

Backtracking search: look-back

ICS 275
Spring 2014

Spring 2014

Look-back:

Backjumping / Learning

- Backjumping:
 - In deadends, go back to the most recent culprit.
- Learning:
 - constraint-recording, no-good recording.
 - good-recording

Backjumping

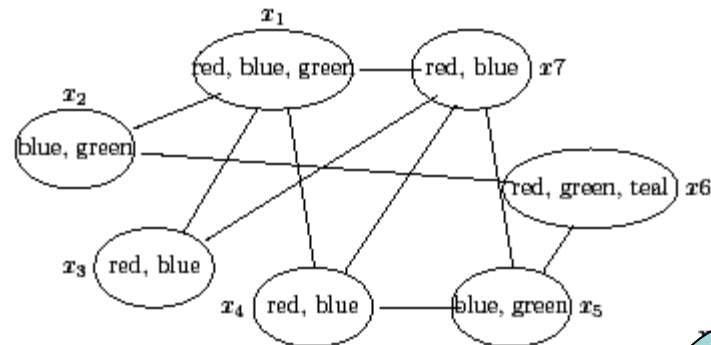


Figure 6.1: A modified coloring problem.

- $(X_1=r, x_2=b, x_3=b, x_4=b, x_5=g, x_6=r, x_7=\{r, b\})$
- (r, b, b, b, g, r) **conflict set** of x_7
- $(r, -, b, b, g, -)$ c.s. of x_7
- $(r, -, b, -, -, -, -)$ **minimal conflict-set**
- **Leaf deadend**: (r, b, b, b, g, r)
- Every conflict-set is a **no-good**

Backjumping

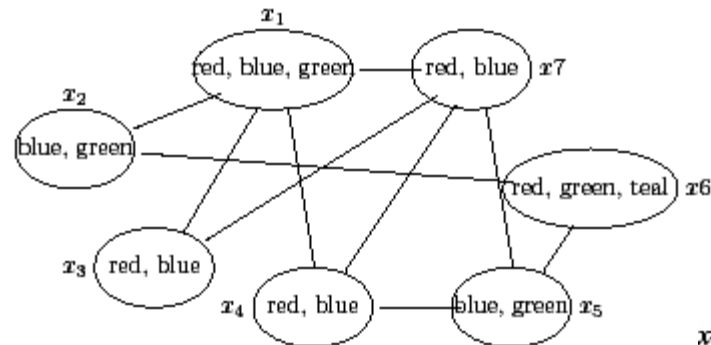
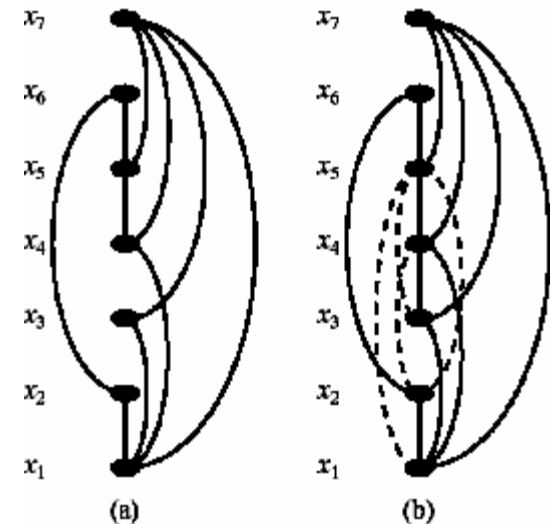


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Gaschnig jumps only at leaf-dead-ends

Internal dead-ends: dead-ends that are non-leaf

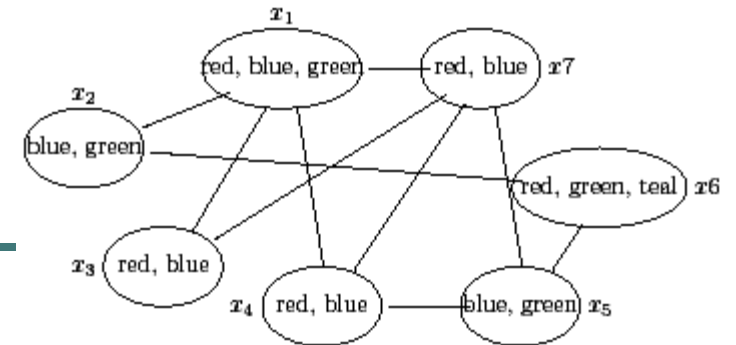
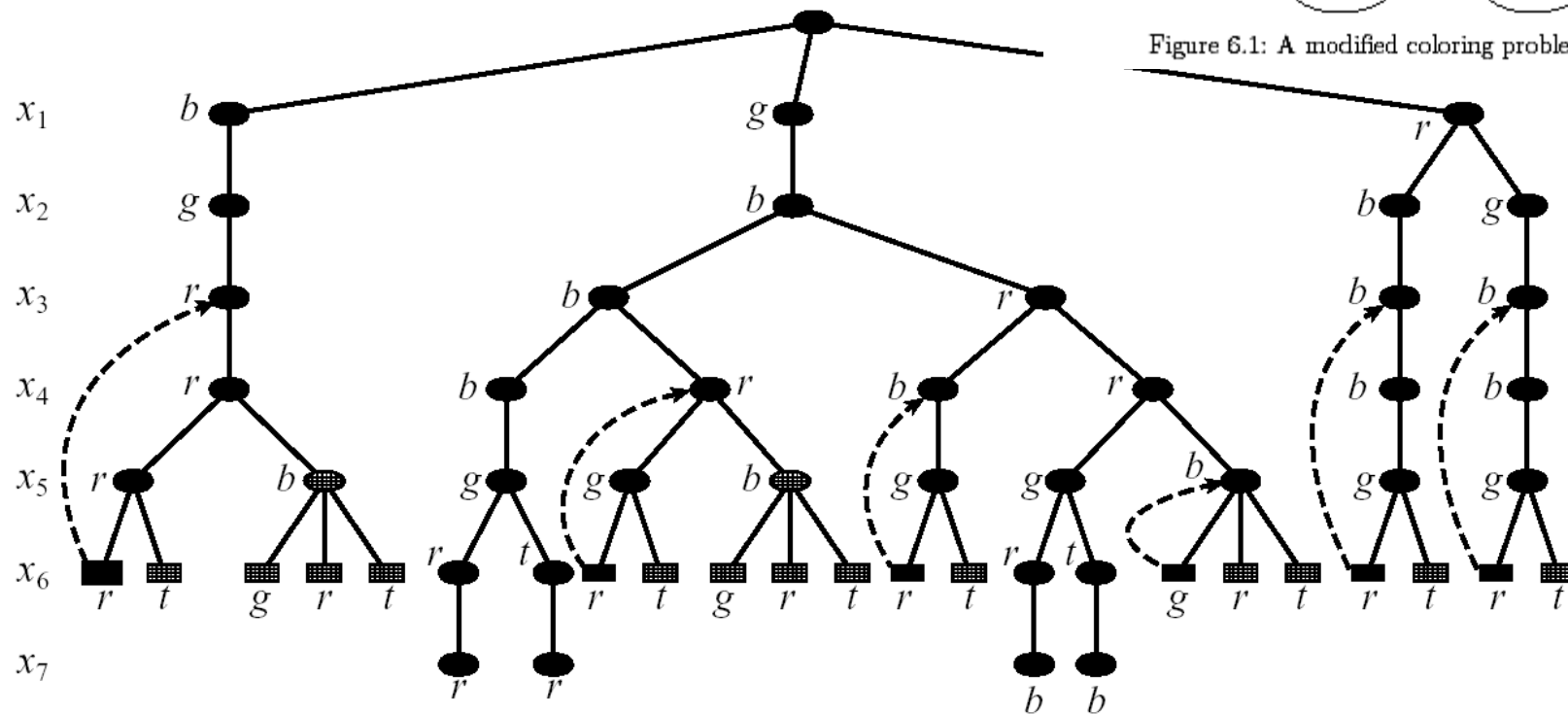


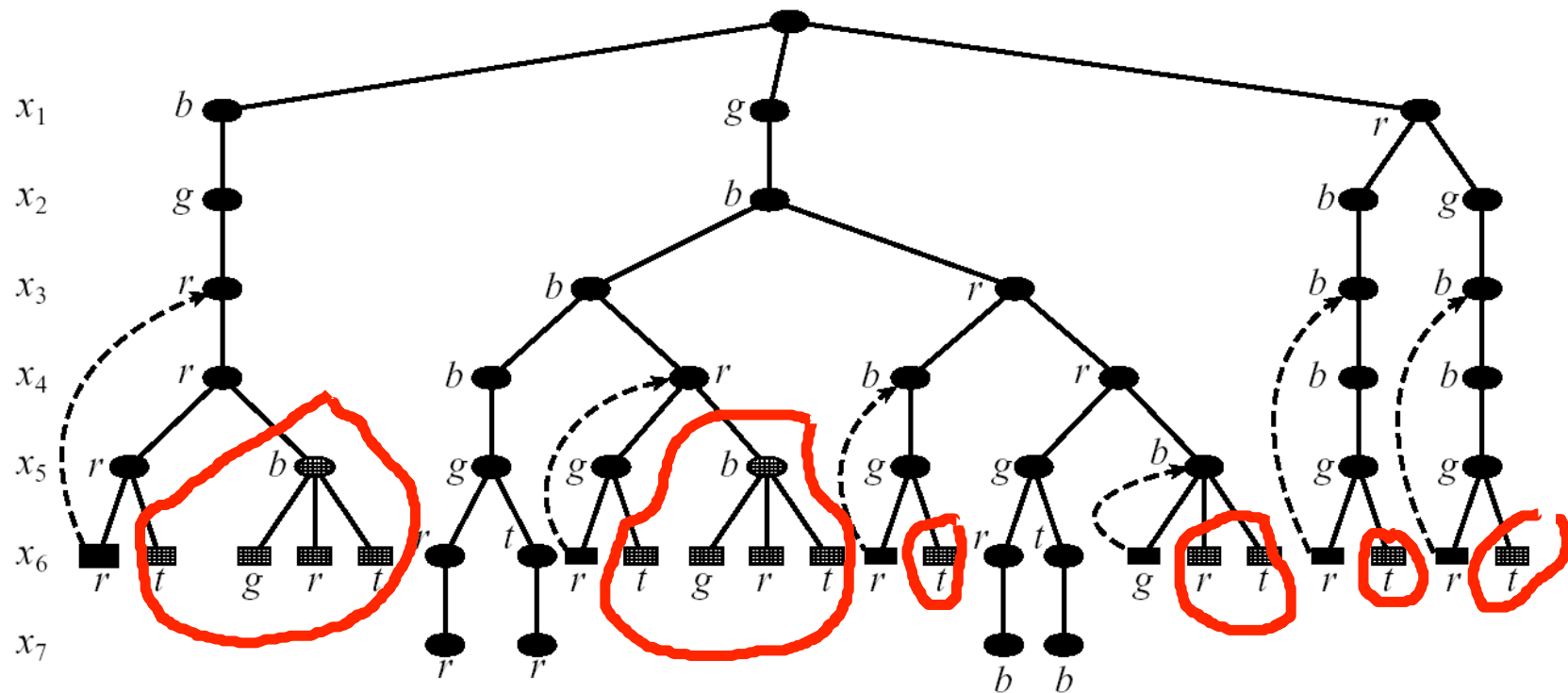
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Example 6.3.1 In Figure 6.4, all of the backjumps illustrated lead to internal dead-ends, except for the jump back to $(\langle x_1, \text{green} \rangle, \langle x_2, \text{blue} \rangle, \langle x_3, \text{red} \rangle, \langle x_4, \text{blue} \rangle)$, because this is the only case where another value exists in the domain of the culprit variable. \square

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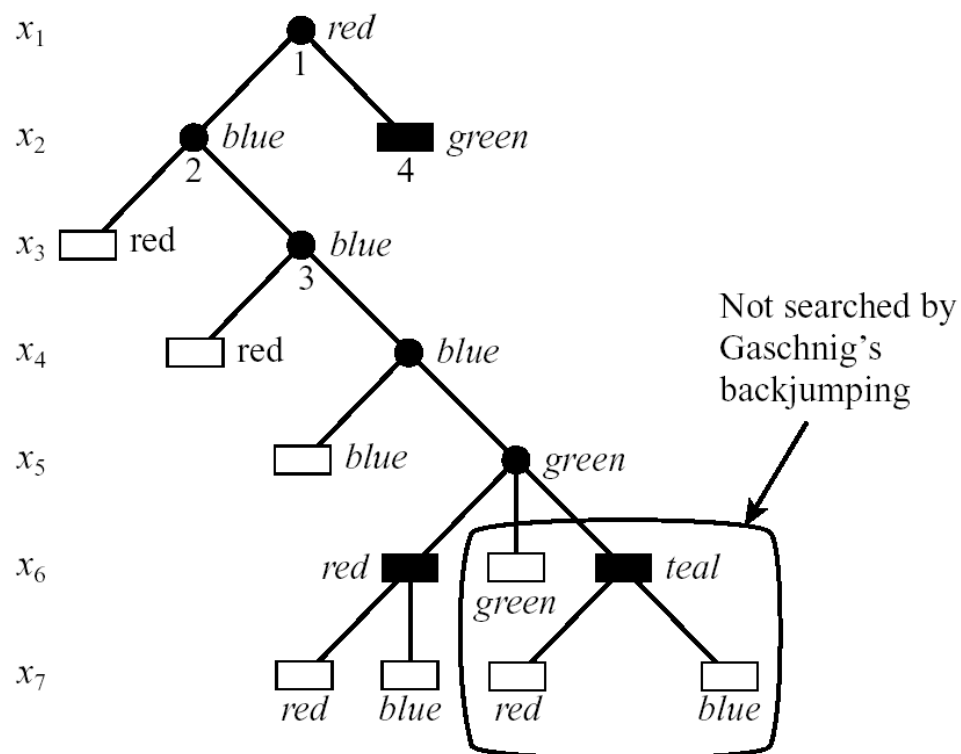


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Backjumping styles

- **Jump at leaf only** (Gaschnig 1977)
 - Context-based
- **Graph-based** (Dechter, 1990)
 - Jumps at leaf and internal dead-ends, graph information
- **Conflict-directed** (Prosser 1993)
 - Context-based, jumps at leaf and internal dead-ends

Conflict Analysis



- Conflict set
- Leaf deadend
- Nogood
- Safe jump

Gaschnig's backjumping: Culprit variable

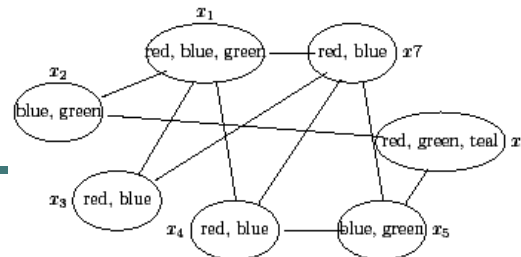
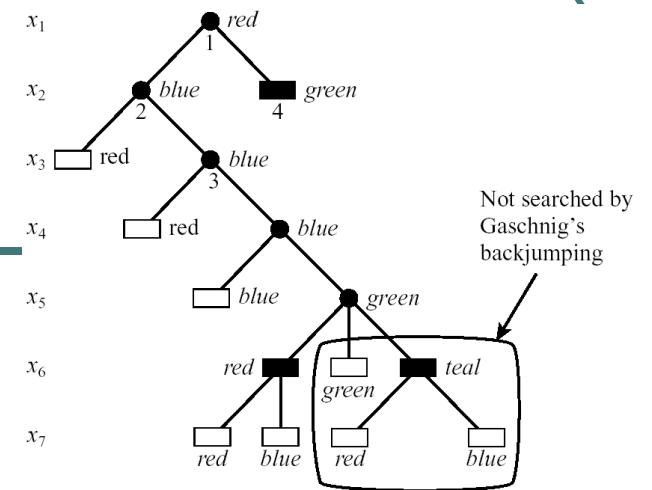


Figure 6.1: A modified coloring problem.



Definition 6.2.1 (culprit variable) Let $\vec{a}_i = (a_1, \dots, a_i)$ be a leaf dead-end. The culprit index relative to \vec{a}_i is defined by $b = \min\{j \leq i \mid \vec{a}_j \text{ conflicts with } x_{i+1}\}$. We define the culprit variable of \vec{a}_i to be x_b .

- If a_i is a leaf deadend and x_b its culprit variable, then a_b is a safe backjump destination and a_j , $j < b$ is not.
- The culprit of x_7 (r,b,b,b,g,r) is (r,b,b) $\rightarrow x_3$

Gaschnig's backjumping Implementation [1979]

- Gaschnig uses a marking technique to compute culprit.
- Each variable x_j maintains a pointer ($latest_j$) to the latest ancestor incompatible with any of its values.
- While forward generating a_i , keep array $latest_i$, $1 \leq j \leq n$, of pointers to the last value conflicted with some value of x_j . The algorithm jumps from a leaf-dead-end x_{i+1} back to $latest_{i+1}$ which is its culprit.

Gaschnig's backjumping

```

procedure GASCHNIG'S-BACKJUMPING
Input: A constraint network  $\mathcal{R} = (X, D, C)$ 
Output: Either a solution, or a decision that the network is inconsistent.

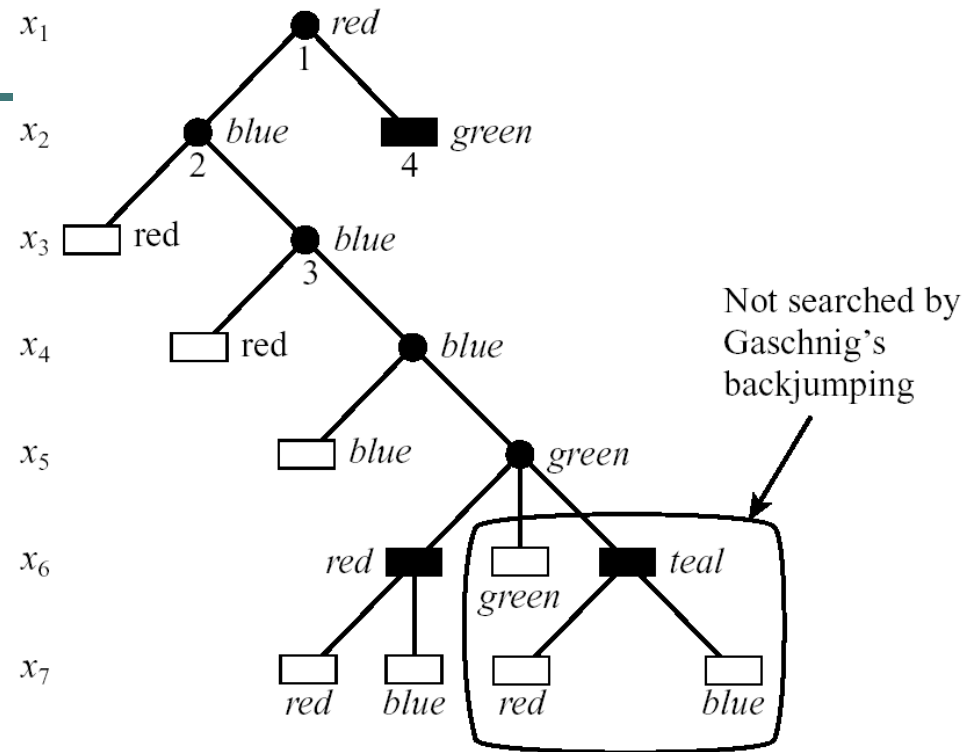
   $i \leftarrow 1$                                 (initialize variable counter)
   $D'_i \leftarrow D_i$                         (copy domain)
   $latest_i \leftarrow 0$                      (initialize pointer to culprit)
  while  $1 \leq i \leq n$ 
    instantiate  $x_i \leftarrow \text{SELECTVALUE-GBJ}$ 
    if  $x_i$  is null                            (no value was returned)
       $i \leftarrow latest_i$                     (backjump)
    else
       $i \leftarrow i + 1$ 
       $D'_i \leftarrow D_i$ 
       $latest_i \leftarrow 0$ 
    end while
    if  $i = 0$ 
      return "inconsistent"
    else
      return instantiated values of  $\{x_1, \dots, x_n\}$ 
  end procedure

procedure SELECTVALUE-GBJ
  while  $D'_i$  is not empty
    select an arbitrary element  $a \in D'_i$ , and remove  $a$  from  $D'_i$ 
     $consistent \leftarrow true$ 
     $k \leftarrow 1$ 
    while  $k < i$  and  $consistent$ 
      if  $k > latest_i$ 
         $latest_i \leftarrow k$ 
      if not CONSISTENT( $\vec{a}_k, x_i = a$ )
         $consistent \leftarrow false$ 
      else
         $k \leftarrow k + 1$ 
      end while
    if  $consistent$ 
      return  $a$ 
    end while
  return null                                (no consistent value)
end procedure
  
```

Spring 2014

Figure 6.3: Gaschnig's backjumping algorithm.

Example of Gaschnig's backjump



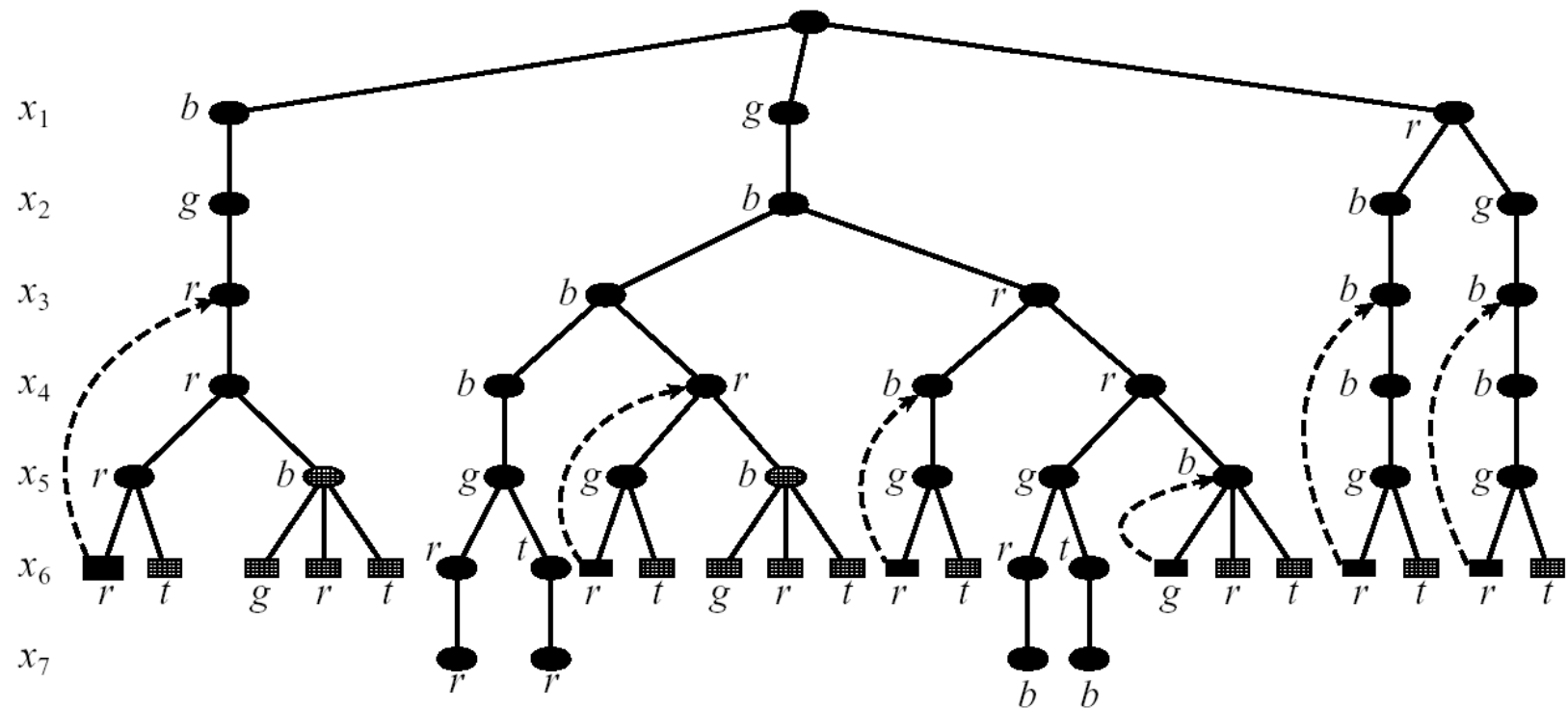
Example 6.2.3 Consider the problem in Figure 6.1 and the order d_1 . At the dead-end for x_7 that results from the partial instantiation $\langle x_1, red \rangle, \langle x_2, blue \rangle, \langle x_3, blue \rangle, \langle x_4, blue \rangle, \langle x_5, green \rangle, \langle x_6, red \rangle$, $latest_7 = 3$, because $x_7 = red$ was ruled out by $\langle x_1, red \rangle$, $x_7 = blue$ was ruled out by $\langle x_3, blue \rangle$, and no later variable had to be examined. On returning to x_3 , the algorithm finds no further values to try ($D'_3 = \emptyset$). Since $latest_3 = 2$, the next variable examined will be x_2 . Thus we see the algorithm's ability to backjump at leaf dead-ends. On subsequent dead-ends, as in x_3 , it goes back to its preceding variable only. An example of the algorithm's practice of pruning the search space is given in Figure 6.2. \square

Properties

- Gaschnig's backjumping implements only safe and maximal backjumps in leaf-deadends.

Gaschnig jumps only at leaf-dead-ends

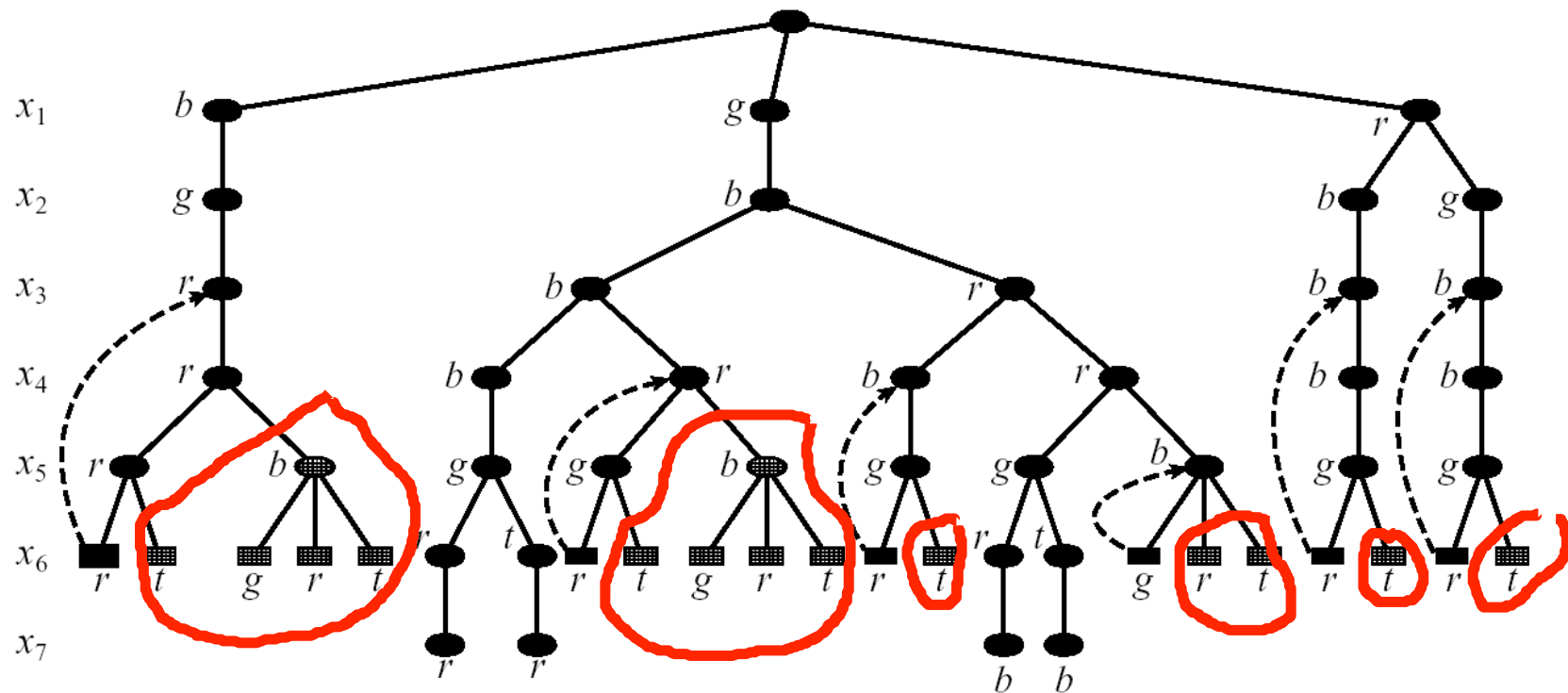
Internal dead-ends: dead-ends that are non-leaf



Example 6.3.1 In Figure 6.4, all of the backjumps illustrated lead to internal dead-ends, except for the jump back to $(\langle x_1, \text{green} \rangle, \langle x_2, \text{blue} \rangle, \langle x_3, \text{red} \rangle, \langle x_4, \text{blue} \rangle)$, because this is the only case where another value exists in the domain of the culprit variable. \square

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Graph-based backjumping scenarios

Internal deadend at X4

- Scenario 1, deadend at x_4 :
- Scenario 2: deadend at x_5 :
- Scenario 3: deadend at x_7 :
- Scenario 4: deadend at x_6 :

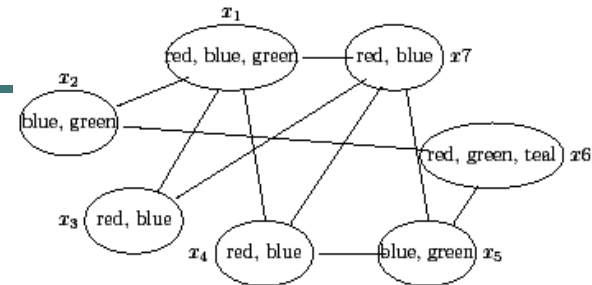
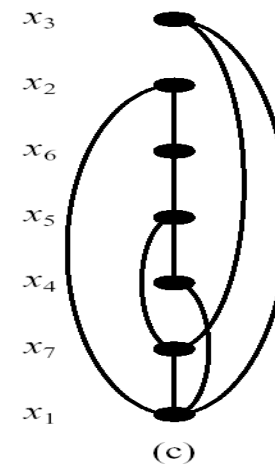
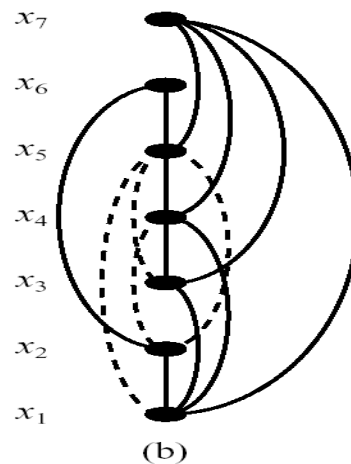
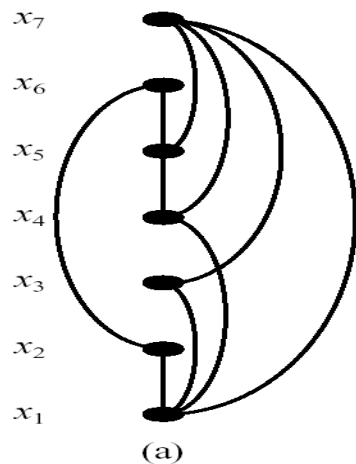


Figure 6.1: A modified coloring problem.

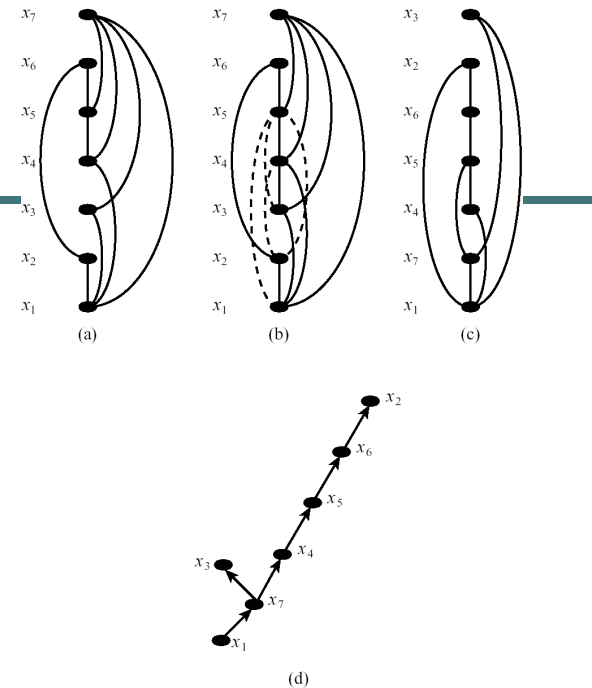


Graph-based backjumping

- Uses only graph information to find culprit
- Jumps both at leaf and at internal dead-ends
- Whenever a deadend occurs at x , it jumps to the most recent variable y connected to x in the graph. If y is an internal deadend it jumps back further to the most recent variable connected to x or y .
- The analysis of conflict is approximated by the graph.
- Graph-based algorithm provide graph-theoretic bounds.

Ancestors and parents

- $\text{anc}(x_7) = \{x_5, x_3, x_4, x_1\}$
- $p(x_7) = x_5$
- $p(r, b, b, b, g, r) = x_5$



Definition 6.3.2 (ancestors, parent) Given a constraint graph and an ordering of the nodes d , the ancestor set of variable x , denoted $\text{anc}(x)$, is the subset of the variables that precede and are connected to x . The parent of x , denoted $p(x)$, is the most recent (or latest) variable in $\text{anc}(x)$. If $\vec{a}_i = (a_1, \dots, a_i)$ is a leaf dead-end, we equate $\text{anc}(\vec{a}_i)$ with $\text{anc}(x_{i+1})$, and $p(\vec{a}_i)$ with $p(x_{i+1})$.

Internal Deadends Analysis

Definition 6.3.5 (session) We say that backtracking invisits x_i if it processes x_i coming from a variable earlier in the ordering. The session of x_i starts upon the invisiting of x_i and ends when retracting to a variable that precedes x_i . At a given state of the search where variable x_i is already instantiated, the current session of x_i is the set of variables processed by the algorithm since the most recent invisit to x_i . The current session of x_i includes x_i and therefore the session of a leaf dead-end variable has a single variable.

Definition 6.3.6 (relevant dead-ends) The relevant dead-ends of x_i 's session are defined recursively as follows. The relevant dead-ends of a leaf dead-end x_i , denoted $r(x_i)$, is x_i . If x_i is variable to which the algorithm retracted from x_i , then the relevant-dead-

6 The induced-parents of a variable X along an ordering, approximates its induced
7 parent set

induced ancestor set of x_i relative to Y , $I_i(Y)$, is the union of all Y 's ancestors, restricted to variables that precede x_i . Formally, $I_i(Y) = \text{anc}(Y) \cap \{x_1, \dots, x_{i-1}\}$. The induced parent of x_i relative to Y , $P_i(Y)$, is the latest variable in $I_i(Y)$. We call $P_i(Y)$ the graph-based culprit of x_i .

Graph-based backjumping scenarios

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- Scenario 2: deadend at x_5 :
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- Scenario 4: deadend at x_6 :

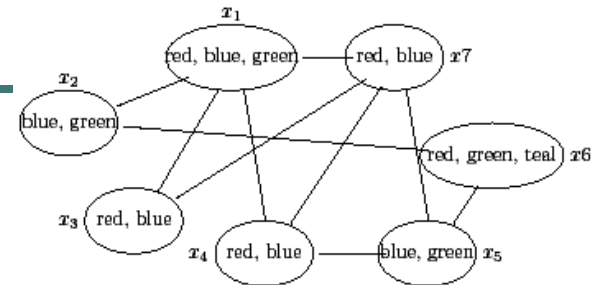
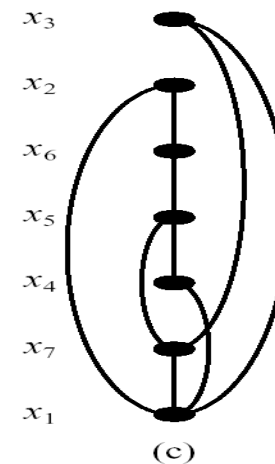
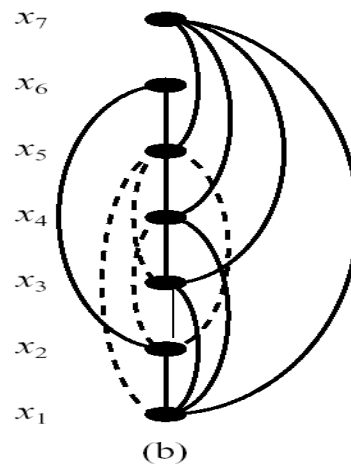
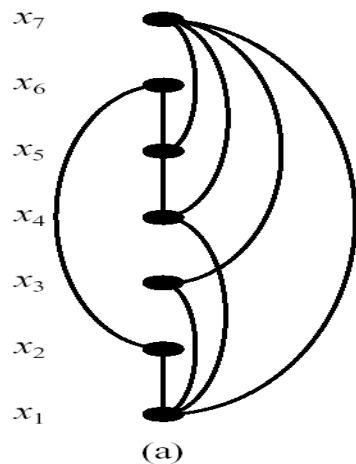


Figure 6.1: A modified coloring problem.



Graph-based backjumping algorithm, but we need to jump at internal deadends too

```

procedure GRAPH-BASED-BACKJUMPING
Input: A constraint network  $\mathcal{R} = (X, D, C)$ 
Output: Either a solution, or a decision that the network is inconsistent.

  compute  $anc(x_i)$  for each  $x_i$  (see Definition 6.3.2 in text)
   $i \leftarrow 1$  (initialize variable counter)
   $D'_i \leftarrow D_i$  (copy domain)
   $I_i \leftarrow anc(x_i)$  (copy of  $anc()$  that can change)
  while  $1 \leq i \leq n$ 
    instantiate  $x_i \leftarrow \text{SELECTVALUE}$ 
    if  $x_i$  is null (no value was returned)
       $i_{prev} \leftarrow i$ 
       $i \leftarrow \text{latest index in } I_i$  (backjump)
       $I_i \leftarrow I_i \cup I_{i_{prev}} - \{x_i\}$ 
    else
       $i \leftarrow i + 1$ 
       $D'_i \leftarrow D_i$ 
       $I_i \leftarrow anc(x_i)$ 
    end while
    if  $i = 0$ 
      return "inconsistent"
    else
      return instantiated values of  $\{x_1, \dots, x_n\}$ 
  end procedure

procedure SELECTVALUE (same as BACKTRACKING's)
  while  $D'_i$  is not empty
    select an arbitrary element  $a \in D'_i$ , and remove  $a$  from  $D'_i$ 
    if  $\text{CONSISTENT}(\bar{a}_{i-1}, x_i = a)$ 
      return  $a$ 
    end while
  return null (no consistent value)
end procedure

```

When not all variables
In the session above
 x_i are relevant deadends?
read example 6.6

Figure 6.5: The graph-based backjumping algorithm.

Properties of graph-based backjumping

- Algorithm graph-based backjumping jumps back at any deadend variable as far as graph-based information allows.
- For each variable, the algorithm maintains the induced-ancestor set l_i relative the relevant dead-ends in its current session.
- The size of the induced ancestor set is at most $w^*(d)$.

Conflict-directed backjumping

(Prosser 1990)

- Extend Gaschnig's backjump to internal dead-ends.
- Exploits information gathered during search.
- For each variable the algorithm maintains an induced **jumpback set**, and jumps to most recent one.
- **Use the following concepts:**
 - An ordering over variables induced a strict ordering between constraints: $R_1 < R_2 < \dots R_t$
 - Use **earliest minimal conflict-set** ($\text{emc}(x_{i+1})$) of a deadend.
 - Define the **jumpback set** of a deadend

Example of conflict-directed backjumping

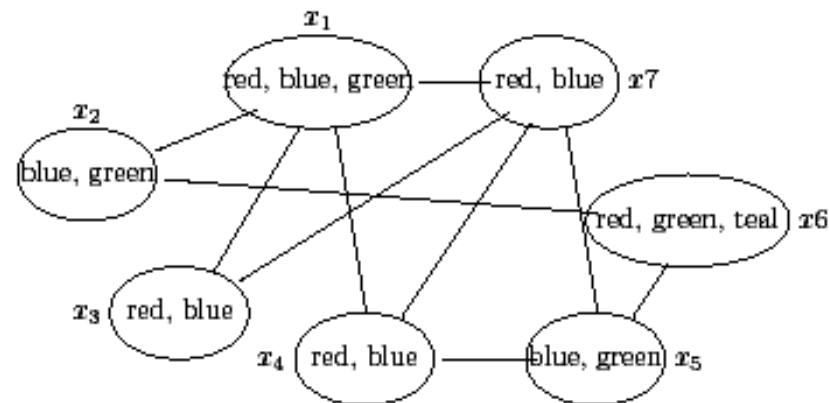


Figure 6.1: A modified coloring problem.

Example 6.4.5 Consider the problem of Figure 6.1 using ordering $d_1 = (x_1, \dots, x_7)$. Given the dead-end at x_7 and the assignment $\vec{a}_6 = (\text{blue}, \text{green}, \text{red}, \text{red}, \text{blue}, \text{red})$, the emc set is $(\langle x_1, \text{blue} \rangle, \langle x_3, \text{red} \rangle)$, since it accounts for eliminating all the values of x_7 . Therefore, algorithm conflict-directed backjumping jumps to x_3 . Since x_3 is an internal dead-end whose own *var-emc* set is $\{x_1\}$, the jumpback set of x_3 includes just x_1 , and the algorithm jumps again, this time back to x_1 . \square

Properties

- Given a dead-end \vec{a}_i , the latest variable in its jumpback set J_i is the earliest variable to which it is safe to jump.
- This is the culprit.
- Algorithm conflict-directed backtracking jumps back to the latest variable in the dead-ends's jumpback set, and is therefore safe and maximal.

Conflict-directed backjumping

```

procedure CONFLICT-DIRECTED-BACKJUMPING
Input: A constraint network  $\mathcal{R} = (X, D, C)$ .
Output: Either a solution, or a decision that the network is inconsistent.

     $i \leftarrow 1$                                 (initialize variable counter)
     $D'_i \leftarrow D_i$                         (copy domain)
     $J_i \leftarrow \emptyset$                     (initialize conflict set)
    while  $1 \leq i \leq n$ 
        instantiate  $x_i \leftarrow \text{SELECTVALUE-CBJ}$ 
        if  $x_i$  is null                        (no value was returned)
             $i_{prev} \leftarrow i$ 
             $i \leftarrow \text{index of last variable in } J_i$  (backjump)
             $J_i \leftarrow J_i \cup J_{i_{prev}} - \{x_i\}$  (merge conflict sets)
        else
             $i \leftarrow i + 1$                 (step forward)
             $D'_i \leftarrow D_i$                 (reset mutable domain)
             $J_i \leftarrow \emptyset$             (reset conflict set)
        end while
    if  $i = 0$ 
        return "inconsistent"
    else
        return instantiated values of  $\{x_1, \dots, x_n\}$ 
    end procedure

subprocedure SELECTVALUE-CBJ

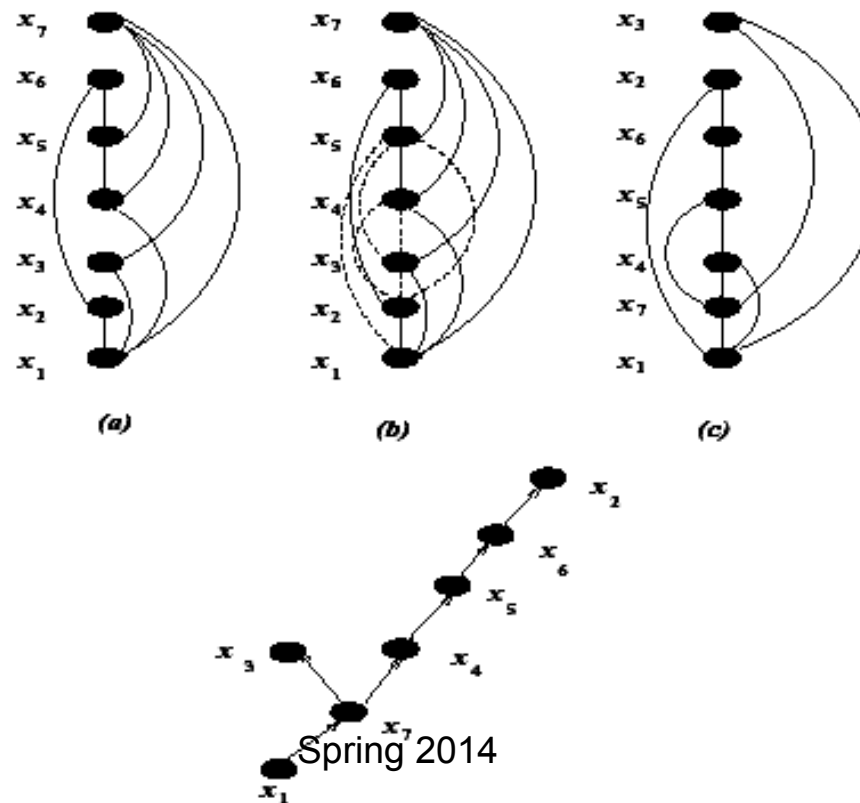
    while  $D'_i$  is not empty
        select an arbitrary element  $a \in D'_i$ , and remove  $a$  from  $D'_i$ 
         $consistent \leftarrow true$ 
         $k \leftarrow 1$ 
        while  $k < i$  and  $consistent$ 
            if  $\text{CONSISTENT}(\bar{a}_k, x_i = a)$ 
                 $k \leftarrow k + 1$ 
            else
                let  $R_S$  be the earliest constraint causing the conflict
                add the variables in  $R_S$ 's scope  $S$ , but not  $x_i$ , to  $J_i$ 
                 $consistent \leftarrow false$ 
            end while
        if  $consistent$ 
            return  $a$ 
        end while
    return null                                (no consistent value)
end procedure

```

Figure 6.7: The conflict-directed backjumping algorithm.

Graph-Based Backjumping on DFS Orderings

Example 6.5.1 Consider, once again, the CSP in Figure 6.1. A *DFS* ordering $d_2 = (x_1, x_7, x_4, x_5, x_6, x_2, x_3)$ and its corresponding *DFS* spanning tree are given in Figure 6.6c,d. If a dead-end occurs at node x_3 , the algorithm retreats to its *DFS* parent, which is x_7 . □



Graph-based Backjumping on DFS ordering

- Example: $d = x_1, x_2, x_3, x_4, x_5, x_6, x_7$
- Constraints: $(6,7)(5,2)(2,3)(5,7)(2,7)(2,1)(2,3)(1,4)3,4)$
- Rule: go back to parent. No need to maintain parent set

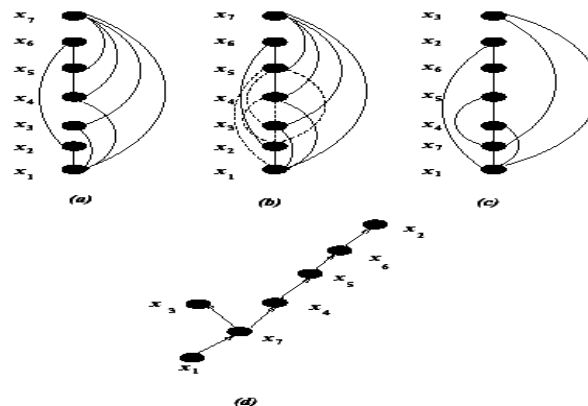


Figure 6.6: Several ordered constraint graphs of the problem in Figure 6.1: (a) along ordering $d_1 = (x_1, x_2, x_3, x_4, x_5, x_6, x_7)$, (b) the induced graph along d_1 , (c) along ordering $d_2 = (x_1, x_7, x_4, x_5, x_6, x_2, x_3)$, and (d) a DFS spanning tree along ordering d_2 .

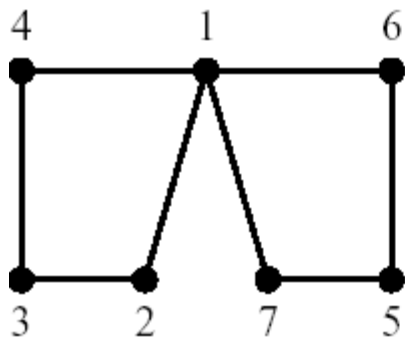
Theorem 6.5.2 *Given a DFS ordering of the constraint graph, if $f(x)$ denotes the DFS parent of x , then, upon a dead-end at x , $f(x)$ is x 's graph-based earliest safe variable for both leaf and internal dead-ends.*

Complexity of Graph-based Backjumping

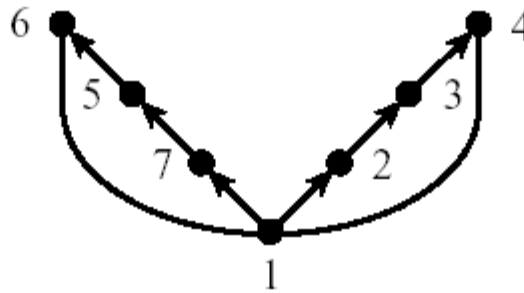
- T_i = number of nodes in the AND/OR search space rooted at x_i (level $m-i$)
- Each assignment of a value to x_i generates subproblems:
 - $T_i = b \cdot T_{i-1}$
 - $T_0 = k$
- Solution: $T_m = b^m k^{m+1}$

Theorem 6.5.3 *When graph-based backjumping is performed on a DFS ordering of the constraint graph, the number of nodes visited is bounded by $O(b^m k^{m+1})$, where b bounds the branching degree of the DFS tree associated with that ordering, m is its depth and k is the domain size. The time complexity (measured by the number of consistency checks) is $O(ek(bk)^m)$, where e is the number of constraints.*

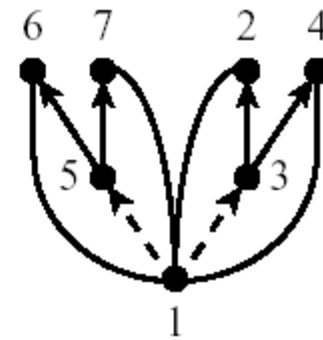
DFS of graph and induced graphs



(a)



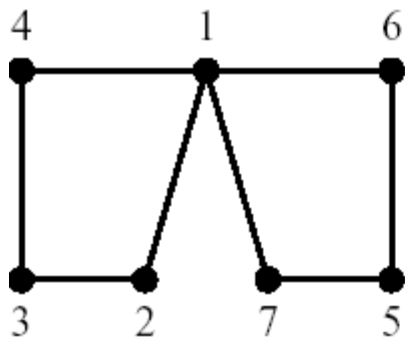
(b)



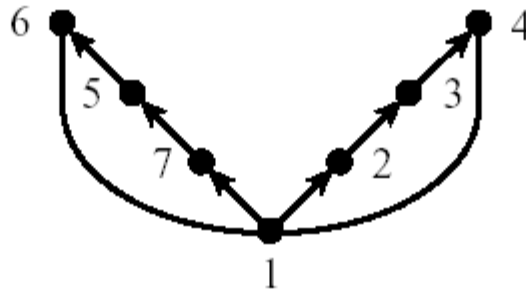
(c)

Spanning-tree of a graph;
DFS spanning trees, Pseudo-tree
Pseudo-tree is a spanning tree that does not allow arcs across branches.

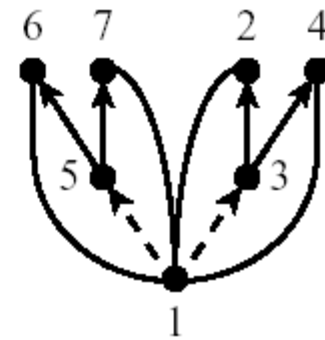
Complexity of Backjumping uses pseudo-tree analysis



(a)



(b)



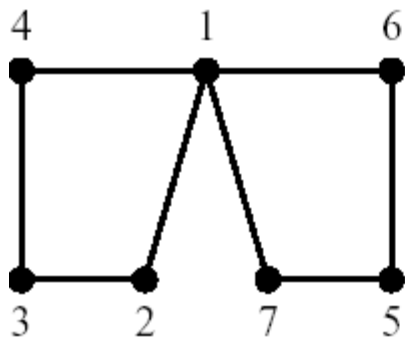
(c)

Simple: always jump back to parent in pseudo tree

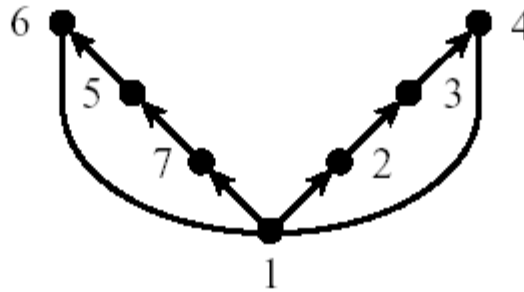
Complexity for csp: $\exp(\text{tree-depth})$

Complexity for csp: $\exp(w \cdot \log n)$

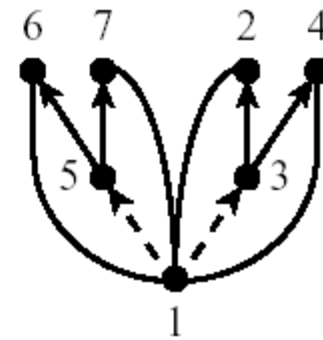
Complexity of Backjumping



(a)



(b)

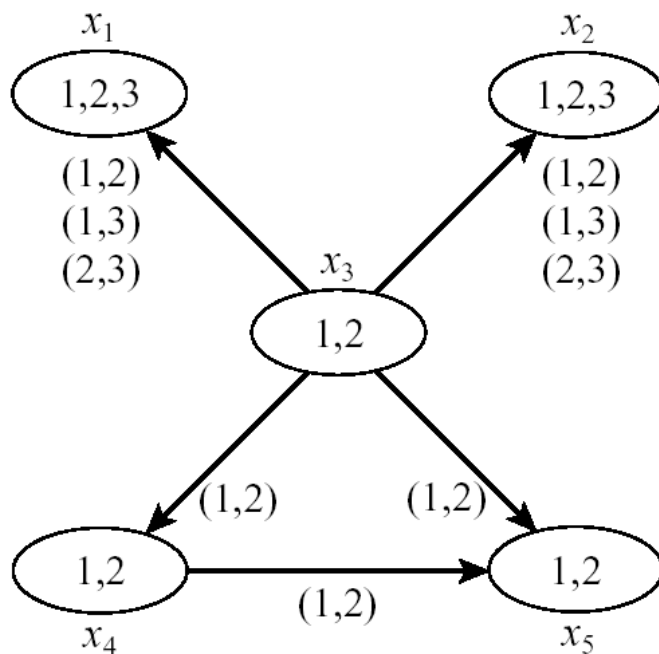


(c)

Theorem 6.5.5 *If d is a DFS ordering of (G^*, d_1) for some ordering d_1 , having depth m_d^* , then the complexity of graph-based backjumping using ordering d is $O(\exp(m_d^*))$.*

Look-back: No-good Learning

Learning means recording conflict sets used as constraints to prune future search space.



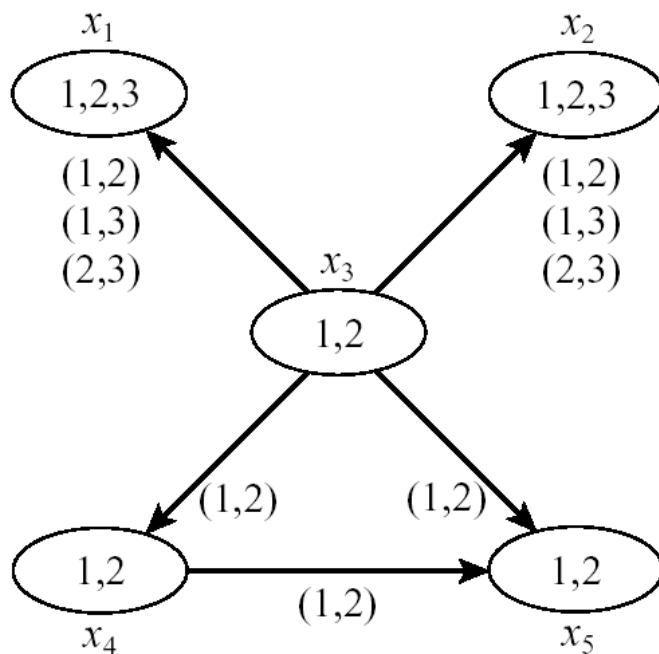
- $(x_1=2, x_2=2, x_3=1, x_4=2)$ is a dead-end
- Conflicts to record:
 - $(x_1=2, x_2=2, x_3=1, x_4=2)$ 4-ary
 - $(x_3=1, x_4=2)$ binary
 - $(x_4=2)$ unary

Learning, constraint recording

- Learning means recording conflict sets
- An opportunity to learn is when deadend is discovered.
- Goal of learning is to not discover the same deadends.
- Try to identify small conflict sets
- Learning prunes the search space.

Nogoods explain deadends

Learning means recording explanations to conflicts
They are implied constraints



- Conflicts to record are explanations
 - $(x_1=2, x_2=2, x_3=1, x_4=2)$ 4-ary
 - $(x_1=2, x_2=2, x_3=1, x_4=2) \rightarrow (x_5 \neq 1)$ and
 - $(x_3=1, x_4=2) \rightarrow (x_5 \neq 1)$
 - $(x_4=2) \rightarrow (x_5 \neq 1)$

Learning example

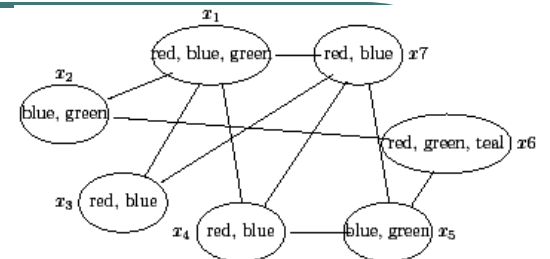
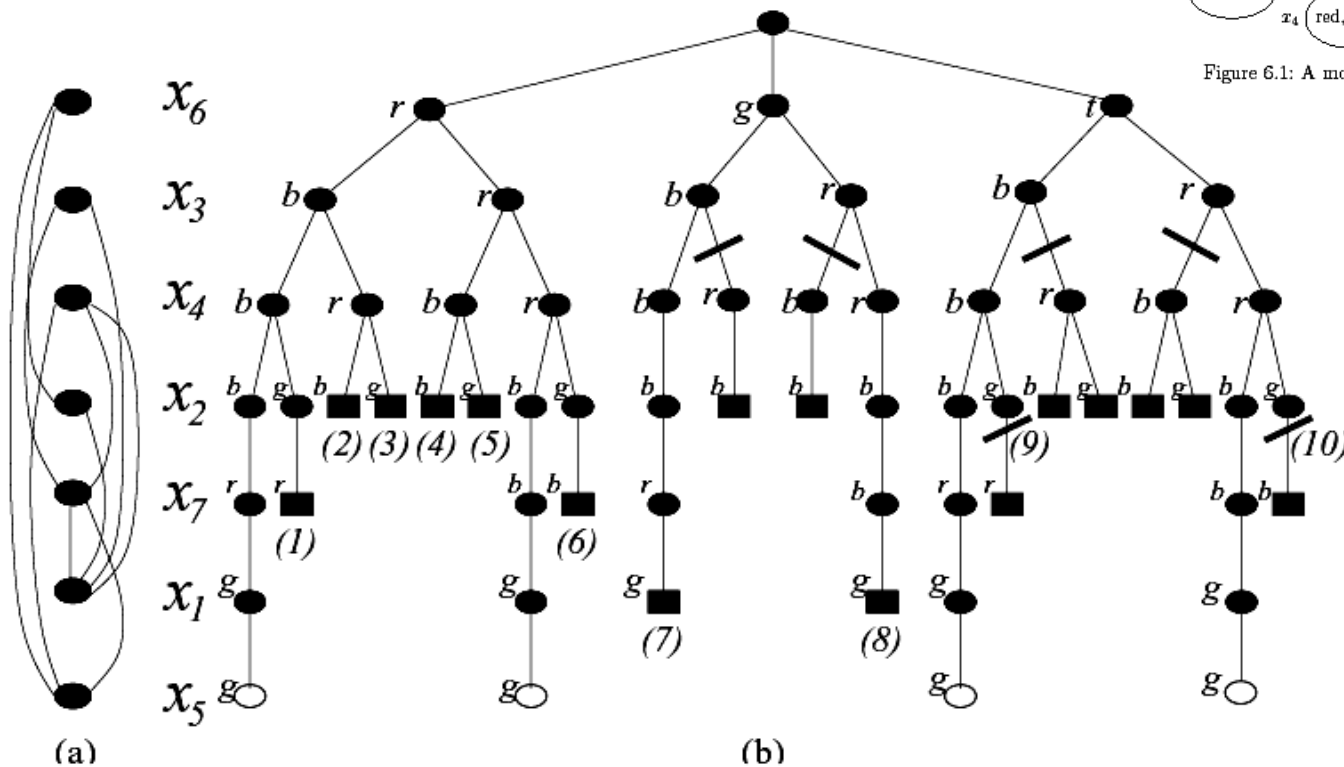


Figure 6.1: A modified coloring problem.

Figure 6.9: The search space explicated by backtracking on the CSP from Figure 6.1, using the variable ordering $(x_6, x_3, x_4, x_2, x_7, x_1, x_5)$ and the value ordering $(blue, red, green, teal)$. Part (a) shows the ordered constraint graph, part (b) illustrates the search space. The cut lines in (b) indicate branches not explored when graph-based learning is used.

Learning Issues

- Learning styles
 - Graph-based or context-based
 - i-bounded, scope-bounded
 - Relevance-based
- Non-systematic randomized learning
- Implies time and space overhead
- Applicable to SAT

Graph-based learning algorithm

procedure GRAPH-BASED-BACKJUMP-LEARNING

 instantiate $x_i \leftarrow \text{SELECTVALUE}$
 if x_i is null (no value was returned)
 record a constraint prohibiting $\vec{a}_{i-1}[I_i]$.
 $i_{prev} \leftarrow i$
 (algorithm continues as in Fig. 6.5)

Figure 6.10: Graph-based backjumping learning, modifying CBJ

Deep learning

- Deep learning: recording all and only minimal conflict sets
- Example:
- Although most accurate, overhead can be prohibitive: the number of conflict sets in the worst-case:

$$\binom{r}{r/2} = 2^r$$

Jumpback Learning

- Record the jumpback assignment

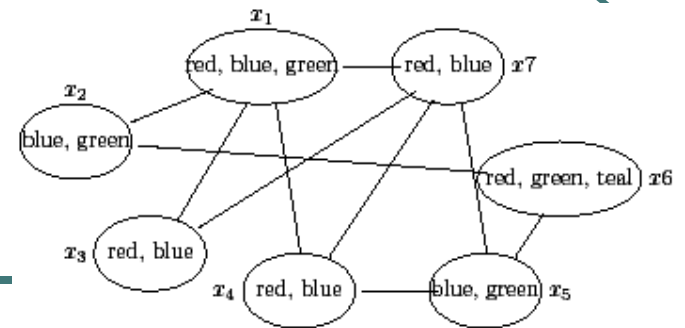


Figure 6.1: A modified coloring problem.

Example 6.7.2 For the problem and ordering of Example 6.7.1 at the first dead-end, jumpback learning will record the no-good ($x_2 = \text{green}$, $x_3 = \text{blue}$, $x_7 = \text{red}$), since that tuple includes the variables in the jumpback set of x_1 . □

procedure CONFLICT-DIRECTED-BACKJUMP-LEARNING

```

instantiate  $x_i \leftarrow \text{SELECTVALUE-CBJ}$ 
if  $x_i$  is null           (no value was returned)
  record a constraint prohibiting  $\vec{a}_{i-1}[J_i]$  and corresponding values
   $i_{prev} \leftarrow i$ 
  (algorithm continues as in Fig. 6.7)
  
```

Figure 6.11: Conflict-directed backjump-learning, modifying CBJ

Bounded and relevance-based learning

Bounding the arity of constraints recorded.

- When bound is i : i -ordered graph-based, i -order jumpback or i -order deep learning.
- Overhead complexity of i -bounded learning is time and space exponential in i .

Definition 6.7.3 (i -relevant) *A no-good is i -relevant if it differs from the current partial assignment by at most i variable-value pairs.*

Definition 6.7.4 (i 'th order relevance-bounded learning) *An i 'th order relevance-bounded learning scheme maintains only those learned no-goods that are i -relevant.*

Complexity of Backtrack-Learning for CSP

- The complexity of learning along d is time and space exponential in $w^*(d)$:

The number of dead-ends is bounded by $O(nk^{w^(d)})$
Number of constraint tests per dead-end are $O(e)$*

Space complexity is

$$O(nk^{w^*(d)})$$

Time complexity is

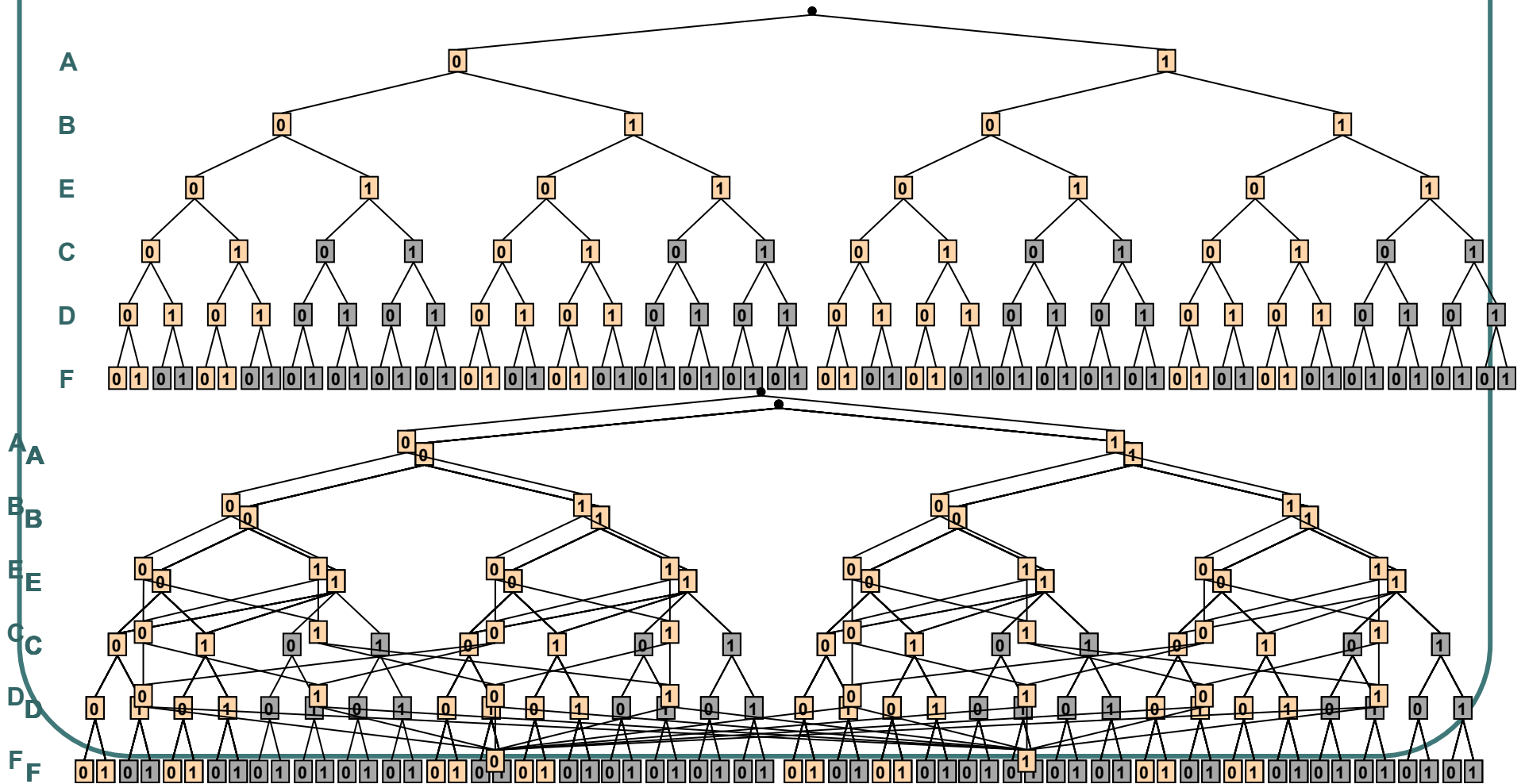
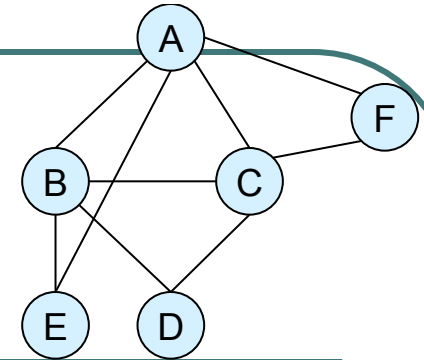
$$O(n^2 \cdot k^{w^*(d)+1})$$

Learning and backjumping:

$$O(nm \cdot k^{w^*(d)+1})$$

m- depth of tree, e- number of constraints

Good caching: Moving from one to all or counting



Summary:

Time-space for constraint processing (consistency and counting)

- **Constraint-satisfaction**

- - Search with backjumping
 - Space: linear, Time: $O(nk^{\log n w^*})$
 - Search with learning no-goods
 - time and space: $O(nk^{w^*})$
 - Variable-elimination
 - time and space: $O(nk^{w^*})$

- **Counting, enumeration**

- Search with backjumping
 - Space: linear, Time: $O(k^n)$
- Search with no-goods caching only
 - space: $O(\exp(w^*))$ Time: $O(\exp(n))$
- Search with goods and no-goods learning
 - Time and space: $O(\exp(\text{path-width}), O(\exp(\log n w^*)))$
- Variable-elimination
 - Time and space: $O(\exp(w^*))$

Non-Systematic Randomized Learning

- Do search in a random way with interrupts, restarts, unsafe backjumping, **but record conflicts**.
- Guaranteed completeness.

Look-back for SAT

- A partial assignment is a set of literals: σ
- A jumpback set if a J-clause:
- Upon a leaf deadend of x resolve two clauses, one enforcing x and one enforcing $\neg x$ relative to the current assignment
- A clause forces x relative to assignment σ if all the literals in the clause are negated in σ .
- Resolving the two clauses we get a nogood.
- If we identify the earliest two clauses we will find the earliest conflict.
- The argument can be extended to internal deadends.

Integration of algorithms

procedure FC-CBJ

Input: A constraint network $\mathcal{R} = (X, D, C)$.

Output: Either a solution, or a decision that the network is inconsistent.

```
 $i \leftarrow 1$                                 (initialize variable counter)
call SELECTVARIABLE                       (determine first variable)
 $D'_i \leftarrow D_i$  for  $1 \leq i \leq n$     (copy all domains)
 $J_i \leftarrow \emptyset$                  (initialize conflict set)
while  $1 \leq i \leq n$ 
    instantiate  $x_i \leftarrow \text{SELECTVALUE-FC-CBJ}$ 
    if  $x_i$  is null                        (no value was returned)
         $i_{prev} \leftarrow i$ 
         $i \leftarrow$  latest index in  $J_i$   (backjump)
         $J_i \leftarrow J_i \cup J_{i_{prev}} - \{x_i\}$ 
        reset each  $D'_k, k > i$ , to its value before  $x_i$  was last instantiated
    else
         $i \leftarrow i + 1$                 (step forward)
        call SELECTVARIABLE               (determine next variable)
         $D'_i \leftarrow D_i$ 
         $J_i \leftarrow \emptyset$ 
    end while
if  $i = 0$ 
    return "inconsistent"
else
    return instantiated values of  $\{x_1, \dots, x_n\}$ 
end procedure
```

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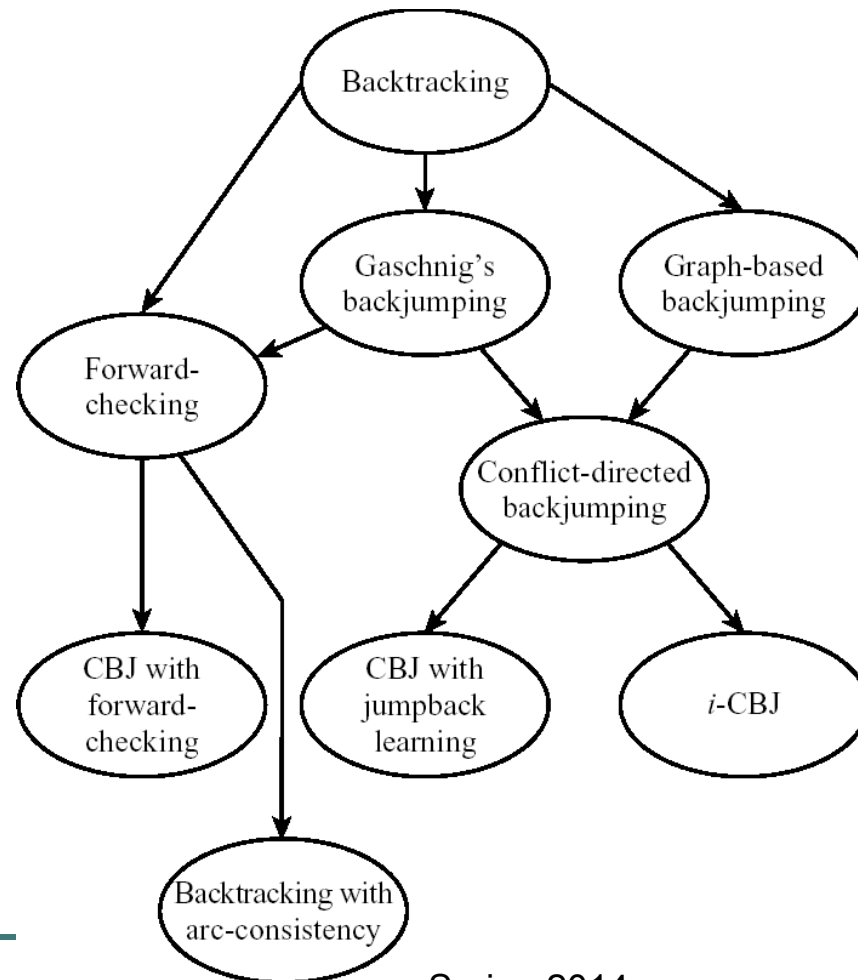
subprocedure SELECTVALUE-FC-CBJ

```
while  $D'_i$  is not empty
  select an arbitrary element  $a \in D'_i$ , and remove  $a$  from  $D'_i$ 
  empty-domain  $\leftarrow$  false
  for all  $k, i < k \leq n$ 
    for all values  $b$  in  $D'_k$ 
      if not CONSISTENT( $\vec{a}_{i-1}, x_i = a, x_k = b$ )
        let  $R_S$  be the earliest constraint causing the conflict
        add the variables in  $R_S$ 's scope  $S$ , but not  $x_k$ , to  $J_k$ 
        remove  $b$  from  $D'_k$ 
      endfor
    if  $D'_k$  is empty      ( $x_i = a$  leads to a dead-end)
      empty-domain  $\leftarrow$  true
    endfor
  if empty-domain      (don't select  $a$ )
    reset each  $D'_k$  and  $j_k, i < k \leq n$ , to status before  $a$  was selected
  else
    return  $a$ 
  end while
return null              (no consistent value)
end subprocedure
```

Figure 6.14: The SelectValue subprocedure for FC-CBJ.

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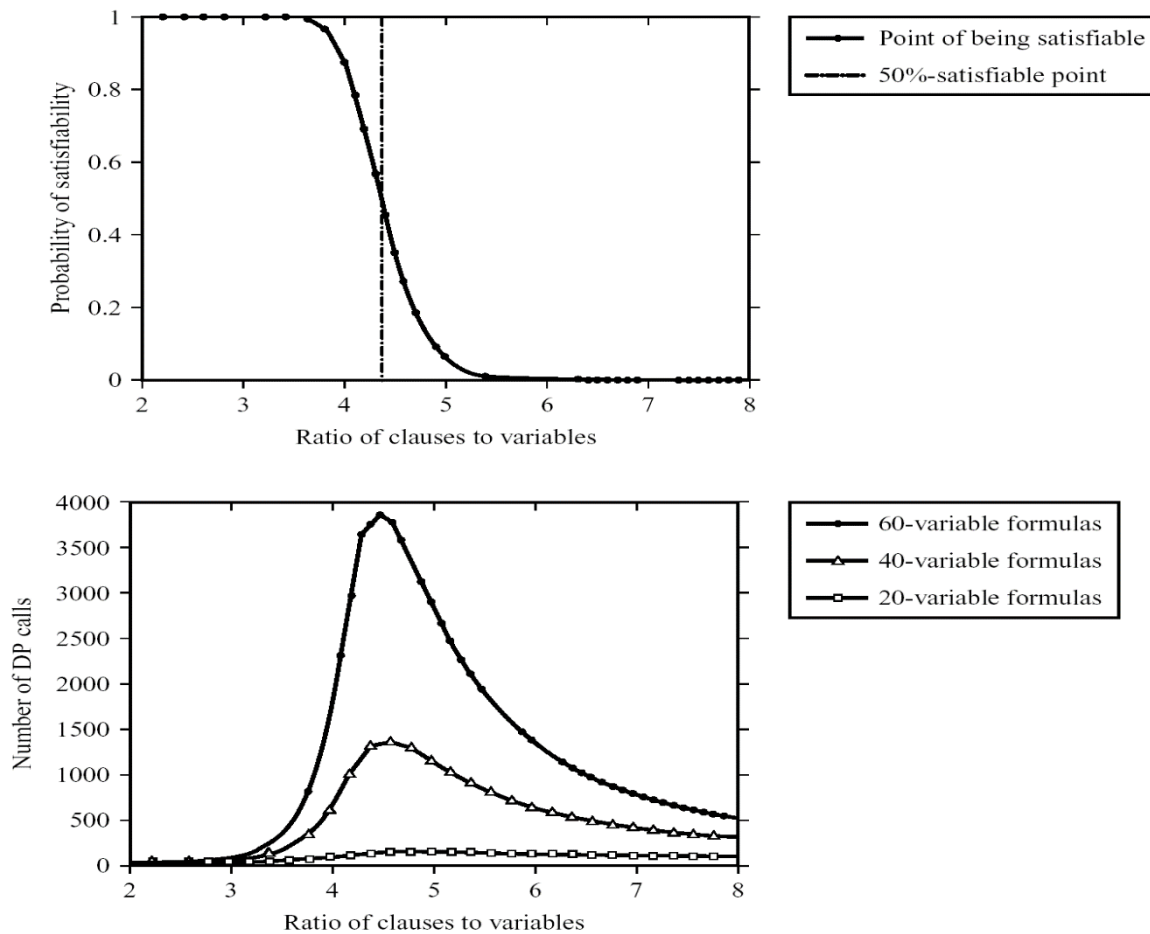
Relationships between various backtracking algorithms



Empirical comparison of algorithms

- Benchmark instances
- Random problems
- Application-based random problems
- Generating fixed length random k-sat (n,m) uniformly at random
- Generating fixed length random CSPs
- (N,K,T,C) also arity, r .

The Phase transition (m/n)



Some empirical evaluation

- Sets 1-3 reports average over 2000 instances of random csps from 50% hardness. Set 1: 200 variables, set 2: 300, Set 3: 350. All had 3 values.:
- Dimacs problems

| Algorithm | Set 1 | | Set 2 | | Set 3 | | ssa 038 | | ssa 158 | |
|----------------|-------|------|-------|-------|-------|-------|---------|------|---------|------|
| FC | 207 | 68.5 | - | - | - | - | 46 | 14.5 | 52 | 20.0 |
| FC+AC | 40 | 55.4 | 1 | 0.6 | 1 | 0.4 | 4 | 3.5 | 18 | 8.2 |
| FCr-CBJ | 189 | 69.2 | 222 | 119.3 | 182 | 140.8 | 40 | 12.2 | 26 | 10.7 |
| FC-CBJ+LVO | 167 | 73.8 | 132 | 86.8 | 119 | 111.8 | 32 | 11.0 | 8 | 4.5 |
| FC-CBJ+LRN | 186 | 63.4 | 32 | 15.6 | 1 | 0.5 | 23 | 5.5 | 19 | 8.6 |
| FC-CBJ+LRN+LVO | 160 | 74.0 | 26 | 14.0 | 1 | 3.8 | 16 | 3.8 | 13 | 7.1 |

Figure 6.16: Empirical comparison of six selected CSP algorithms. See text for explanation. In each column of numbers, the first number indicates the number of nodes in the search tree, rounded to the nearest thousand, and final 000 omitted; the second number is CPU seconds.