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Sage supports solving clauses in Conjunctive Normal Form (see Wikipedia article Conjunctive_normal_form), i.e., SAT solving, via an interface inspired by the usual DIMACS format used in SAT solving [SG09]. For example, to express that:

\[ x_1 \text{ OR } x_2 \text{ OR } (\neg x_3) \]

should be true, we write:

\[ (1, 2, -3) \]

**Warning:** Variable indices must start at one.
By default, Sage solves SAT instances as an Integer Linear Program (see `sage.numerical.mip`), but any SAT solver supporting the DIMACS input format is easily interfaced using the `sage.sat.solvers.dimacs.DIMACS` blueprint. Sage ships with pre-written interfaces for `RSat` [RS] and `Glucose` [GL]. Furthermore, Sage provides an interface to the `CryptoMiniSat` [CMS] SAT solver which can be used interchangeably with DIMACS-based solvers. For this last solver, the optional CryptoMiniSat package must be installed, this can be accomplished by typing the following in the shell:

```
sage -i cryptominisat sagelib
```

We now show how to solve a simple SAT problem.

\[(x_1 \lor x_2 \lor x_3) \land (x_1 \lor x_2 \lor \lnot x_3)\]

In Sage's notation:

```
sage: solver = SAT()
sage: solver.add_clause( ( 1, 2, 3) )
sage: solver.add_clause( ( 1, 2, -3) )
sage: solver()     # random
(None, True, True, False)
```

Note: `add_clause()` creates new variables when necessary. When using CryptoMiniSat, it creates all variables up to the given index. Hence, adding a literal involving the variable 1000 creates up to 1000 internal variables.

DIMACS-base solvers can also be used to write DIMACS files:

```
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()
sage: solver = DIMACS(filename=fn)
sage: solver.add_clause( ( 1, 2, 3) )
sage: solver.add_clause( ( 1, 2, -3) )
sage: _ = solver.write()
sage: for line in open(fn).readlines():
    ....:   print(line)
```

Alternatively, there is `sage.sat.solvers.dimacs.DIMACS.clauses()`:
These files can then be passed external SAT solvers.

### 1.1 Details on Specific Solvers

#### 1.1.1 Abstract SAT Solver

All SAT solvers must inherit from this class.

**Note:** Our SAT solver interfaces are 1-based, i.e., literals start at 1. This is consistent with the popular DIMACS format for SAT solving but not with Python’s 0-based convention. However, this also allows to construct clauses using simple integers.

**AUTHORS:**

- Martin Albrecht (2012): first version

```python
def SAT(solver=None, *args, **kwds):
    """Return a SatSolver instance."""
    return SatSolver(solver=solver, *args, **kwds)
```

Through this class, one can define and solve SAT problems.

**INPUT:**

- `solver` (string) – select a solver. Admissible values are:
  - "cryptominisat" – note that the cryptominisat package must be installed.
  - "picosat" – note that the pycosat package must be installed.
  - "glucose" – note that the glucose package must be installed.
  - "glucose-syrup" – note that the glucose package must be installed.
  - "LP" – use SatLP to solve the SAT instance.
  - None (default) – use CryptoMiniSat if available, else PicoSAT if available, and an LP solver otherwise.

**EXAMPLES:**

```python
sage: SAT(solver="LP")
```

an ILP-based SAT Solver

```python
class SatSolver:
    """Bases: object"""
```

Chapter 1. Solvers
add_clause(lits)
Add a new clause to set of clauses.

INPUT:

• lits - a tuple of integers != 0

Note: If any element e in lits has abs(e) greater than the number of variables generated so far, then new variables are created automatically.

EXAMPLES:

```python
sage: from sage.sat.solvers.satsolver import SatSolver
sage: solver = SatSolver()

sage: solver.add_clause((1, -2, 3))
Traceback (most recent call last):
  ...\nNotImplementedError
```

clauses(filename=None)
Return original clauses.

INPUT:

• filename - if not None, clauses are written to filename in DIMACS format (default: None)

OUTPUT:

If filename is None then a list of lits, is_xor, rhs tuples is returned, where lits is a tuple of literals, is_xor is always False and rhs is always None.

If filename points to a writable file, then the list of original clauses is written to that file in DIMACS format.

EXAMPLES:

```python
sage: from sage.sat.solvers.satsolver import SatSolver
sage: solver = SatSolver()

sage: solver.clauses()
Traceback (most recent call last):
  ...\nNotImplementedError
```

conflict_clause()
Return conflict clause if this instance is UNSAT and the last call used assumptions.

EXAMPLES:

```python
sage: from sage.sat.solvers.satsolver import SatSolver
sage: solver = SatSolver()

sage: solver.conflict_clause()
Traceback (most recent call last):
  ...\nNotImplementedError
```

learnt_clauses(unitary_only=False)
Return learnt clauses.
INPUT:

• unitary_only - return only unitary learnt clauses (default: False)

EXAMPLES:

```python
sage: from sage.sat.solvers.satsolver import SatSolver
dsage: solver = SatSolver()
sage: solver.learnt_clauses()
Traceback (most recent call last):
... Not ImplementedError
sage: solver.learnt_clauses(unitary_only=True)
Traceback (most recent call last):
... Not ImplementedError
```

nvars()

Return the number of variables.

EXAMPLES:

```python
sage: from sage.sat.solvers.satsolver import SatSolver
dsage: solver = SatSolver()
sage: solver.nvars()
Traceback (most recent call last):
... Not ImplementedError
```

read(filename)

Reads DIMAC files.


The differences were summarized in the discussion on the ticket trac ticket #16924. This method assumes the following DIMACS format:

• Any line starting with “c” is a comment
• Any line starting with “p” is a header
• Any variable 1-n can be used
• Every line containing a clause must end with a “0”

The format is extended to allow lines starting with “x” defining xor clauses, with the notation introduced in cryptominisat, see https://www.msoos.org/xor-clauses/

INPUT:

• filename - The name of a file as a string or a file object

EXAMPLES:

```python
sage: from io import StringIO
sage: file_object = StringIO("c A sample .cnf file.
p cnf 3 2
1 -3 0
2 3 -1
...")
```
With xor clauses:

```python
sage: from io import StringIO
sage: file_object = StringIO("c A sample .cnf file with xor clauses.
np cnf 3 3
→n1 2 \n3 \nx1 2 3 0")
sage: from sage.sat.solvers.cryptominisat import CryptoMiniSat  # optional - pycryptosat
sage: solver = CryptoMiniSat()  # optional - pycryptosat
sage: solver.read(file_object)  # optional - pycryptosat
sage: solver.clauses()  # optional - pycryptosat
[[(1, 2), False, None], ((3,), False, None), ((1, 2, 3), True, True)]
sage: solver()  # optional - pycryptosat
(None, True, True, True)
```

`var(decision=None)`

Return a new variable.

**INPUT:**

- decision - is this variable a decision variable?

**EXAMPLES:**

```python
sage: from sage.sat.solvers.satsolver import SatSolver
sage: solver = SatSolver()
sage: solver.var()
Traceback (most recent call last):
... NotImplementedError
```

### 1.1.2 SAT-Solvers via DIMACS Files

Sage supports calling SAT solvers using the popular DIMACS format. This module implements infrastructure to make it easy to add new such interfaces and some example interfaces.

Currently, interfaces to **RSat** and **Glucose** are included by default.

**Note:** Our SAT solver interfaces are 1-based, i.e., literals start at 1. This is consistent with the popular DIMACS format for SAT solving but not with Python’s 0-based convention. However, this also allows to construct clauses using simple integers.

**AUTHORS:**

---

1.1. Details on Specific Solvers 7
Classes and Methods

class sage.sat.solvers.dimacs.DIMACS(command=None, filename=None, verbosity=0, **kwds)
Bases: sage.sat.solvers.satsolver.SatSolver

Generic DIMACS Solver.

Note: Usually, users won’t have to use this class directly but some class which inherits from this class.

__init__(command=None, filename=None, verbosity=0, **kwds)
Construct a new generic DIMACS solver.

INPUT:

• command - a named format string with the command to run. The string must contain \{input\} and may contain \{output\} if the solvers writes the solution to an output file. For example “sat-solver \{input\}” is a valid command. If None then the class variable command is used. (default: None)

• filename - a filename to write clauses to in DIMACS format, must be writable. If None a temporary filename is chosen automatically. (default: None)

• verbosity - a verbosity level, where zero means silent and anything else means verbose output. (default: 0)

• **kwds - accepted for compatibility with other solves, ignored.

__call__(assumptions=None)
Run ‘command’ and collect output.

INPUT:

• assumptions - ignored, accepted for compatibility with other solves (default: None)

add_clause(lits)
Add a new clause to set of clauses.

INPUT:

• lits - a tuple of integers != 0

Note: If any element \(e\) in \(lits\) has \(abs(e)\) greater than the number of variables generated so far, then new variables are created automatically.

EXAMPLES:

```python
sage: from sage.sat.solvers.dimacs import DIMACS
sage: solver = DIMACS()
sage: solver.var()
1
sage: solver.var(decision=True)
2
sage: solver.add_clause( (1, -2 , 3) )
sage: solver
DIMACS Solver: '
```
**clauses** *(filename=None)*

Return original clauses.

**INPUT:**

- `filename` - if not `None` clauses are written to `filename` in DIMACS format (default: `None`)

**OUTPUT:**

If `filename` is `None` then a list of `lits`, `is_xor`, `rhs` tuples is returned, where `lits` is a tuple of literals, `is_xor` is always `False` and `rhs` is always `None`.

If `filename` points to a writable file, then the list of original clauses is written to that file in DIMACS format.

**EXAMPLES:**

```python
given_code_snippet
```

**nvars()**

Return the number of variables.

**EXAMPLES:**

```python
given_code_snippet
```

**static render_dimacs(clauses, filename, nlits)**

Produce DIMACS file `filename` from `clauses`.

**INPUT:**

- `clauses` - a list of clauses, either in simple format as a list of literals or in extended format for CryptoMiniSat: a tuple of literals, `is_xor` and `rhs`.

- `filename` - the file to write to

- `nlits` -- the number of literals appearing in `clauses`

**EXAMPLES:**

```python
given_code_snippet
```
```python
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()

sage: solver = DIMACS()

sage: solver.add_clause( (1, 2, -3) )

sage: DIMACS.render_dimacs(solver.clauses(), fn, solver.nvars())

sage: print(open(fn).read())
p cnf 3 1
 1 2 -3 0

This is equivalent to:

```python
sage: solver.clauses(fn)

sage: print(open(fn).read())
p cnf 3 1
 1 2 -3 0
```

This function also accepts a “simple” format:

```python
sage: DIMACS.render_dimacs([ (1,2), (1,2,-3) ], fn, 3)

sage: print(open(fn).read())
p cnf 3 2
 1 2 0
 1 2 -3 0
```

**var** *(decision=None)*

Return a new variable.

INPUT:

- *decision* - accepted for compatibility with other solvers, ignored.

EXAMPLES:

```python
sage: from sage.sat.solvers.dimacs import DIMACS
sage: solver = DIMACS()

sage: solver.var()
1
```

**write** *(filename=None)*

Write DIMACS file.

INPUT:

- *filename* - if None default filename specified at initialization is used for writing to (default: None)

EXAMPLES:

```python
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()

sage: solver = DIMACS(filename=fn)

sage: solver.add_clause( (1, -2 , 3) )

sage: _ = solver.write()

sage: for line in open(fn).readlines():
.....:     print(line)
p cnf 3 1
 1 -2 3 0
```

(continues on next page)
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()
sage: solver = DIMACS()
sage: solver.add_clause( (1, -2 , 3) )
sage: _ = solver.write(fn)
sage: for line in open(fn).readlines():
    print(line)
    p cnf 3 1
    1 -2 3 0

class sage.sat.solvers.dimacs.Glucose(command=None, filename=None, verbosity=0, **kwds)
    Bases: sage.sat.solvers.dimacs.DIMACS

An instance of the Glucose solver.

For information on Glucose see: http://www.labri.fr/perso/lsimon/glucose/

EXAMPLES:

    sage: from sage.sat.solvers import Glucose
    sage: solver = Glucose()
    sage: solver
    DIMACS Solver: 'glucose -verb=2 {input} {output}'
    sage: solver.add_clause( (1, 2, 3) )
    sage: solver.add_clause( (-1,) )
    sage: solver.add_clause( (-2,) )
    sage: solver()  # optional - glucose
    (None, False, False, True)

class sage.sat.solvers.dimacs.GlucoseSyrup(command=None, filename=None, verbosity=0, **kwds)
    Bases: sage.sat.solvers.dimacs.DIMACS

An instance of the Glucose-syrup parallel solver.

For information on Glucose see: http://www.labri.fr/perso/lsimon/glucose/

class sage.sat.solvers.dimacs.RSat(command=None, filename=None, verbosity=0, **kwds)
    Bases: sage.sat.solvers.dimacs.DIMACS

An instance of the RSat solver.

For information on RSat see: http://reasoning.cs.ucla.edu/rsat/

1.1.3 PicoSAT Solver

This solver relies on the pycosat Python bindings to PicoSAT.
The pycosat package should be installed on your Sage installation.

AUTHORS:

• Thierry Monteil (2018): initial version.

class sage.sat.solvers.picosat.PicoSAT(verbosity=0, prop_limit=0)
    Bases: sage.sat.solvers.satsolver.SatSolver

PicoSAT Solver.
INPUT:

- **verbosity** – an integer between 0 and 2 (default: 0); verbosity
- **prop_limit** – an integer (default: 0); the propagation limit

EXAMPLES:

```python
sage: from sage.sat.solvers.picosat import PicoSAT
sage: solver = PicoSAT()  # optional - pycosat
```

`add_clause(lits)`

Add a new clause to set of clauses.

INPUT:

- **lits** – a tuple of nonzero integers

**Note:** If any element e in lits has $\text{abs}(e)$ greater than the number of variables generated so far, then new variables are created automatically.

EXAMPLES:

```python
sage: from sage.sat.solvers.picosat import PicoSAT
sage: solver = PicoSAT()  # optional - pycosat
sage: solver.add_clause((1, -2, 3))  # optional - pycosat
```

`clauses(filename=None)`

Return original clauses.

INPUT:

- **filename** – (optional) if given, clauses are written to filename in DIMACS format

OUTPUT:

If filename is None then a list of lits is returned, where lits is a list of literals.

If filename points to a writable file, then the list of original clauses is written to that file in DIMACS format.

EXAMPLES:

```python
sage: from sage.sat.solvers.picosat import PicoSAT
sage: solver = PicoSAT()  # optional - pycosat
sage: solver.add_clause((1, 2, 4))  # optional - pycosat
sage: solver.add_clause((1, 2, -4))  # optional - pycosat
sage: fn = tmp_filename()  # optional - pycosat
sage: solver.clauses(fn)  # optional - pycosat
sage: print(open(fn).read())  # optional - pycosat
```

DIMACS format output:

```python
sage: from sage.sat.solvers.picosat import PicoSAT
sage: solver = PicoSAT()  # optional - pycosat
sage: solver.add_clause((1, 2, 3, 4, 5, 6, 7, 8, -9))  # optional - pycosat
sage: solver.clauses()  # optional - pycosat
[[1, 2, 3, 4, 5, 6, 7, 8, -9]]
```
(continues on next page)
**nvars()**

Return the number of variables. Note that for compatibility with DIMACS convention, the number of variables corresponds to the maximal index of the variables used.

**EXAMPLES:**

```python
sage: from sage.sat.solvers.picosat import PicoSAT
sage: solver = PicoSAT()  # optional - pycosat
sage: solver.nvars()  # optional - pycosat
0
```

If a variable with intermediate index is not used, it is still considered as a variable:

```python
sage: solver.add_clause((1,-2,4))  # optional - pycosat
sage: solver.nvars()  # optional - pycosat
4
```

**var**(decision=None)

Return a new variable.

**INPUT:**

- decision – ignored; accepted for compatibility with other solvers

**EXAMPLES:**

```python
sage: from sage.sat.solvers.picosat import PicoSAT
sage: solver = PicoSAT()  # optional - pycosat
sage: solver.var()  # optional - pycosat
1
sage: solver.add_clause((-1,2,-4))  # optional - pycosat
sage: solver.var()  # optional - pycosat
5
```

### 1.1.4 Solve SAT problems Integer Linear Programming

The class defined here is a *SatSolver* that solves its instance using *MixedIntegerLinearProgram*. Its performance can be expected to be slower than when using *CryptoMiniSat*.

```python
class sage.sat.solvers.sat_lp.SatLP(solver, verbose=None, integrality_tolerance=0)
```

**Bases:** *sage.sat.solvers.satsolver.SatSolver*

Initializes the instance

**INPUT:**

- solver – (default: None) Specify a Mixed Integer Linear Programming (MILP) solver to be used. If set to None, the default one is used. For more information on MILP solvers and which default solver is used, see the method *solve* of the class *MixedIntegerLinearProgram*.

- verbose – integer (default: 0). Sets the level of verbosity of the LP solver. Set to 0 by default, which means quiet.
• integrality_tolerance – parameter for use with MILP solvers over an inexact base ring; see MixedIntegerLinearProgram.get_values().

EXAMPLES:

```
sage: S=SAT(solver="LP"); S
an ILP-based SAT Solver
```

`add_clause(lits)`
Add a new clause to set of clauses.

INPUT:
• `lits` - a tuple of integers != 0

**Note:** If any element $e$ in `lits` has $|e|$ greater than the number of variables generated so far, then new variables are created automatically.

EXAMPLES:

```
sage: S=SAT(solver="LP"); S
an ILP-based SAT Solver
sage: for u,v in graphs.CycleGraph(6).edges(sort=False, labels=False):
    ....:    u,v = u+1,v+1
    ....:    S.add_clause((u,v))
    ....:    S.add_clause((-u,-v))
```

`nvars()`
Return the number of variables.

EXAMPLES:

```
sage: S=SAT(solver="LP"); S
an ILP-based SAT Solver
sage: S.var()
1
sage: S.var()
2
sage: S.nvars()
2
```

`var()`
Return a new variable.

EXAMPLES:

```
sage: S=SAT(solver="LP"); S
an ILP-based SAT Solver
sage: S.var()
1
```
1.1.5 CryptoMiniSat Solver

This solver relies on Python bindings provided by upstream cryptominisat.

The `cryptominisat` package should be installed on your Sage installation.

AUTHORS:

• Thierry Monteil (2017): complete rewrite, using upstream Python bindings, works with cryptominisat 5.
• Martin Albrecht (2012): first version, as a cython interface, works with cryptominisat 2.

```python
class sage.sat.solvers.cryptominisat.CryptoMiniSat(verbosity=0, confl_limit=None, threads=None):
    Bases: sage.sat.solvers.satsolver.SatSolver

    CryptoMiniSat Solver.
    INPUT:
    • verbosity – an integer between 0 and 15 (default: 0). Verbosity.
    • confl_limit – an integer (default: None). Abort after this many conflicts. If set to None, never aborts.
    • threads – an integer (default: None). The number of thread to use. If set to None, the number of threads
      used corresponds to the number of cpus.

    EXAMPLES:
```

```python
sage: from sage.sat.solvers.cryptominisat import CryptoMiniSat
sage: solver = CryptoMiniSat()  # optional - pycryptosat
```

`add_clause(lits)`

Add a new clause to set of clauses.

INPUT:

• lits – a tuple of nonzero integers.

**Note:** If any element e in `lits` has abs(e) greater than the number of variables generated so far, then new variables are created automatically.

```python
sage: from sage.sat.solvers.cryptominisat import CryptoMiniSat
sage: solver = CryptoMiniSat()  # optional - pycryptosat
sage: solver.add_clause((1, -2, 3))  # optional - pycryptosat
```

`add_xor_clause(lits, rhs=True)`

Add a new XOR clause to set of clauses.

INPUT:

• lits – a tuple of positive integers.
• rhs – boolean (default: True). Whether this XOR clause should be evaluated to True or False.

EXAMPLES:
```python
sage: from sage.sat.solvers.cryptominisat import CryptoMiniSat
sage: solver = CryptoMiniSat()                      # optional - pycryptosat
sage: solver.add_xor_clause((1, 2, 3), False)       # optional - pycryptosat

clauses(filename=None)
Return original clauses.

INPUT:

• filename – if not None clauses are written to filename in DIMACS format (default: None)

OUTPUT:

If filename is None then a list of lits, is_xor, rhs tuples is returned, where lits is a tuple of literals, is_xor is always False and rhs is always None.

If filename points to a writable file, then the list of original clauses is written to that file in DIMACS format.

EXAMPLES:

```python
sage: from sage.sat.solvers import CryptoMiniSat
sage: solver = CryptoMiniSat()                      # optional - pycryptosat
sage: solver.add_clause((1, 2, 3, 4, 5, 6, 7, 8, -9))  # optional - pycryptosat
sage: solver.add_xor_clause((1, 2, 3, 4, 5, 6, 7, 8, 9), rhs=True)  # optional - pycryptosat

sage: solver.clauses()                               # optional - pycryptosat
[((1, 2, 3, 4, 5, 6, 7, 8, -9), False, None),
 ((1, 2, 3, 4, 5, 6, 7, 8, 9), True, True)]
```

DIMACS format output:

```python
sage: from sage.sat.solvers import CryptoMiniSat
sage: solver = CryptoMiniSat()                      # optional - pycryptosat
sage: solver.add_clause((1, 2, 4))                  # optional - pycryptosat
sage: solver.add_clause((1, 2, -4))                 # optional - pycryptosat
sage: fn = tmp_filename()                           # optional - pycryptosat
sage: solver.clauses(fn)                            # optional - pycryptosat
sage: print(open(fn).read())                        # optional - pycryptosat
p cnf 4 2
1 2 4 0
1 2 -4 0
```

Note that in cryptominisat, the DIMACS standard format is augmented with the following extension: having an x in front of a line makes that line an XOR clause:

```python
sage: solver.add_xor_clause((1, 2, 3), rhs=True)    # optional - pycryptosat
sage: solver.clauses(fn)                            # optional - pycryptosat
sage: print(open(fn).read())                        # optional - pycryptosat
p cnf 4 3
1 2 4 0
```

(continues on next page)
Note that inverting an xor-clause is equivalent to inverting one of the variables:

```python
sage: solver.add_xor_clause((1,2,5), rhs=False)  # optional - pycryptosat
sage: solver.clauses(fn)  # optional - pycryptosat
sage: print(open(fn).read())  # optional - pycryptosat
```

```
p cnf 5 4
1 2 4 0
1 2 -4 0
x1 2 3 0
x1 2 -5 0
```

.. code-block::

    nvars()

Return the number of variables. Note that for compatibility with DIMACS convention, the number of variables corresponds to the maximal index of the variables used.

**EXAMPLES:**

```python
sage: from sage.sat.solvers.cryptominisat import CryptoMiniSat
sage: solver = CryptoMiniSat()  # optional - pycryptosat
sage: solver.nvars()  # optional - pycryptosat
0
```

If a variable with intermediate index is not used, it is still considered as a variable:

```python
sage: solver.add_clause((1,-2,4))  # optional - pycryptosat
sage: solver.nvars()  # optional - pycryptosat
4
```

**var**(decision=None)

Return a new variable.

**INPUT:**

- decision – accepted for compatibility with other solvers, ignored.

**EXAMPLES:**

```python
sage: from sage.sat.solvers.cryptominisat import CryptoMiniSat
sage: solver = CryptoMiniSat()  # optional - pycryptosat
sage: solver.var()  # optional - pycryptosat
1
sage: solver.add_clause((-1,2,-4))  # optional - pycryptosat
sage: solver.var()  # optional - pycryptosat
```

(continues on next page)
Sage supports conversion from Boolean polynomials (also known as Algebraic Normal Form) to Conjunctive Normal Form:

```python
sage: B.<a,b,c> = BooleanPolynomialRing()
sage: from sage.sat.converters.polybori import CNFEncoder
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()
sage: solver = DIMACS(filename=fn)
sage: e = CNFEncoder(solver, B)
sage: e.clauses_sparse(a*b + a + 1)
sage: _ = solver.write()
sage: print(open(fn).read())
P cnf 3 2
-2 0
1 0
```

### 2.1 Details on Specific Converters

#### 2.1.1 An ANF to CNF Converter using a Dense/Sparse Strategy

This converter is based on two converters. The first one, by Martin Albrecht, was based on [CB2007], this is the basis of the “dense” part of the converter. It was later improved by Mate Soos. The second one, by Michael Brickenstein, uses a reduced truth table based approach and forms the “sparse” part of the converter.

AUTHORS:

- Martin Albrecht - (2008-09) initial version of ‘anf2cnf.py’
- Michael Brickenstein - (2009) ‘cnf.py’ for PolyBoRi
- Mate Soos - (2010) improved version of ‘anf2cnf.py’
- Martin Albrecht - (2012) unified and added to Sage
Classes and Methods

class sage.sat.converters.polybori.CNFEncoder(solver, ring, max_vars_sparse=6, use_xor_clauses=None, cutting_number=6, random_seed=16):

Bases: sage.sat.converters.anf2cnf.ANF2CNFConverter

ANF to CNF Converter using a Dense/Sparse Strategy. This converter distinguishes two classes of polynomials.

1. Sparse polynomials are those with at most max_vars_sparse variables. Those are converted using reduced truth-tables based on PolyBoRi’s internal representation.

2. Polynomials with more variables are converted by introducing new variables for monomials and by converting these linearised polynomials.

Linearised polynomials are converted either by splitting XOR chains – into chunks of length cutting_number – or by constructing XOR clauses if the underlying solver supports it. This behaviour is disabled by passing use_xor_clauses=False.

__init__(solver, ring, max_vars_sparse=6, use_xor_clauses=None, cutting_number=6, random_seed=16)

Construct ANF to CNF converter over ring passing clauses to solver.

INPUT:

- solver - a SAT-solver instance
- ring - a sage.rings.polynomial.pbori.BooleanPolynomialRing
- max_vars_sparse - maximum number of variables for direct conversion
- use_xor_clauses - use XOR clauses; if None use if solver supports it. (default: None)
- cutting_number - maximum length of XOR chains after splitting if XOR clauses are not supported (default: 6)
- random_seed - the direct conversion method uses randomness, this sets the seed (default: 16)

EXAMPLES:

We compare the sparse and the dense strategies, sparse first:

```
sage: B.<a,b,c> = BooleanPolynomialRing()
sage: from sage.sat.converters.polybori import CNFEncoder
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()
sage: solver = DIMACS(filename=fn)
sage: e = CNFEncoder(solver, B)
sage: e.clauses_sparse(a*b + a + 1)
sage: _ = solver.write()
sage: print(open(fn).read())
p cnf 3 2
-2 0
1 0
sage: e.phi
[None, a, b, c]
```

Now, we convert using the dense strategy:

```
sage: B.<a,b,c> = BooleanPolynomialRing()
sage: from sage.sat.converters.polybori import CNFEncoder
```

(continues on next page)
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()

sage: solver = DIMACS(filename=fn)

sage: e = CNFEncoder(solver, B)

sage: _ = solver.write()

sage: print(open(fn).read())
p cnf 4 5
1 -4 0
2 -4 0
4 -1 -2 0
-4 -1 0
4 1 0

sage: e.phi
[None, a, b, c, a*b]

Note: This constructor generates SAT variables for each Boolean polynomial variable.

__call__\( (F) \)

Encode the boolean polynomials in \( F \).

INPUT:

- \( F \) - an iterable of \sage.rings.polynomial.pbori.BooleanPolynomial

OUTPUT: An inverse map int \( \rightarrow \) variable

EXAMPLES:

sage: B.<a,b,c> = BooleanPolynomialRing()

sage: from sage.sat.converters.polybori import CNFEncoder

sage: from sage.sat.solvers.dimacs import DIMACS

sage: fn = tmp_filename()

sage: solver = DIMACS(filename=fn)

sage: e = CNFEncoder(solver, B, max_vars_sparse=2)

sage: e([a*b + a + 1, a*b+ a + c])

[None, a, b, c, a*b]

sage: _ = solver.write()

sage: print(open(fn).read())
p cnf 4 9
-2 0
1 0
1 -4 0
2 -4 0
4 -1 -2 0
-4 -1 -3 0
4 1 -3 0
4 -1 3 0
-4 1 3 0

sage: e.phi
[None, a, b, c, a*b]
clauses(/f/)

Convert f using the sparse strategy if f.nvariables() is at most max_vars_sparse and the dense strategy otherwise.

INPUT:

  * f - a sage.rings.polynomial.pbori.BooleanPolynomial

EXAMPLES:

```python
sage: B.<a,b,c> = BooleanPolynomialRing()
sage: from sage.sat.converters.polybori import CNFEncoder
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()
sage: solver = DIMACS(filename=fn)
sage: e = CNFEncoder(solver, B, max_vars_sparse=2)
sage: e.clauses(a*b + a + 1)
sage: _ = solver.write()
sage: print(open(fn).read())
p cnf 3 2
 1 0
-2 0
sage: e.phi
[None, a, b, c]
```

```python
sage: B.<a,b,c> = BooleanPolynomialRing()
sage: from sage.sat.converters.polybori import CNFEncoder
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()
sage: solver = DIMACS(filename=fn)
sage: e = CNFEncoder(solver, B, max_vars_sparse=2)
sage: e.clauses(a*b + a + c)
sage: _ = solver.write()
sage: print(open(fn).read())
p cnf 4 7
 1 -4 0
 2 -4 0
 4 -1 -2 0
-4 -1 -3 0
 4 1 -3 0
 4 -1 3 0
-4 1 3 0
sage: e.phi
[None, a, b, c, a*b]
```

clauses_dense(/f/)

Convert f using the dense strategy.

INPUT:

  * f - a sage.rings.polynomial.pbori.BooleanPolynomial

EXAMPLES:

```python
sage: B.<a,b,c> = BooleanPolynomialRing()
sage: from sage.sat.converters.polybori import CNFEncoder
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()
sage: solver = DIMACS(filename=fn)
sage: e = CNFEncoder(solver, B, max_vars_sparse=2)
sage: e.clauses(a*b + a + c)
sage: _ = solver.write()
sage: print(open(fn).read())
p cnf 4 7
 1 -4 0
 2 -4 0
 4 -1 -2 0
-4 -1 -3 0
 4 1 -3 0
 4 -1 3 0
-4 1 3 0
sage: e.phi
[None, a, b, c, a*b]
```
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()
sage: solver = DIMACS(filename=fn)
sage: e = CNFEncoder(solver, B)
sage: e.clauses_dense(a*b + a + 1)
sage: _ = solver.write()
sage: print(open(fn).read())
p cnf 4 5
  1 -4 0
  2 -4 0
  4 -1 -2 0
  -4 -1 0
  4 1 0
sage: e.phi
[None, a, b, c, a*b]

clauses_sparse(f)

Convert $f$ using the sparse strategy.

INPUT:

- $f$ - a sage.rings.polynomial.pbori.BooleanPolynomial

EXAMPLES:

sage: B.<a,b,c> = BooleanPolynomialRing()
sage: from sage.sat.converters.polybori import CNFEncoder
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()
sage: solver = DIMACS(filename=fn)
sage: e = CNFEncoder(solver, B)
sage: e.clauses_sparse(a*b + a + 1)
sage: _ = solver.write()
sage: print(open(fn).read())
p cnf 3 2
  -2 0
  1 0
sage: e.phi
[None, a, b, c]

monomial(m)

Return SAT variable for $m$

INPUT:

- $m$ - a monomial.

OUTPUT: An index for a SAT variable corresponding to $m$.

EXAMPLES:

sage: B.<a,b,c> = BooleanPolynomialRing()
sage: from sage.sat.converters.polybori import CNFEncoder
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()
.. note::

For correctness, this function is cached.

**permutations**(length, equal_zero)

Return permutations of length length which are equal to zero if equal_zero and equal to one otherwise.

A variable is false if the integer in its position is smaller than zero and true otherwise.

**INPUT:**

- length – the number of variables
- equal_zero – should the sum be equal to zero?

**EXAMPLES:**

```python
sage: from sage.sat.converters.polybori import CNFEncoder
sage: from sage.sat.solvers.dimacs import DIMACS
sage: B.<a,b,c> = BooleanPolynomialRing()

sage: ce = CNFEncoder(DIMACS(), B)

sage: ce.permutations(3, True)
[[[-1, -1, -1], [1, 1, -1], [1, -1, 1], [-1, 1, 1]]

sage: ce.permutations(3, False)
[[[1, -1, -1], [-1, 1, -1], [-1, -1, 1], [1, 1, 1]]
```

**phi**

Map SAT variables to polynomial variables.

**EXAMPLES:**

```python
sage: from sage.sat.converters.polybori import CNFEncoder
sage: from sage.sat.solvers.dimacs import DIMACS
```
sage: B.<a,b,c> = BooleanPolynomialRing()
sage: ce = CNFEncoder(DIMACS(), B)
sage: ce.var()
4
sage: ce.phi
[None, a, b, c, None]

\texttt{split\_xor(monomial\_list, equal\_zero)}

Split XOR chains into subchains.

\textbf{INPUT:}

- monomial\_list - a list of monomials
- equal\_zero - is the constant coefficient zero?

\textbf{EXAMPLES:}

\begin{verbatim}
sage: from sage.sat.converters.polybori import CNFEncoder	sage: from sage.sat.solvers.dimacs import DIMACS	sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()	sage: ce = CNFEncoder(DIMACS(), B, cutting_number=3)	sage: ce.split_xor([1,2,3,4,5,6], False)
[[[1, 7], False], [[7, 2, 8], True], [[8, 3, 9], True], [[9, 4, 10], True], [[10, 5, 11], True], [[11, 6], True]]
sage: ce = CNFEncoder(DIMACS(), B, cutting_number=4)
sage: ce.split_xor([1,2,3,4,5,6], False)
[[[1, 2, 7], False], [[7, 3, 4, 8], True], [[8, 5, 6], True]]
sage: ce = CNFEncoder(DIMACS(), B, cutting_number=5)
sage: ce.split_xor([1,2,3,4,5,6], False)
[[[1, 2, 3, 7], False], [[7, 4, 5, 6], True]]
\end{verbatim}

\texttt{to\_polynomial(c)}

Convert clause to \texttt{sage.rings.polynomial.pbori.BooleanPolynomial}

\textbf{INPUT:}

- c - a clause

\textbf{EXAMPLES:}

\begin{verbatim}
sage: B.<a,b,c> = BooleanPolynomialRing()
sage: from sage.sat.converters.polybori import CNFEncoder	sage: from sage.sat.solvers.dimacs import DIMACS	sage: fn = tmp_filename()	sage: solver = DIMACS(filename=fn)	sage: e = CNFEncoder(solver, B, max_vars_sparse=2)	sage: _ = e([a*b + a + 1, a*b + a + c])	sage: e.to_polynomial( (1,-2,3) )
a*b*c + a*b + b*c + b
\end{verbatim}

\texttt{var(m=None, decision=None)}

Return a new variable.

\section*{2.1. Details on Specific Converters}
This is a thin wrapper around the SAT-solvers function where we keep track of which SAT variable corresponds to which monomial.

INPUT:

- m - something the new variables maps to, usually a monomial
- decision - is this variable a decision variable?

EXAMPLES:

```python
sage: from sage.sat.converters.polybori import CNFEncoder
sage: from sage.sat.solvers.dimacs import DIMACS
sage: B.<a,b,c> = BooleanPolynomialRing()
```

```python
sage: ce = CNFEncoder(DIMACS(), B)
```

```python
sage: ce.var()
4
```

### zero_blocks(f)

Divide the zero set of \( f \) into blocks.

EXAMPLES:

```python
sage: B.<a,b,c> = BooleanPolynomialRing()
```

```python
sage: from sage.sat.converters.polybori import CNFEncoder
sage: from sage.sat.solvers.dimacs import DIMACS
```

```python
sage: e = CNFEncoder(DIMACS(), B)
```

```python
sage: sorted(sorted(d.items()) for d in e.zero_blocks(a*b*c))
```

```
[[[c, 0]], [[b, 0]], [[a, 0]]]
```

**Note:** This function is randomised.
CHAPTER
THREE

HIGHLEVEL INTERFACES

Sage provides various highlevel functions which make working with Boolean polynomials easier. We construct a very small-scale AES system of equations and pass it to a SAT solver:

```
sage: sr = mq.SR(1,1,1,4,gf2=True,polybori=True)
sage: while True:
    try:
        F,s = sr.polynomial_system()
    break
    except ZeroDivisionError:
    pass
sage: from sage.sat.boolean_polynomials import solve as solve_sat  # optional - → pycryptosat
sage: s = solve_sat(F)  # optional - → pycryptosat
sage: F.subs(s[0])  # optional - → pycryptosat
```

Polyomial Sequence with 36 Polynomials in 0 Variables

3.1 Details on Specific Highlevel Interfaces

3.1.1 SAT Functions for Boolean Polynomials

These highlevel functions support solving and learning from Boolean polynomial systems. In this context, “learning” means the construction of new polynomials in the ideal spanned by the original polynomials.

AUTHOR:
• Martin Albrecht (2012): initial version

Functions

```
sage.sat.boolean_polynomials.learn(F, converter=None, solver=None, max_learnt_length=3, interreduction=False, **kwds)
```

Learn new polynomials by running SAT-solver solver on SAT-instance produced by converter from F.

INPUT:
• F - a sequence of Boolean polynomials
• converter - an ANF to CNF converter class or object. If converter is None then sage.sat.converters.polybori.CNFEncoder is used to construct a new converter. (default: None)
• **solver** - a SAT-solver class or object. If **solver** is **None** then *sage.sat.solvers.cryptominisat.CryptoMiniSat* is used to construct a new converter. (default: **None**)

• **max_learnt_length** - only clauses of length <= **max_learnt_length** are considered and converted to polynomials. (default: **3**)

• **interreduction** - inter-reduce the resulting polynomials (default: **False**)

**Note:** More parameters can be passed to the converter and the solver by prefixing them with **c_** and **s_** respectively. For example, to increase CryptoMiniSat’s verbosity level, pass **s_verbosity=1**.

**OUTPUT:**

A sequence of Boolean polynomials.

**EXAMPLES:**

```
sage: from sage.sat.boolean_polynomials import learn as learn_sat # optional - pycryptosat
```

We construct a simple system and solve it:

```
sage: set_random_seed(2300) # optional - pycryptosat
sage: sr = mq.SR(1,2,2,4,gf2=True,polybori=True) # optional - pycryptosat
sage: F,s = sr.polynomial_system() # optional - pycryptosat
sage: H = learn_sat(F) # optional - pycryptosat
sage: H[-1] # optional - pycryptosat
ek033* + 1
```

`sage.sat.boolean_polynomials.solve(F, converter=None, solver=None, n=1, target_variables=None, **kwds)`

Solve system of Boolean polynomials *F* by solving the SAT-problem – produced by **converter** – using **solver**.

**INPUT:**

• **F** - a sequence of Boolean polynomials

• **n** - number of solutions to return. If **n** is +infinity then all solutions are returned. If **n** < infinity then **n** solutions are returned if **F** has at least **n** solutions. Otherwise, all solutions of **F** are returned. (default: **1**)

• **converter** - an ANF to CNF converter class or object. If **converter** is **None** then *sage.sat.converters.polybori.CNFEncoder* is used to construct a new converter. (default: **None**)

• **solver** - a SAT-solver class or object. If **solver** is **None** then *sage.sat.solvers.cryptominisat.CryptoMiniSat* is used to construct a new converter. (default: **None**)

• **target_variables** - a list of variables. The elements of the list are used to exclude a particular combination of variable assignments of a solution from any further solution. Furthermore **target_variables** denotes which variable-value pairs appear in the solutions. If **target_variables** is **None** all variables appearing in the polynomials of **F** are used to construct exclusion clauses. (default: **None**)

• ****kwds - parameters can be passed to the converter and the **solver** by prefixing them with **c_** and **s_** respectively. For example, to increase CryptoMiniSat’s verbosity level, pass **s_verbosity=1**.

**OUTPUT:**

A list of dictionaries, each of which contains a variable assignment solving **F**.

**EXAMPLES:**

We construct a very small-scale AES system of equations:
```python
sage: sr = mq.SR(1,1,1,4,gf2=True,polybori=True)
sage: while True:  # workaround (see :trac:`31891`)
    ....:     try:
    ....:         F, s = sr.polynomial_system()
    ....:         break
    ....:     except ZeroDivisionError:
    ....:         pass

and pass it to a SAT solver:

```python
sage: from sage.sat.boolean_polynomials import solve as solve_sat  # optional ~
                        ~pycryptosat
sage: s = solve_sat(F)  # optional ~
                        ~pycryptosat
sage: F.subs(s[0])  # optional ~
                        ~pycryptosat
Polynomial Sequence with 36 Polynomials in 0 Variables
```

This time we pass a few options through to the converter and the solver:

```python
sage: s = solve_sat(F, c_max_vars_sparse=4, c_cutting_number=8)  # optional ~
                        ~pycryptosat
sage: F.subs(s[0])  # optional ~
                        ~pycryptosat
Polynomial Sequence with 36 Polynomials in 0 Variables
```

We construct a very simple system with three solutions and ask for a specific number of solutions:

```python
sage: B.<a,b> = BooleanPolynomialRing()  # optional - pycryptosat
sage: f = a*b  # optional - pycryptosat
sage: l = solve_sat([f],n=1)  # optional - pycryptosat
sage: len(l) == 1, f.subs(l[0])  # optional - pycryptosat
(True, 0)

sage: l = solve_sat([a*b],n=2)  # optional - pycryptosat
sage: len(l) == 2, f.subs(l[0]), f.subs(l[1])  # optional - pycryptosat
(True, 0, 0)

sage: sorted((d[a], d[b]) for d in solve_sat([a*b],n=3))  # optional - pycryptosat
[(0, 0), (0, 1), (1, 0)]

sage: sorted((d[a], d[b]) for d in solve_sat([a*b],n=4))  # optional - pycryptosat
[(0, 0), (0, 1), (1, 0)]

sage: sorted((d[a], d[b]) for d in solve_sat([a*b],n=infinity))  # optional ~
                        ~pycryptosat
[(0, 0), (0, 1), (1, 0)]
```

In the next example we see how the target_variables parameter works:

```python
sage: from sage.sat.boolean_polynomials import solve as solve_sat  # optional ~
                        ~pycryptosat
sage: R.<a,b,c,d> = BooleanPolynomialRing()  # optional ~
                        ~pycryptosat
sage: F = a+b,a+c+d  # optional ~
                        ~pycryptosat
```

3.1. Details on Specific Highlevel Interfaces
First the normal use case:

```python
sage: sorted((D[a], D[b], D[c], D[d]) for D in solve_sat(F,n=infinity))
optional - pycryptosat
[(0, 0, 0, 0), (0, 0, 1, 1), (1, 1, 0, 1), (1, 1, 1, 0)]
```

Now we are only interested in the solutions of the variables a and b:

```python
sage: solve_sat(F,n=infinity,target_variables=[a,b])
optional - pycryptosat
[{b: 0, a: 0}, {b: 1, a: 1}]
```

Here, we generate and solve the cubic equations of the AES SBox (see trac ticket #26676):

```python
sage: from sage.rings.polynomial.multi_polynomial_sequence import PolynomialSequence
optional - pycryptosat, long time
sage: from sage.sat.boolean_polynomials import solve as solve_sat
optional - pycryptosat, long time
sage: sr = sage.crypto.mq.SR(1, 4, 4, 8, allow_zero_inversions = True)
optional - pycryptosat, long time
sage: sb = sr.sbox()
optional - pycryptosat, long time
sage: eqs = sb.polynomials(degree = 3)
optional - pycryptosat, long time
sage: variables = map(str, eqs.variables())
optional - pycryptosat, long time
sage: variables = ','.join(variables)
optional - pycryptosat, long time
sage: R = BooleanPolynomialRing(16, variables)
optional - pycryptosat, long time
sage: eqs = [R(eq) for eq in eqs]
optional - pycryptosat, long time
sage: sls_aes = solve_sat(eqs, n = infinity)
optional - pycryptosat, long time
sage: len(sls_aes)
256
```

Note: Although supported, passing converter and solver objects instead of classes is discouraged because these objects are stateful.

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