Logic Synthesis and Verification

Jie-Hong Roland Jiang
江介宏

Department of Electrical Engineering
National Taiwan University

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Boolean Function Representation

Reading:

Logic Synthesis in a Nutshell

Section 2

most of the following slides are by courtesy of Andreas Kuehlmann

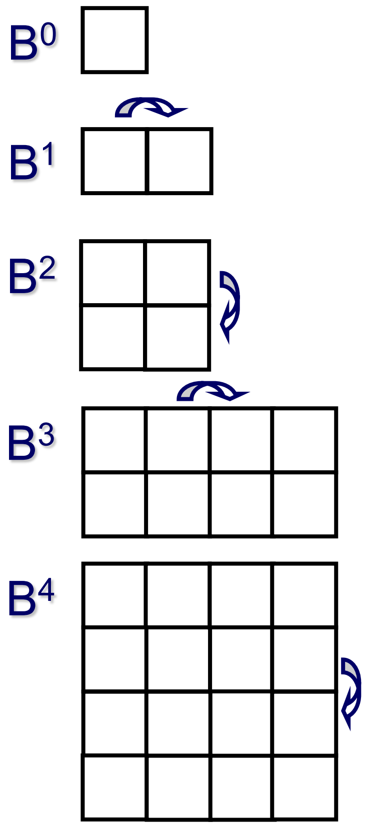
Assumption

- Unless otherwise said, from now on we are concerned with two-element Boolean algebra (i.e. **B** = {0,1})

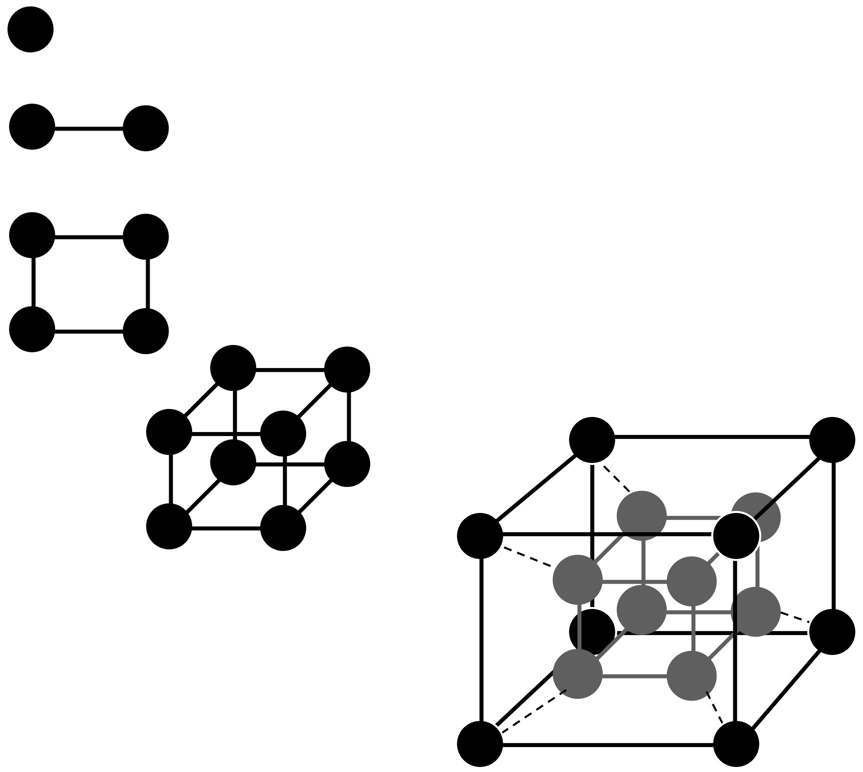
Boolean Space

- $B = \{0,1\}$
- $B^2 = \{0,1\}\times\{0,1\} = \{00, 01, 10, 11\}$

Karnaugh Maps:



Boolean Lattices:

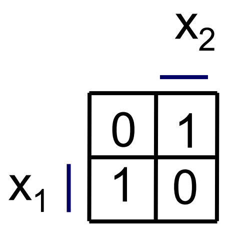


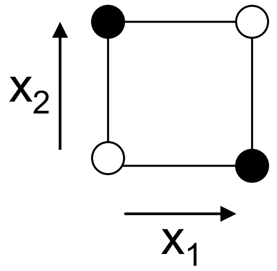
Boolean Function

- For **B** = {0,1}, a Boolean function f: $\mathbf{B}^n \to \mathbf{B}$ over variables $x_1,\ldots,x_n$ maps each Boolean valuation (truth assignment) in $\mathbf{B}^n$ to 0 or 1

Example

$f(x_1,x_2)$ with $f(0,0) = 0$, $f(0,1) = 1$, $f(1,0) = 1$, $f(1,1) = 0$

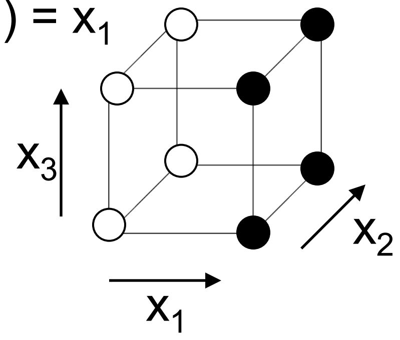




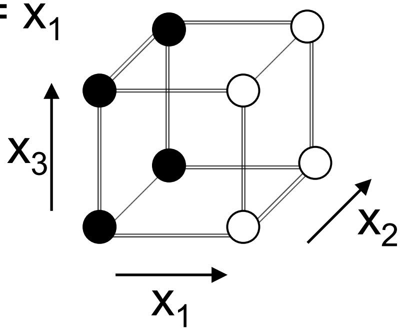
Boolean Function

- Onset of f, denoted as f^1, is $f^1 = \{v \in \mathbf{B}^n \mid f(v)=1\}$
  - If $f^1 = \mathbf{B}^n$, f is a tautology
- Offset of f, denoted as f^0, is $f^0 = \{v \in \mathbf{B}^n \mid f(v)=0\}$
  - If $f^0 = \mathbf{B}^n$, f is unsatisfiable. Otherwise, f is satisfiable.
- f^1 and f^0 are sets, not functions!
- Boolean functions f and g are equivalent if $\forall v \in \mathbf{B}^n.\ f(v) = g(v)$ where v is a truth assignment or Boolean valuation
- A literal is a Boolean variable *x* or its negation x' (or $\overline{x}$, $\neg x$) in a Boolean formula

$f(x_1, x_2, x_3) = x_1$

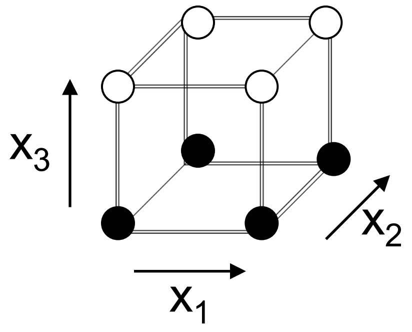


$f(x_1, x_2, x_3) = \overline{x_1}$



Boolean Function

- There are 2^n vertices in $\mathbf{B}^n$
- There are 2^{2^n} distinct Boolean functions
  - Each subset $f^1 \subseteq \mathbf{B}^n$ of vertices in $\mathbf{B}^n$ forms a distinct Boolean function f with onset f^1



$x_1x_2x_3$		f
0 0 0		1
0 0 1		0
0 1 0		1
0 1 1		0
1 0 0	$\Rightarrow$	1
1 0 1		0
1 1 0		1
1 1 1		0

Boolean Operations

Given two Boolean functions:

$f : \mathbf{B}^n \rightarrow \mathbf{B}$

$g : \mathbf{B}^n \rightarrow \mathbf{B}$

- $h = f \wedge g$ from AND operation is defined as

  $h^1 = f^1 \cap g^1;\ h^0 = \mathbf{B}^n \setminus h^1$

- $h = f \vee g$ from OR operation is defined as

  $h^1 = f^1 \cup g^1;\ h^0 = \mathbf{B}^n \setminus h^1$

- $h = \neg f$ from COMPLEMENT operation is defined as

  $h^1 = f^0;\ h^0 = f^1$

Cofactor and Quantification

Given a Boolean function:

$f : \mathbf{B}^n \rightarrow \mathbf{B}$, with the input variable $(x_1,x_2,\ldots,x_i,\ldots,x_n)$

- Positive cofactor on variable x_i
  $h = f_{xi}$ is defined as $h = f(x_1,x_2,\ldots,1,\ldots,x_n)$
- Negative cofactor on variable x_i
  $h = f_{\neg xi}$ is defined as $h = f(x_1,x_2,\ldots,0,\ldots,x_n)$
- Existential quantification over variable x_i
  $h = \exists x_i.\ f$ is defined as $h = f(x_1,x_2,\ldots,0,\ldots,x_n) \vee f(x_1,x_2,\ldots,1,\ldots,x_n)$
- Universal quantification over variable x_i
  $h = \forall x_i.\ f$ is defined as $h = f(x_1,x_2,\ldots,0,\ldots,x_n) \wedge f(x_1,x_2,\ldots,1,\ldots,x_n)$
- Boolean difference over variable x_i
  $h = \partial f/\partial x_i$ is defined as $h = f(x_1,x_2,\ldots,0,\ldots,x_n) \oplus f(x_1,x_2,\ldots,1,\ldots,x_n)$

Representation of Boolean Function

- Represent Boolean functions for two reasons
  - to represent and manipulate the actual circuit we are implementing
  - to facilitate Boolean reasoning

- Data structures for representation
  - Truth table
  - Boolean formula
    - Sum of products (Disjunctive “normal” form, DNF)
    - Product of sums (Conjunctive “normal” form, CNF)
  - Boolean network
    - Circuit (network of Boolean primitives)
    - And-inverter graph (AIG)
  - Binary Decision Diagram (BDD)

Boolean Function Representation
Truth Table

- Truth table (function table for multi-valued functions):
  The truth table of a function f : $\mathbf{B}^n \rightarrow \mathbf{B}$ is a tabulation of its value at each of the 2^n vertices of $\mathbf{B}^n$.

  In other words the truth table lists all mintems

  Example: f = a′b′c′d + a′b′cd + a′bc′d + ab′c′d + ab′cd + abc′d + abcd′ + abcd

  The truth table representation is
  - impractical for large *n*
  - canonical

  If two functions are the same, then their canonical representations are isomorphic.

	abcd	f		abcd	f
0	0000	0	8	1000	0
1	0001	1	9	1001	1
2	0010	0	10	1010	0
3	0011	1	11	1011	1
4	0100	0	12	1100	0
5	0101	1	13	1101	1
6	0110	0	14	1110	1
7	0111	0	15	1111	1

Boolean Function Representation Boolean Formula

- A Boolean formula is defined inductively as an expression with the following formation rules (syntax):

formula ::=		‘(‘ formula ‘)’	
	|	Boolean constant	(**true** or **false**)
	|	Boolean variable	
	|	formula “+” formula	(OR operator)
	|	formula “·” formula	(AND operator)
	|	$\neg$ formula	(complement)

Example

$f = (x_1 \cdot x_2) + (x_3) + \neg(\neg(x_4 \cdot (\neg x_1)))$

typically “·” is omitted and ‘(’, ‘)’ and ‘$\neg$’ are simply reduced by priority,

e.g. $f = x_1\ x_2 + x_3 + x_4 \neg x_1$

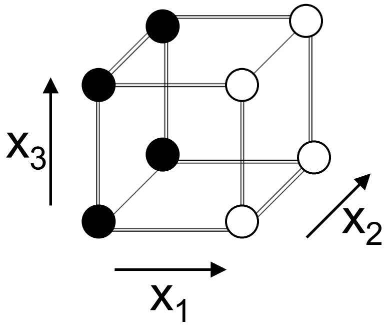
Boolean Function Representation
Boolean Formula in SOP

- A cube is defined as a conjunction of literals, i.e. a product term.

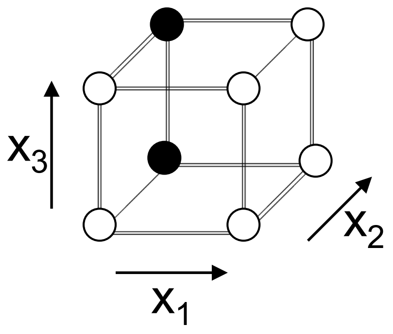
Example

C = $x_1x_2'x_3$ represents the function with onset: $f^1 = \{(x_1=1,x_2=0,x_3=1)\}$ in the Boolean space spanned by x_1,x_2,x_3, or $f^1 = \{(x_1=1,x_2=0,x_3=1, x_4=0), (x_1=1,x_2=0,x_3=1,x_4=1)\}$ in the Boolean space spanned by x_1,x_2,x_3,x_4, or …

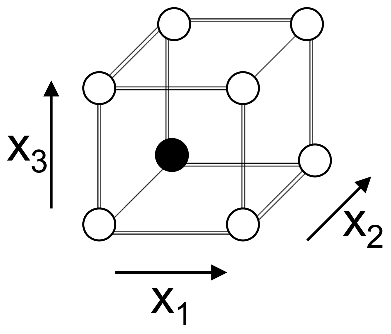
$f = \overline{x}_1$



$f = \overline{x}_1x_2$



$f = \overline{x}_1x_2\overline{x}_3$



Boolean Function Representation
Boolean Formula in SOP

- If $C \subseteq f^1$, C the onset of a cube c, then c is an implicant of f
- If $C \subseteq \mathbf{B}^n$, and c has k literals, then $|C| = 2^{n-k}$, i.e., C has 2^{n-k} elements

  Example

  $c = xy'$ $(c: \mathbf{B}^3 \rightarrow \mathbf{B})$, $C = \{100, 101\} \subseteq \mathbf{B}^3$

  $k = 2$, $n = 3$ $\qquad |C| = 2 = 2^{3-2}$

- An implicant with n literals is a minterm

Boolean Function Representation
Boolean Formula in SOP

- A function can be represented by a sum-of-cubes (products):
  $$f = ab + ac + bc$$
  Since each cube is a product of literals, this is a sum-of-products (SOP) representation or disjunctive normal form (DNF)

- An SOP can be thought of as a set of cubes F
  $$F = \{ab, ac, bc\}$$

- A set of cubes that represents f is called a cover of f.
  $$F_1=\{ab, ac, bc\} \text{ and } F_2=\{abc, abc', ab'c, a'bc\}$$
  are covers of
  $$f = ab + ac + bc.$$

- Mainly used in circuit synthesis; seldom used in Boolean reasoning

Boolean Function Representation
Boolean Formula in POS

- Product-of-sums (POS), or conjunctive normal form (CNF), representation of Boolean functions
  - Dual of the SOP representation

Example

- $\varphi = (a+b'+c)(a'+b+c)(a+b'+c')(a+b+c)$

- A Boolean function in a POS representation can be derived from an SOP representation with De Morgan's law and the distributive law

- Mainly used in Boolean reasoning; rarely used in circuit synthesis (due to the asymmetric characteristics of NMOS and PMOS, and the easiness of adding design constraints)

Boolean Function Representation
Boolean Network

- Used for two main purposes
  - as target structure for logic implementation which gets restructured in a series of logic synthesis steps until result is acceptable
  - as representation for Boolean reasoning engine
- Efficient representation for most Boolean problems
  - memory complexity is similar to the size of circuits that we are actually building
- Close to the input and output representations of logic synthesis

Boolean Function Representation
Boolean Network

A Boolean network is a directed graph $C(G,N)$ where G are the gates and $N \subseteq (G \times G)$ are the directed edges (nets) connecting the gates.

Some of the vertices are designated:

Inputs: $I \subseteq G$

Outputs: $O \subseteq G$

$I \cap O = \emptyset$

Each gate g is assigned a Boolean function f_g which computes the output of the gate in terms of its inputs.

Boolean Function Representation
Boolean Network

- The fanin FI(g) of a gate g are the predecessor gates of g:
  $FI(g) = \{g' \mid (g',g) \in N\}$ (N: the set of nets)

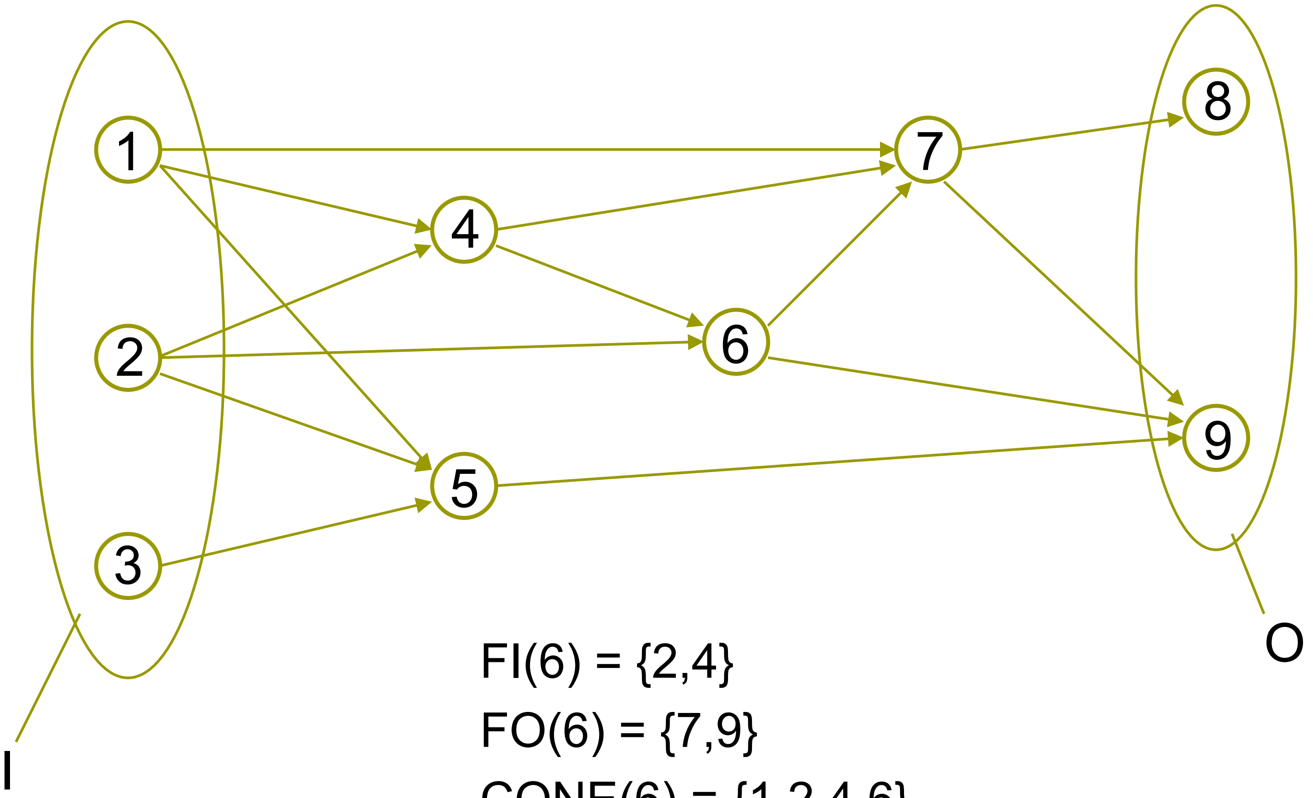
- The fanout FO(g) of a gate g are the successor gates of g:
  $FO(g) = \{g' \mid (g,g') \in N\}$

- The cone CONE(g) of a gate g is the transitive fanin (TFI) of g and g itself

- The support SUPPORT(g) of a gate g are all inputs in its cone:
  $SUPPORT(g) = CONE(g) \cap I$

Boolean Function Representation
Boolean Network

Example



FI(6) = {2,4}

FO(6) = {7,9}

CONE(6) = {1,2,4,6}

SUPPORT(6) = {1,2}

Boolean Function Representation
Boolean Network

- Circuit functions are defined recursively:

$$h_{g_i} = \begin{cases} x_i & \text{if } g_i \in I \\ f_{g_i}(h_{g_j},\ldots,h_{g_k}),\ \ g_j,\ldots,g_k \in FI(g_i) & \text{otherwise} \end{cases}$$

If G is implemented using physical gates with positive (bounded) delays for their evaluation, the computation of h_g depends in general on those delays.

Definition

A circuit C is called combinational if for each input assignment of C for $t\to\infty$ the evaluation of h_g for all outputs is independent of the internal state of C.

Proposition

A circuit C is combinational if it is acyclic. (converse not true!)

Boolean Function Representation
Boolean Network

General Boolean network:

- Vertex can have an arbitrary finite number of inputs and outputs

- Vertex can represent any Boolean function stored in different ways, such as:
  - SOPs (e.g. in SIS, a logic synthesis package)
  - BDDs (to be introduced)
  - AIGs (to be introduced)
  - truth tables
  - Boolean expressions read from a library description
  - other sub-circuits (hierarchical representation)

- The data structure allows general manipulations for insertion and deletion of vertices, pins (connection ports of vertices), and nets
  - general but far too slow for Boolean reasoning

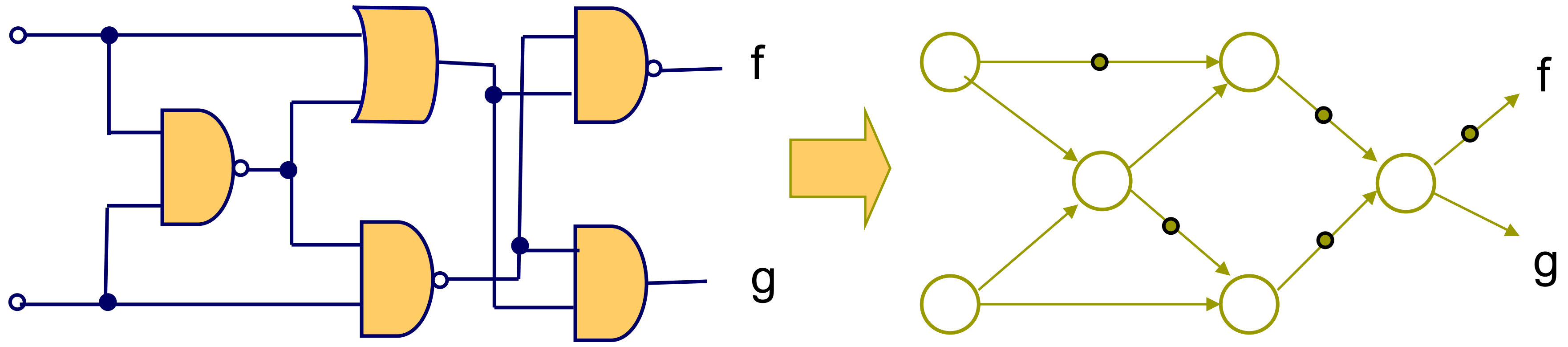
Boolean Function Representation
Boolean Network

Specialized Boolean network:

- Non-canonical representation in general
  - computational effort of Boolean reasoning is due to this non-canonicity (c.f. BDDs)
- Vertices have fixed number of inputs (e.g. two)
- Vertex function is stored as label (e.g. OR, AND, XOR)
- Allow on-the-fly compaction of circuit structure
  - Support incremental, subsequent reasoning on multiple problems

Boolean Function Representation
And-Inverter Graph

- AND-INVERTER graphs (AIGs)
  vertices: 2-input AND gates
  edges: interconnects with (optional) dots representing INVs
- Hash table to identify and reuse structurally isomorphic circuits

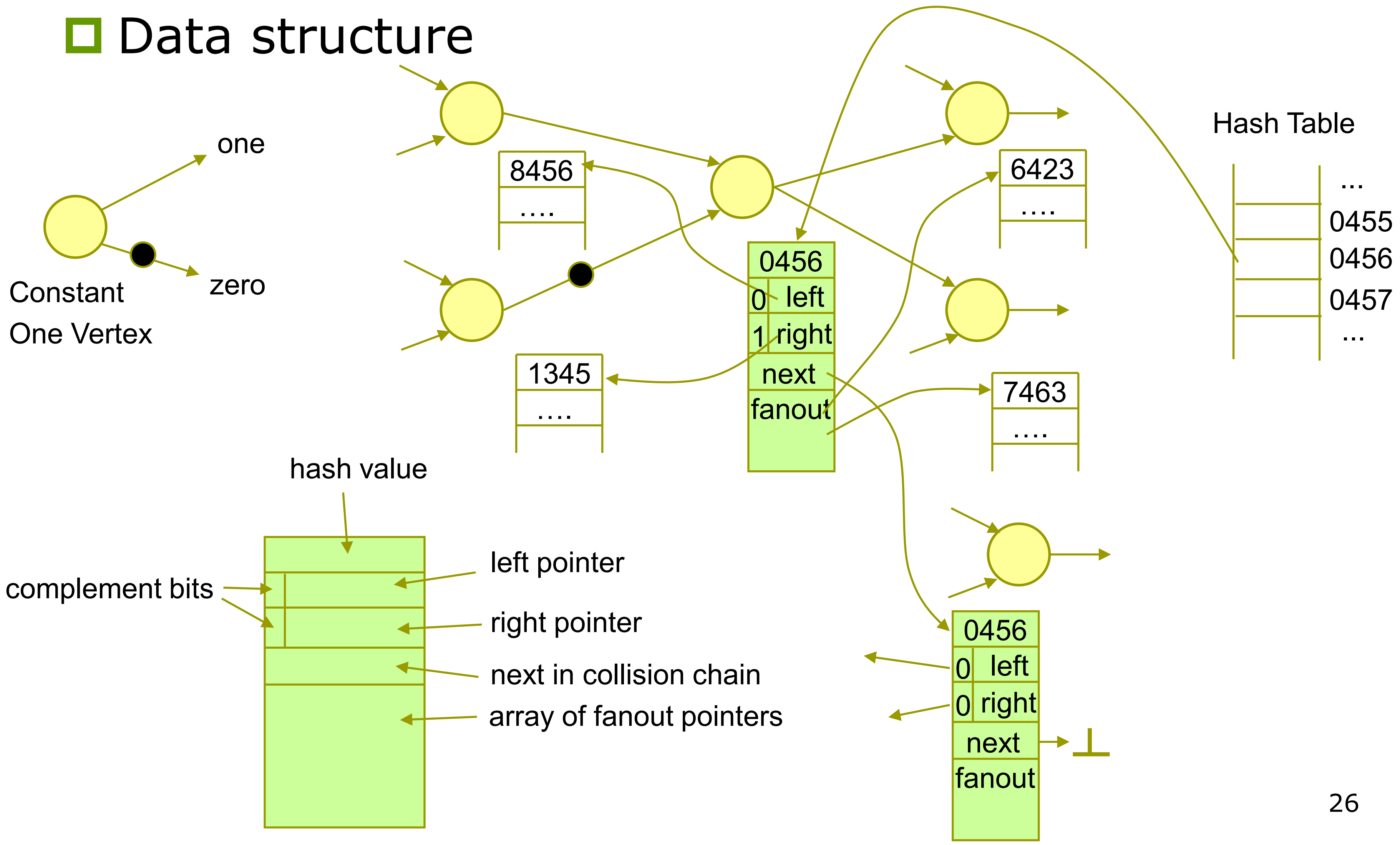


Boolean Function Representation
And-Inverter Graph

- Data structure for implementation
  - Vertex:
    - pointers (integer indices) to left- and right-child and fanout vertices
    - collision chain pointer
    - other data
  - Edge:
    - pointer or index into array
    - one bit to represent inversion
  - Global hash table holds each vertex to identify isomorphic structures
  - Garbage collection to regularly free un-referenced vertices

Boolean Function Representation And-Inverter Graph

- Data structure



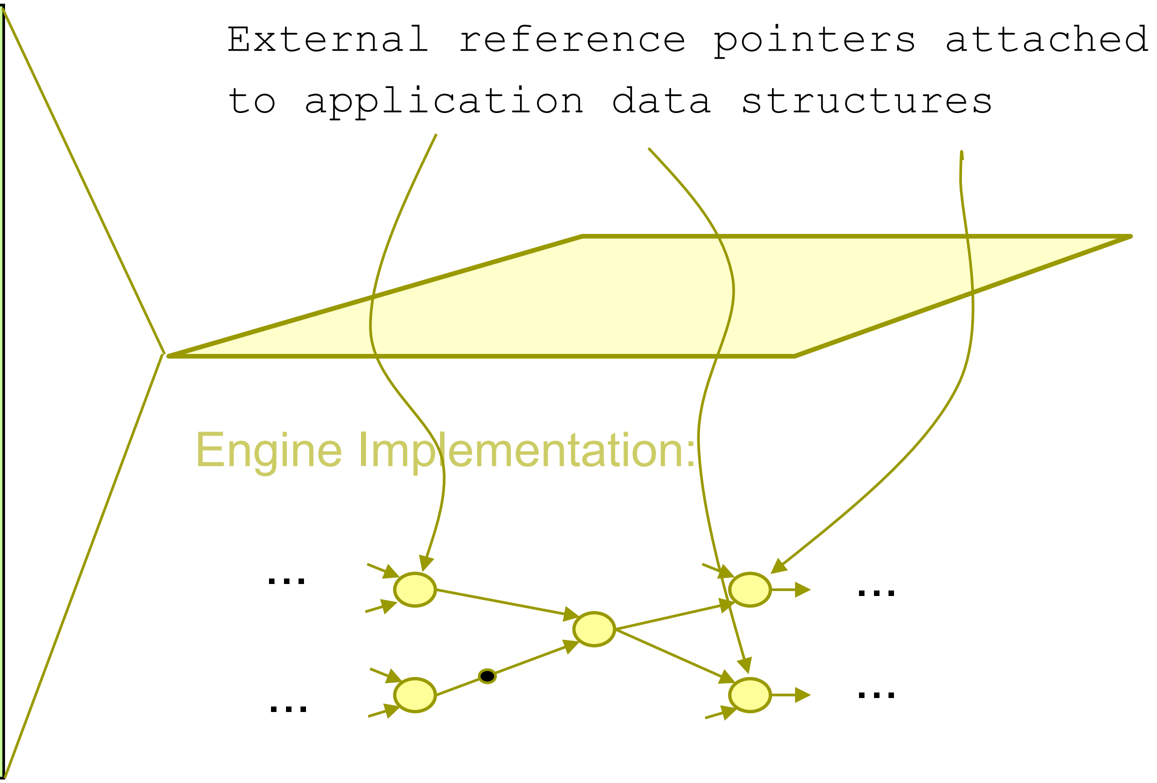
Boolean Function Representation And-Inverter Graph

- AIG package for Boolean reasoning

  Engine application:

  - traverse problem data structure and build Boolean problem using the interface
  - call SAT to make decision

```
Engine Interface:
void INIT()
void QUIT()
Edge VAR()
Edge AND(Edge p1,
         Edge p2)
Edge NOT(Edge p1)
Edge OR(Edge p1
        Edge p2)
...
int  SAT(Edge p1)
```


External reference pointers attached to application data structures
Engine Implementation:
…
…
…
…

Boolean Function Representation And-Inverter Graph

- Hash table look-up

```
Algorithm HASH_LOOKUP(Edge p1, Edge p2) {
   index = HASH_FUNCTION(p1,p2)
   p     = &hash_table[index]
   while(p != NULL) {
    if(p->left == p1 && p->right == p2) return p;
    p = p->next;
   }
   return NULL;
}
```

- Tricks:
  - keep collision chain sorted by the address (or index) of p
  - use memory locations (or array indices) in topological order for better cache performance

Boolean Function Representation And-Inverter Graph

- AND operation

```
Algorithm AND(Edge p1,Edge p2){
  if(p1 == const1) return p2
  if(p2 == const1) return p1
  if(p1 == p2)     return p1
  if(p1 == ¬p2)     return const0
  if(p1 == const0 || p2 == const0) return const0

  if(RANK(p1) > RANK(p2)) SWAP(p1,p2)

  if((p = HASH_LOOKUP(p1,p2)) return p
  return CREATE_AND_VERTEX(p1,p2)
}
```

Boolean Function Representation
And-Inverter Graph

- NOT operation

```
Algorithm NOT(Edge p) {
   return TOOGLE_COMPLEMENT_BIT(p)
}
```

- OR operation

```
Algorithm OR(Edge p1,Edge p2){
   return (NOT(AND(NOT(p1),NOT(p2))))
}
```

Boolean Function Representation And-Inverter Graph

- Cofactor operation

```
Algorithm POSITIVE_COFACTOR(Edge p,Edge v){
  if(IS_VAR(p)) {
    if(p == v) {
      if(IS_INVERTED(v) == IS_INVERTED(p)) return const1
      else                                 return const0
    }
    else                                   return p
  }
  if((c = GET_COFACTOR(p,v)) == NULL) {
    left  = POSITIVE_COFACTOR(p->left, v)
    right = POSITIVE_COFACTOR(p->right, v)
    c = AND(left,right)
    SET_COFACTOR(p,v,c)
  }
  if(IS_INVERTED(p)) return NOT(c)
  else               return c
}
```

Boolean Function Representation
And-Inverter Graph

- Similar algorithm for **`NEGATIVE_COFACTOR`**

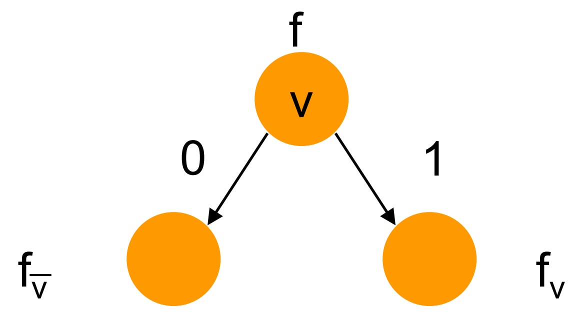
- Existential and universal quantifications can be built from AND, OR and COFACTORS

Exercise: Prove $(f \cdot g)_v = f_v \cdot g_v$ and $(\neg f)_v = \neg(f_v)$

Question: What is the worst-case complexity of performing quantifications over AIGs?

Boolean Function Representation
Binary Decision Diagram (BDD)

- A graphical representation of Boolean function
  - BDD is a Shannon cofactor tree:
    - $f = v\, f_v + v'\, f_{v'}$ (Shannon expansion)
    - vertices represent decision nodes (i.e. multiplexers) controlled by variables
    - leaves are constants “0” and “1”
    - two children of a vertex of f represent two subfunctions f_v and $f_{v'}$
  - Variable ordering restriction and reduction rules make (ROBDD) representation canonical



Boolean Function Representation
BDD – Canonicalization

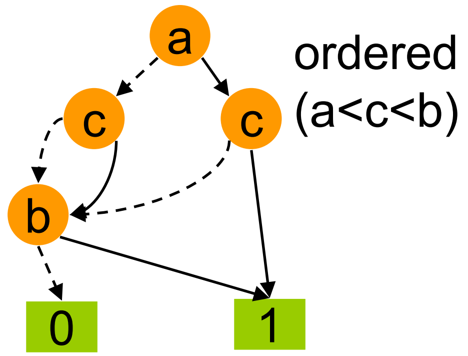
- General idea:
  - instead of exploring sub-cases by enumerating them in time, try to store sub-cases in memory
    - KEY: two hashing mechanisms:
      - unique table: find identical sub-cases and avoid replication
      - computed table: reduce redundant computation of sub-cases
- Represent logic functions as graphs (DAGs):
  - many logic functions can be represented compactly - usually better than SOPs
- Can be made canonical (ROBDD)
  - Shift the effort in a Boolean reasoning engine from SAT algorithm to data representation
- Many logic operations can be performed efficiently on BDD's:
  - usually linear in size of input BDDs
  - tautology checking and complement operation are constant time
- BDD size critically depends on variable ordering

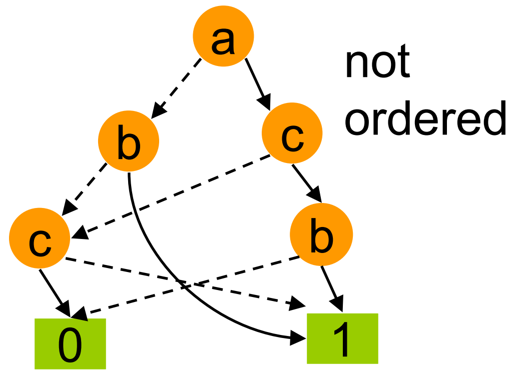
Boolean Function Representation BDD – Canonicalization

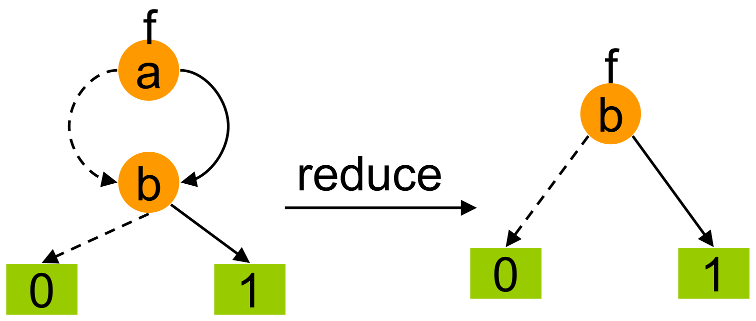
- Directed acyclic graph (DAG)
  - one root node, two terminal-nodes, 0 and 1
  - each node has two children and is controlled by a variable
- Shannon cofactor tree, except reduced and ordered (ROBDD)
  - Ordered:
    - cofactor variables (splitting variables) in the same order along all paths

      $x_{i_1} < x_{i_2} < x_{i_3} < \ldots < x_{i_n}$
  - Reduced:
    - any node with two identical children is removed
    - two nodes with isomorphic BDD's are merged

      These two rules make any node in an ROBDD represent a distinct logic function



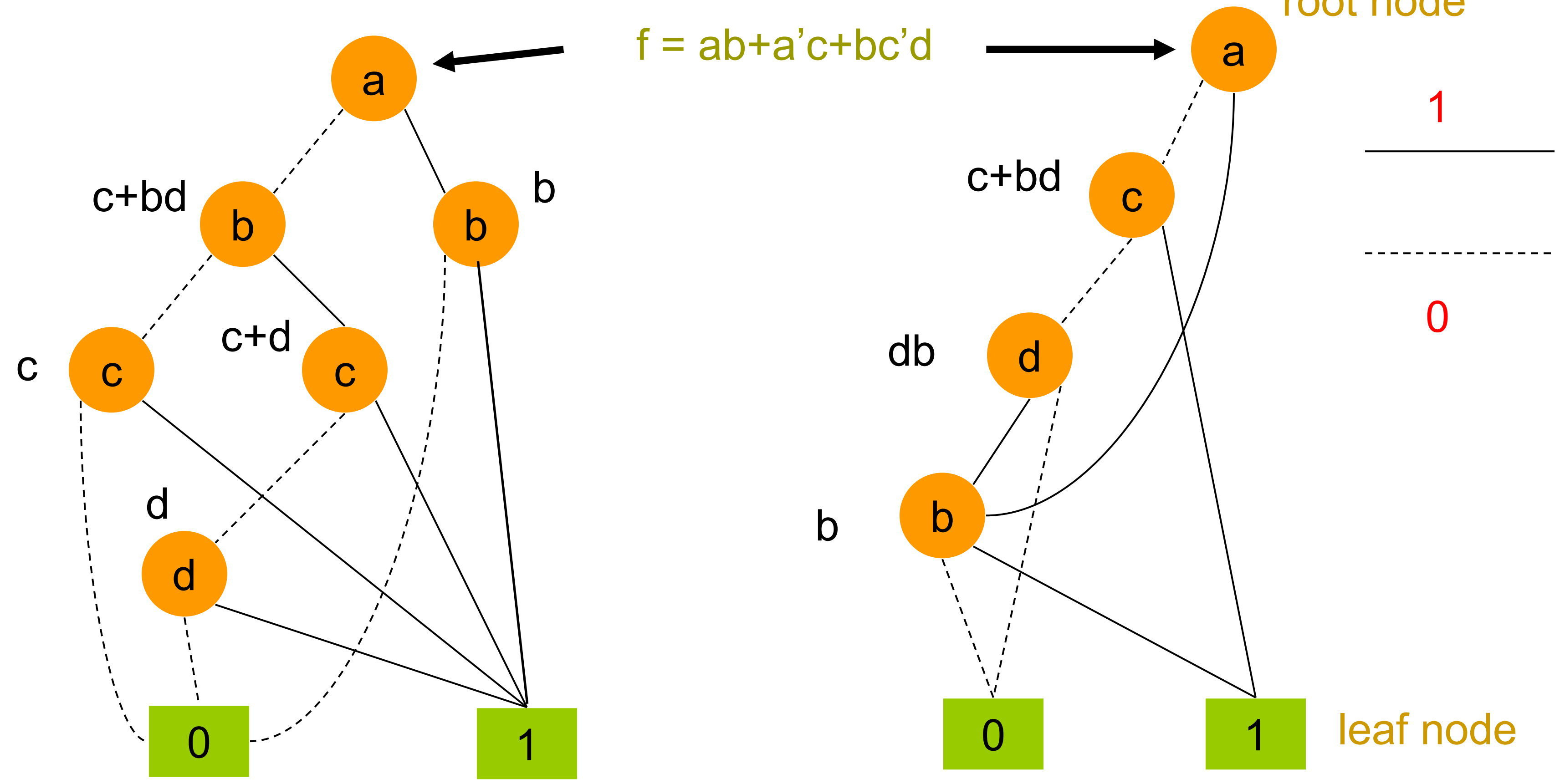




Boolean Function Representation BDD

- Example

f = ab+a'c+bc'd



Same function with two different variable orders

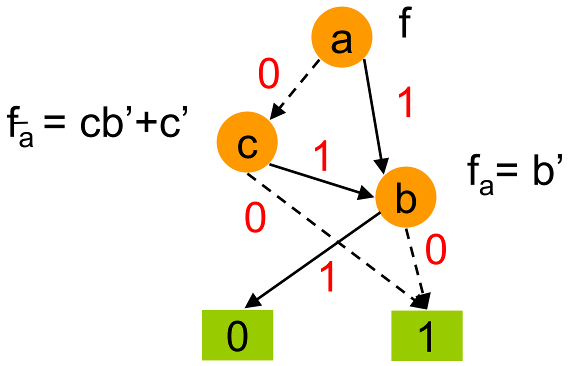
Boolean Function Representation BDD – Canonicity of ROBDD

- Three components make ROBDD canonical (Bryant 1986):
  - unique nodes for constant “0” and “1”
  - identical order of case-splitting variables along each path
  - a hash table that ensures
    - $(\text{node}(f_v) = \text{node}(g_v)) \wedge (\text{node}(f_{v'}) = \text{node}(g_{v'})) \Rightarrow \text{node}(f) = \text{node}(g)$

  and provides recursive argument that node(f) is unique when using the unique hash-table

Boolean Function Representation
BDD – Onset Counting

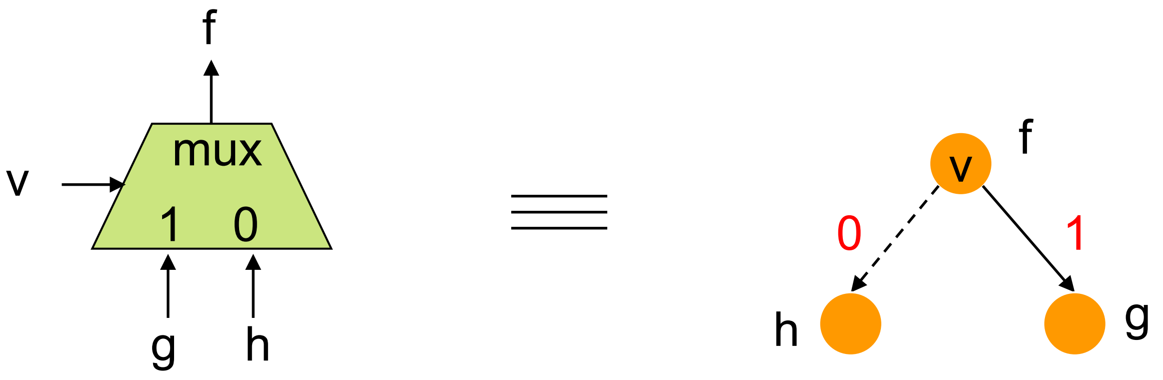
F = b’+a’c’ = ab’+a’cb’+a’c’ (all paths to the 1 node)



- By tracing all paths to the 1 node, we get a cover of pairwise disjoint cubes
- BDD does not explicitly enumerate all paths; rather it represents paths by a graph whose size is measures by its nodes
  - A DAG can represent an exponential number of paths with a linear number of nodes
- BDDs can be used to efficiently represent sets
  - interpret elements of the onset as elements of the set
  - f is called the characteristic function of that set

Boolean Function Representation
BDD – ITE Operator

- Each BDD node can be written as a triplet: f = ite(*v*,g,h) = vg + v'h, where g = f_v and h = $f_{\bar{v}}$, meaning if *v* then g else h



(v is top variable of f)

Boolean Function Representation BDD – ITE Operator

- ite(*f*,g,h) = fg + f'h
  - ITE operator can implement any two variable logic function. There are 16 such functions corresponding to all subsets of vertices of $\mathbf{B}^2$:

Table	Subset	Expression	Equivalent Form
0000	0	0	0
0001	AND(f, g)	f g	ite(f, g, 0)
0010	f > g	f g′	ite(f, g′, 0)
0011	f	f	f
0100	f < g	f′g	ite(f, 0, g)
0101	g	g	g
0110	XOR(f, g)	$f \oplus g$	ite(f, g′, g)
0111	OR(f, g)	f + g	ite(f, 1, g)
1000	NOR(f, g)	(f + g)′	ite(f, 0, g′)
1001	XNOR(f, g)	$f \oplus g'$	ite(f, g, g′)
1010	NOT(g)	g′	ite(g, 0, 1)
1011	$f \geq g$	f + g′	ite(f, 1, g′)
1100	NOT(f)	f′	ite(f, 0, 1)
1101	$f \leq g$	f′ + g	ite(f, g, 1)
1110	NAND(f, g)	(f g)′	ite(f, g′, 1)
1111	1	1	1

Boolean Function Representation BDD – ITE Operator

- Recursive operation of ITE

$$\begin{aligned}
&\mathrm{Ite}(f,g,h)\\
&= f\, g + f'\, h\\
&= v\, (f\, g + f'\, h)_{v} + v'\, (f\, g + f'\, h)_{v'}\\
&= v\, (f_{v}\, g_{v} + f'_{v}\, h_{v}) + v'\, (f_{v'}\, g_{v'} + f'_{v'}\, h_{v'})\\
&= \mathrm{ite}(v, \mathrm{ite}(f_{v},g_{v},h_{v}), \mathrm{ite}(f_{v'},g_{v'},h_{v'}))
\end{aligned}$$

  - Let v be the top-most variable of BDDs f, g, h

Boolean Function Representation BDD – ITE Operator

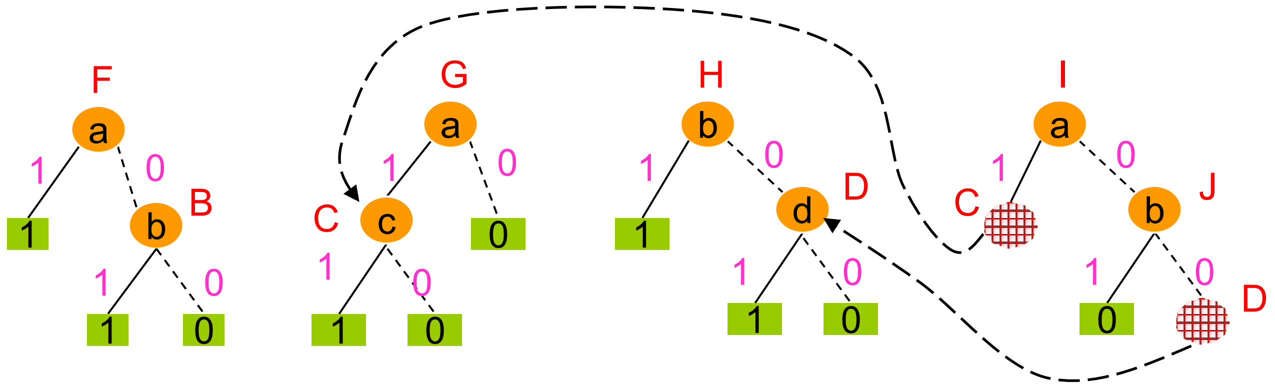
- Recursive computation of ITE

```
Algorithm ITE(f, g, h)
  if(f == 1) return g
  if(f == 0) return h
  if(g == h) return g

  if((p = HASH_LOOKUP_COMPUTED_TABLE(f,g,h)) return p
  v  = TOP_VARIABLE(f, g, h )   // top variable from f,g,h
  fn = ITE($f_v$,$g_v$,$h_v$)             // recursive calls
  gn = ITE($f_{v'}$,$g_{v'}$,$h_{v'}$)
  if(fn == gn) return gn        // reduction
  if(!(p = HASH_LOOKUP_UNIQUE_TABLE(v,fn,gn)) {
     p = CREATE_NODE(v,fn,gn)   // and insert into UNIQUE_TABLE
  }
  INSERT_COMPUTED_TABLE(p,HASH_KEY{f,g,h})
  return p
}
```

Boolean Function Representation BDD – ITE Operator

- Example



F,G,H,I,J,B,C,D are pointers

$$
\begin{aligned}
I &= ite(F, G, H)\\
&= ite(a, ite(F_a, G_a, H_a), ite(F_{\bar a}, G_{\bar a}, H_{\bar a}))\\
&= ite(a, ite(1, C, H), ite(B, 0, H))\\
&= ite(a, C, ite(b, ite(B_b, 0_b, H_b), ite(B_{\bar b}, 0_{\bar b}, H_{\bar b})))\\
&= ite(a, C, ite(b, ite(1, 0, 1), ite(0, 0, D)))\\
&= ite(a, C, ite(b, 0, D))\\
&= ite(a, C, J)
\end{aligned}
$$

Check: $F = a + b$
$G = ac$
$H = b + d$
$ite(F, G, H) = (a + b)(ac) + a'b'(b + d) = ac + a'b'd$

Boolean Function Representation BDD – ITE Operator

- Tautology checking using ITE

```
Algorithm ITE_CONSTANT(f,g,h) {    // returns 0,1, or NC
  if(TRIVIAL_CASE(f,g,h) return result (0,1, or NC)
  if((res = HASH_LOOKUP_COMPUTED_TABLE(f,g,h))) return res
  v = TOP_VARIABLE(f,g,h)
  i = ITE_CONSTANT($f_v$,$g_v$,$h_v$)
  if(i == NC) {
    INSERT_COMPUTED_TABLE(NC, HASH_KEY{f,g,h}) // special table!!
    return NC
  }
  e = ITE_CONSTANT($f_{v'}$,$g_{v'}$,$h_{v'}$)
  if(e == NC) {
    INSERT_COMPUTED_TABLE(NC, HASH_KEY{f,g,h})
    return NC
  }
  if(e != i) {
    INSERT_COMPUTED_TABLE(NC, HASH_KEY{f,g,h})
    return NC
  }
  INSERT_COMPUTED_TABLE(e, HASH_KEY{f,g,h})
  return i;
}
```

Boolean Function Representation BDD – ITE Operator

- Composition using ITE
  - Compose is an important operation, e.g. for building the BDD of a circuit backwards, Compose(*F*, *v*, *G*) : $F(v, x) \rightarrow F(G(x), x)$, means substitute $v = G(x)$

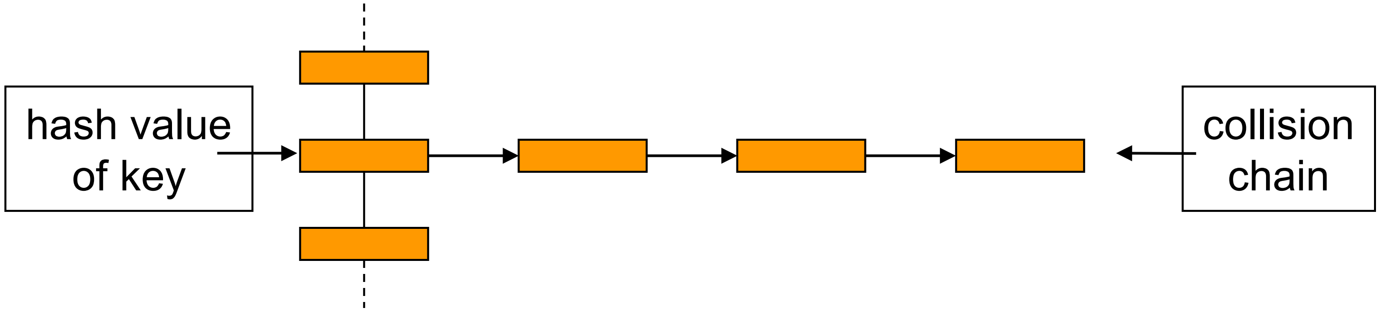
```
Algorithm COMPOSE(F,v,G) {
  if(TOP_VARIABLE(F) > v)  return F  // F does not depend on v
  if(TOP_VARIABLE(F) == v) return ITE(G,F1,F0)
  i = COMPOSE(F1,v,G)
  e = COMPOSE(F0,v,G)
  return ITE(TOP_VARIABLE(F),i,e)
}
```

Note:
1. F1 and F0 are the 1-child and 0-child of F, respectively
2. G, i, e are not functions of v
3. If TOP_VARIABLE of F is v, then ITE(G, F1, F0) does the replacement of v by G

Boolean Function Representation
BDD – Implementation Issues

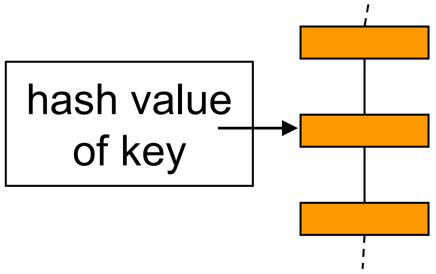
Unique table:

- avoids duplication of existing nodes
  - Hash-Table: hash-function(key) = value
  - identical to the use of a hash-table in AND/INVERTER circuits



Computed table:

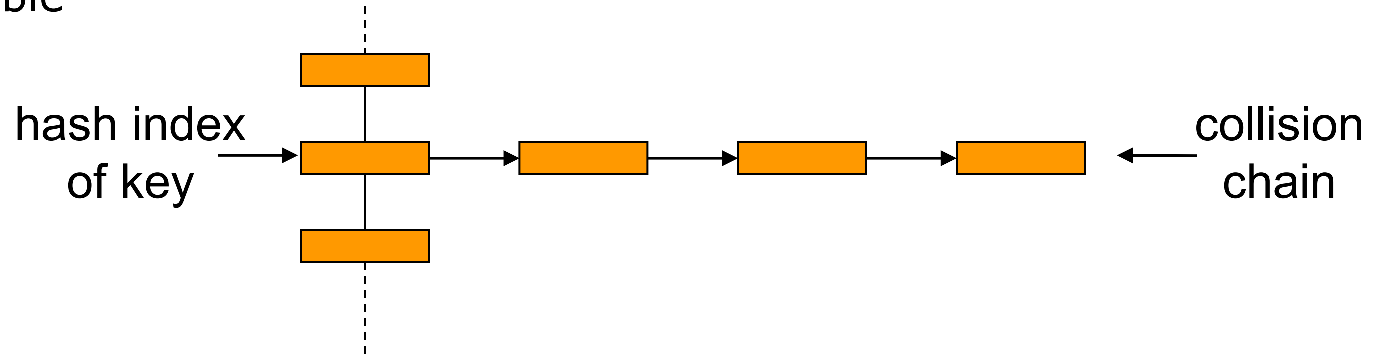
- avoids re-computation of existing results



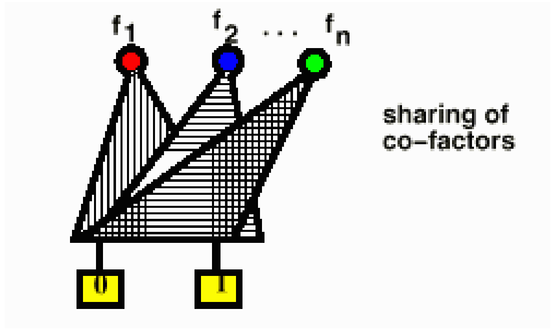
No collision chain

Boolean Function Representation BDD – Implementation Issues

- Unique table

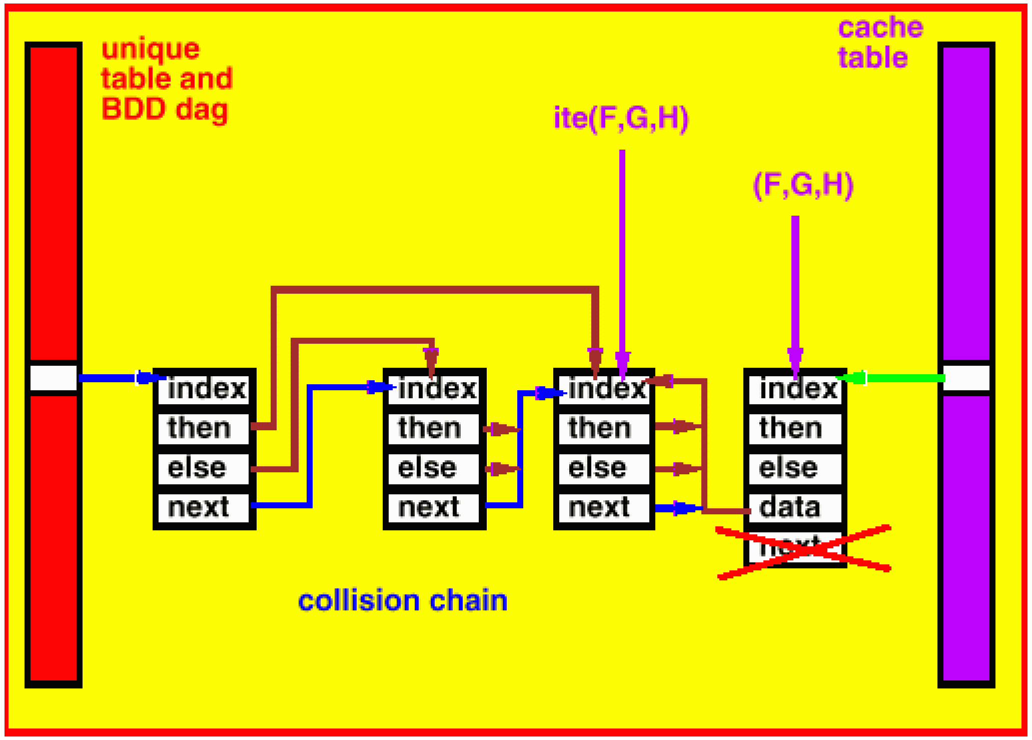


- Before a node ite(v, g, h) is added to BDD database, it is looked up in the "unique-table". If it is there, then existing pointer to node is used to represent the logic function. Otherwise, a new node is added to the unique-table and the new pointer returned.
- Thus a strong canonical form is maintained. The node for f = ite(v, g, h) exists iff ite(v, g, h) is in the unique-table. There is only one pointer for ite(v, g, h) and that is the address to the unique-table entry.
- Unique-table allows single multi-rooted DAG to represent all users' functions



Boolean Function Representation BDD – Implementation Issues

- Computed table
  - Keep a record of (*F*, *G*, *H*) triplets already computed by the ITE operator
    - software cache (*"cache" table*)
    - simply hash-table without collision chain (lossy cache)

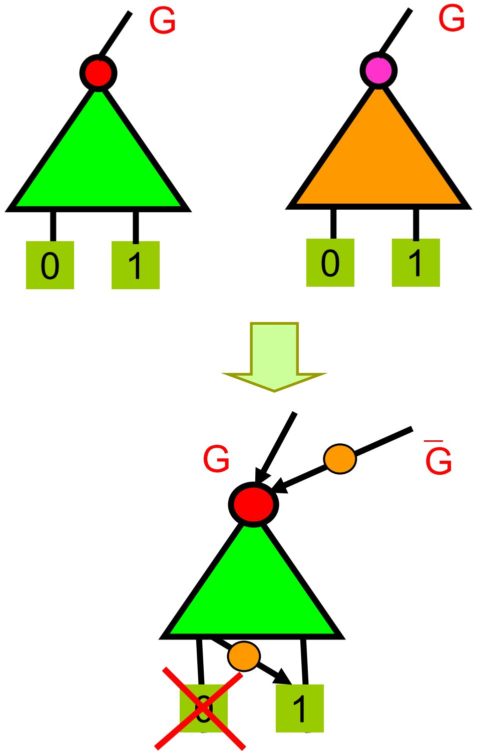


Boolean Function Representation
BDD – Implementation Issues

- Use of computed table
  - BDD packages often use optimized implementations for special operations
    - e.g. `ITE_Constant` (check whether the result would be a constant) `AND_Exist` (AND operation with existential quantification)
  - All operations need a cache for decent performance
    - local cache
      - for one operation only - cache will be thrown away after operation is finished (e.g. `AND_Exist`)
    - special cache for each operation
      - does not need to store operation type
    - shared cache for all operations
      - better memory handling
      - needs to store operation type

Boolean Function Representation BDD – Implementation Issues

- Complemented edges
  - Combine inverted functions by using complemented edges
    - similar to AIG
    - reduces memory requirements
    - more importantly, makes operations NOT, ITE more efficient

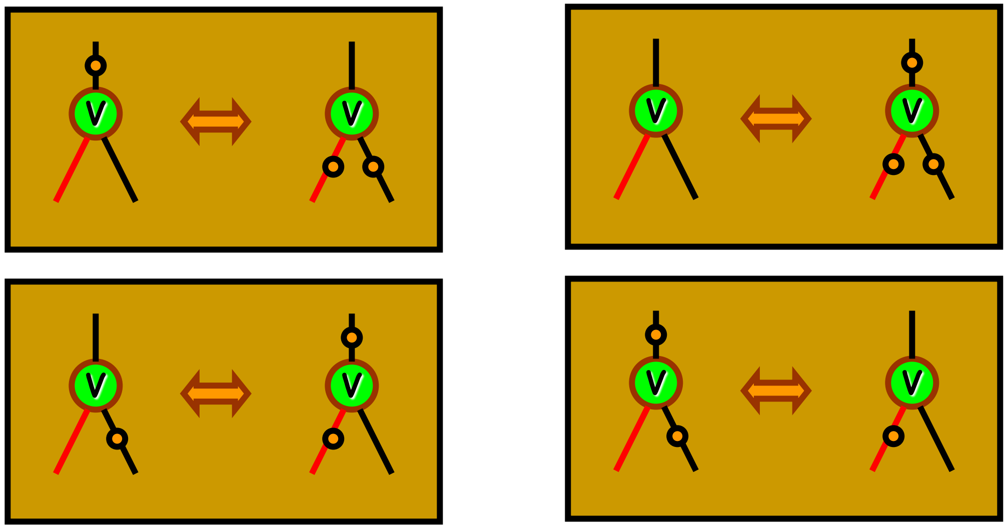


two different DAGs

only one DAG using complement pointer

Boolean Function Representation
BDD – Implementation Issues

- Complemented edges
  - To maintain strong canonical form, need to resolve 4 equivalences:



  - Solution: Always choose the ones on left, i.e. the “then” leg must have no complement edge.

Boolean Function Representation BDD – Implementation Issues

- Complemented edges

Standard triples:

$ite(F, F, G) \Rightarrow ite(F, 1, G)$
$ite(F, G, F) \Rightarrow ite(F, G, 0)$
$ite(F, G, \neg F) \Rightarrow ite(F, G, 1)$
$ite(F, \neg F, G) \Rightarrow ite(F, 0, G)$

To resolve equivalences:

$ite(F, 1, G) \equiv ite(G, 1, F)$
$ite(F, 0, G) \equiv ite(\neg G, 0, \neg F)$
$ite(F, G, 0) \equiv ite(G, F, 0)$
$ite(F, G, 1) \equiv ite(\neg G, \neg F, 1)$
$ite(F, G, \neg G) \equiv ite(G, F, \neg F)$

To maximize matches on computed table:

1. First argument is chosen with smallest top variable.
2. Break ties with smallest address pointer. (breaks PORTABILITY!)

Triples:

$ite(F, G, H) \equiv ite(\neg F, H, G) \equiv \neg ite(F, \neg G, \neg H) \equiv \neg ite(\neg F, \neg H, \neg G)$

Choose the one such that the first and second argument of *ite* should not be complement edges (i.e. the first one above)

Boolean Function Representation
BDD – Implementation Issues

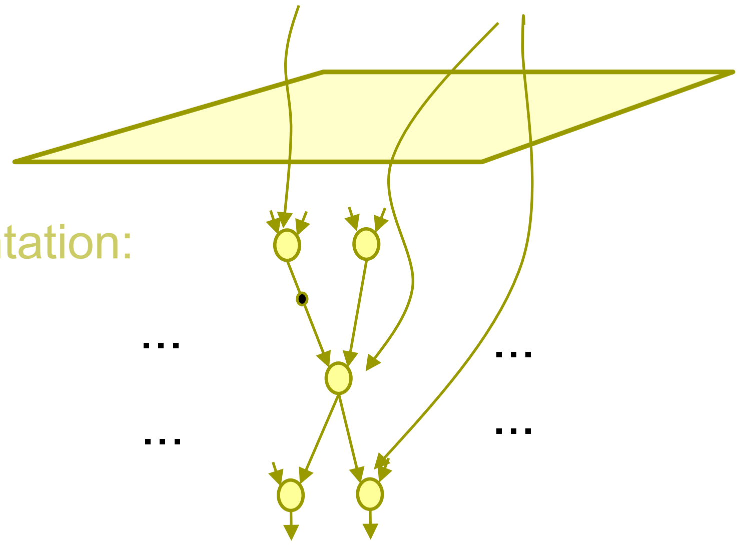
- Variable ordering – static
  - variable ordering is computed up-front based on the problem structure
  - works well for many practical combinational functions
    - general scheme: control variables first
    - DFS order is good for most cases
  - works bad for unstructured problems
    - e.g. using BDDs to represent arbitrary sets
  - lots of ordering algorithms
    - simulated annealing, genetic algorithms
    - give better results but extremely costly

Boolean Function Representation
BDD – Implementation Issues

- Variable ordering – dynamic
  - Changes the order in the middle of BDD applications
    - must keep same global order
  - Problem: External pointers reference internal nodes!

External reference pointers attached to application data structures

BDD Implementation:



Boolean Function Representation BDD – Implementation Issues

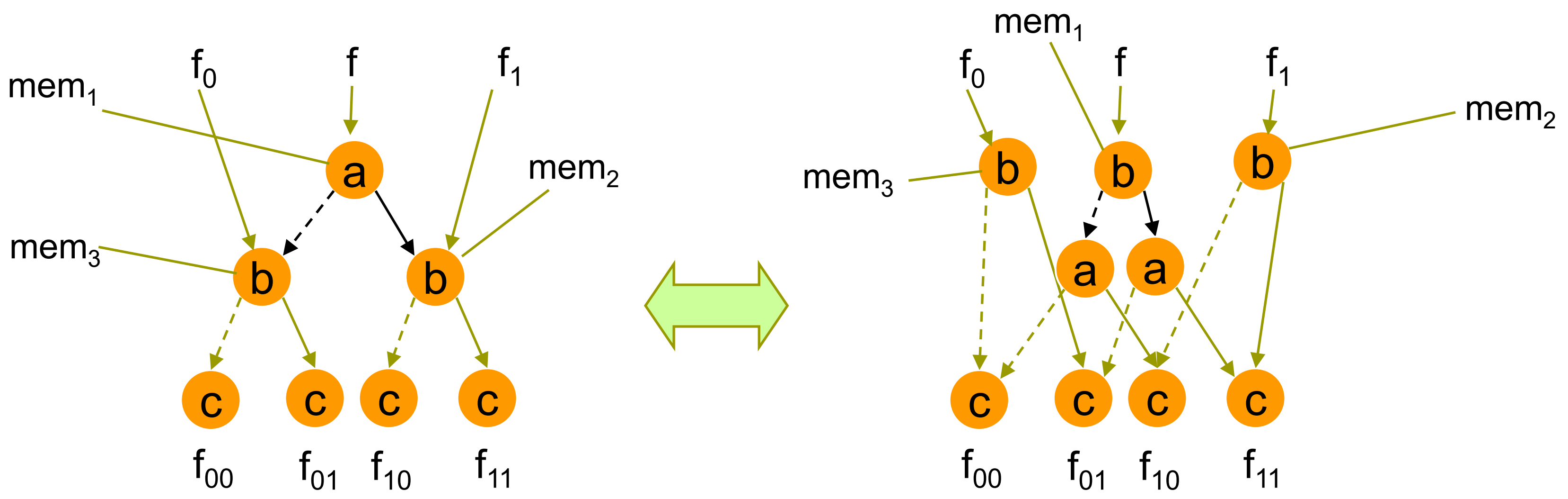
- Variable ordering – dynamic

  Theorem (Friedman):

  Permuting any top part of the variable order has no effect on the nodes labeled by variables in the bottom part.

  Permuting any bottom part of the variable order has no effect on the nodes labeled by variables in the top part.

  - Trick: Two adjacent variable layers can be exchanged by keeping the original memory locations for the nodes



Boolean Function Representation
BDD – Implementation Issues

- Variable ordering – dynamic
  - BDD sifting:
    - shift each BDD variable to the top and then to the bottom and see which position had minimal number of BDD nodes
    - efficient if separate hash-table for each variable
    - can stop if lower bound on size is worse than the best found so far
    - shortcut: two layers can be swapped very cheaply if there is no interaction between them
    - expensive operation
  - grouping of BDD variables:
    - for many applications, grouping variables gives better ordering
      - e.g. current state and next state variables in state traversal
    - grouping variables for sifting

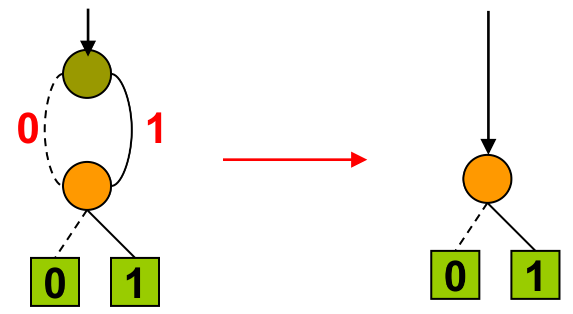
Boolean Function Representation
BDD – Variants

- MDD: Multi-valued DD
  - have more then two branches
  - can be implemented using a regular BDD package with binary encoding
    - the binary variables for one MV variable do not have to stay together and thus potentially better ordering
- ADD: (Algebraic BDDs) MTBDD
  - multi-terminal BDDs
  - decision tree is binary
  - multiple leaves, including real numbers, sets or arbitrary objects
  - efficient for matrix computations and other non-integer applications
- FDD: Free-order BDD
  - variable ordering differs
  - not canonical anymore
- …

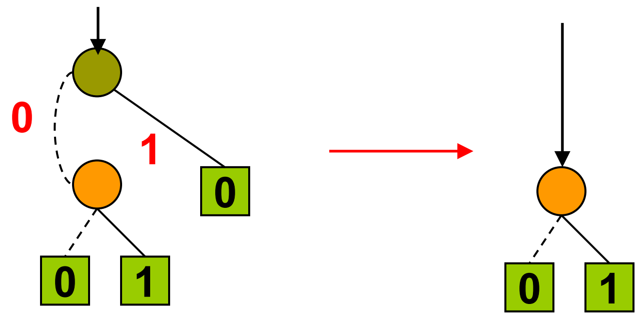
Boolean Function Representation BDD – Variants

- Zero suppressed BDD (ZDD)
  - ZBDDs were invented by Minato to efficiently represent sparse sets. They have turned out to be useful in implicit methods for representing prime implicants (which usually are a sparse subset of all cubes).
  - Different reduction rules:
    - BDD: eliminate all nodes where then edge and else edge point to the same node.
    - ZBDD: eliminate all nodes where the then edge points to 0. Connect incoming edges to else node.
    - For both: share equivalent nodes.

BDD:



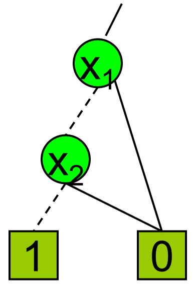
ZBDD:



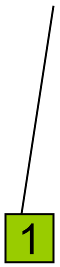
Boolean Function Representation
BDD – Variants

Theorem: ZBDDs are canonical given a variable ordering and the support set

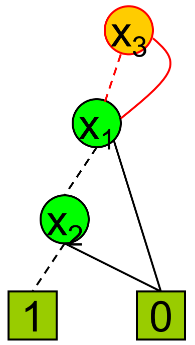
Example

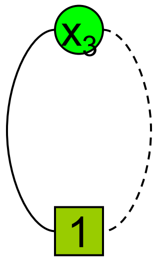


BDD

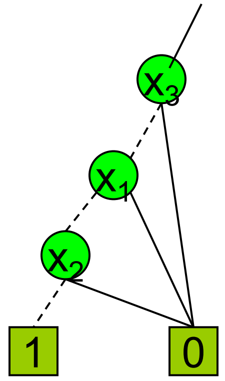


ZBDD if support is x_1, x_2

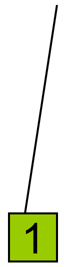




ZBDD if support is x_1, x_2, x_3



BDD



ZBDD if support is x_1, x_2 , x_3

Boolean Function Representation
BDD – Variants

- ZDD applications
  - Represent a set of subsets
  - Represent a cover of a Boolean function

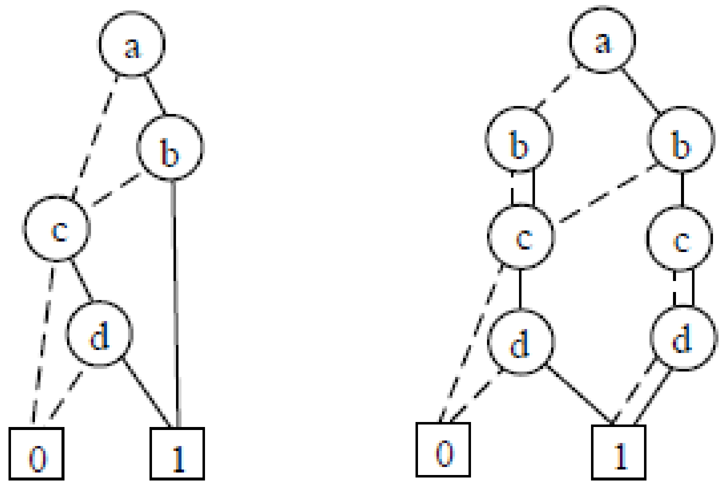


Figure 1. BDD and ZDD for F = ab + cd.

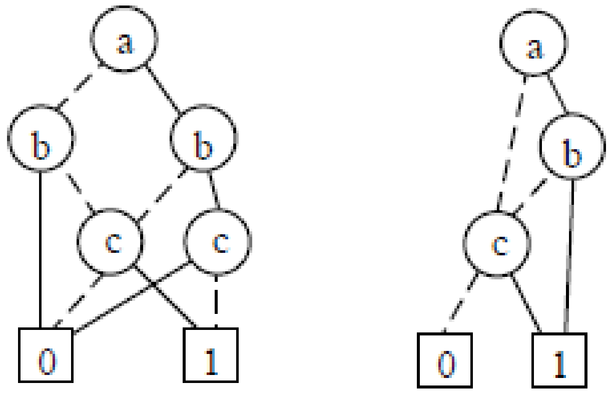


Figure 2. The BDD and the ZDD for the set of subsets {{a,b}, {a,c}, {c}}.

Courtesy: A. Mishchenko
https://en.wikipedia.org/wiki/Zero-suppressed_decision_diagram

Boolean Function Representation Summary

- Sum of products
  - Good for circuit synthesis
- Product of sums
  - Good for Boolean reasoning
- Boolean network
  - Generic network
    - Good for multi-level circuit synthesis
  - And-inverter graph
    - Good for Boolean reasoning
- Binary decision diagram
  - Good for Boolean reasoning

Boolean Reasoning

Reading:

Logic Synthesis in a Nutshell

Section 2

most of the following slides are by courtesy of Andreas Kuehlmann

Boolean Reasoning
Satisfiability (SAT)

- Boolean reasoning engines need:
  - a data structure to represent problem instances
  - a decision procedure to decide about SAT or UNSAT

- Fundamental tradeoff
  - canonical data structure (e.g. truth table, ROBDD)
    - data structure uniquely represents function
    - decision procedure is trivial (e.g., just pointer comparison)
    - Problem: size of data structure is in general exponential
  - non-canonical data structure (e.g. AIG, CNF)
    - systematic search for satisfying assignment
    - size of data structure is linear
    - Problem: decision may take an exponential amount of time

Boolean Reasoning
SAT

- Basic SAT algorithms:
  - branch and bound algorithm
    - branching on the assignments of primary inputs only or those of all variables
      - E.g. PODEM vs. D-algorithms in ATPG

- Basic data structures:
  - circuits or CNF formulas
  - SAT on circuits is **identical** to the justification part in ATPG
    - 1st half of ATPG: justification
      - find an input assignment that forces an internal signal to a required value
    - 2nd half of ATPG: propagation
      - make a signal change at an internal signal observable at some outputs (can be easily formulated as SAT over CNF formulas)

Boolean Reasoning
SAT vs. Tautology

- SAT:
  - find a truth assignment to the inputs making a given Boolean formula true
  - NP-complete
- Tautology:
  - find a truth assignment to the inputs making a given Boolean formula false
  - coNP-complete
- SAT and Tautology are dual to each other
  - checking SAT on formula φ = checking Tautology on formula $\neg\varphi$, and vice versa

Boolean Reasoning
SAT – CNF-based Decision Procedure

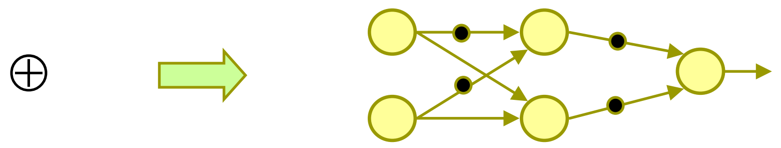
- CNF
  - Product-of-Sums (POS) representation of Boolean function
  - Describes solution using a set of constraints
    - very handy in many applications because new constraints can be simply added to the list of existing constraints
    - very common in AI community
  - Example

    $\varphi = (a+b'+c)(a'+b+c)(a+b'+c')(a+b+c)$

  - SAT on CNF (POS) $\Leftrightarrow$ TAUTOLOGY on DNF (SOP)

Boolean Reasoning
SAT – CNF-based Decision Procedure

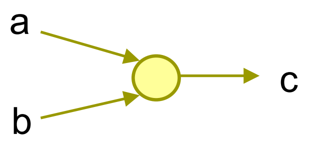
- Circuit to CNF conversion
  - Encountered often in practical applications
  - Naive conversion from circuit to CNF:
    - multiply out expressions of circuit until two level structure
    - Example: $y = x_1 \oplus x_2 \oplus x_3 \oplus \ldots \oplus x_n$ (parity function)
      - circuit size is linear in the number of variables



      - generated chess-board Karnaugh map
      - CNF (or DNF) formula has 2^{n-1} terms (exponential in the # vars)
  - Better approach:
    - introduce one variable per circuit vertex
    - formulate the circuit as a conjunction of constraints imposed on the vertex values by the gates
    - uses more variables but size of formula is linear in the size of the circuit

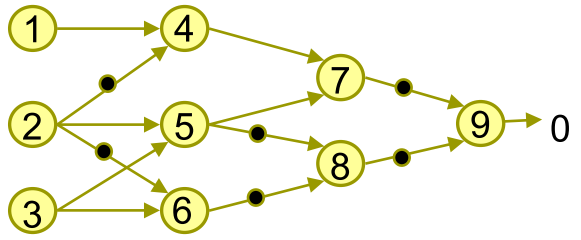
Boolean Reasoning
SAT – CNF-based Decision Procedure

- Circuit to CNF conversion
  - Example
    - Single gate



(¬a + ¬b + c)(a + ¬c)(b + ¬c)

    - Connected gates



(¬1 + 2 + 4)(1 + ¬4)(¬2 + ¬4)

(¬2 + ¬3 + 5)(2 + ¬5)(3 + ¬5)

(2 + ¬3 + 6)(¬2 + ¬6)(3 + ¬6)

(¬4 + ¬5 + 7)(4 + ¬7)(5 + ¬7)

(5 + 6 + 8)(¬5 + ¬8)(¬6 + ¬8)

(7 + 8 + 9)(¬7 + ¬9)(¬8 + ¬9)

(¬9)

Justify to "0"

Boolean Reasoning
SAT – CNF-based Decision Procedure

- DPLL procedure

```
Algorithm DPLL() {
  while ChooseNextAssignment() {
     while Deduce() == CONFLICT  {
        blevel = AnalyzeConflict();
        if (blevel < 0) return UNSATISFIABLE;
        else Backtrack(blevel);
     }
  }
   return SATISFIABLE;
}
```

`ChooseNextAssignment` picks next decision variable and assignment
`Deduce` does Boolean Constraint Propagation (implications)
`AnalyzeConflict` backprocesses from conflict and produces learnt-clause
`Backtrack` undoes assignments

Boolean Reasoning
SAT – CNF-based Decision Procedure

- DPLL (basic case splitting)

1 $(a + b + c)$

2 $(a + b + \neg c)$

3 $(\neg a + b + \neg c)$

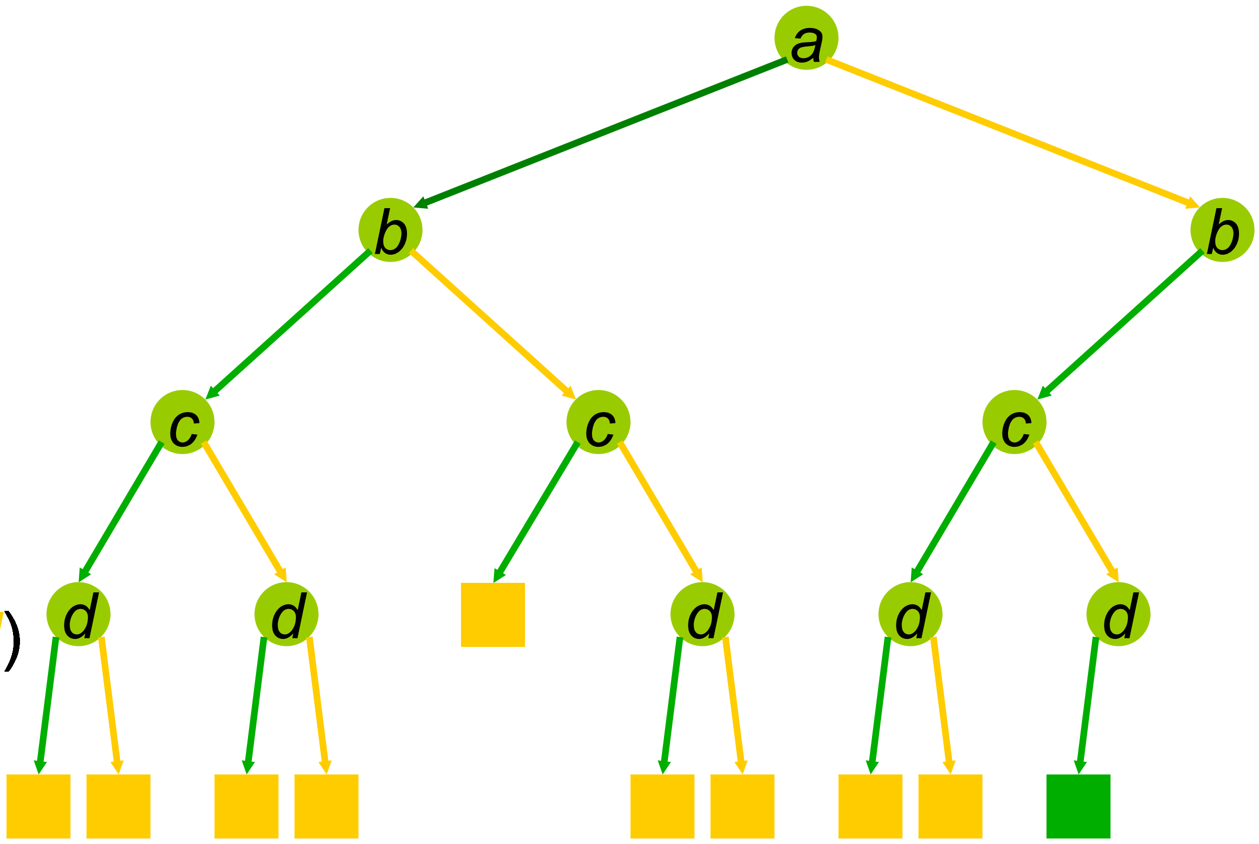
4 $(a + c + d)$

5 $(\neg a + c + d)$

6 $(\neg a + c + \neg d)$

7 $(\neg b + \neg c + \neg d)$

8 $(\neg b + \neg c + d)$



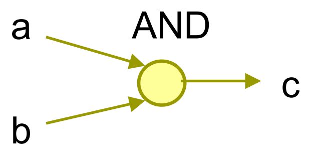
Source: Karem A. Sakallah, Univ. of Michigan

Boolean Reasoning
SAT – CNF-based Decision Procedure

- Implication
  - Implications in a CNF formula are caused by unit clauses
    - A unit clause is a CNF term for which all variables except one are assigned
      - the value of that clause can be implied immediately
    - Example
      clause $(a+\neg b+c)$
      $(a=0)\,(b=1) \Rightarrow (c=1)$

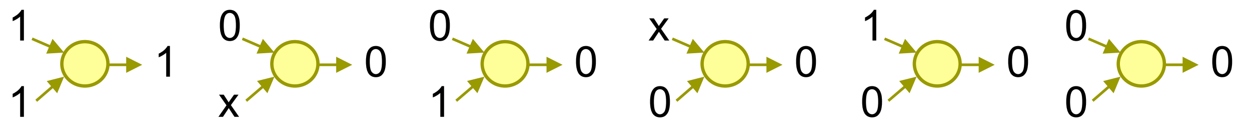
Boolean Reasoning
SAT – CNF-based Decision Procedure

- Implication
  - Example

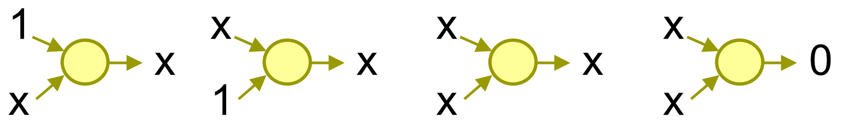


(¬a+¬b+c) (a+¬c) (b+¬c)

Non-implication cases:



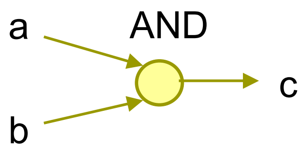
All clauses satisfied



Not all clauses satisfied (avoid exploring this part)

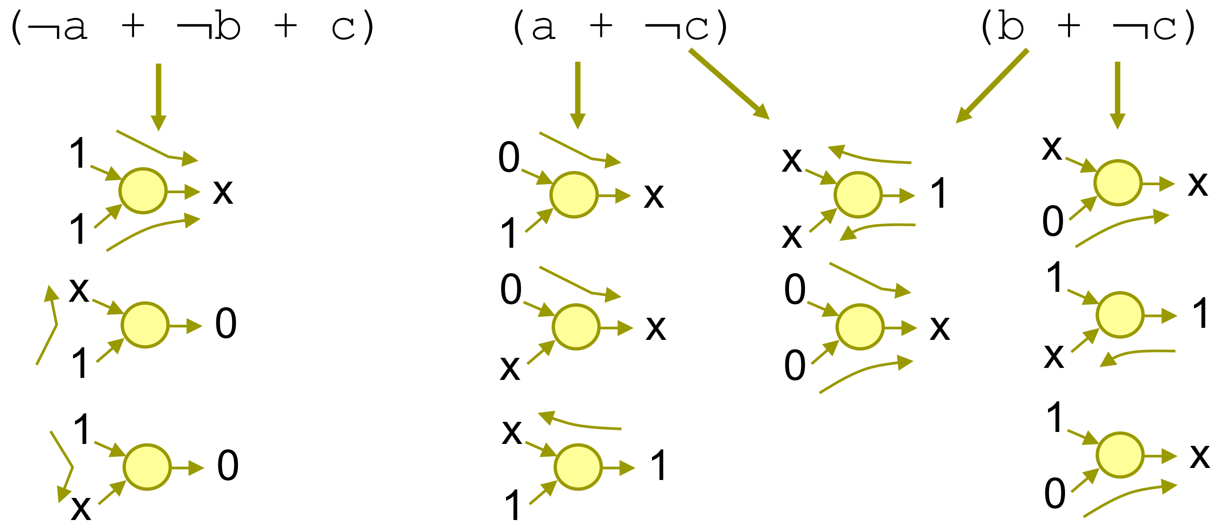
Boolean Reasoning
SAT – CNF-based Decision Procedure

- Implication
  - Example (cont'd)



(¬a+¬b+c) (a+¬c) (b+¬c)

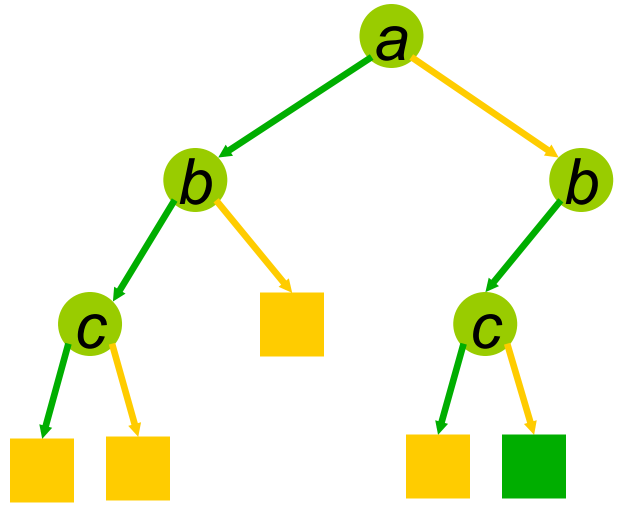
Implication cases:

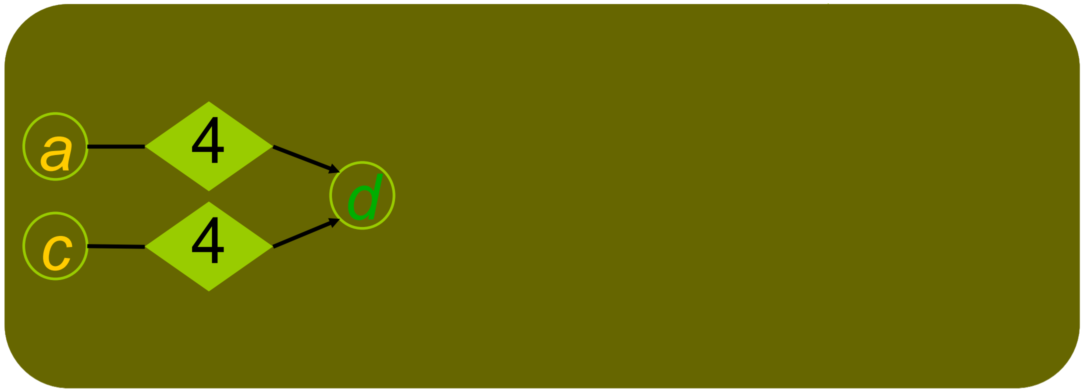


Boolean Reasoning
SAT – CNF-based Decision Procedure

- DPLL (w/ implication)

1 $(a + b + c)$
2 $(a + b + \neg c)$
3 $(\neg a + b + \neg c)$
4 $(a + c + d)$
5 $(\neg a + c + d)$
6 $(\neg a + c + \neg d)$
7 $(\neg b + \neg c + \neg d)$
8 $(\neg b + \neg c + d)$





Source: Karem A. Sakallah, Univ. of Michigan

Boolean Reasoning
SAT – CNF-based Decision Procedure

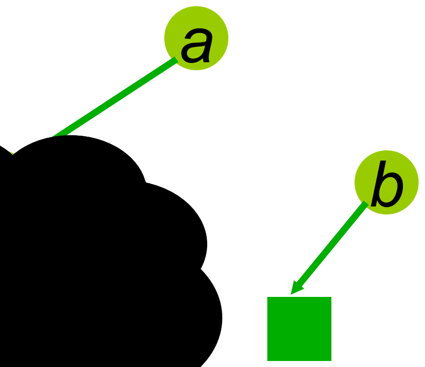
- Conflict-based learning
  - Important detail for cut selection:
    - During implication processing, record decision level for each implication
    - At conflict, select earliest cut such that exactly one node of the implication graph lies on current decision level
      - Either decision variable itself
      - Or UIP ("unique implication point") that represents a dominator node for current decision level in conflict graph
  - By selecting such cut, implication processing will automatically flip decision variable (or UIP variable) to its complementary value

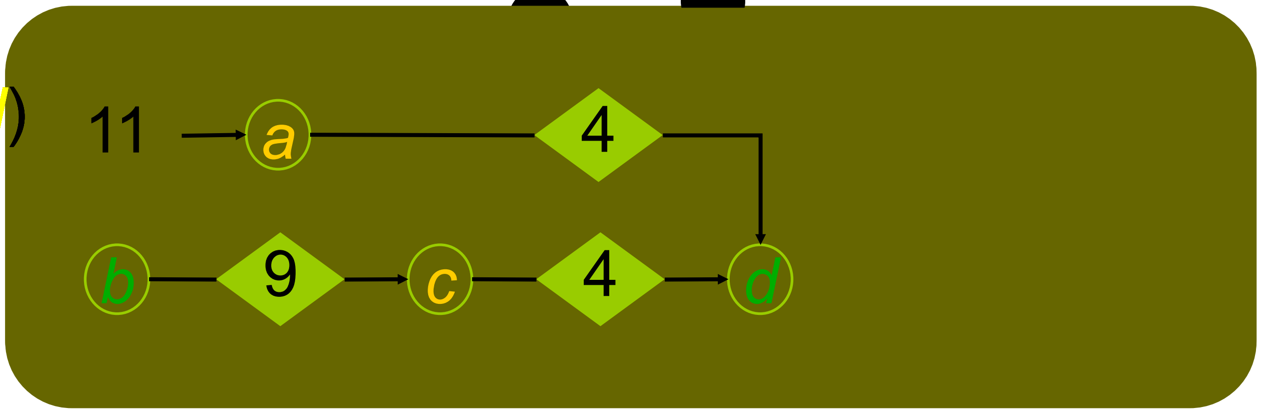
Boolean Reasoning
SAT – CNF-based Decision Procedure

- DPLL (conflict-based learning)

1. $(a + b + c)$
2. $(a + b + \neg c)$
3. $(\neg a + b + \neg c)$
4. $(a + c + d)$
5. $(\neg a + c + d)$
6. $(\neg a + c + \neg d)$
7. $(\neg b + \neg c + \neg d)$
8. $(\neg b + \neg c + d)$
9. $(\neg b + \neg c)$
10. $(\neg a + \neg b)$
11. $\neg a$

$$a \rightarrow \neg\varphi$$
$$\Downarrow$$
$$\varphi \rightarrow (\neg a)$$

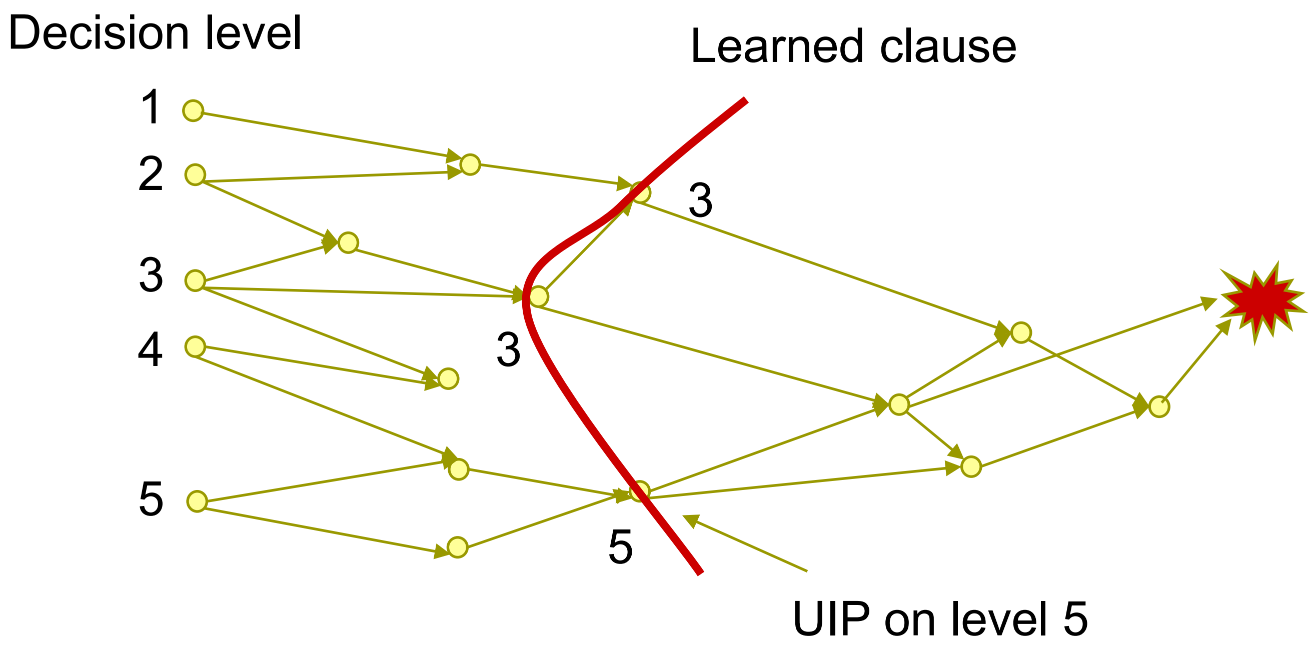




Source: Karem A. Sakallah, Univ. of Michigan

Boolean Reasoning
SAT – CNF-based Decision Procedure

- Conflict-based learning
  - UIP detection
    - Store with each implication the decision level, and a time stamp (integer that is incremented after each decision)
      - UIP on decision level l has the property that all following implications towards the conflict have a larger time stamp
      - When back processing from conflict, put all implications that are to be processed on heap, keeping the one with smallest time stamp on top
      - If during processing there is only one variable on current decision level on heap, then that variable must be a UIP



Boolean Reasoning
SAT – CNF-based Decision Procedure

- Implementation issues
  - Clauses are stores in arrays
  - Track change-sensitive clauses (two-literal watching)
    - all literals but one assigned -> implication
    - all literals but two assigned -> clause is sensitive to a change of either literal
    - all other clauses are insensitive and do not need to be observed
  - Learning:
    - learned implications are added to the CNF formula as additional clauses
      - limit the size of the clause
      - limit the “lifetime” of a clause, will be removed after some time
  - Non-chronological back-tracking
    - similar to circuit case

Boolean Reasoning
SAT – CNF-based Decision Procedure

- Implementation issues (cont'd)
  - Random restarts:
    - stop after a given number of backtracks
      - start search again with modified ordering heuristic
      - keep learned structures !
    - very effective for satisfiable formulas, often also effective for unsat formulas
  - Learning of equivalence relations:
    - if $(a \Rightarrow b) \wedge (b \Rightarrow a)$, then $(a = b)$
    - very powerful for formal equivalence checking
  - Incremental SAT solving
    - solving similar CNF formulas in a row
    - share learned clauses