Centre for
Data Analytics

Insight

Solving Logic Grid Puzzles with an Algorithm that Imitates Human Behavior

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September 19, 2019

DCU NUI Galway OÉ Gaillimh UCC University College Cork, Ireland Coláiste na hOllscoile Corcaigh UCD DUBLIN SFI Science Foundation Ireland

- Third Workshop on Progress Towards the Holy Grail
- Stamford, CT
- Eugene Freuder

Holy Grail of programming[1]

The user states the problem, the computer solves it.

[1] E. C. Freuder, *In Pursuit of the Holy Grail*, Constraints, 1997

Holy Grail Challenge

Goal Achieving the Holy Grail of programming on the logicgridpuzzles.com website.

The Challenge: For puzzles at the website:

1. Accept as input the description and clues in English.
2. Transform the input into an appropriate CSP model.
3. Solve the CSP appropriately.
4. Provide an appropriate English language explanation of how the solution was obtained.

Partial Entry We only partially address Step 1.

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Solving Logic Grid Puzzles with an Algorithm that Imitates Human Behavior

http://ucc.insight-centre.org/gescamocher/Grail.zip

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September 30, 2019

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Formal Definition

Logic grid puzzle

- k categories
- n elements in each category
- clues

Solution

A matching of the elements into k-tuples respecting all clues.
A valid logic grid puzzle has exactly one solution.

Running example

Categories

- First Name: “Angela”, “Donald”, “Leo”
- Country: “Germany”, “Ireland”, “United States”
- Year of Birth: “1946”, “1954”, “1979”

Clues

1. The person from the “United States” was born in “1946”.
2. “Leo” is younger than the person from “Germany”.
3. “Donald” was born in “1946” or he is from “Ireland”.

Solution

- ⟨ “Angela”, “Germany”, “1954”⟩
- ⟨ “Donald”, “United States”, “1946”⟩
- ⟨ “Leo”, “Ireland”, “1979”⟩

Outline

Step 1: Acquisition (partial)

- User is asked to enter the puzzle.
- Clue $\Leftrightarrow$ Set of constraints
- For each constraint, the user picks among the options offered by the program.
- Input files for the website puzzles can be found at http://ucc.insight-centre.org/gescamocher/Grail_Input.zip

Step 2: Modelling

Grid

Each pair of elements from different categories is represented by a cell. Solving a puzzle is filling each cell with *yes* if the two elements are to be matched, or with *no* otherwise.

		Country			Year of Birth		
		Germany	Ireland	USA	1946	1954	1979
First Name	Angela						
	Donald						
	Leo						
Year of Birth	1946						
	1954						
	1979						

Our implementation

- Array of integers.
- Each cell is initialized at 0.
- Value set to 1 (resp. -1) when cell determined to be *yes* (resp. *no*).

Step 3: Solving

One rule, one cell

At each step, the algorithm uses one inference rule to fill one cell of the grid.

Goal: to reason like a human

- same inference rules
- same order

Inference Rules

- Clues rules (58): information that can be derived from the clues.
- Consistency rules: information that can be derived from just the current state of the grid.
  - Basic consistency rules (2): easy, humans love them.
  - Advanced consistency rules (3): tedious, humans try to avoid them.

Clues Rules (standard example)

		Sport			Last Championship		
		Baseball	Basketball	Football	2008	2018	2019
Team	Celtics						
	Patriots						
	Red Sox						
Last Championship	2008						
	2018						
	2019						

- Clue: The “Football” team playing near Boston has won a championship more recently than the “Celtics”.
- Constraint: “Football” is after ”Celtics” in the “Last Championship” category.

Clues Rules (standard example)

		Sport			Last Championship		
		Baseball	Basketball	Football	2008	2018	2019
Team	Celtics						
	Patriots						
	Red Sox						
Last Championship	2008			•			
	2018						
	2019						

- Clue: The “Football” team playing near Boston has won a championship more recently than the “Celtics”.
- Constraint: “Football” is after ”Celtics” in the “Last Championship” category.
- Rule: we know that ”Football” is not the first element in the “Last Championship” category.

Clues Rules (easy example)

		Sport			Last Championship		
		Baseball	Basketball	Football	2008	2018	2019
Team	Celtics		Y				
	Patriots						
	Red Sox						
Last Championship	2008			•			
	2018						
	2019						

- Clue: The “Celtics” are a “Basketball” team.
- Constraint: “Celtics” is ”Basketball”.
- Rule: we know that ”Celtics” is “Basketball”.

Clues Rules (hard example)

		Sport			Last Championship		
		Baseball	Basketball	Football	2008	2018	2019
Team	Celtics		Y				
	Patriots						
	Red Sox						
Last Championship	2008			•			
	2018						
	2019						

- Clue: Either the “Red Sox” are a “Baseball” team, or they last won a championship in “2008”.
- Constraint: “Red Sox” is ”Baseball” xor “Red Sox” is “2008”.

Clues Rules (hard example)

		Sport			Last Championship		
		Baseball	Basketball	Football	2008	2018	2019
Team	Celtics		Y				
	Patriots						
	Red Sox			•			
Last Championship	2008			•			
	2018						
	2019						

- Clue: Either the “Red Sox” are a “Baseball” team, or they last won a championship in “2008”.
- Constraint: “Red Sox” is ”Baseball” xor “Red Sox” is “2008”.
- Rule: we know that ”Football” is not “Red Sox”.

Basic Consistency Rules

		Sport			Last Championship		
		Baseball	Basketball	Football	2008	2018	2019
Team	Celtics		Y				
	Patriots						
	Red Sox			•			
Last Championship	2008			•			
	2018						
	2019						

- If there is a *yes* in the grid, cells in the same row and column can be filled with *no*. This corresponds to the *Arc Consistency* inference rule[2].

[2] M. H. Sqalli and E. C. Freuder, *Inference-Based Constraint Satisfaction Supports Explanation*, AAAI 1996

Basic Consistency Rules

		Sport			Last Championship		
		Baseball	Basketball	Football	2008	2018	2019
Team	Celtics	•	Y	•			
	Patriots		•				
	Red Sox		•	•			
Last Championship	2008			•			
	2018						
	2019						

- If there is a *yes* in the grid, cells in the same row and column can be filled with *no*. This corresponds to the *Arc Consistency* inference rule[2].

[2] M. H. Sqalli and E. C. Freuder, *Inference-Based Constraint Satisfaction Supports Explanation*, AAAI 1996

Basic Consistency Rules

		Sport			Last Championship		
		Baseball	Basketball	Football	2008	2018	2019
Team	Celtics	•	Y	•			
	Patriots		•	Y			
	Red Sox	Y	•	•			
Last Championship	2008			•			
	2018						
	2019						

- If there is a *yes* in the grid, cells in the same row and column can be filled with *no*. This corresponds to the *Arc Consistency* inference rule[2].
- If all cells but one in a row or column are filled with *no*, the remaining cell must be filled with *yes*. This corresponds to the *Clique Consistency* inference rule[2].

[2] M. H. Sqalli and E. C. Freuder, *Inference-Based Constraint Satisfaction Supports Explanation*, AAAI 1996

Advanced Consistency Rules

		Sport			Last Championship		
		Baseball	Basketball	Football	2008	2018	2019
Team	Celtics	•	Y	•			
	Patriots		•	Y	•		
	Red Sox	Y	•	•			
Last Championship	2008			•			
	2018						
	2019						

Transitive properties of the grid format can be exploited. This corresponds to the *Transitivity* inference rule[2].

[2] M. H. Sqalli and E. C. Freuder, *Inference-Based Constraint Satisfaction Supports Explanation*, AAAI 1996

Advanced Consistency Rules

- Rectangles: related to the *Generalized Neighborhood Clique Consistency* inference rule[2].
- NoCommon: Two elements are different if for some third category they do not have at least one common element they can potentially be equal to.

[2] M. H. Sqalli and E. C. Freuder, *Inference-Based Constraint Satisfaction Supports Explanation*, AAAI 1996

Priority

1. Cycle through the clues in order. For each one, check whether a clues rule can be applied. No going back to previous clues, even if progress is made.
2. Apply basic consistency rules as much as possible. If progress is made, check if basic consistency rules that failed previously now work.
3. Only try advanced consistency rules if no progress was made with other types of rules. As soon as any advanced consistency rule fills a cell, go to 1.

Step 4: Explanation

One cell, one line

Every time a cell is filled, a line of explanation is written.

Output files for the website puzzles can be found at
http://ucc.insight-centre.org/gescamocher/Grail_Output.zip

		Country			Year of Birth		
		Germany	Ireland	USA	1946	1954	1979
First Name	Angela						
	Donald						
	Leo						
Year of Birth	1946						
	1954						
	1979						

Clues

1. The person from the "United States" was born in "1946".
2. "Leo" is younger than the person from "Germany".
3. "Donald" was born in "1946" or he is from "Ireland".

		Country			Year of Birth		
		Germany	Ireland	USA	1946	1954	1979
First Name	Angela						
	Donald						
	Leo						
Year of Birth	1946			Y			
	1954						
	1979						

- "United States" is "1946" (Clue 1).

Clues

1. The person from the "United States" was born in "1946".
2. "Leo" is younger than the person from "Germany".
3. "Donald" was born in "1946" or he is from "Ireland".

		Country			Year of Birth		
		Germany	Ireland	USA	1946	1954	1979
First Name	Angela						
	Donald						
	Leo	•					
Year of Birth	1946			Y			
	1954						
	1979						

Clues

1. The person from the "United States" was born in "1946".
2. "Leo" is younger than the person from "Germany".
3. "Donald" was born in "1946" or he is from "Ireland".

- "United States" is "1946" (Clue 1).
- "Leo" is after "Germany" in the "Year of Birth" category (Clue 2), so "Leo" is not "Germany".

		Country			Year of Birth		
		Germany	Ireland	USA	1946	1954	1979
First Name	Angela						
	Donald						
	Leo	•			•		
Year of Birth	1946			Y			
	1954						
	1979						

Clues

1. The person from the "United States" was born in "1946".
2. "Leo" is younger than the person from "Germany".
3. "Donald" was born in "1946" or he is from "Ireland".

- "United States" is "1946" (Clue 1).
- "Leo" is after "Germany" in the "Year of Birth" category (Clue 2), so "Leo" is not "Germany".
- "Leo" is after "Germany" in the "Year of Birth" category (Clue 2), so "Leo" is not the first element in that category, so "Leo" is not "1946".

		Country			Year of Birth		
		Germany	Ireland	USA	1946	1954	1979
First Name	Angela						
	Donald						
	Leo	•			•		
Year of Birth	1946			Y			
	1954						
	1979	•					

Clues

1. The person from the "United States" was born in "1946".
2. "Leo" is younger than the person from "Germany".
3. "Donald" was born in "1946" or he is from "Ireland".

- "United States" is "1946" (Clue 1).
- "Leo" is after "Germany" in the "Year of Birth" category (Clue 2), so "Leo" is not "Germany".
- "Leo" is after "Germany" in the "Year of Birth" category (Clue 2), so "Leo" is not the first element in that category, so "Leo" is not "1946".
- "Leo" is after "Germany" in the "Year of Birth" category (Clue 2), so "Germany" is not the last element in that category, so "Germany" is not "1979".

		Country			Year of Birth		
		Germany	Ireland	USA	1946	1954	1979
First Name	Angela						
	Donald						
	Leo	•			•		
Year of Birth	1946	•	•	Y			
	1954	Y	•	•			
	1979	•	Y	•			

Clues

1. The person from the "United States" was born in "1946".
2. "Leo" is younger than the person from "Germany".
3. "Donald" was born in "1946" or he is from "Ireland".

- 7 cells can be filled from basic consistency.

		Country			Year of Birth		
		Germany	Ireland	USA	1946	1954	1979
First Name	Angela						
	Donald						
	Leo	•			•	•	
Year of Birth	1946	•	•	Y			
	1954	Y	•	•			
	1979	•	Y	•			

Clues

1. The person from the "United States" was born in "1946".
2. "Leo" is younger than the person from "Germany".
3. "Donald" was born in "1946" or he is from "Ireland".

- "Germany" is not one of the first 1 element in the "Year of Birth" category, and "Leo" is after "Germany" in that category (Clue 2), so "Leo" is not one of the first 2 elements in the "Year of Birth" category, so "Leo" is not "1954".

		Country			Year of Birth		
		Germany	Ireland	USA	1946	1954	1979
First Name	Angela						
	Donald	•					
	Leo	•			•	•	
Year of Birth	1946	•	•	Y			
	1954	Y	•	•			
	1979	•	Y	•			

Clues

1. The person from the "United States" was born in "1946".
2. "Leo" is younger than the person from "Germany".
3. "Donald" was born in "1946" or he is from "Ireland".

- "Germany" is not one of the first 1 element in the "Year of Birth" category, and "Leo" is after "Germany" in that category (Clue 2), so "Leo" is not one of the first 2 elements in the "Year of Birth" category, so "Leo" is not "1954".
- "Donald" is "1946" or "Ireland" (Clue 3), and "Germany" is neither "1946" nor "Ireland", so "Donald" is not "Germany".

		Country			Year of Birth		
		Germany	Ireland	USA	1946	1954	1979
First Name	Angela						
	Donald	•				•	
	Leo	•			•	•	
Year of Birth	1946	•	•	Y			
	1954	Y	•	•			
	1979	•	Y	•			

Clues

1. The person from the "United States" was born in "1946".
2. "Leo" is younger than the person from "Germany".
3. "Donald" was born in "1946" or he is from "Ireland".

- "Germany" is not one of the first 1 element in the "Year of Birth" category, and "Leo" is after "Germany" in that category (Clue 2), so "Leo" is not one of the first 2 elements in the "Year of Birth" category, so "Leo" is not "1954".
- "Donald" is "1946" or "Ireland" (Clue 3), and "Germany" is neither "1946" nor "Ireland", so "Donald" is not "Germany".
- "Donald" is "1946" or "Ireland" (Clue 3), and "1954" is neither "1946" nor "Ireland", so "Donald" is not "1954".

		Country			Year of Birth		
		Germany	Ireland	USA	1946	1954	1979
First Name	Angela	Y	•	•	•	Y	•
	Donald	•			Y	•	•
	Leo	•			•	•	Y
Year of Birth	1946	•	•	Y			
	1954	Y	•	•			
	1979	•	Y	•			

Clues

1. The person from the "United States" was born in "1946".
2. "Leo" is younger than the person from "Germany".
3. "Donald" was born in "1946" or he is from "Ireland".

- 9 cells can be filled from basic consistency.

		Country			Year of Birth		
		Germany	Ireland	USA	1946	1954	1979
First Name	Angela	Y	•	•	•	Y	•
	Donald	•		Y	Y	•	•
	Leo	•			•	•	Y
Year of Birth	1946	•	•	Y			
	1954	Y	•	•			
	1979	•	Y	•			

Clues

1. The person from the "United States" was born in "1946".
2. "Leo" is younger than the person from "Germany".
3. "Donald" was born in "1946" or he is from "Ireland".

- 9 cells can be filled from basic consistency.
- "Donald" is "1946" and "1946" is "United States", so "Donald" is "United States".

		Country			Year of Birth		
		Germany	Ireland	USA	1946	1954	1979
First Name	Angela	Y	•	•	•	Y	•
	Donald	•	•	Y	Y	•	•
	Leo	•	Y	•	•	•	Y
Year of Birth	1946	•	•	Y			
	1954	Y	•	•			
	1979	•	Y	•			

Clues

1. The person from the "United States" was born in "1946".
2. "Leo" is younger than the person from "Germany".
3. "Donald" was born in "1946" or he is from "Ireland".

- 9 cells can be filled from basic consistency.
- "Donald" is "1946" and "1946" is "United States", so "Donald" is "United States".
- 3 cells can be filled from basic consistency.

Bonus Features

Clue obsolescence User is notified when a clue will not be looked at again.

Single cell solving Only the cells/explanation leading to the solving of a given cell are filled/displayed.

CNF conversion Puzzles can be written into a CNF file. Useful for debugging.

Outline

Puzzles Considered

Difficulty	Easy	Hard	Zebra	Total
Valid	55	13	1	69
Invalid	5	3		

Most invalid puzzles removed because of too many (> 1) solutions.

Challenges Encountered

- Information in the opening statement is needed.
  - Easy 22 “Baggage Mishaps”
  - Easy 60 “Holiday Decision”
  - Easy 64 “Robbery at Millionaire’s Mansion”
  - Easy 70 “The racehorses”
  - Easy 76 “Three little boys”
  - Easy 83 “The Enchanted Forest”

  Fix: treated opening statement as Clue 0.
- Cross-referencing meta-information that our constraints cannot model.
  - Easy 65 “Sporting Excellence”

  Fix: none found :(
- Objective contains a label that appear in the clues but not in the existing categories.
  - Hard 119 “A New Personal Computer” (label is “Andrew”, objective is “which computer has been chosen by Andrew?”)

  Fix: added an extra category containing the elements {“Andrew”, “NotAndrew1”, “NotAndrew2”, “NotAndrew3”, “NotAndrew4”}.

Success Rate

68/69 (98.6%)

How long does it take to process all these puzzles?

Conclusion

Our program

- Fulfills 3.5/4 steps of the challenge.
- Solved with explanation 67/68 puzzles from the target website, including all the valid Hard ones.
- Runs quickly, anywhere.
- Contains additional features to enhance explanation.

Future Feature

Puzzle difficulty rating

Difficulty of a puzzle could be determined from the inference rules needed to solve it.

Our observations

Hard 105 “Film Festival” uses the most elaborate rules.

The End

Thank you for your attention
Questions are welcome!

- http://ucc.insight-centre.org/gescamocher/Grail.zip
- http://ucc.insight-centre.org/gescamocher/Grail_Input.zip
- http://ucc.insight-centre.org/gescamocher/Grail_Output.zip