BuDDy: Binary Decision Diagram package
Release 2.2

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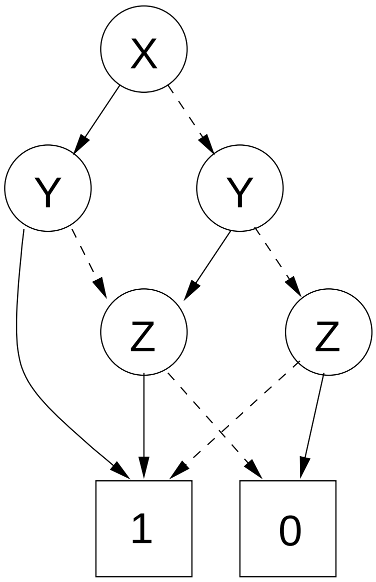

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Chapter 1

Introduction

BuDDy is a Binary Decision Diagram package that provides all of the most used functions for manipulating BDDs. The package also includes functions for integer arithmetics such as addition and relational operators.

BuDDy started as a technology transfer project between the Technical University of Denmark and Bann Visualstate. The later is now using the techniques from BuDDy in their software. See `www.visualstate.com`.

This manual describes only the interface to BuDDy, not the underlying theory of BDDs. More information about that can be found in Henrik Reif Andersen's "An Introduction To Binary Decision Diagrams" which is supplied with the BuDDY distribution. Even more information can of course be found in the original papers by Bryant, Rudell and Brace [1, 3, 2, 4]

1.1 Acknowledgements

Thanks to the following people for new ideas, bug hunts and lots of discussions: Gerd Behrmann, Henrik Reif Andersen, Ken Larsen, Jacob Lichtenberg, Poul Williams, Nikolaj Bjorner, Alan Mishchenko, Henrik Hulgaard, and Malte Helmert.

Chapter 2

Users Guide

2.1 Getting BuDDy

BuDDy can be found on the server `http://www.itu.dk/research/buddy`.

2.2 Installing

1. Edit the file "config" to specify your compiler and install options.
2. Type `make` to make the binary.
3. Type `make install` to copy the BDD files to their appropriate directories
4. Type `make examples` to make the examples

2.3 Compiling

This is rather simple. Just inform the compiler of where the binaries and include files are installed. With Gnu C this is done with the `-I` and `-L` options. Assuming that the binary library `libbdd.a` is installed in `/usr/local/lib` and the include file `bdd.h` is installed in `/usr/local/include`, then the compile command should be

```
cc -I/usr/local/include myfile.c -o myfile -L/usr/include/lib -lbdd
```

If the above directories are included in your search path already, then you might be able to reduce the command to

```
cc myfile.c -o myfile -lbdd
```

2.4 Programming with BuDDy

First of all a program needs to call `bdd_init(nodenum,cachesize)` to initialize the BDD package. The `nodenum` parameter sets the initial number of BDD nodes and `cachesize` sets the size of the caches used for the BDD operators (not the unique node table). These caches are used for `bdd_apply` anmong others.

Good initial values are

Example	nodenum	cachesize
Small test examples	1000	100
Small examples	10000	1000
Medium sized examples	100000	10000
Large examples	1000000	variable

Too few nodes will only result in reduced performance as this increases the number of garbage collections needed. If the package needs more nodes, then it will automatically increase the size of the node table. Use `bdd_setminfreenodes` to change the parameters for when this is done and use `bdd_setcacheratio` to enable dynamical resizing of the operator caches. You may also use the function `bdd_setmaxincrease` to adjust how BuDDy resizes the node table.

After the initialization a call must be done to `bdd_setvarnum` to define how many variables to use in this session. This number may be increased later on either by calls to `bdd_setvarnum` or to `bdd_extvarnum`.

The atomic functions for getting new BDD nodes are `bdd_ithvar(i)` and `bdd_nithvar(i)` which returns references to BDD nodes of the form $(v_i, 0, 1)$ and $(v_i, 1, 0)$. The nodes constructed in this way corresponds to the positive and negative versions of a single variable. Initially the variable order is $v_0 < v_1 < \ldots < v_{n-1} < v_n$.

The BDDs returned from `bdd_ithvar(i)` can then be used to form new BDDs by calling `bdd_apply(a,b,op)` where `op` may be `bddop_and` or any of the other operators defined in `bdd.h`. The apply function performs the binary operation indicated by `op`. Use `bdd_not` to negate a BDD. The result from `bdd_apply` and any other BDD operator *must* be handed over to `bdd_addref` to increase the reference count of the node before any other operation is performed. This is done to prevent the BDD from being garbage collected. When a BDD is no longer in use, it can be de-referenced by a call to `bdd_delref`. The exceptions to this are the return values from `bdd_ithvar` and `bdd_nithvar`. These do not need to be reference counted, although it is not an error to do so. The use of the BDD package ends with a call to `bdd_done`. See the figures 2.1 and 2.2 for an example.

Information on the BDDs can be found using the `bdd_var`, `bdd_low` and `bdd_high` functions that returns the variable labelling a BDD, the low branch and the high branch of a BDD.

Printing BDDs is done using the functions `bdd_printall` that prints *all* used nodes, `bdd_printtable` that prints the part of the nodetable that corresponds to a specific BDD and `bdd_printset` that prints a specific BDD as a list of elements in a set (all paths ending in the true terminal).

2.4.1 More Examples

More complex examples can be found in the `buddy/examples` directory.

2.5 Variable sets

For some functions like `bdd_exist` it is possible to pass a whole set of variables to be quantified, using BDDs that represent the variables. These BDDs are simply the conjunction of all the variables in their positive form and can either be build that way or by a call to `bdd_makeset`. For the `bdd_restrict` function the variables need to be included in both positive and negative form which can only be done manually.

If for example variable 1 and variable 3 are to be included in a set, then it can be done in two ways, as shown in figure 2.3.

```c
#include <bdd.h>

main(void)
{
   bdd x,y,z;

   bdd_init(1000,100);
   bdd_setvarnum(5);

   x = bdd_ithvar(0);
   y = bdd_ithvar(1);
   z = bdd_addref(bdd_apply(x,y,bddop_and));

   bdd_printtable(z);
   bdd_delref(z);
   bdd_done();
}
```

Figure 2.1: Standard C interface to BuDDy. In this mode both 'bdd' and 'BDD' can be used as BuDDy BDD types. The C interface requires the user to ensure garbage collection is handled correctly. This means calling 'bdd_addref' every time a new BDD is created, and 'bdd_delref' whenever a BDD is not in use anymore.

2.6 Dynamic Variable Reordering

Dynamic variable reordering can be done using the functions `bdd_reorder(int method)` and `bdd_autoreorder(int method)`. Where the parameter `method`, for instance can be `BDD_REORDER_WIN2ITE`. The package must know how the BDD variables are related to each other, so the user must define blocks of BDD variables, using `bdd_addvarblock(bdd var, int fixed)`. A block is a range of BDD variables that should be kept together. It may either be a simple contiguous sequence of variables or a sequence of other blocks with ranges inside their parents range. In this way all the blocks form a tree of ranges. Partially overlapping blocks are not allowed.

Example: Assume the block $v_0 \ldots v_9$, is added as the first block and then the block $v_1 \ldots v_8$. This yields the $v_0 \ldots v_9$ block at the top, with the $v_1 \ldots v_8$ block as a child. If now the block $v_1 \ldots v_4$ was added, it would become a child of the $v_1 \ldots v_8$ block, similarly the block $v_5 \ldots v_8$ would be a child of the $v_1 \ldots v_8$ block. If we add the variables v_1, v_2, v_3 and v_4 as single variable blocks we at last get tree showed in figure 2.4. If all variables should be added as single variable blocks then `bdd_varblockall` can be used instead of doing it manually.

The reordering algorithm is then to first reorder the top most blocks and there after descend into each block and reorder these recursively - unless the block is defined as a fixed block.

If the user want to control the swapping of variables himself, then the functions `bdd_swapvar` `bdd_setvarorder` may be used. But this is not possible in conjunction with the use of variable blocks and the `bdd_swapvar` is unfortunately quite slow since a full scan of all the nodes must be done both before and after the swap. Other reordering functions are `bdd_autoreorder_times`, `bdd_reorder_verbose`, `bdd_sizeprobe_hook` and `bdd_reorder_hook`.

```
#include <bdd.h>

main(void)
{
   bdd x,y,z;

   bdd_init(1000,100);
   bdd_setvarnum(5);

   x = bdd_ithvar(0);
   y = bdd_ithvar(1);
   z = x & y;

   cout << bddtable << z << endl;

   bdd_done();
}
```

Figure 2.2: C++ interface to BuDDy. In this mode 'bdd' is a C++ class that wraps a handler around the standard C interface, and the 'BDD' type referes to the standard C BDD type. The C++ interface handles all garbage collection, so no calls to 'bdd_addref' and 'bdd_delref' are needed.

2.7 Error Handling

If an error occurs then a check is done to see if there is any error handler defined and if so it is called with the error code of interest. The default error handler prints an error message on `stderr` and then aborts the program. A handler can also be defined by the user with a call to `bdd_error_hook`.

2.8 The C++ interface

Mostly this consists of a set of overloaded function wrappers that takes a `bdd` class and calls the appropriate C functions with the root number stored in the `bdd` class. The names of these wrappers are exactly the same as for the C functions. In addition to this a lot of the C++ operators like `|`& - = == are overloaded in order to perform most of the `bdd_apply()` operations. These are listed together with `bdd_apply`. The rest are

Operator	**Description**	**Return value**
`=`	assignment	
`==`	test	returns 1 if two BDDs are equal, otherwise 0
`!=`	test	returns 0 if two BDDs are equal, otherwise 1
`bdd.id()`	identity	returns the root number of the BDD

The default constructor for the `bdd` class initializes the bdds to the constant false value. Reference counting is totally automatic when the `bdd` class is used, here the constructors and destructors takes care of *all* reference counting! The C++ interface is also defined in `bdd.h` so nothing extra is needed to use it.

```
#include <bdd.h>

main()
{
   bdd v1, v3;
   bdd seta, setb;
   static int v[2] = {1,3};

   bdd_init(100,100);
   bdd_setvarnum(5);

   v1 = bdd_ithvar(1);
   v3 = bdd_ithvar(3);

      /* One way */
   seta = bdd_addref( bdd_apply(v1,v3,bddop_and) );
   bdd_printtable(seta);

      /* Another way */
   setb = bdd_addref( bdd_makeset(v,2) );
   bdd_printtable(setb);
}
```

Figure 2.3: Two ways to create a variable set.

2.9 Finite Domain Blocks

Included in the BDD package is a set of functions for manipulating values of finite domains, like for example finite state machines. These functions are used to allocate blocks of BDD variables to represent integer values instead of only true and false.

New finite domain blocks are allocated using `fdd_extdomain` and BDDs representing integer values can be build using `fdd_ithvar`. The BDD representing identity between two sets of different domains can be build using `fdd_equals`. BDDs representing finite domain sets can be printed using `fdd_printset` and the overloaded C++ operator `<<`. Pairs for `bdd_replace` can be made using `fdd_setpair` and variable sets can be made using `fdd_ithset` and `fdd_makeset`. The finite domain block interface is defined for both C and C++. To use this interface you must include `"fdd.h"`.

Encoding using FDDs are done with the Least Significant Bits first in the ordering (top of the BDD). Assume variables $V_0 \ldots V_3$ are used to encode the value 12 - this would yield $V_0 = 0, V_1 = 0, V_2 = 1, V_3 = 1$.

An example program using the FDD interface can be found in the examples directory.

2.10 Boolean Vectors

Another interface layer for BuDDy implements boolean vectors for use with integer arithmetics. A boolean vector is simply an array of BDDs where each BDD represents one bit of an expression. To use this interface you must include `"bvec.h"`. As an example, suppose we want to express the following assignment from an expression

$$x := y + 10$$

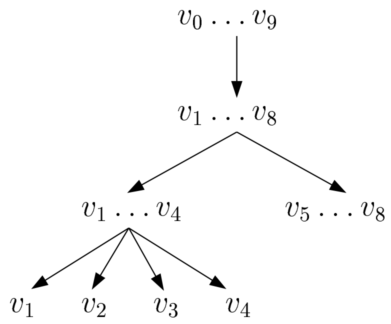

Figure 2.4: The variable tree for the variable blocks $v_0 \dots v_9$, $v_1 \dots v_8$, $v_1 \dots v_4$, $v_5 \dots v_8$, v_1, v_2, v_3 and v_4.

what we do is to encode the variable y and the value 10 as boolean vectors y and v of a fixed length. Assume we use four bits with LSB to the right, then we get

$$y = \langle y_4, \dots, y_1 \rangle$$

$$v = \langle 1, 0, 1, 0 \rangle$$

where each y_i is the BDD variable used to encode the integer variable y. Now the result of the addition can be expressed as the vector $z = \langle z_4, \dots, z_1 \rangle$ where each z_i is:

$$z_i = y_i \text{ xor } v_i \text{ xor } c_{i-1}$$

and the carry in c_i is

$$c_i = (y_i \text{ and } v_i) \text{ or } (c_{i-1} \text{ and } (y_i \text{ or } v_i)).$$

with $c_0 = 0$. What is left now is to assign the result to x. This is a conjunction of a biimplication of each element in the vectors, so the result is

$$R = \bigwedge_{i=1}^{4} x_i \Leftrightarrow z_i.$$

The above example could be carried out with the following C++ program that utilizes the FDD interface for printing the result.

```
#include "bvec.h"

main()
{
   int domain[2] = {16,16};

   bdd_init(100,100);
   fdd_extdomain(domain, 2);

   bvec y = bvec_varfdd(0);
   bvec v = bvec_con(4, 10);
   bvec z = bvec_add(y, v);

   bvec x = bvec_varfdd(1);
```

```
   bdd  result = bddtrue;

   for (int n=0 ; n<x.bitnum() ; n++)
      result &= bdd_apply(x[n], z[n], bddop_biimp);

   cout << fddset << result << endl << endl;
}
```

The relational operators $<, >, \leq, \geq, =, \neq$ can also be encoded. Assume we want to encode $x \leq y$ using the same variables as in the above example. This would be done as:

```
#include "bvec.h"

main()
{
   int domain[2] = {16,16};

   bdd_init(100,100);
   fdd_extdomain(domain, 2);

   bvec y = bvec_varfdd(1);
   bvec x = bvec_varfdd(0);

   bdd  result = bvec_lte(x,y);

   cout << fddset << result << endl << endl;
}
```

Please note that all vectors that are returned from any of the `bvec_xxx` functions are referenced counted by the system.

2.10.1 C++ Interface

The C++ interface defines the class

```
class bvec
{
 public:

   bvec(void);
   bvec(int bitnum);
   bvec(int bitnum, int val);
   bvec(const bvec &v);
   ~bvec(void);

   void set(int i, const bdd &b);
   bdd operator[](int i)  const;
   int bitnum(void) const;
   int empty(void) const;
   bvec operator=(const bvec &src);
}
```

The default constructor makes an empty vector with no elements, the integer constructor creates a vector with `bitnum` elements (all set to false) and the third constructor creates a vector with `bitnum` elements and assigns the integer value `val` to the vector. Reference counting is done automatically. The i'th element in the vector can be changed with `set` and read with `operator[]`. The number of bits can be found with `bitnum` and the method `empty` returns true if the vector is a NULL vector.

Chapter 3

Efficiency Concerns

Getting the most out of any BDD package is not always easy. It requires some knowledge about the optimal order of the BDD variables and it also helps if you have some knowledge of the internals of the package.

First of all — a good initial variable order is a must. Using the automatic reordering methods may be an easy solution, but without a good initial order it may also be a waste of time.

Second — memory is speed. If you allocate as much memory as possible from the very beginning, then BuDDy does not have to waste time trying to allocate more whenever it is needed. So if you really want speed then `bdd_init` should be called with as many nodes as possible. This does unfortunately have the side effect that variable reordering becomes extremely slow since it has to reorder an enormous amount of nodes the first time it is triggered.

Third — the operator caches should be as big as possible. Use the function `bdd_setcacheratio` to make sure the size of these is increased whenever more nodes are allocated. *Please note that BuDDy uses a fixed number of elements for these caches as default.* You must call `bdd_setcacheratio` to change this. I have found a cache ratio of 1:64 fitting for BDDs of more than one million nodes (the solitare example). This may be a bit overkill, but it works.

Fourth — BuDDy allocates by default a maximum of 50000 nodes (1Mb RAM) every time it resizes the node table. If your problem needs millions of nodes, then this is way too small a number. Use `bdd_setmaxincrease` to increase this number. In the solitare example something like 5000000 nodes seems more reasonable.

Fifth — by default, BuDDy increases the node table whenever there is less than 20% nodes free. By increasing this value you can make BuDDy go faster and use more memory or vice versa. You can change the value with `bdd_setminfreenodes`.

So, to sum it up: if you want speed, then allocate as many nodes as possible, use small cache ratios and set `maxincrease`. If you need memory, then allocate a small number of nodes from the beginning, use a fixed size cache, do not change `maxincrease` and lower `minfreenodes`.

Chapter 4

Some Implementation details

- Negated pointers are not used.
- All nodes are stored in one big contiguous array which is also used as the hash table for finding identical nodes.
- The hash function used to find identical nodes from the triple $(level, low, high)$ spreads all nodes evenly in the table. This means the average length of a hash chain is at most 1.
- Each node in the node table contains a reference count, the `level` of the variable (this is its position in the current variable order), the `high` and `low` part, a `hash` index used to find the first node in a hash chain and a `next` index used to link the hash chains. Each node fits into 20 bytes of memory. Other packages uses only 16 bytes for each node but in addition to this they must keep separate tables with hash table entries. The effect of this is that the total memory consumption is 20 bytes for each node on average.
- Reference counting are done on the externally referenced nodes only.
- The ANSI-C `bdd` type is an integer number referring to an index in the node table. In C++ it is a class.
- New nodes are created by doubling (or just extending) the node table, not by adding new blocks of nodes.
- Garbage collection recursively marks all nodes reachable from the externally referenced nodes before dead nodes are removed.
- Reordering interrupts the current BDD operation and restarts it again afterwards.
- Reordering changes the hash function to one where all nodes of a specific level is placed in one continuous block and updates the reference count field to include all recursive dependencies. After reordering the package returns to the normal hash function.

Chapter 5

Reference

Boolean vectors	
bvec	a boolean vector
bvec_add	builds a boolean vector for addition
bvec_addref	increase reference count of a boolean vector
bvec_coerce	adjust the size of a boolean vector
bvec_con	build a boolean vector representing an integer value
bvec_copy	create a copy of a bvec
bvec_delref	decrease the reference count of a boolean vector
bvec_div	builds a boolean vector for division
bvec_divfixed	builds a boolean vector for division by a constant
bvec_equ	calculates the truth value of $x = y$
bvec_false	build a vector of constant false BDDs
bvec_free	frees all memory used by a boolean vector
bvec_gte	calculates the truth value of $x \geq y$
bvec_gth	calculates the truth value of $x > y$
bvec_isconst	test a vector for constant true/false BDDs
bvec_ite	calculates the if-then-else operator for a boolean vector
bvec_lte	calculates the truth value of $x \leq y$
bvec_lth	calculates the truth value of $x < y$
bvec_map1	map a function onto a boolean vector
bvec_map2	map a function onto a boolean vector
bvec_map3	map a function onto a boolean vector
bvec_mul	builds a boolean vector for multiplication
bvec_mulfixed	builds a boolean vector for multiplication with a constant
bvec_neq	calculates the truth value of $x \neq y$
bvec_shl	shift left operation (symbolic)
bvec_shlfixed	shift left operation (fixed number of bits)
bvec_shr	shift right operation (symbolic)
bvec_shrfixed	shift right operation
bvec_sub	builds a boolean vector for subtraction
bvec_true	build a vector of constant true BDDs
bvec_val	calculate the integer value represented by a boolean vector
bvec_var	build a boolean vector with BDD variables

bvec_varfdd	build a boolean vector from a FDD variable block
bvec_varvec	build a boolean vector with the variables passed in an array
Finite domain variable blocks	
fdd_clearall	clear all allocated FDD blocks
fdd_domain	bDD encoding of the domain of a FDD variable
fdd_domainnum	number of defined finite domain blocks
fdd_domainsize	real size of a finite domain block
fdd_equals	returns a BDD setting two FD. blocks equal
fdd_extdomain	adds another set of finite domain blocks
fdd_file_hook	specifies a printing callback handler
fdd_intaddvarblock	adds a new variable block for reordering
fdd_ithset	the variable set for the i'th finite domain block
fdd_ithvar	the BDD for the i'th FDD set to a specific value
fdd_makeset	creates a variable set for N finite domain blocks
fdd_overlapdomain	combine two FDD blocks into one
fdd_printset fdd_fprintset	prints a BDD for a finite domain block
fdd_scanallvar	finds one satisfying value of all FDD variables
fdd_scanset	scans a variable set
fdd_scanvar	finds one satisfying value of a FDD variable
fdd_setpair	defines a pair for two finite domain blocks
fdd_setpairs	defines N pairs for finite domain blocks
fdd_strm_hook	specifies a printing callback handler
fdd_varnum	binary size of a finite domain block
fdd_vars	all BDD variables associated with a finite domain block
File input/output	
bdd_load bdd_fnload	loads a BDD from a file
bdd_printall bdd_fprintall	prints all used entries in the node table
bdd_printdot bdd_fprintdot	prints a description of a BDD in DOT format
bdd_printset bdd_fprintset	prints the set of truth assignments specified by a BDD
bdd_printtable bdd_fprinttable	prints the node table entries used by a BDD
bdd_save bdd_fnsave	saves a BDD to a file
operator<<	c++ output operator for BDDs
Information on BDDs	
bdd_anodecount	counts the number of shared nodes in an array of BDDs
bdd_high	gets the true branch of a bdd
bdd_low	gets the false branch of a bdd
bdd_nodecount	counts the number of nodes used for a BDD
bdd_pathcount	count the number of paths leading to the true terminal

`bdd_satcount` `bdd_setcountset`	calculates the number of satisfying variable assignments
`bdd_satcountln` `bdd_setcountlnset`	calculates the log. number of satisfying variable assignments
`bdd_support`	returns the variable support of a BDD
`bdd_var`	gets the variable labeling the bdd
`bdd_varprofile`	returns a variable profile
Kernel BDD operations and data structures	
`bddCacheStat`	status information about cache usage
`bddGbcStat`	status information about garbage collections
`bddStat`	status information about the bdd package
`bdd_addref`	increases the reference count on a node
`bdd_cachestats`	fetch cache access usage
`bdd_clear_error`	clears an error condition in the kernel
`bdd_delref`	decreases the reference count on a node
`bdd_done`	resets the bdd package
`bdd_error_hook`	set a handler for error conditions
`bdd_errstring`	converts an error code to a string
`bdd_extvarnum`	add extra BDD variables
`bdd_false`	returns the constant false bdd
`bdd_file_hook`	specifies a printing callback handler
`bdd_freepair`	frees a table of pairs
`bdd_gbc_hook`	set a handler for garbage collections
`bdd_getallocnum`	get the number of allocated nodes
`bdd_getnodenum`	get the number of active nodes in use
`bdd_init`	initializes the BDD package
`bdd_isrunning`	test whether the package is started or not
`bdd_ithvar`	returns a bdd representing the I'th variable
`bdd_makeset`	builds a BDD variable set from an integer array
`bdd_newpair`	creates an empty variable pair table
`bdd_nithvar`	returns a bdd representing the negation of the I'th variable
`bdd_printstat` `bdd_fprintstat`	print cache statistics
`bdd_resetpair`	clear all variable pairs
`bdd_resize_hook`	set a handler for nodetable resizes
`bdd_scanset`	returns an integer representation of a variable set
`bdd_setcacheratio`	sets the cache ratio for the operator caches
`bdd_setmaxincrease`	set max. number of nodes used to increase node table
`bdd_setmaxnodenum`	set the maximum available number of bdd nodes
`bdd_setminfreenodes`	set min. no. of nodes to be reclaimed after GBC.
`bdd_setpair` `bdd_setbddpair`	set one variable pair
`bdd_setpairs` `bdd_setbddpairs`	defines a whole set of pairs
`bdd_setvarnum`	set the number of used bdd variables

`bdd_stats`	returns some status information about the bdd package
`bdd_strm_hook`	specifies a printing callback handler
`bdd_true`	returns the constant true bdd
`bdd_varnum`	returns the number of defined variables
`bdd_versionnum`	returns the version number of the bdd package
`bdd_versionstr`	returns a text string with version information
`bddfalse`	the constant false bdd
`bddtrue`	the constant true bdd
BDD operators	
`bdd_allsat`	finds all satisfying variable assignments
`bdd_and`	the logical 'and' of two BDDs
`bdd_appall`	apply operation and universal quantification
`bdd_appex`	apply operation and existential quantification
`bdd_apply`	basic bdd operations
`bdd_appuni`	apply operation and unique quantification
`bdd_biimp`	the logical 'bi-implication' between two BDDs
`bdd_buildcube` `bdd_ibuildcube`	build a cube from an array of variables
`bdd_compose`	functional composition
`bdd_constrain`	generalized cofactor
`bdd_exist`	existential quantification of variables
`bdd_forall`	universal quantification of variables
`bdd_fullsatone`	finds one satisfying variable assignment
`bdd_imp`	the logical 'implication' between two BDDs
`bdd_ite`	if-then-else operator
`bdd_not`	negates a bdd
`bdd_or`	the logical 'or' of two BDDs
`bdd_relprod`	relational product
`bdd_replace`	replaces variables with other variables
`bdd_restrict`	restric a set of variables to constant values
`bdd_satone`	finds one satisfying variable assignment
`bdd_satoneset`	finds one satisfying variable assignment
`bdd_simplify`	coudert and Madre's restrict function
`bdd_unique`	unique quantification of variables
`bdd_veccompose`	simultaneous functional composition
`bdd_xor`	the logical 'xor' of two BDDs
Variable reordering	
`bdd_addvarblock` `bdd_intaddvarblock`	adds a new variable block for reordering
`bdd_autoreorder` `bdd_autoreorder_times`	enables automatic reordering
`bdd_blockfile_hook`	specifies a printing callback handler
`bdd_clrvarblocks`	clears all variable blocks
`bdd_disable_reorder`	disable automatic reordering
`bdd_enable_reorder`	enables automatic reordering

`bdd_getreorder_method`	fetch the current reorder method
`bdd_getreorder_times`	fetch the current number of allowed reorderings
`bdd_level2var`	fetch the variable number of a specific level
`bdd_printorder`	prints the current order
`bdd_reorder`	start dynamic reordering
`bdd_reorder_gain`	calculate the gain in size after a reordering
`bdd_reorder_hook`	sets a handler for automatic reorderings
`bdd_reorder_probe`	define a handler for minimization of BDDs
`bdd_reorder_verbose`	enables verbose information about reorderings
`bdd_setvarorder`	set a specific variable order
`bdd_swapvar`	swap two BDD variables
`bdd_var2level`	fetch the level of a specific BDD variable
`bdd_varblockall`	add a variable block for all variables

bddCacheStat – Status information about cache usage

```
typedef struct s_bddCacheStat
{
   long unsigned int uniqueAccess;
   long unsigned int uniqueChain;
   long unsigned int uniqueHit;
   long unsigned int uniqueMiss;
   long unsigned int opHit;
   long unsigned int opMiss;
   long unsigned int swapCount;
} bddCacheStat;
```

Description

The fields are

Name	**Number of**
uniqueAccess	accesses to the unique node table
uniqueChain	iterations through the cache chains in the unique node table
uniqueHit	entries actually found in the the unique node table
uniqueMiss	entries not found in the the unique node table
opHit	entries found in the operator caches
opMiss	entries not found in the operator caches
swapCount	number of variable swaps in reordering

See also

bdd_cachestats

bddGbcStat – Status information about garbage collections

```
typedef struct s_bddGbcStat
{
   int nodes;
   int freenodes;
   long time;
   long sumtime;
   int num;
} bddGbcStat;
```

Description

The fields are

`nodes`	Total number of allocated nodes in the nodetable
`freenodes`	Number of free nodes in the nodetable
`time`	Time used for garbage collection this time
`sumtime`	Total time used for garbage collection
`num`	number of garbage collections done until now

See also

bdd_gbc_hook

bddStat – Status information about the bdd package

```
typedef struct s_bddStat
{
   long int produced;
   int nodenum;
   int maxnodenum;
   int freenodes;
   int minfreenodes;
   int varnum;
   int cachesize;
   int gbcnum;
} bddStat;
```

Description

The fields are

`produced`	total number of new nodes ever produced
`nodenum`	currently allocated number of bdd nodes
`maxnodenum`	user defined maximum number of bdd nodes
`freenodes`	number of currently free nodes
`minfreenodes`	minimum number of nodes that should be left after a garbage collection.
`varnum`	number of defined bdd variables
`cachesize`	number of entries in the internal caches
`gbcnum`	number of garbage collections done until now

See also

bdd_stats

bdd_addref – increases the reference count on a node

```
BDD bdd_addref(BDD r)
```

Description

Reference counting is done on externaly referenced nodes only and the count for a specific node `r` can and must be increased using this function to avoid loosing the node in the next garbage collection.

Return value

The BDD node `r`.

See also

bdd_delref

bdd_addvarblock – adds a new variable block for reordering

```
int bdd_addvarblock(BDD var, int fixed)
int bdd_intaddvarblock(int first, int last, int fixed)
```

Description

Creates a new variable block with the variables in the variable set `var`. The variables in `var` must be contiguous. In the second form the argument `first` is the first variable included in the block and `last` is the last variable included in the block. This order does not depend on current variable order.

The variable blocks are ordered as a tree, with the largest ranges at top and the smallest at the bottom. Example: Assume the block 0-9 is added as the first block and then the block 0-6. This yields the 0-9 block at the top, with the 0-6 block as a child. If now the block 2-4 was added, it would become a child of the 0-6 block. A block of 0-8 would be a child of the 0-9 block and have the 0-6 block as a child. Partially overlapping blocks are not allowed.

The `fixed` parameter sets the block to be fixed (no reordering of its child blocks is allowed) or free, using the constants `BDD_REORDER_FIXED` and `BDD_REORDER_FREE`. Reordering is always done on the top most blocks first and then recursively downwards.

The return value is an integer that can be used to identify the block later on - with for example `bdd_blockfile_hook`. The values returned will be in the sequence $0, 1, 2, 3, \ldots$.

Return value

A non-negative identifier on success, otherwise a negative error code.

See also

bdd_varblockall, fdd_intaddvarblock, bdd_clrvarblocks

bdd_allsat – finds all satisfying variable assignments

```
BDD bdd_satone(BDD r, bddallsathandler handler)
```

Description

Iterates through all legal variable assignments (those that make the BDD come true) for the bdd `r` and calls the callback handler `handler` for each of them. The array passed to `handler` contains one entry for each of the globaly defined variables. Each entry is either 0 if the variable is false, 1 if it is true, and -1 if it is a don't care.

The following is an example of a callback handler that prints 'X' for don't cares, '0' for zero, and '1' for one:

```
void allsatPrintHandler(char* varset, int size)
{
  for (int v=0; v<size ; ++v)
  {
    cout << (varset[v] < 0 ? 'X' : (char)('0' + varset[v]));
  }
  cout << endl;
}
```

The handler can be used like this: `bdd_allsat(r, allsatPrintHandler);`

See also

bdd_satone bdd_satoneset, bdd_fullsatone, bdd_satcount, bdd_satcountln

bdd_and – The logical 'and' of two BDDs

```
BDD bdd_and(BDD l, BDD r)
```

Description

This a wrapper that calls `bdd_apply(l,r,bddop_and)`.

Return value

The logical 'and' of `l` and `r`.

See also

bdd_apply, bdd_or, bdd_xor

bdd_anodecount – counts the number of shared nodes in an array of BDDs

```
int bdd_anodecount(BDD *r, int num)
```

Description

Traverses all of the BDDs in `r` and counts all distinct nodes that are used in the BDDs–if a node is used in more than one BDD then it only counts once. The `num` parameter holds the size of the array.

Return value

The number of nodes

See also

bdd_nodecount

bdd_appall – apply operation and universal quantification

```
BDD bdd_appall(BDD left, BDD right, int opr, BDD var)
```

Description

Applies the binary operator `opr` to the arguments `left` and `right` and then performs an universal quantification of the variables from the variable set `var`. This is done in a bottom up manner such that both the apply and quantification is done on the lower nodes before stepping up to the higher nodes. This makes the `bdd_appall` function much more efficient than an apply operation followed by a quantification.

Return value

The result of the operation.

See also

bdd_appex, bdd_appuni, bdd_apply, bdd_exist, bdd_forall, bdd_unique, bdd_makeset

bdd_appex – apply operation and existential quantification

```
BDD bdd_appex(BDD left, BDD right, int opr, BDD var)
```

Description

Applies the binary operator `opr` to the arguments `left` and `right` and then performs an existential quantification of the variables from the variable set `var`. This is done in a bottom up manner such that both the apply and quantification is done on the lower nodes before stepping up to the higher nodes. This makes the `bdd_appex` function much more efficient than an apply operation followed by a quantification. If the operator is a conjunction then this is similar to the relational product of the two BDDs.

Return value

The result of the operation.

See also

bdd_appall, bdd_appuni, bdd_apply, bdd_exist, bdd_forall, bdd_unique, bdd_makeset

bdd_apply – basic bdd operations

```
BDD bdd_apply(BDD left, BDD right, int opr)
```

Description

The `bdd_apply` function performs all of the basic bdd operations with two operands, such as AND, OR etc. The `left` argument is the left bdd operand and `right` is the right operand. The `opr` argument is the requested operation and must be one of the following

Identifier	Description	Truth table	C++ opr.
`bddop_and`	logical and ($A \wedge B$)	[0,0,0,1]	`&`
`bddop_xor`	logical xor ($A \oplus B$)	[0,1,1,0]	`^`
`bddop_or`	logical or ($A \vee B$)	[0,1,1,1]	`|`
`bddop_nand`	logical not-and	[1,1,1,0]	
`bddop_nor`	logical not-or	[1,0,0,0]	
`bddop_imp`	implication ($A \Rightarrow B$)	[1,1,0,1]	`>>`
`bddop_biimp`	bi-implication ($A \Leftrightarrow B$)	[1,0,0,1]	
`bddop_diff`	set difference ($A \setminus B$)	[0,0,1,0]	`-`
`bddop_less`	less than ($A < B$)	[0,1,0,0]	`<`
`bddop_invimp`	reverse implication ($A \Leftarrow B$)	[1,0,1,1]	`<<`

Return value

The result of the operation.

See also

bdd_ite

bdd_appuni – apply operation and unique quantification

```
BDD bdd_appuni(BDD left, BDD right, int opr, BDD var)
```

Description

Applies the binary operator `opr` to the arguments `left` and `right` and then performs a unique quantification of the variables from the variable set `var`. This is done in a bottom up manner such that both the apply and quantification is done on the lower nodes before stepping up to the higher nodes. This makes the `bdd_appuni` function much more efficient than an apply operation followed by a quantification.

Return value

The result of the operation.

See also

bdd_appex, bdd_appall, bdd_apply, bdd_exist, bdd_unique, bdd_forall, bdd_makeset

bdd_autoreorder – enables automatic reordering

```
int bdd_autoreorder(int method)
int bdd_autoreorder_times(int method, int num)
```

Description

Enables automatic reordering using `method` as the reordering method. If `method` is `BDD_REORDER_NONE` then automatic reordering is disabled. Automatic reordering is done every time the number of active nodes in the node table has been doubled and works by interrupting the current BDD operation, doing the reordering and the retrying the operation.

In the second form the argument `num` specifies the allowed number of reorderings. So if for example a "one shot" reordering is needed, then the `num` argument would be set to one.

Values for `method` can be found under `bdd_reorder`.

Return value

Returns the old value of `method`

See also

bdd_reorder

bdd_biimp – The logical 'bi-implication' between two BDDs

```
BDD bdd_biimp(BDD l, BDD r)
```

Description

This a wrapper that calls `bdd_apply(l,r,bddop_biimp)`.

Return value

The logical 'bi-implication' of `l` and `r` ($l \Leftrightarrow r$).

See also

bdd_apply, bdd_imp

bdd_blockfile_hook – Specifies a printing callback handler

```
bddfilehandler bdd_blockfile_hook(bddfilehandler handler)
```

Description

A printing callback handler is used to convert the variable block identifiers into something readable by the end user. Use `bdd_blockfile_hook` to pass a handler to BuDDy. A typical handler could look like this:

```
void printhandler(FILE *o, int block)
{
   extern char **blocknames;
   fprintf(o, "%s", blocknames[block]);
}
```

The handler is then called from `bdd_printorder` and `bdd_reorder` (depending on the verbose level) with the block numbers returned by `bdd_addvarblock` as arguments. No default handler is supplied. The argument `handler` may be NULL if no handler is needed.

Return value

The old handler

See also

bdd_printorder

bdd_buildcube – build a cube from an array of variables

```
BDD bdd_buildcube(int value, int width, BDD *var)
BDD bdd_ibuildcube(int value, int width, int *var)
```

Description

This function builds a cube from the variables in `var`. It does so by interpreting the `width` low order bits of `value` as a bit mask–a set bit indicates that the variable should be added in it's positive form, and a cleared bit the opposite. The most significant bits are encoded with the first variables in `var`. Consider as an example the call `bdd_buildcube(0xB, 4, var)`. This corresponds to the expression: $var[0] \wedge \neg var[1] \wedge var[2] \wedge var[3]$. The first version of the function takes an array of BDDs, whereas the second takes an array of variable numbers as used in `bdd_ithvar`.

Return value

The resulting cube

See also

bdd_ithvar, fdd_ithvar

bdd_cachestats – Fetch cache access usage

```
void bdd_cachestats(bddCacheStat *s)
```

Description

Fetches cache usage information and stores it in `s`. The fields of `s` can be found in the documentaion for `bddCacheStat`. This function may or may not be compiled into the BuDDy package - depending on the setup at compile time of BuDDy.

See also

bddCacheStat, bdd_printstat

bdd_clear_error – clears an error condition in the kernel

```
void bdd_clear_error(void)
```

Description

The BuDDy kernel may at some point run out of new ROBDD nodes if a maximum limit is set with `bdd_setmaxnodenum`. In this case the current error handler is called and an internal error flag is set. Further calls to BuDDy will always return `bddfalse`. From here BuDDy must either be restarted or `bdd_clear_error` may be called after action is taken to let BuDDy continue. This may not be especially usefull since the default error handler exits the program - other needs may of course exist.

See also

bdd_error_hook, bdd_setmaxnodenum

bdd_clrvarblocks – clears all variable blocks

```
void bdd_clrvarblocks(void)
```

Description

Clears all the variable blocks that has been defined by calls to bdd_addvarblock.

See also

bdd_addvarblock

bdd_compose – functional composition

```
BDD bdd_compose(BDD f, BDD g, int var)
```

Description

Substitutes the variable `var` with the BDD `g` in the BDD `f`: result = $f[g/var]$.

Return value

The composed BDD

See also

bdd_veccompose, bdd_replace, bdd_restrict

bdd_constrain – generalized cofactor

```
BDD bdd_constrain(BDD f, BDD c)
```

Description

Computes the generalized cofactor of `f` with respect to `c`.

Return value

The constrained BDD

See also

bdd_restrict, bdd_simplify

bdd_delref – decreases the reference count on a node

```
BDD bdd_delref(BDD r)
```

Description

Reference counting is done on externaly referenced nodes only and the count for a specific node `r` can and must be decreased using this function to make it possible to reclaim the node in the next garbage collection.

Return value

The BDD node `r`.

See also

bdd_addref

bdd_disable_reorder – Disable automatic reordering

```
void bdd_disable_reorder(void)
```

Description

Disables automatic reordering until `bdd_enable_reorder` is called. Reordering is enabled by default as soon as any variable blocks have been defined.

See also

bdd_enable_reorder

bdd_done – resets the bdd package

```
void bdd_done(void)
```

Description

This function frees all memory used by the bdd package and resets the package to it's initial state.

See also

bdd_init

bdd_enable_reorder – Enables automatic reordering

```
void bdd_enable_reorder(void)
```

Description

Re-enables reordering after a call to `bdd_disable_reorder`.

See also

bdd_disable_reorder

bdd_error_hook – set a handler for error conditions

```
bddinthandler bdd_error_hook(bddinthandler handler)
```

Description

Whenever an error occurs in the bdd package a test is done to see if an error handler is supplied by the user and if such exists then it will be called with an error code in the variable `errcode`. The handler may then print any usefull information and return or exit afterwards.

This function sets the handler to be `handler`. If a `NULL` argument is supplied then no calls are made when an error occurs. Possible error codes are found in `bdd.h`. The default handler is `bdd_default_errhandler` which will use `exit()` to terminate the program.

Any handler should be defined like this:

```
void my_error_handler(int errcode)
{
   ...
}
```

Return value

The previous handler

See also

bdd_errstring

bdd_errstring – converts an error code to a string

```
const char *bdd_errstring(int errorcode)
```

Description

Converts a negative error code `errorcode` to a descriptive string that can be used for error handling.

Return value

An error description string if `e` is known, otherwise `NULL`.

See also

bdd_err_hook

bdd_exist – existential quantification of variables

```
BDD bdd_exist(BDD r, BDD var)
```

Description

Removes all occurences in `r` of variables in the set `var` by existential quantification.

Return value

The quantified BDD.

See also

bdd_forall, bdd_unique, bdd_makeset

bdd_extvarnum – add extra BDD variables

```
int bdd_extvarnum(int num)
```

Description

Extends the current number of allocated BDD variables with `num` extra variables.

Return value

The old number of allocated variables or a negative error code.

See also

bdd_setvarnum, bdd_ithvar, bdd_nithvar

bdd_false – returns the constant false bdd

```
BDD bdd_false(void)
```

Description

This function returns the constant false bdd and can freely be used together with the `bddtrue` and `bddfalse` constants.

Return value

The constant false bdd

See also

bdd_true, bddtrue, bddfalse

bdd_file_hook – Specifies a printing callback handler

```
bddfilehandler bdd_file_hook(bddfilehandler handler)
```

Description

A printing callback handler for use with BDDs is used to convert the BDD variable number into something readable by the end user. Typically the handler will print a string name instead of the number. A handler could look like this:

```
void printhandler(FILE *o, int var)
{
   extern char **names;
   fprintf(o, "%s", names[var]);
}
```

The handler can then be passed to BuDDy like this: `bdd_file_hook(printhandler)`.

No default handler is supplied. The argument `handler` may be NULL if no handler is needed.

Return value

The old handler

See also

bdd_printset, bdd_strm_hook, fdd_file_hook

bdd_forall – universal quantification of variables

```
BDD bdd_forall(BDD r, BDD var)
```

Description

Removes all occurences in `r` of variables in the set `var` by universal quantification.

Return value

The quantified BDD.

See also

bdd_exist, bdd_unique, bdd_makeset

bdd_freepair – frees a table of pairs

```
void bdd_freepair(bddPair *pair)
```

Description

Frees the table of pairs `pair` that has been allocated by a call to `bdd_newpair`.

See also

bdd_replace, bdd_newpair, bdd_setpair, bdd_resetpair

bdd_fullsatone – finds one satisfying variable assignment

```
BDD bdd_fullsatone(BDD r)
```

Description

Finds a BDD with exactly one variable at all levels. This BDD implies `r` and is not false unless `r` is false.

Return value

The result of the operation.

See also

bdd_allsat bdd_satone, bdd_satoneset, bdd_satcount, bdd_satcountln

bdd_gbc_hook – set a handler for garbage collections

```
bddgbchandler bdd_gbc_hook(bddgbchandler handler)
```

Description

Whenever a garbage collection is required, a test is done to see if a handler for this event is supplied by the user and if such exists then it is called, both before and after the garbage collection takes places. This is indicated by an integer flag `pre` passed to the handler, which will be one before garbage collection and zero after garbage collection.

This function sets the handler to be `handler`. If a `NULL` argument is supplied then no calls are made when a garbage collection takes place. The argument `pre` indicates pre vs. post garbage collection and the argument `stat` contains information about the garbage collection. The default handler is `bdd_default_gbchandler`.

Any handler should be defined like this:

```
void my_gbc_handler(int pre, bddGbcStat *stat)
{
   ...
}
```

Return value

The previous handler

See also

bdd_resize_hook, bdd_reorder_hook

bdd_getallocnum – get the number of allocated nodes

```
int bdd_getallocnum(void)
```

Description

Returns the number of nodes currently allocated. This includes both dead and active nodes.

Return value

The number of nodes.

See also

bdd_getnodenum, bdd_setmaxnodenum

bdd_getnodenum – get the number of active nodes in use

```
int bdd_getnodenum(void)
```

Description

Returns the number of nodes in the nodetable that are currently in use. Note that dead nodes that have not been reclaimed yet by a garbage collection are counted as active.

Return value

The number of nodes.

See also

bdd_getallocnum, bdd_setmaxnodenum

bdd_getreorder_method – Fetch the current reorder method

```
int bdd_getreorder_method(void)
```

Description

Returns the current reorder method as defined by `bdd_autoreorder`.

See also

bdd_reorder, bdd_getreorder_times

bdd_getreorder_times – Fetch the current number of allowed reorderings

```
int bdd_getreorder_times(void)
```

Description

Returns the current number of allowed reorderings left. This value can be defined by `bdd_autoreorder_times`.

See also

bdd_reorder_times, bdd_getreorder_method

bdd_high – gets the true branch of a bdd

```
BDD bdd_high(BDD r)
```

Description

Gets the true branch of the bdd `r`.

Return value

The bdd of the true branch

See also

bdd_low

bdd_imp – The logical 'implication' between two BDDs

```
BDD bdd_imp(BDD l, BDD r)
```

Description

This a wrapper that calls `bdd_apply(l,r,bddop_imp)`.

Return value

The logical 'implication' of `l` and `r` ($l \Rightarrow r$).

See also

bdd_apply, bdd_biimp

bdd_init – initializes the BDD package

```
int bdd_init(int nodesize, int cachesize)
```

Description

This function initiates the bdd package and *must* be called before any bdd operations are done. The argument `nodesize` is the initial number of nodes in the nodetable and `cachesize` is the fixed size of the internal caches. Typical values for `nodesize` are 10000 nodes for small test examples and up to 1000000 nodes for large examples. A cache size of 10000 seems to work good even for large examples, but lesser values should do it for smaller examples.

The number of cache entries can also be set to depend on the size of the nodetable using a call to `bdd_setcacheratio`.

The initial number of nodes is not critical for any bdd operation as the table will be resized whenever there are to few nodes left after a garbage collection. But it does have some impact on the efficency of the operations.

Return value

If no errors occur then 0 is returned, otherwise a negative error code.

See also

bdd_done, bdd_resize_hook

bdd_isrunning – test whether the package is started or not

```
void bdd_isrunning(void)
```

Description

This function tests the internal state of the package and returns a status.

Return value

1 (true) if the package has been started, otherwise 0.

See also

bdd_init, bdd_done

bdd_ite – if-then-else operator

```
BDD bdd_ite(BDD f, BDD g, BDD h)
```

Description

Calculates the BDD for the expression $(f \wedge g) \vee (\neg f \wedge h)$ more efficiently than doing the three operations separately. `bdd_ite` can also be used for conjunction, disjunction and any other boolean operator, but is not as efficient for the binary and unary operations.

Return value

The BDD for $(f \wedge g) \vee (\neg f \wedge h)$

See also

bdd_apply

bdd_ithvar – returns a bdd representing the I'th variable

```
BDD bdd_ithvar(int var)
```

Description

This function is used to get a bdd representing the I'th variable (one node with the childs true and false). The requested variable must be in the range define by `bdd_setvarnum` starting with 0 being the first. For ease of use then the bdd returned from `bdd_ithvar` does not have to be referenced counted with a call to `bdd_addref`. The initial variable order is defined by the the index `var` that also defines the position in the variable order – variables with lower indecies are before those with higher indecies.

Return value

The I'th variable on succes, otherwise the constant false bdd

See also

bdd_setvarnum, bdd_nithvar, bddtrue, bddfalse

bdd_level2var – Fetch the variable number of a specific level

```
int bdd_level2var(int level)
```

Description

Returns the variable placed at position `level` in the current variable order.

See also

bdd_reorder, bdd_var2level

bdd_load – loads a BDD from a file

```
int bdd_fnload(char *fname, BDD *r)
int bdd_load(FILE *ifile, BDD *r)
```

Description

Loads a BDD from a file into the BDD pointed to by `r`. The file can either be the file `ifile` which must be opened for reading or the file named `fname` which will be opened automatically for reading.

The input file format consists of integers arranged in the following manner. First the number of nodes N used by the BDD and then the number of variables V allocated and the variable ordering in use at the time the BDD was saved. If N and V are both zero then the BDD is either the constant true or false BDD, indicated by a 1 or a 0 as the next integer.

In any other case the next N sets of 4 integers will describe the nodes used by the BDD. Each set consists of first the node number, then the variable number and then the low and high nodes.

The nodes *must* be saved in a order such that any low or high node must be defined before it is mentioned.

Return value

Zero on succes, otherwise an error code from `bdd.h`.

See also

bdd_save

bdd_low – gets the false branch of a bdd

```
BDD bdd_low(BDD r)
```

Description

Gets the false branch of the bdd `r`.

Return value

The bdd of the false branch

See also

bdd_high

bdd_makeset – builds a BDD variable set from an integer array

```
BDD bdd_makeset(int *v, int n)
```

Description

Reads a set of variable numbers from the integer array `v` which must hold exactly `n` integers and then builds a BDD representing the variable set.

The BDD variable set is represented as the conjunction of all the variables in their positive form and may just as well be made that way by the user. The user should keep a reference to the returned BDD instead of building it every time the set is needed.

Return value

A BDD variable set.

See also

bdd_scanset

bdd_newpair – creates an empty variable pair table

```
bddPair *bdd_newpair(void)
```

Description

Variable pairs of the type `bddPair` are used in `bdd_replace` to define which variables to replace with other variables. This function allocates such an empty table. The table can be freed by a call to *bdd_freepair*.

Return value

Returns a new table of pairs.

See also

bdd_freepair, bdd_replace, bdd_setpair, bdd_setpairs

bdd_nithvar – returns a bdd representing the negation of the I'th variable

```
BDD bdd_nithvar(int var)
```

Description

This function is used to get a bdd representing the negation of the I'th variable (one node with the childs false and true). The requested variable must be in the range define by `bdd_setvarnum` starting with 0 being the first. For ease of use then the bdd returned from `bdd_nithvar` does not have to be referenced counted with a call to `bdd_addref`.

Return value

The negated I'th variable on succes, otherwise the constant false bdd

See also

bdd_setvarnum, bdd_ithvar, bddtrue, bddfalse

bdd_nodecount – counts the number of nodes used for a BDD

```
int bdd_nodecount(BDD r)
```

Description

Traverses the BDD and counts all distinct nodes that are used for the BDD.

Return value

The number of nodes.

See also

bdd_pathcount, bdd_satcount, bdd_anodecount

bdd_not – negates a bdd

```
BDD bdd_not(BDD r)
```

Description

Negates the BDD `r` by exchanging all references to the zero-terminal with references to the one-terminal and vice versa.

Return value

The negated bdd.

bdd_or – The logical 'or' of two BDDs

```
BDD bdd_or(BDD l, BDD r)
```

Description

This a wrapper that calls `bdd_apply(l,r,bddop_or)`.

Return value

The logical 'or' of `l` and `r`.

See also

bdd_apply, bdd_xor, bdd_and

bdd_pathcount – count the number of paths leading to the true terminal

```
double bdd_pathcount(BDD r)
```

Description

Counts the number of paths from the root node `r` leading to the terminal true node.

Return value

The number of paths

See also

bdd_nodecount, bdd_satcount

bdd_printall – prints all used entries in the node table

```
void bdd_printall(void)
void bdd_fprintall(FILE* ofile)
```

Description

Prints to either stdout or the file `ofile` all the used entries in the main node table. The format is:

```
[Nodenum] Var/level Low High
```

Where `Nodenum` is the position in the node table and level is the position in the current variable order.

See also

bdd_printtable, bdd_printset, bdd_printdot

bdd_printdot – prints a description of a BDD in DOT format

```
void bdd_printdot(BDD r)
int bdd_fnprintdot(char* fname, BDD r)
void bdd_fprintdot(FILE* ofile, BDD r)
```

Description

Prints a BDD in a format suitable for use with the graph drawing program DOT to either stdout, a designated file `ofile` or the file named by `fname`. In the last case the file will be opened for writing, any previous contents destroyed and then closed again.

See also

bdd_printall, bdd_printtable, bdd_printset

bdd_printorder – prints the current order

```
void bdd_printorder(void)
bdd_fprint_order(FILE *f)
```

Description

Prints an indented list of the variable blocks, showing the top most blocks to the left and the lower blocks to the right. Example:

```
2{
   0
   1
2}
3
4
```

This shows 5 variable blocks. The first one added is block zero, which is on the same level as block one. These two blocks are then sub-blocks of block two and block two is on the same level as block three and four. The numbers are the identifiers returned from `bdd_addvarblock`. The block levels depends on the variables included in the blocks.

See also

bdd_reorder, bdd_addvarblock

bdd_printset – prints the set of truth assignments specified by a BDD

```
bdd_printset(BDD r)
bdd_fprintset(FILE* ofile, BDD r)
```

Description

Prints all the truth assignments for `r` that would yield it true. The format is:

$<\ x_{1,1} : c_{1,1}, \ldots, x_{1,n_1} : c_{1,n_1}\ >$
$<\ x_{2,1} : c_{2,1}, \ldots, x_{2,n_2} : c_{2,n_2}\ >$
$\ldots$
$<\ x_{N,1} : c_{N,1}, \ldots, x_{N,n_3} : c_{N,n_3}\ >$

Where the x's are variable numbers (and the position in the current order) and the c's are the possible assignments to these. Each set of brackets designates one possible assignment to the set of variables that make up the BDD. All variables not shown are don't cares. It is possible to specify a callback handler for printing of the variables using `bdd_file_hook` or `bdd_strm_hook`.

See also

bdd_printall, bdd_printtable, bdd_printdot, bdd_file_hook, bdd_strm_hook

bdd_printstat – print cache statistics

```
void bdd_printstat(void)
void bdd_fprintstat(FILE *ofile)
```

Description

Prints information about the cache performance on standard output (or the supplied file). The information contains the number of accesses to the unique node table, the number of times a node was (not) found there and how many times a hash chain had to traversed. Hit and miss count is also given for the operator caches.

See also

bddCacheStat, bdd_cachestats

bdd_printtable – prints the node table entries used by a BDD

```
void bdd_printtable(BDD r)
void bdd_fprinttable(FILE* ofile, BDD r)
```

Description

Prints to either stdout or the file `ofile` all the entries in the main node table used by `r`. The format is:

```
[Nodenum] Var/level :  Low High
```

Where `Nodenum` is the position in the node table and level is the position in the current variable order.

See also

bdd_printall, bdd_printset, bdd_printdot

bdd_relprod – relational product

```
#define bdd_relprod(a,b,var) bdd_appex(a,b,bddop_and,var)
```

Description

Calculates the relational product of `a` and `b` as `a AND b` with the variables in `var` quantified out afterwards.

Return value

The relational product or `bddfalse` on errors.

See also

bdd_appex

bdd_reorder – start dynamic reordering

```
void bdd_reorder(int method)
```

Description

This function initiates dynamic reordering using the heuristic defined by `method`, which may be one of the following

`BDD_REORDER_WIN2`
: Reordering using a sliding window of size 2. This algorithm swaps two adjacent variable blocks and if this results in more nodes then the two blocks are swapped back again. Otherwise the result is kept in the variable order. This is then repeated for all variable blocks.

`BDD_REORDER_WIN2ITE`
: The same as above but the process is repeated until no further progress is done. Usually a fast and efficient method.

`BDD_REORDER_WIN3`
: The same as above but with a window size of 3.

`BDD_REORDER_WIN2ITE`
: The same as above but with a window size of 3.

`BDD_REORDER_SIFT`
: Reordering where each block is moved through all possible positions. The best of these is then used as the new position. Potentially a very slow but good method.

`BDD_REORDER_SIFTITE`
: The same as above but the process is repeated until no further progress is done. Can be extremely slow.

`BDD_REORDER_RANDOM`
: Mostly used for debugging purpose, but may be usefull for others. Selects a random position for each variable.

See also

bdd_autoreorder, bdd_reorder_verbose, bdd_addvarblock, bdd_clrvarblocks

bdd_reorder_gain – Calculate the gain in size after a reordering

`int bdd_reorder_gain(void)`

Description

Returns the gain in percent of the previous number of used nodes. The value returned is

$$(100 * (A - B))/A$$

Where A is previous number of used nodes and B is current number of used nodes.

bdd_reorder_hook – sets a handler for automatic reorderings

`bddinthandler bdd_reorder_hook(bddinthandler handler)`

Description

Whenever automatic reordering is done, a check is done to see if the user has supplied a handler for that event. If so then it is called with the argument `prestate` being 1 if the handler is called immediately *before* reordering and `prestate` being 0 if it is called immediately after. The default handler is `bdd_default_reohandler` which will print information about the reordering.

A typical handler could look like this:

```
void reorderhandler(int prestate)
{
   if (prestate)
      printf("Start reordering");
   else
      printf("End reordering");
}
```

Return value

The previous handler

See also

bdd_reorder, bdd_autoreorder, bdd_resize_hook

bdd_reorder_probe – Define a handler for minimization of BDDs

```
bddsizehandler bdd_reorder_probe(bddsizehandler handler)
```

Description

Reordering is typically done to minimize the global number of BDD nodes in use, but it may in some cases be usefull to minimize with respect to a specific BDD. With `bdd_reorder_probe` it is possible to define a callback function that calculates the size of a specific BDD (or anything else in fact). This handler will then be called by the reordering functions to get the current size information. A typical handle could look like this:

```
int sizehandler(void)
{
   extern BDD mybdd;
   return bdd_nodecount(mybdd);
}
```

No default handler is supplied. The argument `handler` may be NULL if no handler is needed.

Return value

The old handler

See also

bdd_reorder

bdd_reorder_verbose – enables verbose information about reorderings

```
int bdd_reorder_verbose(int v)
```

Description

With `bdd_reorder_verbose` it is possible to set the level of information which should be printed during reordering. A value of zero means no information, a value of one means some information and any greater value will result in a lot of reordering information. The default value is zero.

Return value

The old verbose level

See also

bdd_reorder

bdd_replace – replaces variables with other variables

```
BDD bdd_replace(BDD r, bddPair *pair)
```

Description

Replaces all variables in the BDD `r` with the variables defined by `pair`. Each entry in `pair` consists of a old and a new variable. Whenever the old variable is found in `r` then a new node with the new variable is inserted instead.

Return value

The result of the operation.

See also

bdd_newpair, bdd_setpair, bdd_setpairs

bdd_resetpair – clear all variable pairs

```
void bdd_resetpair(bddPair *pair)
```

Description

Resets the table of pairs `pair` by setting all substitutions to their default values (that is no change).

See also

bdd_newpair, bdd_setpair, bdd_freepair

bdd_resize_hook – set a handler for nodetable resizes

```
bdd2inthandler bdd_resize_hook(bdd2inthandler handler)
```

Description

Whenever it is impossible to get enough free nodes by a garbage collection then the node table is resized and a test is done to see if a handler is supllied by the user for this event. If so then it is called with `oldsize` being the old nodetable size and `newsize` being the new nodetable size.

This function sets the handler to be `handler`. If a `NULL` argument is supplied then no calls are made when a table resize is done. No default handler is supplied.

Any handler should be defined like this:

```
void my_resize_handler(int oldsize, int newsize)
{
   ...
}
```

Return value

The previous handler

See also

bdd_gbc_hook, bdd_reorder_hook, bdd_setminfreenodes

bdd_restrict – restric a set of variables to constant values

```
BDD bdd_restrict(BDD r, BDD var)
```

Description

This function restricts the variables in `r` to constant true or false. How this is done depends on how the variables are included in the variable set `var`. If they are included in their positive form then they are restricted to true and vice versa. Unfortunately it is not possible to insert variables in their negated form using `bdd_makeset`, so the variable set has to be build manually as a conjunction of the variables. Example: Assume variable 1 should be restricted to true and variable 3 to false.

```
bdd X = make_user_bdd();
bdd R1 = bdd_ithvar(1);
bdd R2 = bdd_nithvar(3);
bdd R = bdd_addref( bdd_apply(R1,R2, bddop_and) );
bdd RES = bdd_addref( bdd_restrict(X,R) );
```

Return value

The restricted bdd.

See also

bdd_makeset, bdd_exist, bdd_forall

bdd_satcount – calculates the number of satisfying variable assignments

```
double bdd_satcount(BDD r)
double bdd_satcountset(BDD r, BDD varset)
```

Description

Calculates how many possible variable assignments there exists such that `r` is satisfied (true). All defined variables are considered in the first version. In the second version, only the variables in the variable set `varset` are considered. This makes the function a *lot* slower.

Return value

The number of possible assignments.

See also

bdd_satone, bdd_fullsatone, bdd_satcountln

bdd_satcountln – calculates the log. number of satisfying variable assignments

```
double bdd_satcountln(BDD r)
double bdd_satcountlnset(BDD r, BDD varset)
```

Description

Calculates how many possible variable assignments there exists such that `r` is satisfied (true) and returns the logarithm of this. The result is calculated in such a manner that it is practically impossible to get an overflow, which is very possible for `bdd_satcount` if the number of defined variables is too large. All defined variables are considered in the first version. In the second version, only the variables in the variable set `varset` are considered. This makes the function a *lot* slower!

Return value

The logarithm of the number of possible assignments.

See also

bdd_satone, bdd_fullsatone, bdd_satcount

bdd_satone – finds one satisfying variable assignment

```
BDD bdd_satone(BDD r)
```

Description

Finds a BDD with at most one variable at each level. This BDD implies `r` and is not false unless `r` is false.

Return value

The result of the operation.

See also

bdd_allsat bdd_satoneset, bdd_fullsatone, bdd_satcount, bdd_satcountln

bdd_satoneset – finds one satisfying variable assignment

```
BDD bdd_satoneset(BDD r, BDD var, BDD pol)
```

Description

Finds a minterm in `r`. The `var` argument is a variable set that defines a set of variables that *must* be mentioned in the result. The polarity of these variables in result—in case they are undefined in `r`—are defined by the `pol` parameter. If `pol` is the false BDD then the variables will be in negative form, and otherwise they will be in positive form.

Return value

The result of the operation.

See also

bdd_allsat bdd_satone, bdd_fullsatone, bdd_satcount, bdd_satcountln

bdd_save – saves a BDD to a file

```
int bdd_fnsave(char *fname, BDD r)
int bdd_save(FILE *ofile, BDD r)
```

Description

Saves the nodes used by `r` to either a file `ofile` which must be opened for writing or to the file named `fname`. In the last case the file will be truncated and opened for writing.

Return value

Zero on succes, otherwise an error code from `bdd.h`.

See also

bdd_load

bdd_scanset – returns an integer representation of a variable set

```
int bdd_scanset(BDD r, int **v, int *n)
```

Description

Scans a variable set `r` and copies the stored variables into an integer array of variable numbers. The argument `v` is the address of an integer pointer where the array is stored and `n` is a pointer to an integer where the number of elements are stored. It is the users responsibility to make sure the array is deallocated by a call to `free(v)`. The numbers returned are guaranteed to be in ascending order.

Return value

Zero on success, otherwise a negative error code.

See also

bdd_makeset

bdd_setcacheratio – Sets the cache ratio for the operator caches

```
int bdd_setcacheratio(int r)
```

Description

The ratio between the number of nodes in the nodetable and the number of entries in the operator cachetables is called the cache ratio. So a cache ratio of say, four, allocates one cache entry for each four unique node entries. This value can be set with `bdd_setcacheratio` to any positive value. When this is done the caches are resized instantly to fit the new ratio. The default is a fixed cache size determined at initialization time.

Return value

The previous cache ratio or a negative number on error.

See also

bdd_init

bdd_setmaxincrease – set max. number of nodes used to increase node table

```
int bdd_setmaxincrease(int size)
```

Description

The node table is expanded by doubling the size of the table when no more free nodes can be found, but a maximum for the number of new nodes added can be set with `bdd_maxincrease` to `size` nodes. The default is 50000 nodes (1 Mb).

Return value

The old threshold on succes, otherwise a negative error code.

See also

bdd_setmaxnodenum, bdd_setminfreenodes

bdd_setmaxnodenum – set the maximum available number of bdd nodes

```
int bdd_setmaxnodenum(int size)
```

Description

This function sets the maximal number of bdd nodes the package may allocate before it gives up a bdd operation. The argument `size` is the absolute maximal number of nodes there may be allocated for the nodetable. Any attempt to allocate more nodes results in the constant false being returned and the error handler being called until some nodes are deallocated. A value of 0 is interpreted as an unlimited amount. It is *not* possible to specify fewer nodes than there has already been allocated.

Return value

The old threshold on succes, otherwise a negative error code.

See also

bdd_setmaxincrease, bdd_setminfreenodes

bdd_setminfreenodes – set min. no. of nodes to be reclaimed after GBC.

```
int bdd_setminfreenodes(int n)
```

Description

Whenever a garbage collection is executed the number of free nodes left are checked to see if a resize of the node table is required. If $X = (\mathit{bddfreenum} * 100)/\mathit{maxnum}$ is less than or equal to `n` then a resize is initiated. The range of `X` is of course $0 \ldots 100$ and has some influence on how fast the package is. A low number means harder attempts to avoid resizing and saves space, and a high number reduces the time used in garbage collections. The default value is 20.

Return value

The old threshold on succes, otherwise a negative error code.

See also

bdd_setmaxnodenum, bdd_setmaxincrease

bdd_setpair – set one variable pair

```
int bdd_setpair(bddPair *pair, int oldvar, int newvar)
int bdd_setbddpair(bddPair *pair, BDD oldvar, BDD newvar)
```

Description

Adds the pair `(oldvar,newvar)` to the table of pairs `pair`. This results in `oldvar` being substituted with `newvar` in a call to `bdd_replace`. In the first version `newvar` is an integer representing the variable to be replaced with the old variable. In the second version `oldvar` is a BDD. In this case the variable `oldvar` is substituted with the BDD `newvar`. The possibility to substitute with any BDD as `newvar` is utilized in bdd_compose, whereas only the topmost variable in the BDD is used in bdd_replace.

Return value

Zero on success, otherwise a negative error code.

See also

bdd_newpair, bdd_setpairs, bdd_resetpair, bdd_replace, bdd_compose

bdd_setpairs – defines a whole set of pairs

```
int bdd_setpairs(bddPair *pair, int *oldvar, int *newvar, int size)
int bdd_setbddpairs(bddPair *pair, int *oldvar, BDD *newvar, int size)
```

Description

As for `bdd_setpair` but with `oldvar` and `newvar` being arrays of variables (BDDs) of size `size`.

Return value

Zero on success, otherwise a negative error code.

See also

bdd_newpair, bdd_setpair, bdd_replace, bdd_compose

bdd_setvarnum – set the number of used bdd variables

```
int bdd_setvarnum(int num)
```

Description

This function is used to define the number of variables used in the bdd package. It may be called more than one time, but only to increase the number of variables. The argument `num` is the number of variables to use.

Return value

Zero on succes, otherwise a negative error code.

See also

bdd_ithvar, bdd_varnum, bdd_extvarnum

bdd_setvarorder – set a specific variable order

```
void bdd_setvarorder(int *neworder)
```

Description

This function sets the current variable order to be the one defined by `neworder`. The parameter `neworder` is interpreted as a sequence of variable indecies and the new variable order is exactly this sequence. The array *must* contain all the variables defined so far. If for instance the current number of variables is 3 and `neworder` contains $[1, 0, 2]$ then the new variable order is $v_1 < v_0 < v_2$.

See also

bdd_reorder, bdd_printorder

bdd_simplify – coudert and Madre's restrict function

```
BDD bdd_simplify(BDD f, BDD d)
```

Description

Tries to simplify the BDD `f` by restricting it to the domaine covered by `d`. No checks are done to see if the result is actually smaller than the input. This can be done by the user with a call to `bdd_nodecount`.

Return value

The simplified BDD

See also

bdd_restrict

bdd_stats – returns some status information about the bdd package

```
void bdd_stats(bddStat* stat)
```

Description

This function acquires information about the internal state of the bdd package. The status information is written into the `stat` argument.

See also

bddStat

bdd_strm_hook – Specifies a printing callback handler

`bddstrmhandler bdd_strm_hook(bddstrmhandler handler)`

Description

A printing callback handler for use with BDDs is used to convert the BDD variable number into something readable by the end user. Typically the handler will print a string name instead of the number. A handler could look like this:

```
void printhandler(ostream &o, int var)
{
   extern char **names;
   o << names[var];
}
```

The handler can then be passed to BuDDy like this: `bdd_strm_hook(printhandler)`.

No default handler is supplied. The argument `handler` may be NULL if no handler is needed.

Return value

The old handler

See also

bdd_printset, bdd_file_hook, fdd_strm_hook

bdd_support – returns the variable support of a BDD

`BDD bdd_support(BDD r)`

Description

Finds all the variables that `r` depends on. That is the support of `r`.

Return value

A BDD variable set.

See also

bdd_makeset

bdd_swapvar – Swap two BDD variables

```
int bdd_swapvar(int v1, int v2)
```

Description

Use `bdd_swapvar` to swap the position (in the current variable order) of the two BDD variables `v1` and `v2`. There are no constraints on the position of the two variables before the call. This function may *not* be used together with user defined variable blocks. The swap is done by a series of adjacent variable swaps and requires the whole node table to be rehashed twice for each call to `bdd_swapvar`. It should therefore not be used were efficiency is a major concern.

Return value

Zero on succes and a negative error code otherwise.

See also

bdd_reorder, bdd_addvarblock

bdd_true – returns the constant true bdd

```
BDD bdd_true(void)
```

Description

This function returns the constant true bdd and can freely be used together with the `bddtrue` and `bddfalse` constants.

Return value

The constant true bdd

See also

bdd_false, bddtrue, bddfalse

bdd_unique – unique quantification of variables

```
BDD bdd_unique(BDD r, BDD var)
```

Description

Removes all occurences in `r` of variables in the set `var` by unique quantification. This type of quantification uses a XOR operator instead of an OR operator as in the existential quantification, and an AND operator as in the universal quantification.

Return value

The quantified BDD.

See also

bdd_exist, bdd_forall, bdd_makeset

bdd_var – gets the variable labeling the bdd

```
int bdd_var(BDD r)
```

Description

Gets the variable labeling the bdd `r`.

Return value

The variable number.

bdd_var2level – Fetch the level of a specific BDD variable

```
int bdd_var2level(int var)
```

Description

Returns the position of the variable `var` in the current variable order.

See also

bdd_reorder, bdd_level2var

bdd_varblockall – add a variable block for all variables

```
void bdd_varblockall(void)
```

Description

Adds a variable block for all BDD variables declared so far. Each block contains one variable only. More variable blocks can be added later with the use of `bdd_addvarblock` – in this case the tree of variable blocks will have the blocks of single variables as the leafs.

See also

bdd_addvarblock, bdd_intaddvarblock

bdd_varnum – returns the number of defined variables

```
int bdd_varnum(void)
```

Description

This function returns the number of variables defined by a call to `bdd_setvarnum`.

Return value

The number of defined variables

See also

bdd_setvarnum, bdd_ithvar

bdd_varprofile – returns a variable profile

```
int *bdd_varprofile(BDD r)
```

Description

Counts the number of times each variable occurs in the bdd `r`. The result is stored and returned in an integer array where the i'th position stores the number of times the i'th variable occured in the BDD. It is the users responsibility to free the array again using a call to `free`.

Return value

A pointer to an integer array with the profile or NULL if an error occured.

bdd_veccompose – simultaneous functional composition

```
BDD bdd_veccompose(BDD f, bddPair *pair)
```

Description

Uses the pairs of variables and BDDs in `pair` to make the simultaneous substitution: $f[g_1/V_1, \ldots, g_n/V_n]$. In this way one or more BDDs may be substituted in one step. The BDDs in `pair` may depend on the variables they are substituting. `bdd_compose` may be used instead of `bdd_replace` but is not as efficient when g_i is a single variable, the same applies to `bdd_restrict`. Note that simultaneous substitution is not necessarily the same as repeated substitution. Example: $(x_1 \vee x_2)[x_3/x_1, x_4/x_3] = (x_3 \vee x_2) \neq ((x_1 \vee x_2)[x_3/x_1])[x_4/x_3] = (x_4 \vee x_2)$.

Return value

The composed BDD

See also

bdd_compose, bdd_replace, bdd_restrict

bdd_versionnum – returns the version number of the bdd package

```
int bdd_versionnum(void)
```

Description

This function returns the version number of the bdd package. The number is in the range 10-99 for version 1.0 to 9.9.

See also

bdd_versionstr

bdd_versionstr – returns a text string with version information

```
char* bdd_versionstr(void)
```

Description

This function returns a text string with information about the version of the bdd package.

See also

bdd_versionnum

bdd_xor – The logical 'xor' of two BDDs

```
BDD bdd_xor(BDD l, BDD r)
```

Description

This a wrapper that calls `bdd_apply(l,r,bddop_xor)`.

Return value

The logical 'xor' of `l` and `r`.

See also

bdd_apply, bdd_or, bdd_and

bddfalse – the constant false bdd

```
extern const BDD bddfalse;
```

Description

This bdd holds the constant false value

See also

bddtrue, bdd_true, bdd_false

bddtrue – the constant true bdd

```
extern const BDD bddtrue;
```

Description

This bdd holds the constant true value

See also

bddfalse, bdd_true, bdd_false

bvec – A boolean vector

```
typedef struct s_bvec
{
   int bitnum;
   BDD *bitvec;
} BVEC;

typedef BVEC bvec;
```

Description

This data structure is used to store boolean vectors. The field `bitnum` is the number of elements in the vector and the field `bitvec` contains the actual BDDs in the vector. The C++ version of `bvec` is documented at the beginning of this document

bvec_add – builds a boolean vector for addition

```
bvec bvec_add(bvec l, bvec r)
```

Description

Builds a new boolean vector that represents the addition of two other vectors. Each element x_i in the result will represent the function

$$x_i = l_i \text{ xor } r_i \text{ xor } c_{i-1}$$

where the carry in c_i is

$$c_i = (l_i \text{ and } r_i) \text{ or } (c_{i-1} \text{ and } (l_i \text{ or } r_i)).$$

It is important for efficency that the BDD variables used in `l` and `r` are interleaved.

Return value

The result of the addition (which is already reference counted)

See also

bvec_sub, bvec_mul, bvec_shl

bvec_addref – increase reference count of a boolean vector

```
bvec bvec_addref(bvec v)
```

Description

Use this function to increase the reference count of all BDDs in a `v`. Please note that all boolean vectors returned from BuDDy are reference counted from the beginning.

Return value

The boolean vector `v`

See also

bvec_delref

bvec_coerce – adjust the size of a boolean vector

```
bvec bvec_coerce(int bitnum, bvec v)
```

Description

Build a boolean vector with `bitnum` elements copied from `v`. If the number of elements in `v` is greater than `bitnum` then the most significant bits are removed, otherwise if number is smaller then the vector is padded with constant false BDDs (zeros).

Return value

The new boolean vector (which is already reference counted)

bvec_con – Build a boolean vector representing an integer value

```
bvec bvec_con(int bitnum, int val)
```

Description

Builds a boolean vector that represents the value `val` using `bitnum` bits. The value will be represented with the LSB at the position 0 and the MSB at position `bitnum`-1.

Return value

The boolean vector (which is already reference counted)

See also

bvec_true, bvec_false, bvec_var

bvec_copy – create a copy of a bvec

```
bvec bvec_copy(bvec src)
```

Description

Returns a copy of `src`. The result is reference counted.

See also

bvec_con

bvec_delref – decrease the reference count of a boolean vector

```
bvec bvec_delref(bvec v)
```

Description

Use this function to decrease the reference count of all the BDDs in `v`.

Return value

The boolean vector `v`

See also

bvec_addref

bvec_div – builds a boolean vector for division

```
int bvec_div(bvec l, bvec r, bvec *res, bvec *rem)
```

Description

Builds a new boolean vector representing the integer division of `l` with `r`. The result of the division will be stored in `res` and the remainder of the division will be stored in `rem`. Both vectors should be initialized as the function will try to release the nodes used by them. If an error occurs then the nodes will *not* be freed.

Return value

Zero on success or a negative error code on error.

See also

bvec_mul, bvec_divfixed, bvec_add, bvec_shl

bvec_divfixed – builds a boolean vector for division by a constant

```
int bvec_div(bvec e, int c, bvec *res, bvec *rem)
```

Description

Builds a new boolean vector representing the integer division of `e` with `c`. The result of the division will be stored in `res` and the remainder of the division will be stored in `rem`. Both vectors should be initialized as the function will try to release the nodes used by them. If an error occurs then the nodes will *not* be freed.

Return value

Zero on success or a negative error code on error.

See also

bvec_div, bvec_mul, bvec_add, bvec_shl

bvec_equ – calculates the truth value of $x = y$

```
bdd bvec_equ(bvec l, bvec r)
```

Description

Returns the BDD representing `l = r` (*not* reference counted). Both vectors must have the same number of bits.

See also

bvec_lth, bvec_lte, bvec_gth, bvec_gte, bvec_neq

bvec_false – build a vector of constant false BDDs

```
bvec bvec_false(int bitnum)
```

Description

Builds a boolean vector with `bitnum` elements, each of which are the constant false BDD.

Return value

The boolean vector (which is already reference counted)

See also

bvec_true, bvec_con, bvec_var

bvec_free – frees all memory used by a boolean vector

```
void bvec_free(bvec v)
```

Description

Use this function to release any unused boolean vectors. The decrease of the reference counts on the BDDs in `v` is done by `bvec_free`.

bvec_gte – calculates the truth value of $x \geq y$

```
bdd bvec_gte(bvec l, bvec r)
```

Description

Returns the BDD representing `l`≥`r` (*not* reference counted). Both vectors must have the same number of bits.

See also

bvec_lth, bvec_gth, bvec_gth, bvec_equ, bvec_neq

bvec_gth – calculates the truth value of $x > y$

```
bdd bvec_gth(bvec l, bvec r)
```

Description

Returns the BDD representing `l > r` (*not* reference counted). Both vectors must have the same number of bits.

See also

bvec_lth, bvec_lte, bvec_gte, bvec_equ, bvec_neq

bvec_isconst – test a vector for constant true/false BDDs

```
int bvec_isconst(bvec v)
```

Description

Returns non-zero if the vector `v` consists of only constant true or false BDDs. Otherwise zero is returned. This test should prelude any call to `bvec_val`.

See also

bvec_val, bvec_con

bvec_ite – calculates the if-then-else operator for a boolean vector

```
bvec bvec_ite(bdd a, bvec b, bvec c)
```

Description

Builds a vector where the bdd `a` has been applied bitwise to `b` and `c` in an if-then-else operation, such that the result r is:

$$r_i = ite(a, b_i, c_i);$$

Return value

The if-then-else result.

See also

bdd_ite

bvec_lte – calculates the truth value of $x \leq y$

```
bdd bvec_lte(bvec l, bvec r)
```

Description

Returns the BDD representing `l`≤`r` (*not* reference counted). Both vectors must have the same number of bits.

See also

bvec_lth, bvec_gth, bvec_gte, bvec_equ, bvec_neq

bvec_lth – calculates the truth value of $x < y$

```
bdd bvec_lth(bvec l, bvec r)
```

Description

Returns the BDD representing `l < r` (*not* reference counted). Both vectors must have the same number of bits.

See also

bvec_lte, bvec_gth, bvec_gte, bvec_equ, bvec_neq

bvec_map1 – map a function onto a boolean vector

```
bvec bvec_map1(bvec a, bdd (*fun)(bdd))
```

Description

Maps the function `fun` onto all the elements in `a`. The value returned from `fun` is stored in a new vector which is then returned. An example of a mapping function is `bdd_not` which can be used like this

```
bvec res = bvec_map1(a, bdd_not)
```

to negate all the BDDs in `a`.

Return value

The new vector (which is already reference counted)

See also

bvec_map2, bvec_map3

bvec_map2 – map a function onto a boolean vector

```
bvec bvec_map2(bvec a, bvec b, bdd (*fun)(bdd,bdd))
```

Description

Maps the function `fun` onto all the elements in `a` and `b`. The value returned from `fun` is stored in a new vector which is then returned. An example of a mapping function is `bdd_and` which can be used like this

```
bvec res = bvec_map2(a, b, bdd_and)
```

to calculate the logical 'and' of all the BDDs in `a` and `b`.

Return value

The new vector (which is already reference counted)

See also

bvec_map1, bvec_map3

bvec_map3 – map a function onto a boolean vector

```
bvec bvec_map3(bvec a, bvec b, bvec c, bdd (*fun)(bdd,bdd,bdd))
```

Description

Maps the function `fun` onto all the elements in `a`, `b` and `c`. The value returned from `fun` is stored in a new vector which is then returned. An example of a mapping function is `bdd_ite` which can be used like this

```
bvec res = bvec_map3(a, b, c, bdd_ite)
```

to calculate the if-then-else function for each element in `a`, `b` and `c`.

Return value

The new vector (which is already reference counted)

See also

bvec_map1, bvec_map2

bvec_mul – builds a boolean vector for multiplication

```
bvec bvec_mul(bvec l, bvec r)
```

Description

Builds a boolean vector representing the multiplication of `l` and `r`.

Return value

The result of the multiplication (which is already reference counted)

See also

bvec_mulfixed, bvec_div, bvec_add, bvec_shl

bvec_mulfixed – builds a boolean vector for multiplication with a constant

```
bvec bvec_mulfixed(bvec e, int c)
```

Description

Builds a boolean vector representing the multiplication of `e` and `c`.

Return value

The result of the multiplication (which is already reference counted)

See also

bvec_mul, bvec_div, bvec_add, bvec_shl

bvec_neq – calculates the truth value of $x \neq y$

```
bdd bvec_neq(bvec l, bvec r)
```

Description

Returns the BDD representing `l`≠`r` (*not* reference counted). Both vectors must have the same number of bits.

See also

bvec_lte, bvec_lth, bvec_gth, bvec_gth, bvec_equ

bvec_shl – shift left operation (symbolic)

```
bvec bvec_shl(bvec l, bvec r, BDD c)
```

Description

Builds a boolean vector that represents `l` shifted `r` times to the left. The new empty elements will be set to `c`. The shift operation is fully symbolic and the number of bits shifted depends on the current value encoded by `r`.

Return value

The result of the operation (which is already reference counted)

See also

bvec_add, bvec_mul, bvec_shlfixed, bvec_shr

bvec_shlfixed – shift left operation (fixed number of bits)

```
bvec bvec_shlfixed(bvec v, int pos, BDD c)
```

Description

Builds a boolean vector that represents `v` shifted `pos` times to the left. The new empty elements will be set to `c`.

Return value

The result of the operation (which is already reference counted)

See also

bvec_add, bvec_mul, bvec_shl, bvec_shr

bvec_shr – shift right operation (symbolic)

```
bvec bvec_shr(bvec l, bvec r, BDD c)
```

Description

Builds a boolean vector that represents `l` shifted `r` times to the right. The new empty elements will be set to `c`. The shift operation is fully symbolic and the number of bits shifted depends on the current value encoded by `r`.

Return value

The result of the operation (which is already reference counted)

See also

bvec_add, bvec_mul, bvec_shl, bvec_shrfixed

bvec_shrfixed – shift right operation

```
bvec bvec_shrfixed(bvec v, int pos, BDD c)
```

Description

Builds a boolean vector that represents `v` shifted `pos` times to the right. The new empty elements will be set to `c`.

Return value

The result of the operation (which is already reference counted)

See also

bvec_add, bvec_mul, bvec_shr, bvec_shl

bvec_sub – builds a boolean vector for subtraction

```
bvec bvec_sub(bvec l, bvec r)
```

Description

Builds a new boolean vector that represents the subtraction of two other vectors. Each element x_i in the result will represent the function

$$x_i = l_i \text{ xor } r_i \text{ xor } c_{i-1}$$

where the carry in c_i is

$$c_i = (l_i \text{ and } r_i \text{ and } c_{i-1}) \text{ or } (\text{not } l_i \text{ and } (r_i \text{ or } c_{i-1})).$$

It is important for efficency that the BDD variables used in `l` and `r` are interleaved.

Return value

The result of the subtraction (which is already reference counted)

See also

bvec_add, bvec_mul, bvec_shl

bvec_true – build a vector of constant true BDDs

```
bvec bvec_true(int bitnum)
```

Description

Builds a boolean vector with `bitnum` elements, each of which are the constant true BDD.

Return value

The boolean vector (which is already reference counted)

See also

bvec_false, bvec_con, bvec_var

bvec_val – calculate the integer value represented by a boolean vector

```
int bvec_val(bvec v)
```

Description

Calculates the value represented by the bits in `v` assuming that the vector `v` consists of only constant true or false BDDs. The LSB is assumed to be at position zero.

Return value

The integer value represented by `v`.

See also

bvec_isconst, bvec_con

bvec_var – build a boolean vector with BDD variables

```
bvec bvec_var(int bitnum, int offset, int step)
```

Description

Builds a boolean vector with the BDD variables $v_1, \ldots, v_n$ as the elements. Each variable will be the the variabled numbered `offset + N*step` where `N` ranges from 0 to `bitnum`-1.

Return value

The boolean vector (which is already reference counted)

See also

bvec_true, bvec_false, bvec_con

bvec_varfdd – build a boolean vector from a FDD variable block

```
bvec bvec_varfdd(int var)
```

Description

Builds a boolean vector which will include exactly the variables used to define the FDD variable block `var`. The vector will have the LSB at position zero.

Return value

The boolean vector (which is already reference counted)

See also

bvec_var

bvec_varvec – build a boolean vector with the variables passed in an array

```
bvec bvec_varvec(int bitnum, int *var)
```

Description

Builds a boolean vector with the BDD variables listed in the array `var`. The array must be of size `bitnum`.

Return value

The boolean vector (which is already reference counted)

See also

bvec_var

fdd_clearall – clear all allocated FDD blocks

```
void fdd_clearall(void)
```

Description

Removes all defined finite domain blocks defined by `fdd_extdomain()` and `fdd_overlapdomain()`

fdd_domain – BDD encoding of the domain of a FDD variable

```
BDD fdd_domain(int var)
```

Description

Returns what corresponds to a disjunction of all possible values of the variable `var`. This is more efficient than doing `fdd_ithvar(var,0) OR fdd_ithvar(var,1) ...` explicitely for all values in the domain of `var`.

Return value

The encoding of the domain

fdd_domainnum – number of defined finite domain blocks

```
int fdd_domainnum(void)
```

Description

Returns the number of finite domain blocks define by calls to `bdd_extdomain`.

Return value

The number of defined finite domain blocks or a negative error code

See also

fdd_domainsize, fdd_extdomain

fdd_domainsize – real size of a finite domain block

```
int fdd_domainsize(int var)
```

Description

Returns the size of the domain for the finite domain block `var`.

Return value

The size or a negative error code

See also

fdd_domainnum

fdd_equals – returns a BDD setting two FD. blocks equal

```
BDD fdd_equals(int f, int g)
```

Description

Builds a BDD which is true for all the possible assignments to the variable blocks `f` and `g` that makes the blocks equal. This is more or less just a shorthand for calling `fdd_equ()`.

Return value

The correct BDD or the constant false on errors.

fdd_extdomain – adds another set of finite domain blocks

```
int fdd_extdomain(int *dom, int num)
```

Description

Extends the set of finite domain blocks with the `num` domains in `dom`. Each entry in `dom` defines the size of a new finite domain which later on can be used for finite state machine traversal and other operations on finte domains. Each domain allocates $\log_2(|dom[i]|)$ BDD variables to be used later. The ordering is interleaved for the domains defined in each call to `bdd_extdomain`. This means that assuming domain D_0 needs 2 BDD variables x_1 and x_2, and another domain D_1 needs 4 BDD variables y_1, y_2, y_3 and y_4, then the order will be $x_1, y_1, x_2, y_2, y_3, y_4$. The index of the first domain in `dom` is returned. The index of the other domains are offset from this index with the same offset as in `dom`.

The BDD variables needed to encode the domain are created for the purpose and do not interfere with the BDD variables already in use.

Return value

The index of the first domain or a negative error code.

See also

fdd_ithvar, fdd_equals, fdd_overlapdomain

fdd_file_hook – Specifies a printing callback handler

```
bddfilehandler fdd_file_hook(bddfilehandler handler)
```

Description

A printing callback handler for use with FDDs is used to convert the FDD integer identifier into something readable by the end user. Typically the handler will print a string name instead of the identifier. A handler could look like this:

```
void printhandler(FILE *o, int var)
{
   extern char **names;
   fprintf(o, "%s", names[var]);
}
```

The handler can then be passed to BuDDy like this: `fdd_file_hook(printhandler)`.

No default handler is supplied. The argument `handler` may be NULL if no handler is needed.

Return value

The old handler

See also

fdd_printset, bdd_file_hook

fdd_intaddvarblock – adds a new variable block for reordering

```
int fdd_intaddvarblock(int first, int last, int fixed)
```

Description

Works exactly like `bdd_addvarblock` except that `fdd_intaddvarblock` takes a range of FDD variables instead of BDD variables.

Return value

Zero on success, otherwise a negative error code.

See also

bdd_addvarblock, bdd_intaddvarblock, bdd_reorder

fdd_ithset – the variable set for the i'th finite domain block

```
BDD fdd_ithset(int var)
```

Description

Returns the variable set that contains the variables used to define the finite domain block `var`.

Return value

The variable set or the constant false BDD on error.

See also

fdd_ithvar

fdd_ithvar – the BDD for the i'th FDD set to a specific value

```
BDD fdd_ithvar(int var, int val)
```

Description

Returns the BDD that defines the value `val` for the finite domain block `var`. The encoding places the Least Significant Bit at the top of the BDD tree (which means they will have the lowest variable index). The returned BDD will be $V_0 \land V_1 \land \ldots \land V_N$ where each V_i will be in positive or negative form depending on the value of `val`.

Return value

The correct BDD or the constant false BDD on error.

See also

fdd_ithset

fdd_makeset – creates a variable set for N finite domain blocks

```
BDD fdd_makeset(int *varset, int varnum)
```

Description

Returns a BDD defining all the variable sets used to define the variable blocks in the array `varset`. The argument `varnum` defines the size of `varset`.

Return value

The correct BDD or the constant false on errors.

See also

fdd_ithset, bdd_makeset

fdd_overlapdomain – combine two FDD blocks into one

```
int fdd_overlapdomain(int v1, int v2)
```

Description

This function takes two FDD blocks and merges them into a new one, such that the new one is encoded using both sets of BDD variables. If `v1` is encoded using the BDD variables $a_1, \ldots, a_n$ and has a domain of $[0, N_1]$, and `v2` is encoded using $b_1, \ldots, b_n$ and has a domain of $[0, N_2]$, then the result will be encoded using the BDD variables $a_1, \ldots, a_n, b_1, \ldots, b_n$ and have the domain $[0, N_1 * N_2]$. The use of this function may result in some strange output from `fdd_printset`.

Return value

The index of the finite domain block

See also

fdd_extdomain

fdd_printset – prints a BDD for a finite domain block

```
void fdd_printset(BDD r)
void fdd_fprintset(FILE *ofile, BDD f)
```

Description

Prints the BDD `f` using a set notation as in `bdd_printset` but with the index of the finite domain blocks included instead of the BDD variables. It is possible to specify a printing callback function with `fdd_file_hook` or `fdd_strm_hook` which can be used to print the FDD identifier in a readable form.

See also

bdd_printset, fdd_file_hook, fdd_strm_hook

fdd_scanallvar – Finds one satisfying value of all FDD variables

```
int* fdd_scanallvar(BDD r)
```

Description

Finds one satisfying assignment in `r` of all the defined FDD variables. Each value is stored in an array which is returned. The size of this array is exactly the number of FDD variables defined. It is the user's responsibility to free this array using `free()`.

Return value

An array with all satisfying values. If `r` is the trivially false BDD, then NULL is returned.

See also

fdd_scanvar

fdd_scanset – scans a variable set

```
int fdd_scanset(BDD r, int **varset, int *varnum)
```

Description

Scans the BDD `r` to find all occurences of FDD variables and then stores these in `varset`. `varset` will be set to point to an array of size `varnum` which will contain the indices of the found FDD variables. It is the users responsibility to free `varset` after use.

Return value

Zero on success or a negative error code on error.

See also

fdd_makeset

fdd_scanvar – Finds one satisfying value of a FDD variable

```
int fdd_scanvar(BDD r, int var)
```

Description

Finds one satisfying assignment of the FDD variable `var` in the BDD `r` and returns this value.

Return value

The value of a satisfying assignment of `var`. If `r` is the trivially false BDD, then a negative value is returned.

See also

fdd_scanallvar

fdd_setpair – defines a pair for two finite domain blocks

```
int fdd_setpair(bddPair *pair, int p1, int p2)
```

Description

Defines each variable in the finite domain block `p1` to be paired with the corresponding variable in `p2`. The result is stored in `pair` which must be allocated using `bdd_makepair`.

Return value

Zero on success or a negative error code on error.

See also

fdd_setpairs

fdd_setpairs – defines N pairs for finite domain blocks

```
int fdd_setpairs(bddPair *pair, int *p1, int *p2, int size)
```

Description

Defines each variable in all the finite domain blocks listed in the array `p1` to be paired with the corresponding variable in `p2`. The result is stored in `pair` which must be allocated using `bdd_makeset`.

Return value

Zero on success or a negative error code on error.

See also

bdd_setpair

fdd_strm_hook – Specifies a printing callback handler

```
bddstrmhandler fdd_strm_hook(bddstrmhandler handler)
```

Description

A printing callback handler for use with FDDs is used to convert the FDD integer identifier into something readable by the end user. Typically the handler will print a string name instead of the identifier. A handler could look like this:

```
void printhandler(ostream &o, int var)
{
   extern char **names;
   o << names[var];
}
```

The handler can then be passed to BuDDy like this: `fdd_strm_hook(printhandler)`.

No default handler is supplied. The argument `handler` may be NULL if no handler is needed.

Return value

The old handler

See also

fdd_printset, bdd_file_hook

fdd_varnum – binary size of a finite domain block

```
int fdd_varnum(int var)
```

Description

Returns the number of BDD variables used for the finite domain block `var`.

Return value

The number of variables or a negative error code

See also

fdd_vars

fdd_vars – all BDD variables associated with a finite domain block

```
int *fdd_vars(int var)
```

Description

Returns an integer array containing the BDD variables used to define the finite domain block `var`. The size of the array is the number of variables used to define the finite domain block. The array will have the Least Significant Bit at pos 0. The array must *not* be deallocated.

Return value

Integer array contaning the variable numbers or NULL if `v` is an unknown block.

See also

fdd_varnum

operator<< – C++ output operator for BDDs

```
ostream &operator<<(ostream &o, const bdd_ioformat &f)
ostream &operator<<(ostream &o, const bdd &r)
```

Description

BDDs can be printed in various formats using the C++ iostreams library. The formats are the those used in `bdd_printset`, `bdd_printtable`, `fdd_printset` and `bdd_printdot`. The format can be specified with the following format objects:

`bddset`	BDD level set format
`bddtable`	BDD level table format
`bdddot`	Output for use with Dot
`bddall`	The whole node table
`fddset`	FDD level set format

So a BDD `x` can for example be printed as a table with the command

`cout << bddtable << x << endl`.

Return value

The specified output stream

See also

bdd_strm_hook, fdd_strm_hook

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