

ECE 510 OCE
 BDDs and Their Applications

**Lecture 14. Covering Problems and
 Two-Level Sum-of-Products
 Minimization**

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Overview

- Covering problems
 - Unate and binate covering problems
 - Branch-and-bound procedure
 - Explicit vs. implicit reduction of the covering table
- Two-level sum-of-products minimization
 - Irredundant cover computation (Minato/Morreale)
 - Explicit Quine-McCluskey procedure
 - Implicit Quine-McCluskey procedure based on formulas with quantifiers
 - Implicit minimization procedure based on transposing functions (Coudert/Madre)

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Unate Covering Problem (UCP)

- Given is the covering table F , each cell of which is filled with either 0 or 1. A subset of columns $S = \{s_i\}$ is called a solution of UCP, if for every row there exists a column in S having 1 on the intersection.
- If the cost function is defined, $\min[\sum_j (w_j \cdot s_j)]$, then the minimum solution of the covering problem is a solution, for which the cost function is minimum
- UPC is solved using branch-and-bound algorithm. The efficiency of this algorithm, to a large degree, depends on the quality of lower bound and upper bound used to prune the search space

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Example of UCP

x_1	x_2	x_3	x_4	x_5	x_6
1	-	1	-	-	-
-	1	-	1	-	1
-	-	1	1	1	-
-	1	-	-	-	1
1	-	-	-	-	1
-	-	1	1	1	-

- Solution 1:
 $\{x_1, x_2, x_5\}$
- Solution 2:
 $\{x_3, x_6\}$

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Branch-and-Bound Algorithm

```
BCP ( F, U, currentSol ) {
  (F, currentSol) = REDUCE(F, currentSol);
  if ( terminalCase(F) {
    if ( COST( currentSol < U )
      { U = COST( currentSol ); return (currentSol) }
    else return ("No solution");
  }
  L = LOWER_BOUND( F, currentSol );
  if ( L ≥ U ) return ("No solution");
  xi = CHOOSE_VAR( F );
  S1 = BCP( Fxi, U, currentSol ∪ {xi} );
  if ( COST(S1) = L ) return S1;
  S2 = BCP( Fxi', U, currentSol );
  return BEST_SOLUTION( S1, S2 ); }
```

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Reduction of Covering Table

```
reduce( R,C,U ) {
  do { CollapseColumns( C );
    RemoveDominatedColumns( R,C );
    Solution = Solution ∪ EssentialColumns( R,C );
    if ( |Sol| ≥ U ) return ∅;
    CollapseRows( R );
    RemoveDominatedRows( R,C );
  } while ( either R or C has changed );
  return ( R,C ); }
```

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Binate Covering Problem (BCP)

- Given the covering table F and the cost function $\min[\sum_j (w_j x_j)]$, BCP is formulated as follows
- Find a subset of columns $S = \{s_i\}$ of minimum cost such that for every row R_j either (1) $\exists_j: (F_{ij}=1), s_j \in S$ or (2) $\exists_j: (F_{ij}=0), s_j \notin S$
- BCP arises in incompletely-specified FSM state minimization, technology mapping, decomposition of functions with DCs, BDD minimization, etc.
- BCP is reduced to the problem of finding the shortest path on the BDD representing the product of all the constraints

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Example of BCP

x_1	x_2	x_3	x_4	x_5	x_6
1	-	1	-	-	-
-	1	-	1	-	1
-	-	0	1	1	-
-	-	-	-	-	0
0	-	-	-	-	0
-	-	1	0	1	-

- Solution 1: $\{x_1, x_2\}$
- Solution 2: $\{x_3, x_4\}$

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Reduction of UCP/BCP to Satisfiability

- Create the product of constraints for each column (see previous example)
 $F(x) = (x_1 + x_3) \& (x_2 + x_4 + x_6) \& (x'_3 + x_4 + x_5) \& x'_6$
 $\& (x'_1 + x'_6) \& (x_3 + x'_4 + x_5)$
- Find the shortest path in the BDD for $F(x)$

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Implicit Formulation of UCP/BCP

- If there are many columns (>100), the satisfiability approach does not work well
- The alternative method is:
 - (1) logarithmically encode columns and rows using two sets of variables c and r ,
 - (2) represent the covering table as a relation $U(c,r)$,
 - (3) apply the branch-and-bound procedure with implicit covering table reduction

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Example of Implicit Reduction Step: Finding/Collapsing Duplicated Columns

Duplicated columns can be computed as

$$\text{dup_col}(c_1, c_2) = \forall r [R(r) \Rightarrow (1(r, c_1) \Leftrightarrow 1(r, c_2))]$$

Duplicated columns can be collapsed by

$$C(c_1) = C(c_1) \& \exists c_2 [C(c_2) \& (c_2 < c_1) \& \text{dup_col}(c_1, c_2)],$$

where $(c < c')$ is the relation which is true for c and c' if the binary code of c is less than that of c'

$$(x < y) = x'_1 \& y_1 \mid x'_1 \& y'_1 \& x'_2 \& y_2 \mid x'_1 \& y'_1 \& x'_2 \& y'_2 \& x'_3 \& y_3 \mid \dots$$

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Two-Level SOP Minimization

- Approximate minimization
 - Irredundant cover computation (Minato/Morreal algorithm)
- Exact minimization
 - Explicit Quine-McCluskey procedure
 - Implicit Quine-McCluskey procedure based on formulas with quantifiers
 - Minimization procedure based on transposing functions (Coudert/Madre algorithm)

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Implicit Cube Representation

- To represent cubes of n-variable function $F(x_1, x_2, \dots, x_n)$, two sets of n vars are used: signature variables $S = (s_1, s_2, \dots, s_n)$ and polarity variables $P = (p_1, p_2, \dots, p_n)$
 s_i variable is true iff i-th variable is present in the cube; p_i variable is true iff i-th variable enters this cube in positive polarity
- For example, cube $x_2 x_3' x_4$ is represented by the pair [(0111), (-101)]

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Observations

- All cube sets in two-level minimization algorithms are represented using characteristic functions depending on signature and polarity variables
- Graph representations of cube sets using Zero-Suppressed BDDs have 2-5 times less nodes than classical BDDs

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Irredundant Cover Computation

- The main idea of irredundant cover computation is to divide the cover into three part
 - the one that has literal x_k in negative polarity
 - the one that has literal x_k in positive polarity
 - the one that does not have literal x_k at all
- These three sets are computed independently by calling irredundant cover recursively for problems of smaller size. Finally, the resulting cover is assembled from the parts

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Complete Source Code for IrrCover()

```
bdd IrrCover( bdd F1, bdd F12, int k )
{
  if ( F1 == bddfals ) return bddfals;
  if ( F12 == bddtrue ) return AllS0VarsZeros[k];
  // check cache for results
  bdd F1_low = bdd_restrict( F1, !P0Vars[k] );
  bdd F1_high = bdd_restrict( F1, P0Vars[k] );
  bdd F12_low = bdd_restrict( F12, !P0Vars[k] );
  bdd F12_high = bdd_restrict( F12, P0Vars[k] );
  bdd g0 = F1_low & !F12_high;
  bdd P0 = IrrCover( g0, F12_low, k+1 );
  bdd g1 = F1_high & !F12_low;
  bdd P1 = IrrCover( g1, F12_high, k+1 );
  bdd c0 = bdd_exist( P0, S0Vars );
  bdd c1 = bdd_exist( P1, S0Vars );
  bdd h1 = ( F1_low & !c0 ) | ( F1_high & !c1 );
  bdd h12 = F12_low & F12_high;
  bdd P = IrrCover( h1, h12, k+1 );
  bdd Cover = (S0Vars[k] & P) | (S0Vars[k] & !P0Vars[k] & P0) | (S0Vars[k] & P0Vars[k] & P1);
  // insert the result into cache
  return Cover;
}
```

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Coudert/Madre Minimization Procedure

- Recursively build implicit representations of all primes and all minterms
- Iteratively transform cube sets by applying transposing functions; remove essential cubes after each iteration
- Solve the resulting cyclic core (if any) using explicit branch-and-bound techniques

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Source Code for BuildPrimeCubeSet()

```
bdd BuildPrimeCubeSet( bdd F, int k )
{
  if ( F == bddfals ) return bddfals;
  if ( F == bddtrue ) return g_AllSVarsZeros[k];
  // check cache for results
  bdd F_low = bdd_restrict( F, !g_XVars[k] );
  bdd F_high = bdd_restrict( F, g_XVars[k] );
  bdd P = BuildPrimeCubeSet( F_low & F_high, k+1 );
  bdd P0 = BuildPrimeCubeSet( F_low, k+1 ) - P;
  bdd P1 = BuildPrimeCubeSet( F_high, k+1 ) - P;
  bdd Setn = !g_SVars[k] & P;
  bdd Set0 = g_SVars[k] & !g_PVars[k] & P0;
  bdd Set1 = g_SVars[k] & g_PVars[k] & P1;
  bdd Result = Setn | Set0 | Set1;
  // insert the result into cache
  return Result;
}
```

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