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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:

\[ x_1 \text{ OR } x_2 \text{ OR } (\text{NOT } x_3) \]

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.

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

In Sage’s notation:

```
sage: solver = SAT()
sage: solver.add_clause( ( 1, 2, 3) )
sage: solver.add_clause( ( 1, 2, -3) )
sage: solver()       # random
(Non, 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)
p cnf 3 2
  1 2 3 0
  1 2 -3 0
```

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

```
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()
sage: solver = DIMACS()
sage: solver.add_clause( ( 1, 2, 3 ) )
sage: solver.add_clause( ( 1, 2, -3 ) )
sage: solver.clauses(fn)
sage: for line in open(fn).readlines():
    ....:     print(line)
p cnf 3 2
1 2 3 0
1 2 -3 0
```

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 a LP solver otherwise.

**EXAMPLES:**

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

**class** `sage.sat.solvers.satsolver.SatSolver`

Bases: `object`
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:
```
sage: from sage.sat.solvers.satsolver import SatSolver
sage: solver = SatSolver()
sage: solver.add_clause( (1, -2, 3) )
Traceback (most recent call last):
...  
NotImplementedError
```

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

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

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

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
sage: solver = SatSolver()
sage: solver.learnt_clauses()
Traceback (most recent call last):
... Not Implemented Error

sage: solver.learnt_clauses(unitary_only=True)
Traceback (most recent call last):
... Not Implemented Error
```

`nvars()`

Return the number of variables.

EXAMPLES:

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

`read(filename)`

Reads DIMACS 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
...")
```
```python
from sage.sat.solvers.dimacs import DIMACS
sage: solver = DIMACS()
sage: solver.read(file_object)
sage: solver.clauses()
[((1, -3), False, None), ((2, 3, -1), False, None)]
```

With xor clauses:

```python
from io import StringIO
sage: file_object = StringIO("c A sample .cnf file with xor clauses.
p cnf 3 3
\n1 2 3 0
3 0
x1 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)
```

### trait_names()
Allow alias to appear in tab completion.

**EXAMPLES:**

```python
from sage.sat.solvers.satsolver import SatSolver
sage: solver = SatSolver()
sage: solver.trait_names()
['gens']
```

### var(decision=None)
Return a new variable.

**INPUT:**

- decision - is this variable a decision variable?

**EXAMPLES:**

```python
from sage.sat.solvers.satsolver import SatSolver
sage: solver = SatSolver()
sage: solver.var()
Traceback (most recent call last):
  ... Not Implemented Error
```
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:**

- Martin Albrecht (2012): first version

**Classes and Methods**

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

    __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 solvers (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
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()
sage: solver = DIMACS()
sage: solver.add_clause( (1, 2, 3) )
sage: solver.clauses()
[[((1, 2, 3), False, None)]
```

`nvars()`
Return the number of variables.

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.nvars()
2
```
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 Crypt-toMiniSat: a tuple of literals, is_xor and rhs.

• filename - the file to write to

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

EXAMPLES:

```
sage: from sage.sat.solvers.dimacs import DIMACS
dsage: fn = tmp_filename()
dsage: solver = DIMACS()
dsage: solver.add_clause( (1, 2, -3) )
dsage: DIMACS.render_dimacs(solver.clauses(), fn, solver.nvars())
dsage: print(open(fn).read())
p cnf 3 1
 1 2 -3 0
```

This is equivalent to:

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

This function also accepts a “simple” format:

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

```
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:
```
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
```

```
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. Details on Specific Solvers  11
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)

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 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, 3))  # optional - pycosat
```
sage: solver.clauses()  # optional - pycosat
[[1, 2, 3, 4, 5, 6, 7, 8, -9]]

DIMACS format output:

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
p cnf 4 2
1 2 4 0
1 2 -4 0

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:

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:

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:

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. Details on Specific Solvers
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:**

```python
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 abs(e) greater than the number of variables generated so far, then new variables are created automatically.

**EXAMPLES:**

```python
sage: S=SAT(solver="LP"); S
an ILP-based SAT Solver
sage: for u,v in graphs.CycleGraph(6).edges(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:**

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

(continues on next page)
var()

Return a new variable.

EXAMPLES:

```python
sage: S=nvars()
2
```

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:


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

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
from sage.sat.solvers.cryptominisat import CryptoMiniSat
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.

EXAMPLES:
```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_clause((1, 2, -4))  # optional - pycryptosat
```

DIMACS format output:
```python
sage: from sage.sat.solvers import CryptoMiniSat
sage: solver = CryptoMiniSat()  # optional - pycryptosat
sage: solver.clause()  # optional - pycryptosat
[[(1, 2, 3, 4, 5, 6, 7, 8, -9), False, None],
 (1, 2, 3, 4, 5, 6, 7, 8, 9), True, True]
```

(continues on next page)
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:

```
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
1 2 -4 0
x1 2 3 0
```

Note that inverting an xor-clause is equivalent to inverting one of the variables:

```
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
```

`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:

```
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:

```
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
5
```
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 \texttt{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 \texttt{cutting_number} –
or by constructing XOR clauses if the underlying solver supports it. This behaviour is disabled by passing
\texttt{use_xor_clauses=False}.

\texttt{__init__}(solver, ring, max_vars_sparse=6, use_xor_clauses=None, cutting_number=6, random_seed=16)

Construct ANF to CNF converter over \texttt{ring} passing clauses to \texttt{solver}.

INPUT:

• \texttt{solver} - a SAT-solver instance

• \texttt{ring} - a \texttt{sage.rings.polynomial.pbori.BooleanPolynomialRing}

• \texttt{max_vars_sparse} - maximum number of variables for direct conversion

• \texttt{use_xor_clauses} - use XOR clauses; if \texttt{None} use if \texttt{solver} supports it. (default: \texttt{None})

• \texttt{cutting_number} - maximum length of XOR chains after splitting if XOR clauses are not supported
  (default: 6)

• \texttt{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:

\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)
    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]
\end{verbatim}

Now, we convert using the dense strategy:

\begin{verbatim}
    sage: B.<a,b,c> = BooleanPolynomialRing()
    sage: from sage.sat.converters.polybori import CNFEncoder
\end{verbatim}
```python
sage: from sage.sat.solvers.dimacs import DIMACS
sage: fn = tmp_filename()
```

```python
sage: solver = DIMACS(filename=fn)
```

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

```python
sage: e.clauses_dense(a*b + a + 1)
```

```python
sage: _ = solver.write()
```

```python
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
```

```python
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 -> variable

**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([a*b + a + 1, a*b+ a + c])
```

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

```python
sage: _ = solver.write()

sage: print(open(fn).read())
```

```
-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
```

```python
sage: e.phi
```

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

---

2.1. Details on Specific Converters
**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
-2 0
1 0
```

```python
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
```

```python
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
```

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

(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: 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

(continues on next page)
sage: fn = tmp_filename()
sage: solver = DIMACS(filename=fn)
sage: e = CNFEncoder(solver, B)
sage: e.clauses_dense(a*b + a + 1)
sage: e.phi
[None, a, b, c, a*b]

If monomial is called on a new monomial, a new variable is created:

sage: e.monomial(a*b*c)
5
sage: e.phi
[None, a, b, c, a*b, a*b*c]

If monomial is called on a monomial that was queried before, the index of the old variable is returned and
no new variable is created:

sage: e.monomial(a*b)
4
sage: e.phi
[None, a, b, c, a*b, a*b*c]

.. 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:

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:

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

(continues on next page)
sage: B.<a,b,c> = BooleanPolynomialRing()
sage: ce = CNFEncoder(DIMACS(), B)
sage: ce.var()
4
sage: ce.phi
[None, a, b, c, None]

split_xor(monomial_list, equal_zero)
Split XOR chains into subchains.

INPUT:
• monomial_list - a list of monomials
• equal_zero - is the constant coefficient zero?

EXAMPLES:

```
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]]
```

to_polynomial(c)
Convert clause to sage.rings.polynomial.pbori:BooleanPolynomial

INPUT:
• c - a clause

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])
sage: e.to_polynomial( (1,-2,3) )
a*b*c + a*b + b*c + b
```

var(n=0, decision=None)
Return a new variable.
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
- \( \text{decision} \) - 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()
sage: ce = CNFEncoder(DIMACS(), B)
sage: ce.var()
4
```

**zero_blocks**

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

**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: e = CNFEncoder(DIMACS(), B)
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.
Sage provides various high-level 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:

```python
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
Polynomial Sequence with 36 Polynomials in 0 Variables
```

### 3.1 Details on Specific Highlevel Interfaces

#### 3.1.1 SAT Functions for Boolean Polynomials

These high-level 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_length_learnt** 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
k033 + 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:
sage: sr = mq.SR(1,1,1,4,gf2=True,polybori=True)
sage: while True:
    try:
        F, s = sr.polynomial_system()
    except ZeroDivisionError:
        break
    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, s_verbosity=1, c_max_vars_sparse=4, c_cutting_number=8)
    # optional - pycryptosat
c ...
...  
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
```

(continues on next page)
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: eqs = PolynomialSequence(eqs)  # 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)  # optional - pycryptosat, long time
256
```

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

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