

**Mathematics of Sudoku: Enumeration of the  $16 \times 16$  Magic X Sudokus**

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by

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## Abstract

A  $16 \times 16$  Magic X Sudoku is a Sudoku with the additional constraints that each block is a Magic Square and each number appears once on the two long diagonals. Nine binary orthogonal symmetries were discovered, for a reduction of the solution space by a factor of 512, and 1 non-orthogonal binary symmetry, which further reduces the problem by a factor between 1 and 2. Enumerating the  $16 \times 16$  Magic X Sudokus requires significantly more computational resources than available even after optimization.

## Acknowledgments

Brigitte Sevatius, for encouraging me to follow my mind  
as it wanders to new vistas, both in this endeavor and other.

Kathi Fisler, without whom Branch would still be a toy language of little value.

And to all those who serve as sounding board and compass while I wander.

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# 1 Introduction

How many  $16 \times 16$  “Magic X Sudokus” are there? Answering this question is, to the best of anyone’s knowledge, equivalent to enumeration all the solutions: Takayuki Yato proved the NP-completeness of Sudoku [Yat03], and no results suggest Magic Squares are otherwise. As the question is equivalent to enumeration, heavy use of computers is needed to have any hope of success. Even fast computers can have trouble on NP hard problems however, and the size of the solution space,  $16^{256}$ , or about  $1.8 * 10^{308}$ , dwarfs the processing power of any current computer. Therefore a great deal of reduction is needed, and while much of it is easy, by the use of specific types of computer algorithms in the constraint satisfaction field, these are not enough because of the NP nature of the problem. Other, more complicated ways to reduce the computation are needed. More difficult to encode, the representation of only one element of the symmetry (automorphism) group can be a potential great help, rendering many problems that otherwise are too slow feasible. The question remained whether this problem was one of those made possible though careful use of the symmetry group would render this problem possible. Though similar enumeration problems existed, Sudoku is new enough that little work has been done in this area, and while a useful guideline, the work on enumerating Sudokus has focused mostly on the  $9 \times 9$  Sudoku, which has decidedly different symmetries.

I arrived at this particular problem for this project in large part due to background: I had done work in all 3 of the major parts involved. I was attempting to finish work for my CS MQP on Branch, the programming language used for all the coding involved in this investigation. Though that project is still unfinished as of this writing, I intend to return to it, among other things using this problem as my guiding problem for the future development of the language. I was already familiar with Sudokus, having been caught in the current craze of solving them. Though I knew these two fit together well, it was the Magic Square component that finally cemented the problem. I had, over the past five years, been intermittently working at enumerating magic squares, culminating in my discovery of the “Ring Swap” symmetry, and the listing of all  $5 \times 5$  magic squares in a half hour. Even more tantalizing was a surprise, and ultimately incorrect, conjecture: in hopes of reducing the complexity of the problem slightly, I added the constraint known as an “X Sudoku”, and proceeded to find no  $16 \times 16$  Magic X Sudokus. In the end it was due to their relative rarity, not a complete absence, and a fluke in the ordering of earlier search algorithms. In final tally, there are still too many, not too few, as enumeration requires too much computational power.

## 2 Definitions

- **$n^2 \times n^2$  Magic X Sudoku** - A  $n^2 \times n^2$  Sudoku with the additional constraints that it is an X Sudoku and a Magic Sudoku. By convention in this paper,  $n^2 = 16$  unless otherwise noted.
- **$n^2 \times n^2$  Sudoku** - A  $n^2 \times n^2$  grid where the numbers  $1, 2, \dots, n^2$  appear exactly once in each row, column, and block. A block is a  $n \times n$  subsection of the grid formed from dividing each dimension of the grid into  $n$  contiguous sections.
- **X Sudoku** - A  $n^2 \times n^2$  Sudoku where the two longest diagonals (which are the same length as the rows and columns) also have the constraint that the numbers  $1, 2, \dots, n^2$  appear exactly once.
- **Magic Sudoku** - A  $n^2 \times n^2$  Sudoku where each block is also a  $n \times n$  Magic Square.
- **$n \times n$  Magic Square** - A  $n \times n$  grid where the numbers  $1, 2, \dots, n^2$  appear exactly once and where every row, column, and the two long diagonals all sum to the same value. By convention row, column, or long diagonal can all be called row.
- **Solution** - A solution of any of the above objects is any configuration of numbers that satisfies all the constraints.
- **Symmetry** - A symmetry of any of the above objects is a transform  $T$  that, for all solutions  $S$ ,  $T(S)$  is also a solution. By convention in this paper, a symmetry without specification as to which object is a symmetry of the Magic X Sudokus. (The plural is used as the symmetry applies for all solutions.)

Some definitions of a Sudoku phrase the requirement as the numbers  $1, 2, \dots, n^2$  appear no more than once. As there are exactly as many spaces as there are numbers to occupy them, these conditions are equivalent. A great many variants of Sudoku already exist, most commonly a  $12 \times 12$  Sudoku and even one called a Magic Sudoku: these uses of the terms are ignored. (Though the other use of Magic Sudoku predates my usage, it makes no use of Magic Squares, and its name mostly appears to be a marketing ploy. I therefore submit my usage of Magic Sudoku as a better use for the term.) The definition of Magic Square is generally more standardized, though variants sometimes do not require the numbers  $1, 2, \dots, n^2$  but some other set, and sometimes leave out the diagonal constraint. The latter is referenced at one point later; its meaning is specified explicitly there as well.

### 3 Simple Observations

Some simple observations follow from these definitions. First and foremost, a  $n \times n$  Magic Square must have a fixed sum of  $(n^3 + n)/2$ . This is because all the numbers  $1, 2, \dots, n^2$  are used exactly once, for a sum of  $(n^4 + n^2)/2$ , and this value must be divided evenly between  $n$  rows (or between the  $n$  columns). In the case of a  $4 \times 4$  magic square this gives a sum of 34. Knowing this sum ahead of time proves important by allowing earlier checking, helping the fast fail component of Branch. Though it requires enumeration, the number of  $4 \times 4$  Magic Squares is known: 7040. Optimized C++ code can achieve this in about a second, while Branch finds them all in around 10 seconds. Sudokus are a subset of Latin Squares, as a Latin Square is a Sudoku without the block requirement. (Only the rows and columns must have each numbers once). Latin Squares have been enumerated up to  $11 \times 11$ , but only estimates exist for larger sizes. The extra constraint of Sudokus means many fewer exist than do Latin Squares, which makes for an easier search; however fewer symmetries exist for the Sudokus than for the Latin Squares. The number of  $9 \times 9$  Sudokus is known, as successful enumeration is described by Frazer Jarvis [Jar06].

When it comes to Magic X Sudokus, all sizes below  $16 \times 16$  prove trivial. There is one  $1 \times 1$  Magic Square, which is the same as the  $1 \times 1$  Sudoku. There are no  $2 \times 2$  Magic Squares; therefore, there can be no  $4 \times 4$  Magic Sudokus. There are 8 different  $3 \times 3$  Magic Squares, but they all have 5 in the center, which causes a trivial contradiction with the Sudoku constraint. Leaving out the diagonal constraint makes these  $9 \times 9$  Magic Sudokus possible, and they proved to provide an interesting novelty against a normal Sudoku puzzle according to a Discrete Math class that was asked to complete a sample puzzle version. Enumerating the  $5 \times 5$  Magic Squares is computationally difficult in its own right, and enumerating  $25 \times 25$  Latin Squares is completely impractical. Therefore only  $16 \times 16$  Magic X Sudokus are open but feasible. A final note, the Magic Square constraint requires each block have the numbers  $1, 2, \dots, n^2$  exactly once, as does the block constraint of a Sudoku. As this constraint is repeated, it needs only be checked once.

## 4 Symmetry

As defined, a symmetry is a very general property, as it applies to all solutions. Most enlightening is to first examine the symmetries of the  $4 \times 4$  Magic Square, before proceeding on to the symmetries of Magic X Sudokus. Reproduced in **Appendix A** is the presentation accompanying the talk on this subject, which gives a good visual representation of all the symmetries here.

The first 8x symmetries are well known, as they are the symmetries of the geometric square. A square can be rotated by one the four multiples of a  $90^\circ$  rotation, as well as being flipped over. Because rows and columns can exchange rolls in the definition of a Magic Square, reorienting the entire square by one of these 8 symmetries does not invalidate it. For convenience, symmetries are described (and implemented) as orthogonal basis transforms, and the full symmetry group is the space described by this basis. Therefore the symmetries of a square are encoded as Horizontal Flip, Vertical Flip, and Diagonal Flip. The first two reflect around the central line in their respective direction, while the Diagonal Flip reflects around the long diagonal running from upper left to lower right. Using the diagonal from upper right to lower left would serve as well; it is produced from doing all three basis symmetries. In similar manner any of the 8 symmetries of the square arise from this basis.

A further symmetry arose from my previous work on  $5 \times 5$  Magic Squares, the Ring Swap symmetry. Only applicable for Magic Squares at least as large as  $4 \times 4$ , it embodies the idea of exchanging the numbers in the ring near the center with the number on the outer ring. Since numbers that start on the diagonal must stay on it to guarantee a valid solution, this leaves only one way to switch the rings. The four central numbers move out to their corners, the four corner numbers move in, and in each quarter the remaining numbers switch places. As this is orthogonal to all the other symmetries, it serves to double the size of the full symmetry group. As a side note,  $6 \times 6$  Magic Squares and larger have multiple symmetries of this nature, but  $4 \times 4$  and  $5 \times 5$  only have one. (If you are able to imagine a  $5 \times 5$  Magic Square under this operation, the origin of the name becomes clearer, as there are now two rings round the fixed central square.)

Though initially the only symmetries included concerning the individual Magic Squares composing the Magic X Sudoku, a final symmetry discovered from the entire puzzle turned out to be applicable to  $4 \times 4$  Magic Squares as well: the Core Scramble. This symmetry is interesting in that the 4 corners of the Magic Square do not change at all, they are held fixed. Within the center 4 squares, both diagonals have a flip, requiring the remaining 8 squares not at the corners in the outer ring to swap places. Again all the original rows and columns remain, just in different locations, and the diagonals are in a new order but have



the same elements. It would appear that there is also a Corner Scramble, but that symmetry is not orthogonal to the already existing symmetries, it is composed of a Core Scramble, a Horizontal Flip and a Vertical Flip. With a grand total of 5 binary basis symmetries, a 32x reduction in the solution space requiring examination is possible. Though not immediately apparent, the Magic X Sudoku has the same internal structure as the  $4 \times 4$  Magic Squares if the composition of each block is considered fixed. The X Sudoku constraint enforces a difference between elements on either of the two long diagonal exactly like the diagonal constraint of a Magic Square. All 32 symmetries apply, and the basis from the Magic Squares serves here as well. By happenstance these symmetries are referred to as macro, while the others are referred to as small. (Not micro, because then their names are too similar within the code.)

Unlike a  $4 \times 4$  Magic Square, a Magic X Sudoku can have symmetries based on the orientation of the items inside the blocks as well. Picking one of the blocks not on a diagonal, it is possible to apply all 5 of the basis symmetries, and by cascading effects through the other blocks, maintain all of them as Magic Squares. The effects of the cascade to maintain all the constraints result in no further basis symmetries being possible, as all valid modifications to each magic square will already have occurred from the modification of the initial square. Furthermore, though valid, the small Diagonal Flip is a combination of existing symmetries, and is therefore not part of the basis. The loss of this reduction results in a final tally of 9 basis symmetries for the Magic X Sudoku, for a total of 512 symmetrically equivalent solutions for every solution generated.

One further symmetry is known and has been implemented, however it brings with it currently unresolved problems. Unlike all the previous symmetries, which map locations within the Magic X Sudoku to different locations, this one maps the value at a location to a new value. The concept is both more illuminating and produces a better reduction for a normal Sudoku; it features prominently in the enumeration of the  $9 \times 9$  Sudokus. In a Sudoku, the numbers  $1, 2, \dots, n^2$  are merely convenient symbols, as no arithmetic constraint is placed on them. Therefore any one to one mapping will produce another valid Sudoku. To wit, saying all the 1s become 2s and all the 2s become 1s is guaranteed to remain valid. As this applies to all solutions, this satisfies the definition of a symmetry. Though much less powerful than the  $9!$  reduction achieved for the  $9 \times 9$  Sudokus, there is one binary symmetry applicable to  $4 \times 4$  Magic Squares, and from there to Magic X Sudokus. The mapping is as follows  $f(x) = 17 - x$ . It is one to one, and therefore the resulting table can not violate the Sudoku constraints. This preserves the sum, as the new sum =  $17 * 4 - \text{old sum}$ , and as the old sum must be 34, the new sum of every row must also be 34. Applying this

same symmetry to the whole Magic X Sudoku also preserves all constraints, and therefore it counts a symmetry. Other mappings (besides the identity, which is trivially covered) can not produce this effect, as at least one magic row will have its sum changed by other mappings.

The problems with this symmetry come in because it is not fully orthogonal to the other symmetries: sometimes it in combination with other symmetries can transform itself into itself. While the reduction is still useful, the counting becomes mired in technical difficulties, as now some solutions represent 1024 different solutions, and some represent 512. This effect represents interference, and its initial effect is impressive. In place of a reduction of the first Magic Square in the puzzle to 110, it is only reduced to 166. However, the effect diminishes as more of the grid is filled in. This means that the program must keep explicit count, instead of depending on the orthogonality to keep implicit count. Though simple in theory, in practice most approaches use prohibitive resources to do so. Though a general system will be added to Branch, it is unclear if it will be as efficient as simply leaving the final factor of 2 off for faster code. (It is still a useful tool to develop for other problems, as the  $9 \times 9$  Sudokus for example are dependent on it for efficient enumeration.) The current code includes this relabeling symmetry, without correcting for it, in the hope that a best of both worlds approach might at least have rendered a nearly accurate solution.

## 5 Branch

Branch is a programming language. More specifically, it is a finite integer domain Constraint Satisfaction language I wrote for my CS MQP. Commonly known either as a CLP, for Constraint Logic Programming, or CSP, for (solving) Constraint Satisfaction Problems, this family of languages ranges from the well known Prolog to dozens of theoretical languages to which not a single line of code has been written. Though still incomplete as of this writing, Branch has already experienced a total of 4 generations, culminating with the writing of the current version, which specifically targets enumerations like the Magic X Sudoku enumeration though the addition of tools designed to ease the implementation of symmetries.

Though many languages exists that can perform the work needed, a CSP language was particularly well suited for the problem: notice the use of constraint within the definition of a Magic X Sudoku. As its name implies, programming in a constraint satisfaction language requires entering in all the constraints of the problem; other than that there is minimal programming needed. These savings in programming time and complexity outweigh the speed improvements from optimizing for a lower level language. It is worth noting a final speed increase can still be achieved by switching languages, but the benefit is so small as to not be worth the time unless it will make the difference between having a successful enumeration and not.

Programming in Branch is especially simple because there are only two commands in the base language, branch, and prune. Branch creates a new variable, and assigns a range to that variable. Prune adds a constraint, using a C++ conditional. Although in theory there is no need for anything else, many of the constraints are very repetitive, and a style of creating a function to evaluate large scale constraints, like Sudoku or Magic Square, is the primary method of programming Branch in practice. This mix of constraint satisfaction programming and procedural programming is one of the great conveniences of the language. For best efficiency these functions should catch contradictions as soon as possible, which can require a little bit of careful coding, but it otherwise fairly straightforward.

While the programmer of a CSP language need not concern themselves with how the solutions are arrived at once they have entered the problem, serving as implementer of the language meant I did need to do so. Poor choice of a solution method would produce unacceptable slowdowns, more than negating the benefit of using a more convenient language. Though much of the more technical points to the internal operation of Branch belong in its MQP write and not here, an overview is important. Branch operates by keeping stored in a large tree in memory every valid solution for the part of the grid it has completed. A branch

command adds a new level to this tree, increasing its size, while prune commands remove solutions, and therefore decrease the tree's size. The branch and prune commands execute in sequence, and while internally a loop has to progress over all valid solutions and execute the next command, this is transparent to the programmer. This method of keeping all potential solutions stored simultaneously is known as a Breath First Search, commonly abbreviated BFS. Much more common is a Depth First Search (DFS), which has many practical benefits; however this newest version of Branch makes use of the simultaneity to ease the encoding of other features. The biggest drawback to BFS is that, while in theory it takes the same time as DFS, it uses memory (RAM) proportional to the solution space, which on large problems often exceeds the available memory. The loop command in recent versions of Branch allows a balance, as it turns the program into a DFS at the point the loop is used. It is also worth noting that BFS will not find any solutions until it finds them all, but for an enumeration attempt this is a minor annoyance only.

Another component, touched upon elsewhere, is the need to remove invalid solutions as early as possible. Though very critical for all CSP languages, it is even more important for Branch, as earlier removal not only lowers run time, but also lowers memory usage. Known as a fast fail algorithm, it increases the speed of the search by using a little work early on to remove what is right now one invalid partial solution, but that would be thousands of invalid solutions later on. Though a few languages implement automatic decision making to determine what part of the problem will generate the most fails early, many have the programmer make those decisions because the overhead of making the decision can sometimes outweighs the gain. Branch is of the latter (though I hope to add some ability to optimize itself soon), which is why the programmer wants to design a function for testing the validity of all the constraints that detects fails as early as possible.

Most convenient and newest of the features in Branch is the ability to conveniently input symmetries. A symmetry object gets created with a transform stored as a reorder array, and whenever appropriate this transform is applied to see if it generates an already existing solution. Though originally the check for already existing actually involved checking against all existing solutions (made reasonably quick by a hash), using a lexicographical ordering to decide which ones survive proved significantly faster. Another helpful speed increase came from the implementation of the far, Full Automatic Reduction, symmetry object. Its purpose is to find all the symmetries that might be valid at a given point in the completion of the grid, and to then check only those symmetries and no others. With these improvements in place, the use of symmetries because not only easy to implement for the programmer, but nearly as beneficial in practice as they are in theory. The overhead for all these checks is

very low compared to the work required for the search of even the now restricted solution space.

## 6 Results

At root, the drive to enumerate the Magic X Sudokus has proven a failure: despite all the work, the problem is still too large for even modern computers. However, the initial conjecture that there were no Magic X Sudokus has been proven false, as over 300 MB worth of them have been found in one day long run using the entire CCC computer cluster of 20 processors. This lists many thousands of solutions after symmetry reduction, which with the older version of the code that lacked two of the symmetries that produced the file, still equates to well over 1 million Magic X Sudokus. This represents but a tiny fraction of the total number out there however, and such a small section of the total solution space has been explored by even that many that it is unclear if the density is representative of the entire problem or not.

Regardless of the lack of a full enumeration, a great deal of progress has been made, and much of it falls into categories that are applicable to other similar problems. The listing of symmetries is the most notable achievement from a mathematical standpoint, as the Core Scramble symmetry is a previously unsuspected optimization for Magic Square like structures. The Ring Swap symmetry also is not immediately apparent, and potentially enjoys application to many different structures. The development of the tools in Branch to allow the simple implementation of new symmetries will find great use in much of my future work, and will the completion of its project soon will hopefully enjoy wider distribution.

A great deal of the work on the actual code of this particular project falls into the category of faster fail. Improvements in this section qualify as making speed increases of nearly 100x over the course of this project, however these are still dwarfed by the 1024x (minus interference) reduction achieved by the symmetries. The current version of the Branch code now places entire Magic Squares into the grid in one operation, using a hard-coded list of all the  $4 \times 4$  Magic Squares. It also pre-generates a list of Magic Squares that can be in the same row as other Magic Squares, to lower time spent checking the Sudoku constraint. However there is still a bug in the latter process, as a few extra are making it though that should not be. These improvements are not as widely applicable, but serve well in furthering the approach to enumeration. Once these final bugs are worked out and interference accounted for, the problem may come within feasible range for the available computational power. Then it becomes a matter of simply throwing enough computers at the problem for long enough to get it done.

Future work spans a broad spectrum of subjects, so only immediate questions are covered here. Of course the enumeration of the Magic X Sudokus is still open, and even if the most recent attempts do not prove sufficient, I intend to keep an eye out for any further ideas that

might help. Branch will continue development due to its own project, though I expect it will never be done, as new approaches and tools will always exist for a programming language. Concerning the classic  $9 \times 9$  Sudokus, I hope to use very similar techniques to confirm the existing enumeration, preferably with a shorter computation time. Also a currently open problem is the fewest number of givens that can uniquely determine a  $9 \times 9$  Sudoku, which looks to be very hard to prove, but still worth investigating.

On a final note, I hope to create a set of Magic X Sudoku puzzles, which like normal Sudokus require logical deduction for a person to arrive at the unique solution from the givens.

## References

- [Jar06] Frazer Jarvis. Sudoku enumeration problems, January 2006. Online <http://www.afjarvis.staff.shef.ac.uk/sudoku/>.
- [Yat03] Takayuki Yato. Complexity and completeness of finding another solution and its application to puzzles. Master's thesis, University of Tokyo Graduate School of Science, 2003.



# A Presentation

A reproduction of the slides used for the presentation of this project to the Math Department of WPI. It is most useful for the graphical representation of symmetries, in the section by that name.

11	5	2	16	4	14	15	1	10	8	3	13	7	9	12	6
8	10	13	3	12	6	9	7	5	11	16	2	14	4	1	15
14	4	7	9	5	11	8	10	15	1	6	12	2	16	13	3
1	15	12	6	13	3	2	16	4	14	9	7	11	5	8	10
12	6	1	15	8	2	13	11	9	4	7	14	5	3	10	16
13	3	8	10	15	9	6	4	16	5	2	11	12	14	7	1
7	9	14	4	10	16	3	5	6	15	12	1	8	2	11	13
2	16	11	5	1	7	12	14	3	10	13	8	9	15	6	4
4	14	9	7	2	8	11	13	1	12	15	6	16	10	3	5
5	11	16	2	9	15	4	6	8	13	10	3	1	7	14	12
15	1	6	12	16	10	5	3	14	7	4	9	13	11	2	8
10	8	3	13	7	1	14	12	11	2	5	16	4	6	15	9
3	13	10	8	6	12	7	9	2	16	11	5	15	1	4	14
16	2	5	11	14	4	1	15	13	3	8	10	6	12	9	7
6	12	15	1	3	13	16	2	7	9	14	4	10	8	5	11
9	7	4	14	11	5	10	8	12	6	1	15	3	13	16	2

# Mathematics of Sudoku: Enumerating the 16x16 Magic X Sudokus

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## Sections:

- Definitions
- Symmetries
- Programing
- Results

# Definitions

## Sudoku

- A  $n^2 \times n^2$  Sudoku is a  $n^2$  by  $n^2$  grid, where every row, column, and block contains the numbers 1 through  $n^2$  exactly once.

11	5	2	16	4	14	15	1	10	8	3	13	7	9	12	6
8	10	13	3	12	6	9	7	5	11	16	2	14	4	1	15
14	4	7	9	5	11	8	10	15	1	6	12	2	16	13	3
1	15	12	6	13	3	2	16	4	14	9	7	11	5	8	10
12	6	1	15	8	2	13	11	9	4	7	14	5	3	10	16
13	3	8	10	15	9	6	4	16	5	2	11	12	14	7	1
7	9	14	4	10	16	3	5	6	15	12	1	8	2	11	13
2	16	11	5	1	7	12	14	3	10	13	8	9	15	6	4
4	14	9	7	2	8	11	13	1	12	15	6	16	10	3	5
5	11	16	2	9	15	4	6	8	13	10	3	1	7	14	12
15	1	6	12	16	10	5	3	14	7	4	9	13	11	2	8
10	8	3	13	7	1	14	12	11	2	5	16	4	6	15	9
3	13	10	8	6	12	7	9	2	16	11	5	15	1	4	14
16	2	5	11	14	4	1	15	13	3	8	10	6	12	9	7
6	12	15	1	3	13	16	2	7	9	14	4	10	8	5	11
9	7	4	14	11	5	10	8	12	6	1	15	3	13	16	2

# X Sudoku

- An X Sudoku is a Sudoku with the additional constraint that the two long diagonals of the grid have the numbers 1 through  $n^2$  exactly once.

11	5	2	16	4	14	15	1	10	8	3	13	7	9	12	6
8	10	13	3	12	6	9	7	5	11	16	2	14	4	1	15
14	4	7	9	5	11	8	10	15	1	6	12	2	16	13	3
1	15	12	6	13	3	2	16	4	14	9	7	11	5	8	10
12	6	1	15	8	2	13	11	9	4	7	14	5	3	10	16
13	3	8	10	15	9	6	4	16	5	2	11	12	14	7	1
7	9	14	4	10	16	3	5	6	15	12	1	8	2	11	13
2	16	11	5	1	7	12	14	3	10	13	8	9	15	6	4
4	14	9	7	2	8	11	13	1	12	15	6	16	10	3	5
5	11	16	2	9	15	4	6	8	13	10	3	1	7	14	12
15	1	6	12	16	10	5	3	14	7	4	9	13	11	2	8
10	8	3	13	7	1	14	12	11	2	5	16	4	6	15	9
3	13	10	8	6	12	7	9	2	16	11	5	15	1	4	14
16	2	5	11	14	4	1	15	13	3	8	10	6	12	9	7
6	12	15	1	3	13	16	2	7	9	14	4	10	8	5	11
9	7	4	14	11	5	10	8	12	6	1	15	3	13	16	2

# Magic Square

- A  $n \times n$  magic square is a  $n$  by  $n$  grid with the numbers 1 through  $n^2$  exactly once where the rows, columns, and two long diagonals all sum to the same value.

11	5	2	16
8	10	13	3
14	4	7	9
1	15	12	6

# Magic X Sudoku

- A Magic X Sudoku is a X Sudoku where every block of the Sudoku is also a Magic Square.
- Any filling of the grid that satisfies all these conditions is referred to as a solution.

11	5	2	16	4	14	15	1	10	8	3	13	7	9	12	6
8	10	13	3	12	6	9	7	5	11	16	2	14	4	1	15
14	4	7	9	5	11	8	10	15	1	6	12	2	16	13	3
1	15	12	6	13	3	2	16	4	14	9	7	11	5	8	10
12	6	1	15	8	2	13	11	9	4	7	14	5	3	10	16
13	3	8	10	15	9	6	4	16	5	2	11	12	14	7	1
7	9	14	4	10	16	3	5	6	15	12	1	8	2	11	13
2	16	11	5	1	7	12	14	3	10	13	8	9	15	6	4
4	14	9	7	2	8	11	13	1	12	15	6	16	10	3	5
5	11	16	2	9	15	4	6	8	13	10	3	1	7	14	12
15	1	6	12	16	10	5	3	14	7	4	9	13	11	2	8
10	8	3	13	7	1	14	12	11	2	5	16	4	6	15	9
3	13	10	8	6	12	7	9	2	16	11	5	15	1	4	14
16	2	5	11	14	4	1	15	13	3	8	10	6	12	9	7
6	12	15	1	3	13	16	2	7	9	14	4	10	8	5	11
9	7	4	14	11	5	10	8	12	6	1	15	3	13	16	2

## Symmetries

# What are Symmetries?

- A symmetry of a Magic X Sudoku is a transform  $\sigma$  such that for all solutions  $S$ ,  $S^\sigma$  is also a solution.
- Simple examples are the 4  $90^\circ$  rotations of a square, as well as the reflection over the horizontal axis.
- Equivalent to components of the automorphism group of the set of all solutions.

## Symmetries of the 4x4 Magic Square

- Horizontal Flip
- Vertical Flip
- Diagonal Flip
- Ring Swap
- Core Scramble

## Horizontal Flip

11	5	2	16
8	10	13	3
14	4	7	9
1	15	12	6

16	2	5	11
3	13	10	8
9	7	4	14
6	12	15	1

## Vertical Flip

11	5	2	16
8	10	13	3
14	4	7	9
1	15	12	6

1	15	12	6
14	4	7	9
8	10	13	3
11	5	2	16

## Diagonal Flip

11	5	2	16
8	10	13	3
14	4	7	9
1	15	12	6

11	8	14	1
5	10	4	15
2	13	7	12
16	3	9	6

## Ring Swap

11	5	2	16
8	10	13	3
14	4	7	9
1	15	12	6

10	8	3	13
5	11	16	2
15	1	6	12
4	14	9	7



## Core Scramble

11	5	2	16
8	10	13	3
14	4	7	9
1	15	12	6

11	2	5	16
14	7	4	9
8	13	10	3
1	12	15	6

## Composite Symmetries

- Symmetries can be combined to produce new symmetries.
- The previous symmetries represent the basis for the symmetries for the 4x4 magic square.
- The next slide shows the “Corner Scramble” - made up of a Core Scramble, a Horizontal Flip, and a Vertical Flip.

11	5	2	16
8	10	13	3
14	4	7	9
1	15	12	6

11	2	5	16
14	7	4	9
8	13	10	3
1	12	15	6

16	5	2	11
9	4	7	14
3	10	13	8
6	15	12	1

6	15	12	1
3	10	13	8
9	4	7	14
16	2	5	11

## Magic X Sudoku Symmetries

- Even if we consider the contents of the blocks fixed, the Magic X Sudoku has the same symmetries as a 4x4 Magic Square.

11	5	2	16	4	14	15	1	10	8	3	13	7	9	12	6
8	10	13	3	12	6	9	7	5	11	16	2	14	4	1	15
14	4	7	9	5	11	8	10	15	1	6	12	2	16	13	3
1	15	12	6	13	3	2	16	4	14	9	7	11	5	8	10
12	6	1	15	8	2	13	11	9	4	7	14	5	3	10	16
13	3	8	10	15	9	6	4	16	5	2	11	12	14	7	1
7	9	14	4	10	16	3	5	6	15	12	1	8	2	11	13
2	16	11	5	1	7	12	14	3	10	13	8	9	15	6	4
4	14	9	7	2	8	11	13	1	12	15	6	16	10	3	5
5	11	16	2	9	15	4	6	8	13	10	3	1	7	14	12
15	1	6	12	16	10	5	3	14	7	4	9	13	11	2	8
10	8	3	13	7	1	14	12	11	2	5	16	4	6	15	9
3	13	10	8	6	12	7	9	2	16	11	5	15	1	4	14
16	2	5	11	14	4	1	15	13	3	8	10	6	12	9	7
6	12	15	1	3	13	16	2	7	9	14	4	10	8	5	11
9	7	4	14	11	5	10	8	12	6	1	15	3	13	16	2

# Other Symmetries

- It works out all 5 of the symmetries of the can be applied to the green magic square.
- Performing any transform on the green block has a ripple effect to the other blocks.

11	5	2	16	4	14	15	1	10	8	3	13	7	9	12	6
8	10	13	3	12	6	9	7	5	11	16	2	14	4	1	15
14	4	7	9	5	11	8	10	15	1	6	12	2	16	13	3
1	15	12	6	13	3	2	16	4	14	9	7	11	5	8	10
12	6	1	15	8	2	13	11	9	4	7	14	5	3	10	16
13	3	8	10	15	9	6	4	16	5	2	11	12	14	7	1
7	9	14	4	10	16	3	5	6	15	12	1	8	2	11	13
2	16	11	5	1	7	12	14	3	10	13	8	9	15	6	4
4	14	9	7	2	8	11	13	1	12	15	6	16	10	3	5
5	11	16	2	9	15	4	6	8	13	10	3	1	7	14	12
15	1	6	12	16	10	5	3	14	7	4	9	13	11	2	8
10	8	3	13	7	1	14	12	11	2	5	16	4	6	15	9
3	13	10	8	6	12	7	9	2	16	11	5	15	1	4	14
16	2	5	11	14	4	1	15	13	3	8	10	6	12	9	7
6	12	15	1	3	13	16	2	7	9	14	4	10	8	5	11
9	7	4	14	11	5	10	8	12	6	1	15	3	13	16	2

## Symmetry ripple effects

- The ripple effects of 4 of the symmetries prevent using another square for more basis symmetries.
- The jury is out on the ripple effects of the Diagonal Flip: it may not be a valid new symmetry.

# Symmetries Conclusion

- By only enumerating one version of all the symmetric solutions, only 1 out of every 512 solutions needs to be examined.
- In theory this also reduces the search space for a computer program by the same factor.

## Programming

# Programming Overview

- I used the programming language I wrote for my CS MQP: Branch
- Branch is a language designed for Constraint Satisfaction Problems on finite integer domains.
- It gained the ability to automatically remove symmetries once the transform was defined.

## A Magic Row in Branch

```
init();
branch(1,16); //this is x[0]
branch(1,16); //this is x[1]
prune if(x[0]==x[1]) kill
branch(1,16); //this is x[2]
prune if(x[0]==x[2] || x[1]==x[2]) kill
branch(1,16); //this is x[3]
prune if(x[0]==x[3] || x[1]==x[3] || x[2]==x[3]) kill
prune if(x[0]+x[1]+x[2]+x[3] != 34) kill
```

# Fast Fail

- Filling in the grid to produce a contradiction as soon as possible allows the computer to do less work later removing all the invalid solutions.
- This is one of the best orders found so far.

6	5	4	3	38	37	36	35	54	53	52	51	22	21	20	19
7	9	2	10	39	41	34	42	55	57	50	58	23	25	18	26
8	1	12	14	40	33	44	46	56	49	60	62	24	17	28	30
0	11	15	13	32	43	47	45	48	59	63	61	16	27	31	29
70	69	68	67	86	85	84	83	102	101	100	99	118	117	116	115
71	73	66	74	87	89	82	90	103	105	98	106	119	121	114	122
72	65	76	78	88	81	92	94	104	97	108	110	120	113	124	126
64	75	79	77	80	91	95	93	96	107	111	109	112	123	127	125
134	133	132	131	150	149	148	147	166	165	164	163	182	181	180	179
135	137	130	138	151	153	146	154	167	169	162	170	183	185	178	186
136	129	140	142	152	145	156	158	168	161	172	174	184	177	188	190
128	139	143	141	144	155	159	157	160	171	175	173	176	187	191	189
198	197	196	195	214	213	212	211	230	229	228	227	246	245	244	243
199	201	194	202	215	217	210	218	231	233	226	234	247	249	242	250
200	193	204	206	216	209	220	222	232	225	236	238	248	241	252	254
192	203	207	205	208	219	223	221	224	235	239	237	240	251	255	253

## The Problem Proves Larger than Expected

- Despite enlisting the entire CCC cluster and implementing all but two of the symmetries, the problem still has too large a solution space to make full enumeration possible.
- Recent improvements in the code remain insufficiently tested for estimates: the last well tested version would take years to run.

# New Tools

## New Symmetries

- The Core Scramble symmetry is apparently previously unobserved, all symmetries have applications in problems with similar structures.
- The new tools added to Branch greatly ease future work on problems which benefit from symmetry removal.

## Future work

- The latest round of improvements to the code, plus the newest symmetries, may yet render the initial problem computationally feasible with current resources.
- Improvements to Branch to improve speed and continue to simplify creation of these types of programs - most notably, an automatic symmetry generation tool.

# Special Thanks

Brigitte Servatius, for encouraging me to follow my mind as it wanders to new vistas, both in this endeavor and others.

Kathi Fisler, without whom Branch would still be a toy language of little value.

And to all those who serve as sounding board and compass while I wander.

## B Code

The current snapshot of my most recent code. It currently uses both the remapping symmetry without accounting for the interference, and the final attempted optimization of preprocessing valid row pairs of magic squares, which has an as yet undetermined bug. It is however the fastest code to date. I include it here mostly for completeness, a cleaned and streamlined version of Branch is expected before the end of the calendar year, and this one should not be used to gain the Branch language. (If you really want it, I'll send you a more stable, and less integrated, copy.)

### **branch\_mgk.h**

```
#include <stdio.h>
#include <stdlib.h>
#include <time.h>

#define null NULL
double MSPC = 1000/CLOCKS_PER_SEC;

#define x_size 256
//hardcoded limit to number of branches!

int x[x_size];
```



```

int raw[16];

int hash_store_dif[x_size];
int hash_store_min[x_size];

int twoize(int m, int n){
    int ret = 1;
    while((1<<ret) <= (m-n)) ret = ++ret;
    return ret;
}

/* commands:
void init(void);
void branch(int min, int max);
prune if(!good()) kill
inline_branch min to max inline_prune if(good()) nokill
loop
endloop
print
sprintf

new commands:
void sym_prune(int){

classes:
node
state
Hash
LL
stack
Symmetry

*/
void ARG(int*);

int node_count;
int node_local;
int state_count;
int state_local;
int prev_state_local;
clock_t start_time, cur_time, prev_time;

int collision;
double sym_factor;

int tipper;

class node{
public:
    int x_data;
    int n;
    node* above;

```

```

node(int x_in, node* above_in){
    x_data = x_in;
    n = 0;
    above = above_in;
    if(above!= null) ++(above->n);
    ++node_local;
    ++node_count;
}

~node(){
    if(above!=null){
        if(--(above->n)<=0) delete above;//<= could be ==
    }
    --node_local;
    --node_count;
}

void read(int xer){
    if(above != null && (tipper-xer)>=0) {
        raw[tipper-xer] = x_data;
        for(int i=0; i<16; ++i) x[(tipper-xer)*16+i] = table[x_data][i];
        above->read(xer+1);
    }
}

int equal(int* x_in, int tipper_in){
    if(tipper_in < 0 || above == null) return 1;
    for(int i=0; i<16; ++i) if(x_in[tipper_in*16+i] != table[x_data][i]) return 0;
    return above->equal(x_in, tipper_in-1);
}

};

int hack[9];

class state{
public:
    node* cur;
    state* next;

    state(node* cur_in, state* next_in){
        cur = cur_in;
        next = next_in;
        ++state_local;
        ++state_count;
    }

    //the destructor should be shallow, as used from many places... in many ways
    ~state(){

        --state_local;
        --state_count;
    }
}

```

```

}

void kill_solution(state* prev){
    prev -> next = next;
    delete cur;
    delete this;
}

// void kill_list(){//capping stack... now works, but only with optimization!
// delete this;
// if(next!=null) next->kill_list();
// }

int equal(int* x_in, int tipper_in){ // ought to always be (tipper-1) I think
    return cur->equal(x_in, tipper_in);
}

void read(){
    if(cur==null) {printf("cur==null"); exit(2);}
    cur->read(1);//tipper indexed (!), tipper gives 0 index
}
};

class LL{
public:
    state* solution;
    LL* next;

    LL(state* sol, LL* nex){
        solution = sol;
        next = nex;
    }

    ~LL(){
        if(next != null) delete next;
    }

    int has_state(int* x_in){
        if(solution->equal(x_in, tipper-1) == 1) return 1;
        if(next!=null) return next->has_state(x_in);
        return 0;
    }
};

class Hash{
public:
    LL** h;
    int max_size;

    Hash(int size){
        collision = 0;
        if(size<=0) size = 1;
    }
};

```

```

    max_size = size;
    h = new LL* [max_size];
    for(int i=0; i<max_size; ++i) h[i] = null;
    // h = (LL**) (new int (max_size));
    //the above line was all the trouble, between 5-6 HOURS to find
}

~Hash(){
    for(int i=0; i<max_size; ++i) if(h[i]!=null) delete h[i];
    delete h;
}

int hash_func(int* x_in){
    int sum = 0, ret = 0;
    for(int i=0; i<tipper*16; ++i){
        if(sum+hash_store_dif[i]>=31) sum = 0;
        ret = ret ^ ((x_in[i]-hash_store_min[i])<<sum);
        sum+=hash_store_dif[i];
    }
    return ret%max_size;
}

int has_state(int* x_in){
    int n = hash_func(x_in);
    if(n<0) return 0;
    if(h[n] == null) return 0;
    if(h[n]->has_state(x_in) == 1) return 1;
    else return 0;
}

void add_state(state* sol, int* x_in){//x_in better be the read of sol!
    int n = hash_func(x_in);
    if(h[n]!=null) ++collision;
    h[n] = new LL(sol, h[n]);
}

};

int y[x_size];
int sym_tipper;
int tog, got;

class Symmetry{
public:
    int num;
    int** s;
    Symmetry* next;
    int temp_loc;

    Symmetry(int num_in, int** s_in, Symmetry* next_in){
        num = num_in;
        next = next_in;
        temp_loc = 0;
    }
};

```

```

s = new int*[num];
for(int i=0; i<num; ++i) {
    s[i] = new int[x_size];
    for(int j=0; j<x_size; ++j) s[i][j]=s_in[i][j];
}
}

~Symmetry(){
    for(int i=0; i<num; ++i) delete s[i];
    if(s!=null) delete s;
    if(next!=null) delete next;
}

int append(int* yin, int relevant){
    for(int i=0; i<num; ++i){
        tog = 1;
        for(int j=0; j<relevant && tog; ++j) if(s[i][j]!=yin[j]) tog=0;
        /*
        // for(int j=0; j<relevant && tog; ++j) if(s[i][s[0][j]]!=yin[s[0][j]]) tog=0;

        int s_ord[x_size];
        for(int k=0; k<x_size; ++k){
            s_ord[s[0][k]] = s[i][k];
        }

        int y_ord[x_size];
        for(int k=0; k<x_size; ++k){
            y_ord[s[0][k]] = yin[k];
        }

        for(int j=0; j<relevant && tog; ++j) if(s_ord[j]!=y_ord[j]) tog=0;
        */
        if(tog) return 0;
    }
    ++num;
    int** s_in = s;
    s = new int*[num];
    for(int i=0; i<num-1; ++i) {
        s[i] = new int[x_size];
        for(int j=0; j<x_size; ++j) s[i][j]=s_in[i][j];
    }
    s[num-1] = new int[x_size];
    for(int j=0; j<x_size; ++j) s[num-1][j]=yin[j];
    for(int i=0; i<num-1; ++i) delete s_in[i];
    delete s_in;
    return 1;
}

void reset(){
    temp_loc = 0;
    if(next!=null) next->reset();
}

```

```

int transform(int* x_in, int inc){
    temp_loc+=inc;
    if(temp_loc>=num) temp_loc = 0;
    for(int i=0; i<x_size; ++i){
        y[s[0][i]] = x_in[s[temp_loc][i]];
    }
    for(int i=0; i<x_size; ++i){
        x_in[i] = y[i];
    }
    if(next!=null) return next->transform(x_in, temp_loc==0 && inc) + temp_loc;
    else return temp_loc;
}

int use_far(){
    for(int temp_loc = 1; temp_loc<num; ++temp_loc){ // 1 cause 0 is normal
        tog=1;
        got=1;
        for(int i=0; i<sym_tipper*16 && (tog || got); ++i){
            y[i] = x[s[temp_loc][i]];
            if(y[i]<x[i]) if(tog == 1) return 1;
            if((17-y[i])<x[i]) if(got == 1) return 1;
            if(y[i]>x[i]) tog = 0;
            if((17-y[i])>x[i]) got=0;
        }
    }
    return 0;
}

};

state* list;
state* new_list;
state* here;
state* back;

Symmetry* sym = null; //protect against no define
Symmetry* far; //Full Automatic Reduction

class stack{
public:
    stack* prev;
    int sl;
    int nl;
    state* lst;
    int tppr;
    state* hr;
    state* bck;

    stack(stack* prev_in){
        prev = prev_in;
        sl = state_local;
        nl = node_local;
    }
};

```

```

    lst = list;
    tppr = tipper;
    hr = here;
    bck = back;
}

~stack(){
    state_local = sl;
    node_local = nl;
    list = lst;
    tipper = tppr;
    here = hr;
    back = bck;
}
};

state* kf = list;
state* kb;

#define kill_LIST \
kf = list; \
while(kf!=null){ \
    kb = kf; \
    kf = kf->next; \
    delete kb; \
}

stack* now;
stack* temp_now;

void init();
void init(){
    for(int i=0; i<x_size; ++i) x[i] = -i;
    tipper = 0;
    start_time = clock();
    prev_state_local = 1;
    state_count = 0;
    state_local = 0;
    node_count = 0;
    node_local = 0;
    now = null;
    sym_factor = 1;
    far = null;

    list = new state(new node(-1, null), null);
}

void branch(int, int);
void branch(int min, int max){
    if(state_local <= 0) return;
    prev_time = clock();
    for(int i=0; i<16; ++i) hash_store_dif[tipper*16+i] = twoize(16,1);
    for(int i=0; i<16; ++i) hash_store_min[tipper*16+i] = 1;
}

```

```

state* new_list = null;
for(here = list; here!=null; here = here->next){
    for(int i=min; i<=max; ++i){
        new_list = new state(new node(i,here->cur),new_list);
    }
}
kill_LIST
    list = new_list;
++tipper;

//io
cur_time = clock();
printf("branch%3d from%3d to%4d,%8d /%8d s,%9d /%9d n,%6ld /%7ld ms, bf%9f\n",
tipper-1, min, max, state_local, state_count,
node_local, node_count,
int((cur_time-prev_time)*MSPC),
int((cur_time-start_time)*MSPC),
double(state_count)/double(prev_state_local));
prev_state_local = state_local;
}

#define prune prev_time = clock(); rune

#define rune \
back = new state(null,list); \
list = back; \
for(here = list->next; here != null; back = here, here = here->next) { \
    here->read();
//CONDITIONAL GOES HERE
#define ill \
{ \
    here->kill_solution(back); \
    here = back; \
} \
} \
back = list; \
list = list->next; \
delete back;

#define kill ill cur_time = clock(); \
printf("pruned          ,%8d /%8d s,%9d /%9d n,%6ld /%7ld ms, bf%9f\n",
state_local, state_count, node_local, node_count,
int((cur_time-prev_time)*MSPC), int((cur_time-start_time)*MSPC),
double(state_local)/double(prev_state_local)); \
prev_state_local = state_local;

void sprint(int);
void sprint(int size){
    rune
    for(int ix=0; ix<=size; ++ix){
        printf("%3d ",x[ix]);
    }
}

```



```

    }
    printf("\n");
    if(0) ill
    }

//file dependent
void print(int, FILE*);
void print(int size, FILE* fp_in){
    rune
    for(int ix=0; ix<=size; ++ix){
        fprintf(fp_in,"%3d",x[ix]);
    }
    fprintf(fp_in,"\n");
    if(0) ill
    fflush(fp_in); // needed?
}

int min, max;

int feedback;

#define inline_branch min =
#define to ; max =
#define inline_prune ; \
    if(state_local > 0) { \
        prev_time = clock(); \
for(int iprot=0; iprot<16; ++iprot) hash_store_dif[tipper*16+iprot] = twoize(16,1); \
for(int iprot=0; iprot<16; ++iprot) hash_store_min[tipper*16+iprot] = 1; \
        new_list = null; \
        feedback = 0; \
        for(here = list; here!=null; here = here->next){ \
            if(++feedback%100==0) {printf("."); fflush(stdout);} \
            if((feedback%10000)==0) {printf("\n"); fflush(stdout);} \
            if((feedback%100000)==0) {printf("feedback = %d\n",feedback); fflush(stdout);} \
            here->read(); \
            for(int ii=min; ii<=max; ++ii) { \
                raw[tipper] = ii; \
                for(int prot=0; prot<16; ++prot) x[tipper*16+prot] = table[ii][prot];
//CONDITIONAL GOES HERE
#define nokill { \
    new_list = new state(new node(ii,here->cur),new_list); \
    } \
} \
if(here->cur->n<=0){ \
    delete here->cur; \
} \
} \
kill_LIST \
list = new_list; \
++tipper; \
cur_time = clock(); \
printf("\nbranch%3d from%3d to%4d,%8d /%8d s,%9d /%9d n,%6ld /%7ld ms, bf%9f\n",
        tipper-1, min, max, state_local, state_count, node_local, node_count,

```

```

        int((cur_time-prev_time)*MSPC), int((cur_time-start_time)*MSPC),
        double(state_local)/double(prev_state_local)); \
        prev_state_local = state_local; \
    }

#define loop \
    rune \
        now = new stack(now); \
        node_local = 0; \
        state_local = 0; \
        prev_state_local = 1; \
        list = new state(new node(-1, null), null); \
    printf("\n  LOOP%3d on %8d s,%8d /%8d s,%9d /%9d n,%6ld /%7ld ms, bf%9f\n",
        tipper-1, now->sl,state_local,state_count,node_local,node_count,
        int((cur_time-prev_time)*MSPC),int((cur_time-start_time)*MSPC),
        double(state_local)/double(prev_state_local));

//DO LOOP STUFF HERE

#define endloop \
    rune if(1) ill \
        if(node_local != 0) printf( "MEMORY LEAK of %d nodes\n", node_local); \
        if(state_local !=0) printf( "MEMORY LEAK of %d states\n", state_local); \
        temp_now = now; \
        delete now; \
        now = temp_now; \
        for(int i=tipper*16; i<x_size; ++i) x[i] = -i; \
    if(1) ill

Hash* sym_hash;
int y_out[x_size];

int **normal = new int*[1];

void reord(int* flip){
    int temp[x_size];
    for(int i=0; i<x_size; ++i) temp[i] = normal[0][flip[i]];
    for(int i=0; i<x_size; ++i) flip[i] = temp[i];
}

void ARG(int* flip){
    int temp[x_size];
    for(int i=0; i<x_size; ++i) temp[i] = flip[normal[0][i]];
    for(int i=0; i<x_size; ++i) flip[i] = temp[i];
}

int needed(){
    if(far != null) delete far;
    far = new Symmetry(1,normal,null);
    int tog;
    int ret = 0;
    sym->reset();
    for(int i=0; i<x_size; ++i) y_out[i] = i*(1-2*(i>=sym_tipper*16));
}

```

```

while(sym->transform(y_out,1)){
    tog = 1;
    for(int i=0; i<sym_tipper*16 && tog; ++i) if(y_out[i]<0) tog = 0;
    if(tog) {
        for(int i=0; i<x_size; ++i) if(y_out[i]<0) y_out[i]=-y_out[i];
        // for(int i=0; i<16; ++i) printf("%4d",y_out[i]);
        //printf("  pre!\n");
        //  ARG(y_out);
        // for(int i=0; i<16; ++i) printf("%4d",y_out[i]);
        //printf("  arged!  ret = %3d",ret);
        ret+= far->append(y_out,sym_tipper*16);
        //printf("  ret = %3d\n",ret);
    }
    for(int i=0; i<x_size; ++i) y_out[i] = i*(1-2*(i>=sym_tipper*16));
}

printf("sym = %4d\n",ret);
fflush(stdout);
/*
    far->reset();
    for(int i=0; i<x_size; ++i) y_out[i] = i;
    while(far->transform(y_out,1)){
        for(int i=0; i<16; ++i) printf("%4d",y_out[i]);
        printf("  switched!\n");
        for(int i=0; i<x_size; ++i) y_out[i] = i;
    }
*/

return ret;
}

void sym_prune(){
    if(sym == null){printf("no sym!"); return;}
    sym_tipper = tipper;
    int hack = needed();
    if(hack){
        printf("sym%5d  ",hack);
        fflush(stdout);
        feedback=0;
        prune if(far->use_far()) ill
            sym_factor *=(double(prev_state_local)/double(state_local));
        cur_time=clock();
        printf("hit =%9f,%8d /%8d s,%9d /%9d n,%6ld /%7ld ms, bf%9f\n",
            double(collision)/double(state_local),
            state_local, state_count, node_local, node_count,
            int((cur_time-prev_time)*MSPC), int((cur_time-start_time)*MSPC),
            double(state_local)/double(prev_state_local));
        prev_state_local = state_local;
        delete sym_hash;
    }
}
}

```

## LMXS.cpp

```
int table[7040][16] = {
  { 1, 4,13,16, 2, 5,11, 8,14,10, 3,15, 7, 6, 9,12},
  { 1, 4,13,16, 2, 9, 7,12,14, 6, 3,15,11,10, 5, 8},
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  { 1, 4,14,15, 2, 9, 8,12,13, 5, 3,16,11,10, 6, 7},
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#include "branch_mgk.h"

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    natural ordering

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48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63
64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79
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160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175
176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191
192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207
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xx xx 7 xx
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3, 19, 35, 51, 67, 83, 99,115,131,147,163,179,195,211,227,243,
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7, 23, 39, 55, 71, 87,103,119,135,151,167,183,199,215,231,247,
8, 24, 40, 56, 72, 88,104,120,136,152,168,184,200,216,232,248,
9, 25, 41, 57, 73, 89,105,121,137,153,169,185,201,217,233,249,
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4, 5, 6, 7, 0, 1, 2, 3, 12, 13, 14, 15, 8, 9, 10, 11,
20, 21, 22, 23, 16, 17, 18, 19, 28, 29, 30, 31, 24, 25, 26, 27,
36, 37, 38, 39, 32, 33, 34, 35, 44, 45, 46, 47, 40, 41, 42, 43,

```

```
52, 53, 54, 55, 48, 49, 50, 51, 60, 61, 62, 63, 56, 57, 58, 59,
196,197,198,199,192,193,194,195,204,205,206,207,200,201,202,203,
212,213,214,215,208,209,210,211,220,221,222,223,216,217,218,219,
228,229,230,231,224,225,226,227,236,237,238,239,232,233,234,235,
244,245,246,247,240,241,242,243,252,253,254,255,248,249,250,251,
132,133,134,135,128,129,130,131,140,141,142,143,136,137,138,139,
148,149,150,151,144,145,146,147,156,157,158,159,152,153,154,155,
164,165,166,167,160,161,162,163,172,173,174,175,168,169,170,171,
180,181,182,183,176,177,178,179,188,189,190,191,184,185,186,187
};
```

```
int macro_core_scrm[x_size] = {
0, 1, 2, 3, 8, 9, 10, 11, 4, 5, 6, 7, 12, 13, 14, 15,
16, 17, 18, 19, 24, 25, 26, 27, 20, 21, 22, 23, 28, 29, 30, 31,
32, 33, 34, 35, 40, 41, 42, 43, 36, 37, 38, 39, 44, 45, 46, 47,
48, 49, 50, 51, 56, 57, 58, 59, 52, 53, 54, 55, 60, 61, 62, 63,
128,129,130,131,136,137,138,139,132,133,134,135,140,141,142,143,
144,145,146,147,152,153,154,155,148,149,150,151,156,157,158,159,
160,161,162,163,168,169,170,171,164,165,166,167,172,173,174,175,
176,177,178,179,184,185,186,187,180,181,182,183,188,189,190,191,
64, 65, 66, 67, 72, 73, 74, 75, 68, 69, 70, 71, 76, 77, 78, 79,
80, 81, 82, 83, 88, 89, 90, 91, 84, 85, 86, 87, 92, 93, 94, 95,
96, 97, 98, 99,104,105,106,107,100,101,102,103,108,109,110,111,
112,113,114,115,120,121,122,123,116,117,118,119,124,125,126,127,
192,193,194,195,200,201,202,203,196,197,198,199,204,205,206,207,
208,209,210,211,216,217,218,219,212,213,214,215,220,221,222,223,
224,225,226,227,232,233,234,235,228,229,230,231,236,237,238,239,
240,241,242,243,248,249,250,251,244,245,246,247,252,253,254,255
};
```

```
int small_horz_flip[x_size] = {
0, 1, 2, 3, 7, 6, 5, 4, 11, 10, 9, 8, 12, 13, 14, 15,
16, 17, 18, 19, 23, 22, 21, 20, 27, 26, 25, 24, 28, 29, 30, 31,
32, 33, 34, 35, 39, 38, 37, 36, 43, 42, 41, 40, 44, 45, 46, 47,
48, 49, 50, 51, 55, 54, 53, 52, 59, 58, 57, 56, 60, 61, 62, 63,
112,113,114,115,119,118,117,116,123,122,121,120,124,125,126,127,
96, 97, 98, 99,103,102,101,100,107,106,105,104,108,109,110,111,
80, 81, 82, 83, 87, 86, 85, 84, 91, 90, 89, 88, 92, 93, 94, 95,
64, 65, 66, 67, 71, 70, 69, 68, 75, 74, 73, 72, 76, 77, 78, 79,
176,177,178,179,183,182,181,180,187,186,185,184,188,189,190,191,
160,161,162,163,167,166,165,164,171,170,169,168,172,173,174,175,
144,145,146,147,151,150,149,148,155,154,153,152,156,157,158,159,
128,129,130,131,135,134,133,132,139,138,137,136,140,141,142,143,
192,193,194,195,199,198,197,196,203,202,201,200,204,205,206,207,
208,209,210,211,215,214,213,212,219,218,217,216,220,221,222,223,
224,225,226,227,231,230,229,228,235,234,233,232,236,237,238,239,
240,241,242,243,247,246,245,244,251,250,249,248,252,253,254,255
};
```

```
int small_vert_flip[x_size] = {
51, 50, 49, 48, 52, 53, 54, 55, 56, 57, 58, 59, 63, 62, 61, 60,
35, 34, 33, 32, 36, 37, 38, 39, 40, 41, 42, 43, 47, 46, 45, 44,
19, 18, 17, 16, 20, 21, 22, 23, 24, 25, 26, 27, 31, 30, 29, 28,
```

```
3, 2, 1, 0, 4, 5, 6, 7, 8, 9, 10, 11, 15, 14, 13, 12,
67, 66, 65, 64, 68, 69, 70, 71, 72, 73, 74, 75, 79, 78, 77, 76,
83, 82, 81, 80, 84, 85, 86, 87, 88, 89, 90, 91, 95, 94, 93, 92,
99, 98, 97, 96, 100, 101, 102, 103, 104, 105, 106, 107, 111, 110, 109, 108,
115, 114, 113, 112, 116, 117, 118, 119, 120, 121, 122, 123, 127, 126, 125, 124,
131, 130, 129, 128, 132, 133, 134, 135, 136, 137, 138, 139, 143, 142, 141, 140,
147, 146, 145, 144, 148, 149, 150, 151, 152, 153, 154, 155, 159, 158, 157, 156,
163, 162, 161, 160, 164, 165, 166, 167, 168, 169, 170, 171, 175, 174, 173, 172,
179, 178, 177, 176, 180, 181, 182, 183, 184, 185, 186, 187, 191, 190, 189, 188,
243, 242, 241, 240, 244, 245, 246, 247, 248, 249, 250, 251, 255, 254, 253, 252,
227, 226, 225, 224, 228, 229, 230, 231, 232, 233, 234, 235, 239, 238, 237, 236,
211, 210, 209, 208, 212, 213, 214, 215, 216, 217, 218, 219, 223, 222, 221, 220,
195, 194, 193, 192, 196, 197, 198, 199, 200, 201, 202, 203, 207, 206, 205, 204
};
```

```
int small_ring_swap[x_size] = {
    17, 16, 19, 18, 21, 20, 23, 22, 25, 24, 27, 26, 29, 28, 31, 30,
    1, 0, 3, 2, 5, 4, 7, 6, 9, 8, 11, 10, 13, 12, 15, 14,
    49, 48, 51, 50, 53, 52, 55, 54, 57, 56, 59, 58, 61, 60, 63, 62,
    33, 32, 35, 34, 37, 36, 39, 38, 41, 40, 43, 42, 45, 44, 47, 46,
    81, 80, 83, 82, 85, 84, 87, 86, 89, 88, 91, 90, 93, 92, 95, 94,
    65, 64, 67, 66, 69, 68, 71, 70, 73, 72, 75, 74, 77, 76, 79, 78,
    113, 112, 115, 114, 117, 116, 119, 118, 121, 120, 123, 122, 125, 124, 127, 126,
    97, 96, 99, 98, 101, 100, 103, 102, 105, 104, 107, 106, 109, 108, 111, 110,
    145, 144, 147, 146, 149, 148, 151, 150, 153, 152, 155, 154, 157, 156, 159, 158,
    129, 128, 131, 130, 133, 132, 135, 134, 137, 136, 139, 138, 141, 140, 143, 142,
    177, 176, 179, 178, 181, 180, 183, 182, 185, 184, 187, 186, 189, 188, 191, 190,
    161, 160, 163, 162, 165, 164, 167, 166, 169, 168, 171, 170, 173, 172, 175, 174,
    209, 208, 211, 210, 213, 212, 215, 214, 217, 216, 219, 218, 221, 220, 223, 222,
    193, 192, 195, 194, 197, 196, 199, 198, 201, 200, 203, 202, 205, 204, 207, 206,
    241, 240, 243, 242, 245, 244, 247, 246, 249, 248, 251, 250, 253, 252, 255, 254,
    225, 224, 227, 226, 229, 228, 231, 230, 233, 232, 235, 234, 237, 236, 239, 238
};
```

```
int small_core_scrm[x_size] = {
    0, 2, 1, 3, 4, 6, 5, 7, 8, 10, 9, 11, 12, 14, 13, 15,
    32, 34, 33, 35, 36, 38, 37, 39, 40, 42, 41, 43, 44, 46, 45, 47,
    16, 18, 17, 19, 20, 22, 21, 23, 24, 26, 25, 27, 28, 30, 29, 31,
    48, 50, 49, 51, 52, 54, 53, 55, 56, 58, 57, 59, 60, 62, 61, 63,
    64, 66, 65, 67, 68, 70, 69, 71, 72, 74, 73, 75, 76, 78, 77, 79,
    96, 98, 97, 99, 100, 102, 101, 103, 104, 106, 105, 107, 108, 110, 109, 111,
    80, 82, 81, 83, 84, 86, 85, 87, 88, 90, 89, 91, 92, 94, 93, 95,
    112, 114, 113, 115, 116, 118, 117, 119, 120, 122, 121, 123, 124, 126, 125, 127,
    128, 130, 129, 131, 132, 134, 133, 135, 136, 138, 137, 139, 140, 142, 141, 143,
    160, 162, 161, 163, 164, 166, 165, 167, 168, 170, 169, 171, 172, 174, 173, 175,
    144, 146, 145, 147, 148, 150, 149, 151, 152, 154, 153, 155, 156, 158, 157, 159,
    176, 178, 177, 179, 180, 182, 181, 183, 184, 186, 185, 187, 188, 190, 189, 191,
    192, 194, 193, 195, 196, 198, 197, 199, 200, 202, 201, 203, 204, 206, 205, 207,
    224, 226, 225, 227, 228, 230, 229, 231, 232, 234, 233, 235, 236, 238, 237, 239,
    208, 210, 209, 211, 212, 214, 213, 215, 216, 218, 217, 219, 220, 222, 221, 223,
    240, 242, 241, 243, 244, 246, 245, 247, 248, 250, 249, 251, 252, 254, 253, 255
};
```

```

//END SYMMETRIES

int cx, cy;
void rev(int n){
    for(int i=0; i<x_size; ++i) if(base[i] == n){
        cx = ((i%16)/4)*4;
        cy = (i/64)*4;
        //printf("cx = %d, cy = %d\n",cx,cy);
        return;
    }
}

int sudoku(){

    for(int i=0; i<16; ++i){
        for(int j=cx; j<cx+4; ++j){
            for(int k=cy; k<cy+4; ++k){
                if(i!=j) if(x[base[i + 16*k]]==x[base[j + 16*k]]) return 0;
            }
        }
    }

    for(int i=cy; i<cy+4; ++i){
        for(int j=0; j<16; ++j){
            for(int k=cx; k<cx+4; ++k){
                if(i!=j) if(x[base[k + 16*i]]==x[base[k + 16*j]]) return 0;
            }
        }
    }

    if(cx==cy){
        for(int i=0; i<16; ++i){
            for(int j=cy; j<cy+4; ++j){
                if(i!=j) if(x[base[i + 16*i]]==x[base[j + 16*j]]) return 0;
            }
        }
    }

    if(cx+cy==12){
        for(int i=0; i<16; ++i){
            for(int j=cy; j<cy+4; ++j){
                if(i!=j) if(x[base[15-i + 16*i]]==x[base[15-j + 16*j]]) return 0;
            }
        }
    }

    return 1;
}

int *mhf[2] = {base,macro_horz_flip};
int *mvf[2] = {base,macro_vert_flip};

```

```

int *mdf[2] = {base,macro_diag_flip};
int *mrs[2] = {base,macro_ring_swap};
int *mcs[2] = {base,macro_core_scrm};
int *shf[2] = {base,small_horz_flip};
int *svf[2] = {base,small_vert_flip};
// int *sdf[2] = {base,small_diag_flip};
int *srs[2] = {base,small_ring_swap};
int *scs[2] = {base,small_core_scrm};

FILE* fp = fopen("sudoku_list.txt","w");
FILE* f_num = fopen("sudoku_num.txt","w");

char* huge[7040];

void generate(){
    for(int i=0; i<7040; ++i) huge[i] = new char[i];

    for(int i=0; i<7040; ++i) for(int j=0; j<i; ++j) huge[i][j] = 0;

    int inord[16] = { 6, 5, 4, 3,
        7, 9, 2,10,
        8, 1,12,14,
        0,11,15,13
    };

    int out_ord[16] = { 2, 0, 1, 3,
        6, 4, 5, 7,
        10, 8, 9,11,
        13,15,14,12
    };

    for(int i=0; i<256; ++i) {
        base[i] = inord[(i%16)%4 + 4*((i/16)%4)]
            + 16*out_ord[(i%16)/4 + 4*((i/16)/4)];
    }

    init();
    rev(0);
    inline_branch 0 to 7039 inline_prune if(sudoku()) nokill
    rev(16);
    inline_branch 0 to 7039 inline_prune if((raw[0] > raw[1]) && sudoku()) nokill
    prune huge[raw[0]][raw[1]]+=1; if(1) kill

    /*
        for(int i=0; i<7040; ++i){ for(int j=0; j<i; ++j) printf("%5d,%5d=%3d ",i,j,huge[i][j]);
        printf("\n");
        }
    */

    int out_ord2[16] = {
        2, 0, 4, 3,
        6, 1, 5, 7,

```

```

    10, 8, 9,11,
    13,15,14,12
};

for(int i=0; i<256; ++i) {
    base[i] = inord[(i%16)%4 + 4*((i/16)%4)]
        + 16*out_ord2[(i%16)/4 + 4*((i/16)/4)];
}

init();
rev(0);
inline_branch 0 to 7039 inline_prune if(sudoku()) nokill
rev(16);
inline_branch 0 to 7039 inline_prune if((raw[0] > raw[1]) && sudoku()) nokill
prune huge[raw[0]][raw[1]]+=2; if(1) kill

int out_ord3[16] = {
    0, 2, 4, 3,
    6, 1, 5, 7,
    10, 8, 9,11,
    13,15,14,12
};

for(int i=0; i<256; ++i) {
    base[i] = inord[(i%16)%4 + 4*((i/16)%4)] + 16*out_ord3[(i%16)/4 + 4*((i/16)/4)];
}

init();
rev(0);
inline_branch 0 to 7039 inline_prune if(sudoku()) nokill
rev(16);
inline_branch 0 to 7039 inline_prune if((raw[0] > raw[1]) && sudoku()) nokill
prune huge[raw[0]][raw[1]]+=4; if(1) kill

int out_ord4[16] = {
    2, 3, 5, 0,
    6, 4, 1, 7,
    10, 8, 9,11,
    13,15,14,12
};

for(int i=0; i<256; ++i) {
    base[i] = inord[(i%16)%4 + 4*((i/16)%4)] + 16*out_ord4[(i%16)/4 + 4*((i/16)/4)];
}

init();
rev(0);
inline_branch 0 to 7039 inline_prune if(sudoku()) nokill
rev(16);
inline_branch 0 to 7039 inline_prune if((raw[0] > raw[1]) && sudoku()) nokill
prune huge[raw[0]][raw[1]]+=8; if(1) kill

/*

```



```

    for(int i=0; i<7040; ++i){ for(int j=0; j<i; ++j) printf("%5d,%5d=%3d ",i,j,huge[i][j]);
    printf("\n");
    }
    */

    init();
}

int test(int a, int b, int mask){
    if(raw[a]>raw[b]) return (huge[raw[a]][raw[b]] & mask);
    else return (huge[raw[b]][raw[a]] & mask);
}

int splitter(int i){
    switch( i ){
    case 0: return 1;
    case 1: return test(1,0,1);
    case 2: return test(2,0,1) && test(2,1,1);
    case 3: return test(3,0,1) && test(3,1,1) && test(3,2,1);
    case 4: return test(4,0,2) && test(4,2,4);
    case 5: return test(5,4,1) && test(5,1,2) && test(5,3,8);
    case 6: return test(6,5,1) && test(6,4,1) && test(6,4,2);
    case 7: return test(7,4,1) && test(7,5,1) && test(7,6,1) && test(7,3,2);
    case 8: return test(8,4,2) && test(8,0,2) && test(8,5,8) && test(8,3,8);
    case 9: return test(9,8,1) && test(9,5,2) && test(9,1,2) && test(9,4,4)
        && test(9,2,4);
    case 10: return test(10,9,1) && test(10,8,1) && test(10,6,2) && test(10,2,2);
    case 11: return test(11,10,1) && test(11,9,1) && test(11,8,1) && test(11,7,2)
        && test(11,3,2);
    case 12: return test(12,11,2) && test(12,7,2) && test(12,3,2) && test(12,9,4)
        && test(12,4,4) && test(12,2,4);
    case 13: return test(13,12,1) && test(13,10,2) && test(13,6,2) && test(13,2,2)
        && test(13,8,8) && test(13,5,8) && test(13,3,8);
    case 14: return test(14,13,1) && test(14,12,1) && test(14,9,2) && test(14,5,2)
        && test(14,1,2);
    case 15: return test(15,14,1) && test(15,13,1) && test(15,12,1) && test(15,8,2)
        && test(15,4,2) && test(15,0,2);
    default: printf("huh?\n"); return 1;

    /*
        int out_ord[16] = { 2, 0, 1, 3,
            6, 4, 5, 7,
            10, 8, 9,11,
            13,15,14,12
        };
    */
    }
}

int main()
{

    generate();
}

```

```

/*
  int ih[4] = {0,2,1,3};
  int jh[4] = {0,1,2,3};
  int kh[4] = {0,2,1,3};
  int lh[4] = {0,1,2,3};

  for(int i=0; i<4; ++i){
  for(int j = 0; j<4; ++j){
  for(int k = 0; k<4; ++k){
  for(int l = 0; l<4; ++l){
  printf("%3d,",lh[l] + 4*kh[k] + 16*jh[j] + 64*ih[i]);
  }
  }
  }
  printf("\n");
  }
  }
  return 0;
*/

int inord[16] = { 6, 5, 4, 3,
  7, 9, 2,10,
  8, 1,12,14,
  0,11,15,13
};

int out_ord[16] = { 2, 0, 1, 3,
  6, 4, 5, 7,
  10, 8, 9,11,
  13,15,14,12
};

for(int i=0; i<256; ++i) {
  base[i] = inord[(i%16)%4 + 4*((i/16)%4)] + 16*out_ord[(i%16)/4 + 4*((i/16)/4)];
}

normal[0] = base;

reord(macro_horz_flip);
reord(macro_vert_flip);
reord(macro_diag_flip);
reord(macro_ring_swap);
reord(macro_core_scrm);
reord(small_horz_flip);
reord(small_vert_flip);
// reord(small_diag_flip);
reord(small_ring_swap);
reord(small_core_scrm);

sym = new Symmetry(2,mhf,null);
sym = new Symmetry(2,mvf,sym);

```

```

sym = new Symmetry(2,mdf,sym);
sym = new Symmetry(2,mrs,sym);
sym = new Symmetry(2,mcs,sym);
sym = new Symmetry(2,shf,sym);
sym = new Symmetry(2,svf,sym);
// sym = new Symmetry(2,sdf,sym);
sym = new Symmetry(2,srs,sym);
sym = new Symmetry(2,scs,sym);

init();

for(int i=0; i<4; ++i) {
    rev(i*16);
    sym_tipper = tipper+1;

    if(needed()){
        inline_branch 0 to 7039 inline_prune
if(splitter(i)
    //    && sudoku()
    && !far->use_far()
    ) nokill
    } else {
        inline_branch 0 to 7039 inline_prune
if(sudoku()
    && splitter(i)
    ) nokill
    }
}

loop

    for(int i=4; i<16; ++i){
        rev(i*16);
        sym_tipper = tipper+1;
        if(needed()){
inline_branch 0 to 7039 inline_prune
            if(splitter(i)
                //    && sudoku()
                && !far->use_far()
            ) nokill
            } else {
inline_branch 0 to 7039 inline_prune
if(sudoku()
    && splitter(i)
    ) nokill
    }
        }

print(255,fp);

fprintf(f_num,"%d\n",state_local);

```

```
endloop  
printf("finished!\n\n");  
}
```