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Optimal Tile Salvage

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ABSTRACT

A map is a tiling of a finite region of the plane with unit squares such that some tiles have been removed. The optimal $x \times y$ -Tile Salvage Problem is: Given a map, find the maximum number of non-overlapping $x \times y$ tiled rectangles. A polynomial time algorithm is given for the 1×2 case, i.e., adjacent pairs. It is shown that the problem is NP-complete for the 2×2 case. A polynomial time algorithm is presented for finding 2×2 groups that is no worse than one half optimal. The problem is motivated by a technique for increasing the size of very large scale integrated (VLSI) circuit chips.

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Introduction

In very large scale integrated (VLSI) circuit technology, there is a continuing effort to place more transistors on a chip. Although this is often accomplished by making the devices denser with more sophisticated processing technology, the necessary equipment is complex and expensive, and the procedures are very exacting. Another approach is to make the chips larger. But for a fixed fabrication process this causes a reduction in yield, i.e., a reduction in the average number of error-free chips per process run [1, 2]. An alternative method of increasing the number of transistors per chip is to use configurability [3, 4].

Recall that chips are regions of a larger unit called a "wafer." Ordinarily after fabrication a wafer is tested and faulty chips are marked; then the wafer is diced using scribing corridors provided for the purpose, the faulty chips are discarded, and the functional chips are packaged. To use configurability, this process is changed somewhat. Special circuitry is added in the scribing corridors that enables adjacent chips to be connected. Then, after the wafer is tested, adjacent functional chips are connected into a group and the entire group is used as a single enlarged chip.

For example, a large circuit can be divided into two parts, A and B , and the wafer can be laid out in a checkerboard pattern of alternating A and B die types. After testing, adjacent functional A , B pairs can be located. Each pair can be diced as a unit and configured to yield a double chip that implements the large circuit.

Notice that in the checkerboard pattern, there are four adjacent B 's with which each A could be paired. Choosing a particular B could influence which B 's are available to pair with other A 's. The problem is to find the *maximum* number of adjacent A , B pairs given a map of the error-free dice on the wafer. The purpose of this paper is to show that this problem can be solved in polynomial time, that important generalizations of this problem are NP-complete, and that there is a linear-time algorithm for approximating the NP-complete problem.

Preliminaries

A map is an $n^{\frac{1}{2}} \times n^{\frac{1}{2}}$ region of the plane tiled with unit squares some of which have been removed. The tiles represent functional chips and the interstices represent faulty chips (see Figure 1). The optimal x, y Tile Salvage Problem is to find the maximum number of non-overlapping $x \times y$ tiled rectangles. The orientation of the rectangles does not matter. For example, the selection of A , B pairs mentioned above is an instance of the 1×2 Tile Salvage Problem. The intended semantics, that each group contain an A and a B , is accomplished by patterning the wafer in an A , B checkerboard.

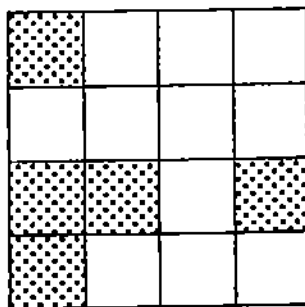


Figure 1. A map; $n = 16$.

Related problems have been studied. In the context of the Tile Salvage Problem, Fowler, Paterson and Tanimoto [7] show that the 3×3 case is NP-complete. (They left open the question for smaller rectangles.) They also found closely related covering problems NP-complete as has Masek [8]. Partitioning problems have also been considered and these have shown a remarkable variety [9-11]. See also Johnson [12].

The 1×2 Case

The selection of the maximum number of adjacent pairs of tiles, i.e., the 1×2 Tile Salvage Problem, can be accomplished in polynomial time. To prove this, label the tiles in a checkerboard pattern of alternate A 's and B 's. By interpreting the problem as an instance of the "marriage" problem (2-dimensional matching), we can obtain a polynomial solution [5]. In particular, let the A tiles in the map correspond to "girls" and the B tiles correspond to "boys" in the 2-dimensional matching problem. The maximum set of girl-boy pairs gives the maximum set of mutually non-intersecting 1×2 rectangles. See Figure 2.

The 2×2 Case

The complexity of the problem changes dramatically if we consider circuits which can be divided into four mutually adjacent tiles. Consider

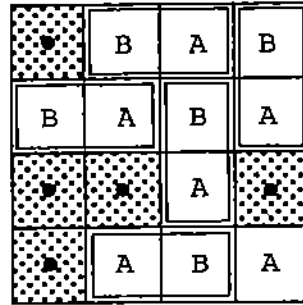


Figure 2. An optimal selection for the 1×2 Tile Salvage Problem. maps with alternating rows of two types: one type with alternating A and B dice and one type with alternating C and D dice. See Figure 3.

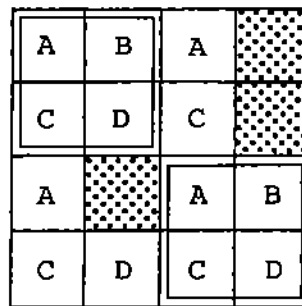


Figure 3. Checkerboard Pattern with A, B, C, D Die Types.

Each die can participate as a component in four different 2×2 tiles. The problem, as before, is to find the maximum number of non-overlapping 2×2 tiled rectangles given a map. In this section we show that the 2×2 Tile Salvage Problem is NP-complete. It is interesting to notice that in both the 1×2 case and the 2×2 case the number of rectangles a single die can participate in is the same, although the complexity of the two problems is quite different.

Let the Tile Salvage Predicate be defined as the statement

"Given a map and an integer z , are there at least z non-overlapping 2×2 tiled rectangles in the map?"

Clearly the problem is in NP. To complete the argument, our strategy

will be to show that the NP-complete problem Planar 3-SAT [6] can be reduced to the Tile Salvage Predicate in polynomial time.

Planar 3-SAT can be defined as follows: Let B be a formula with clauses c_1, \dots, c_m and variables v_1, \dots, v_n . Assume that B is in conjunctive normal form with at most 3 literals per clause. Define $G(B)$ to be the undirected graph with vertices V and edges E where

$$V = \{v_1, \dots, v_n\} \cup \{c_1, \dots, c_m\}$$

$$E = \{\{v_i, v_{i+1}\} \mid 1 \leq i < n\} \cup \{\{v_n, v_1\}\} \cup$$

$$\{\{c_i, v_j\} \mid \text{if } v_j \text{ or } -v_j \text{ occurs in } c_i\}.$$

Lichtenstein defines Planar 3-SAT to be the statement

"Given a formula B in conjunctive normal form with at most 3 literals per clause and for which $G(B)$ is planar, is there an assignment of values to variables for which B has the value true?"

Lichtenstein has shown that Planar 3-SAT is NP-Complete [6].

It will be convenient to adopt a new representation for maps and new vocabulary. For the remainder of the paper, a map will be a graph formed by placing a vertex at the center of each (1×1) tile and connecting it to any vertices that are a unit distance away (see Figure 4). It is easy to see that the 2×2 Tile Salvage Problem on the graph form of the map is simply that of selecting the maximum number of non-intersecting unit square regions. For brevity, we will hereafter call these unit squares "tiles," and understand that they actually represent 2×2 rectangles.

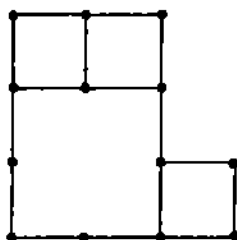


Figure 4. Alternate map representation based on Figure 3.

Theorem: *The 2×2 Tile Salvage Problem is NP-complete.*

Proof: It is easy to show that the 2×2 Tile Salvage Problem is in NP. For the reduction, we will take an arbitrary instance B of Planar 3-SAT and show that there is a satisfying assignment of truth values to B if and only if there are at least z non-intersecting 2×2 rectangles on a map C_B . The map C_B and parameter z will depend upon the structure of B .

By definition, $G(B)$ is planar and of a special form: There are nodes representing both variables and clauses, edges linking variables, and edges linking variables and clauses. We will represent the variables in $G(B)$ by constructs called *generators*, the clauses in $G(B)$ by constructs called *receptors*, and edges in $G(B)$ by constructs called *transmission lines* in the map C_B .

To construct the generator for a node v_i , consider the graph $G(B)$. v_i has edges to v_{i-1} , v_{i+1} and to some set of clauses c_{i_1}, \dots, c_{i_k} . Construct the following generator to represent v_i in C_B : The ring of the generator is a rectangular structure without corners of $2g_i$ tiles. Adjacent transmission lines should be separated by at least two tiles. The transmission lines corresponding to consecutive positive or consecutive negative occurrences of v_i should be separated by an odd number of tiles. The transmission lines corresponding to consecutive complementary occurrences (a positive occurrence and a negative occurrence) should be

separated by an even number of tiles. The transmission lines linking the generator for v_i with the generators for v_{i-1} and v_{i+1} should each have an odd number of tiles. See Figure 5.

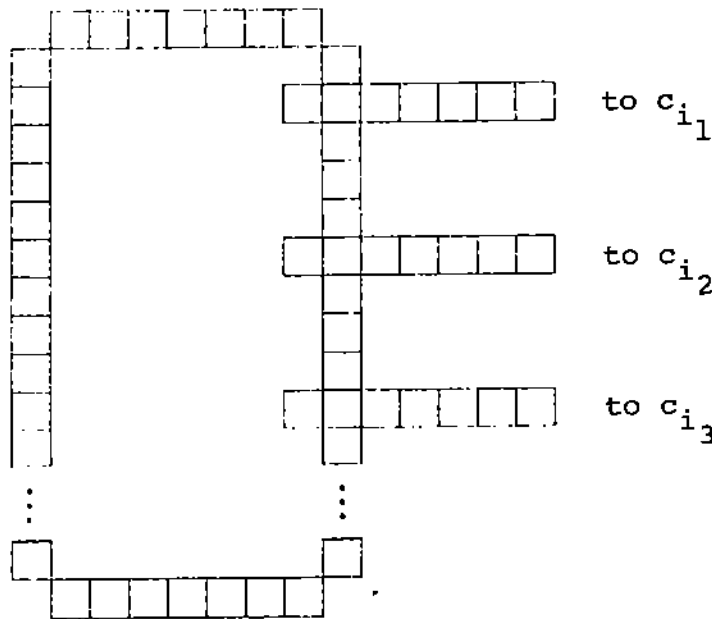


Figure 5. Generator for v_i Transmission Lines.

To construct the receptor for the clause c_i , we observe that in $G(B)$, the node representing c_i has degree between 1 and 3. Let $v_{i_1}, v_{i_2}, v_{i_3}$ be the literals in clause c_i . Construct the following receptor to represent c_i .

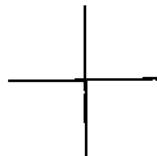


Figure 6. Receptor for c_i without transmission lines.

The transmission lines from $v_{i_1}, v_{i_2}, v_{i_3}$ each fit into a corner of the receptor (in no particular order) as follows:

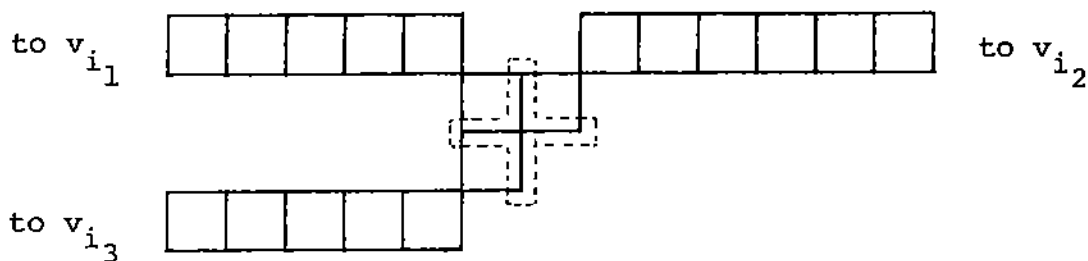
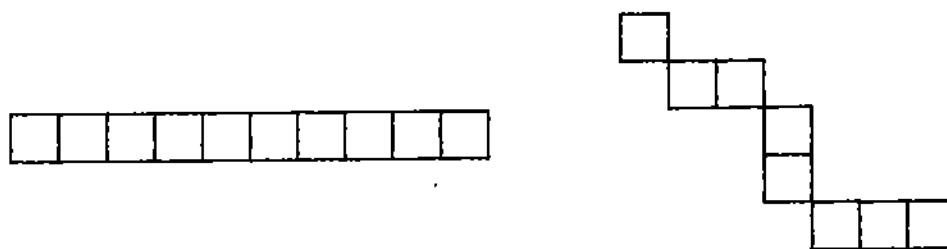


Figure 7. Receptor with Transmission Lines to $v_{i_1}, v_{i_2}, v_{i_3}$.

The edges connecting the variables and linking the variables and clauses in $G(B)$ will be represented by transmission lines in the map. A horizontal transmission line is essentially a row of tiles. These lines may be bent vertically or diagonally on the lattice as shown in Figure 8.



Horizontal Transmission Line Non-Horizontal Transmission Line

Figure 8.

We define the length of a transmission line to be the number of tiles which compose the transmission line. We will always count the tiles on a transmission line from the *innermost* tile emanating from the generator.

This completes the translation of the components of the graph $G(B)$ to portions of the map C_B . C_B can now be constructed from the above specifications with the following additional requirements:

- 1) Transmission lines between generators should be composed of an odd number of tiles.
- 2) Transmission lines between generators and receptors should be

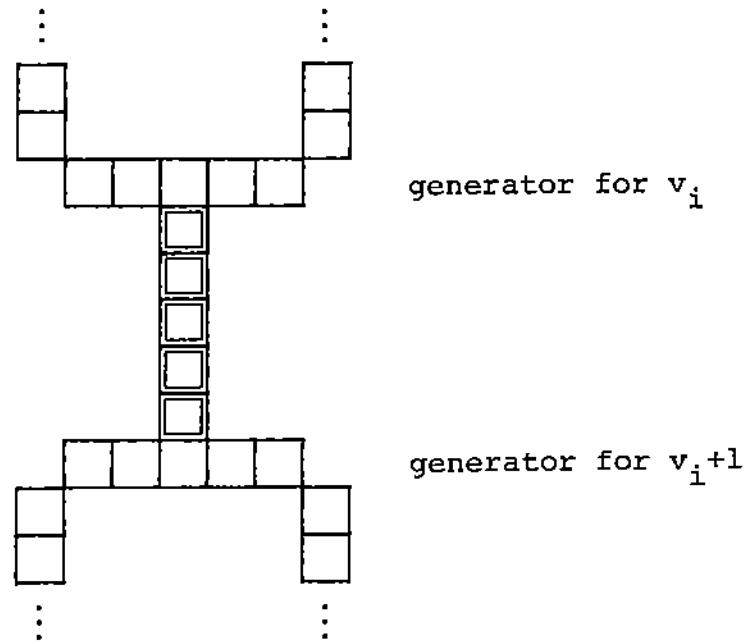


Figure 9. Transmission Line (Highlighted) Between the Generators for v_i and v_{i+1} .

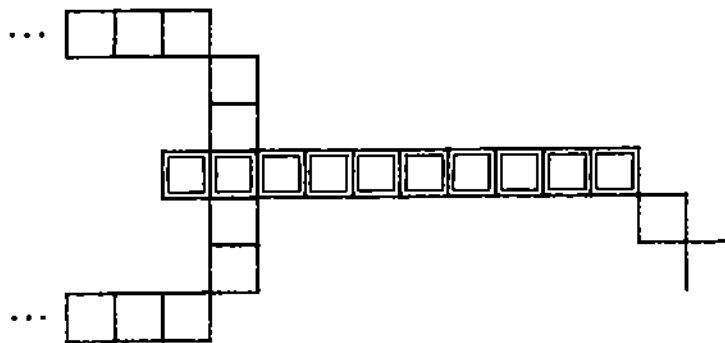


Figure 10. Transmission Line (Highlighted) from a Generator to a Receptor with 10 Tiles.

composed of an even number of tiles. This does **not** include the tile incident to the middle node of the receptor.

- 3) Non-intersecting components of the map should always be separated by at least two tiles.
- 4) The construction can proceed without regard to parity constraints. Once the diagram has been constructed, the parity of

any line segment can be set by first refining the grid, say by a factor of 10. If the line segment has the right parity, we are done. Otherwise, by the dilation, there is a straight line segment of length at least seven tiles that can be replaced by the sequence given in Figure 11. This changes the parity of the number of tiles and because of the dilation, preserves the tile separation constraints.

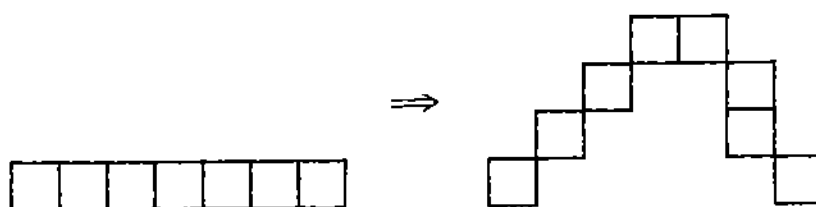


Figure 11. Dilation to Change the Parity of a Line.

As an example of our construction, let B be the formula $(v_1 + v_2 + v_3)(-v_1 + v_4 + v_5)$. One way of constructing $G(B)$ is shown in Figure 12.

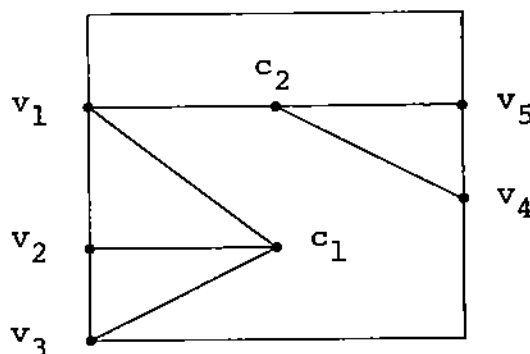


Figure 12. $G(B)$.

Clearly $G(B)$ is planar. Figure 13 shows the map C_B produced using the preceding construction. Note the parity fix used in the transmission line from the generator for v_3 to the receptor for c_1 .

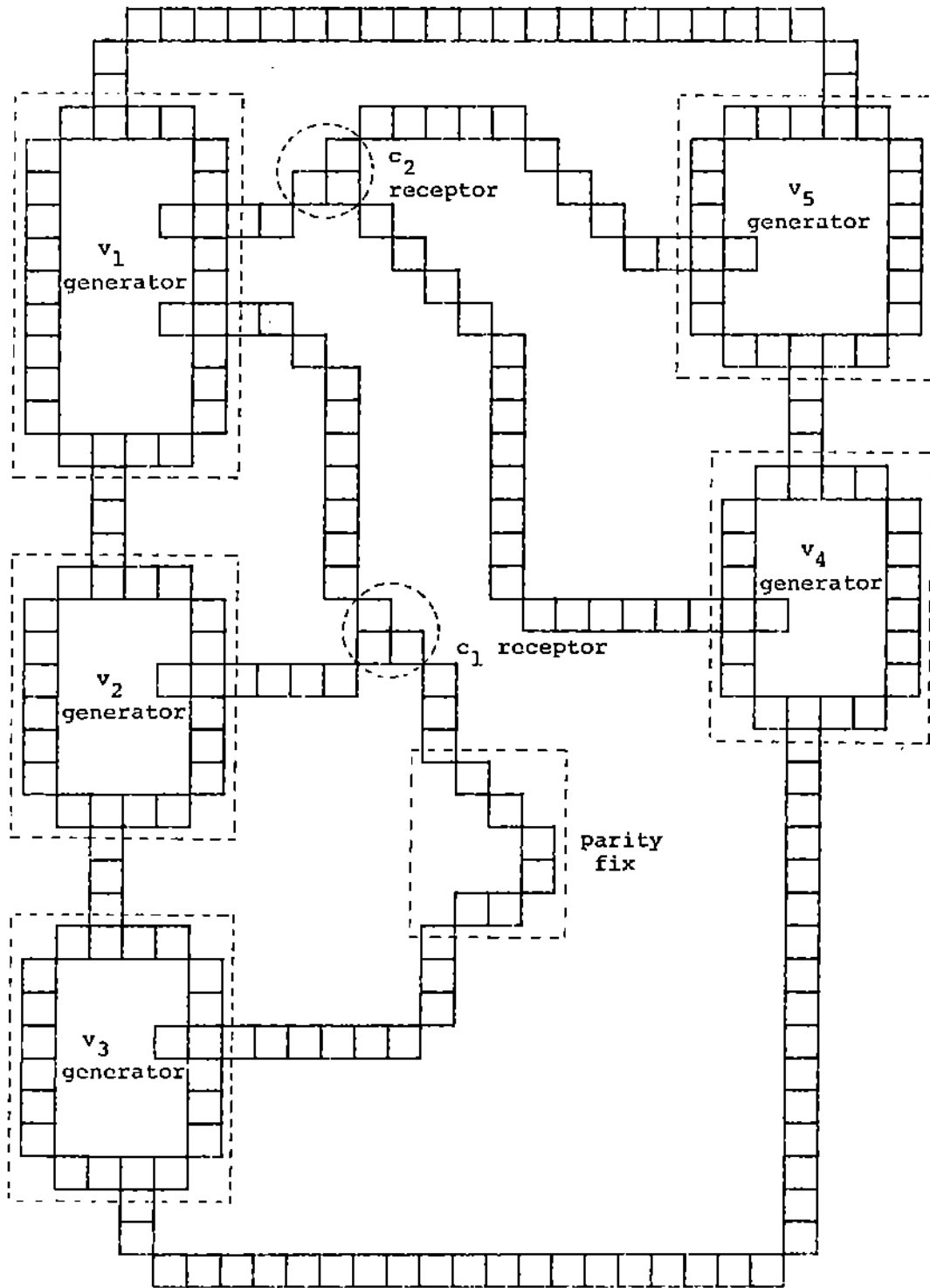


Figure 13. The map C_B for $G(B)$.

Let C_B be the map composed of the generators, receptors and transmission lines which represent the nodes and edges of $G(B)$. Clearly the construction of C_B from $G(B)$ can be accomplished in polynomial time. To determine the parameter z , let $\{v_1, \dots, v_n\}$ be the variables occurring in B and $\{c_1, \dots, c_m\}$ be the clauses. By construction, for each i , the ring of the generator for v_i is composed of $2g_i$ tiles. Let $2t_i + 1$ be the number of tiles in the transmission line linking the generator for v_i with the generator for v_{i+1} ($2t_n + 1$ will be the number of tiles in the line between the v_n generator and the v_1 generator). Similarly, let $2t$ represent the *total* number of tiles in all transmission lines linking a generator and a receptor. Say there are y of these.

Given the parameters described above, we let $z = \sum_{i=1}^n g_i + \sum_{i=1}^n t_i + t + m - y$. Recall that if $2g_i$ gives the number of tiles which are in the generator for v_i and $2t$ gives the number of tiles in all transmission lines between generators and receptors, then subtracting y ensures that we do not count twice the tiles which are both in a transmission line and on the ring of some generator. Recall also that m is the number of receptors (clauses) each of which will contribute one tile if and only if B is satisfiable. For example, for the formula B with map C_B given in Figure 13, $z=120$. An assignment of non-overlapping tiles to C_B is shown in Figure 14.

To review, given formula B in 3CNF and planar $G(B)$, we have shown how to construct the map C_B and determine the parameter z in polynomial time. To complete our reduction, we must show that there are at least z non-intersecting tiles in C_B iff there is a satisfying assignment of truth values to $\{v_1, \dots, v_n\}$ in B .

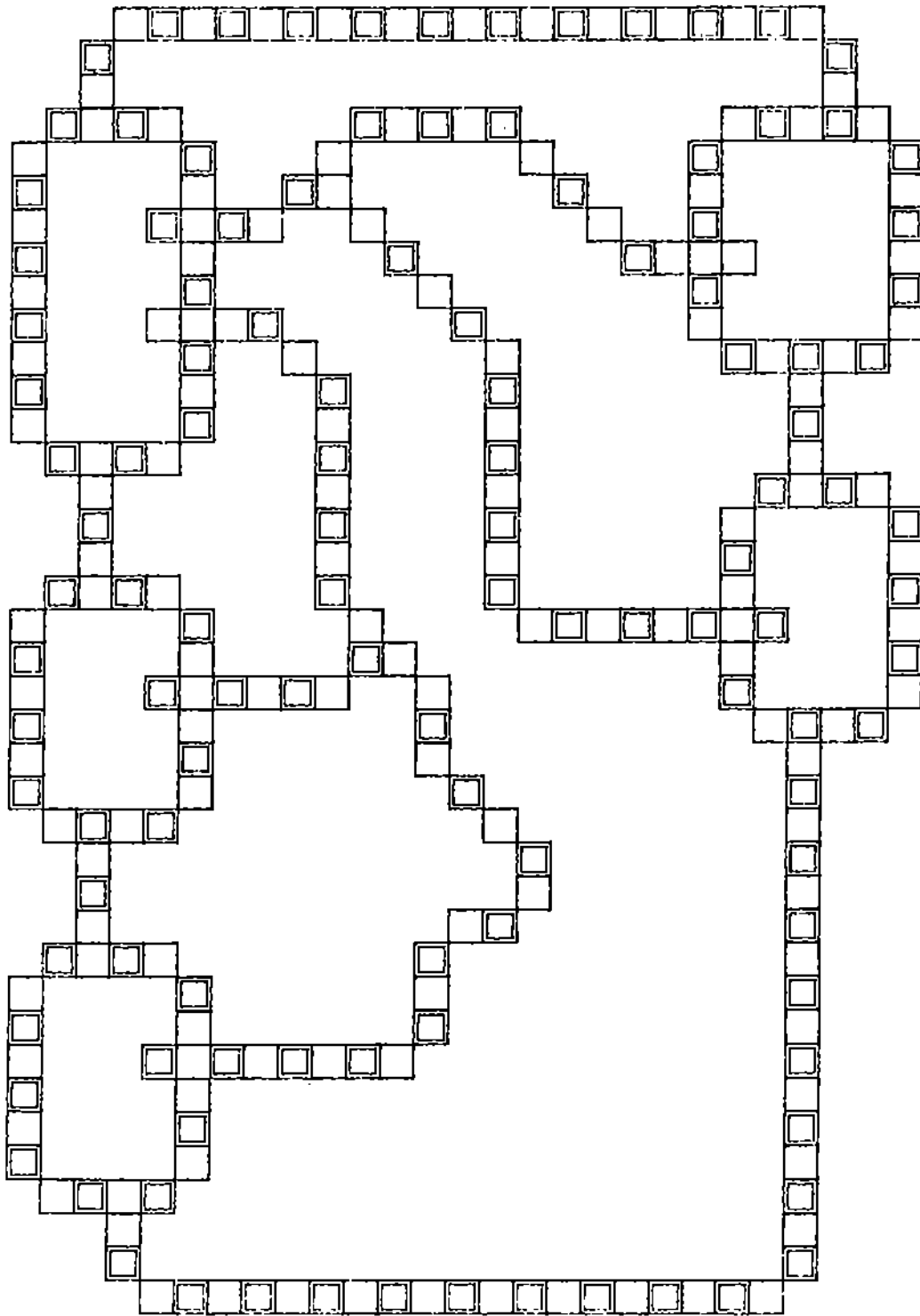


Figure 14. Non-Intersecting Tiles on the Map C_D .

For the first direction, assume that there are z non-intersecting tiles in the map C_B . Then by construction, for each j , the receptor for c_j contains a transmission line whose assignment of non-intersecting tiles includes a tile incident to the middle node of c_j .

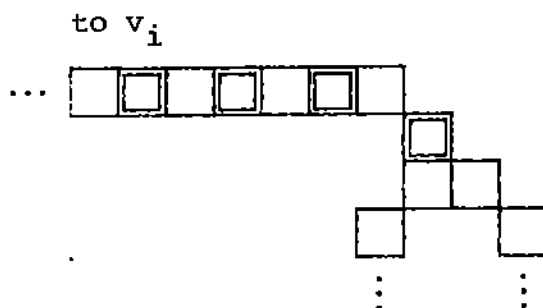


Figure 15. Receptor for c_j in S .

Let v_i be the variable generator from which this transmission line emanates. Then assign the literal corresponding to v_i in c_j with the value true.

Do this for every receptor (clause). Note that if there is an assignment of values to $\{v_1, \dots, v_n\}$ consistent with this assignment then B will be satisfiable. We will show that we can find at least z non-intersecting tiles only if it is impossible for literals v_i and $\neg v_i$ both to be assigned the value true by the given procedure.

Assume without loss of generality that v_i appears in c_1 and $\neg v_i$ appears in c_2 . Then the v_i generator has the form given in Figure 16

where the ring has $2g_i$ tiles. Assume towards a contradiction that there are z non-intersecting tiles in C_B with the corresponding assignment of true to both v_i and $\neg v_i$. Then the assignment of non-intersecting tiles to both the transmission lines to c_1 and c_2 are incident to the middle nodes of those receptors. Hence without loss of generality, the generator for v_i can be assigned non-intersecting tiles as in Figure 17.

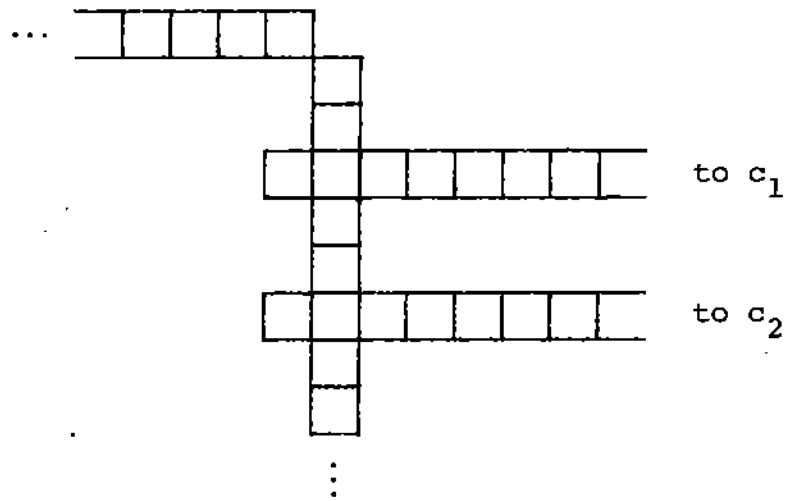


Figure 16. The Generator for v_i .

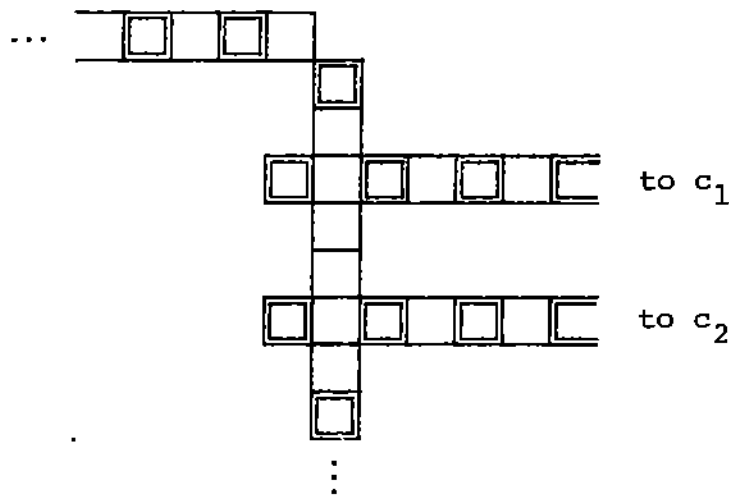
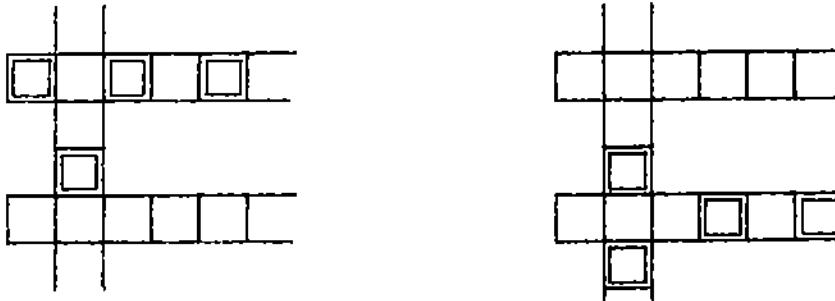


Figure 17. Assignment of Tiles to the v_i generator.

If the transmission lines are completely assigned with non-intersecting tiles, the generator ring can be assigned with at most $g_i - 3$ non-intersecting tiles. Note that if all other transmission lines and receptors are completely assigned with non-intersecting tiles, we can still only achieve a count of $z - 1$ tiles contradicting our hypothesis. In particular, unless we shift the non-intersecting tiles towards their receptor three places on one of the transmission lines *and* their receptor can preserve

its contribution of one tile (incident to the middle node but from another transmission line), we will not be able to achieve an assignment of z non-intersecting tiles in the map. Hence if there is an assignment of z non-intersecting tiles in C_p , we can construct a consistent assignment of values to variables so that B will be satisfiable.

For the other direction, assume that the formula B is satisfiable. Then there is an assignment of values to variables so that in each clause, there is at least one literal with the value true. Consider the generator for variable v_i . Assume without loss of generality that v_i has been assigned the value true by the satisfying assignment. (The argument is analogous if $\neg v_i$ is assigned the value true). Mark the innermost tile of each transmission line in the v_i generator which corresponds to v_i . For the complementary literal $\neg v_i$, mark the first tile incident to the innermost three tiles of each transmission line in the v_i generator. In addition, mark the tiles in the generator ring adjacent to all transmission lines corresponding to the literal $\neg v_i$. See Figure 18.



Assignment for a True Literal

Assignment for a False Literal

Figure 18.

Propagate this assignment of non-intersecting tiles around the generator ring until the ring is filled as completely as possible. Since complementary occurrences of the variable are separated by an even number

of tiles and same-value occurrences of the variable are separated by an odd number of tiles, this assignment will contribute $g_i - x$ tiles where x is the number of transmission lines corresponding to a true literal. Next, fill the transmission lines from the generator as completely as possible to the receptor with an assignment of non-intersecting tiles. Leave unmarked all tiles in each receptor incident to the middle node.

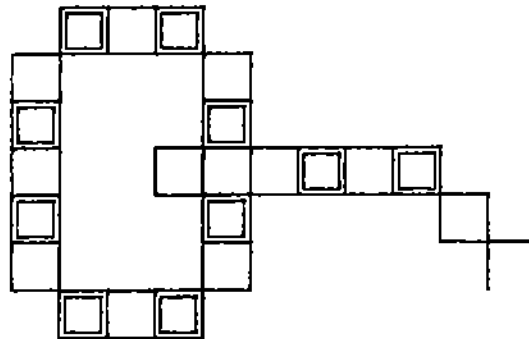


Figure 19. Assignment of Tiles to Generator and Transmission Lines for a false literal.

Assign tiles to the transmission lines linking the generators as completely as possible.

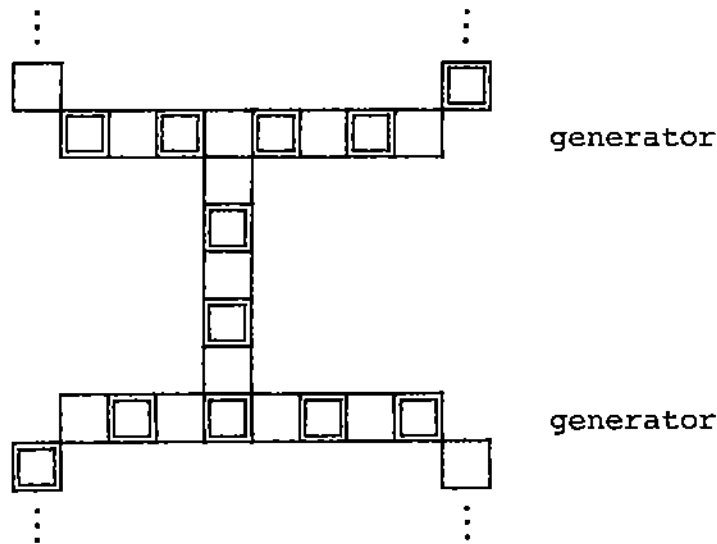


Figure 20. Assignment of Tiles to Lines Between Generators.

The assignment is now complete except for the receptors. Since we were given a satisfying assignment to the formula B , there is at least one literal v^* in each clause c_i which has been assigned the value true. By construction, the transmission line for v^* has an assignment of non-intersecting tiles which has been propagated from the innermost tile of its generator to the receptor for c_i . Since the length of v^* 's transmission line from the innermost tile to the receptor (not including the tile in the receptor incident to the middle node) is even, the last tile in the transmission line is unmarked. Hence we can mark the tile in the receptor incident to both the middle node and the transmission line for v^* adding one tile from c_i to the assignment of non-intersecting tiles on the map. Do so for every receptor (clause).

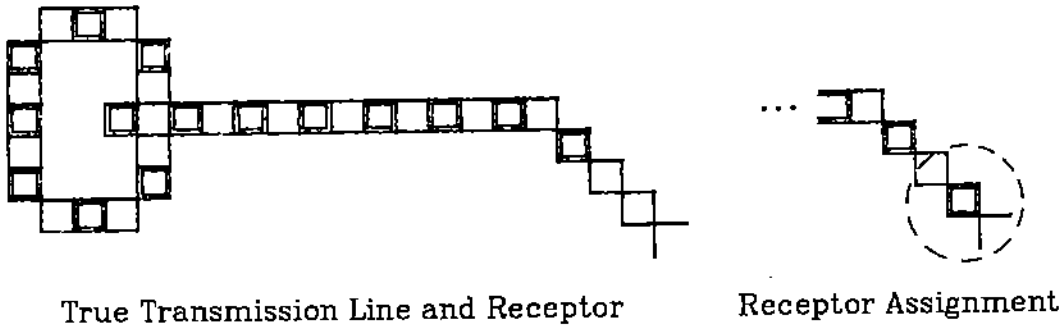


Figure 21.

By construction, we have created an assignment of z non-intersecting tiles in C_B from the satisfying assignment of values to variables in B . Hence the 2×2 Tile Salvage Problem is NP-Complete. ■

An Approximation Algorithm

In this section we show that a greedy algorithm serves as a linear time approximation algorithm for the 2×2 Tile Salvage Problem. (N.B. We continue to use our "map" and "tile" notions.)

Given a map, the algorithm is simply stated: Repeatedly select the leftmost, uppermost tile, and remove it and its incident edges from the map. See Figure 22. The algorithm terminates when the map is empty or has become a collection of disconnected line segments, and obviously requires only a linear amount of time.

In order to assess the algorithm's effectiveness, let OPT_M be the solution for a given map M of the 2×2 Tile Salvage problem.

Theorem: For a given map M , the algorithm finds a solution that is at least $\frac{1}{2}OPT_M$.

Proof: Let M be a map and apply the algorithm. The algorithm induces a partitioning of the tiles of the map as follows: Each subset of tiles contains a selected tile and those tiles having as a side one of the removed incident edges. (See Figure 23.)

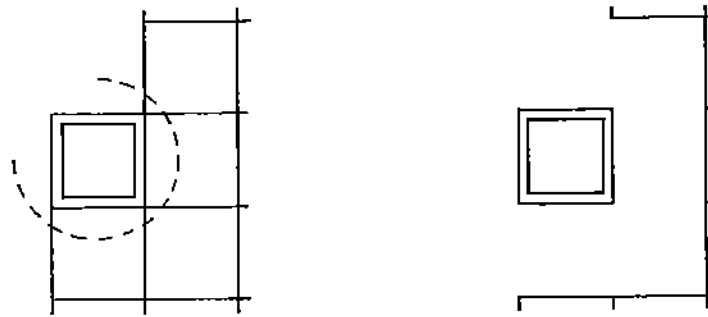


Figure 22. Application of one step of the algorithm.

By the leftmost, uppermost condition, selections will be performed in neighborhoods that are subgraphs of Figure 23(a), although there may also be some extraneous edges. Thus each subset of the partitioning will contain at most five tiles.

Consider an optimal solution for M of the 2×2 Tile Salvage Problem and mark a satisfying set of OPT_M tiles. Because of the number and configuration of tiles in each subset from the partitioning induced by the

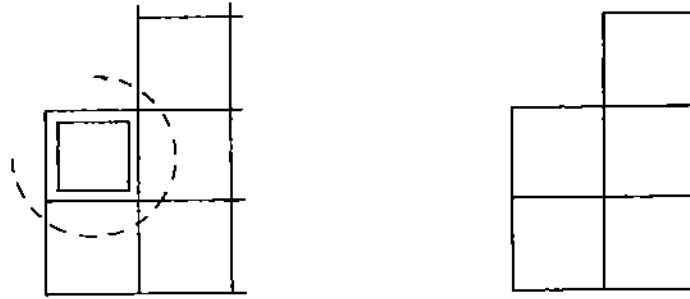
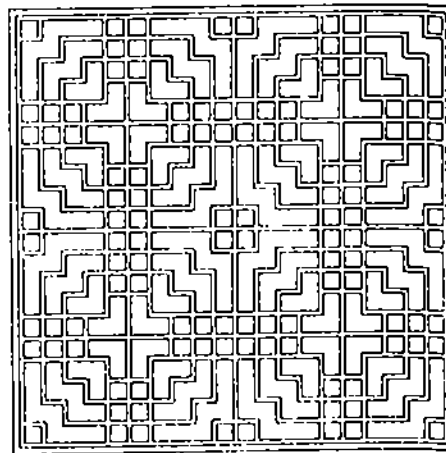


Figure 23. Subset induced by a tile selection.

algorithm, no subset contains more than two marked tiles. Since the greedy algorithm selected one tile each subset, its result can be no worse than $\frac{1}{2}OPT_M$. ■



East gate suburb, Chengtu, Szechwan, 1875 A.D.

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