How Difficult Is A Sudoku?

Hang Chen and Curtis Cooper
University of Central Missouri

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Introduction

Commonly Used Rules

Rectangle Rule

Difficulty Levels

Uniqueness

Beyond Daily Sudoku

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How Difficult Is A Sudoku?
Easiest Sudoku Puzzle

[Image of a Sudoku puzzle with the words "BINARY SU DOKU"]

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How Difficult Is A Sudoku?
**Very Hard Sudoku Puzzle, Al Escargot (Arto Inkala, Finland, 11/6/2006)**

```
 1  3  9
 7  2  8
 9  6  5
 5  3  9
 1  8  2
 6  4
 3  1
 4  7
 7  3
```
Another Very Hard Sudoku Puzzle, Easter Monster

```
1 2
  9 4 5
  6 7
  5 9 3
  7
  8 5 4
  3 9 8
  2 1
7 6
3 9 8
2 1
1 2
```

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How Difficult Is A Sudoku?
Sudoku is a logic-based number placement puzzle. In a 9 × 9 grid, we fill in integers from 1 to 9 such that all the numbers in a row are distinct, all the numbers in a column are distinct, and furthermore, the 9 × 9 grid is divided into nine 3 × 3 squares, all the numbers in a 3 × 3 square are distinct too. A Sudoku is such a puzzle that is partially filled with numbers.
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Howard Garns invented the puzzle in 1979. It was called “Number Place” and was published by Dell Magazines.
Sudoku is a logic-based number placement puzzle. In a $9 \times 9$ grid, we fill in integers from 1 to 9 such that all the numbers in a row are distinct, all the numbers in a column are distinct, and furthermore, the $9 \times 9$ grid is divided into nine $3 \times 3$ squares, all the numbers in a $3 \times 3$ square are distinct too. A Sudoku is such a puzzle that is partially filled with numbers.

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It became popular in Japan in 1986, after it was published by Nikoli and given the name Sudoku, meaning unique numbers.
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It became popular in Japan in 1986, after it was published by Nikoli and given the name Sudoku, meaning unique numbers.

It became internationally popular in 2005.


d 1 8 7 5 
5 4 3 
3 4 
4 1 2 5 
2 
9 3 7 
2 5 
2 1 6 8 
9

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*How Difficult Is A Sudoku?*
Solution to Demanding 46.

Numbers in black were originally provided as hints and numbers in red were filled in as the solution.
Generally, a valid Sudoku puzzle should have a unique solution. That is, there is only one way to fill in all the missing numbers.
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And a Sudoku puzzle should be minimal too. Deleting any of the given hints should result in more than one solution.
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And a Sudoku puzzle should be minimal too. Deleting any of the given hints should result in more than one solution.

As far as we know, all published Sudoku puzzles satisfy these two requirements.
How many given hints does a minimum Sudoku puzzle have?
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As far as we know: 17. This has not been proved.
How many given hints does a minimum Sudoku puzzle have?

As far as we know: 17. This has not been proved.

We have found that many of the minimum Sudoku are very easy to solve.
1 Introduction
2 Commonly Used Rules
3 Rectangle Rule
4 Difficulty Levels
5 Uniqueness
6 Beyond Daily Sudoku

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How Difficult Is A Sudoku?
We are searching for “deterministic” rules that can either fill-in a number or eliminate a number from an entry.
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Row-Column-Square Rule:
Only one number is missing in the combination of row, column, and square.
Minimum Sudoku S17-3,
(Solution in progress).
Row Cancelation:
A number cannot be in a certain row of a square due to:

1. This number is determined to be in the row outside the square;
2. The row in the square is filled in.
Column Cancelation: similar to Row Cancelation with row replaced by column
• Row Cancelation:
  A number cannot be in a certain row of a square due to:

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2. The row in the square is filled in.

Column Cancelation: similar to Row Cancelation with row replaced by column
Moderate 33, *The Ultimate Sudoku Challenge* by Will Shortz.

```
<table>
<thead>
<tr>
<th>4</th>
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<td>9</td>
</tr>
</tbody>
</table>
```
Two Numbers:
Only two numbers are missing in only two entries of a row or a column or a square.
Egame 14, *Electronic SuDoku* by Excalibur Electronics, Inc. (Solution in progress)

In the lower left square, entries 71 and 91 must be a 6 or 8.
Three (Four, etc.) Numbers:
Only three (four, etc.) numbers are missing in only three (four, etc.) entries of a row or a column or a square.
Final Fiend, 2007 *The Times* National Championship (Solution in progress).

In column 2, the numbers 1, 4, 6, and 8 can only be in rows 1, 2, 6, and 9.

```
  7   5   8   2
  3   7   
  8   6   4   2   1
  7   3   6   4   1   2
  5   6   1   3   7   8
  6   7   3   9   6   5
```

```
  7   8   1   5   4
  9   
  5   3   2   7
```
In general, we would like to have “independent” Sudoku rules. That is, one or more rules will not imply another rule.
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However, sometimes for convenience and simplicity, we may use some rules which may imply other rules.
When a human solves a Sudoku, their notation is usually simple and brief.
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For example, with certain techniques that we use, we try to keep track of numbers that can be put in exactly two places in a particular square.
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We need to rely on our memory to recall certain facts we have learned while working on the Sudoku. But our memory is limited.
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For example, with certain techniques that we use, we try to keep track of numbers that can be put in exactly two places in a particular square.

We need to rely on our memory to recall certain facts we have learned while working on the Sudoku. But our memory is limited.

And the calculations we can perform are limited by the speed and complexity that our brain can handle.
When a computer solves a Sudoku, its memory is vast and the computations it can perform can be complex and extensive.
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The computer can keep track of everything like the absolute numbers that remain for a certain entry in a Sudoku.
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The computer can keep track of everything like the absolute numbers that remain for a certain entry in a Sudoku.

In our study of Sudoku puzzles, we have relied heavily on a program we wrote to solve Sudokus.
Introduction
Commonly Used Rules
Rectangle Rule
Difficulty Levels
Uniqueness
Beyond Daily Sudoku

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How Difficult Is A Sudoku?
We found some patterns that can lead to two solutions.
We found some patterns that can lead to two solutions.
We found some patterns that can lead to two solutions.

However, we could also complete the Sudoku by swapping the numbers on the rectangle. Then the solution to the Sudoku would not be unique.
Rectangle Rule:
We must fill in at least 3 different numbers among 4 unhinted entries from 2 different squares that form a rectangle.
Rectangle Rule:
We must fill in at least 3 different numbers among 4 unhinted entries from 2 different squares that form a rectangle.

Proof. If we have only 2 different entries for the rectangle, entries on the diagonals of the rectangle are the same. Interchanging the numbers on the rectangle results in another solution to the Sudoku, contradicting the uniqueness of the Sudoku.
Expert 92, live-sudoku.com (Solution in progress).

By the Rectangle Rule, entry 37 cannot be a 2.
The entries at 47, 97, and 99 can only be 1 or 9. By a corollary to the Rectangle Rule, entry 49 cannot be a 1 or 9.
How Difficult Is A Sudoku?
A published Sudoku is often rated with a difficulty level. Here are some among we have seen:
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Will Shortz (The Ultimate Sudoku Challenge): Light and Easy, Moderate, Demanding, Beware! Very Challenging, The Ultimate Challenge!
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Will Shortz (The Ultimate Sudoku Challenge): Light and Easy, Moderate, Demanding, Beware! Very Challenging, The Ultimate Challenge!

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Universal Press Syndicate (Kansas City Star): *, **, · · · , *****.
Although these ratings give us a general idea on the difficulty levels, often we find they are far from informative.
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Difficulty: Skill - logic, counting; Time - back tracking.
Although these ratings give us a general idea on the difficulty levels, often we find they are far from informative.

Difficulty: Skill - logic, counting; Time - back tracking.

We propose our own rating system suing the Missouri State Animal.
Introduction

Commonly Used Rules

Row-Column-Square Rule.

Difficulty Levels

Rectangle Rule

Row or Column Cancelation Rule.

Two Numbers Rule and Rectangle Rule.

Three or More Numbers Rules and Advanced Counting.

One-Level Guess.

Two or Higher Level Guess.

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Introduction

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Row-Column-Square Rule.

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Row-Column-Square Rule.
Row or Column Cancelation Rule.
Two Numbers Rule and Rectangle Rule.
Row-Column-Square Rule.
Row or Column Cancelation Rule.
Two Numbers Rule and Rectangle Rule.
Three or More Numbers Rules and Advanced Counting.
Commonly Used Rules

- Row-Column-Square Rule.
- Row or Column Cancelation Rule.
- Two Numbers Rule and Rectangle Rule.
- Three or More Numbers Rules and Advanced Counting.
- One-Level Guess.
- Row-Column-Square Rule.
- Row or Column Cancelation Rule.
- Two Numbers Rule and Rectangle Rule.
- Three or More Numbers Rules and Advanced Counting.
- One-Level Guess.
- Two or Higher Level Guess.
Examples.

- **Moderate 34 (WS)**
- **The Ultimate Challenge! 100 (WS), Diabolically Hard 100 (MH), UPS (KCS-4/12/08, 6 Stars)**
- **Demanding 56 (WS)**
- **UPS (KCS-2/16/08, 6 Stars), Expert 22 (Live Sudoku)**
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How Difficult Is A Sudoku?
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How Difficult Is A Sudoku?
Based on the uniqueness of the solution to a Sudoku, we established the Rectangle Rule.
Based on the uniqueness of the solution to a Sudoku, we established the Rectangle Rule.

These 4 numbers may not all be part of a solution.
We found a class of structures similar to this related to the uniqueness of solutions.
We found a class of structures similar to this related to the uniqueness of solutions.

A cycle of \( pq \) is a minimal structure such that swapping of the numbers \( p \) and \( q \) will result in a different solution of the Sudoku.

If the length of a cycle of \( pq \) is \( k \), we call it a \( k \)-cycle of \( pq \), where \( k = 2, 3, 4, 5, 6, 7, 9 \).
Examples of cycles of $pq$.

- A 2-cycle of 12:
A 3-cycle of 12:
Another 3-cycle of 12:
A 9-cycle of 12:
Every pair of numbers $p$ and $q$ belongs to a cycle of $pq$. Furthermore, if we decomposed a Sudoku solution into cycles of $pq$, then these cycles can have lengths of $2, 2, 2, 3$; $2, 2, 5$; $2, 3, 4$; $2, 7$; $3, 3, 3$; $3, 6$; $4, 5$; $9$. 
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Although we have practically used Rectangle Rule (2-cycle of $pq$), we have not had chances to use anything based on larger cycles to solve a real Sudoku.
Here is a minimum Sudoku (as we know so far) with 17 hints, S17-4.

```
9 6 1 7
2 5 8 3
6 4 1 7
```

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How Difficult Is A Sudoku?
From its solution, we conclude that those dotted numbers may not be removed as hints since otherwise the solution would contain cycles of pq and, therefore, is not unique.

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How Difficult Is A Sudoku?
Introduction

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Rectangle Rule

Difficulty Levels

Uniqueness

Beyond Daily Sudoku
In the previous example, what if we remove 3 as a hint from the entry 49 to get a puzzle with 16 hints, S17-4-493?

```
 1 7

9 6

2

5

6 2 3

8

4

1

4 1 7

1 7

5

8 3

4 1 3
```

Then the possible numbers for this entry are: 3, 1, 5, 6, 9.
In the previous example, what if we remove 3 as a hint from the entry 49 to get a puzzle with 16 hints, S17-4-493?

Then the possible numbers for this entry are: 3, 1, 5, 6, 9.
We know that filling in the entry 49 with 3 leads to a unique solution.
- We know that filling in the entry 49 with 3 leads to a unique solution.

- Now, let’s try to put 1 in the entry. There is a solution!
In fact, the solution is not unique! It contains the following 4-cycle of 89 as part of solution.
Filling in the entry with 5, we get a solution too. It is not unique.

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How Difficult Is A Sudoku?
Let’s try 6. There is a solution, and it is not unique.
Finally, with 9 in the entry, there is also a solution. Again, it is not unique!

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First, we have seen that there are many ways to complete S17-4-493.
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Furthermore, we have also observed that, filling in any of numbers of 1, 5, 6, or 9 in the entry 49 will result in more than one solution from that point on.

In the entry 49, only when 3 is filled in, the puzzle may be completed in a unique way.
Can we relax the definition of Sudoku a little?
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Uniqueness: Every number we fill in guarantees that there is a unique way to complete the puzzle.
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Based on this modification, S17-493 is such a “Sudoku”. We know that the puzzle has a unique solution if and only if we fill in the “correct” number 3 in the entry 49.
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Based on this modification, S17-493 is such a “Sudoku”. We know that the puzzle has a unique solution if and only if we fill in the “correct” number 3 in the entry 49.

Do you think that, with this relaxed definition, the puzzle is easier to solve?