performant way to declare conic constraints. The Mosek solver interface includes special handling of these objects that recognizes them as convex constraints. Other solver interfaces will treat these objects as general nonlinear or quadratic expressions, and may or may not have the ability to identify their convexity.

Summary

pyomo.core.kernel.conic.quadratic(r, x)	A quadratic conic constraint of the form:
pyomo.core.kernel.conic.rotated_quadratic(r1, ...)	A rotated quadratic conic constraint of the form:
pyomo.core.kernel.conic.primal_exponential(r, ...)	A primal exponential conic constraint of the form:
pyomo.core.kernel.conic.primal_power(r1, r2, ...)	A primal power conic constraint of the form:
pyomo.core.kernel.conic.dual_exponential(r, ...)	A dual exponential conic constraint of the form:
pyomo.core.kernel.conic.dual_power(r1, r2, ...)	A dual power conic constraint of the form:

Member Documentation

class pyomo.core.kernel.conic.**quadratic**(*r*, *x*)

Bases: pyomo.core.kernel.conic._ConicBase

A quadratic conic constraint of the form:
x[0]^2 + ... + x[n-1]^2 <= r^2,
which is recognized as convex for r >= 0.

Parameters

- **r** (variable) – A variable.
- **x** (list[variable]) – An iterable of variables.

classmethod as_domain(*r*, *x*)

Builds a conic domain. Input arguments take the same form as those of the conic constraint, but in place of each variable, one can optionally supply a constant, linear expression, or None.

Returns A block object with the core conic constraint (block.q) expressed using auxiliary variables (block.r, block.x) linked to the input arguments through auxiliary constraints (block.c).

Return type *block*

check_convexity_conditions(*relax=False*)

Returns True if all convexity conditions for the conic constraint are satisfied. If relax is True, then variable domains are ignored and it is assumed that all variables are continuous.

class pyomo.core.kernel.conic.**rotated_quadratic**(*r1*, *r2*, *x*)

Bases: pyomo.core.kernel.conic._ConicBase

A rotated quadratic conic constraint of the form:
x[0]^2 + ... + x[n-1]^2 <= 2*r1*r2,
which is recognized as convex for r1,r2 >= 0.

Parameters

- **r1** (variable) – A variable.
- **r2** (variable) – A variable.
- **x** (list[variable]) – An iterable of variables.

classmethod as_domain(*r1*, *r2*, *x*)

Builds a conic domain. Input arguments take the same form as those of the conic constraint, but in place of each variable, one can optionally supply a constant, linear expression, or None.

Returns A block object with the core conic constraint (block.q) expressed using auxiliary variables (block.r1, block.r2, block.x) linked to the input arguments through auxiliary constraints (block.c).

Return type *block*

check_convexity_conditions(*relax=False*)

Returns True if all convexity conditions for the conic constraint are satisfied. If relax is True, then variable domains are ignored and it is assumed that all variables are continuous.

class pyomo.core.kernel.conic.**primal_exponential**(*r*, *x1*, *x2*)

Bases: pyomo.core.kernel.conic._ConicBase

A primal exponential conic constraint of the form:
x1*exp(x2/x1) <= r,
which is recognized as convex for x1,r >= 0.

Parameters

- **r** (variable) – A variable.
- **x1** (variable) – A variable.
- **x2** (variable) – A variable.

classmethod as_domain(*r*, *x1*, *x2*)

Builds a conic domain. Input arguments take the same form as those of the conic constraint, but in place of each variable, one can optionally supply a constant, linear expression, or None.

Returns A block object with the core conic constraint (block.q) expressed using auxiliary variables (block.r, block.x1, block.x2) linked to the input arguments through auxiliary constraints (block.c).

Return type *block*

check_convexity_conditions(*relax=False*)

Returns True if all convexity conditions for the conic constraint are satisfied. If relax is True, then variable domains are ignored and it is assumed that all variables are continuous.

class pyomo.core.kernel.conic.**primal_power**(*r1*, *r2*, *x*, *alpha*)

Bases: pyomo.core.kernel.conic._ConicBase

A primal power conic constraint of the form: sqrt(x[0]^2 + … + x[n-1]^2) <= (r1^alpha)*(r2^(1-alpha))
which is recognized as convex for r1,r2 >= 0 and 0 < alpha < 1.

Parameters

- **r1** (variable) – A variable.
- **r2** (variable) – A variable.
- **x** (list[variable]) – An iterable of variables.
- **alpha** (float, parameter, etc.) – A constant term.

classmethod as_domain(*r1*, *r2*, *x*, *alpha*)

Builds a conic domain. Input arguments take the same form as those of the conic constraint, but in place of each variable, one can optionally supply a constant, linear expression, or None.

Returns A block object with the core conic constraint (block.q) expressed using auxiliary variables (block.r1, block.r2, block.x) linked to the input arguments through auxiliary constraints (block.c).

Return type *block*

check_convexity_conditions(*relax=False*)

Returns True if all convexity conditions for the conic constraint are satisfied. If relax is True, then variable domains are ignored and it is assumed that all variables are continuous.

class pyomo.core.kernel.conic.**dual_exponential**(*r*, *x1*, *x2*)
Bases: pyomo.core.kernel.conic._ConicBase

A dual exponential conic constraint of the form:
-x2*exp((x1/x2)-1) <= r
which is recognized as convex for x2 <= 0 and r >= 0.

Parameters

- **r** (variable) – A variable.
- **x1** (variable) – A variable.
- **x2** (variable) – A variable.

classmethod **as_domain**(*r*, *x1*, *x2*)
Builds a conic domain. Input arguments take the same form as those of the conic constraint, but in place of each variable, one can optionally supply a constant, linear expression, or None.

Returns A block object with the core conic constraint (block.q) expressed using auxiliary variables (block.r, block.x1, block.x2) linked to the input arguments through auxiliary constraints (block.c).

Return type *block*

check_convexity_conditions(*relax=False*)
Returns True if all convexity conditions for the conic constraint are satisfied. If relax is True, then variable domains are ignored and it is assumed that all variables are continuous.

class pyomo.core.kernel.conic.**dual_power**(*r1*, *r2*, *x*, *alpha*)
Bases: pyomo.core.kernel.conic._ConicBase

A dual power conic constraint of the form:
sqrt(x[0]^2 + ... + x[n-1]^2) <= ((r1/alpha)^alpha) * ((r2/(1-alpha))^(1-alpha))
which is recognized as convex for r1,r2 >= 0 and 0 < alpha < 1.

Parameters

- **r1** (variable) – A variable.
- **r2** (variable) – A variable.
- **x** (list[variable]) – An iterable of variables.
- **alpha** (float, parameter, etc.) – A constant term.

classmethod **as_domain**(*r1*, *r2*, *x*, *alpha*)
Builds a conic domain. Input arguments take the same form as those of the conic constraint, but in place of each variable, one can optionally supply a constant, linear expression, or None.

Returns A block object with the core conic constraint (block.q) expressed using auxiliary variables (block.r1, block.r2, block.x) linked to the input arguments through auxiliary constraints (block.c).

Return type *block*

check_convexity_conditions(*relax=False*)
Returns True if all convexity conditions for the conic constraint are satisfied. If relax is True, then variable domains are ignored and it is assumed that all variables are continuous.

Base API:

Base Object Storage Interface

class pyomo.core.kernel.base.**ICategorizedObject**
Bases: object

Interface for objects that maintain a weak reference to a parent storage object and have a category type.

This class is abstract. It assumes any derived class declares the attributes below with or without slots:

_ctype
Stores the object's category type, which should be some class derived from ICategorizedObject. This attribute may be declared at the class level.

_parent
Stores a weak reference to the object's parent container or None.

_storage_key
Stores key this object can be accessed with through its parent container.

_active
Stores the active status of this object.
Type bool

activate()
Activate this object.

property active
The active status of this object.

clone()
Returns a copy of this object with the parent pointer set to None.

A clone is almost equivalent to deepcopy except that any categorized objects encountered that are not descendents of this object will reference the same object on the clone.

property ctype
The object's category type.

deactivate()
Deactivate this object.

getname(*fully_qualified=False*, *name_buffer={}*, *convert=<class 'str'>*, *relative_to=None*)
Dynamically generates a name for this object.
Parameters
- **fully_qualified** (*bool*) – Generate a full name by iterating through all ancestor containers. Default is False.
- **convert** (*function*) – A function that converts a storage key into a string representation. Default is the built-in function str.
- **relative_to** (*object*) – When generating a fully qualified name, generate the name relative to this block.

Returns If a parent exists, this method returns a string representing the name of the object in the context of its parent; otherwise (if no parent exists), this method returns None.

property local_name
The object's local name within the context of its parent. Alias for *obj.getname(fully_qualified=False)*.

property name
The object's fully qualified name. Alias for *obj.getname(fully_qualified=True)*.

property parent
The object's parent (possibly None).

property storage_key
The object's storage key within its parent

class pyomo.core.kernel.base.**ICategorizedObjectContainer**
Bases: *pyomo.core.kernel.base.ICategorizedObject*

Interface for categorized containers of categorized objects.

activate(*shallow=True*)
Activate this container.

child(**args*, ***kwds*)
Returns a child of this container given a storage key.

children(**args*, ***kwds*)
A generator over the children of this container.

components(**args*, ***kwds*)
A generator over the set of components stored under this container.

deactivate(*shallow=True*)
Deactivate this container.

Homogeneous Object Containers

class pyomo.core.kernel.homogeneous_container.**IHomogeneousContainer**
Bases: *pyomo.core.kernel.base.ICategorizedObjectContainer*

A partial implementation of the ICategorizedObjectContainer interface for implementations that store a single category of objects and that uses the same category as the objects it stores.

Complete implementations need to set the _ctype attribute and declare the remaining required abstract properties of the ICategorizedObjectContainer base class.

Note that this implementation allows nested storage of other `ICategorizedObjectContainer` implementations that are defined with the same ctype.

components(*active=True*)
Generates an efficient traversal of all components stored under this container. Components are categorized objects that are either (1) not containers, or (2) are heterogeneous containers.

Parameters **active** (`True`/`None`) – Controls whether or not to filter the iteration to include only the active part of the storage tree. The default is `True`. Setting this keyword to `None` causes the active status of objects to be ignored.

Returns iterator of components in the storage tree

Heterogeneous Object Containers

class pyomo.core.kernel.heterogeneous_container.**IHeterogeneousContainer**

Bases: *pyomo.core.kernel.base.ICategorizedObjectContainer*

A partial implementation of the ICategorizedObjectContainer interface for implementations that store multiple categories of objects.

Complete implementations need to set the _ctype attribute and declare the remaining required abstract properties of the ICategorizedObjectContainer base class.

child_ctypes(**args*, ***kwds*)

Returns the set of child object category types stored in this container.

collect_ctypes(*active=True*, *descend_into=True*)

Returns the set of object category types that can be found under this container.

Parameters

- **active** (True/None) – Controls whether or not to filter the iteration to include only the active part of the storage tree. The default is True. Setting this keyword to None causes the active status of objects to be ignored.
- **descend_into** (*bool, function*) – Indicates whether or not to descend into a heterogeneous container. Default is True, which is equivalent to *lambda x: True*, meaning all heterogeneous containers will be descended into.

Returns A set of object category types

components(*ctype=<class 'pyomo.core.kernel.base._no_ctype'>*, *active=True*, *descend_into=True*)

Generates an efficient traversal of all components stored under this container. Components are categorized objects that are either (1) not containers, or (2) are heterogeneous containers.

Parameters

- **ctype** – Indicates the category of components to include. The default value indicates that all categories should be included.
- **active** (True/None) – Controls whether or not to filter the iteration to include only the active part of the storage tree. The default is True. Setting this keyword to None causes the active status of objects to be ignored.
- **descend_into** (*bool, function*) – Indicates whether or not to descend into a heterogeneous container. Default is True, which is equivalent to *lambda x: True*, meaning all heterogeneous containers will be descended into.

Returns iterator of components in the storage tree

pyomo.core.kernel.heterogeneous_container.**heterogeneous_containers**(*node*, *ctype=<class 'pyomo.core.kernel.base._no_ctype'>*, *active=True*, *descend_into=True*)

A generator that yields all heterogeneous containers included in an object storage tree, including the root object. Heterogeneous containers are categorized objects with a category type different from their children.

Parameters

- **node** – The root object.
- **ctype** – Indicates the category of objects to include. The default value indicates that all categories should be included.
- **active** (True/None) – Controls whether or not to filter the iteration to include only the active part of the storage tree. The default is True. Setting this keyword to None causes the active status of objects to be ignored.

- **descend_into** (*bool, function*) – Indicates whether or not to descend into a heterogeneous container. Default is True, which is equivalent to *lambda x: True*, meaning all heterogeneous containers will be descended into.

Returns iterator of heterogeneous containers in the storage tree, include the root object.

Containers:

Tuple-like Object Storage

class pyomo.core.kernel.tuple_container.**TupleContainer**(**args*)

Bases: *pyomo.core.kernel.homogeneous_container.IHomogeneousContainer*, collections.abc.Sequence

A partial implementation of the IHomogeneousContainer interface that provides tuple-like storage functionality.

Complete implementations need to set the _ctype property at the class level and initialize the remaining ICategorizedObject attributes during object creation. If using __slots__, a slot named "_data" must be included.

Note that this implementation allows nested storage of other ICategorizedObjectContainer implementations that are defined with the same ctype.

__eq__(*other*)
Return self==value.

__init__(**args*)

__ne__(*other*)
Return self!=value.

__str__()
Convert this object to a string by first attempting to generate its fully qualified name. If the object does not have a name (because it does not have a parent, then a string containing the class name is returned.

classmethod __subclasshook__(*C*)
Abstract classes can override this to customize issubclass().

This is invoked early on by abc.ABCMeta.__subclasscheck__(). It should return True, False or NotImplemented. If it returns NotImplemented, the normal algorithm is used. Otherwise, it overrides the normal algorithm (and the outcome is cached).

activate(*shallow=True*)
Activate this container.

property active
The active status of this object.

child(*key*)
Get the child object associated with a given storage key for this container.
Raises KeyError – if the argument is not a storage key for any children of this container

children()
A generator over the children of this container.

clone()
Returns a copy of this object with the parent pointer set to None.

A clone is almost equivalent to deepcopy except that any categorized objects encountered that are not descendents of this object will reference the same object on the clone.

components(*active=True*)
Generates an efficient traversal of all components stored under this container. Components are categorized objects that are either (1) not containers, or (2) are heterogeneous containers.

Parameters **active** (True/None) – Controls whether or not to filter the iteration to include only the active part of the storage tree. The default is True. Setting this keyword to None causes the active status of objects to be ignored.

Returns iterator of components in the storage tree

count(*value*) → integer – return number of occurrences of value

property ctype
The object's category type.

deactivate(*shallow=True*)
Deactivate this container.

getname(*fully_qualified=False*, *name_buffer={}*, *convert=<class 'str'>*, *relative_to=None*)
Dynamically generates a name for this object.

Parameters

- **fully_qualified** (*bool*) – Generate a full name by iterating through all ancestor containers. Default is False.
- **convert** (*function*) – A function that converts a storage key into a string representation. Default is the built-in function str.
- **relative_to** (*object*) – When generating a fully qualified name, generate the name relative to this block.

Returns If a parent exists, this method returns a string representing the name of the object in the context of its parent; otherwise (if no parent exists), this method returns None.

index(*value*[, *start*[, *stop*]]) → integer – return first index of value.
Raises ValueError if the value is not present.

property local_name
The object's local name within the context of its parent. Alias for *obj.getname(fully_qualified=False)*.

property name
The object's fully qualified name. Alias for *obj.getname(fully_qualified=True)*.

property parent
The object's parent (possibly None).

property storage_key
The object's storage key within its parent

List-like Object Storage

class pyomo.core.kernel.list_container.ListContainer(**args*)
Bases: *pyomo.core.kernel.tuple_container.TupleContainer*, collections.abc.MutableSequence

A partial implementation of the IHomogeneousContainer interface that provides list-like storage functionality.

Complete implementations need to set the _ctype property at the class level and initialize the remaining ICategorizedObject attributes during object creation. If using __slots__, a slot named "_data" must be included.

Note that this implementation allows nested storage of other ICategorizedObjectContainer implementations that are defined with the same ctype.

__eq__(*other*)
Return self==value.

__init__(**args*)

__ne__(*other*)
Return self!=value.

__str__()
Convert this object to a string by first attempting to generate its fully qualified name. If the object does not have a name (because it does not have a parent, then a string containing the class name is returned.

classmethod __subclasshook__(*C*)
Abstract classes can override this to customize issubclass().

This is invoked early on by abc.ABCMeta.__subclasscheck__(). It should return True, False or NotImplemented. If it returns NotImplemented, the normal algorithm is used. Otherwise, it overrides the normal algorithm (and the outcome is cached).

activate(*shallow=True*)
Activate this container.

property active
The active status of this object.

append(*value*)
S.append(value) – append value to the end of the sequence

child(*key*)
Get the child object associated with a given storage key for this container.
Raises KeyError – if the argument is not a storage key for any children of this container

children()
A generator over the children of this container.

clear() → None – remove all items from S

clone()
Returns a copy of this object with the parent pointer set to None.

A clone is almost equivalent to deepcopy except that any categorized objects encountered that are not descendents of this object will reference the same object on the clone.

components(*active=True*)
Generates an efficient traversal of all components stored under this container. Components are categorized objects that are either (1) not containers, or (2) are heterogeneous containers.
Parameters active (True/None) – Controls whether or not to filter the iteration to include only the active part of the storage tree. The default is True. Setting this keyword to None causes the active status of objects to be ignored.
Returns iterator of components in the storage tree

count(*value*) → integer – return number of occurrences of value

property ctype
The object's category type.

deactivate(*shallow=True*)
Deactivate this container.

extend(*values*)
S.extend(iterable) – extend sequence by appending elements from the iterable

getname(*fully_qualified=False*, *name_buffer={}*, *convert=<class 'str'>*, *relative_to=None*)
Dynamically generates a name for this object.

Parameters

- **fully_qualified** (*bool*) – Generate a full name by iterating through all ancestor containers. Default is `False`.
- **convert** (*function*) – A function that converts a storage key into a string representation. Default is the built-in function str.
- **relative_to** (*object*) – When generating a fully qualified name, generate the name relative to this block.

Returns If a parent exists, this method returns a string representing the name of the object in the context of its parent; otherwise (if no parent exists), this method returns `None`.

index(*value*[, *start*[, *stop*]]) → integer – return first index of value.
Raises ValueError if the value is not present.

insert(*i*, *item*)
S.insert(index, object) – insert object before index

property local_name
The object's local name within the context of its parent. Alias for *obj.getname(fully_qualified=False)*.

property name
The object's fully qualified name. Alias for *obj.getname(fully_qualified=True)*.

property parent
The object's parent (possibly None).

pop([*index*]) → item – remove and return item at index (default last).
Raise IndexError if list is empty or index is out of range.

remove(*value*)
S.remove(value) – remove first occurrence of value. Raise ValueError if the value is not present.

reverse()
S.reverse() – reverse *IN PLACE*

property storage_key
The object's storage key within its parent

Dict-like Object Storage

class pyomo.core.kernel.dict_container.**DictContainer**(**args*, ***kwds*)
Bases: *pyomo.core.kernel.homogeneous_container.IHomogeneousContainer*, collections.abc.MutableMapping

A partial implementation of the IHomogeneousContainer interface that provides dict-like storage functionality.

Complete implementations need to set the _ctype property at the class level and initialize the remaining ICategorizedObject attributes during object creation. If using __slots__, a slot named "_data" must be included.

Note that this implementation allows nested storage of other ICategorizedObjectContainer implementations that are defined with the same ctype.

__eq__(*other*)
Return self==value.

__init__(**args*, ***kwds*)

__ne__(*other*)
Return self!=value.

__str__()
Convert this object to a string by first attempting to generate its fully qualified name. If the object does not have a name (because it does not have a parent, then a string containing the class name is returned.

classmethod __subclasshook__(*C*)
Abstract classes can override this to customize issubclass().

This is invoked early on by abc.ABCMeta.__subclasscheck__(). It should return True, False or NotImplemented. If it returns NotImplemented, the normal algorithm is used. Otherwise, it overrides the normal algorithm (and the outcome is cached).

activate(*shallow=True*)
Activate this container.

property active
The active status of this object.

child(*key*)
Get the child object associated with a given storage key for this container.
Raises KeyError – if the argument is not a storage key for any children of this container

children()
A generator over the children of this container.

clear() → None. Remove all items from D.

clone()
Returns a copy of this object with the parent pointer set to None.

A clone is almost equivalent to deepcopy except that any categorized objects encountered that are not descendents of this object will reference the same object on the clone.

components(*active=True*)
Generates an efficient traversal of all components stored under this container. Components are categorized objects that are either (1) not containers, or (2) are heterogeneous containers.
Parameters active (True/None) – Controls whether or not to filter the iteration to include only the active part of the storage tree. The default is True. Setting this keyword to None causes the active status of objects to be ignored.

Returns iterator of components in the storage tree

property ctype
The object's category type.

deactivate(*shallow=True*)
Deactivate this container.

get(*k*[, *d*]) → D[k] if k in D, else d. d defaults to None.

getname(*fully_qualified=False*, *name_buffer={}*, *convert=<class 'str'>*, *relative_to=None*)
Dynamically generates a name for this object.
Parameters

- **fully_qualified** (*bool*) – Generate a full name by iterating through all anscestor containers. Default is False.
- **convert** (*function*) – A function that converts a storage key into a string representation. Default is the built-in function str.

- **relative_to** (*object*) – When generating a fully qualified name, generate the name relative to this block.

Returns If a parent exists, this method returns a string representing the name of the object in the context of its parent; otherwise (if no parent exists), this method returns None.

items() → a set-like object providing a view on D's items

keys() → a set-like object providing a view on D's keys

property local_name
The object's local name within the context of its parent. Alias for *obj.getname(fully_qualified=False)*.

property name
The object's fully qualified name. Alias for *obj.getname(fully_qualified=True)*.

property parent
The object's parent (possibly None).

pop(*k*[, *d*]) → v, remove specified key and return the corresponding value.
If key is not found, d is returned if given, otherwise KeyError is raised.

popitem() → (k, v), remove and return some (key, value) pair
as a 2-tuple; but raise KeyError if D is empty.

setdefault(*k*[, *d*]) → D.get(k,d), also set D[k]=d if k not in D

property storage_key
The object's storage key within its parent

update([*E*], ***F*) → None. Update D from mapping/iterable E and F.
If E present and has a .keys() method, does: for k in E: D[k] = E[k] If E present and lacks .keys() method, does: for (k, v) in E: D[k] = v In either case, this is followed by: for k, v in F.items(): D[k] = v

values() → an object providing a view on D's values

CHAPTER

FOURTEEN

CONTRIBUTING TO PYOMO

We welcome all contributions including bug fixes, feature enhancements, and documentation improvements. Pyomo manages source code contributions via GitHub pull requests (PRs).

14.1 Contribution Requirements

A PR should be 1 set of related changes. PRs for large-scale non-functional changes (i.e. PEP8, comments) should be separated from functional changes. This simplifies the review process and ensures that functional changes aren't obscured by large amounts of non-functional changes.

We do not squash and merge PRs so all commits in your branch will appear in the main history. In addition to well-documented PR descriptions, we encourage modular/targeted commits with descriptive commit messages.

14.1.1 Coding Standards

- Required: 4 space indentation (no tabs)
- Desired: PEP8
- No use of __author__
- Inside `pyomo.contrib`: Contact information for the contribution maintainer (such as a Github ID) should be included in the Sphinx documentation

Sphinx-compliant documentation is required for:

- Modules
- Public and Private Classes
- Public and Private Functions

We also encourage you to include examples, especially for new features and contributions to `pyomo.contrib`.

14.1.2 Testing

Pyomo uses unittest, nose, GitHub Actions, and Jenkins for testing and continuous integration. Submitted code should include tests to establish the validity of its results and/or effects. Unit tests are preferred but we also accept integration tests. We require at least 70% coverage of the lines modified in the PR and prefer coverage closer to 90%. We also require that all tests pass before a PR will be merged.

The Pyomo main branch provides a Github Actions workflow (configured in the `.github/` directory) that will test any changes pushed to a branch with a subset of the complete test harness that includes multiple virtual machines (ubuntu, mac-os, windows) and multiple Python versions. For existing forks, fetch and merge your fork (and branches) with Pyomo's main. For new forks, you will need to enable GitHub Actions in the 'Actions' tab on your fork. This will enable the tests to run automatically with each push to your fork.

At any point in the development cycle, a "work in progress" pull request may be opened by including '[WIP]' at the beginning of the PR title. This allows your code changes to be tested by the full suite of Pyomo's automatic testing infrastructure. Any pull requests marked '[WIP]' will not be reviewed or merged by the core development team. In addition, any '[WIP]' pull request left open for an extended period of time without active development may be marked 'stale' and closed.

14.2 Working on Forks and Branches

All Pyomo development should be done on forks of the Pyomo repository. In order to fork the Pyomo repository, visit https://github.com/Pyomo/pyomo, click the "Fork" button in the upper right corner, and follow the instructions.

This section discusses two recommended workflows for contributing pull-requests to Pyomo. The first workflow, labeled *Working with my fork and the GitHub Online UI*, does not require the use of 'remotes', and suggests updating your fork using the GitHub online UI. The second workflow, labeled *Working with remotes and the git command-line*, outlines a process that defines separate remotes for your fork and the main Pyomo repository.

More information on git can be found at https://git-scm.com/book/en/v2. Section 2.5 has information on working with remotes.

14.2.1 Working with my fork and the GitHub Online UI

After creating your fork (per the instructions above), you can then clone your fork of the repository with

```
git clone https://github.com/<username>/pyomo.git
```

For new development, we strongly recommend working on feature branches. When you have a new feature to implement, create the branch with the following.

```
cd pyomo/     # to make sure you are in the folder managed by git
git branch <branch_name>
git checkout <branch_name>
```

Development can now be performed. When you are ready, commit any changes you make to your local repository. This can be done multiple times with informative commit messages for different tasks in the feature development.

```
git add <filename>
git status  # to check that you have added the correct files
git commit -m 'informative commit message to describe changes'
```

In order to push the changes in your local branch to a branch on your fork, use

```
git push origin <branch_name>
```

When you have completed all the changes and are ready for a pull request, make sure all the changes have been pushed to the branch <branch_name> on your fork.

- visit https://github.com/<username>/pyomo.
- Just above the list of files and directories in the repository, you should see a button that says "Branch: main". Click on this button, and choose the correct branch.
- Click the "New pull request" button just to the right of the "Branch: <branch_name>" button.
- Fill out the pull request template and click the green "Create pull request" button.

At times during your development, you may want to merge changes from the Pyomo main development branch into the feature branch on your fork and in your local clone of the repository.

Using GitHub UI to merge Pyomo main into a branch on your fork

To update your fork, you will actually be merging a pull-request from the head Pyomo repository into your fork.

- Visit https://github.com/Pyomo/pyomo.
- Click on the "New pull request" button just above the list of files and directories.
- You will see the title "Compare changes" with some small text below it which says "Compare changes across branches, commits, tags, and more below. If you need to, you can also compare across forks." Click the last part of this: "compare across forks".
- You should now see four buttons just below this: "base repository: Pyomo/pyomo", "base: main", "head repository: Pyomo/pyomo", and "compare: main". Click the leftmost button and choose "<username>/Pyomo".
- Then click the button which is second to the left, and choose the branch which you want to merge Pyomo main into. The four buttons should now read: "base repository: <username>/pyomo", "base: <branch_name>", "head repository: Pyomo/pyomo", and "compare: main". This is setting you up to merge a pull-request from Pyomo's main branch into your fork's <branch_name> branch.
- You should also now see a pull request template. If you fill out the pull request template and click "Create pull request", this will create a pull request which will update your fork and branch with any changes that have been made to the main branch of Pyomo.
- You can then merge the pull request by clicking the green "Merge pull request" button from your fork on GitHub.

14.2.2 Working with remotes and the git command-line

After you have created your fork, you can clone the fork and setup git 'remotes' that allow you to merge changes from (and to) different remote repositories. Below, we have included a set of recommendations, but, of course, there are other valid GitHub workflows that you can adopt.

The following commands show how to clone your fork and setup two remotes, one for your fork, and one for the head Pyomo repository.

```
git clone https://github.com/<username>/pyomo.git
git remote rename origin my-fork
git remote add head-pyomo https://github.com/pyomo/pyomo.git
```

Note, you can see a list of your remotes with

```
git remote -v
```

The commands for creating a local branch and performing local commits are the same as those listed in the previous section above. Below are some common tasks based on this multi-remote setup.

If you have changes that have been committed to a local feature branch (<branch_name>), you can push these changes to the branch on your fork with,

```
git push my-fork <branch_name>
```

In order to update a local branch with changes from a branch of the Pyomo repository,

```
git checkout <branch_to_update>
git fetch head-pyomo
git merge head-pyomo/<branch_to_update_from> --ff-only
```

The "–ff-only" only allows a merge if the merge can be done by a fast-forward. If you do not require a fast-forward, you can drop this option. The most common concrete example of this would be

```
git checkout main
git fetch head-pyomo
git merge head-pyomo/main --ff-only
```

The above commands pull changes from the main branch of the head Pyomo repository into the main branch of your local clone. To push these changes to the main branch on your fork,

```
git push my-fork main
```

14.2.3 Setting up your development environment

After cloning your fork, you will want to install Pyomo from source.

Step 1 (recommended): Create a new conda environment.

```
conda create --name pyomodev
```

You may change the environment name from `pyomodev` as you see fit. Then activate the environment:

```
conda activate pyomodev
```

Step 2 (optional): Install PyUtilib

The hard dependency on PyUtilib was removed in Pyomo 6.0.0. There is still a soft dependency for any code related to `pyomo.dataportal.plugins.sheet`.

If your contribution requires PyUtilib, you will likely need the main branch of PyUtilib to contribute. Clone a copy of the repository in a new directory:

```
git clone https://github.com/PyUtilib/pyutilib
```

Then in the directory containing the clone of PyUtilib run:

```
python setup.py develop
```

Step 3: Install Pyomo

Finally, move to the directory containing the clone of your Pyomo fork and run:

```
python setup.py develop
```

These commands register the cloned code with the active python environment (`pyomodev`). This way, your changes to the source code for `pyomo` are automatically used by the active environment. You can create another conda environment to switch to alternate versions of pyomo (e.g., stable).

14.3 Review Process

After a PR is opened it will be reviewed by at least two members of the core development team. The core development team consists of anyone with write-access to the Pyomo repository. Pull requests opened by a core developer only require one review. The reviewers will decide if they think a PR should be merged or if more changes are necessary.

Reviewers look for:

- Outside of `pyomo.contrib`: Code rigor and standards, edge cases, side effects, etc.
- Inside of `pyomo.contrib`: No "glaringly obvious" problems with the code
- Documentation and tests

The core development team tries to review pull requests in a timely manner but we make no guarantees on review timeframes. In addition, PRs might not be reviewed in the order they are opened in.

14.4 Where to put contributed code

In order to contribute to Pyomo, you must first make a fork of the Pyomo git repository. Next, you should create a branch on your fork dedicated to the development of the new feature or bug fix you're interested in. Once you have this branch checked out, you can start coding. Bug fixes and minor enhancements to existing Pyomo functionality should be made in the appropriate files in the Pyomo code base. New examples, features, and packages built on Pyomo should be placed in `pyomo.contrib`. Follow the link below to find out if `pyomo.contrib` is right for your code.

14.5 `pyomo.contrib`

Pyomo uses the `pyomo.contrib` package to facilitate the inclusion of third-party contributions that enhance Pyomo's core functionality. The are two ways that `pyomo.contrib` can be used to integrate third-party packages:

- `pyomo.contrib` can provide wrappers for separate Python packages, thereby allowing these packages to be imported as subpackages of pyomo.
- `pyomo.contrib` can include contributed packages that are developed and maintained outside of the Pyomo developer team.

Including contrib packages in the Pyomo source tree provides a convenient mechanism for defining new functionality that can be optionally deployed by users. We expect this mechanism to include Pyomo extensions and experimental modeling capabilities. However, contrib packages are treated as optional packages, which are not maintained by the Pyomo developer team. Thus, it is the responsibility of the code contributor to keep these packages up-to-date.

Contrib package contributions will be considered as pull-requests, which will be reviewed by the Pyomo developer team. Specifically, this review will consider the suitability of the proposed capability, whether tests are available to check the execution of the code, and whether documentation is available to describe the capability. Contrib packages

will be tested along with Pyomo. If test failures arise, then these packages will be disabled and an issue will be created to resolve these test failures.

The following two examples illustrate the two ways that `pyomo.contrib` can be used to integrate third-party contributions.

14.5.1 Including External Packages

The pyomocontrib_simplemodel package is derived from Pyomo, and it defines the class SimpleModel that illustrates how Pyomo can be used in a simple, less object-oriented manner. Specifically, this class mimics the modeling style supported by PuLP.

While `pyomocontrib_simplemodel` can be installed and used separate from Pyomo, this package is included in `pyomo/contrib/simplemodel`. This allows this package to be referenced as if were defined as a subpackage of `pyomo.contrib`. For example:

```
from pyomo.contrib.simplemodel import *
from math import pi

m = SimpleModel()

r = m.var('r', bounds=(0,None))
h = m.var('h', bounds=(0,None))

m += 2*pi*r*(r + h)
m += pi*h*r**2 == 355

status = m.solve("ipopt")
```

This example illustrates that a package can be distributed separate from Pyomo while appearing to be included in the `pyomo.contrib` subpackage. Pyomo requires a separate directory be defined under `pyomo/contrib` for each such package, and the Pyomo developer team will approve the inclusion of third-party packages in this manner.

14.5.2 Contrib Packages within Pyomo

Third-party contributions can also be included directly within the `pyomo.contrib` package. The `pyomo/contrib/example` package provides an example of how this can be done, including a directory for plugins and package tests. For example, this package can be imported as a subpackage of `pyomo.contrib`:

```
from pyomo.environ import *
from pyomo.contrib.example import a

# Print the value of 'a' defined by this package
print(a)
```

Although `pyomo.contrib.example` is included in the Pyomo source tree, it is treated as an optional package. Pyomo will attempt to import this package, but if an import failure occurs, Pyomo will silently ignore it. Otherwise, this pyomo package will be treated like any other. Specifically:

- Plugin classes defined in this package are loaded when *pyomo.environ* is loaded.
- Tests in this package are run with other Pyomo tests.

CHAPTER

FIFTEEN

THIRD-PARTY CONTRIBUTIONS

Pyomo includes a variety of additional features and functionality provided by third parties through the `pyomo.contrib` package. This package includes both contributions included with the main Pyomo distribution and wrappers for third-party packages that must be installed separately.

These packages are maintained by the original contributors and are managed as *optional* Pyomo packages.

Contributed packages distributed with Pyomo:

15.1 Community Detection for Pyomo models

This package separates model components (variables, constraints, and objectives) into different communities distinguished by the degree of connectivity between community members.

15.1.1 Description of Package and `detect_communities` function

The community detection package allows users to obtain a community map of a Pyomo model - a Python dictionary-like object that maps sequential integer values to communities within the Pyomo model. The package takes in a model, organizes the model components into a graph of nodes and edges, then uses Louvain community detection (Blondel et al, 2008) to determine the communities that exist within the model.

In graph theory, a community is defined as a subset of nodes that have a greater degree of connectivity within themselves than they do with the rest of the nodes in the graph. In the context of Pyomo models, a community represents a subproblem within the overall optimization problem. Identifying these subproblems and then solving them independently can save computational work compared with trying to solve the entire model at once. Thus, it can be very useful to know the communities that exist in a model.

The manner in which the graph of nodes and edges is constructed from the model directly affects the community detection. Thus, this package provides the user with a lot of control over the construction of the graph. The function we use for this community detection is shown below:

pyomo.contrib.community_detection.detection.**detect_communities**(*model*, *type_of_community_map='constraint'*, *with_objective=True*, *weighted_graph=True*, *random_seed=None*, *use_only_active_components=True*)

Detects communities in a Pyomo optimization model

This function takes in a Pyomo optimization model and organizes the variables and constraints into a graph of nodes and edges. Then, by using Louvain community detection on the graph, a dictionary (community_map) is created, which maps (arbitrary) community keys to the detected communities within the model.

Parameters

- **model** (Block) – a Pyomo model or block to be used for community detection
- **type_of_community_map** (*str, optional*) – a string that specifies the type of community map to be returned, the default is 'constraint'. 'constraint' returns a dictionary (community_map) with communities based on constraint nodes, 'variable' returns a dictionary (community_map) with communities based on variable nodes, 'bipartite' returns a dictionary (community_map) with communities based on a bipartite graph (both constraint and variable nodes)
- **with_objective** (*bool, optional*) – a Boolean argument that specifies whether or not the objective function is included in the model graph (and thus in 'community_map'); the default is True
- **weighted_graph** (*bool, optional*) – a Boolean argument that specifies whether community_map is created based on a weighted model graph or an unweighted model graph; the default is True (type_of_community_map='bipartite' creates an unweighted model graph regardless of this parameter)
- **random_seed** (*int, optional*) – an integer that is used as the random seed for the (heuristic) Louvain community detection
- **use_only_active_components** (*bool, optional*) – a Boolean argument that specifies whether inactive constraints/objectives are included in the community map

Returns The CommunityMap object acts as a Python dictionary, mapping integer keys to tuples containing two lists (which contain the components in the given community) - a constraint list and variable list. Furthermore, the CommunityMap object stores relevant information about the given community map (dict), such as the model used to create it, its networkX representation, etc.

Return type CommunityMap object (dict-like object)

As stated above, the characteristics of the NetworkX graph of the Pyomo model are very important to the community detection. The main graph features the user can specify are the type of community map, whether the graph is weighted or unweighted, and whether the objective function(s) is included in the graph generation. Below, the significance and reasoning behind including each of these options are explained in greater depth.

Type of Community Map (*type_of_community_map*) In this package's main function (`detect_communities`), the user can select `'bipartite'`, `'constraint'`, or `'variable'` as an input for the 'type_of_community_map' argument, and these result in a community map based on a bipartite graph, a constraint node graph, or a variable node graph (respectively).

If the user sets `type_of_community_map='constraint'`, then each entry in the community map (which is a dictionary) contains a list of all the constraints in the community as well as all the variables contained in those constraints. For the model graph, a node is created for every active constraint in the model, an edge between two constraint nodes is created only if those two constraint equations share a variable, and the weight of each edge is equal to the number of variables the two constraint equations have in common.

If the user sets `type_of_community_map='variable'`, then each entry in the community map (which is a dictionary) contains a list of all the variables in the community as well as all the constraints that contain those variables. For the model graph, a node is created for every variable in the model, an edge between two variable nodes is created only if those two variables occur in the same constraint equation, and the weight of each edge is equal to the number of constraint equations in which the two variables occur together.

If the user sets `type_of_community_map='bipartite'`, then each entry in the community map (which is a dictionary) is simply all of the nodes in the community but split into a list of constraints and a list of variables. For the model graph, a node is created for every variable and every constraint in the model. An edge is created between a constraint node and a variable node only if the constraint equation contains the variable. (Edges are not drawn between nodes of the same type in a bipartite graph.) And as for the edge weights, the edges in the

bipartite graph are unweighted regardless of what the user specifies for the `weighted_graph` parameter. (This is because for our purposes, the number of times a variable appears in a constraint is not particularly useful.)

Weighted Graph/Unweighted Graph (*weighted_graph*) The Louvain community detection algorithm takes edge weights into account, so depending on whether the graph is weighted or unweighted, the communities that are found will vary. This can be valuable depending on how the user intends to use the community detection information. For example, if a user plans on feeding that information into an algorithm, the algorithm may be better suited to the communities detected in a weighted graph (or vice versa).

With/Without Objective in the Graph (*with_objective*) This argument determines whether the objective function(s) will be included when creating the graphical representation of the model and thus whether the objective function(s) will be included in the community map. Some models have an objective function that contains so many of the model variables that it obscures potential communities within a model. Thus, it can be useful to call `detect_communities(model, with_objective=False)` on such a model to see whether isolating the other components of the model provides any new insights.

15.1.2 External Packages

- NetworkX
- Python-Louvain

The community detection package relies on two external packages, the NetworkX package and the Louvain community detection package. Both of these packages can be installed at the following URLs (respectively):

https://pypi.org/project/networkx/

https://pypi.org/project/python-louvain/

The pip install and conda install commands are included below as well:

```
pip install networkx
pip install python-louvain
conda install -c anaconda networkx
conda install -c conda-forge python-louvain
```

15.1.3 Usage Examples

Let's start off by taking a look at how we can use `detect_communities` to create a CommunityMap object. We'll first use a model from Allman et al, 2019 :

```
Required Imports
>>> from pyomo.contrib.community_detection.detection import detect_communities, detect_
↪communities, CommunityMap, generate_model_graph
>>> from pyomo.contrib.mindtpy.tests.eight_process_problem import EightProcessFlowsheet
>>> from pyomo.core import ConcreteModel, Var, Constraint
>>> import networkx as nx

Let's define a model for our use
>>> def decode_model_1():
...     model = m = ConcreteModel()
...     m.x1 = Var(initialize=-3)
...     m.x2 = Var(initialize=-1)
...     m.x3 = Var(initialize=-3)
...     m.x4 = Var(initialize=-1)
```

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```
...     m.c1 = Constraint(expr=m.x1 + m.x2 <= 0)
...     m.c2 = Constraint(expr=m.x1 - 3 * m.x2 <= 0)
...     m.c3 = Constraint(expr=m.x2 + m.x3 + 4 * m.x4 ** 2 == 0)
...     m.c4 = Constraint(expr=m.x3 + m.x4 <= 0)
...     m.c5 = Constraint(expr=m.x3 ** 2 + m.x4 ** 2 - 10 == 0)
...     return model
>>> model = m = decode_model_1()
>>> seed = 5  # To be used as a random seed value for the heuristic Louvain community␣
↪detection

Let's create an instance of the CommunityMap class (which is what gets returned by the
function detect_communities):
>>> community_map_object = detect_communities(model, type_of_community_map='bipartite',␣
↪random_seed=seed)
```

This community map object has many attributes that contain the relevant information about the community map itself (such as the parameters used to create it, the networkX representation, and other useful information).

An important point to note is that the community_map attribute of the CommunityMap class is the actual dictionary that maps integers to the communities within the model. It is expected that the user will be most interested in the actual dictionary itself, so dict-like usage is permitted.

If a user wishes to modify the actual dictionary (the community_map attribute of the CommunityMap object), creating a deep copy is highly recommended (or else any destructive modifications could have unintended consequences): `new_community_map = copy.deepcopy(community_map_object.community_map)`

Let's take a closer look at the actual community map object generated by *detect_communities*:

```
>>> print(community_map_object)
{0: (['c1', 'c2'], ['x1', 'x2']), 1: (['c3', 'c4', 'c5'], ['x3', 'x4'])}
```

Printing a community map object is made to be user-friendly (by showing the community map with components replaced by their strings). However, if the default Pyomo representation of components is desired, then the community_map attribute or the repr() function can be used:

```
>>> print(community_map_object.community_map)  # or print(repr(community_map_object))
{0: ([<pyomo.core.base.constraint.ScalarConstraint object at 0x0000028DA74BB588>, <pyomo.
↪core.base.constraint.ScalarConstraint object at 0x0000028DA74BB5F8>], [<pyomo.core.
↪base.var.ScalarVar object at 0x0000028DA74BB3C8>, <pyomo.core.base.var.ScalarVar␣
↪object at 0x0000028DA74BB438>]), 1: ([<pyomo.core.base.constraint.ScalarConstraint␣
↪object at 0x0000028DA74BB668>, <pyomo.core.base.constraint.ScalarConstraint object at␣
↪0x0000028DA74BB6D8>, <pyomo.core.base.constraint.ScalarConstraint object at␣
↪0x0000028DA74BB748>], [<pyomo.core.base.var.ScalarVar object at 0x0000028DA74BB4A8>,
↪<pyomo.core.base.var.ScalarVar object at 0x0000028DA74BB518>])}
```

***generate_structured_model* method of CommunityMap objects** It may be useful to create a new model based on the communities found in the model - we can use the `generate_structured_model` method of the CommunityMap class to do this. Calling this method on a CommunityMap object returns a new model made up of blocks that correspond to each of the communities found in the original model. Let's take a look at the example below:

```
Use the CommunityMap object made from the first code example
>>> structured_model = community_map_object.generate_structured_model()
>>> structured_model.pprint()
2 Set Declarations
```

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```
    b_index : Size=1, Index=None, Ordered=Insertion
        Key  : Dimen : Domain : Size : Members
        None :     1 :    Any :    2 : {0, 1}
    equality_constraint_list_index : Size=1, Index=None, Ordered=Insertion
        Key  : Dimen : Domain : Size : Members
        None :     1 :    Any :    1 :    {1,}

1 Var Declarations
    x2 : Size=1, Index=None
        Key  : Lower : Value : Upper : Fixed : Stale : Domain
        None :  None :  None :  None : False :  True :  Reals

1 Constraint Declarations
    equality_constraint_list : Equality Constraints for the different forms of a␣
↪given variable
        Size=1, Index=equality_constraint_list_index, Active=True
        Key : Lower : Body         : Upper : Active
          1 :   0.0 : b[0].x2 - x2 :   0.0 :   True

1 Block Declarations
    b : Size=2, Index=b_index, Active=True
        b[0] : Active=True
            2 Var Declarations
                x1 : Size=1, Index=None
                    Key  : Lower : Value : Upper : Fixed : Stale : Domain
                    None :  None :  None :  None : False :  True :  Reals
                x2 : Size=1, Index=None
                    Key  : Lower : Value : Upper : Fixed : Stale : Domain
                    None :  None :  None :  None : False :  True :  Reals

            2 Constraint Declarations
                c1 : Size=1, Index=None, Active=True
                    Key  : Lower : Body              : Upper : Active
                    None :  -Inf : b[0].x1 + b[0].x2 :   0.0 :   True
                c2 : Size=1, Index=None, Active=True
                    Key  : Lower : Body                : Upper : Active
                    None :  -Inf : b[0].x1 - 3*b[0].x2 :   0.0 :   True

            4 Declarations: x1 x2 c1 c2
        b[1] : Active=True
            2 Var Declarations
                x3 : Size=1, Index=None
                    Key  : Lower : Value : Upper : Fixed : Stale : Domain
                    None :  None :  None :  None : False :  True :  Reals
                x4 : Size=1, Index=None
                    Key  : Lower : Value : Upper : Fixed : Stale : Domain
                    None :  None :  None :  None : False :  True :  Reals

            3 Constraint Declarations
                c3 : Size=1, Index=None, Active=True
                    Key  : Lower : Body                          : Upper : Active
                    None :   0.0 : x2 + b[1].x3 + 4*b[1].x4**2 :   0.0 :   True
```

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```
                c4 : Size=1, Index=None, Active=True
                    Key  : Lower : Body              : Upper : Active
                    None :  -Inf : b[1].x3 + b[1].x4 :   0.0 :   True
                c5 : Size=1, Index=None, Active=True
                    Key  : Lower : Body                        : Upper : Active
                    None :   0.0 : b[1].x3**2 + b[1].x4**2 - 10 :   0.0 :   True

            5 Declarations: x3 x4 c3 c4 c5

5 Declarations: b_index b x2 equality_constraint_list_index equality_constraint_list
```

We see that there is an equality constraint list (*equality_constraint_list*) that has been created. This is due to the fact that the `detect_communities` function can return a community map that has Pyomo components (variables, constraints, or objectives) in more than one community, and thus, an equality_constraint_list is created to ensure that the new model still corresponds to the original model. This is explained in more detail below.

Consider the case where community detection is done on a constraint node graph - this would result in communities that are made up of the corresponding constraints as well as all the variables that occur in the given constraints. Thus, it is possible for certain Pyomo components to be in multiple communities (and a similar argument exists for community detection done on a variable node graph). As a result, our structured model (the model returned by the `generate_structured_model` method) may need to have several "copies" of a certain component. For example, a variable *original_model.x1* that exists in the original model may have corresponding forms *structured_model.b[0].x1*, *structured_model.b[0].x1*, *structured_model.x1*. In order for these components to meaningfully correspond to their counterparts in the original model, they must be bounded by equality constraints. Thus, we use an *equality_constraint_list* to bind different forms of a component from the original model.

The last point to make about this method is that variables will be created outside of blocks if (1) an objective is not inside a block (for example if the community detection is done *with_objective=False*) or if (2) an objective/constraint contains a variable that is not in the same block as the given objective/constraint.

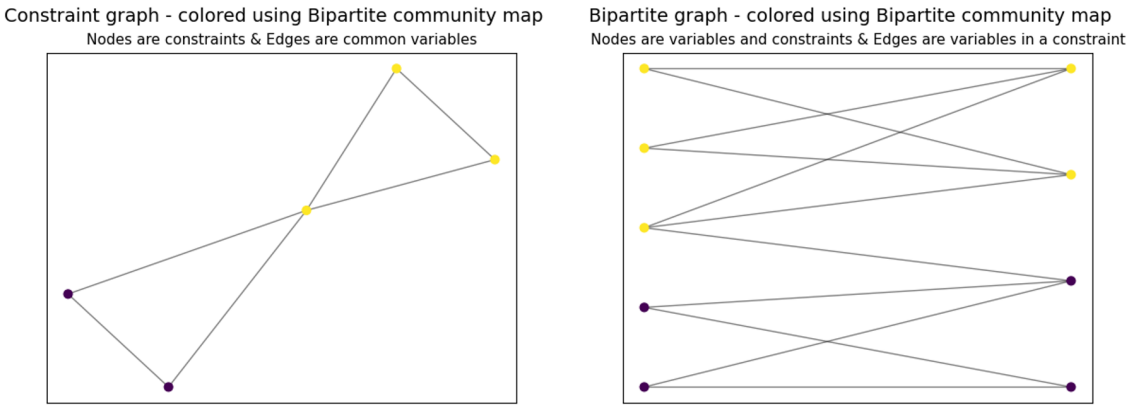
***visualize_model_graph* method of CommunityMap objects** If we want a visualization of the communities within the Pyomo model, we can use `visualize_model_graph` to do so. Let's take a look at how this can be done in the following example:

```
Create a CommunityMap object (so we can demonstrate the visualize_model_graph␣
↪method)
>>> community_map_object = cmo = detect_communities(model, type_of_community_map=
↪'bipartite', random_seed=seed)

Generate a matplotlib figure (left_figure) - a constraint graph of the community map
>>> left_figure, _ = cmo.visualize_model_graph(type_of_graph='constraint')

Now, we will generate the figure on the right (a bipartite graph of the community␣
↪map)
>>> right_figure, _ = cmo.visualize_model_graph(type_of_graph='bipartite')
```

An example of the two separate graphs created for these two function calls is shown below:



These graph drawings very clearly demonstrate the communities within this model. The constraint graph (which is colored using the bipartite community map) shows a very simple illustration - one node for each constraint, with only one edge connecting the two communities (which represents the variable *m.x2* common to *m.c2* and *m.c3* in separate communities) The bipartite graph is slightly more complicated and we can see again how there is only one edge between the two communities and more edges within each community. This is an ideal situation for breaking a model into separate communities since there is little connectivity between the communities. Also, note that we can choose different graph types (such as a variable node graph, constraint node graph, or bipartite graph) for a given community map.

Let's try a more complicated model (taken from Duran & Grossmann, 1986) - this example will demonstrate how the same graph can be illustrated using different community maps (in the previous example we illustrated different graphs with a single community map):

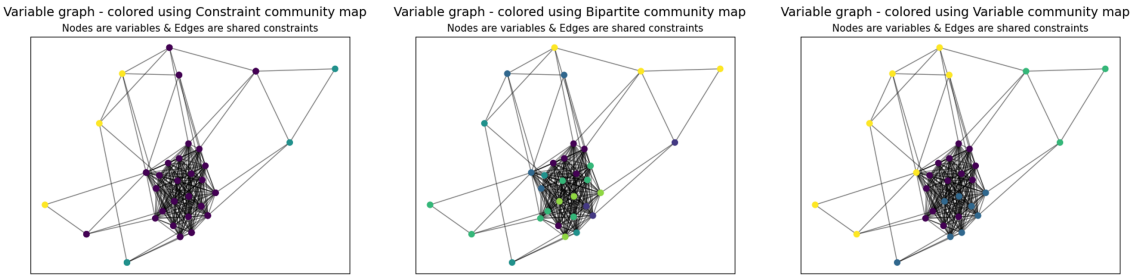
```
Define the model
>>> model = EightProcessFlowsheet()

Now, we follow steps similar to the example above (see above for explanations)
>>> community_map_object = cmo = detect_communities(model, type_of_community_map=
↪'constraint', random_seed=seed)
>>> left_fig, pos = cmo.visualize_model_graph(type_of_graph='variable')

As we did before, we will use the returned 'pos' to create a consistent graph layout
>>> community_map_object = cmo = detect_communities(model, type_of_community_map=
↪'bipartite')
>>> middle_fig, _ = cmo.visualize_model_graph(type_of_graph='variable', pos=pos)

>>> community_map_object = cmo = detect_communities(model, type_of_community_map=
↪'variable')
>>> right_fig, _ = cmo.visualize_model_graph(type_of_graph='variable', pos=pos)
```

We can see an example for the three separate graphs created by these three function calls below:



The three graphs above are all variable graphs - which means the nodes represent variables in the model, and the edges represent constraint equations. The coloring differs because the three graphs rely on community maps that were created based on a constraint node graph, a bipartite graph, and a variable node graph (from left to right). For example, the community map that was generated from a constraint node graph (`type_of_community_map='constraint'`) resulted in three communities (as seen by the purple, yellow, and blue nodes).

***generate_model_graph* function** Now, we will take a look at `generate_model_graph` - this function can be used to create a NetworkX graph for a Pyomo model (and is used in *detect_communities*). Here, we will create a NetworkX graph from the model in our first example and then create the edge and adjacency list for the graph.

`generate_model_graph` returns three things:

- a NetworkX graph of the given model
- a dictionary that maps the numbers used to represent the model components to the actual components (because Pyomo components cannot be directly added to a NetworkX graph)
- a dictionary that maps constraints to the variables in them.

For this example, we will only need the NetworkX graph of the model and the number-to-component mapping.

```
Define the model
>>> model = decode_model_1()

See above for the description of the items returned by 'generate_model_graph'
>>> model_graph, number_component_map, constr_var_map = generate_model_graph(model,␣
↪type_of_graph='constraint')

The next two lines create and implement a mapping to change the node values from␣
↪numbers into
strings. The second line uses this mapping to create string_model_graph, which has
the relabeled nodes (strings instead of numbers).

>>> string_map = dict((number, str(comp)) for number, comp in number_component_map.
↪items())
>>> string_model_graph = nx.relabel_nodes(model_graph, string_map)

Now, we print the edge list and the adjacency list:
Edge List:
>>> for line in nx.generate_edgelist(string_model_graph): print(line)
c1 c2 {'weight': 2}
c1 c3 {'weight': 1}
c2 c3 {'weight': 1}
c3 c5 {'weight': 2}
c3 c4 {'weight': 2}
```

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```
c4 c5 {'weight': 2}

Adjacency List:
>>> print(list(nx.generate_adjlist(string_model_graph)))
['c1 c2 c3', 'c2 c3', 'c3 c5 c4', 'c4 c5', 'c5']
```

It's worth mentioning that in the code above, we do not have to create `string_map` to create an edge list or adjacency list, but for the sake of having an easily understandable output, it is quite helpful. (Without relabeling the nodes, the output below would not have the strings of the components but instead would have integer values.) This code will hopefully make it easier for a user to do the same.

15.1.4 Functions in this Package

Main module for community detection integration with Pyomo models.

This module separates model components (variables, constraints, and objectives) into different communities distinguished by the degree of connectivity between community members.

Original implementation developed by Rahul Joglekar in the Grossmann research group.

class pyomo.contrib.community_detection.detection.**CommunityMap**(*community_map*, *type_of_community_map*, *with_objective*, *weighted_graph*, *random_seed*, *use_only_active_components*, *model*, *graph*, *graph_node_mapping*, *constraint_variable_map*, *graph_partition*)

This class is used to create CommunityMap objects which are returned by the detect_communities function. Instances of this class allow dict-like usage and store relevant information about the given community map, such as the model used to create them, their networkX representation, etc.

The CommunityMap object acts as a Python dictionary, mapping integer keys to tuples containing two lists (which contain the components in the given community) - a constraint list and variable list.

Methods: generate_structured_model visualize_model_graph

generate_structured_model()

Using the community map and the original model used to create this community map, we will create structured_model, which will be based on the original model but will place variables, constraints, and objectives into or outside of various blocks (communities) based on the community map.

Returns **structured_model** – a Pyomo model that reflects the nature of the community map

Return type *Block*

visualize_model_graph(*type_of_graph='constraint'*, *filename=None*, *pos=None*)

This function draws a graph of the communities for a Pyomo model.

The type_of_graph parameter is used to create either a variable-node graph, constraint-node graph, or bipartite graph of the Pyomo model. Then, the nodes are colored based on the communities they are in - which is based on the community map (self.community_map). A filename can be provided to save the figure, otherwise the figure is illustrated with matplotlib.

Parameters

- **type_of_graph** (*str, optional*) – a string that specifies the types of nodes drawn on the model graph, the default is 'constraint'. 'constraint' draws a graph

with constraint nodes, 'variable' draws a graph with variable nodes, 'bipartite' draws a bipartite graph (with both constraint and variable nodes)

- **filename** (*str, optional*) – a string that specifies a path for the model graph illustration to be saved
- **pos** (*dict, optional*) – a dictionary that maps node keys to their positions on the illustration

Returns

- **fig** (*matplotlib figure*) – the figure for the model graph drawing
- **pos** (*dict*) – a dictionary that maps node keys to their positions on the illustration - can be used to create consistent layouts for graphs of a given model

pyomo.contrib.community_detection.detection.**detect_communities**(*model*, *type_of_community_map='constraint'*, *with_objective=True*, *weighted_graph=True*, *random_seed=None*, *use_only_active_components=True*)

Detects communities in a Pyomo optimization model

This function takes in a Pyomo optimization model and organizes the variables and constraints into a graph of nodes and edges. Then, by using Louvain community detection on the graph, a dictionary (community_map) is created, which maps (arbitrary) community keys to the detected communities within the model.

Parameters

- **model** (Block) – a Pyomo model or block to be used for community detection
- **type_of_community_map** (*str, optional*) – a string that specifies the type of community map to be returned, the default is 'constraint'. 'constraint' returns a dictionary (community_map) with communities based on constraint nodes, 'variable' returns a dictionary (community_map) with communities based on variable nodes, 'bipartite' returns a dictionary (community_map) with communities based on a bipartite graph (both constraint and variable nodes)
- **with_objective** (*bool, optional*) – a Boolean argument that specifies whether or not the objective function is included in the model graph (and thus in 'community_map'); the default is True
- **weighted_graph** (*bool, optional*) – a Boolean argument that specifies whether community_map is created based on a weighted model graph or an unweighted model graph; the default is True (type_of_community_map='bipartite' creates an unweighted model graph regardless of this parameter)
- **random_seed** (*int, optional*) – an integer that is used as the random seed for the (heuristic) Louvain community detection
- **use_only_active_components** (*bool, optional*) – a Boolean argument that specifies whether inactive constraints/objectives are included in the community map

Returns The CommunityMap object acts as a Python dictionary, mapping integer keys to tuples containing two lists (which contain the components in the given community) - a constraint list and variable list. Furthermore, the CommunityMap object stores relevant information about the given community map (dict), such as the model used to create it, its networkX representation, etc.

Return type CommunityMap object (dict-like object)

Model Graph Generator Code

pyomo.contrib.community_detection.community_graph.**generate_model_graph**(*model*, *type_of_graph*, *with_objective=True*, *weighted_graph=True*, *use_only_active_components=True*)

Creates a networkX graph of nodes and edges based on a Pyomo optimization model

This function takes in a Pyomo optimization model, then creates a graphical representation of the model with specific features of the graph determined by the user (see Parameters below).

(This function is designed to be called by detect_communities, but can be used solely for the purpose of creating model graphs as well.)

Parameters

- **model** (Block) – a Pyomo model or block to be used for community detection
- **type_of_graph** (*str*) – a string that specifies the type of graph that is created from the model 'constraint' creates a graph based on constraint nodes, 'variable' creates a graph based on variable nodes, 'bipartite' creates a graph based on constraint and variable nodes (bipartite graph).
- **with_objective** (*bool, optional*) – a Boolean argument that specifies whether or not the objective function is included in the graph; the default is True
- **weighted_graph** (*bool, optional*) – a Boolean argument that specifies whether a weighted or unweighted graph is to be created from the Pyomo model; the default is True (type_of_graph='bipartite' creates an unweighted graph regardless of this parameter)
- **use_only_active_components** (*bool, optional*) – a Boolean argument that specifies whether inactive constraints/objectives are included in the networkX graph

Returns

- **bipartite_model_graph/projected_model_graph** (*nx.Graph*) – a NetworkX graph with nodes and edges based on the given Pyomo optimization model
- **number_component_map** (*dict*) – a dictionary that (deterministically) maps a number to a component in the model
- **constraint_variable_map** (*dict*) – a dictionary that maps a numbered constraint to a list of (numbered) variables that appear in the constraint

15.2 GDPopt logic-based solver

The GDPopt solver in Pyomo allows users to solve nonlinear Generalized Disjunctive Programming (GDP) models using logic-based decomposition approaches, as opposed to the conventional approach via reformulation to a Mixed Integer Nonlinear Programming (MINLP) model.

The main advantage of these techniques is their ability to solve subproblems in a reduced space, including nonlinear constraints only for `True` logical blocks. As a result, GDPopt is most effective for nonlinear GDP models.

Three algorithms are available in GDPopt:

1. Logic-based outer approximation (LOA) [Turkay & Grossmann, 1996]
2. Global logic-based outer approximation (GLOA) [Lee & Grossmann, 2001]
3. Logic-based branch-and-bound (LBB) [Lee & Grossmann, 2001]

Usage and implementation details for GDPopt can be found in the PSE 2018 paper (Chen et al., 2018), or via its preprint.

Credit for prototyping and development can be found in the `GDPopt` class documentation, below.

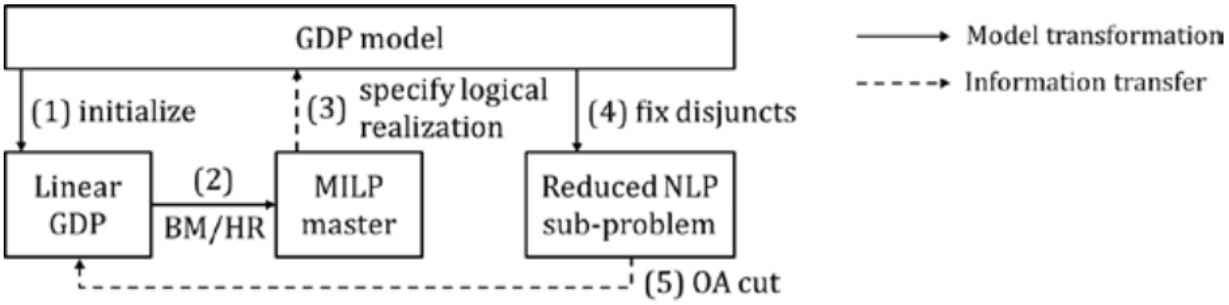
Usage of GDPopt to solve a Pyomo.GDP concrete model involves:

```
>>> SolverFactory('gdpopt').solve(model)
```

Note: By default, GDPopt uses the GDPopt-LOA strategy. Other strategies may be used by specifying the `strategy` argument during `solve()`. All GDPopt options are listed below.

15.2.1 Logic-based Outer Approximation

Chen et al., 2018 contains the following flowchart, taken from the preprint version:



An example which includes the modeling approach may be found below.

```
Required imports
>>> from pyomo.environ import *
>>> from pyomo.gdp import *

Create a simple model
>>> model = ConcreteModel(name='LOA example')

>>> model.x = Var(bounds=(-1.2, 2))
>>> model.y = Var(bounds=(-10,10))
>>> model.c = Constraint(expr= model.x + model.y == 1)

>>> model.fix_x = Disjunct()
>>> model.fix_x.c = Constraint(expr=model.x == 0)

>>> model.fix_y = Disjunct()
>>> model.fix_y.c = Constraint(expr=model.y == 0)

>>> model.d = Disjunction(expr=[model.fix_x, model.fix_y])
>>> model.objective = Objective(expr=model.x + 0.1*model.y, sense=minimize)

Solve the model using GDPopt
>>> results = SolverFactory('gdpopt').solve(
...     model, strategy='LOA', mip_solver='glpk')

Display the final solution
>>> model.display()
Model LOA example
```

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```
  Variables:
    x : Size=1, Index=None
        Key  : Lower : Value : Upper : Fixed : Stale : Domain
        None :  -1.2 :   0.0 :     2 : False : False :  Reals
    y : Size=1, Index=None
        Key  : Lower : Value : Upper : Fixed : Stale : Domain
        None :   -10 :   1.0 :    10 : False : False :  Reals

  Objectives:
    objective : Size=1, Index=None, Active=True
        Key  : Active : Value
        None :   True :   0.1

  Constraints:
    c : Size=1
        Key  : Lower : Body : Upper
        None :   1.0 :  1.0 :   1.0
```

Note: When troubleshooting, it can often be helpful to turn on verbose output using the `tee` flag.

```
>>> SolverFactory('gdpopt').solve(model, tee=True)
```

15.2.2 Logic-based Branch-and-Bound

The GDPopt-LBB solver branches through relaxed subproblems with inactive disjunctions. It explores the possibilities based on best lower bound, eventually activating all disjunctions and presenting the globally optimal solution.

To use the GDPopt-LBB solver, define your Pyomo GDP model as usual:

```
Required imports
>>> from pyomo.environ import *
>>> from pyomo.gdp import Disjunct, Disjunction

Create a simple model
>>> m = ConcreteModel()
>>> m.x1 = Var(bounds = (0,8))
>>> m.x2 = Var(bounds = (0,8))
>>> m.obj = Objective(expr=m.x1 + m.x2, sense=minimize)
>>> m.y1 = Disjunct()
>>> m.y2 = Disjunct()
>>> m.y1.c1 = Constraint(expr=m.x1 >= 2)
>>> m.y1.c2 = Constraint(expr=m.x2 >= 2)
>>> m.y2.c1 = Constraint(expr=m.x1 >= 3)
>>> m.y2.c2 = Constraint(expr=m.x2 >= 3)
>>> m.djn = Disjunction(expr=[m.y1, m.y2])

Invoke the GDPopt-LBB solver
>>> results = SolverFactory('gdpopt').solve(m, strategy='LBB')
```

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```
>>> print(results)
>>> print(results.solver.status)
ok
>>> print(results.solver.termination_condition)
optimal

>>> print([value(m.y1.indicator_var), value(m.y2.indicator_var)])
[True, False]
```

15.2.3 GDPopt implementation and optional arguments

Warning: GDPopt optional arguments should be considered beta code and are subject to change.

class pyomo.contrib.gdpopt.GDPopt.**GDPoptSolver**

Decomposition solver for Generalized Disjunctive Programming (GDP) problems.

The GDPopt (Generalized Disjunctive Programming optimizer) solver applies a variety of decomposition-based approaches to solve Generalized Disjunctive Programming (GDP) problems. GDP models can include nonlinear, continuous variables and constraints, as well as logical conditions.

These approaches include:

- Logic-based outer approximation (LOA)
- Logic-based branch-and-bound (LBB)
- Partial surrogate cuts [pending]
- Generalized Bender decomposition [pending]

This solver implementation was developed by Carnegie Mellon University in the research group of Ignacio Grossmann.

For nonconvex problems, LOA may not report rigorous lower/upper bounds.

Questions: Please make a post at StackOverflow and/or contact Qi Chen <https://github.com/qtothec>.

Several key GDPopt components were prototyped by BS and MS students:

- Logic-based branch and bound: Sunjeev Kale
- MC++ interface: Johnny Bates
- LOA set-covering initialization: Eloy Fernandez

available(*exception_flag=True*)

Check if solver is available.

TODO: For now, it is always available. However, sub-solvers may not always be available, and so this should reflect that possibility.

solve(*model*, ***kwds*)

Solve the model.

Warning: this solver is still in beta. Keyword arguments subject to change. Undocumented keyword arguments definitely subject to change.

This function performs all of the GDPopt solver setup and problem validation. It then calls upon helper functions to construct the initial master approximation and iteration loop.

Parameters **model** (Block) – a Pyomo model or block to be solved

Keyword Arguments

- **iterlim** – Iteration limit.
- **time_limit** – Seconds allowed until terminated. Note that the time limit can currently only be enforced between subsolver invocations. You may need to set subsolver time limits as well.
- **strategy** – Decomposition strategy to use.
- **tee** – Stream output to terminal.
- **logger** – The logger object or name to use for reporting.
- **init_strategy** – Selects the initialization strategy to use when generating the initial cuts to construct the master problem.
- **custom_init_disjuncts** – List of disjunct sets to use for initialization.
- **max_slack** – Upper bound on slack variables for OA
- **OA_penalty_factor** – Penalty multiplication term for slack variables on the objective value.
- **set_cover_iterlim** – Limit on the number of set covering iterations.
- **call_before_master_solve** – callback hook before calling the master problem solver
- **call_after_master_solve** – callback hook after a solution of the master problem
- **call_before_subproblem_solve** – callback hook before calling the subproblem solver
- **call_after_subproblem_solve** – callback hook after a solution of the nonlinear subproblem
- **call_after_subproblem_feasible** – callback hook after feasible solution of the nonlinear subproblem
- **algorithm_stall_after** – number of non-improving master iterations after which the algorithm will stall and exit.
- **round_discrete_vars** – flag to round subproblem discrete variable values to the nearest integer. Rounding is done before fixing disjuncts.
- **force_subproblem_nlp** – Force subproblems to be NLP, even if discrete variables exist.
- **mip_presolve** – Flag to enable or diable GDPopt MIP presolve. Default=True.
- **subproblem_presolve** – Flag to enable or disable subproblem presolve. Default=True.
- **calc_disjunctive_bounds** – Calculate special disjunctive variable bounds for GLOA. False by default.
- **obbt_disjunctive_bounds** – Use optimality-based bounds tightening rather than feasibility-based bounds tightening to compute disjunctive variable bounds. False by default.
- **check_sat** – When True, GDPopt-LBB will check satisfiability at each node via the pyomo.contrib.satsolver interface
- **solve_local_rnGDP** – When True, GDPopt-LBB will solve a local MINLP at each node.

- **mip_solver** – Mixed integer linear solver to use.
- **mip_solver_args** – Keyword arguments to send to the MILP subsolver solve() invocation
- **nlp_solver** – Nonlinear solver to use
- **nlp_solver_args** – Keyword arguments to send to the NLP subsolver solve() invocation
- **minlp_solver** – MINLP solver to use
- **minlp_solver_args** – Keyword arguments to send to the MINLP subsolver solve() invocation
- **local_minlp_solver** – MINLP solver to use
- **local_minlp_solver_args** – Keyword arguments to send to the local MINLP subsolver solve() invocation
- **bound_tolerance** – Tolerance for bound convergence.
- **small_dual_tolerance** – When generating cuts, small duals multiplied by expressions can cause problems. Exclude all duals smaller in absolue value than the following.
- **integer_tolerance** – Tolerance on integral values.
- **constraint_tolerance** – Tolerance on constraint satisfaction.
- **variable_tolerance** – Tolerance on variable bounds.
- **zero_tolerance** – Tolerance on variable equal to zero.

version()
Return a 3-tuple describing the solver version.

15.3 MindtPy solver

The Mixed-Integer Nonlinear Decomposition Toolbox in Pyomo (MindtPy) solver allows users to solve Mixed-Integer Nonlinear Programs (MINLP) using decomposition algorithms. These decomposition algorithms usually rely on the solution of Mixed-Intger Linear Programs (MILP) and Nonlinear Programs (NLP).

MindtPy currently implements the Outer Approximation (OA) algorithm originally described in [Duran & Grossmann, 1986] and the Extended Cutting Plane (ECP) algorithm originally described in [Westerlund & Petterson, 1995]. Usage and implementation details for MindtPy can be found in the PSE 2018 paper Bernal et al., (ref, preprint).

Usage of MindtPy to solve a Pyomo concrete model involves:

```
>>> SolverFactory('mindtpy').solve(model)
```

An example which includes the modeling approach may be found below.

```
Required imports
>>> from pyomo.environ import *

Create a simple model
>>> model = ConcreteModel()

>>> model.x = Var(bounds=(1.0,10.0),initialize=5.0)
```

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```
>>> model.y = Var(within=Binary)

>>> model.c1 = Constraint(expr=(model.x-4.0)**2 - model.x <= 50.0*(1-model.y))
>>> model.c2 = Constraint(expr=model.x*log(model.x)+5.0 <= 50.0*(model.y))

>>> model.objective = Objective(expr=model.x, sense=minimize)

Solve the model using MindtPy
>>> SolverFactory('mindtpy').solve(model, mip_solver='glpk', nlp_solver='ipopt')
```

The solution may then be displayed by using the commands

```
>>> model.objective.display()
>>> model.display()
>>> model.pprint()
```

Note: When troubleshooting, it can often be helpful to turn on verbose output using the `tee` flag.

```
>>> SolverFactory('mindtpy').solve(model, mip_solver='glpk', nlp_solver='ipopt',␣
↪tee=True)
```

MindtPy also supports setting options for mip solver and nlp solver.

```
>>> SolverFactory('mindtpy').solve(model,
                                   strategy='OA',
                                   time_limit=3600,
                                   mip_solver='gams',
                                   mip_solver_args=dict(solver='cplex', warmstart=True),
                                   nlp_solver='ipopt',
                                   tee=True)
```

There are three initialization strategies in MindtPy: rNLP, initial_binary, max_binary. In OA and GOA strategies, the default initialization strategy is rNLP. In ECP strategy, the default initialization strategy is max_binary.

15.3.1 Single tree implementation

MindtPy also supports single tree implementation of Outer Approximation (OA) algorithm, which is known as LP/NLP algorithm originally described in [Quesada & Grossmann]. The LP/NLP algorithm in MindtPy is implemeted based on the LazyCallback function in commercial solvers.

Note: The single tree implementation currently only works with CPLEX. To use LazyCallback function of CPLEX from Pyomo, the CPLEX Python API is required. This means both IBM ILOG CPLEX Optimization Studio and the CPLEX-Python modules should be installed on your computer.

A usage example for single tree is as follows:

```
>>> import pyomo.environ as pyo
>>> model = pyo.ConcreteModel()
```

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```
>>> model.x = pyo.Var(bounds=(1.0, 10.0), initialize=5.0)
>>> model.y = pyo.Var(within=Binary)

>>> model.c1 = Constraint(expr=(model.x-4.0)**2 - model.x <= 50.0*(1-model.y))
>>> model.c2 = pyo.Constraint(expr=model.x*log(model.x)+5.0 <= 50.0*(model.y))

>>> model.objective = pyo.Objective(expr=model.x, sense=pyo.minimize)

Solve the model using single tree implementation in MindtPy
>>> pyo.SolverFactory('mindtpy').solve(
...     model, strategy='OA',
...     mip_solver='cplex_persistent', nlp_solver='ipopt', single_tree=True)
>>> model.objective.display()
```

15.3.2 Global Outer Approximation

Apart of the decomposition methods for convex MINLP problems [Kronqvist et al., 2019], MindtPy provides an implementation of Global Outer Approximation (GOA) as described in [Kesavan et al., 2004], to provide optimality guaranteed for nonconvex MINLP problems. Here, the validity of the Mixed-integer Linear Programming relaxation of the original problem is guaranteed via the usage of Generalized McCormick envelopes, computed using the package MC++. The NLP subproblems in this case need to be solved to global optimality, which can be achieved through global NLP solvers such as BARON or SCIP. No-good cuts are added to each iteration, guaranteeing the finite convergence of the algorithm. Notice that this method is more computationally expensive than the other strategies implemented for convex MINLP like OA and ECP, which in turn can be used as heuristics for nonconvex MINLP problems.

15.3.3 Regularization

As a new implementation in MindtPy, we provide a flexible regularization technique implementation. In this technique, an extra mixed-integer problem is solved in each decomposition iteration or incumbent solution of the single-tree solution methods. The extra mixed-integer program is constructed to provide a point where the NLP problem is solved closer to the feasible region described by the non-linear constraint. This approach has been proposed in [Kronqvist et al., 2020] and it has shown to be efficient for highly nonlinear convex MINLP problems. In [Kronqvist et al., 2020] two different regularization approaches are proposed, using an squared Euclidean norm which was proved to make the procedure equivalent to adding trust-region constraints to Outer-approximation, and a second order approximation of the Lagrangian of the problem, which showed better performance. We implement these methods, using PyomoNLP as the interface to compute the second order approximation of the Lagrangian, and extend them to consider linear norm objectives and first order approximations of the Lagrangian. Finally, we implemented an approximated second order expansion of the Lagrangian, drawing inspiration from the Sequential Quadratic Programming (SQP) literature. The details of this implementation are included in an upcoming paper.

15.3.4 MindtPy implementation and optional arguments

Warning: MindtPy optional arguments should be considered beta code and are subject to change.

class pyomo.contrib.mindtpy.MindtPy.**MindtPySolver**
A decomposition-based MINLP solver.

available(*exception_flag=True*)
Check if solver is available.

solve(*model*, ***kwds*)
Solve the model.

Warning: this solver is still in beta. Keyword arguments subject to change. Undocumented keyword arguments definitely subject to change.

Parameters **model** (Block) – a Pyomo model or block to be solved

version()
Return a 3-tuple describing the solver version.

15.4 Multistart Solver

The multistart solver is used in cases where the objective function is known to be non-convex but the global optimum is still desired. It works by running a non-linear solver of your choice multiple times at different starting points, and returns the best of the solutions.

15.4.1 Using Multistart Solver

To use the multistart solver, define your Pyomo model as usual:

```
Required import
>>> from pyomo.environ import *

Create a simple model
>>> m = ConcreteModel()
>>> m.x = Var()
>>> m.y = Var()
>>> m.obj = Objective(expr=m.x**2 + m.y**2)
>>> m.c = Constraint(expr=m.y >= -2*m.x + 5)

Invoke the multistart solver
>>> SolverFactory('multistart').solve(m)
```

15.4.2 Multistart wrapper implementation and optional arguments

class pyomo.contrib.multistart.multi.**MultiStart**

Solver wrapper that initializes at multiple starting points.

TODO: also return appropriate duals

For theoretical underpinning, see https://www.semanticscholar.org/paper/How-many-random-restarts-are-enough-Dick-Wong/55b248b398a03dc1ac9a65437f88b835554329e0

Keyword arguments below are specified for the `solve` function.

Keyword Arguments

- **strategy** – Specify the restart strategy.
  - "rand": random choice between variable bounds
  - "midpoint_guess_and_bound": midpoint between current value and farthest bound
  - "rand_guess_and_bound": random choice between current value and farthest bound
  - "rand_distributed": random choice among evenly distributed values
  - "midpoint": exact midpoint between the bounds. If using this option, multiple iterations are useless.
- **solver** – solver to use, defaults to ipopt
- **solver_args** – Dictionary of keyword arguments to pass to the solver.
- **iterations** – Specify the number of iterations, defaults to 10. If -1 is specified, the high confidence stopping rule will be used
- **stopping_mass** – Maximum allowable estimated missing mass of optima for the high confidence stopping rule, only used with the random strategy. The lower the parameter, the stricter the rule. Value bounded in (0, 1].
- **stopping_delta** – 1 minus the confidence level required for the stopping rule for the high confidence stopping rule, only used with the random strategy. The lower the parameter, the stricter the rule. Value bounded in (0, 1].
- **suppress_unbounded_warning** – True to suppress warning for skipping unbounded variables.
- **HCS_max_iterations** – Maximum number of iterations before interrupting the high confidence stopping rule.
- **HCS_tolerance** – Tolerance on HCS objective value equality. Defaults to Python float equality precision.

available(*exception_flag=True*)

Check if solver is available.

TODO: For now, it is always available. However, sub-solvers may not always be available, and so this should reflect that possibility.

15.5 Nonlinear Preprocessing Transformations

`pyomo.contrib.preprocessing` is a contributed library of preprocessing transformations intended to operate upon nonlinear and mixed-integer nonlinear programs (NLPs and MINLPs), as well as generalized disjunctive programs (GDPs).

This contributed package is maintained by Qi Chen and his colleagues from Carnegie Mellon University.

The following preprocessing transformations are available. However, some may later be deprecated or combined, depending on their usefulness.

var_aggregator.VariableAggregator	Aggregate model variables that are linked by equality constraints.
bounds_to_vars.ConstraintToVarBoundTransform	Change constraints to be a bound on the variable.
induced_linearity.InducedLinearity	Reformulate nonlinear constraints with induced linearity.
constraint_tightener.TightenContraintFromVars	DEPRECATED.
deactivate_trivial_constraints.TrivialConstraintDeactivator	Deactivates trivial constraints.
detect_fixed_vars.FixedVarDetector	Detects variables that are de-facto fixed but not considered fixed.
equality_propagate.FixedVarPropagator	Propagate variable fixing for equalities of type $x = y$.
equality_propagate.VarBoundPropagator	Propagate variable bounds for equalities of type $x = y$.
init_vars.InitMidpoint	Initialize non-fixed variables to the midpoint of their bounds.
init_vars.InitZero	Initialize non-fixed variables to zero.
remove_zero_terms.RemoveZeroTerms	Looks for $0v$ in a constraint and removes it.
strip_bounds.VariableBoundStripper	Strip bounds from variables.
zero_sum_propagator.ZeroSumPropagator	Propagates fixed-to-zero for sums of only positive (or negative) vars.

15.5.1 Variable Aggregator

The following code snippet demonstrates usage of the variable aggregation transformation on a concrete Pyomo model:

```
>>> from pyomo.environ import *
>>> m = ConcreteModel()
>>> m.v1 = Var(initialize=1, bounds=(1, 8))
>>> m.v2 = Var(initialize=2, bounds=(0, 3))
>>> m.v3 = Var(initialize=3, bounds=(-7, 4))
>>> m.v4 = Var(initialize=4, bounds=(2, 6))
>>> m.c1 = Constraint(expr=m.v1 == m.v2)
>>> m.c2 = Constraint(expr=m.v2 == m.v3)
>>> m.c3 = Constraint(expr=m.v3 == m.v4)
>>> TransformationFactory('contrib.aggregate_vars').apply_to(m)
```

To see the results of the transformation, you could then use the command

```
>>> m.pprint()
```

class pyomo.contrib.preprocessing.plugins.var_aggregator.**VariableAggregator**(***kwds*)

Aggregate model variables that are linked by equality constraints.

Before:

$$x = y$$
$$a = 2x + 6y + 7$$
$$b = 5y + 6$$

After:

$$z = x = y$$
$$a = 8z + 7$$
$$b = 5z + 6$$

Warning: TODO: unclear what happens to "capital-E" Expressions at this point in time.

apply_to(*model*, ***kwds*)
Apply the transformation to the given model.

create_using(*model*, ***kwds*)
Create a new model with this transformation

update_variables(*model*)
Update the values of the variables that were replaced by aggregates.

TODO: reduced costs

15.5.2 Explicit Constraints to Variable Bounds

```
>>> from pyomo.environ import *
>>> m = ConcreteModel()
>>> m.v1 = Var(initialize=1)
>>> m.v2 = Var(initialize=2)
>>> m.v3 = Var(initialize=3)
>>> m.c1 = Constraint(expr=m.v1 == 2)
>>> m.c2 = Constraint(expr=m.v2 >= -2)
>>> m.c3 = Constraint(expr=m.v3 <= 5)
>>> TransformationFactory('contrib.constraints_to_var_bounds').apply_to(m)
```

class pyomo.contrib.preprocessing.plugins.bounds_to_vars.**ConstraintToVarBoundTransform**(***kwds*)
Change constraints to be a bound on the variable.

Looks for constraints of form: $k * v + c_1 \leq c_2$. Changes variable lower bound on v to match $(c_2 - c_1)/k$ if it results in a tighter bound. Also does the same thing for lower bounds.

Keyword arguments below are specified for the `apply_to` and `create_using` functions.

Keyword Arguments

- **tolerance** – tolerance on bound equality ($LB = UB$)
- **detect_fixed** – If True, fix variable when $|LB - UB| \leq tolerance$.

apply_to(*model*, ***kwds*)
Apply the transformation to the given model.

create_using(*model*, ***kwds*)
Create a new model with this transformation

15.5.3 Induced Linearity Reformulation

class pyomo.contrib.preprocessing.plugins.induced_linearity.**InducedLinearity**(***kwds*)

Reformulate nonlinear constraints with induced linearity.

Finds continuous variables v where $v = d_1 + d_2 + d_3$, where d's are discrete variables. These continuous variables may participate nonlinearly in other expressions, which may then be induced to be linear.

The overall algorithm flow can be summarized as:

1. Detect effectively discrete variables and the constraints that imply discreteness.
2. Determine the set of valid values for each effectively discrete variable
3. Find nonlinear expressions in which effectively discrete variables participate.
4. Reformulate nonlinear expressions appropriately.

Note: Tasks 1 & 2 must incorporate scoping considerations (Disjuncts)

Keyword arguments below are specified for the `apply_to` and `create_using` functions.

Keyword Arguments

- **equality_tolerance** – Tolerance on equality constraints.
- **pruning_solver** – Solver to use when pruning possible values.

apply_to(*model*, ***kwds*)

Apply the transformation to the given model.

create_using(*model*, ***kwds*)

Create a new model with this transformation

15.5.4 Constraint Bounds Tightener

This transformation was developed by Sunjeev Kale at Carnegie Mellon University.

class pyomo.contrib.preprocessing.plugins.constraint_tightener.**TightenContraintFromVars**

DEPRECATED.

Tightens upper and lower bound on constraints based on variable bounds.

Iterates through each variable and tightens the constraint bounds using the inferred values from the variable bounds.

For now, this only operates on linear constraints.

Deprecated since version 5.7: Use of the constraint tightener transformation is deprecated. Its functionality may be partially replicated using *pyomo.contrib.fbbt.compute_bounds_on_expr(constraint.body)*.

apply_to(*model*, ***kwds*)

Apply the transformation to the given model.

create_using(*model*, ***kwds*)

Create a new model with this transformation

15.5.5 Trivial Constraint Deactivation

class pyomo.contrib.preprocessing.plugins.deactivate_trivial_constraints.**TrivialConstraintDeactivator**(**

Deactivates trivial constraints.

Trivial constraints take form $k_1 = k_2$ or $k_1 \leq k_2$, where k_1 and k_2 are constants. These constraints typically arise when variables are fixed.

Keyword arguments below are specified for the `apply_to` and `create_using` functions.

Keyword Arguments

- **tmp** – True to store a set of transformed constraints for future reversion of the transformation.
- **ignore_infeasible** – True to skip over trivial constraints that are infeasible instead of raising a ValueError.
- **return_trivial** – a list to which the deactivated trivialconstraints are appended (side effect)
- **tolerance** – tolerance on constraint violations

apply_to(*model*, ***kwds*)

Apply the transformation to the given model.

create_using(*model*, ***kwds*)

Create a new model with this transformation

revert(*instance*)

Revert constraints deactivated by the transformation.

Parameters **instance** – the model instance on which trivial constraints were earlier deactivated.

15.5.6 Fixed Variable Detection

class pyomo.contrib.preprocessing.plugins.detect_fixed_vars.**FixedVarDetector**(***kwds*)

Detects variables that are de-facto fixed but not considered fixed.

For each variable v found on the model, check to see if its lower bound v^{LB} is within some tolerance of its upper bound v^{UB}. If so, fix the variable to the value of v^{LB}.

Keyword arguments below are specified for the `apply_to` and `create_using` functions.

Keyword Arguments

- **tmp** – True to store the set of transformed variables and their old values so that they can be restored.
- **tolerance** – tolerance on bound equality (LB == UB)

apply_to(*model*, ***kwds*)

Apply the transformation to the given model.

create_using(*model*, ***kwds*)

Create a new model with this transformation

revert(*instance*)

Revert variables fixed by the transformation.

15.5.7 Fixed Variable Equality Propagator

class pyomo.contrib.preprocessing.plugins.equality_propagate.**FixedVarPropagator**(***kwds*)

Propagate variable fixing for equalities of type $x = y$.

If x is fixed and y is not fixed, then this transformation will fix y to the value of x.

This transformation can also be performed as a temporary transformation, whereby the transformed variables are saved and can be later unfixed.

Keyword arguments below are specified for the `apply_to` and `create_using` functions.

Keyword Arguments **tmp** – True to store the set of transformed variables and their old states so that they can be later restored.

apply_to(*model*, ***kwds*)

Apply the transformation to the given model.

create_using(*model*, ***kwds*)

Create a new model with this transformation

revert(*instance*)

Revert variables fixed by the transformation.

15.5.8 Variable Bound Equality Propagator

class pyomo.contrib.preprocessing.plugins.equality_propagate.**VarBoundPropagator**(***kwds*)

Propagate variable bounds for equalities of type $x = y$.

If x has a tighter bound then y, then this transformation will adjust the bounds on y to match those of x.

Keyword arguments below are specified for the `apply_to` and `create_using` functions.

Keyword Arguments **tmp** – True to store the set of transformed variables and their old states so that they can be later restored.

apply_to(*model*, ***kwds*)

Apply the transformation to the given model.

create_using(*model*, ***kwds*)

Create a new model with this transformation

revert(*instance*)

Revert variable bounds.

15.5.9 Variable Midpoint Initializer

class pyomo.contrib.preprocessing.plugins.init_vars.**InitMidpoint**(***kwds*)

Initialize non-fixed variables to the midpoint of their bounds.

- If the variable does not have bounds, set the value to zero.
- If the variable is missing one bound, set the value to that of the existing bound.

apply_to(*model*, ***kwds*)

Apply the transformation to the given model.

create_using(*model*, ***kwds*)

Create a new model with this transformation

15.5.10 Variable Zero Initializer

class pyomo.contrib.preprocessing.plugins.init_vars.**InitZero**(***kwds*)

Initialize non-fixed variables to zero.

- If setting the variable value to zero will violate a bound, set the variable value to the relevant bound value.

apply_to(*model*, ***kwds*)

Apply the transformation to the given model.

create_using(*model*, ***kwds*)

Create a new model with this transformation

15.5.11 Zero Term Remover

class pyomo.contrib.preprocessing.plugins.remove_zero_terms.**RemoveZeroTerms**(***kwds*)

Looks for $0v$ in a constraint and removes it.

Currently limited to processing linear constraints of the form $x_1 = 0x_3$, occurring as a result of fixing $x_2 = 0$.

Note: TODO: support nonlinear expressions

---

apply_to(*model*, ***kwds*)

Apply the transformation to the given model.

create_using(*model*, ***kwds*)

Create a new model with this transformation

15.5.12 Variable Bound Remover

class pyomo.contrib.preprocessing.plugins.strip_bounds.**VariableBoundStripper**(***kwds*)

Strip bounds from variables.

Keyword arguments below are specified for the `apply_to` and `create_using` functions.

Keyword Arguments

- **strip_domains** – strip the domain for discrete variables as well
- **reversible** – Whether the bound stripping will be temporary. If so, store information for reversion.

apply_to(*model*, ***kwds*)

Apply the transformation to the given model.

create_using(*model*, ***kwds*)

Create a new model with this transformation

revert(*instance*)

Revert variable bounds and domains changed by the transformation.

15.5.13 Zero Sum Propagator

class pyomo.contrib.preprocessing.plugins.zero_sum_propagator.**ZeroSumPropagator**(***kwds*)

Propagates fixed-to-zero for sums of only positive (or negative) vars.

If z is fixed to zero and $z = x_1 + x_2 + x_3$ and x_1, x_2, x_3 are all non-negative or all non-positive, then x_1, x_2, and x_3 will be fixed to zero.

apply_to(*model*, ***kwds*)

Apply the transformation to the given model.

create_using(*model*, ***kwds*)

Create a new model with this transformation

15.6 Parameter Estimation with `parmest`

`parmest` is a Python package built on the Pyomo optimization modeling language ([PyomoJournal], [PyomoBookII]) to support parameter estimation using experimental data along with confidence regions and subsequent creation of scenarios for PySP.

15.6.1 Citation for parmest

If you use parmest, please cite [ParmestPaper]

15.6.2 Index of parmest documenation

Overview

The Python package called parmest facilitates model-based parameter estimation along with characterization of uncertainty associated with the estimates. For example, parmest can provide confidence regions around the parameter estimates. Additionally, parameter vectors, each with an attached probability estimate, can be used to build scenarios for design optimization.

Functionality in parmest includes:

- Model based parameter estimation using experimental data
- Bootstrap resampling for parameter estimation
- Confidence regions based on single or multi-variate distributions
- Likelihood ratio
- Leave-N-out cross validation
- Parallel processing

Background

The goal of parameter estimation is to estimate values for a vector, θ, to use in the functional form

$$y = g(x; \theta)$$

where x is a vector containing measured data, typically in high dimension, θ is a vector of values to estimate, in much lower dimension, and the response vectors are given as $y_i, i = 1, \ldots, m$ with m also much smaller than the dimension of x. This is done by collecting S data points, which are $\tilde{x}, \tilde{y}$ pairs and then finding θ values that minimize some function of the deviation between the values of $\tilde{y}$ that are measured and the values of $g(\tilde{x}; \theta)$ for each corresponding $\tilde{x}$, which is a subvector of the vector x. Note that for most experiments, only small parts of x will change from one experiment to the next.

The following least squares objective can be used to estimate parameter values, where data points are indexed by $s = 1, \ldots, S$

$$\min_{\theta} Q(\theta; \tilde{x}, \tilde{y}) \equiv \sum_{s=1}^{S} q_s(\theta; \tilde{x}_s, \tilde{y}_s)$$

where

$$q_s(\theta; \tilde{x}_s, \tilde{y}_s) = \sum_{i=1}^{m} w_i \left[\tilde{y}_{si} - g_i(\tilde{x}_s; \theta)\right]^2,$$

i.e., the contribution of sample s to Q, where $w \in \Re^m$ is a vector of weights for the responses. For multi-dimensional y, this is the squared weighted L_2 norm and for univariate y the weighted squared deviation. Custom objectives can also be defined for parameter estimation.

In the applications of interest to us, the function $g(\cdot)$ is usually defined as an optimization problem with a large number of (perhaps constrained) optimization variables, a subset of which are fixed at values $\tilde{x}$ when the optimization is performed. In other applications, the values of θ are fixed parameter values, but for the problem formulation above, the values of θ are the primary optimization variables. Note that in general, the function $g(\cdot)$ will have a large set of parameters that are not included in θ. Often, the y_{is} will be vectors themselves, perhaps indexed by time with index sets that vary with s.

Installation Instructions

parmest is included in Pyomo (pyomo/contrib/parmest). To run parmest, you will need Python version 3.x along with various Python package dependencies and the IPOPT software library for non-linear optimization.

Python package dependencies

1. numpy
2. pandas
3. pyomo
4. matplotlib (optional)
5. scipy.stats (optional)
6. seaborn (optional)
7. mpi4py.MPI (optional)

IPOPT

IPOPT can be downloaded from https://projects.coin-or.org/Ipopt.

Testing

The following commands can be used to test parmest:

```
cd pyomo/contrib/parmest/tests
python test_parmest.py
```

Parameter Estimation

Parameter Estimation using parmest requires a Pyomo model, experimental data which defines multiple scenarios, and a list of parameter names (thetas) to estimate. parmest uses PySP [PyomoBookII] to solve a two-stage stochastic programming problem, where the experimental data is used to create a scenario tree. The objective function needs to be written in PySP form with the Pyomo Expression for first stage cost (named "FirstStageCost") set to zero and the Pyomo Expression for second stage cost (named "SecondStageCost") defined as the deviation between the model and the observations (typically defined as the sum of squared deviation between model values and observed values).

If the Pyomo model is not formatted as a two-stage stochastic programming problem in this format, the user can supply a custom function to use as the second stage cost and the Pyomo model will be modified within parmest to match the specifications required by PySP. The PySP callback function is also defined within parmest. The callback function returns a populated and initialized model for each scenario.

To use parmest, the user creates a *Estimator* object which includes the following methods:

theta_est	Parameter estimation using all scenarios in the data
theta_est_bootstrap	Parameter estimation using bootstrap resampling of the data
theta_est_leaveNout	Parameter estimation where N data points are left out of each sample
objective_at_theta	Objective value for each theta
confidence_region_test	Confidence region test to determine if theta values are within a rectangular, multivariate normal, or Gaussian kernel density distribution for a range of alpha values
likelihood_ratio_test	Likelihood ratio test to identify theta values within a confidence region using the χ^2 distribution
leaveNout_bootstrap_test	Leave-N-out bootstrap test to compare theta values where N data points are left out to a bootstrap analysis using the remaining data, results indicate if theta is within a confidence region determined by the bootstrap analysis

Additional functions are available in parmest to group data, plot results, and fit distributions to theta values.

group_data	Group data by scenario
pairwise_plot	Plot pairwise relationship for theta values, and optionally alpha-level confidence intervals and objective value contours
grouped_boxplot	Plot a grouped boxplot to compare two datasets

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Table 15.3 – continued from previous page

grouped_violinplot	Plot a grouped violinplot to compare two datasets
fit_rect_dist	Fit an alpha-level rectangular distribution to theta values
fit_mvn_dist	Fit a multivariate normal distribution to theta values
fit_kde_dist	Fit a Gaussian kernel-density distribution to theta values

A *Estimator* object can be created using the following code. A description of each argument is listed below. Examples are provided in the *Examples* Section.

```
>>> import pyomo.contrib.parmest.parmest as parmest
>>> pest = parmest.Estimator(model_function, data, theta_names, objective_function)
```

Optionally, solver options can be supplied, e.g.,

```
>>> solver_options = {"max_iter": 6000}
>>> pest = parmest.Estimator(model_function, data, theta_names, objective_function,␣
↪solver_options)
```

Model function

The first argument is a function which uses data for a single scenario to return a populated and initialized Pyomo model for that scenario. Parameters that the user would like to estimate must be defined as variables (Pyomo *Var*). The variables can be fixed (parmest unfixes variables that will be estimated). The model does not have to be specifically written for parmest. That is, parmest can modify the objective for PySP, see *Objective function* below.

Data

The second argument is the data which will be used to populate the Pyomo model. Supported data formats include:

- **Pandas Dataframe** where each row is a separate scenario and column names refer to observed quantities. Pandas DataFrames are easily stored and read in from csv, excel, or databases, or created directly in Python.
- **List of dictionaries** where each entry in the list is a separate scenario and the keys (or nested keys) refer to observed quantities. Dictionaries are often preferred over DataFrames when using static and time series data. Dictionaries are easily stored and read in from json or yaml files, or created directly in Python.
- **List of json file names** where each entry in the list contains a json file name for a separate scenario. This format is recommended when using large datasets in parallel computing.

The data must be compatible with the model function that returns a populated and initialized Pyomo model for a single scenario. Data can include multiple entries per variable (time series and/or duplicate sensors). This information can be included in custom objective functions, see *Objective function* below.

Theta names

The third argument is a list of variable names that the user wants to estimate. The list contains strings with *Var* names from the Pyomo model.

Objective function

The fourth argument is an optional argument which defines the optimization objective function to use in parameter estimation. If no objective function is specified, the Pyomo model is used "as is" and should be defined with "FirstStageCost" and "SecondStageCost" expressions that are used to build an objective for PySP. If the Pyomo model is not written as a two stage stochastic programming problem in this format, and/or if the user wants to use an objective that is different than the original model, a custom objective function can be defined for parameter estimation. The objective function arguments include *model* and *data* and the objective function returns a Pyomo expression which is used to define "SecondStageCost". The objective function can be used to customize data points and weights that are used in parameter estimation.

Data Reconciliation

The method *theta_est* can optionally return model values. This feature can be used to return reconciled data using a user specified objective. In this case, the list of variable names the user wants to estimate (theta_names) is set to an empty list and the objective function is defined to minimize measurement to model error. Note that the model used for data reconciliation may differ from the model used for parameter estimation.

The following example illustrates the use of parmest for data reconciliation. The functions *grouped_boxplot* or *grouped_violinplot* can be used to visually compare the original and reconciled data.

Here's a stylized code snippet showing how box plots might be created:

```
>>> import pyomo.contrib.parmest.parmest as parmest
>>> pest = parmest.Estimator(model_function, data, [], objective_function)
>>> obj, theta, data_rec = pest.theta_est(return_values=['A', 'B'])
>>> parmest.graphics.grouped_boxplot(data, data_rec)
```

Returned Values

Here's a full program that can be run to see returned values (in this case it is the response function that is defined in the model file):

```
>>> import pandas as pd
>>> import pyomo.contrib.parmest.parmest as parmest
>>> from pyomo.contrib.parmest.examples.rooney_biegler.rooney_biegler import rooney_
↪biegler_model

>>> theta_names = ['asymptote', 'rate_constant']

>>> data = pd.DataFrame(data=[[1,8.3],[2,10.3],[3,19.0],
...                           [4,16.0],[5,15.6],[7,19.8]],
...                     columns=['hour', 'y'])

>>> def SSE(model, data):
...     expr = sum((data.y[i]\
...                 - model.response_function[data.hour[i]])**2 for i in data.index)
...     return expr

>>> pest = parmest.Estimator(rooney_biegler_model, data, theta_names, SSE,
...                          solver_options=None)
```

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```
>>> obj, theta, var_values = pest.theta_est(return_values=['response_function'])
>>> #print(var_values)
```

Covariance Matrix Estimation

If the optional argument `calc_cov=True` is specified for *theta_est*, parmest will calculate the covariance matrix V_θ as follows:

$$V_\theta = 2\sigma^2 H^{-1}$$

This formula assumes all measurement errors are independent and identically distributed with variance σ^2. H^{-1} is the inverse of the Hessian matrix for a unweighted sum of least squares problem. Currently, the covariance approximation is only valid if the objective given to parmest is the sum of squared error. Moreover, parmest approximates the variance of the measurement errors as $\sigma^2 = \frac{1}{n-l}\sum e_i^2$ where n is the number of data points, l is the number of fitted parameters, and e_i is the residual for experiment i.

Scenario Creation

In addition to model-based parameter estimation, parmest can create scenarios for use in optimization under uncertainty. To do this, one first creates an `Estimator` object, then a `ScenarioCreator` object, which has methods to add `ParmestScen` scenario objects to a `ScenarioSet` object, which can write them to a csv file or output them via an iterator method.

This example is in the semibatch subdirectory of the examples directory in the file `scencreate.py`. It creates a csv file with scenarios that correspond one-to-one with the experiments used as input data. It also creates a few scenarios using the bootstrap methods and outputs prints the scenarios to the screen, accessing them via the `ScensItator` a `print`

```
# scenario creation example; DLW March 2020

import os
import json
import pyomo.contrib.parmest.parmest as parmest
from pyomo.contrib.parmest.examples.semibatch.semibatch import generate_model
import pyomo.contrib.parmest.scenariocreator as sc

def main(dirname):
    """ dirname gives the location of the experiment input files"""
    # Semibatch Vars to estimate in parmest
    theta_names = ['k1', 'k2', 'E1', 'E2']

    # Semibatch data: list of dictionaries
    data = []
    for exp_num in range(10):
        fname = os.path.join(dirname, 'exp'+str(exp_num+1)+'.out')
        with open(fname,'r') as infile:
            d = json.load(infile)
            data.append(d)

    pest = parmest.Estimator(generate_model, data, theta_names)
```

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```
    scenmaker = sc.ScenarioCreator(pest, "ipopt")

    ofile = "delme_exp.csv"
    print("Make one scenario per experiment and write to {}".format(ofile))
    experimentscens = sc.ScenarioSet("Experiments")
    scenmaker.ScenariosFromExperiments(experimentscens)
    ###experimentscens.write_csv(ofile)

    numtomake = 3
    print("\nUse the bootstrap to make {} scenarios and print.".format(numtomake))
    bootscens = sc.ScenarioSet("Bootstrap")
    scenmaker.ScenariosFromBoostrap(bootscens, numtomake)
    for s in bootscens.ScensIterator():
        print("{}, {}".format(s.name, s.probability))
        for n,v in s.ThetaVals.items():
            print("   {}={}".format(n, v))

if __name__ == "__main__":
    main(".")
```

Note: This example may produce an error message your version of Ipopt is not based on a good linear solver.

Graphics

parmest includes the following functions to help visualize results:

- *grouped_boxplot*
- *grouped_violinplot*
- *pairwise_plot*

Grouped boxplots and violinplots are used to compare datasets, generally before and after data reconciliation. Pairwise plots are used to visualize results from parameter estimation and include a histogram of each parameter along the diagonal and a scatter plot for each pair of parameters in the upper and lower sections. The pairwise plot can also include the following optional information:

- A single value for each theta (generally theta* from parameter estimation).
- Confidence intervals for rectangular, multivariate normal, and/or Gaussian kernel density estimate distributions at a specified level (i.e. 0.8). For plots with more than 2 parameters, theta* is used to extract a slice of the confidence region for each pairwise plot.
- Filled contour lines for objective values at a specified level (i.e. 0.8). For plots with more than 2 parameters, theta* is used to extract a slice of the contour lines for each pairwise plot.

The following examples were generated using the reactor design example. Fig. 15.1 uses output from data reconciliation, Fig. 15.2 uses output from the bootstrap analysis, and Fig. 15.3 uses output from the likelihood ratio test.

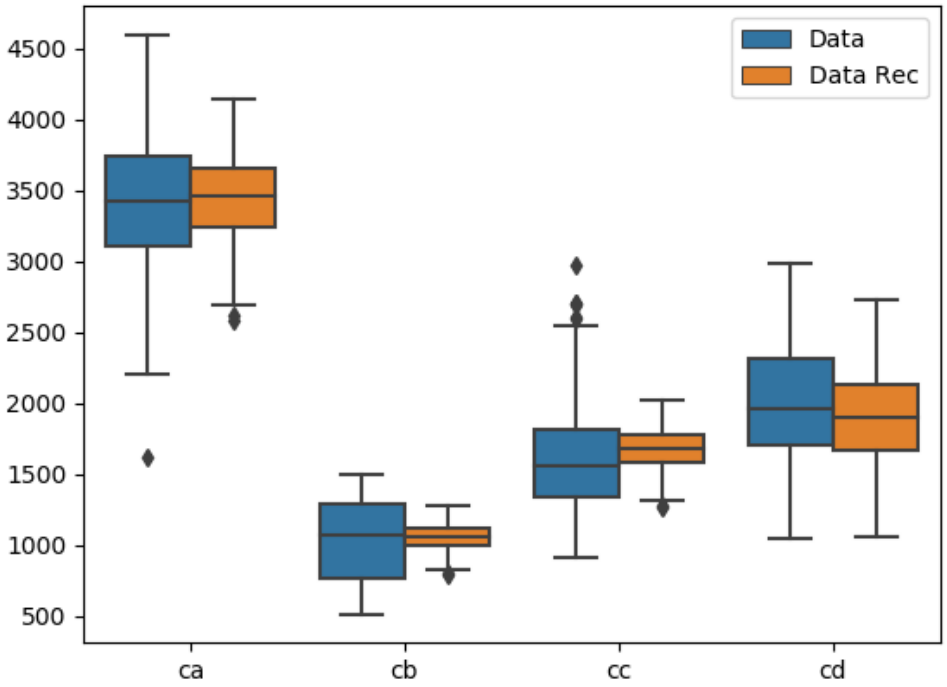

Fig. 15.1: Grouped boxplot showing data before and after data reconciliation.

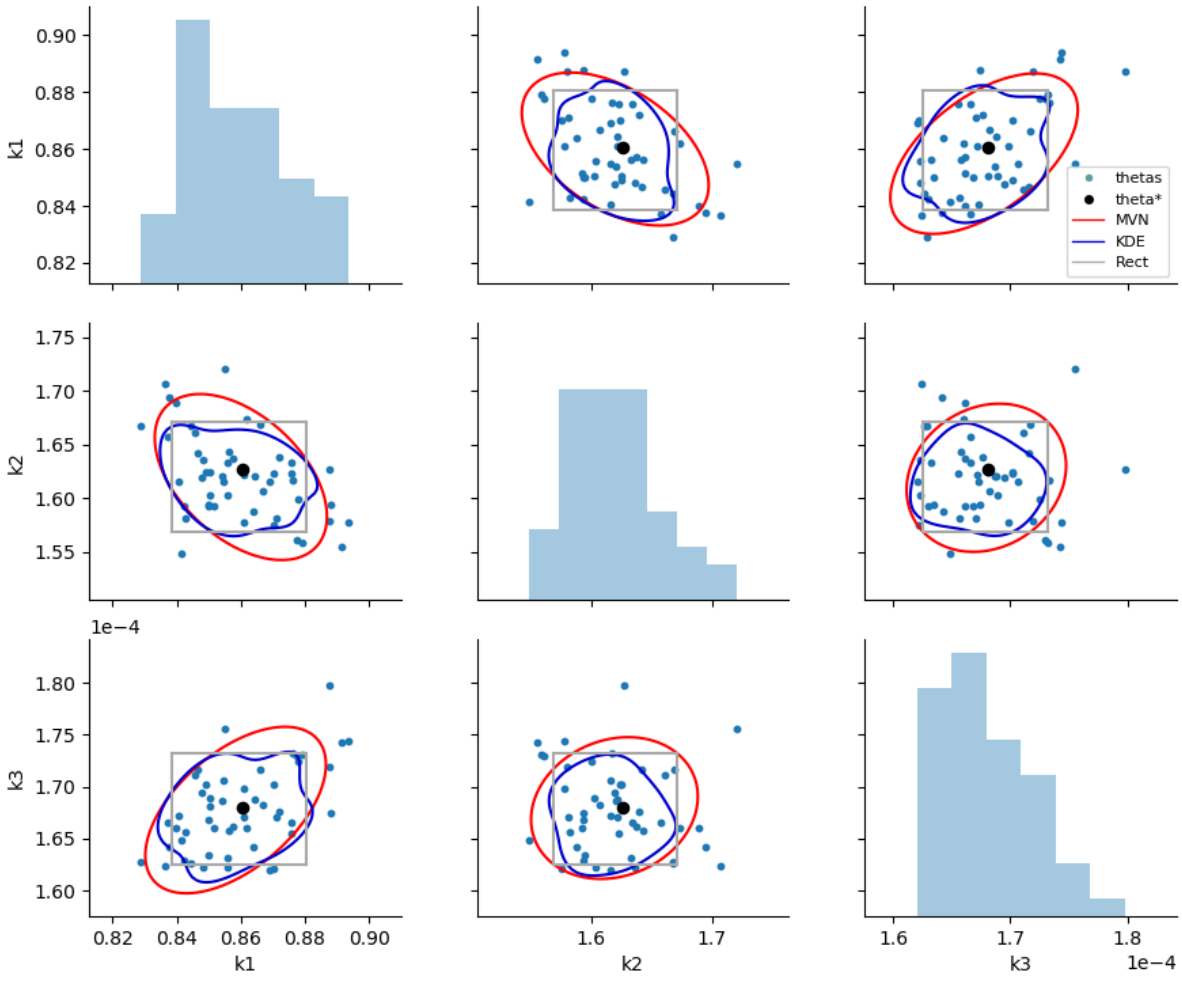

Fig. 15.2: Pairwise bootstrap plot with rectangular, multivariate normal and kernel density estimation confidence region.

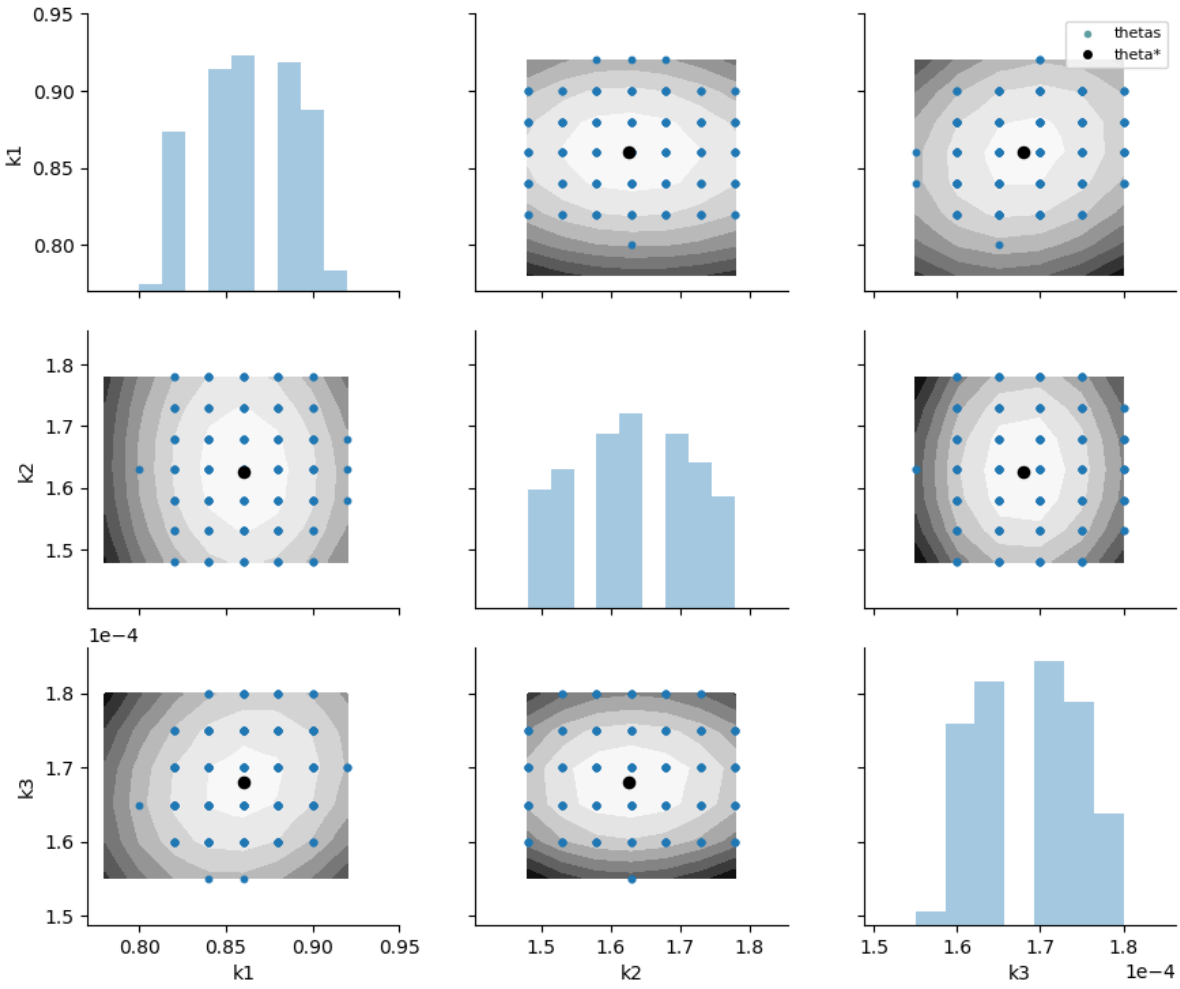

Fig. 15.3: Pairwise likelihood ratio plot with contours of the objective and points that lie within an alpha confidence region.

Examples

Examples can be found in *pyomo/contrib/parmest/examples* and include:

- Reactor design example [PyomoBookII]
- Semibatch example [SemiBatch]
- Rooney Biegler example [RooneyBiegler]

Each example includes a Python file that contains the Pyomo model and a Python file to run parameter estimation.

Additional use cases include:

- Data reconciliation (reactor design example)
- Parameter estimation using data with duplicate sensors and time-series data (reactor design example)
- Parameter estimation using mpi4py, the example saves results to a file for later analysis/graphics (semibatch example)

The description below uses the reactor design example. The file **reactor_design.py** includes a function which returns an populated instance of the Pyomo model. Note that the model is defined to maximize *cb* and that *k1*, *k2*, and *k3* are fixed. The _main_ program is included for easy testing of the model declaration.

```
#  ___________________________________________________________________________
#
#  Pyomo: Python Optimization Modeling Objects
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#  ___________________________________________________________________________
"""
Continuously stirred tank reactor model, based on
pyomo\examples\doc\pyomobook\nonlinear-ch\react_design\ReactorDesign.py
"""
import pandas as pd
from pyomo.environ import ConcreteModel, Var, PositiveReals, Objective, Constraint,␣
↪maximize, SolverFactory

def reactor_design_model(data):

    # Create the concrete model
    model = ConcreteModel()

    # Rate constants
    model.k1 = Var(initialize = 5.0/6.0, within=PositiveReals) # min^-1
    model.k2 = Var(initialize = 5.0/3.0, within=PositiveReals) # min^-1
    model.k3 = Var(initialize = 1.0/6000.0, within=PositiveReals) # m^3/(gmol min)
    model.k1.fixed = True
    model.k2.fixed = True
    model.k3.fixed = True

    # Inlet concentration of A, gmol/m^3
    model.caf = Var(initialize = float(data['caf']), within=PositiveReals)
    model.caf.fixed = True
```

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```
        # Space velocity (flowrate/volume)
    model.sv = Var(initialize = float(data['sv']), within=PositiveReals)
    model.sv.fixed = True

    # Outlet concentration of each component
    model.ca = Var(initialize = 5000.0, within=PositiveReals)
    model.cb = Var(initialize = 2000.0, within=PositiveReals)
    model.cc = Var(initialize = 2000.0, within=PositiveReals)
    model.cd = Var(initialize = 1000.0, within=PositiveReals)

    # Objective
    model.obj = Objective(expr = model.cb, sense=maximize)

    # Constraints
    model.ca_bal = Constraint(expr = (0 == model.sv * model.caf \
                    - model.sv * model.ca - model.k1 * model.ca \
                    -  2.0 * model.k3 * model.ca ** 2.0))

    model.cb_bal = Constraint(expr=(0 == -model.sv * model.cb \
                    + model.k1 * model.ca - model.k2 * model.cb))

    model.cc_bal = Constraint(expr=(0 == -model.sv * model.cc \
                    + model.k2 * model.cb))

    model.cd_bal = Constraint(expr=(0 == -model.sv * model.cd \
                    + model.k3 * model.ca ** 2.0))

    return model

if __name__ == "__main__":

    # For a range of sv values, return ca, cb, cc, and cd
    results = []
    sv_values = [1.0 + v * 0.05 for v in range(1, 20)]
    caf = 10000
    for sv in sv_values:
        model = reactor_design_model({'caf': caf, 'sv': sv})
        solver = SolverFactory('ipopt')
        solver.solve(model)
        results.append([sv, caf, model.ca(), model.cb(), model.cc(), model.cd()])

    results = pd.DataFrame(results, columns=['sv', 'caf', 'ca', 'cb', 'cc', 'cd'])
    print(results)
```

The file **parmest_example.py** uses parmest to estimate values of *k1*, *k2*, and *k3* by minimizing the sum of squared error between model and observed values of *ca*, *cb*, *cc*, and *cd*. The file also uses parmest to run parameter estimation with bootstrap resampling and perform a likelihood ratio test over a range of theta values.

```
#  _____________________________________________________________________________
#
```

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```
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#  _____________________________________________________________________________

import numpy as np
import pandas as pd
from itertools import product
import pyomo.contrib.parmest.parmest as parmest
from pyomo.contrib.parmest.examples.reactor_design.reactor_design import reactor_design_
↪model

### Parameter estimation

# Vars to estimate
theta_names = ['k1', 'k2', 'k3']

# Data
data = pd.read_excel('reactor_data.xlsx')

# Sum of squared error function
def SSE(model, data):
    expr = (float(data['ca']) - model.ca)**2 + \
           (float(data['cb']) - model.cb)**2 + \
           (float(data['cc']) - model.cc)**2 + \
           (float(data['cd']) - model.cd)**2
    return expr

pest = parmest.Estimator(reactor_design_model, data, theta_names, SSE)
obj, theta = pest.theta_est()
print(obj)
print(theta)

### Parameter estimation with bootstrap resampling

bootstrap_theta = pest.theta_est_bootstrap(50)
print(bootstrap_theta.head())

parmest.graphics.pairwise_plot(bootstrap_theta, title='Bootstrap theta estimates')
parmest.graphics.pairwise_plot(bootstrap_theta, theta, 0.8, ['MVN', 'KDE', 'Rect'],
                       title='Bootstrap theta with confidence regions')

### Likelihood ratio test

k1 = np.arange(0.78, 0.92, 0.02)
k2 = np.arange(1.48, 1.79, 0.05)
k3 = np.arange(0.000155, 0.000185, 0.000005)
theta_vals = pd.DataFrame(list(product(k1, k2, k3)), columns=theta_names)
```

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```
obj_at_theta = pest.objective_at_theta(theta_vals)
print(obj_at_theta.head())

LR = pest.likelihood_ratio_test(obj_at_theta, obj, [0.8, 0.85, 0.9, 0.95])
print(LR.head())

parmest.graphics.pairwise_plot(LR, theta, 0.8,
                       title='LR results within 80% confidence region')
```

The semibatch and Rooney Biegler examples are defined in a similar manner.

Parallel Implementation

Parallel implementation in parmest is **preliminary**. To run parmest in parallel, you need the mpi4py Python package and a *compatible* MPI installation. If you do NOT have mpi4py or a MPI installation, parmest still works (you should not get MPI import errors).

For example, the following command can be used to run the semibatch model in parallel:

```
mpiexec -n 4 python parmest_parallel_example.py
```

The file **parmest_parallel_example.py** is shown below. Results are saved to file for later analysis.

```
#  ___________________________________________________________________________
#
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#  This software is distributed under the 3-clause BSD License.
#  ___________________________________________________________________________

"""
The following script can be used to run semibatch parameter estimation in
parallel and save results to files for later analysis and graphics.
Example command: mpiexec -n 4 python semibatch_parmest_parallel.py
"""
import numpy as np
import pandas as pd
from itertools import product
import pyomo.contrib.parmest.parmest as parmest
from pyomo.contrib.parmest.examples.semibatch.semibatch import generate_model

### Parameter estimation

# Vars to estimate
theta_names = ['k1', 'k2', 'E1', 'E2']

# Data, list of json file names
data = []
for exp_num in range(10):
```

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```
    data.append('exp'+str(exp_num+1)+'.out')

# Note, the model already includes a 'SecondStageCost' expression
# for sum of squared error that will be used in parameter estimation

pest = parmest.Estimator(generate_model, data, theta_names)

### Parameter estimation with bootstrap resampling

bootstrap_theta = pest.theta_est_bootstrap(100)
bootstrap_theta.to_csv('bootstrap_theta.csv')

### Compute objective at theta for likelihood ratio test

k1 = np.arange(4, 24, 3)
k2 = np.arange(40, 160, 40)
E1 = np.arange(29000, 32000, 500)
E2 = np.arange(38000, 42000, 500)
theta_vals = pd.DataFrame(list(product(k1, k2, E1, E2)), columns=theta_names)

obj_at_theta = pest.objective_at_theta(theta_vals)
obj_at_theta.to_csv('obj_at_theta.csv')
```

Installation

The mpi4py Python package should be installed using conda. The following installation instructions were tested on a Mac with Python 3.5.

Create a conda environment and install mpi4py using the following commands:

```
conda create -n parmest-parallel python=3.5
source activate parmest-parallel
conda install -c conda-forge mpi4py
```

This should install libgfortran, mpi, mpi4py, and openmpi.

To verify proper installation, create a Python file with the following:

```
from mpi4py import MPI
import time
comm = MPI.COMM_WORLD
rank = comm.Get_rank()
print('Rank = ',rank)
time.sleep(10)
```

Save the file as test_mpi.py and run the following command:

```
time mpiexec -n 4 python test_mpi.py
time python test_mpi.py
```

The first one should be faster and should start 4 instances of Python.

API

parmest

class pyomo.contrib.parmest.parmest.**Estimator**(*model_function*, *data*, *theta_names*, *obj_function=None*, *tee=False*, *diagnostic_mode=False*, *solver_options=None*)

Bases: object

Parameter estimation class

Parameters

- **model_function** (*function*) – Function that generates an instance of the Pyomo model using 'data' as the input argument
- **data** (*pandas DataFrame, list of dictionaries, or list of json file names*) – Data that is used to build an instance of the Pyomo model and build the objective function
- **theta_names** (*list of strings*) – List of Var names to estimate
- **obj_function** (*function, optional*) – Function used to formulate parameter estimation objective, generally sum of squared error between measurements and model variables. If no function is specified, the model is used "as is" and should be defined with a "FirstStageCost" and "SecondStageCost" expression that are used to build an objective.
- **tee** (*bool, optional*) – Indicates that ef solver output should be teed
- **diagnostic_mode** (*bool, optional*) – If True, print diagnostics from the solver
- **solver_options** (*dict, optional*) – Provides options to the solver (also the name of an attribute)

confidence_region_test(*theta_values*, *distribution*, *alphas*, *test_theta_values=None*)

Confidence region test to determine if theta values are within a rectangular, multivariate normal, or Gaussian kernel density distribution for a range of alpha values

Parameters

- **theta_values** (*DataFrame, columns = theta_names*) – Theta values used to generate a confidence region (generally returned by theta_est_bootstrap)
- **distribution** (*string*) – Statistical distribution used to define a confidence region, options = 'MVN' for multivariate_normal, 'KDE' for gaussian_kde, and 'Rect' for rectangular.
- **alphas** (*list*) – List of alpha values used to determine if theta values are inside or outside the region.
- **test_theta_values** (*dictionary or DataFrame, keys/columns = theta_names, optional*) – Additional theta values that are compared to the confidence region to determine if they are inside or outside.

Returns

- **training_results** (*DataFrame*) – Theta value used to generate the confidence region along with True (inside) or False (outside) for each alpha
- **test_results** (*DataFrame*) – If test_theta_values is not None, returns test theta value along with True (inside) or False (outside) for each alpha

leaveNout_bootstrap_test(*lNo*, *lNo_samples*, *bootstrap_samples*, *distribution*, *alphas*, *seed=None*)

Leave-N-out bootstrap test to compare theta values where N data points are left out to a bootstrap analysis using the remaining data, results indicate if theta is within a confidence region determined by the bootstrap analysis

Parameters

- **lNo** (*int*) – Number of data points to leave out for parameter estimation
- **lNo_samples** (*int*) – Leave-N-out sample size. If lNo_samples=None, the maximum number of combinations will be used
- **bootstrap_samples** (*int:*) – Bootstrap sample size
- **distribution** (*string*) – Statistical distribution used to define a confidence region, options = 'MVN' for multivariate_normal, 'KDE' for gaussian_kde, and 'Rect' for rectangular.
- **alphas** (*list*) – List of alpha values used to determine if theta values are inside or outside the region.
- **seed** (*int or None, optional*) – Random seed

Returns

- *List of tuples with one entry per lNo_sample*
- ** The first item in each tuple is the list of N samples that are left* – out.
- ** The second item in each tuple is a DataFrame of theta estimated using* – the N samples.
- ** The third item in each tuple is a DataFrame containing results from* – the bootstrap analysis using the remaining samples.
- *For each DataFrame a column is added for each value of alpha which*
- *indicates if the theta estimate is in (True) or out (False) of the*
- *alpha region for a given distribution (based on the bootstrap results)*

likelihood_ratio_test(*obj_at_theta*, *obj_value*, *alphas*, *return_thresholds=False*)

Likelihood ratio test to identify theta values within a confidence region using the χ^2 distribution

Parameters

- **obj_at_theta** (*DataFrame, columns = theta_names + 'obj'*) – Objective values for each theta value (returned by objective_at_theta)
- **obj_value** (*int or float*) – Objective value from parameter estimation using all data
- **alphas** (*list*) – List of alpha values to use in the chi2 test
- **return_thresholds** (*bool, optional*) – Return the threshold value for each alpha

Returns

- **LR** (*DataFrame*) – Objective values for each theta value along with True or False for each alpha
- **thresholds** (*dictionary*) – If return_threshold = True, the thresholds are also returned.

objective_at_theta(*theta_values*)

Objective value for each theta

Parameters **theta_values** (*DataFrame, columns=theta_names*) – Values of theta used to compute the objective

Returns **obj_at_theta** – Objective value for each theta (infeasible solutions are omitted).

Return type DataFrame

theta_est(*solver='ef_ipopt'*, *return_values=[]*, *bootlist=None*, *calc_cov=False*)

Parameter estimation using all scenarios in the data

Parameters

- **solver** (*string, optional*) – "ef_ipopt" or "k_aug". Default is "ef_ipopt".
- **return_values** (*list, optional*) – List of Variable names used to return values from the model
- **bootlist** (*list, optional*) – List of bootstrap sample numbers, used internally when calling theta_est_bootstrap
- **calc_cov** (*boolean, optional*) – If True, calculate and return the covariance matrix (only for "ef_ipopt" solver)

Returns

- **objectiveval** (*float*) – The objective function value
- **thetavals** (*dict*) – A dictionary of all values for theta
- **variable values** (*pd.DataFrame*) – Variable values for each variable name in return_values (only for solver='ef_ipopt')
- **Hessian** (*dict*) – A dictionary of dictionaries for the Hessian (only for solver='k_aug')
- **cov** (*pd.DataFrame*) – Covariance matrix of the fitted parameters (only for solver='ef_ipopt')

theta_est_bootstrap(*bootstrap_samples*, *samplesize=None*, *replacement=True*, *seed=None*, *return_samples=False*)

Parameter estimation using bootstrap resampling of the data

Parameters

- **bootstrap_samples** (*int*) – Number of bootstrap samples to draw from the data
- **samplesize** (*int or None, optional*) – Size of each bootstrap sample. If samplesize=None, samplesize will be set to the number of samples in the data
- **replacement** (*bool, optional*) – Sample with or without replacement
- **seed** (*int or None, optional*) – Random seed
- **return_samples** (*bool, optional*) – Return a list of sample numbers used in each bootstrap estimation

Returns **bootstrap_theta** – Theta values for each sample and (if return_samples = True) the sample numbers used in each estimation

Return type DataFrame

theta_est_leaveNout(*lNo*, *lNo_samples=None*, *seed=None*, *return_samples=False*)

Parameter estimation where N data points are left out of each sample

Parameters

- **lNo** (*int*) – Number of data points to leave out for parameter estimation

- **lNo_samples** (*int*) – Number of leave-N-out samples. If lNo_samples=None, the maximum number of combinations will be used
- **seed** (*int or None, optional*) – Random seed
- **return_samples** (*bool, optional*) – Return a list of sample numbers that were left out

Returns **lNo_theta** – Theta values for each sample and (if return_samples = True) the sample numbers left out of each estimation

Return type DataFrame

pyomo.contrib.parmest.parmest.**ef_nonants**(*ef*)

pyomo.contrib.parmest.parmest.**group_data**(*data*, *groupby_column_name*, *use_mean=None*)

Group data by scenario

Parameters

- **data** (*DataFrame*) – Data
- **groupby_column_name** (*strings*) – Name of data column which contains scenario numbers
- **use_mean** (*list of column names or None, optional*) – Name of data columns which should be reduced to a single value per scenario by taking the mean

Returns **grouped_data** – Grouped data

Return type list of dictionaries

scenariocreator

class pyomo.contrib.parmest.scenariocreator.**ParmestScen**(*name*, *ThetaVals*, *probability*)

Bases: object

A little container for scenarios; the Args are the attributes.

Parameters

- **name** (*str*) – name for reporting; might be “”
- **ThetaVals** (*dict*) – ThetaVals[name]=val
- **probability** (*float*) – probability of occurance “near” these ThetaVals

class pyomo.contrib.parmest.scenariocreator.**ScenarioCreator**(*pest*, *solvername*)

Bases: object

Create scenarios from parmest.

Parameters

- **pest** (Estimator) – the parmest object
- **solvername** (*str*) – name of the solver (e.g. “ipopt”)

ScenariosFromBoostrap(*addtoSet*, *numtomake*, *seed=None*)

Creates new self.Scenarios list using the experiments only.

Parameters

- **addtoSet** (ScenarioSet) – the scenarios will be added to this set
- **numtomake** (*int*) – number of scenarios to create

ScenariosFromExperiments(*addtoSet*)

Creates new self.Scenarios list using the experiments only.

Parameters **addtoSet** (ScenarioSet) – the scenarios will be added to this set

Returns a ScenarioSet

class pyomo.contrib.parmest.scenariocreator.**ScenarioSet**(*name*)

Bases: object

Class to hold scenario sets

Args: name (str): name of the set (might be "")

ScenarioNumber(*scennum*)

Returns the scenario with the given, zero-based number

ScensIterator()

Usage: for scenario in ScensIterator()

addone(*scen*)

Add a scenario to the set

Parameters **scen** (ParmestScen) – the scenario to add

append_bootstrap(*bootstrap_theta*)

Append a boostrap theta df to the scenario set; equally likely

Parameters **boostrap_theta** (*dataframe*) – created by the bootstrap

Note: this can be cleaned up a lot with the list becomes a df, which is why I put it in the ScenarioSet class.

write_csv(*filename*)

write a csv file with the scenarios in the set

Parameters **filename** (*str*) – full path and full name of file

graphics

pyomo.contrib.parmest.graphics.**fit_kde_dist**(*theta_values*)

Fit a Gaussian kernel-density distribution to theta values

Parameters **theta_values** (*DataFrame*) – Theta values, columns = variable names

Returns

Return type scipy.stats.gaussian_kde distribution

pyomo.contrib.parmest.graphics.**fit_mvn_dist**(*theta_values*)

Fit a multivariate normal distribution to theta values

Parameters **theta_values** (*DataFrame*) – Theta values, columns = variable names

Returns

Return type scipy.stats.multivariate_normal distribution

pyomo.contrib.parmest.graphics.**fit_rect_dist**(*theta_values*, *alpha*)

Fit an alpha-level rectangular distribution to theta values

Parameters

- **theta_values** (*DataFrame*) – Theta values, columns = variable names
- **alpha** (*float, optional*) – Confidence interval value

Returns

Return type tuple containing lower bound and upper bound for each variable

pyomo.contrib.parmest.graphics.**grouped_boxplot**(*data1*, *data2*, *normalize=False*, *group_names=['data1', 'data2']*, *filename=None*)

Plot a grouped boxplot to compare two datasets

The datasets can be normalized by the median and standard deviation of data1.

Parameters

- **data1** (*DataFrame*) – Data set, columns = variable names
- **data2** (*DataFrame*) – Data set, columns = variable names
- **normalize** (*bool, optional*) – Normalize both datasets by the median and standard deviation of data1
- **group_names** (*list, optional*) – Names used in the legend
- **filename** (*string, optional*) – Filename used to save the figure

pyomo.contrib.parmest.graphics.**grouped_violinplot**(*data1*, *data2*, *normalize=False*, *group_names=['data1', 'data2']*, *filename=None*)

Plot a grouped violinplot to compare two datasets

The datasets can be normalized by the median and standard deviation of data1.

Parameters

- **data1** (*DataFrame*) – Data set, columns = variable names
- **data2** (*DataFrame*) – Data set, columns = variable names
- **normalize** (*bool, optional*) – Normalize both datasets by the median and standard deviation of data1
- **group_names** (*list, optional*) – Names used in the legend
- **filename** (*string, optional*) – Filename used to save the figure

pyomo.contrib.parmest.graphics.**pairwise_plot**(*theta_values*, *theta_star=None*, *alpha=None*, *distributions=[]*, *axis_limits=None*, *title=None*, *add_obj_contour=True*, *add_legend=True*, *filename=None*)

Plot pairwise relationship for theta values, and optionally alpha-level confidence intervals and objective value contours

Parameters

- **theta_values** (*DataFrame or tuple*) –
  - If theta_values is a DataFrame, then it contains one column for each theta variable and (optionally) an objective value column ('obj') and columns that contains Boolean results from confidence interval tests (labeled using the alpha value). Each row is a sample.
    - Theta variables can be computed from `theta_est_bootstrap`, `theta_est_leaveNout`, and `leaveNout_bootstrap_test`.
    - The objective value can be computed using the `likelihood_ratio_test`.
    - Results from confidence interval tests can be computed using the `leaveNout_bootstrap_test`, `likelihood_ratio_test`, and `confidence_region_test`.
  - If theta_values is a tuple, then it contains a mean, covariance, and number of samples (mean, cov, n) where mean is a dictionary or Series (indexed by variable name), covariance is a DataFrame (indexed by variable name, one column per variable name), and n is an integer. The mean and covariance are used to create a multivariate normal sample of n theta values. The covariance can be computed using `theta_est(calc_cov=True)`.

- **theta_star** (*dict or Series, optional*) – Estimated value of theta. The dictionary or Series is indexed by variable name. Theta_star is used to slice higher dimensional contour intervals in 2D
- **alpha** (*float, optional*) – Confidence interval value, if an alpha value is given and the distributions list is empty, the data will be filtered by True/False values using the column name whose value equals alpha (see results from `leaveNout_bootstrap_test`, `likelihood_ratio_test`, and `confidence_region_test`)
- **distributions** (*list of strings, optional*) – Statistical distribution used to define a confidence region, options = 'MVN' for multivariate_normal, 'KDE' for gaussian_kde, and 'Rect' for rectangular. Confidence interval is a 2D slice, using linear interpolation at theta_star.
- **axis_limits** (*dict, optional*) – Axis limits in the format {variable: [min, max]}
- **title** (*string, optional*) – Plot title
- **add_obj_contour** (*bool, optional*) – Add a contour plot using the column 'obj' in theta_values. Contour plot is a 2D slice, using linear interpolation at theta_star.
- **add_legend** (*bool, optional*) – Add a legend to the plot
- **filename** (*string, optional*) – Filename used to save the figure

Indices and Tables

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- modindex
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15.7 PyNumero

PyNumero is a package for developing parallel algorithms for nonlinear programs (NLPs). This documentation provides a brief introduction to PyNumero. For more details, see the API documentation (*PyNumero API*).

15.7.1 PyNumero Installation

PyNumero is a module within Pyomo. Therefore, Pyomo must be installed to use PyNumero. PyNumero also has some extensions that need built. There are many ways to build the PyNumero extensions. Common use cases are listed below. However, more information can always be found at https://github.com/Pyomo/pyomo/blob/main/pyomo/contrib/pynumero/build.py and https://github.com/Pyomo/pyomo/blob/main/pyomo/contrib/pynumero/src/CMakeLists.txt.

Method 1

One way to build PyNumero extensions is with the pyomo download-extensions and build-extensions subcommands. Note that this approach will build PyNumero without support for the HSL linear solvers.

```
pyomo download-extensions
pyomo build-extensions
```

Method 2

If you want PyNumero support for the HSL solvers and you have an IPOPT compilation for your machine, you can build PyNumero using the build script

```
cd pyomo/contrib/pynumero/
python build.py -DBUILD_ASL=ON -DBUILD_MA27=ON -DIPOPT_DIR=<path/to/ipopt/build/>
```

15.7.2 10 Minutes to PyNumero

NLP Interfaces

Below are examples of using PyNumero's interfaces to ASL for function and derivative evaluation. More information can be found in the API documentation (*PyNumero API*).

Relevant imports

```
>>> import pyomo.environ as pe
>>> from pyomo.contrib.pynumero.interfaces.pyomo_nlp import PyomoNLP
>>> import numpy as np
```

Create a Pyomo model

```
>>> m = pe.ConcreteModel()
>>> m.x = pe.Var(bounds=(-5, None))
>>> m.y = pe.Var(initialize=2.5)
>>> m.obj = pe.Objective(expr=m.x**2 + m.y**2)
>>> m.c1 = pe.Constraint(expr=m.y == (m.x - 1)**2)
>>> m.c2 = pe.Constraint(expr=m.y >= pe.exp(m.x))
```

Create a `pyomo.contrib.pynumero.interfaces.pyomo_nlp.PyomoNLP` instance

```
>>> nlp = PyomoNLP(m)
```

Get values of primals and duals

```
>>> nlp.get_primals()
array([0. , 2.5])
>>> nlp.get_duals()
array([0., 0.])
```

Get variable and constraint bounds

```
>>> nlp.primals_lb()
array([ -5., -inf])
>>> nlp.primals_ub()
array([inf, inf])
>>> nlp.constraints_lb()
array([  0., -inf])
>>> nlp.constraints_ub()
array([0., 0.])
```

Objective and constraint evaluations

```
>>> nlp.evaluate_objective()
6.25
>>> nlp.evaluate_constraints()
array([ 1.5, -1.5])
```

Derivative evaluations

```
>>> nlp.evaluate_grad_objective()
array([0., 5.])
>>> nlp.evaluate_jacobian()
<2x2 sparse matrix of type '<class 'numpy.float64'>'
    with 4 stored elements in COOrdinate format>
>>> nlp.evaluate_jacobian().toarray()
array([[ 2.,  1.],
       [ 1., -1.]])
>>> nlp.evaluate_hessian_lag().toarray()
array([[2., 0.],
       [0., 2.]])
```

Set values of primals and duals

```
>>> nlp.set_primals(np.array([0, 1]))
>>> nlp.evaluate_constraints()
array([0., 0.])
>>> nlp.set_duals(np.array([-2/3, 4/3]))
>>> nlp.evaluate_grad_objective() + nlp.evaluate_jacobian().transpose() * nlp.get_duals()
array([0., 0.])
```

Equality and inequality constraints separately

```
>>> nlp.evaluate_eq_constraints()
array([0.])
>>> nlp.evaluate_jacobian_eq().toarray()
array([[2., 1.]])
>>> nlp.evaluate_ineq_constraints()
array([0.])
>>> nlp.evaluate_jacobian_ineq().toarray()
array([[ 1., -1.]])
>>> nlp.get_duals_eq()
array([-0.66666667])
>>> nlp.get_duals_ineq()
array([1.33333333])
```

Linear Solver Interfaces

PyNumero's interfaces to linear solvers are very thin wrappers, and, hence, are rather low-level. It is relatively easy to wrap these again for specific applications. For example, see the linear solver interfaces in https://github.com/Pyomo/pyomo/tree/main/pyomo/contrib/interior_point/linalg, which wrap PyNumero's linear solver interfaces.

The motivation to keep PyNumero's interfaces as such thin wrappers is that different linear solvers serve different purposes. For example, HSL's MA27 can factorize symmetric indefinite matrices, while MUMPS can factorize unsymmetric, symmetric positive definite, or general symmetric matrices. PyNumero seeks to be independent of the application, giving more flexibility to algorithm developers.

Interface to MA27

```
>>> import numpy as np
>>> from scipy.sparse import coo_matrix
>>> from scipy.sparse import tril
>>> from pyomo.contrib.pynumero.linalg.ma27 import MA27Interface
>>> row = np.array([0, 1, 0, 1, 0, 1, 2, 3, 3, 4, 4, 4])
>>> col = np.array([0, 1, 3, 3, 4, 4, 4, 0, 1, 0, 1, 2])
>>> data = np.array([1.67025575, 2, -1.64872127,  1, -1, -1, -1, -1.64872127, 1, -1, -1,␣
↪-1])
>>> A = coo_matrix((data, (row, col)), shape=(5,5))
>>> A.toarray()
array([[ 1.67025575,  0.        ,  0.        , -1.64872127, -1.        ],
       [ 0.        ,  2.        ,  0.        ,  1.        , -1.        ],
       [ 0.        ,  0.        ,  0.        ,  0.        , -1.        ],
       [-1.64872127,  1.        ,  0.        ,  0.        ,  0.        ],
       [-1.        , -1.        , -1.        ,  0.        ,  0.        ]])
>>> rhs = np.array([-0.67025575, -1.2,  0.1,  1.14872127,  1.25])
>>> solver = MA27Interface()
>>> solver.set_cntl(1, 1e-6)  # set the pivot tolerance
>>> A_tril = tril(A)  # extract lower triangular portion of A
>>> status = solver.do_symbolic_factorization(dim=5, irn=A_tril.row, icn=A_tril.col)
>>> status = solver.do_numeric_factorization(dim=5, irn=A_tril.row, icn=A_tril.col,␣
↪entries=A_tril.data)
>>> x = solver.do_backsolve(rhs)
>>> np.max(np.abs(A*x - rhs)) <= 1e-15
True
```

Interface to MUMPS

```
>>> import numpy as np
>>> from scipy.sparse import coo_matrix
>>> from scipy.sparse import tril
>>> from pyomo.contrib.pynumero.linalg.mumps_interface import␣
↪MumpsCentralizedAssembledLinearSolver
>>> row = np.array([0, 1, 0, 1, 0, 1, 2, 3, 3, 4, 4, 4])
>>> col = np.array([0, 1, 3, 3, 4, 4, 4, 0, 1, 0, 1, 2])
>>> data = np.array([1.67025575, 2, -1.64872127,  1, -1, -1, -1, -1.64872127, 1, -1, -1,␣
↪-1])
>>> A = coo_matrix((data, (row, col)), shape=(5,5))
```

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```
>>> A.toarray()
array([[ 1.67025575,  0.        ,  0.        , -1.64872127, -1.        ],
       [ 0.        ,  2.        ,  0.        ,  1.        , -1.        ],
       [ 0.        ,  0.        ,  0.        ,  0.        , -1.        ],
       [-1.64872127,  1.        ,  0.        ,  0.        ,  0.        ],
       [-1.        , -1.        , -1.        ,  0.        ,  0.        ]])
>>> rhs = np.array([-0.67025575, -1.2,  0.1,  1.14872127,  1.25])
>>> solver = MumpsCentralizedAssembledLinearSolver(sym=2, par=1, comm=None)  # symmetric␣
↪matrix; solve in serial
>>> A_tril = tril(A)  # extract lower triangular portion of A
>>> solver.do_symbolic_factorization(A_tril)
>>> solver.do_numeric_factorization(A_tril)
>>> x = solver.do_back_solve(rhs)
>>> np.max(np.abs(A*x - rhs)) <= 1e-15
True
```

Of course, SciPy solvers can also be used. See SciPy documentation for details.

Block Vectors and Matrices

Block vectors and matrices (*BlockVector* and `BlockMatrix`) provide a mechanism to perform linear algebra operations with very structured matrices and vectors.

When a BlockVector or BlockMatrix is constructed, the number of blocks must be specified.

```
>>> import numpy as np
>>> from scipy.sparse import coo_matrix
>>> from pyomo.contrib.pynumero.sparse import BlockVector, BlockMatrix
>>> v = BlockVector(3)
>>> m = BlockMatrix(3, 3)
```

Setting blocks:

```
>>> v.set_block(0, np.array([-0.67025575, -1.2]))
>>> v.set_block(1, np.array([0.1, 1.14872127]))
>>> v.set_block(2, np.array([1.25]))
>>> v.flatten()
array([-0.67025575, -1.2       ,  0.1       ,  1.14872127,  1.25      ])
```

The *flatten* method converts the BlockVector into a NumPy array.

```
>>> m.set_block(0, 0, coo_matrix(np.array([[1.67025575, 0], [0, 2]])))
>>> m.set_block(0, 1, coo_matrix(np.array([[0, -1.64872127], [0, 1]])))
>>> m.set_block(0, 2, coo_matrix(np.array([[-1.0], [-1]])))
>>> m.set_block(1, 0, coo_matrix(np.array([[0, -1.64872127], [0, 1]])).transpose())
>>> m.set_block(1, 2, coo_matrix(np.array([[-1.0], [0]])))
>>> m.set_block(2, 0, coo_matrix(np.array([[-1.0], [-1]])).transpose())
>>> m.set_block(2, 1, coo_matrix(np.array([[-1.0], [0]])).transpose())
>>> m.tocoo().toarray()
array([[ 1.67025575,  0.        ,  0.        , -1.64872127, -1.        ],
       [ 0.        ,  2.        ,  0.        ,  1.        , -1.        ],
       [ 0.        ,  0.        ,  0.        ,  0.        , -1.        ],
```

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```
       [-1.64872127,  1.        ,  0.        ,  0.        ,  0.        ],
       [-1.        , -1.        , -1.        ,  0.        ,  0.        ]])
```

The *tocoo* method converts the *BlockMatrix* to a SciPy sparse *coo_matrix*.

Once the dimensions of a block have been set, they cannot be changed:

```
>>> v.set_block(0, np.ones(3))
Traceback (most recent call last):
  ...
ValueError: Incompatible dimensions for block 0; got 3; expected 2
```

Properties:

```
>>> v.shape
(5,)
>>> v.size
5
>>> v.nblocks
3
>>> v.bshape
(3,)
>>> m.shape
(5, 5)
>>> m.bshape
(3, 3)
>>> m.nnz
12
```

Much of the *BlockVector* API matches that of NumPy arrays:

```
>>> v.sum()
0.62846552
>>> v.max()
1.25
>>> np.abs(v).flatten()
array([0.67025575, 1.2       , 0.1       , 1.14872127, 1.25      ])
>>> (2*v).flatten()
array([-1.3405115 , -2.4       ,  0.2       ,  2.29744254,  2.5       ])
>>> (v + v).flatten()
array([-1.3405115 , -2.4       ,  0.2       ,  2.29744254,  2.5       ])
>>> v.dot(v)
4.781303326558476
```

Similarly, *BlockMatrix* behaves very similarly to SciPy sparse matrices:

```
>>> (2*m).tocoo().toarray()
array([[ 3.3405115 ,  0.        ,  0.        , -3.29744254, -2.        ],
       [ 0.        ,  4.        ,  0.        ,  2.        , -2.        ],
       [ 0.        ,  0.        ,  0.        ,  0.        , -2.        ],
       [-3.29744254,  2.        ,  0.        ,  0.        ,  0.        ],
       [-2.        , -2.        , -2.        ,  0.        ,  0.        ]])
>>> (m - m).tocoo().toarray()
```

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```
array([[0., 0., 0., 0., 0.],
       [0., 0., 0., 0., 0.],
       [0., 0., 0., 0., 0.],
       [0., 0., 0., 0., 0.],
       [0., 0., 0., 0., 0.]])
>>> m * v
BlockVector(3,)
>>> (m * v).flatten()
array([-4.26341971, -2.50127873, -1.25      , -0.09493509,  1.77025575])
```

Accessing blocks

```
>>> v.get_block(1)
array([0.1       , 1.14872127])
>>> m.get_block(1, 0).toarray()
array([[ 0.        ,  0.        ],
       [-1.64872127,  1.        ]])
```

Empty blocks in a *BlockMatrix* return *None*:

```
>>> print(m.get_block(1, 1))
None
```

The dimensions of a blocks in a *BlockMatrix* can be set without setting a block:

```
>>> m2 = BlockMatrix(2, 2)
>>> m2.set_row_size(0, 5)
>>> m2.set_block(0, 0, m.get_block(0, 0))
Traceback (most recent call last):
  ...
ValueError: Incompatible row dimensions for row 0; got 2; expected 5.0
```

Note that operations on *BlockVector* and *BlockMatrix* cannot be performed until the dimensions are fully specified:

```
>>> v2 = BlockVector(3)
>>> v + v2
Traceback (most recent call last):
  ...
NotFullyDefinedBlockVectorError: Operation not allowed with None blocks.
>>> m2 = BlockMatrix(3, 3)
>>> m2 * 2
Traceback (most recent call last):
  ...
NotFullyDefinedBlockMatrixError: Operation not allowed with None rows. Specify at least␣
↪one block in every row
```

The *has_none* property can be used to see if a *BlockVector* is fully specified. If *has_none* returns *True*, then there are *None* blocks, and the *BlockVector* is not fully specified.

```
>>> v.has_none
False
>>> v2.has_none
True
```

For *BlockMatrix*, use the *has_undefined_row_sizes()* and *has_undefined_col_sizes()* methods:

```
>>> m.has_undefined_row_sizes()
False
>>> m.has_undefined_col_sizes()
False
>>> m2.has_undefined_row_sizes()
True
>>> m2.has_undefined_col_sizes()
True
```

To efficiently iterate over non-empty blocks in a *BlockMatrix*, use the *get_block_mask()* method, which returns a 2-D array indicating where the non-empty blocks are:

```
>>> m.get_block_mask(copy=False)
array([[ True,  True,  True],
       [ True, False,  True],
       [ True,  True, False]])
>>> for i, j in zip(*np.nonzero(m.get_block_mask(copy=False))):
...     assert m.get_block(i, j) is not None
```

Copying data:

```
>>> v2 = v.copy()
>>> v2.flatten()
array([-0.67025575, -1.2       ,  0.1       ,  1.14872127,  1.25      ])
>>> v2 = v.copy_structure()
>>> v2.block_sizes()
array([2, 2, 1])
>>> v2.copyfrom(v)
>>> v2.flatten()
array([-0.67025575, -1.2       ,  0.1       ,  1.14872127,  1.25      ])
>>> m2 = m.copy()
>>> (m - m2).tocoo().toarray()
array([[0., 0., 0., 0., 0.],
       [0., 0., 0., 0., 0.],
       [0., 0., 0., 0., 0.],
       [0., 0., 0., 0., 0.],
       [0., 0., 0., 0., 0.]])
>>> m2 = m.copy_structure()
>>> m2.has_undefined_row_sizes()
False
>>> m2.has_undefined_col_sizes()
False
>>> m2.copyfrom(m)
>>> (m - m2).tocoo().toarray()
array([[0., 0., 0., 0., 0.],
       [0., 0., 0., 0., 0.],
       [0., 0., 0., 0., 0.],
       [0., 0., 0., 0., 0.],
       [0., 0., 0., 0., 0.]])
```

Nested blocks:

```
>>> v2 = BlockVector(2)
>>> v2.set_block(0, v)
>>> v2.set_block(1, np.ones(2))
>>> v2.block_sizes()
array([5, 2])
>>> v2.flatten()
array([-0.67025575, -1.2       ,  0.1       ,  1.14872127,  1.25      ,
        1.        ,  1.        ])
>>> v3 = v2.copy_structure()
>>> v3.fill(1)
>>> (v2 + v3).flatten()
array([ 0.32974425, -0.2       ,  1.1       ,  2.14872127,  2.25      ,
        2.        ,  2.        ])
>>> np.abs(v2).flatten()
array([0.67025575, 1.2       , 0.1       , 1.14872127, 1.25      ,
       1.        , 1.        ])
>>> v2.get_block(0)
BlockVector(3,)
```

Nested *BlockMatrix* applications work similarly.

For more information, see the API documentation (*PyNumero API*).

MPI-Based Block Vectors and Matrices

PyNumero's MPI-based block vectors and matrices (`MPIBlockVector` and `MPIBlockMatrix`) behave very similarly to *BlockVector* and *BlockMatrix*. The primary difference is in construction. With *MPIBlockVector* and *MPIBlockMatrix*, each block is owned by either a single process/rank or all processes/ranks.

Consider the following example (in a file called "parallel_vector_ops.py").

```
import numpy as np
from mpi4py import MPI
from pyomo.contrib.pynumero.sparse.mpi_block_vector import MPIBlockVector


def main():
    comm = MPI.COMM_WORLD
    rank = comm.Get_rank()

    owners = [2, 0, 1, -1]
    x = MPIBlockVector(4, rank_owner=owners, mpi_comm=comm)
    x.set_block(owners.index(rank), np.ones(3)*(rank + 1))
    x.set_block(3, np.array([1, 2, 3]))

    y = MPIBlockVector(4, rank_owner=owners, mpi_comm=comm)
    y.set_block(owners.index(rank), np.ones(3)*(rank + 1))
    y.set_block(3, np.array([1, 2, 3]))

    z1: MPIBlockVector = x + y  # add x and y
    z2 = x.dot(y)  # dot product
    z3 = np.abs(x).max()  # infinity norm
```

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```
    z1_local = z1.make_local_copy()
    if rank == 0:
        print(z1_local.flatten())
        print(z2)
        print(z3)

    return z1_local, z2, z3


if __name__ == '__main__':
    main()
```

This example can be run with

```
mpirun -np 3 python -m mpi4py parallel_vector_ops.py
```

The output is

```
[6. 6. 6. 2. 2. 2. 4. 4. 4. 2. 4. 6.]
56.0
3
```

Note that the *make_local_copy()* method is not efficient and should only be used for debugging.

The -1 in *owners* means that the block at that index (index 3 in this example) is owned by all processes. The non-negative integer values indicate that the block at that index is owned by the process with rank equal to the value. In this example, rank 0 owns block 1, rank 1 owns block 2, and rank 2 owns block 0. Block 3 is owned by all ranks. Note that blocks should only be set if the process/rank owns that block.

The operations performed with *MPIBlockVector* are identical to the same operations peformed with *BlockVector* (or even NumPy arrays), except that the operations are now performed in parallel.

MPIBlockMatrix construction is very similar. Consider the following example in a file called "parallel_matvec.py".

```
import numpy as np
from mpi4py import MPI
from pyomo.contrib.pynumero.sparse.mpi_block_vector import MPIBlockVector
from pyomo.contrib.pynumero.sparse.mpi_block_matrix import MPIBlockMatrix
from scipy.sparse import random


def main():
    comm = MPI.COMM_WORLD
    rank = comm.Get_rank()

    owners = [0, 1, 2, -1]
    x = MPIBlockVector(4, rank_owner=owners, mpi_comm=comm)

    owners = np.array([[ 0, -1, -1, 0],
                       [-1,  1, -1, 1],
                       [-1, -1,  2, 2]])
    a = MPIBlockMatrix(3, 4, rank_ownership=owners, mpi_comm=comm)

    np.random.seed(0)
```

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```
    x.set_block(3, np.random.uniform(-10, 10, size=10))

    np.random.seed(rank)
    x.set_block(rank, np.random.uniform(-10, 10, size=10))
    a.set_block(rank, rank, random(10, 10, density=0.1))
    a.set_block(rank, 3, random(10, 10, density=0.1))

    b = a * x  # parallel matrix-vector dot product

    # check the answer
    local_x = x.make_local_copy().flatten()
    local_a = a.to_local_array()
    local_b = b.make_local_copy().flatten()

    err = np.abs(local_a.dot(local_x) - local_b).max()

    if rank == 0:
        print('error: ', err)

    return err


if __name__ == '__main__':
    main()
```

Which can be run with

```
mpirun -np 3 python -m mpi4py parallel_matvec.py
```

The output is

```
error:  4.440892098500626e-16
```

The most difficult part of using *MPIBlockVector* and *MPIBlockMatrix* is determining the best structure and rank ownership to maximize parallel efficiency.

Other examples may be found at https://github.com/Pyomo/pyomo/tree/main/pyomo/contrib/pynumero/examples.

15.7.3 PyNumero API

PyNumero Block Linear Algebra

BlockVector

Methods specific to *pyomo.contrib.pynumero.sparse.block_vector.BlockVector*:

- *set_block()*
- *get_block()*
- *block_sizes()*
- *get_block_size()*
- *is_block_defined()*

- *copyfrom()*
- *copyto()*
- *copy_structure()*
- *set_blocks()*
- *pprint()*

Attributes specific to *pyomo.contrib.pynumero.sparse.block_vector.BlockVector*:

- *nblocks()*
- *bshape()*
- *has_none()*

NumPy compatible methods:

- numpy.ndarray.dot()
- numpy.ndarray.sum()
- numpy.ndarray.all()
- numpy.ndarray.any()
- numpy.ndarray.max()
- numpy.ndarray.astype()
- numpy.ndarray.clip()
- numpy.ndarray.compress()
- numpy.ndarray.conj()
- numpy.ndarray.conjugate()
- numpy.ndarray.nonzero()
- numpy.ndarray.ptp()
- numpy.ndarray.round()
- numpy.ndarray.std()
- numpy.ndarray.var()
- numpy.ndarray.tofile()
- numpy.ndarray.min()
- numpy.ndarray.mean()
- numpy.ndarray.prod()
- numpy.ndarray.fill()
- numpy.ndarray.tolist()
- numpy.ndarray.flatten()
- numpy.ndarray.ravel()
- numpy.ndarray.argmax()
- numpy.ndarray.argmin()
- numpy.ndarray.cumprod()

- numpy.ndarray.cumsum()
- numpy.ndarray.copy()

For example,

```
>>> import numpy as np
>>> from pyomo.contrib.pynumero.sparse import BlockVector
>>> v = BlockVector(2)
>>> v.set_block(0, np.random.normal(size=100))
>>> v.set_block(1, np.random.normal(size=30))
>>> avg = v.mean()
```

NumPy compatible functions:

- numpy.log10()
- numpy.sin()
- numpy.cos()
- numpy.exp()
- numpy.ceil()
- numpy.floor()
- numpy.tan()
- numpy.arctan()
- numpy.arcsin()
- numpy.arccos()
- numpy.sinh()
- numpy.cosh()
- numpy.abs()
- numpy.tanh()
- numpy.arccosh()
- numpy.arcsinh()
- numpy.arctanh()
- numpy.fabs()
- numpy.sqrt()
- numpy.log()
- numpy.log2()
- numpy.absolute()
- numpy.isfinite()
- numpy.isinf()
- numpy.isnan()
- numpy.log1p()
- numpy.logical_not()

- numpy.expm1()
- numpy.exp2()
- numpy.sign()
- numpy.rint()
- numpy.square()
- numpy.positive()
- numpy.negative()
- numpy.rad2deg()
- numpy.deg2rad()
- numpy.conjugate()
- numpy.reciprocal()
- numpy.signbit()
- numpy.add()
- numpy.multiply()
- numpy.divide()
- numpy.subtract()
- numpy.greater()
- numpy.greater_equal()
- numpy.less()
- numpy.less_equal()
- numpy.not_equal()
- numpy.maximum()
- numpy.minimum()
- numpy.fmax()
- numpy.fmin()
- numpy.equal()
- numpy.logical_and()
- numpy.logical_or()
- numpy.logical_xor()
- numpy.logaddexp()
- numpy.logaddexp2()
- numpy.remainder()
- numpy.heaviside()
- numpy.hypot()

For example,

```
>>> import numpy as np
>>> from pyomo.contrib.pynumero.sparse import BlockVector
>>> v = BlockVector(2)
>>> v.set_block(0, np.random.normal(size=100))
>>> v.set_block(1, np.random.normal(size=30))
>>> inf_norm = np.max(np.abs(v))
```

class pyomo.contrib.pynumero.sparse.block_vector.**BlockVector**(*nblocks*)

Structured vector interface. This interface can be used to performe operations on vectors composed by vectors. For example,

>> import numpy as np >> from pyomo.contrib.pynumero.sparse import BlockVector >> bv = BlockVector(3) >> v0 = np.ones(3) >> v1 = v0*2 >> v2 = np.random.normal(size=4) >> bv.set_block(0, v0) >> bv.set_block(1, v1) >> bv.set_block(2, v2) >> bv2 = BlockVector(2) >> bv2.set_block(0, v0) >> bv2.set_block(1, bv)

_nblocks

number of blocks

Type int

_brow_lengths

1D-Array of size nblocks that specifies the length of each entry in the block vector

Type numpy.ndarray

_undefined_brows

A set of block indices for which the blocks are still None (i.e., the dimensions have not yet ben set). Operations with BlockVectors require all entries to be different than None.

Type set

Parameters **nblocks** (*int*) – The number of blocks in the BlockVector

BlockVector.**set_block**(*key*, *value*)

Set a block. The value can be a NumPy array or another BlockVector.

Parameters

- **key** (*int*) – This is the block index
- **value** – This is the block. It can be a NumPy array or another BlockVector.

BlockVector.**get_block**(*key*)

Access a block.

Parameters **key** (*int*) – This is the block index

Returns **block** – The block corresponding to the index key.

Return type np.ndarray or *BlockVector*

BlockVector.**block_sizes**(*copy=True*)

Returns 1D-Array with sizes of individual blocks in this BlockVector

BlockVector.**get_block_size**(*ndx*)

BlockVector.**is_block_defined**(*ndx*)

BlockVector.**copyfrom**(*other*)

Copy entries of other vector into this vector

Parameters **other** (BlockVector *or* *numpy.ndarray*) – vector to be copied to this BlockVector

Returns

Return type None

BlockVector.**copyto**(*other*)

Copy entries of this BlockVector into other

Parameters **other** (BlockVector *or* *numpy.ndarray*) –
Returns
Return type None

BlockVector.**copy_structure**()
Returns a copy of the BlockVector structure filled with zeros

BlockVector.**set_blocks**(*blocks*)
Assigns vectors in blocks
Parameters **blocks** (*list*) – list of numpy.ndarrays and/or BlockVectors
Returns
Return type None

BlockVector.**pprint**()
Prints BlockVector in pretty format

BlockVector.**nblocks**()
Returns the number of blocks.

BlockVector.**bshape**()
Returns the number of blocks in this BlockVector in a tuple.

BlockVector.**has_none**()
Indicate if this BlockVector has any none entries.

PyNumero NLP Interfaces

NLP Interface

class pyomo.contrib.pynumero.interfaces.nlp.**NLP**
Bases: object

constraint_names()
Override this to provide string names for the constraints

abstract constraints_lb()
Returns vector of lower bounds for the constraints
Returns
Return type vector-like

abstract constraints_ub()
Returns vector of upper bounds for the constraints
Returns
Return type vector-like

abstract create_new_vector(*vector_type*)
Creates a vector of the appropriate length and structure as requested
Parameters **vector_type** (*{'primals', 'constraints', 'duals'}*) – String identifying the appropriate vector to create.
Returns
Return type vector-like

abstract evaluate_constraints(*out=None*)
Returns the values for the constraints evaluated at the values given for the primal variales in set_primals
Parameters **out** (*array_like, optional*) – Output array. Its type is preserved and it must be of the right shape to hold the output.

Returns

Return type vector_like

abstract evaluate_grad_objective(*out=None*)

Returns gradient of the objective function evaluated at the values given for the primal variables in set_primals

Parameters **out** (*vector_like, optional*) – Output vector. Its type is preserved and it must be of the right shape to hold the output.

Returns

Return type vector_like

abstract evaluate_hessian_lag(*out=None*)

Return the Hessian of the Lagrangian function evaluated at the values given for the primal variables in set_primals and the dual variables in set_duals

Parameters **out** (*matrix_like (e.g., coo_matrix), optional*) – Output matrix with the structure of the hessian already defined. Optional

Returns

Return type matrix_like

abstract evaluate_jacobian(*out=None*)

Returns the Jacobian of the constraints evaluated at the values given for the primal variables in set_primals

Parameters **out** (*matrix_like (e.g., coo_matrix), optional*) – Output matrix with the structure of the jacobian already defined.

Returns

Return type matrix_like

abstract evaluate_objective()

Returns value of objective function evaluated at the values given for the primal variables in set_primals

Returns

Return type float

abstract get_constraints_scaling()

Return the desired scaling factors to use for the for the constraints. None indicates no scaling. This indicates potential scaling for the model, but the evaluation methods should return *unscaled* values

Returns

Return type array-like or None

abstract get_duals()

Get a copy of the values of the dual variables as provided in set_duals. These are the values that will be used in calls to the evaluation methods.

abstract get_obj_factor()

Get the value of the objective function factor as set by set_obj_factor. This is the value that will be used in calls to the evaluation of the hessian of the lagrangian (evaluate_hessian_lag)

abstract get_obj_scaling()

Return the desired scaling factor to use for the for the objective function. None indicates no scaling. This indicates potential scaling for the model, but the evaluation methods should return *unscaled* values

Returns

Return type float or None

abstract get_primals()
Get a copy of the values of the primal variables as provided in set_primals. These are the values that will be used in calls to the evaluation methods

abstract get_primals_scaling()
Return the desired scaling factors to use for the for the primals. None indicates no scaling. This indicates potential scaling for the model, but the evaluation methods should return *unscaled* values

Returns

Return type array-like or None

abstract init_duals()
Returns vector with initial values for the dual variables of the constraints

abstract init_primals()
Returns vector with initial values for the primal variables

abstract n_constraints()
Returns number of constraints

abstract n_primals()
Returns number of primal variables

abstract nnz_hessian_lag()
Returns number of nonzero values in hessian of the lagrangian function

abstract nnz_jacobian()
Returns number of nonzero values in jacobian of equality constraints

abstract primals_lb()
Returns vector of lower bounds for the primal variables

Returns

Return type vector-like

primals_names()
Override this to provide string names for the primal variables

abstract primals_ub()
Returns vector of upper bounds for the primal variables

Returns

Return type vector-like

abstract report_solver_status(*status_code*, *status_message*)
Report the solver status to NLP class using the values for the primals and duals defined in the set methods

abstract set_duals(*duals*)
Set the value of the dual variables for the constraints to be used in calls to the evaluation methods (hessian_lag)

Parameters **duals** (*vector_like*) – Vector with the values of dual variables for the equality constraints

abstract set_obj_factor(*obj_factor*)
Set the value of the objective function factor to be used in calls to the evaluation of the hessian of the lagrangian (evaluate_hessian_lag)

Parameters **obj_factor** (*float*) – Value of the objective function factor used in the evaluation of the hessian of the lagrangian

abstract set_primals(*primals*)
Set the value of the primal variables to be used in calls to the evaluation methods

Parameters **primals** (*vector_like*) – Vector with the values of primal variables.

Extended NLP Interface

class pyomo.contrib.pynumero.interfaces.nlp.**ExtendedNLP**

Bases: *pyomo.contrib.pynumero.interfaces.nlp.NLP*

This interface extends the NLP interface to support a presentation of the problem that separates equality and inequality constraints

constraint_names()

Override this to provide string names for the constraints

abstract constraints_lb()

Returns vector of lower bounds for the constraints

Returns

Return type vector-like

abstract constraints_ub()

Returns vector of upper bounds for the constraints

Returns

Return type vector-like

abstract create_new_vector(*vector_type*)

Creates a vector of the appropriate length and structure as requested

Parameters **vector_type** ({*'primals'*, *'constraints'*, *'eq_constraints'*, *'ineq_constraints'*,}) – 'duals', 'duals_eq', 'duals_ineq'} String identifying the appropriate vector to create.

Returns

Return type vector-like

abstract evaluate_constraints(*out=None*)

Returns the values for the constraints evaluated at the values given for the primal variales in set_primals

Parameters **out** (*array_like, optional*) – Output array. Its type is preserved and it must be of the right shape to hold the output.

Returns

Return type vector_like

abstract evaluate_eq_constraints(*out=None*)

Returns the values for the equality constraints evaluated at the values given for the primal variales in set_primals

Parameters **out** (*array_like, optional*) – Output array. Its type is preserved and it must be of the right shape to hold the output.

Returns

Return type vector_like

abstract evaluate_grad_objective(*out=None*)

Returns gradient of the objective function evaluated at the values given for the primal variables in set_primals

Parameters **out** (*vector_like, optional*) – Output vector. Its type is preserved and it must be of the right shape to hold the output.

Returns

Return type vector_like

abstract evaluate_hessian_lag(*out=None*)

Return the Hessian of the Lagrangian function evaluated at the values given for the primal variables in set_primals and the dual variables in set_duals

Parameters **out** (*matrix_like (e.g., coo_matrix), optional*) – Output matrix with the structure of the hessian already defined. Optional

Returns

Return type matrix_like

abstract evaluate_ineq_constraints(*out=None*)

Returns the values of the inequality constraints evaluated at the values given for the primal variables in set_primals

Parameters **out** (*array_like, optional*) – Output array. Its type is preserved and it must be of the right shape to hold the output.

Returns

Return type vector_like

abstract evaluate_jacobian(*out=None*)

Returns the Jacobian of the constraints evaluated at the values given for the primal variables in set_primals

Parameters **out** (*matrix_like (e.g., coo_matrix), optional*) – Output matrix with the structure of the jacobian already defined.

Returns

Return type matrix_like

abstract evaluate_jacobian_eq(*out=None*)

Returns the Jacobian of the equality constraints evaluated at the values given for the primal variables in set_primals

Parameters **out** (*matrix_like (e.g., coo_matrix), optional*) – Output matrix with the structure of the jacobian already defined.

Returns

Return type matrix_like

abstract evaluate_jacobian_ineq(*out=None*)

Returns the Jacobian of the inequality constraints evaluated at the values given for the primal variables in set_primals

Parameters **out** (*matrix_like (e.g., coo_matrix), optional*) – Output matrix with the structure of the jacobian already defined.

Returns

Return type matrix_like

abstract evaluate_objective()

Returns value of objective function evaluated at the values given for the primal variables in set_primals

Returns

Return type float

abstract get_constraints_scaling()

Return the desired scaling factors to use for the for the constraints. None indicates no scaling. This indicates potential scaling for the model, but the evaluation methods should return *unscaled* values

Returns

Return type array-like or None

abstract get_duals()
Get a copy of the values of the dual variables as provided in set_duals. These are the values that will be used in calls to the evaluation methods.

abstract get_duals_eq()
Get a copy of the values of the dual variables of the equality constraints as provided in set_duals_eq. These are the values that will be used in calls to the evaluation methods.

abstract get_duals_ineq()
Get a copy of the values of the dual variables of the inequality constraints as provided in set_duals_eq. These are the values that will be used in calls to the evaluation methods.

abstract get_eq_constraints_scaling()
Return the desired scaling factors to use for the for the equality constraints. None indicates no scaling. This indicates potential scaling for the model, but the evaluation methods should return *unscaled* values
Returns

Return type array-like or None

abstract get_ineq_constraints_scaling()
Return the desired scaling factors to use for the for the inequality constraints. None indicates no scaling. This indicates potential scaling for the model, but the evaluation methods should return *unscaled* values
Returns

Return type array-like or None

abstract get_obj_factor()
Get the value of the objective function factor as set by set_obj_factor. This is the value that will be used in calls to the evaluation of the hessian of the lagrangian (evaluate_hessian_lag)

abstract get_obj_scaling()
Return the desired scaling factor to use for the for the objective function. None indicates no scaling. This indicates potential scaling for the model, but the evaluation methods should return *unscaled* values
Returns

Return type float or None

abstract get_primals()
Get a copy of the values of the primal variables as provided in set_primals. These are the values that will be used in calls to the evaluation methods

abstract get_primals_scaling()
Return the desired scaling factors to use for the for the primals. None indicates no scaling. This indicates potential scaling for the model, but the evaluation methods should return *unscaled* values
Returns

Return type array-like or None

abstract ineq_lb()
Returns vector of lower bounds for inequality constraints
Returns

Return type vector-like

abstract ineq_ub()
Returns vector of upper bounds for inequality constraints
Returns

Return type vector-like

abstract init_duals()
Returns vector with initial values for the dual variables of the constraints

abstract init_duals_eq()
Returns vector with initial values for the dual variables of the equality constraints

abstract init_duals_ineq()
Returns vector with initial values for the dual variables of the inequality constraints

abstract init_primals()
Returns vector with initial values for the primal variables

abstract n_constraints()
Returns number of constraints

abstract n_eq_constraints()
Returns number of equality constraints

abstract n_ineq_constraints()
Returns number of inequality constraints

abstract n_primals()
Returns number of primal variables

abstract nnz_hessian_lag()
Returns number of nonzero values in hessian of the lagrangian function

abstract nnz_jacobian()
Returns number of nonzero values in jacobian of equality constraints

abstract nnz_jacobian_eq()
Returns number of nonzero values in jacobian of equality constraints

abstract nnz_jacobian_ineq()
Returns number of nonzero values in jacobian of inequality constraints

abstract primals_lb()
Returns vector of lower bounds for the primal variables
Returns

Return type vector-like

primals_names()
Override this to provide string names for the primal variables

abstract primals_ub()
Returns vector of upper bounds for the primal variables
Returns

Return type vector-like

abstract report_solver_status(*status_code*, *status_message*)
Report the solver status to NLP class using the values for the primals and duals defined in the set methods

abstract set_duals(*duals*)
Set the value of the dual variables for the constraints to be used in calls to the evaluation methods (hessian_lag)
Parameters duals (*vector_like*) – Vector with the values of dual variables for the equality constraints

abstract set_duals_eq(*duals_eq*)
Set the value of the dual variables for the equality constraints to be used in calls to the evaluation methods (hessian_lag)
Parameters duals_eq (*vector_like*) – Vector with the values of dual variables for the equality constraints

abstract set_duals_ineq(*duals_ineq*)
Set the value of the dual variables for the inequality constraints to be used in calls to the evaluation methods (hessian_lag)
Parameters duals_ineq (*vector_like*) – Vector with the values of dual variables for the inequality constraints

abstract set_obj_factor(*obj_factor*)
Set the value of the objective function factor to be used in calls to the evaluation of the hessian of the lagrangian (evaluate_hessian_lag)
Parameters obj_factor (*float*) – Value of the objective function factor used in the evaluation of the hessian of the lagrangian

abstract set_primals(*primals*)
Set the value of the primal variables to be used in calls to the evaluation methods
Parameters primals (*vector_like*) – Vector with the values of primal variables.

ASL NLP Interface

AMPL NLP Interface

Pyomo NLP Interface

Projected NLP Interface

External Grey Box Model

Pyomo Grey Box NLP Interface

PyNumero Linear Solver Interfaces

HSL MA27

class pyomo.contrib.pynumero.linalg.ma27.**MA27Interface**(*iw_factor=None*, *a_factor=None*)
Bases: object

classmethod available()

do_backsolve(*rhs*)

do_numeric_factorization(*irn*, *icn*, *dim*, *entries*)

do_symbolic_factorization(*dim*, *irn*, *icn*)

get_cntl(*i*)

get_icntl(*i*)

get_info(*i*)

libname
alias of pyomo.contrib.pynumero.linalg.utils._NotSet

set_cntl(*i*, *val*)

set_icntl(*i*, *val*)

HSL MA57

class pyomo.contrib.pynumero.linalg.ma57.**MA57Interface**(*work_factor=None*, *fact_factor=None*, *ifact_factor=None*)

Bases: object

classmethod available()

do_backsolve(*rhs*)

do_numeric_factorization(*dim*, *entries*)

do_symbolic_factorization(*dim*, *irn*, *jcn*)

get_cntl(*i*)

get_icntl(*i*)

get_info(*i*)

get_rinfo(*i*)

libname
alias of pyomo.contrib.pynumero.linalg.utils._NotSet

set_cntl(*i*, *val*)

set_icntl(*i*, *val*)

MUMPS

15.7.4 Developers

The development team includes:

- Jose Santiago Rodriguez
- Michael Bynum
- Carl Laird
- Bethany Nicholson
- Robby Parker
- John Siirola

15.7.5 Packages built on PyNumero

- https://github.com/Pyomo/pyomo/tree/main/pyomo/contrib/interior_point
- https://github.com/parapint/parapint

15.7.6 Papers utilizing PyNumero

- Rodriguez, J. S., Laird, C. D., & Zavala, V. M. (2020). Scalable preconditioning of block-structured linear algebra systems using ADMM. Computers & Chemical Engineering, 133, 106478.

15.7.7 Indices and Tables

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15.8 PyROS Solver

PyROS (Pyomo Robust Optimization Solver) is a metasolver capability within Pyomo for solving non-convex, two-stage optimization models using adjustable robust optimization.

It was developed by **Natalie M. Isenberg** and **Chrysanthos E. Gounaris** of Carnegie Mellon University, in collaboration with **John D. Siirola** of Sandia National Labs. The developers gratefully acknowledge support from the U.S. Department of Energy's Institute for the Design of Advanced Energy Systems (IDAES).

15.8.1 Methodology Overview

Below is an overview of the type of optimization models PyROS can accomodate.

- PyROS is suitable for optimization models of **continuous variables** that may feature non-linearities (including **non-convexities**) in both the variables and uncertain parameters.
- PyROS can handle **equality constraints** defining state variables, including implicit state variables that cannot be eliminated via reformulation.
- PyROS allows for **two-stage** optimization problems that may feature both first-stage and second-stage degrees of freedom.

The general form of a deterministic optimization problem that can be passed into PyROS is shown below:

$$\begin{aligned} \min_{\substack{x\in\mathcal{X},\\ z\in\mathbb{R}^n, y\in\mathbb{R}^a}} \quad & f_1(x) + f_2\left(x, z, y; q^0\right) & \\ \text{s.t.} \quad & g_i\left(x, z, y; q^0\right) \leq 0 & \forall i \in \mathcal{I} \\ & h_j\left(x, z, y; q^0\right) = 0 & \forall j \in \mathcal{J} \end{aligned}$$

where:

- $x \in \mathcal{X}$ are the "design" variables (i.e., first-stage degrees of freedom), where $\mathcal{X} \subseteq \mathbb{R}^m$ is the feasible space defined by the model constraints that only reference these variables
- $z \in \mathbb{R}^n$ are the "control" variables (i.e., second-stage degrees of freedom)
- $y \in \mathbb{R}^a$ are the "state" variables
- $q \in \mathbb{R}^w$ is the vector of parameters that we shall later consider to be uncertain, and q^0 is the vector of nominal values associated with those.
- $f_1(x)$ are the terms of the objective function that depend only on design variables

- $f_2\left(x, z, y; q\right)$ are the terms of the objective function that depend on control and/or state variables
- $g_i\left(x, z, y; q\right)$ is the i^{th} inequality constraint in set $\mathcal{I}$ (see Note)
- $h_j\left(x, z, y; q\right)$ is the j^{th} equality constraint in set $\mathcal{J}$ (see Note)

Note:

- Applicable bounds on variables z and/or y are assumed to have been incorporated in the set of inequality constraints $\mathcal{I}$.
- A key requirement of PyROS is that each value of (x, z, q) maps to a unique value of y, a property that is assumed to be properly enforced by the system of equality constraints $\mathcal{J}$. If such unique mapping does not hold, then the selection of 'state' (i.e., not degree of freedom) variables y is incorrect, and one or more of the y variables should be appropriately redesignated to be part of either x or z.

In order to cast the robust optimization counterpart formulation of the above model, we shall now assume that the uncertain parameters may attain any realization from within an uncertainty set $\mathcal{Q} \subseteq \mathbb{R}^w$, such that $q^0 \in \mathcal{Q}$. The set $\mathcal{Q}$ is assumed to be closed and bounded, while it can be **either continuous or discrete**.

Based on the above notation, the form of the robust counterpart addressed in PyROS is shown below:

$$
\begin{array}{lll}
\min\limits_{x \in \mathcal{X}} \max\limits_{q \in \mathcal{Q}} & \min\limits_{z \in \mathbb{R}^n, y \in \mathbb{R}^a} & f_1\left(x\right) + f_2\left(x, z, y, q\right) \\
& \text{s.t.} & g_i\left(x, z, y, q\right) \leq 0 \qquad \forall i \in \mathcal{I} \\
& & h_j\left(x, z, y, q\right) = 0 \qquad \forall j \in \mathcal{J}
\end{array}
$$

In order to solve problems of the above type, PyROS implements the Generalized Robust Cutting-Set algorithm developed in [GRCSPaper].

When using PyROS, please consider citing the above paper.

15.8.2 PyROS Required Inputs

The required inputs to the PyROS solver are the following:

- The determinisitic optimization model
- List of first-stage ("design") variables
- List of second-stage ("control") variables
- List of parameters to be considered uncertain
- The uncertainty set
- Subordinate local and global NLP optimization solvers

Below is a list of arguments that PyROS expects the user to provide when calling the `solve` command. Note how all but the `model` argument **must** be specified as `kwargs`.

model [`ConcreteModel`] A `ConcreteModel` object representing the deterministic model.

first_stage_variables [`list(Var)`] A list of Pyomo `Var` objects representing the first-stage degrees of freedom (design variables) in `model`.

second_stage_variables [`list(Var)`] A list of Pyomo `Var` objects representing second-stage degrees of freedom (control variables) in `model`.

uncertain_params [`list(Param)`] A list of Pyomo `Param` objects in `deterministic_model` to be considered uncertain. These specified `Param` objects must have the property `mutable=True`.

uncertainty_set [UncertaintySet] A PyROS UncertaintySet object representing uncertainty in the space of those parameters listed in the uncertain_params object.

local_solver [Solver] A Pyomo Solver instance for a local NLP optimization solver.

global_solver [Solver] A Pyomo Solver instance for a global NLP optimization solver.

Note: Any variables in the model not specified to be first- or second-stage variables are automatically considered to be state variables.

15.8.3 PyROS Solver Interface

class pyomo.contrib.pyros.**PyROS**

PyROS (Pyomo Robust Optimization Solver) implementing a generalized robust cutting-set algorithm (GRCS) to solve two-stage NLP optimization models under uncertainty.

solve(*model*, *first_stage_variables*, *second_stage_variables*, *uncertain_params*, *uncertainty_set*, *local_solver*, *global_solver*, ***kwds*)

Solve the model.

Parameters

- **model** (ConcreteModel) – A ConcreteModel object representing the deterministic model, cast as a minimization problem.
- **first_stage_variables** (*List[Var]*) – The list of Var objects referenced in model representing the design variables.
- **second_stage_variables** (*List[Var]*) – The list of Var objects referenced in model representing the control variables.
- **uncertain_params** (*List[Param]*) – The list of Param objects referenced in model representing the uncertain parameters. MUST be mutable. Assumes entries are provided in consistent order with the entries of 'nominal_uncertain_param_vals' input.
- **uncertainty_set** (UncertaintySet) – UncertaintySet object representing the uncertainty space that the final solutions will be robust against.
- **local_solver** (Solver) – Solver object to utilize as the primary local NLP solver.
- **global_solver** (Solver) – Solver object to utilize as the primary global NLP solver.

Keyword Arguments

- **time_limit** – Optional. Default = None. Total allotted time for the execution of the PyROS solver in seconds (includes time spent in sub-solvers). 'None' is no time limit.
- **keepfiles** – Optional. Default = False. Whether or not to write files of subproblems for use in debugging. Must be paired with a writable directory supplied via subproblem_file_directory.
- **tee** – Optional. Default = False. Sets the tee for all sub-solvers utilized.
- **load_solution** – Optional. Default = True. Whether or not to load the final solution of PyROS into the model object.

- **objective_focus** – Optional. Default = ObjectiveType.nominal. Choice of objective function to optimize in the master problems. Choices are: ObjectiveType.worst_case, ObjectiveType.nominal. See Note for details.
- **nominal_uncertain_param_vals** – Optional. Default = deterministic model Param values. List of nominal values for all uncertain parameters. Assumes entries are provided in consistent order with the entries of uncertain_params input.
- **decision_rule_order** – Optional. Default = 0. Order of decision rule functions for handling second-stage variable recourse. Choices are: '0' for constant recourse (a.k.a. static approximation), '1' for affine recourse (a.k.a. affine decision rules), '2' for quadratic recourse.
- **solve_master_globally** – Optional. Default = False. 'True' for the master problems to be solved with the user-supplied global solver(s); or 'False' for the master problems to be solved with the user-supplied local solver(s).
- **max_iter** – Optional. Default = -1. Iteration limit for the GRCS algorithm. '-1' is no iteration limit.
- **robust_feasibility_tolerance** – Optional. Default = 1e-4. Relative tolerance for assessing robust feasibility violation during separation phase.
- **separation_priority_order** – Optional. Default = {}. Dictionary mapping inequality constraint names to positive integer priorities for separation. Constraints not referenced in the dictionary assume a priority of 0 (lowest priority).
- **progress_logger** – Optional. Default = "pyomo.contrib.pyros". The logger object to use for reporting.
- **backup_local_solvers** – Optional. Default = []. List of additional Solver objects to utilize as backup whenever primary local NLP solver fails to identify solution to a sub-problem.
- **backup_global_solvers** – Optional. Default = []. List of additional Solver objects to utilize as backup whenever primary global NLP solver fails to identify solution to a sub-problem.
- **subproblem_file_directory** – Optional. Path to a directory where subproblem files and logs will be written in the case that a subproblem fails to solve.
- **bypass_local_separation** – This is an advanced option. Default = False. 'True' to only use global solver(s) during separation; 'False' to use local solver(s) at intermediate separations, using global solver(s) only before termination to certify robust feasibility.
- **p_robustness** – This is an advanced option. Default = {}. Whether or not to add p-robustness constraints to the master problems. If the dictionary is empty (default), then p-robustness constraints are not added. See Note for how to specify arguments.

Note: Solving the master problems globally (via option solve_masters_globally=True) is one of the requirements to guarantee robust optimality; solving the master problems locally can only lead to a robust feasible solution.

Note: Selecting worst-case objective (via option objective_focus=ObjectiveType.worst_case) is one of the requirements to guarantee robust optimality; selecting nominal objective can only lead to a robust feasible solution,

albeit one that has optimized the sum of first- and (nominal) second-stage objectives.

Note: To utilize option `p_robustness`, a dictionary of the following form must be supplied via the `kwarg`: There must be a key (`str`) called 'rho', which maps to a non-negative value, where '1+rho' defines a bound for the ratio of the objective that any scenario may exhibit compared to the nominal objective.

15.8.4 PyROS Uncertainty Sets

PyROS contains pre-implemented `UncertaintySet` specializations for many types of commonly used uncertainty sets. Additional capabilities for intersecting multiple PyROS `UncertaintySet` objects so as to create custom sets are also provided via the `IntersectionSet` class. Custom user-specified sets can also be defined via the base `UncertaintySet` class.

Mathematical representations of the sets are shown below, followed by the class descriptions.

Table 15.4: PyROS Uncertainty Sets

Uncertainty Set Type	Set Representation
`BoxSet` $\mathrm{q}^\ell \in \mathbb{R}^n$ $\mathrm{q}^u \in \mathbb{R}^n : \left\{q^\ell \leq q^u\right\}$	$Q_X = \left\{q \in \mathbb{R}^n : q^\ell \leq q \leq q^u\right\}$
`CardinalitySet` $\Xi_C = \left\{\xi \in [0,1]^n : \sum_{i=1}^{n} \xi_i \leq \Gamma\right\}$ $\Gamma \in [0, n]$ $\in \mathbb{R}^n_+$ $\mathrm{q}^0 \in \mathbb{R}^n$	$Q_C = \left\{q \in \mathbb{R}^n : q = q^0 + (\hat{q} \circ \xi) \text{ for some } \xi \in \Xi_C\right\}$
`BudgetSet` $\mathrm{b}_\ell \in \mathbb{R}^L_+$	$Q_B = \left\{q \in \mathbb{R}^n_+ : \sum_{i \in B_\ell} q_i \leq b_\ell \; \forall \ell \in \{1, \ldots, L\}\right\}$
`FactorModelSet` $\Xi_F = \left\{\xi \in [-1,1]^F, \left\lvert\sum_{f=1}^{F} \xi_f\right\rvert \leq \beta F\right\}$ $\beta \in [0,1]$ $\Psi \in \mathbb{R}^{n \times F}_+$ $\mathrm{q}^0 \in \mathbb{R}^n$	$Q_F = \left\{q \in \mathbb{R}^n : q = q^0 + \Psi\xi \text{ for some } \xi \in \Xi_F\right\}$
`PolyhedralSet` $\mathrm{A} \in \mathbb{R}^{m \times n}$ $\mathrm{b} \in \mathbb{R}^m$ $\mathrm{q}^0 \in \mathbb{R}^n : Aq^0 \leq b$	$Q_P = \{q \in \mathbb{R}^n : Aq \leq b\}$
`AxisAlignedEllipsoidalSet` $\alpha \in \mathbb{R}^n_+,$ $\mathrm{q}^0 \in \mathbb{R}^n$	$Q_A = \left\{q \in \mathbb{R}^n : \sum_{\substack{i=1: \\ \{\alpha_i > 0\}}} \left(\frac{q_i - q_i^0}{\alpha_i}\right)^2 \leq 1, \quad q_i = q_i^0 \quad \forall i : \{\alpha_i = 0\}\right\}$
`EllipsoidalSet` $\Xi_E = \left\{\xi \in \mathbb{R} : \xi^T \xi \leq s\right\}$ $\mathrm{P} \in \mathbb{S}^{n \times n}_+$ $\mathrm{s} \in \mathbb{R}_+$ $\mathrm{q}^0 \in \mathbb{R}^n$	$Q_E = \left\{q \in \mathbb{R}^n : q = q^0 + P^{1/2}\xi \text{ for some } \xi \in \Xi_E\right\}$
`UncertaintySet` $\mathrm{m} \in \mathbb{N}_+$ $\mathrm{g}_i : \mathbb{R}^n \mapsto \mathbb{R} \, \forall i \in \{1, \ldots, m\},$ $\mathrm{q}^0 \in \mathbb{R}^n : \left\{g_i(q^0) \leq 0 \; \forall i \in \{1, \ldots, m\}\right\}$	$Q_U = \{q \in \mathbb{R}^n : g_i(q) \leq 0 \quad \forall i \in \{1, \ldots, m\}\}$
`DiscreteScenariosSet` $\mathrm{D} \in \mathbb{N}$ $\mathrm{q}^s \in \mathbb{R}^n \forall s \in \{0, \ldots, D\}$	$Q_D = \{q^s : s = 0, \ldots, D\}$
`IntersectionSet` $\mathrm{Q}_i \subset \mathbb{R}^n \quad \forall i \in \{1, \ldots, m\}$	$Q_I = \left\{q \in \mathbb{R}^n : q \in \bigcap_{i \in \{1,\ldots,m\}} Q_i\right\}$

Note: Each of the PyROS uncertainty set classes inherits from the `UncertaintySet` base class.

PyROS Uncertainty Set Classes

class pyomo.contrib.pyros.uncertainty_sets.**BoxSet**(*bounds*)
Hyper-rectangle (a.k.a. "Box")

__init__(*bounds*)
BoxSet constructor
Parameters **bounds** – A list of tuples providing lower and upper bounds (lb, ub) for each uncertain parameter, in the same order as the 'uncertain_params' required input that is to be supplied to the PyROS solve statement.

property dim
Dimension of the uncertainty set, i.e., number of parameters in "uncertain_params" list.

property parameter_bounds
Bounds on the realizations of the uncertain parameters, as inferred from the uncertainty set.

point_in_set(*point*)
Calculates if supplied `point` is contained in the uncertainty set. Returns True or False.
Parameters **point** – The point being checked for membership in the set. The coordinates of the point should be supplied in the same order as the elements of `uncertain_params` that is to be supplied to the PyROS solve statement. This point must match the dimension of the uncertain parameters of the set.

class pyomo.contrib.pyros.uncertainty_sets.**CardinalitySet**(*origin*, *positive_deviation*, *gamma*)
Cardinality-constrained (a.k.a "Gamma") uncertainty set

__init__(*origin*, *positive_deviation*, *gamma*)
CardinalitySet constructor
Parameters

- **origin** – The origin of the set (e.g., the nominal point).
- **positive_deviation** – Vector (`list`) of maximal deviations of each parameter.
- **gamma** – Scalar to bound the total number of uncertain parameters that can maximally deviate from their respective 'origin'. Setting 'gamma = 0' reduces the set to the 'origin' point. Setting 'gamma' to be equal to the number of parameters produces the hyper-rectangle [origin, origin+positive_deviation]

property dim
Dimension of the uncertainty set, i.e., number of parameters in "uncertain_params" list.

property parameter_bounds
Bounds on the realizations of the uncertain parameters, as inferred from the uncertainty set.

point_in_set(*point*)
Calculates if supplied `point` is contained in the uncertainty set. Returns True or False.
Parameters **point** – the point being checked for membership in the set

class pyomo.contrib.pyros.uncertainty_sets.**BudgetSet**(*budget_membership_mat*, *rhs_vec*)
Budget uncertainty set

__init__(*budget_membership_mat*, *rhs_vec*)
BudgetSet constructor
Parameters

- **budget_membership_mat** – A matrix with 0-1 entries to designate which uncertain parameters participate in each budget constraint. Here, each row is associated with a separate budget constraint.
- **rhs_vec** – Vector (`list`) of right-hand side values for the budget constraints.

property dim
Dimension of the uncertainty set, i.e., number of parameters in "uncertain_params" list.

property parameter_bounds
Bounds on the realizations of the uncertain parameters, as inferred from the uncertainty set.

point_in_set(*point*)
Calculates if supplied `point` is contained in the uncertainty set. Returns True or False.

Parameters **point** – The point being checked for membership in the set. The coordinates of the point should be supplied in the same order as the elements of `uncertain_params` that is to be supplied to the PyROS solve statement. This point must match the dimension of the uncertain parameters of the set.

class pyomo.contrib.pyros.uncertainty_sets.**FactorModelSet**(*origin*, *number_of_factors*, *psi_mat*, *beta*)
Factor model (a.k.a. "net-alpha" model) uncertainty set

__init__(*origin*, *number_of_factors*, *psi_mat*, *beta*)
FactorModelSet constructor

Parameters

- **origin** – Vector (`list`) of uncertain parameter values around which deviations are restrained.
- **number_of_factors** – Natural number representing the dimensionality of the space to which the set projects.
- **psi** – Matrix with non-negative entries designating each uncertain parameter's contribution to each factor. Here, each row is associated with a separate uncertain parameter and each column with a separate factor.
- **beta** – Number in [0,1] representing the fraction of the independent factors that can simultaneously attain their extreme values. Setting 'beta = 0' will enforce that as many factors will be above 0 as there will be below 0 (i.e., "zero-net-alpha" model). Setting 'beta = 1' produces the hyper-rectangle [origin - psi e, origin + psi e], where 'e' is the vector of ones.

property dim
Dimension of the uncertainty set, i.e., number of parameters in "uncertain_params" list.

property parameter_bounds
Bounds on the realizations of the uncertain parameters, as inferred from the uncertainty set.

point_in_set(*point*)
Calculates if supplied `point` is contained in the uncertainty set. Returns True or False.

Parameters **point** – the point being checked for membership in the set

class pyomo.contrib.pyros.uncertainty_sets.**PolyhedralSet**(*lhs_coefficients_mat*, *rhs_vec*)
Polyhedral uncertainty set

__init__(*lhs_coefficients_mat*, *rhs_vec*)
PolyhedralSet constructor

Parameters

- **lhs_coefficients_mat** – Matrix of left-hand side coefficients for the linear inequality constraints defining the polyhedral set.

- **rhs_vec** – Vector (list) of right-hand side values for the linear inequality constraints defining the polyhedral set.

property dim
Dimension of the uncertainty set, i.e., number of parameters in "uncertain_params" list.

property parameter_bounds
Bounds on the realizations of the uncertain parameters, as inferred from the uncertainty set. PolyhedralSet bounds are not computed at set construction because they cannot be algebraically determined and require access to an optimization solver.

point_in_set(*point*)
Calculates if supplied point is contained in the uncertainty set. Returns True or False.

Parameters **point** – The point being checked for membership in the set. The coordinates of the point should be supplied in the same order as the elements of uncertain_params that is to be supplied to the PyROS solve statement. This point must match the dimension of the uncertain parameters of the set.

class pyomo.contrib.pyros.uncertainty_sets.**AxisAlignedEllipsoidalSet**(*center*, *half_lengths*)
Axis-aligned ellipsoidal uncertainty set

__init__(*center*, *half_lengths*)
AxisAlignedEllipsoidalSet constructor

Parameters

- **center** – Vector (list) of uncertain parameter values around which deviations are restrained.
- **half_lengths** – Vector (list) of half-length values representing the maximal deviations for each uncertain parameter.

property dim
Dimension of the uncertainty set, i.e., number of parameters in "uncertain_params" list.

property parameter_bounds
Bounds on the realizations of the uncertain parameters, as inferred from the uncertainty set.

point_in_set(*point*)
Calculates if supplied point is contained in the uncertainty set. Returns True or False.

Parameters **point** – The point being checked for membership in the set. The coordinates of the point should be supplied in the same order as the elements of uncertain_params that is to be supplied to the PyROS solve statement. This point must match the dimension of the uncertain parameters of the set.

class pyomo.contrib.pyros.uncertainty_sets.**EllipsoidalSet**(*center*, *shape_matrix*, *scale=1*)
Ellipsoidal uncertainty set

__init__(*center*, *shape_matrix*, *scale=1*)
EllipsoidalSet constructor

Parameters

- **center** – Vector (list) of uncertain parameter values around which deviations are restrained.
- **shape_matrix** – Positive semi-definite matrix, effectively a covariance matrix for
- **determination.** (*constraint and bounds*) –
- **scale** – Right-hand side value for the ellipsoid.

property dim
Dimension of the uncertainty set, i.e., number of parameters in "uncertain_params" list.

property parameter_bounds
Bounds on the realizations of the uncertain parameters, as inferred from the uncertainty set.

point_in_set(*point*)
Calculates if supplied `point` is contained in the uncertainty set. Returns True or False.
Parameters **point** – The point being checked for membership in the set. The coordinates of the point should be supplied in the same order as the elements of `uncertain_params` that is to be supplied to the PyROS solve statement. This point must match the dimension of the uncertain parameters of the set.

class pyomo.contrib.pyros.uncertainty_sets.**UncertaintySet**(***kwargs*)
Base class for custom user-defined uncertainty sets.

__init__(***kwargs*)
Constructor for UncertaintySet base class
Parameters **kwargs** – Use the kwargs for specifying data for the UncertaintySet object. This data should be used in defining constraints in the 'set_as_constraint' function.

abstract property dim
Dimension of the uncertainty set, i.e., number of parameters in "uncertain_params" list.

abstract property parameter_bounds
Bounds on the realizations of the uncertain parameters, as inferred from the uncertainty set.

point_in_set(*point*)
Calculates if supplied `point` is contained in the uncertainty set. Returns True or False.
Parameters **point** – The point being checked for membership in the set. The coordinates of the point should be supplied in the same order as the elements of `uncertain_params` that is to be supplied to the PyROS solve statement. This point must match the dimension of the uncertain parameters of the set.

class pyomo.contrib.pyros.uncertainty_sets.**DiscreteScenarioSet**(*scenarios*)
Set of discrete scenarios (i.e., finite collection of realizations)

__init__(*scenarios*)
DiscreteScenarioSet constructor
Parameters **scenarios** – Vector (`list`) of discrete scenarios where each scenario represents a realization of the uncertain parameters.

property dim
Dimension of the uncertainty set, i.e., number of parameters in "uncertain_params" list.

property parameter_bounds
Bounds on the realizations of the uncertain parameters, as inferred from the uncertainty set.

point_in_set(*point*)
Calculates if supplied `point` is contained in the uncertainty set. Returns True or False.
Parameters **point** – the point being checked for membership in the set

class pyomo.contrib.pyros.uncertainty_sets.**IntersectionSet**(***kwargs*)
Set stemming from intersecting previously constructed sets of any type

__init__(***kwargs*)
IntersectionSet constructor
Parameters ****kwargs** – Keyword arguments for specifying all PyROS UncertaintySet objects to be intersected.

property dim
Dimension of the uncertainty set, i.e., number of parameters in "uncertain_params" list.

property parameter_bounds
Bounds on the realizations of the uncertain parameters, as inferred from the uncertainty set. IntersectedSet bounds are not computed at set construction because they cannot be algebraically determined and require access to an optimization solver.

point_in_set(*point*)
Calculates if supplied `point` is contained in the uncertainty set. Returns True or False.
Parameters `point` – the point being checked for membership in the set

15.8.5 PyROS Usage Example

We will use an example to illustrate the usage of PyROS. The problem we will use is called *hydro* and comes from the GAMS example problem database in The GAMS Model Library. The model was converted to Pyomo format via the GAMS Convert tool.

This model is a QCQP with 31 variables. Of these variables, 13 represent degrees of freedom, with the additional 18 being state variables. The model features 6 linear inequality constraints, 6 linear equality constraints, 6 non-linear (quadratic) equalities, and a quadratic objective. We have augmented this model by converting one objective coefficient, two constraint coefficients, and one constraint right-hand side into Param objects so that they can be considered uncertain later on.

Note: Per our analysis, the *hydro* problem satisfies the requirement that each value of (x, z, q) maps to a unique value of y, which indicates a proper partition of variables between (first- or second-stage) degrees of freedom and state variables.

Step 0: Import Pyomo and the PyROS Module

In anticipation of using the PyROS solver and building the deterministic Pyomo model:

```
>>> # === Required import ===
>>> import pyomo.environ as pyo
>>> import pyomo.contrib.pyros as pyros

>>> # === Instantiate the PyROS solver object ===
>>> pyros_solver = pyo.SolverFactory("pyros")
```

Step 1: Define the Deterministic Problem

The deterministic Pyomo model for *hydro* is shown below.

Note: Primitive data (Python literals) that have been hard-coded within a deterministic model cannot be later considered uncertain, unless they are first converted to `Param` objects within the `ConcreteModel` object. Furthermore, any `Param` object that is to be later considered uncertain must have the property `mutable=True`.

Note: In case modifying the `mutable` property inside the deterministic model object itself is not straight-forward in your context, you may consider adding the following statement **after** `import pyomo.environ as pyo` but **before**

defining the model object: `pyo.Param.DefaultMutable = True`. Note how this sets the default `mutable` property in all `Param` objects in the ensuing model instance to `True`; consequently, this solution will not work with `Param` objects for which the `mutable=False` property was explicitly enabled inside the model object.

```
>>> # === Construct the Pyomo model object ===
>>> m = pyo.ConcreteModel()
>>> m.name = "hydro"

>>> # === Define variables ===
>>> m.x1 = pyo.Var(within=pyo.Reals,bounds=(150,1500),initialize=150)
>>> m.x2 = pyo.Var(within=pyo.Reals,bounds=(150,1500),initialize=150)
>>> m.x3 = pyo.Var(within=pyo.Reals,bounds=(150,1500),initialize=150)
>>> m.x4 = pyo.Var(within=pyo.Reals,bounds=(150,1500),initialize=150)
>>> m.x5 = pyo.Var(within=pyo.Reals,bounds=(150,1500),initialize=150)
>>> m.x6 = pyo.Var(within=pyo.Reals,bounds=(150,1500),initialize=150)
>>> m.x7 = pyo.Var(within=pyo.Reals,bounds=(0,1000),initialize=0)
>>> m.x8 = pyo.Var(within=pyo.Reals,bounds=(0,1000),initialize=0)
>>> m.x9 = pyo.Var(within=pyo.Reals,bounds=(0,1000),initialize=0)
>>> m.x10 = pyo.Var(within=pyo.Reals,bounds=(0,1000),initialize=0)
>>> m.x11 = pyo.Var(within=pyo.Reals,bounds=(0,1000),initialize=0)
>>> m.x12 = pyo.Var(within=pyo.Reals,bounds=(0,1000),initialize=0)
>>> m.x13 = pyo.Var(within=pyo.Reals,bounds=(0,None),initialize=0)
>>> m.x14 = pyo.Var(within=pyo.Reals,bounds=(0,None),initialize=0)
>>> m.x15 = pyo.Var(within=pyo.Reals,bounds=(0,None),initialize=0)
>>> m.x16 = pyo.Var(within=pyo.Reals,bounds=(0,None),initialize=0)
>>> m.x17 = pyo.Var(within=pyo.Reals,bounds=(0,None),initialize=0)
>>> m.x18 = pyo.Var(within=pyo.Reals,bounds=(0,None),initialize=0)
>>> m.x19 = pyo.Var(within=pyo.Reals,bounds=(0,None),initialize=0)
>>> m.x20 = pyo.Var(within=pyo.Reals,bounds=(0,None),initialize=0)
>>> m.x21 = pyo.Var(within=pyo.Reals,bounds=(0,None),initialize=0)
>>> m.x22 = pyo.Var(within=pyo.Reals,bounds=(0,None),initialize=0)
>>> m.x23 = pyo.Var(within=pyo.Reals,bounds=(0,None),initialize=0)
>>> m.x24 = pyo.Var(within=pyo.Reals,bounds=(0,None),initialize=0)
>>> m.x25 = pyo.Var(within=pyo.Reals,bounds=(100000,100000),initialize=100000)
>>> m.x26 = pyo.Var(within=pyo.Reals,bounds=(60000,120000),initialize=60000)
>>> m.x27 = pyo.Var(within=pyo.Reals,bounds=(60000,120000),initialize=60000)
>>> m.x28 = pyo.Var(within=pyo.Reals,bounds=(60000,120000),initialize=60000)
>>> m.x29 = pyo.Var(within=pyo.Reals,bounds=(60000,120000),initialize=60000)
>>> m.x30 = pyo.Var(within=pyo.Reals,bounds=(60000,120000),initialize=60000)
>>> m.x31 = pyo.Var(within=pyo.Reals,bounds=(60000,120000),initialize=60000)

>>> # === Define parameters ===
>>> m.set_of_params = pyo.Set(initialize=[0, 1, 2, 3])
>>> nominal_values = {0:82.8*0.0016, 1:4.97, 2:4.97, 3:1800}
>>> m.p = pyo.Param(m.set_of_params, initialize=nominal_values, mutable=True)

>>> # === Specify the objective function ===
>>> m.obj = pyo.Objective(expr=m.p[0]*m.x1**2 + 82.8*8*m.x1 + 82.8*0.0016*m.x2**2 +
...                            82.8*82.8*8*m.x2 + 82.8*0.0016*m.x3**2 + 82.8*8*m.x3 +
...                            82.8*0.0016*m.x4**2 + 82.8*8*m.x4 + 82.8*0.0016*m.
↪x5**2 +
...                            82.8*8*m.x5 + 82.8*0.0016*m.x6**2 + 82.8*8*m.x6 +␣
↪248400,
```

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```
...                                 sense=pyo.minimize)

>>> # === Specify the constraints ===
>>> m.c2 = pyo.Constraint(expr=-m.x1 - m.x7 + m.x13 + 1200<= 0)
>>> m.c3 = pyo.Constraint(expr=-m.x2 - m.x8 + m.x14 + 1500 <= 0)
>>> m.c4 = pyo.Constraint(expr=-m.x3 - m.x9 + m.x15 + 1100 <= 0)
>>> m.c5 = pyo.Constraint(expr=-m.x4 - m.x10 + m.x16 + m.p[3] <= 0)
>>> m.c6 = pyo.Constraint(expr=-m.x5 - m.x11 + m.x17 + 950 <= 0)
>>> m.c7 = pyo.Constraint(expr=-m.x6 - m.x12 + m.x18 + 1300 <= 0)
>>> m.c8 = pyo.Constraint(expr=12*m.x19 - m.x25 + m.x26 == 24000)
>>> m.c9 = pyo.Constraint(expr=12*m.x20 - m.x26 + m.x27 == 24000)
>>> m.c10 = pyo.Constraint(expr=12*m.x21 - m.x27 + m.x28 == 24000)
>>> m.c11 = pyo.Constraint(expr=12*m.x22 - m.x28 + m.x29 == 24000)
>>> m.c12 = pyo.Constraint(expr=12*m.x23 - m.x29 + m.x30 == 24000)
>>> m.c13 = pyo.Constraint(expr=12*m.x24 - m.x30 + m.x31 == 24000)
>>> m.c14 = pyo.Constraint(expr=-8e-5*m.x7**2 + m.x13 == 0)
>>> m.c15 = pyo.Constraint(expr=-8e-5*m.x8**2 + m.x14 == 0)
>>> m.c16 = pyo.Constraint(expr=-8e-5*m.x9**2 + m.x15 == 0)
>>> m.c17 = pyo.Constraint(expr=-8e-5*m.x10**2 + m.x16 == 0)
>>> m.c18 = pyo.Constraint(expr=-8e-5*m.x11**2 + m.x17 == 0)
>>> m.c19 = pyo.Constraint(expr=-8e-5*m.x12**2 + m.x18 == 0)
>>> m.c20 = pyo.Constraint(expr=-4.97*m.x7 + m.x19 == 330)
>>> m.c21 = pyo.Constraint(expr=-m.p[1]*m.x8 + m.x20 == 330)
>>> m.c22 = pyo.Constraint(expr=-4.97*m.x9 + m.x21 == 330)
>>> m.c23 = pyo.Constraint(expr=-4.97*m.x10 + m.x22 == 330)
>>> m.c24 = pyo.Constraint(expr=-m.p[2]*m.x11 + m.x23 == 330)
>>> m.c25 = pyo.Constraint(expr=-4.97*m.x12 + m.x24 == 330)
```

Step 2: Define the Uncertainty

First, we need to collect into a list those `Param` objects of our model that represent potentially uncertain parameters. For purposes of our example, we shall assume uncertainty in the model parameters (`m.p[0]`, `m.p[1]`, `m.p[2]`, `m.p[3]`), for which we can conveniently utilize the `m.p` object (itself an indexed `Param` object).

```
>>> # === Specify which parameters are uncertain ===
>>> uncertain_parameters = [m.p] # We can pass IndexedParams this way to PyROS, or as an␣
↪expanded list per index
```

Note: Any `Param` object that is to be considered uncertain by PyROS must have the property `mutable=True`.

PyROS will seek to identify solutions that remain feasible for any realization of these parameters included in an uncertainty set. To that end, we need to construct an `UncertaintySet` object. In our example, let us utilize the `BoxSet` constructor to specify an uncertainty set of simple hyper-rectangular geometry. For this, we will assume each parameter value is uncertain within a percentage of its nominal value. Constructing this specific `UncertaintySet` object can be done as follows.

```
>>> # === Define the pertinent data ===
>>> relative_deviation = 0.15
>>> bounds = [(nominal_values[i] - relative_deviation*nominal_values[i],
...               nominal_values[i] + relative_deviation*nominal_values[i])
```

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```
...                 for i in range(4)]

>>> # === Construct the desirable uncertainty set ===
>>> box_uncertainty_set = pyros.BoxSet(bounds=bounds)
```

Step 3: Solve with PyROS

PyROS requires the user to supply one local and one global NLP solver to be used for solving sub-problems. For convenience, we shall have PyROS invoke BARON as both the local and the global NLP solver.

```
>>> # === Designate local and global NLP solvers ===
>>> local_solver = pyo.SolverFactory('baron')
>>> global_solver = pyo.SolverFactory('baron')
```

Note: Additional solvers to be used as backup can be designated during the `solve` statement via the config options `backup_local_solvers` and `backup_global_solvers` presented above.

The final step in solving a model with PyROS is to designate the remaining required inputs, namely `first_stage_variables` and `second_stage_variables`. Below, we present two separate cases.

PyROS Termination Conditions

PyROS will return one of six termination conditions upon completion. These termination conditions are tabulated below.

Termination Condition	Description
`pyrosTerminationCondition.robust_optimal`	The final solution is robust optimal
`pyrosTerminationCondition.robust_feasible`	The final solution is robust feasible
`pyrosTerminationCondition.robust_infeasible`	The posed problem is robust infeasible
`pyrosTerminationCondition.max_iter`	Maximum number of GRCS iteration reached
`pyrosTerminationCondition.time_out`	Maximum number of time reached
`pyrosTerminationCondition.subsolver_error`	Unacceptable return status(es) from a user-supplied sub-solver

A Single-Stage Problem

If we choose to designate all variables as either design or state variables, without any control variables (i.e., all degrees of freedom are first-stage), we can use PyROS to solve the single-stage problem as shown below. In particular, let us instruct PyROS that variables `m.x1` through `m.x6`, `m.x19` through `m.x24`, and `m.x31` correspond to first-stage degrees of freedom.

```
>>> # === Designate which variables correspond to first- and second-stage degrees of␣
↪freedom ===
>>> first_stage_variables =[m.x1, m.x2, m.x3, m.x4, m.x5, m.x6,
...                         m.x19, m.x20, m.x21, m.x22, m.x23, m.x24, m.x31]
>>> second_stage_variables = []
>>> # The remaining variables are implicitly designated to be state variables
```

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```
>>> # === Call PyROS to solve the robust optimization problem ===
>>> results_1 = pyros_solver.solve(model = m,
...                                first_stage_variables = first_stage_variables,
...                                second_stage_variables = second_stage_variables,
...                                uncertain_params = uncertain_parameters,
...                                uncertainty_set = box_uncertainty_set,
...                                local_solver = local_solver,
...                                global_solver= global_solver,
...                                options = {
...                                   "objective_focus": pyros.ObjectiveType.worst_
↪case,
...                                   "solve_master_globally": True,
...                                   "load_solution":False
...                                 })
==============================================================================================
PyROS: Pyomo Robust Optimization Solver ...
==============================================================================================
...
INFO: Robust optimal solution identified. Exiting PyROS.

>>> # === Query results ===
>>> time = results_1.time
>>> iterations = results_1.iterations
>>> termination_condition = results_1.pyros_termination_condition
>>> objective = results_1.final_objective_value
>>> # === Print some results ===
>>> single_stage_final_objective = round(objective,-1)
>>> print("Final objective value: %s" % single_stage_final_objective)
Final objective value: 48367380.0
>>> print("PyROS termination condition: %s" % termination_condition)
PyROS termination condition: pyrosTerminationCondition.robust_optimal
```

PyROS Results Object

The results object returned by PyROS allows you to query the following information from the solve call: total iterations of the algorithm `iterations`, CPU time `time`, the GRCS algorithm termination condition `pyros_termination_condition`, and the final objective function value `final_objective_value`. If the option `load_solution = True` (default), the variables in the model will be loaded to the solution determined by PyROS and can be obtained by querying the model variables. Note that in the results obtained above, we set `load_solution = False`. This is to ensure that the next set of runs shown here can utilize the original deterministic model, as the initial point can affect the performance of sub-solvers.

Note: The reported `final_objective_value` and final model variable values depend on the selection of the option `objective_focus`. The `final_objective_value` is the sum of first-stage and second-stage objective functions. If `objective_focus = ObjectiveType.nominal`, second-stage objective and variables are evaluated at the nominal realization of the uncertain parameters, q^0. If `objective_focus = ObjectiveType.worst_case`, second-stage objective and variables are evaluated at the worst-case realization of the uncertain parameters, q^{k^*} where $k^* = argmax_{k \in \mathcal{K}} f_2(x, z^k, y^k, q^k)$.

An example of how to query these values on the previously obtained results is shown in the code above.

A Two-Stage Problem

For this next set of runs, we will assume that some of the previously designated first-stage degrees of freedom are in fact second-stage ones. PyROS handles second-stage degrees of freedom via the use of decision rules, which is controlled with the config option `decision_rule_order` presented above. Here, we shall select affine decision rules by setting `decision_rule_order` to the value of *1*.

```
>>> # === Define the variable partitioning
>>> first_stage_variables =[m.x5, m.x6, m.x19, m.x22, m.x23, m.x24, m.x31]
>>> second_stage_variables = [m.x1, m.x2, m.x3, m.x4, m.x20, m.x21]
>>> # The remaining variables are implicitly designated to be state variables

>>> # === Call PyROS to solve the robust optimization problem ===
>>> results_2 = pyros_solver.solve(model = m,
...                                first_stage_variables = first_stage_variables,
...                                second_stage_variables = second_stage_variables,
...                                uncertain_params = uncertain_parameters,
...                                uncertainty_set = box_uncertainty_set,
...                                local_solver = local_solver,
...                                global_solver = global_solver,
...                                options = {
...                                   "objective_focus": pyros.ObjectiveType.worst_
↪case,
...                                   "solve_master_globally": True,
...                                   "decision_rule_order": 1
...                                })
==============================================================================================
PyROS: Pyomo Robust Optimization Solver ...
...
INFO: Robust optimal solution identified. Exiting PyROS.

>>> # === Compare final objective to the singe-stage solution
>>> two_stage_final_objective = round(pyo.value(results_2.final_objective_value),-1)
>>> percent_difference = 100 * (two_stage_final_objective - single_stage_final_
↪objective)/(single_stage_final_objective)
>>> print("Percent objective change relative to constant decision rules objective: %.2f %
↪%" % percent_difference)
Percent objective change relative to constant decision rules objective: -24...
```

In this example, when we compare the final objective value in the case of constant decision rules (no second-stage recourse) and affine decision rules, we see there is a ~25% decrease in total objective value.

The Price of Robustness

Using appropriately constructed hierarchies, PyROS allows for the facile comparison of robust optimal objectives across sets to determine the "price of robustness." For the set we considered here, the `BoxSet`, we can create such a hierarchy via an array of `relative_deviation` parameters to define the size of these uncertainty sets. We can then loop through this array and call PyROS within a loop to identify robust solutions in light of each of the specified `BoxSet` objects.

```
>>> # This takes a long time to run and therefore is not a doctest
>>> # === An array of maximum relative deviations from the nominal uncertain parameter␣
↪values to utilize in constructing box sets
```

(continues on next page)

(continued from previous page)

```
>>> relative_deviation_list = [0.00, 0.10, 0.20, 0.30, 0.40]
>>> # === Final robust optimal objectives
>>> robust_optimal_objectives = []
>>> for relative_deviation in relative_deviation_list:
...     bounds = [(nominal_values[i] - relative_deviation*nominal_values[i],
...                     nominal_values[i] + relative_deviation*nominal_values[i])
...                     for i in range(4)]
...     box_uncertainty_set = pyros.BoxSet(bounds = bounds)
...     results = pyros_solver.solve(model = m,
...                                      first_stage_variables = first_stage_variables,
...                                      second_stage_variables = second_stage_variables,
...                                      uncertain_params = uncertain_parameters,
...                                      uncertainty_set = box_uncertainty_set,
...                                      local_solver = local_solver,
...                                      global_solver = global_solver,
...                                      options = {
...                                         "objective_focus": pyros.ObjectiveType.worst_
↪case,
...                                         "solve_master_globally": True,
...                                         "decision_rule_order": 1
...                                      })
...     if results.pyros_termination_condition != pyros.pyrosTerminationCondition.robust_
↪optimal:
...         print("This instance didn't solve to robust optimality.")
...         robust_optimal_objective.append("-----")
...     else:
...         robust_optimal_objectives.append(str(results.final_objective_value))
```

For this example, we obtain the following price of robustness results:

Uncertainty Set Size (+/-) [o]	Robust Optimal Objective	% Increase [x]
0.00	35,837,659.18	0.00 %
0.10	36,135,191.59	0.82 %
0.20	36,437,979.81	1.64 %
0.30	43,478,190.92	17.57 %
0.40	robust_infeasible	—

Note how, in the case of the last uncertainty set, we were able to utilize PyROS to show the robust infeasibility of the problem.

[o] **Relative Deviation from Nominal Realization**

[x] **Relative to Deterministic Optimal Objective**

This clearly illustrates the impact that the uncertainty set size can have on the robust optimal objective values. Price of robustness studies like this are easily implemented using PyROS.

Warning: PyROS is still under a beta release. Please provide feedback and/or report any problems by opening an issue on the Pyomo GitHub page.

15.9 Sensitivity Toolbox

The sensitivity toolbox provides a Pyomo interface to sIPOPT and k_aug to very quickly compute approximate solutions to nonlinear programs with a small perturbation in model parameters.

See the sIPOPT documentation or the following paper for additional details:

H. Pirnay, R. Lopez-Negrete, and L.T. Biegler, Optimal Sensitivity based on IPOPT, Math. Prog. Comp., 4(4):307–331, 2012.

The details of *k_aug* can be found in the following link:

David Thierry (2020). k_aug, https://github.com/dthierry/k_aug

15.9.1 Using the Sensitivity Toolbox

We will start with a motivating example:

$$\begin{aligned} \min_{x_1,x_2,x_3} \quad & x_1^2 + x_2^2 + x_3^2 \\ \text{s.t.} \quad & 6x_1 + 3x_2 + 2x_3 - p_1 = 0 \\ & p_2 x_1 + x_2 - x_3 - 1 = 0 \\ & x_1, x_2, x_3 \geq 0 \end{aligned}$$

Here x_1, x_2, and x_3 are the decision variables while p_1 and p_2 are parameters. At first, let's consider $p_1 = 4.5$ and $p_2 = 1.0$. Below is the model implemented in Pyomo.

```
# Import Pyomo and the sensitivity toolbox
>>> from pyomo.environ import *
>>> from pyomo.contrib.sensitivity_toolbox.sens import sensitivity_calculation

# Create a concrete model
>>> m = ConcreteModel()

# Define the variables with bounds and initial values
>>> m.x1 = Var(initialize = 0.15, within=NonNegativeReals)
>>> m.x2 = Var(initialize = 0.15, within=NonNegativeReals)
>>> m.x3 = Var(initialize = 0.0, within=NonNegativeReals)

# Define the parameters
>>> m.eta1 = Param(initialize=4.5,mutable=True)
>>> m.eta2 = Param(initialize=1.0,mutable=True)

# Define the constraints and objective
>>> m.const1 = Constraint(expr=6*m.x1+3*m.x2+2*m.x3-m.eta1 ==0)
>>> m.const2 = Constraint(expr=m.eta2*m.x1+m.x2-m.x3-1 ==0)
>>> m.cost = Objective(expr=m.x1**2+m.x2**2+m.x3**2)
```

The solution of this optimization problem is $x_1^* = 0.5$, $x_2^* = 0.5$, and $x_3^* = 0.0$. But what if we change the parameter values to $\hat{p}_1 = 4.0$ and $\hat{p}_2 = 1.0$? Is there a quick way to approximate the new solution $\hat{x}_1^*$, $\hat{x}_2^*$, and $\hat{x}_3^*$? Yes! This is the main functionality of sIPOPT and k_aug.

Next we define the perturbed parameter values $\hat{p}_1$ and $\hat{p}_2$:

```
>>> m.perturbed_eta1 = Param(initialize = 4.0)
>>> m.perturbed_eta2 = Param(initialize = 1.0)
```

And finally we call sIPOPT or k_aug:

```
>>> m_sipopt = sensitivity_calculation('sipopt', m, [m.eta1, m.eta2], [m.perturbed_eta1,␣
↪m.perturbed_eta2], tee=False)
>>> m_kaug_dsdp = sensitivity_calculation('k_aug', m, [m.eta1, m.eta2], [m.perturbed_
↪eta1, m.perturbed_eta2], tee=False)
```

The first argument specifies the method, either 'sipopt' or 'k_aug'. The second argument is the Pyomo model. The third argument is a list of the original parameters. The fourth argument is a list of the perturbed parameters. It's important that these two lists are the same length and in the same order.

First, we can inspect the initial point:

```
>>> print("eta1 = %0.3f" % m.eta1())
eta1 = 4.500

>>> print("eta2 = %0.3f" % m.eta2())
eta2 = 1.000

# Initial point (not feasible):
>>> print("Objective = %0.3f" % m.cost())
Objective = 0.045

>>> print("x1 = %0.3f" % m.x1())
x1 = 0.150

>>> print("x2 = %0.3f" % m.x2())
x2 = 0.150

>>> print("x3 = %0.3f" % m.x3())
x3 = 0.000
```

Next, we inspect the solution x_1^*, x_2^*, and x_3^*:

```
# Solution with the original parameter values:
>>> print("Objective = %0.3f" % m_sipopt.cost())
Objective = 0.500

>>> print("x1 = %0.3f" % m_sipopt.x1())
x1 = 0.500

>>> print("x2 = %0.3f" % m_sipopt.x2())
x2 = 0.500

>>> print("x3 = %0.3f" % m_sipopt.x3())
x3 = 0.000
```

Note that k_aug does not save the solution with the original parameter values. Finally, we inspect the approximate solution $\hat{x}_1^*$, $\hat{x}_2^*$, and $\hat{x}_3^*$:

```
# *sIPOPT*
# New parameter values:
>>> print("eta1 = %0.3f" %m_sipopt.perturbed_eta1())
eta1 = 4.000

>>> print("eta2 = %0.3f" % m_sipopt.perturbed_eta2())
eta2 = 1.000

# (Approximate) solution with the new parameter values:
>>> x1 = m_sipopt.sens_sol_state_1[m_sipopt.x1]
>>> x2 = m_sipopt.sens_sol_state_1[m_sipopt.x2]
>>> x3 = m_sipopt.sens_sol_state_1[m_sipopt.x3]
>>> print("Objective = %0.3f" % (x1**2 + x2**2 + x3**2))
Objective = 0.556

>>> print("x1 = %0.3f" % x1)
x1 = 0.333

>>> print("x2 = %0.3f" % x2)
x2 = 0.667

>>> print("x3 = %0.3f" % x3)
x3 = -0.000

# *k_aug*
# New parameter values:
>>> print("eta1 = %0.3f" %m_kaug_dsdp.perturbed_eta1())
eta1 = 4.000

>>> print("eta2 = %0.3f" % m_kaug_dsdp.perturbed_eta2())
eta2 = 1.000

# (Approximate) solution with the new parameter values:
>>> x1 = m_kaug_dsdp.x1()
>>> x2 = m_kaug_dsdp.x2()
>>> x3 = m_kaug_dsdp.x3()
>>> print("Objective = %0.3f" % (x1**2 + x2**2 + x3**2))
Objective = 0.556

>>> print("x1 = %0.3f" % x1)
x1 = 0.333

>>> print("x2 = %0.3f" % x2)
x2 = 0.667

>>> print("x3 = %0.3f" % x3)
x3 = -0.000
```

15.9.2 Installing sIPOPT and k_aug

The sensitivity toolbox requires either sIPOPT or k_aug to be installed and available in your system PATH. See the sIPOPT and k_aug documentation for detailed instructions:

- https://coin-or.github.io/Ipopt/INSTALL.html
- https://projects.coin-or.org/Ipopt/wiki/sIpopt
- https://coin-or.github.io/coinbrew/
- https://github.com/dthierry/k_aug

Note: If you get an error that `ipopt_sens` or `k_aug` and `dot_sens` cannot be found, double check your installation and make sure the build directories containing the executables were added to your system PATH.

15.9.3 Sensitivity Toolbox Interface

pyomo.contrib.sensitivity_toolbox.sens.**sensitivity_calculation**(*method*, *instance*, *paramList*, *perturbList*, *cloneModel=True*, *tee=False*, *keepfiles=False*, *solver_options=None*)

This function accepts a Pyomo ConcreteModel, a list of parameters, and their corresponding perturbation list. The model is then augmented with dummy constraints required to call sipopt or k_aug to get an approximation of the perturbed solution.

Parameters

- **method** (*string*) – 'sipopt' or 'k_aug'
- **instance** (Block) – pyomo block or model object
- **paramSubList** (*list*) – list of mutable parameters or fixed variables
- **perturbList** (*list*) – list of perturbed parameter values
- **cloneModel** (*bool, optional*) – indicator to clone the model. If set to False, the original model will be altered
- **tee** (*bool, optional*) – indicator to stream solver log
- **keepfiles** (*bool, optional*) – preserve solver interface files
- **solver_options** (*dict, optional*) – Provides options to the solver (also the name of an attribute)

Returns

Return type The model that was manipulated by the sensitivity interface

Contributed Pyomo interfaces to other packages:

15.10 MC++ Interface

The Pyomo-MC++ interface allows for bounding of factorable functions using the MC++ library developed by the OMEGA research group at Imperial College London. Documentation for MC++ may be found on the MC++ website.

15.10.1 Default Installation

Pyomo now supports automated downloading and compilation of MC++. To install MC++ and other third party compiled extensions, run:

```
pyomo download-extensions
pyomo build-extensions
```

To get and install just MC++, run the following commands in the `pyomo/contrib/mcpp` directory:

```
python getMCPP.py
python build.py
```

This should install MC++ to the pyomo plugins directory, by default located at `$HOME/.pyomo/`.

15.10.2 Manual Installation

Support for MC++ has only been validated by Pyomo developers using Linux and OSX. Installation instructions for the MC++ library may be found on the MC++ website.

We assume that you have installed MC++ into a directory of your choice. We will denote this directory by `$MCPP_PATH`. For example, you should see that the file `$MCPP_PATH/INSTALL` exists.

Navigate to the `pyomo/contrib/mcpp` directory in your pyomo installation. This directory should contain a file named `mcppInterface.cpp`. You will need to compile this file using the following command:

```
g++ -I $MCPP_PATH/src/3rdparty/fadbad++ -I $MCPP_PATH/src/mc -I /usr/include/python3.6 -
↪fPIC -O2 -c mcppInterface.cpp
```

This links the MC++ required library FADBAD++, MC++ itself, and Python to compile the Pyomo-MC++ interface. If successful, you will now have a file named `mcppInterface.o` in your working directory. If you are not using Python 3.6, you will need to link to the appropriate Python version. You now need to create a shared object file with the following command:

```
g++ -shared mcppInterface.o -o mcppInterface.so
```

You may then test your installation by running the test file:

```
python test_mcpp.py
```

15.11 z3 SMT Sat Solver Interface

The z3 Satisfiability Solver interface can convert pyomo variables and expressions for use with the z3 Satisfiability Solver

15.11.1 Installation

z3 is required for use of the Sat Solver can be installed via the command

```
pip install z3-solver
```

15.11.2 Using z3 Sat Solver

To use the sat solver define your pyomo model as usual:

```
Required import
>>> from pyomo.environ import *
>>> from pyomo.contrib.satsolver.satsolver import SMTSatSolver

Create a simple model
>>> m = ConcreteModel()
>>> m.x = Var()
>>> m.y = Var()
>>> m.obj = Objective(expr=m.x**2 + m.y**2)
>>> m.c = Constraint(expr=m.y >= -2*m.x + 5)

Invoke the sat solver using optional argument model to automatically process
pyomo model
>>> is_feasible = SMTSatSolver(model = m).check()
```

Contributed packages distributed independently of Pyomo, but accessible through `pyomo.contrib`:

- pyomo.contrib.simplemodel

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RELATED PACKAGES

The following is list of software packages that utilize or build off of Pyomo. This is certainly not a comprehensive list.[1]

16.1 Modeling Extensions

Package Name	Link	Description
Coramin	https://github.com/coramin/coramin	A suite of tools for developing MINLP algorithms
PAO	https://github.com/or-fusion/pao	Formulation and solution of multilevel optimization problems

16.2 Solvers and Solution Strategies

Package Name	Link	Description
Galini	https://github.com/cog-imperial/galini	An extensible, Python-based MIQCQP Solver
mpi-sppy	https://github.com/pyomo/mpi-sppy	Parallel solution of stochastic programming problems
Parapint	https://github.com/parapint/parapint	Parallel solution of structured NLPs.
Suspect	https://github.com/cog-imperial/suspect	FBBT and convexity detection

[1] Please note that the Pyomo team does not evaluate or endorse the packages listed above.

16.3 Domain-Specific Applications

Package Name	Link	Description
Chama	https://github.com/sandialabs/chama	Sensor placement optimization
Egret	https://github.com/grid-parity-exchange/egret	Formulation and solution of Unit Commitment and optimal power flow problems
IDAES	https://github.com/idaes/idaes-pse	Institute for the Design of Advanced Energy Systems
Prescient	https://github.com/grid-parity-exchange/prescient	Parallel solution of structured NLPs.
PyPSA	https://github.com/pypsa/pypsa	Python for Power system Analysis

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PYOMO RESOURCES

The Pyomo home page provides resources for Pyomo users:

- http://pyomo.org

Pyomo development is hosted at GitHub:

- https://github.com/Pyomo/pyomo

See the Pyomo Forum for online discussions of Pyomo:

- http://groups.google.com/group/pyomo-forum/

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