

# Planning and Optimization

## C6. Symbolic Search: Binary Decision Diagrams

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C6.1 Motivation

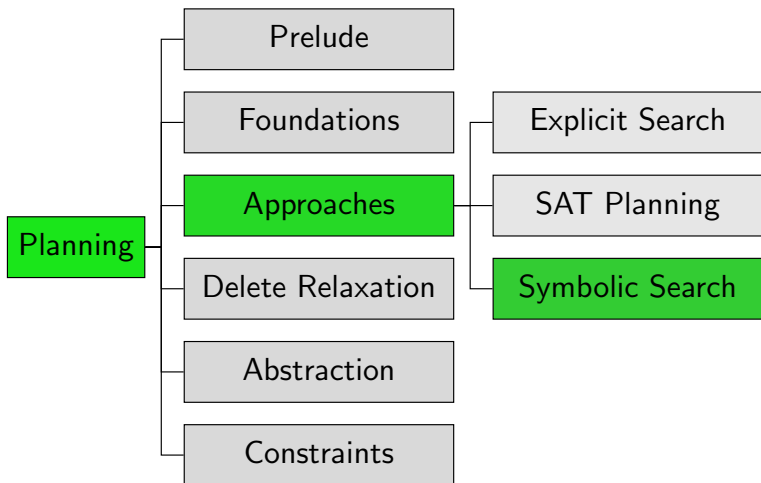
C6.2 Data Structures for State Sets

C6.3 Binary Decision Diagrams

C6.4 BDDs as Canonical Representations

C6.5 Summary

# Content of the Course



# C6.1 Motivation

# Symbolic Search Planning: Basic Ideas

- ▶ come up with a good **data structure** for **sets of states**
- ▶ **hope**: (at least some) exponentially large state sets can be represented as polynomial-size data structures
- ▶ simulate a standard search algorithm like **breadth-first search** using these set representations

# Symbolic Breadth-First Progression Search

## Symbolic Breadth-First Progression Search

```

def bfs-progression( $V, I, O, \gamma$ ):
     $goal\_states := models(\gamma)$ 
     $reached_0 := \{I\}$ 
     $i := 0$ 
    loop:
        if  $reached_i \cap goal\_states \neq \emptyset$ :
            return solution found
         $reached_{i+1} := reached_i \cup apply(reached_i, O)$ 
        if  $reached_{i+1} = reached_i$ :
            return no solution exists
         $i := i + 1$ 
  
```

$\rightsquigarrow$  If we can implement operations *models*,  $\{I\}$ ,  $\cap$ ,  $\neq \emptyset$ ,  $\cup$ , *apply* and  $=$  efficiently, this is a reasonable algorithm.

## C6.2 Data Structures for State Sets

# Representing State Sets

We need to represent and manipulate state sets (again)!

- ▶ How about an explicit representation, like a **hash table**?
- ▶ And how about our good old friend, the **formula**?



# Time Complexity: Explicit Representations vs. Formulas

Let  $k$  be the **number of state variables**,  
 $|S|$  the **number of states** in  $S$  and  
 $\|S\|$  the **size of the representation** of  $S$ .

	Hash table	Formula
$s \in S?$	$O(k)$	$O(\ S\ )$
$S := S \cup \{s\}$	$O(k)$	$O(k)$
$S := S \setminus \{s\}$	$O(k)$	$O(k)$
$S \cup S'$	$O(k S  + k S' )$	$O(1)$
$S \cap S'$	$O(k S  + k S' )$	$O(1)$
$S \setminus S'$	$O(k S  + k S' )$	$O(1)$
$\bar{S}$	$O(k2^k)$	$O(1)$
$\{s \mid s(v) = \mathbf{T}\}$	$O(k2^k)$	$O(1)$
$S = \emptyset?$	$O(1)$	co-NP-complete
$S = S'?$	$O(k S )$	co-NP-complete
$ S $	$O(1)$	#P-complete

# Which Operations are Important?

- ▶ **Explicit representations** such as hash tables are unsuitable because their size grows linearly with the number of represented states.
- ▶ **Formulas** are very efficient for some operations, but not for other important operations needed by the breadth-first search algorithm.
  - ▶ Examples:  $S \neq \emptyset?$ ,  $S = S'?$

# Canonical Representations

- ▶ One of the problems with formulas is that they allow **many different representations** for the same set.
  - ▶ For example, all unsatisfiable formulas represent  $\emptyset$ .

This makes equality tests expensive.
- ▶ We would like data structures with a **canonical representation**, i.e., with only **one possible representation** for every state set.
- ▶ Reduced ordered **binary decision diagrams** (BDDs) are an example of such a canonical representation.

# Time Complexity: Formulas vs. BDDs

Let  $k$  be the **number of state variables**,  
 $|S|$  the **number of states** in  $S$  and  
 $\|S\|$  the **size of the representation** of  $S$ .

	Formula	BDD
$s \in S?$	$O(\ S\ )$	$O(k)$
$S := S \cup \{s\}$	$O(k)$	$O(k)$
$S := S \setminus \{s\}$	$O(k)$	$O(k)$
$S \cup S'$	$O(1)$	$O(\ S\  \ S'\ )$
$S \cap S'$	$O(1)$	$O(\ S\  \ S'\ )$
$S \setminus S'$	$O(1)$	$O(\ S\  \ S'\ )$
$\bar{S}$	$O(1)$	$O(\ S\ )$
$\{s \mid s(v) = \mathbf{T}\}$	$O(1)$	$O(1)$
$S = \emptyset?$	co-NP-complete	$O(1)$
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$ S $	#P-complete	$O(\ S\ )$

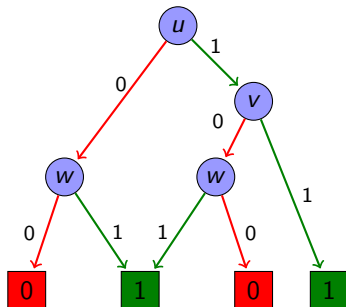
**Remark:** Optimizations allow BDDs with complementation ( $\bar{S}$ ) in constant time, but we will not discuss this here.

## C6.3 Binary Decision Diagrams

# BDD Example

## Example

Possible BDD for  $(u \wedge v) \vee w$



# Binary Decision Diagrams: Definition

## Definition (BDD)

Let  $V$  be a set of propositional variables.

A **binary decision diagram** (BDD) over  $V$  is a directed acyclic graph with labeled arcs and labeled vertices such that:

- ▶ There is exactly one node without incoming arcs.
- ▶ All sinks (nodes without outgoing arcs) are labeled **0** or **1**.
- ▶ All other nodes are labeled with a variable  $v \in V$  and have exactly two outgoing arcs, labeled **0** and **1**.

A note on notation:

- ▶ In BDDs, **1** stands for **T** and **0** for **F**.
- ▶ We follow this customary notation in BDDs, but stick to **T** and **F** when speaking of logic.

# Binary Decision Diagrams: Terminology

## BDD Terminology

- ▶ The node without incoming arcs is called the **root**.
- ▶ The labeling variable of an internal node is called the **decision variable** of the node.
- ▶ The nodes reached from node  $n$  via the arc labeled  $i \in \{0, 1\}$  is called the  **$i$ -successor** of  $n$ .
- ▶ The BDDs which only consist of a single sink are called the **zero BDD** and **one BDD**.

**Observation:** If  $B$  is a BDD and  $n$  is a node of  $B$ , then the subgraph induced by all nodes reachable from  $n$  is also a BDD.

- ▶ This BDD is called the **BDD rooted at  $n$** .



## BDD Semantics

### Testing whether a BDD Includes a Variable Assignment

**def** `bdd-includes`( $B$ : BDD,  $I$ : variable assignment):

Set  $n$  to the root of  $B$ .

**while**  $n$  is not a sink:

Set  $v$  to the decision variable of  $n$ .

Set  $n$  to the 1-successor of  $n$  if  $I(v) = \mathbf{T}$  and  
to the 0-successor of  $n$  if  $I(v) = \mathbf{F}$ .

**return true** if  $n$  is labeled 1, **false** if it is labeled 0.

### Definition (Set Represented by a BDD)

Let  $B$  be a BDD over variables  $V$ .

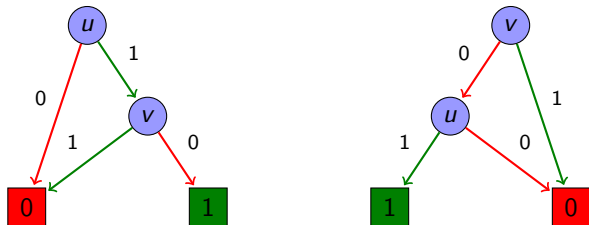
The **set represented by  $B$** , in symbols  $r(B)$ , consists of all variable assignments  $I : V \rightarrow \{\mathbf{T}, \mathbf{F}\}$  for which `bdd-includes`( $B, I$ ) returns true.

# C6.4 BDDs as Canonical Representations

## Ordered BDDs: Motivation

In general, BDDs are not a canonical representation for sets of interpretations. Here is a simple counter-example ( $V = \{u, v\}$ ):

Example (BDDs for  $u \wedge \neg v$  with Different Variable Order)



Both BDDs represent the same state set, namely the singleton set  $\{\{u \mapsto \mathbf{T}, v \mapsto \mathbf{F}\}\}$ .

## Ordered BDDs: Definition

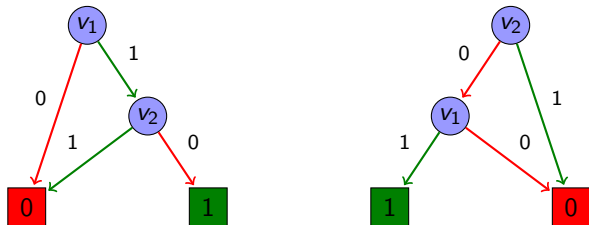
- ▶ As a first step towards a canonical representation, we now require that the set of variables is **totally ordered** by some ordering  $\prec$ .
- ▶ In particular, we will only use variables  $v_1, v_2, v_3, \dots$  and assume the ordering  $v_i \prec v_j$  iff  $i < j$ .

### Definition (Ordered BDD)

A BDD is **ordered** (w.r.t.  $\prec$ ) iff for each arc from a node with decision variable  $u$  to a node with decision variable  $v$ , we have  $u \prec v$ .

# Ordered BDDs: Example

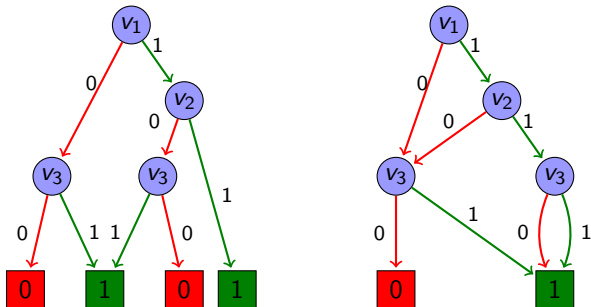
## Example (Ordered and Unordered BDD)



The left BDD is ordered w.r.t. the ordering we use in this chapter, the right one is not.

# Reduced Ordered BDDs: Are Ordered BDDs Canonical?

Example (Two equivalent BDDs that can be reduced)



- ▶ Ordered BDDs are still not canonical:  
both ordered BDDs represent the same set.
- ▶ However, ordered BDDs can easily be **made** canonical.

# Reduced Ordered BDDs: Reductions (1)

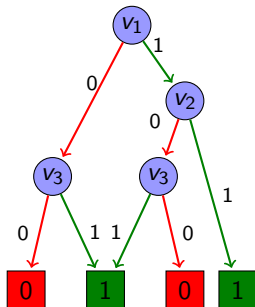
There are two important operations on BDDs that do not change the set represented by it:

## Definition (Isomorphism Reduction)

If the BDDs rooted at two different nodes  $n$  and  $n'$  are **isomorphic**, then all incoming arcs of  $n'$  can be redirected to  $n$ , and all BDD nodes unreachable from the root can be removed.

# Reduced Ordered BDDs: Reductions (2)

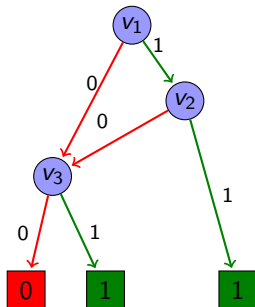
## Example (Isomorphism Reduction)





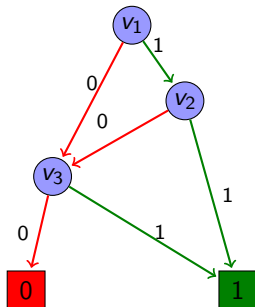
# Reduced Ordered BDDs: Reductions (2)

## Example (Isomorphism Reduction)



# Reduced Ordered BDDs: Reductions (2)

## Example (Isomorphism Reduction)



## Reduced Ordered BDDs: Reductions (3)

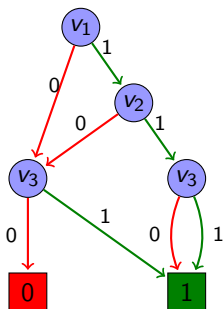
There are two important operations on BDDs that do not change the set represented by it:

### Definition (Shannon Reduction)

If both outgoing arcs of an internal node  $n$  of a BDD lead to the same node  $m$ , then  $n$  can be removed from the BDD, with all incoming arcs of  $n$  going to  $m$  instead.

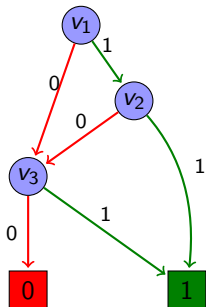
# Reduced Ordered BDDs: Reductions (4)

## Example (Shannon Reduction)



# Reduced Ordered BDDs: Reductions (4)

## Example (Shannon Reduction)



## Reduced Ordered BDDs: Definition

### Definition (Reduced Ordered BDD)

An ordered BDD is **reduced** iff it does not admit any isomorphism reduction or Shannon reduction.

### Theorem (Bryant 1986)

*For every state set  $S$  and a fixed variable ordering, there exists exactly one reduced ordered BDD representing  $S$ .*

*Moreover, given any ordered BDD  $B$ , the equivalent reduced ordered BDD can be computed in linear time in the size of  $B$ .*

↔ Reduced ordered BDDs are the canonical representation we are looking for.

From now on, we simply say **BDD** for **reduced ordered BDD**.

## C6.5 Summary

# Summary

- ▶ **Symbolic search** is based on the idea of performing a state-space search where many states are considered “at once” by operating on **sets of states** rather than individual states.
- ▶ **Binary decision diagrams** are a data structure to compactly represent and manipulate sets of variable assignments.
- ▶ **Reduced ordered BDDs** are a **canonical representation** of such sets.