

# Hard Tiling Problems with Simple Tiles

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**Abstract.** It is well-known that the question of whether a given finite region can be tiled with a given set of tiles is **NP**-complete. We show that the same is true for the right tromino and square tetromino on the square lattice, or for the right tromino alone. In the process, we show that Monotone 1-in-3 Satisfiability is **NP**-complete for planar cubic graphs. In higher dimensions, we show **NP**-completeness for the domino and straight tromino for general regions on the cubic lattice, and for simply-connected regions on the four-dimensional hypercubic lattice.

## 1 Introduction

Tilings of the plane have long intrigued statistical physicists, computer scientists, and recreational mathematicians. If we have as many copies as we like of a finite set of shapes, can we fill a given region with them? Tiling problems are potentially very hard: in fact, telling whether a finite set of tiles can tile the infinite plane is undecidable, since the non-existence of a tiling is equivalent to the Halting Problem [1, 2]. For finite regions, this problem becomes **NP**-complete [3], meaning that it is just as hard as combinatorial search problems like Traveling Salesman or Hamiltonian Path [4].

In fact, tiling problems can be difficult even for small sets of very simple tiles, such as polyominoes [5] with as few as three cells. Specifically, Beauquier, Nivat, Rémila and Robson [6] showed that for general regions of the square lattice the tiling problem is **NP**-complete for horizontal dominoes and vertical trominoes, and for any other pair of bars where either has length greater than 2. This includes the straight tromino alone when rotations are allowed. For simply-connected regions in the plane, on the other hand, Kenyon and Kenyon [7] provided a linear-time algorithm for this problem. When rotations are allowed, Rémila provided a polynomial-time algorithm for bars of length 2 and 3 in two dimensions, both in simply-connected regions [8] and in general [9].

In this paper, we give some additional examples of this kind. For the right tromino and square tetromino, we show that tiling a region on the square lattice

is **NP**-complete, and that the problem of counting how many tilings exist is **#P**-complete, making it as hard as enumeration problems like calculating the permanent of a matrix [10]. For the right tromino alone, we show **NP**-completeness using a more complicated construction based on 1-in-3 Satisfiability for planar cubic graphs, but unfortunately we have no result on the counting problem.

In higher dimensions, we consider the domino and straight tromino with rotations allowed. We show that this tiling problem is **NP**-complete for general regions in the cubic lattice, and for simply-connected regions in the four-dimensional hypercubic lattice.

We end with a discussion of some open problems, and a discussion of whether these results could be tightened further.

## 2 Building circuits with tiles

We call the question of whether a given set of shapes can tile a given finite subset of the square lattice, and how many such tilings exist, the *existence* and *counting* problems. These problems are trivially in **NP** and **#P** respectively, since we can confirm that a proposed tiling works in polynomial time. In this section we will consider the set of tiles shown in figure 1, namely the right tromino and the square tetromino, with rotations allowed.

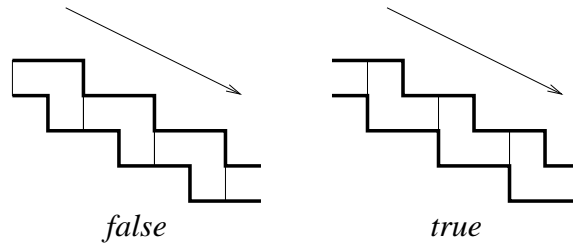


**Fig. 1.** The right tromino and square tetromino.

While the first hardness results about tiling relied on simulating steps of a Turing machine from row to row, here we will instead simulate Boolean circuits, where ‘wires’ with two possible tilings carry truth values, and junctions in these wires simulate logical gates. Similar approaches are taken in [6, 9, 11–13]. The question of whether a tiling exists then corresponds to the canonical **NP**-complete problem Satisfiability, which asks whether a set of truth values for the inputs exists that makes the output true [4].

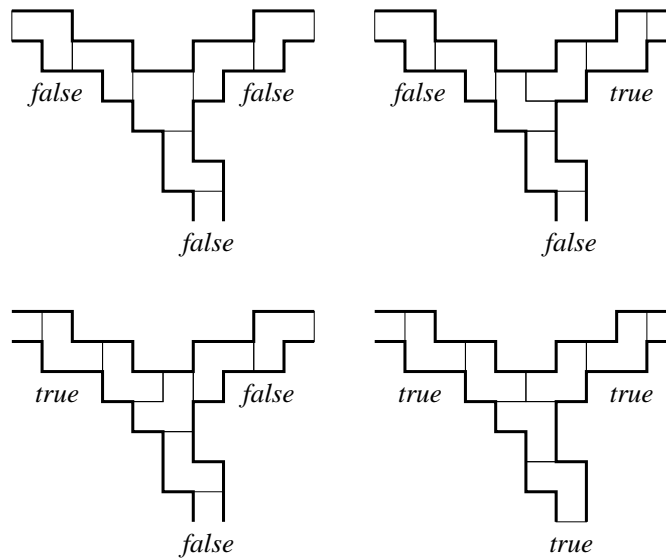
Our wire is shown in figure 2. It moves in knight’s moves in eight possible directions across the lattice. Given an orientation of the wire leading from input to output, the tilings where cells in between jogs are occupied by trominoes upstream and downstream from them will be considered ‘true’ and ‘false’ respectively.

Given this encoding of truth values in wires, figure 3 shows an AND gate. Each pair of truth values for the inputs  $a$  and  $b$  has one and only one tiling, which causes the output to have the value  $a \wedge b$ . Figure 4 shows a NOT gate, where the output has the opposite truth value from the input. By combining AND

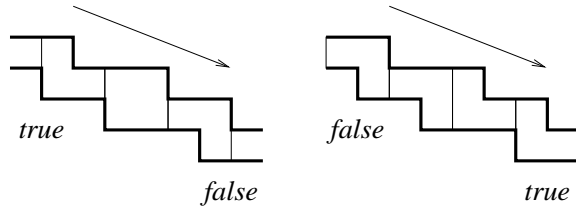


**Fig. 2.** The wire for tilings by the right tromino and square tetromino. Each wire is given an orientation, and we define its value as true or false depending on whether the tromino occupying the ‘middle’ cell of each step comes from upstream or downstream.

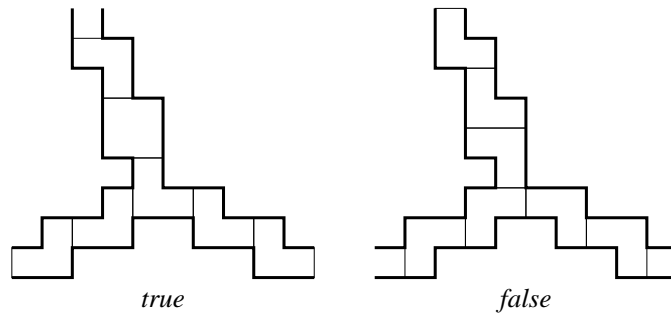
and NOT gates we can generate any Boolean function, including a ‘crossover gadget’ that allows us to cross wires in the plane [14]. Since we may want to use the output of one gate as the input of several others, figure 5 shows how to split a wire into two copies with the same truth value. To create our inputs and outputs, we need to be able to start variable wires with either truth value, and end wires in a way that requires them to be true. Figure 6 shows how to do both of these.



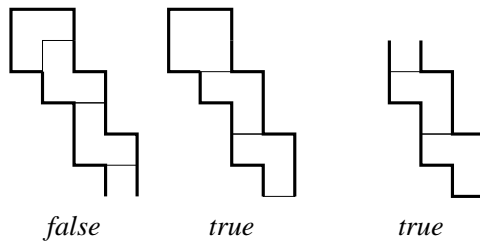
**Fig. 3.** Our AND gate. Two input wires enter a  $2 \times 2$  square from above, and the output exits from below. For each set of truth values for the inputs, there is exactly one tiling as shown.



**Fig. 4.** Our NOT gate, which negates the signal along a wire.

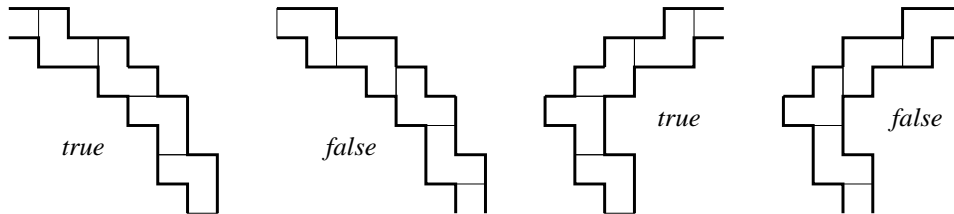


**Fig. 5.** How to split a wire (entering from above) into two copies with the same truth value.

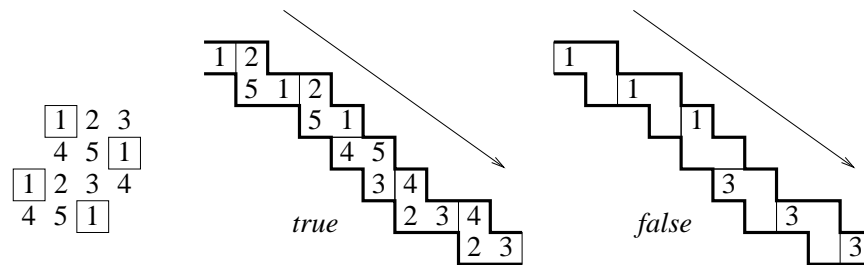


**Fig. 6.** Our variables. The bulb at the top can be tiled in two ways, which produce a true or false value on the wire it's connected to. On the right, how to end a wire so that it must be true for a tiling to exist.

There are two more subtleties that must be dealt with. First, it must be possible to bend wires among their eight possible orientations. We can do this by rotating and reflecting a wire's direction as in figure 7; these turns are derived simply by setting one of an AND gate's inputs to be true. Secondly, a wire of a given orientation has a knight's move periodicity, so that if we color the cells of the lattice as in figure 8 each step can only land on one of the five colors. This gives each wire a kind of phase, and the zig-zag shown in the figure allows us to change this phase so that a wire's truth value can be delivered to cells of any color. Then the output of any gate can become the input of any other, as long as the gates are separated widely enough. It is easy to show that this separation need only be polynomially large.



**Fig. 7.** How to bend wires. On the left the wire's direction is reflected around a diagonal line, and on the right it is rotated 90°. These allow us to change from any of the eight directions to any other.



**Fig. 8.** Changing the phase of a wire. The zig-zag shown keeps the truth value the same, but cycles among the five colors of the lattice.

It is clear from this construction that for any Boolean circuit, we can construct a region of the plane such that the right tromino and square tetromino can tile it if and only if the circuit is satisfiable. Moreover, this reduction is *parsimonious*, i.e. the mapping between solutions of the two problems is one-to-one, so the number of solutions is the same in both cases. Thus the question of whether

any tilings exist, and how many there are, are equivalent to Satisfiability and #Satisfiability, which are **NP**-complete and #**P**-complete respectively [4, 10].

### 3 Right Trominoes Alone

We now improve on the result of the previous section, and show that the existence problem is **NP**-complete for the set of tiles consisting only of the right tromino (with rotations allowed). The main reason that this is more difficult than for the tromino and square tetromino is that every tile covers three squares. If we use the same wires as before, where the truth value depends on the protrusion, or lack of it, of a single site, then we can only represent gates where the output is a linear function of the inputs mod 3. While this prevents us from coding Boolean circuits directly, we can still represent a version of Satisfiability which we will show is **NP**-complete.

First, we represent variables with nodes as in Figure 9, in which three outgoing wires are constrained to be all true or all false. (The same node can be used to enforce equality among three incoming wires.) This gate is essentially the wire splitter of Figure 5 with the NOT gate removed from the top wire.

Secondly, we represent clauses with the nodes of Figure 10, which require that exactly one of three incoming wires be true, and that the other two be false. This is a slightly modified version of the AND gate of Figure 3. If exactly one wire is true, the tilings of the wires cover exactly one square of the central  $2 \times 2$  square, leaving a space for one right tromino. Otherwise the number of squares left in the central square is not a multiple of 3 and so cannot be tiled by trominoes.

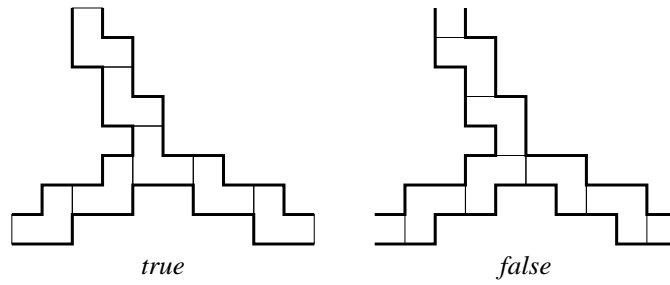
If we consider a bipartite graph of these two types of nodes connected with wires as in the previous section, then the tiling problem becomes a variant of 1-in-3 Satisfiability. That is, we have a set of variables and a set of three-variable clauses, and we want to know if there is an assignment of truth values to the variables such that exactly one of the three variables in each clause is true.

However, here we have a restricted case of this problem in which the expression's graph is planar, there is no negation, and each variable occurs in exactly three clauses since our variable nodes have three wires emanating from them. Thus, to complete our proof we need to show that Cubic Planar Monotone 1-in-3 Satisfiability is **NP**-complete, and we do this in the next section.

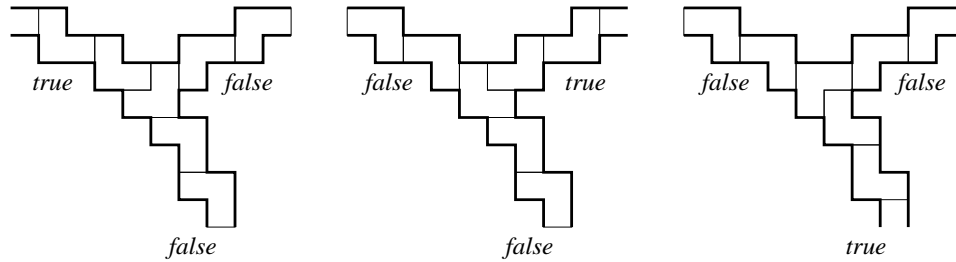
#### 3.1 Cubic Planar Monotone 1-in-3 Satisfiability

LaRoche [15] showed that Planar Monotone 1-in-3 SAT is **NP**-complete. This is the restriction of Monotone 1-in-3 SAT to expressions whose graph  $G$  is planar, where  $G$  is defined with a vertex for each variable and each clause of the expression, and an edge joining each clause to each variable appearing in it.

We will show that this problem remains **NP**-complete when restricted to expressions where every variable has exactly three occurrences, i.e. those whose graph is cubic. (An alternate formulation is to consider a hypergraph where each



**Fig. 9.** The variable nodes for our reduction of cubic planar 1-in-3 Satisfiability to tromino tiling. All three outgoing wires have the same truth value. We can also use this node to enforce equality between three incoming wires.



**Fig. 10.** The clause nodes for our reduction of cubic planar 1-in-3 Satisfiability to tromino tiling. Exactly one of the three incoming wires must be true.

clause is a node and each variable is a hyperedge joining three nodes. Since each true variable “covers” three clauses and every clause must be covered exactly once, we can then regard this problem as Exact Cover by 3-Sets in the case where the associated hypergraph is planar.)

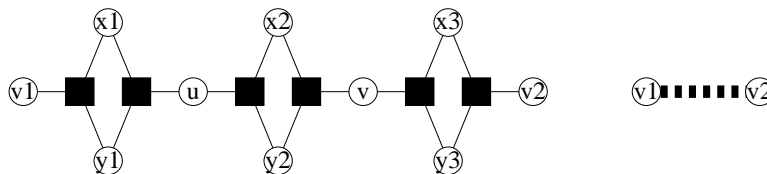
While the reduction from this version of SAT to the tiling problem we gave in the previous section is parsimonious, this does not show that the counting problem is  $\#\mathbf{P}$ -complete, since we do not have such a result for Cubic Planar Monotone 1-in-3 SAT. We leave this as an open problem for the reader.

Our reduction is from unrestricted Planar Monotone 1-in-3 SAT. In the diagrams of this section we use the same convention as in [15] that circles represent variables and squares represent clauses.

The reduction proceeds in two stages. The first stage produces an expression  $E'$  which is planar and satisfiable if and only if the original was, and where each variable has three or fewer occurrences. The second stage, rather more intricate, adds new clauses and auxiliary variables producing an expression  $E''$  where all variables have exactly three occurrences.

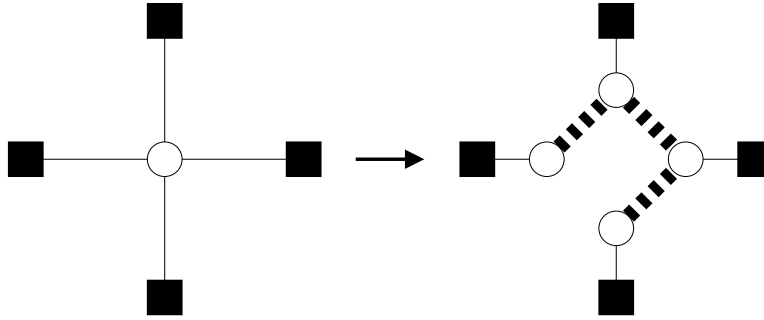
### 3.2 The reduction

We start by introducing some simple components to be used in the first stage. An *equality verifier* for two variables  $v_1$  and  $v_2$  consists of two new variables  $x$  and  $y$  together with the two clauses  $(v_1, x, y)$  and  $(v_2, x, y)$ . Clearly this can be satisfied if and only if  $v_1 = v_2$ ; moreover, if  $v_1$  and  $v_2$  are false, then exactly one of  $x$  and  $y$  is true. A *chain* between two variables  $v_1$  and  $v_2$  consists of new variables  $u$  and  $w$  and three equality verifiers: one between  $v_1$  and  $u$ , one between  $u$  and  $w$ , and one between  $w$  and  $v_2$ . Again a chain forces  $v_1 = u = w = v_2$  in any satisfying assignment and when  $v_1$  and  $v_2$  are false, the choice of  $x$  or  $y$  being true is independent for the three equality verifiers. A chain is shown in Figure 11.



**Fig. 11.** A chain that forces two variables  $v_1$  and  $v_2$  to be equal, and our abbreviation for it.

Given an expression  $E$  which is an instance of Planar Monotone 1-in-3 SAT, we choose a planar embedding of its graph  $G$ . For each variable  $v_i$  that occurs in  $k > 1$  clauses, we replace it with a set of variables  $v_{i,j}$  for  $j = 1 \dots k$ , one for each occurrence. We then link these  $k$  variables together with chains as in Figure 12. We call the resulting expression  $E'$  and its planar graph  $G'$ . Note that



**Fig. 12.** Replacing variables with  $k > 1$  occurrences with  $k$  variables connected by chains. One link is omitted arbitrarily, say between  $v_{i,1}$  and  $v_{i,k}$ , so as not to form a complete cycle.

this sequence of links between the  $v_{ij}$  is not completed to form a cycle; we omit an arbitrarily chosen link, say between  $v_{i,1}$  and  $v_{i,k}$ . Therefore, any boundary between two faces that includes a chain in fact includes chains from two different variables that appear in the same clause, a fact which we will use below.

This completes the first stage of the reduction. Clearly  $E'$  is satisfiable if and only if  $E$  was, and every variable has three or fewer occurrences. The variables with less than three occurrences are the  $x$  and  $y$  variables of each equality verifier, the intermediate  $u$  and  $w$  variables of each chain, the two unlinked variables  $v_{i,1}$  and  $v_{i,k}$  for each  $v_i$  with  $k > 1$  occurrences, and the original variables  $v_i$  which have only one occurrence in  $E$ . The total number of missing occurrences is a multiple of 3 since each variable must have three occurrences and each clause absorbs three.

We now consider the faces of  $G'$ . Our goal is to associate each missing occurrence to a face so that each face has a multiple of three additional occurrences along its boundary. There are some faces bordered by the  $v_1, x, v_2, y$  of an equality verifier; we will call these faces trivial, and assign no missing occurrences to them. The remaining assignments are made as follows.

Since the  $x$  and  $y$  variables of the chains have only one face adjacent to them, we start with each non-trivial face having a certain number of additional occurrences mod 3. We now note that every non-trivial face has at least one chain along its boundary. Each chain has two variables  $u$  and  $v$  with one occurrence each that can be assigned either to this face or to one adjacent to it. In this way, we can transfer 0, 1 or 2 (mod 3) additional occurrences from this face to the next one. If we define a tree of faces (i.e. a spanning tree of the dual graph) we can start at the leaves and change the number of additional occurrences in each face to 0 mod 3, until we reach the root, where the number of occurrences left is also 0 mod 3 since the total is a multiple of 3.

We use a similar strategy to control, for each face, how many of the additional occurrences entering it are true, assuming that  $E'$  is satisfiable. Recall that along the boundary between any pair of adjacent non-trivial faces are chains

corresponding to two different variables that appear in the same clause. In any satisfying assignment, at least one of these is false, and so in each link of its chain we can take either  $x$  or  $y$  to be true. In this way, we can transfer 0, 1 or 2 (mod 3) true variables from one face to another. If we again define a tree of faces, we can start at the leaves and change the number of true additional occurrences in each face to  $0 \pmod 3$ , until we reach the root. At the root face, the number of true additional occurrences is simply the total mod 3. This is  $-(\text{the number of clauses of } E') \pmod 3$ , since variables provide true values in multiples of 3 and each clause of  $E'$  absorbs one of these.

We will now construct our final expression  $E''$ , and its graph  $G''$ , by gathering the additional occurrences around each face into a *gadget* as described in Section 3.3. This gadget will enforce that the correct number mod 3 of the additional occurrences are true. In what follows, we will sometimes write 0 and 1 for true and false respectively.

### 3.3 Gadgets

The purpose of a gadget is to be satisfiable provided the correct number mod 3, say  $c$ , of its  $3m$  input edges are true. Thus we will complete the construction of  $G''$  by placing a gadget in each face of  $G''$ .

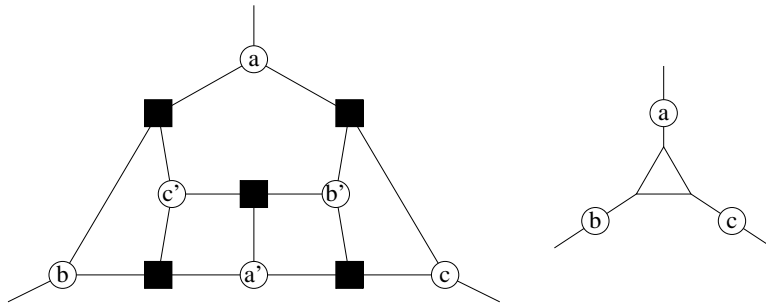
A gadget is composed of a sequence of *optional switches* that allow the true and false values to be sorted in any order, and checked in groups of three. Specifically, we wish for the rightmost  $c$  groups of three variables to have one true input each, and for all other groups of three variables to be either all true or all false. To do this, we terminate the rightmost  $c$  groups with a single clause vertex, and all other groups with a *3-way equality verifier* as defined below.

An optional switch has two entry edges and two exit edges. It can be satisfied in all cases where the two values on the exit edges are the same as the two values on the entry edges in either order. It uses two sub-gadgets, the *partial switch* which behaves the same way except that it cannot be satisfied if both entry edges are true, and the *3-way equality verifier*, which requires all its inputs to have the same truth value.

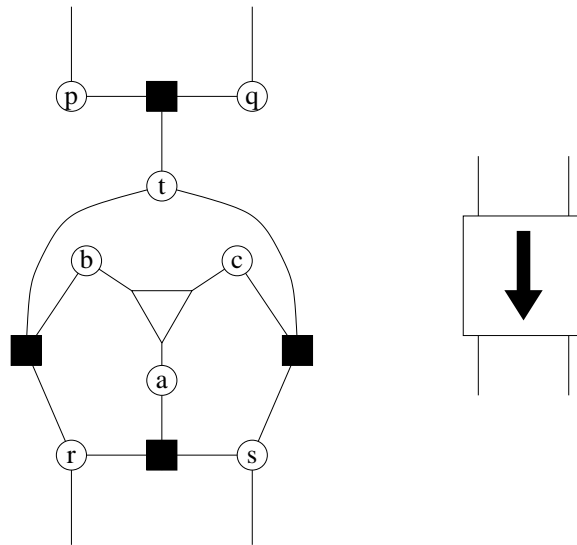
The partial switch itself has a sub-gadget which we call a *triangle*. This is a component with three variable vertices  $(a, b, c)$ , each with one edge to the exterior, which requires that exactly one of  $a$ ,  $b$  and  $c$  is true. In other words, it acts just like a clause, except that it uses two of each variable's occurrences. Note that we cannot achieve this simply by doubling the clause  $(a, b, c)$  since this would violate planarity.

The triangle has three internal variables  $a'$ ,  $b'$ , and  $c'$ , and the clauses  $(a, b, c')$ ,  $(b, a', c')$ ,  $(c, a', b')$ ,  $(a, c, b')$  and  $(a', b', c')$ . Clearly this is satisfied by taking  $a' = a$ ,  $b' = b$  and  $c' = c$ , and the central clause then ensures that exactly one of these is true. A triangle is shown in Figure 13 together with the symbol used to denote it in larger components.

The partial switch is shown in Figure 14. It has two input variables  $p, q$  and two output variables  $r, s$ . It contains internal variables  $a, b, c$  and  $t$ , a triangle  $(a, b, c)$ , and the clauses  $(p, q, t)$ ,  $(b, r, t)$ ,  $(c, s, t)$ ,  $(a, r, s)$ . If  $p = q = 0$ , the partial



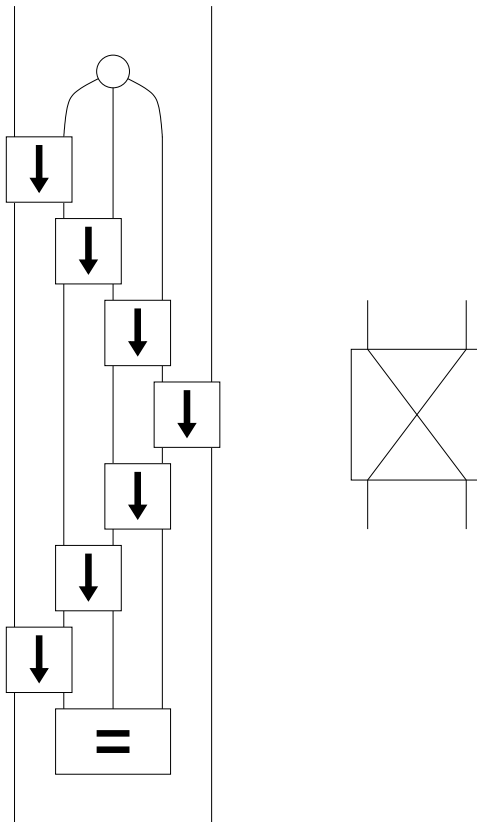
**Fig. 13.** A triangle and our abbreviation for it.



**Fig. 14.** A partial switch and its abbreviation.

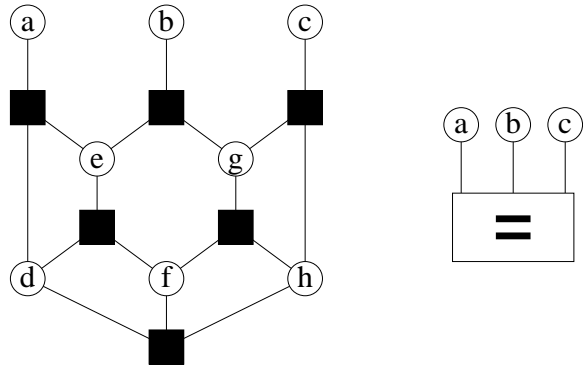
switch is satisfied by taking  $a = t = 1$  and  $b = c = r = s = 0$ . If  $p \neq q$ , we can take either  $r = c = 1$  and  $a = b = s = t = 0$  or  $s = b = 1$  and  $a = c = r = t = 0$ , and in either case  $r \neq s$ . Thus the partial switch copies the two inputs to the two outputs in either order, except when both inputs are true.

Note that each partial switch uses two occurrences each of its input variables, and only one each of its output variables. Thus partial switches can be strung together in series. We use this to build the full optional switch shown in Figure 15. This is composed of a new variable vertex (which may always be false) placed between the two entry edges followed by two sequences of partial switches. These permit a single true value to be transmitted from entry 1 to exit 2 or vice versa. This leaves three edges between the two exit edges and these three edges are then passed into a 3-way equality verifier.

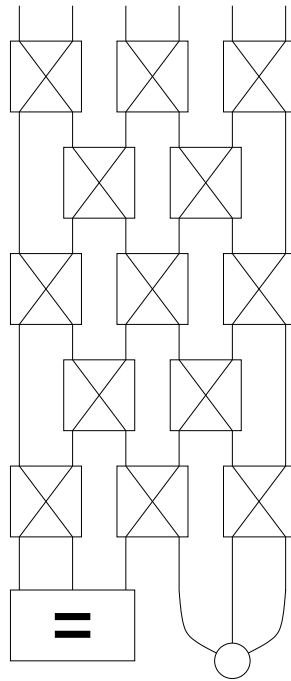


**Fig. 15.** An optional switch and its abbreviation.

For a 3-way equality verifier in the tromino tiling problem, we can simply use the variable node of Figure 9 with three incoming wires rather than three



**Fig. 16.** A 3-way equality verifier and its abbreviation.



**Fig. 17.** A gadget which allows 6 inputs to be sorted and confirms that 1 mod 3 of them are true.

outgoing ones. However, to complete our proof for Cubic Planar Monotone 1-in-3 SAT, we construct a verifier as in Figure 16. It has three input edges from variables  $a, b, c$  and five internal variables  $d, e, f, g, h$ . It contains the clauses  $(a, d, e)$ ,  $(b, e, g)$ ,  $(c, g, h)$ ,  $(d, e, f)$ ,  $(f, g, h)$ , and  $(d, f, h)$ . If  $a = b = c = 0$ , we take either  $d = g = 1$  and  $e = f = h = 0$  or  $e = h = 1$  and  $d = f = g = 0$ . If  $a = b = c = 1$  we take  $f = 1$  and  $d = e = g = h = 0$ .

Finally, to construct a gadget for  $3m$  inputs of which  $c \bmod 3$  are to be true, we form a sorting network from a polynomial number of optional switches that allows the inputs to be sorted in any order. We then divide the outputs of the sorting network into triples, and add a suitable checker to each triple. This checker will be a single clause for  $c$  of the triples and a 3-way equality verifier for the rest. An example is shown in Figure 17, where  $m = 2$  and  $c = 1$ .

After the appropriate gadget is added to each face to absorb its additional occurrences, it is clear that  $E''$  is satisfiable if and only if  $E$  is. This completes our proof that Cubic Planar Monotone 1-in-3 Satisfiability, and therefore the existence problem for tilings by the right tromino, is **NP**-complete.

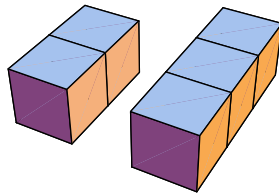
## 4 Monotone circuits in three and four dimensions

In this section, we construct wires and gates in three dimensions with the domino and straight tromino, or (if you prefer) the dicube and straight tricube, shown in figure 18. The construction is similar to that in Section 2, except that it will be limited to *monotone* Boolean circuits, whose outputs are non-decreasing functions of their inputs.

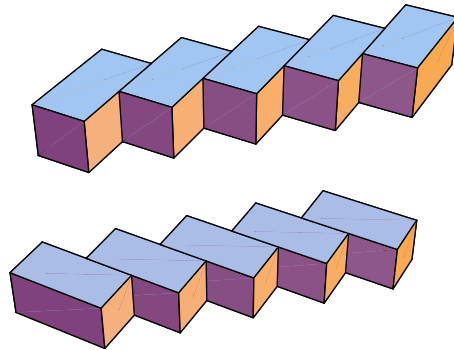
Our wires will consist of zig-zags as in figure 19, which can be tiled by dominoes in either of two ways. As before, we give each wire an orientation. Then if we two-color the lattice as a three-dimensional checkerboard, dividing it into odd and even cells, we define true and false wires as those where the downstream end of each domino lies on an odd or even cell respectively. Note that this allows wires to turn quite freely. Then the reader can easily check that the configuration in figure 20, with two inputs entering from above and an output exiting from below, acts as an AND gate if its central cell is even, and an OR gate if its central cell is odd. There is a unique tiling for each truth value of the inputs; in one of these four tilings the central crossbar is filled with a tromino, while the other tilings consist entirely of dominoes.

With AND and OR gates, we can build any monotone Boolean circuit. It seems to be difficult to build a NOT gate with these two tiles, and we conjecture that this is impossible. However, monotone circuits are enough for our purposes, since we can use De Morgan's laws  $\overline{a \wedge b} = \overline{a} \vee \overline{b}$  and  $\overline{a \vee b} = \overline{a} \wedge \overline{b}$  to move negations up through our gates [14], and thus convert any Boolean circuit with variables  $x_1, \dots, x_n$  to a monotone one with variables  $x_1, \overline{x}_1, \dots, x_n, \overline{x}_n$ .

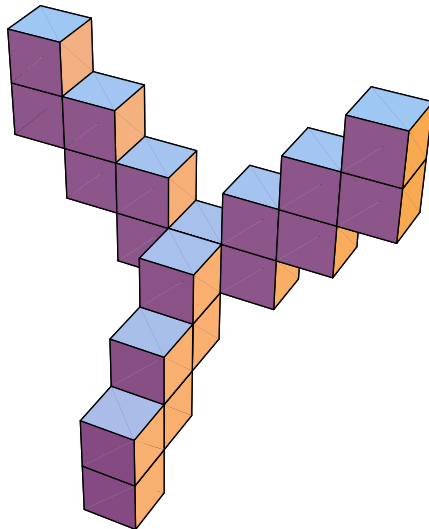
To make a one-to-one correspondence between satisfying assignments of this circuit and the original one, we just have to add the non-monotone condition that exactly one of  $x_i$  and  $\overline{x}_i$  be true for each  $i$ . We can do this by connecting these two variables with a zig-zag wire; using our definition of orientation, this



**Fig. 18.** The domino and straight tromino in three dimensions.



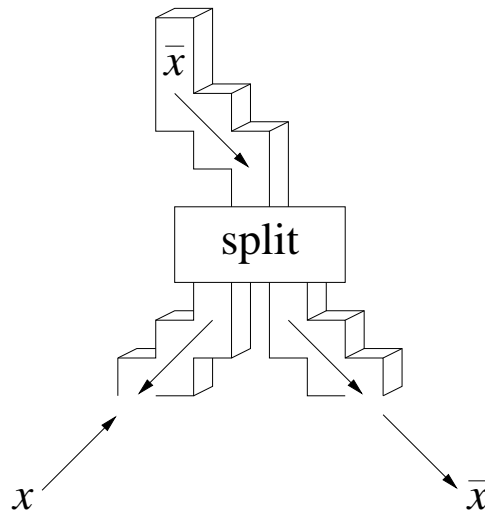
**Fig. 19.** The wire for tilings by the domino and straight tromino. It can be tiled by dominoes in either of two ways, such that the downstream end of each domino lies on either an odd cell (true) or an even cell (false).



**Fig. 20.** This configuration serves as an AND or OR gate, depending on whether the central cell is even or odd.

wire's tiling will come out as true at one end and false at the other. Finally, we require the output wire to be true by ending it on an odd cell.

To complete the argument, we need to be able to split wires. However, if we can do this, we can construct a NOT gate as shown in figure 21. Since our definition of truth is negated if we reverse the orientation of a wire, if we attach one output of a splitter backwards to a wire with value  $x$ , and attach its input to a variable that can be true or false, the other output will yield  $\bar{x}$ . Thus if we are correct that we can't build a NOT gate, we can't build a wire splitter either.



**Fig. 21.** If we had a wire splitter, we could make a NOT gate by feeding a wire with value  $x$  into one of its outputs in reverse, and connecting its input into a region which can be tiled either true or false. Since our definition of truth value is negated if we reverse orientation, the other output will then carry the negated value  $\bar{x}$ .

Since a perfect wire splitter doesn't seem to exist, we consider instead a "dirty splitter" where the outputs are equal to or less than the inputs; for instance, an OR gate in reverse has this property. Since the circuit is monotone, this can create false negatives but not false positives, so this "dirty circuit" can have a true output if and only if the original circuit can. Thus we have shown how to convert a monotone Boolean circuit to a region of the cubic lattice that can be tiled with dominoes and straight trominoes if and only if the circuit is satisfiable, and the existence problem for such tilings is **NP**-complete.

We would like to say that the counting problem for such tilings is **#P**-complete, but using dirty splitters means that in some cases there will be more than one tiling for a given satisfying assignment. Specifically, if a wire coming out of a dirty splitter is true but is not essential to making the output true, we can tile it false and the circuit will still be satisfied. Thus the mapping between assignments and tilings is not one-to-one, and our reduction from Satisfiability

to the existence problem is not parsimonious. While it seems likely that counting these tilings is  $\#\mathbf{P}$ -complete, it is not clear how to prove this.

It is unlikely that the number of dimensions in this construction can be reduced from three to two. While planar circuits and monotone circuits can both simulate Boolean circuits in general [14], circuits which are both planar and monotone cannot.

Finally, we note that we can convert any finite region  $R$  in the cubic lattice into a simply-connected region  $R'$  in the four-dimensional hypercubic lattice with an equivalent tiling problem [16]. Simply choose a set of sites  $S$  such that  $R \cup S$  is simply-connected, two-color them, and add each one along with an additional site adjacent to it in the fourth dimension, alternating up and down according to the two-coloring. Then these sites can only be filled by dominoes aligned along the fourth dimension, and only the sites in  $R$  are left. Thus the tiling problem for dominoes and straight trominoes is also  $\mathbf{NP}$ -complete for simply-connected regions in the four-dimensional cubic lattice.

## 5 Discussion

For the right tromino and square tetromino on the square lattice, or the right tromino alone, we have shown that the existence problem for tiling regions of the square lattice is  $\mathbf{NP}$ -complete. In the former case, we have shown that the counting problem is  $\#\mathbf{P}$ -complete. For the domino and straight tromino, we have shown that the existence problem is  $\mathbf{NP}$ -complete for general regions in the cubic lattice, and for simply-connected regions in the four-dimensional hypercubic lattice.

Intuitively, the  $\mathbf{NP}$ -completeness of tiling with polyominoes with three or more cells comes from the fact that, while telling whether a graph can be covered with dimers is related to the Perfect Matching problem and can be solved in polynomial time, telling whether it can be covered by trimers is  $\mathbf{NP}$ -complete [4]. While there is no strict connection between a system's computational complexity and its statistical mechanics, we might expect that tiling problems for tiles consisting of three or more cells are generally not exactly solvable in two or more dimensions (although the statistics of triangular trimers on the triangular lattice can be solved with a Bethe ansatz [17]).

For dominoes the existence and counting problems have an especially elegant solution. The number of ways to tile a region of a regular lattice with dominoes can be calculated by expressing it as a determinant of a modified adjacency matrix [18, 19]. This puts the existence and counting problems for the domino in the class  $\mathbf{DET} \subset \mathbf{P}$  and allows the statistics of the dimer model to be solved exactly.

It would be interesting to find other small sets of tiles for which tiling problems are hard, or find larger sets of tiles for which existence and/or counting are in  $\mathbf{P}$ . As noted above, in two dimensions the existence problem for dominoes and straight trominoes is in  $\mathbf{P}$  when rotations are allowed [8, 9]

Another solvable case is that of a single polyomino without rotation, or one which is rotationally symmetric. Then there is at most one tiling of a given finite region, which we can find by scanning from left to right and top to bottom and adding a tile to each unoccupied cell we meet. Beauquier and Nivat [20] showed that this case of the tiling problem is decidable for the infinite plane as well. Finally, we note that the existence of an isohedral tiling of the infinite plane by a single polyomino — one whose symmetry group acts transitively on the set of tiles — was recently shown to be decidable by Keating and Vince [21].

Some open questions include:

1. Is the counting problem for the right tromino on the square lattice, or for the domino and straight tromino on the cubic lattice,  $\#\mathbf{P}$ -complete?
2. Is the existence problem for the right tromino in  $\mathbf{P}$  for simply-connected regions in the square lattice?
3. Is the existence problem for dominoes and trominoes in  $\mathbf{P}$  for simply-connected regions in the cubic lattice?

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